OUR COVER

. . . artist's concept of the Lunar Excursion Module (LEM), manned by two astronauts, after its separation from the Apollo Command-Service Module (seen in background) and the start of its descent to the surface of the moon. A third astronaut stays in the Command Service Module, which awaits the return of LEM in a lunar parking orbit. After the return of LEM, the flight back to earth is made in the CSM while LEM stays in a moon orbit. RCA-built electronics provide: communications to and from LEM, control of the LEM attitude and engines during its descent to and ascent from the lunar surface, and the means for rendezvous when LEM leaves the lunar surface. (Cover Art Director, J. Parvin)

Man on the Moon

A listing of man's major achievements might include the building of the pyramids, the crossing of an unknown ocean by Christopher Columbus, the invention of the steam engine, the discovery of polio vaccine, and the harnessing of atomic energy.

Any future listing will certainly include the landing of man on the moon. This accomplishment will encompass significant achievements in planning and managing the efforts of many people over many years, the development and application of the sciences, and the personal courage and calculated daring of exploration.

This issue contains details of some of the contributions of RCA engineers and scientists to this venture.

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A TECHNICAL JOURNAL PUBLISHED BY **RADIO CORPORATION OF AMERICA,** PRODUCT ENGINEERING 2-8, CAMDEN, N. J.

• To disseminate to RCA engineers technical information of professional value. • To publish in an appropriate manner important technical developments at RCA, and the role of the engineer. • To serve as a medium of interchange of technical information between various groups at RCA. • To create a community of engineering interest within the company by stressing the interrelated nature of all technical contributions. • To help publicize engineering achievements in a manner that will promote the interests and reputation of RCA in the engineering field. • To provide a convenient means by which the RCA engineer may review his professional work before associates and engineering management. • To announce outstanding and unusual achievements of RCA engineers in a manner most likely to enhance their prestige and professional status.

RCA ENGINEER articles are indexed annually in the April-May issue and in the "Index to RCA Technical Papers."

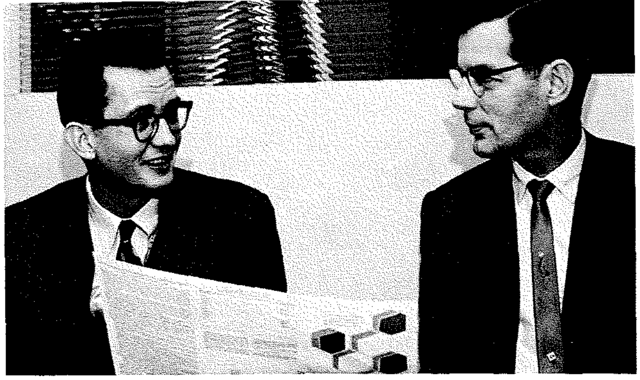
A FUNDAMENTAL change in the character of the defense business was initiated in the early 1960's by the Secretary of Defense, Robert S. McNamara. Despite major improvements in management procedures, it was recognized in the spring of 1961 that further advances were required. Accordingly, the budget estimates for fiscal year 1963 were prepared during the summer of 1961 in *Program Package* terms. For the first time, primary emphasis was placed on military missions, such as Strategic Retaliatory Forces, rather than on individual military services. Further, programs were specified over a 5-year period to provide a better basis for making decisions having long-range effects. These

The Engineer and the Corporation

THE CHANGING CHARACTER OF THE DEFENSE BUSINESS

New Customer Disciplines

J. A. DOUGHTY and R. B. HINES
*Communications Systems Div.
Camden, N.J.*



Authors R. B. Hines, left, and J. A. Doughty

J. A. DOUGHTY received his BS degree in Physics in 1947 and his MS in Physics in 1948 from Indiana State College. From 1950 to 1953 he was Assistant Professor and Research Associate at the University of Arkansas. He joined RCA in 1953 as a senior engineer. Assigned to such programs as Time Division Data Link and DynaSoar Communications and Tracking System, he was promoted to Engineering Leader and Manager, Systems Plans and Liaison. In 1961 he transferred to Marketing as Manager, Proposals, Aerospace Communications and Controls Division. Later he was named Manager, Proposals and Presentations on the staff of the Communications Systems Division. He became Manager, Data Configuration Control in July 1965. He is the author of approximately 30 publications and papers, including "Baseline Management" and "Guide for Proposals," copyrighted and published by RCA.

ROBERT HINES received his BA degree in Physics from the University of Virginia in 1949. Prior to joining RCA, he worked for Minneapolis-Honeywell as a marketing specialist and with Burroughs Corporation as Supervisor of Technical Publications. He joined RCA in 1958 as an "A" engineer. Mr. Hines has 14 years of experience in the preparation of proposals and the marketing of instrumentation, digital computers, and aerospace systems. In September 1963 he was named Manager, Proposals in the Communications Systems Division. As such he is concerned with RCA's response to changing defense marketing requirements. Mr. Hines is the author of 14 papers and publications.

policies were designed to increase the effectiveness of the office of the Secretary of Defense as a point of decision, to decrease the number of DoD efforts that might work at cross-purposes, and—perhaps most significantly—to obtain more total value for each dollar spent. By now these policy decisions have been translated into regulations, procedures have been developed, handbooks have been prepared, and contracts have been written. The total effect of all of this is that contractors to the Government have had to examine and evaluate their methods of executing Government work in order to compete successfully.

THE ROLE OF EXPANDING TECHNOLOGY

The post-World War II technological explosion created a need for management techniques that could use and control that explosion effectively. Development programs of increasing complexity and scope were undertaken as technology permitted imaginative concepts to be translated into defense and space hardware. Typical programs of this type are Atlas, Minuteman, Ranger, and Apollo. Along the way the technical complexity was more than matched by management complexity. The Department of Defense and NASA developed management techniques, philosophies, and procedures all directed to harnessing and efficiently channelling the increasingly rapid technological advances to useful ends. These philosophies were evolved to avoid unhappy occasions in which the Government might receive either much less or much more capability than it had initially planned to procure.

In the modern approach that has evolved, the total defense capability of the United States is continually examined on a *military mission* basis. Emphasis is placed on achieving maximum capability for the total defense budget. Both the Military Services and the defense industry have discovered that the Office of the Secretary of Defense is the ultimate customer. This office exercises firm approval and disapproval prerogatives on the initiation of all new weapons systems, and it demands more and more trade-off studies—studies now considered necessary to verify that a proposed system offers the best solution to the approved operational requirement. And the best solution is not necessarily the most technologically advanced one. Thus, advanced technology is now viewed in a relative sense—relative to real needs and reasonable costs.

NEW MANAGEMENT PHILOSOPHY

Prior to the 1960's there was no easy or clear-cut way to make objective decisions on the fate of programs because competing programs could not be compared. It was difficult or impossible to decide whether to initiate, continue, modify, or terminate any particular system. The only basis of evaluation was technology and gross estimates of research and development costs. Other costs, such as those for training, installation, operation, and support were paid from several other budgets —usually in different commands—and could not, or were not, easily considered. As a result, it was sometimes enough to show that a need existed and that an answer *could be postulated* to obtain authority to proceed with development.

Today, technical, schedule, and budgetary thresholds are established for each program, and the program is then regularly measured against them. Those programs that fulfill expectations and proceed to a useful predetermined end are continued, and their managers have a clearly defined set of objectives against which to measure progress.

As an example, the Air Force calls its management philosophies and procedures *system management* and defines them in the "375 series" of procedural documents; similar Army philosophies and procedures are defined in Army Material Command Regulation 11-16; the Navy has started defining its management philosophy and procedures in Weapons Requirements-30, which deals with integrated maintenance management; and NASA is setting forth its philosophy and

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procedures in a pending *Phased Project Planning* Directive and in the NPC 500 series Apollo Management Manuals.

Each of these sets of management philosophies and procedures is based on extensive experience, and each is structured to avoid pitfalls experienced on previous Government contracts. Although developed independently, all share much the same basic philosophy. Their emergence and use represent a significant development in the art of management.

The Air Force's 375 series of documents are used here to illustrate the changing character of the defense business.

SOME IMPORTANT DEFINITIONS

The common significant concept that underlies all of these management methods is *system management by baseline. System management* is the organization, policies, and procedures required to manage a package of work, where the work to be done is defined by performance, funding, and schedule criteria—and its accomplishment is measured against a baseline.

By *baseline* is meant, ". . . an approved and defined point of departure for control of future changes in system or equipment performance and design." At first, it is a technical description of an equipment configuration, consisting of specifications for what is known and detailed plans of how to define what is as yet unknown. The overall system (equipment and facilities) to be delivered is subdivided into *contractor end items* which are the prime level of assembly (or equipment) for Air Force and contractor management control and accountability. As the program moves ahead, the baseline for each end item is refined to successively tighter tolerances. Secondly, the baseline itself is changed as required by experience on the program; and thirdly, the composition of the baseline is changed as plans are succeeded by specifications, and specifications are succeeded by drawings, reflecting program progress. A baseline is *not* a freeze which excludes further change. Rather, it is an initial point from which revisions or changes can be documented and controlled to assure that all requirements are properly interfaced. Its purpose is to insure that no gross system incompatabilities are introduced as the program progresses, and that a common reference point is available for further detail cost and schedule planning. The preparation of a realistic, self-consistent baseline is an act of planning and management that establishes a firm foundation for the entire program.

Underlying the new method of baseline management is the concept that system management is identical with decision management, which is identical with change management.

EXTENSION OF FORMALIZED CONTRACTING CONCEPT TO ALL LEVELS OF THE DOD

It is not surprising that industry tends to view the Government procurement office not only as *the customer* but also as the primary monitor and arbiter of contractor performance. As a corollary to this, the degree to which a Government procurement office achieves effective performance depends directly on how well the contractors with which it deals perform. For them to be effective, the contractor must be effective. It is important, then, for really good overall management of defense programs, that management methods be used that will provide measures of performance at more than just the immediate contractor/procurement-office level. By so doing, the DoD can effectively measure and integrate its many complex programs into an efficient overall management of the defense effort.

In the newest version of Air Force Regulation 375-1, *Management of System Programs* (and other directives and regulations), a method is imposed which requires that each level in the Air Force, beginning with the procurement office and going up to the Office of the Secretary of Defense, make a contract with its superior level defining what it will do, for how much money, and over what period of time. In this way every program is fitted together and integrated with every other program, and accountability is fixed. With accountability fixed by contract, and with each echelon having broader and more comprehensive responsibility than the one below it, the possibility of contractor/procurement office self-protection actions is decreased, whereas responsibilities and authorities are defined.

PROGRAM PHASING AND BASELINES

Defense programs now go through four formal phases in their life cycle—*conception, definition, acquisition,* and *operation*—each of which is funded separately. Firm requirements have been established for going from one phase to the next, with decision reserved by the Office of the Secretary of Defense as to whether the requirements have been met for proceeding to the next phase.

Conceptual Phase

The conceptual phase includes the earliest feasibility studies and the study leading to a precise definition of the specific military operational requirement to be filled or, alternatively, statements of the objective of the proposed advanced development. When the sponsoring service feels that it has met the requirements for proceeding to the definition phase, it submits to the Office of the Secretary of Defense a series of formal documents making up the program requirements baseline. In addition, documentation is submitted that defines completely the scope of the program, its budget and schedule, and its effectiveness relative to competing systems. It also specifies that engineering rather than experimentation is required. This is the major threshold to be crossed in the life cycle of the system; if approval is given here and nothing changes radically during subsequent phases, there is a strong likelihood that the system will pass the other thresholds leading to operational deployment. Conceptual-phase work is often performed by several companies, and sometimes military laboratories, attacking the same problem competitively. This competition often becomes fierce as contractors may invest in the studies to gain an advantage or headstart on the definition phase work. Often more than one service and several weapons systems will be in competition, with the ultimate decision resting with the Secretary of Defense.

Definition Phase

The documents that led to approval to begin the definition phase form the overall guidelines that constrain the system and its functions for the remainder of its life. All subsequent work on the system during definition, development, and production is no more than further refinements of the system concept within these guidelines. If a change is desired in the program requirements baseline, it has to be made by a formal change proposal, which goes through the same steps as the original program requirements baseline. For example, the definition phase ends with the approval of the plans, definitions, and specifications that make up the design requirements baseline; these documents govern the scope of the system program and are the basis of all subsequent efforts to phase-out. The scope of the systems engineering job is so well defined at this point that industry has submitted competitive fixed price or incentive proposals for the engineering development that follows in the acquisition phase.

Since the definition process is both competitive and evolutionary, a preconceived technical approach is unlikely to result in an optimum solution. The contractor must evolve multiple technical approaches, and as the operational requirement becomes further defined, perform trade-off studies and analyses to optimize the proposed conceptual solution. (This process is often called "homework," since it represents substantial effort that is often not immediately apparent in the presentation of the optimized solution.)

The fundamental purpose of the new management procedures is clear. They provide an environment of directed effort that leads to the classic engineering solution of a product that meets the stated requirement on time and at the least overall cost. Solid engineering achievement, in its broadest terms, is highlighted, and the effects of other, extraneous factors are reduced. To enter the competitive arena during the definition phase is almost assuredly too late—and to have supported the wrong technical approach is equally disastrous.

Acquisition and Operational Phase

The acquisition phase starts with the initial production order and ends with acceptance of the last production item and the completion of rigorous systems tests, by service personnel, which demonstrate that the production systems meet all requirements.

Even though the system concept, technical approach, and contract end items were defined and specified during the definition phase, the actual developmental effort does not begin until the acquisition phase. Again, the effect of the new procedures is to put a premium on effective engineering. With the system defined to a black-box level, each unit of which has approved performance specifications, the engineering task is clear and straightforward, althought not easy. Equipment must be developed that meets these specifications, within schedule, at lowest cost. Unless the contractor has participated in specifying the successful system, he is barred from the system development effort; that is, the developmental contractor is chosen at the end of the definition phase on the following bases: 1) the technical solution he proposed to meet the operational requirement, and 2) how completely he specified that solution. If a contractor loses the system development contract, he, at best, is relegated to bidding as a subcontractor on some of the black-box developments. After the initial production run by the developmental contractor, other contractors can bid on subsequent production runs. It is obvious, however, that the advantage in bidding on these subsequent production runs lies with the contractor who developed the equipment and put it into production. The key role played by engineering, even in a follow-on production effort, is apparent.

The operational phase covers the operational use of the system for its intended purpose, from introduction up until disposition of the last element of the system. Support for a system in the field rarely is provided, at least initially, by anyone other than the equipment manufacturer. The importance of winning the competition for the definition phase is again reinforced.

The Risks to be Faced

Definition-phase work is almost always competitive, with the development contract as the prize. The spur of competition may well cause a contractor to invest his own funds so that his plans and preparations for the job will be more advanced than those of his competitors. The overall result can be a large contractor investment in the effort to qualify for consideration for a major development contract. Beyond the direct financial costs that may be involved in conceptual and definition studies, the contractor will probably have to decide whether or not to hold his team together should there be unfunded or partially funded periods between phases. While it is not impossible to compete for this business and make a fair return, the cost of failing to win a given development contract, or after winning it, to make a profit on it at a fixed price, is high.

It must be emphasized that understanding the management systems is a *necessary but not sufficient* condition. The competitive advantage always rests with the best technical solution. This *best technical solution* is the best application of technology to the satisfaction of the customer's assessment of the requirement. The decision as to which solution to buy is ultimately based on weighted competitive factors which include performance, schedule, and cost. The heaviest weight is placed by the customer on those factors which he considers crucial to satisfying the requirement. This weighting is usually not discernable in the RFP and its attachments. The only effective way to ascertain the probable weighting is through direct engineer-to-engineer contact with the customer. Through this process, the contractor's technical people can explore the problem in depth and understand more fully the relatively undefined parts of the requirement. Consequently, the success of the contractor in obtaining new work is largely dependent on the competence of the engineers who represent him during these crucial interviews. The successful contractor's program ultimately evolves from the engineering process which combines technical and business judgment to define the *best technical solution.*

DOCUMENTATION AND MANAGEMENT

The DoD has developed methods of management, finance, production, and engineering that can be applied to a wide variety of engineering projects, using the tools of baseline definition. The contractor is required to follow these methods and document in detail the record of compliance with each procedural step and its logical resolution.

Each of these methods (e.g., PERT/cost, configuration management, and systems engineering management) highlights the act of decision—who makes it, with what information, and what its expected results will be. The documentation required provides a systematic structure that tells both contractor and Government where the job stands in detail. It provides a discipline that insures that no step is overlooked or skipped, and the impact of decision on every program element is clearly displayed.

As the DoD has progressively instituted the new requirements, the Military Services have trained their own project office personnel to assure contractor compliance with these requirements. The Military project office can track and evaluate each contractor decision and compare it against the established plan as the program progresses between the initial major decision and subsequent approval points that represent the major milestones. The contractor must reflect this approach in order to interface effectively and provide the services demanded by the customer.

BASELINE MANAGEMENT APPLIED TO PROPOSALS

In a contractor's drive for new defense business, the concept of baseline management and its impact on proposals is of major importance. The DoD requires submission of a completely definitive baseline as the central part of proposals or solicitations for new business. In the past, proposals were largely resumes of experience, a plan for a management organization, and a technical discussion that displayed the firm's competence in the particular application of technology required. Today, major systems proposals must present such thorough description and planning of all aspects of the job that the process of proposal preparation is in itself a demonstration of qualifications and ability to perform the job.

For example, a recent Air Force Systems Command procurement for development and prototype production of a communications system required 27 individual comprehensive plans and specifications as part of the proposal. These ranged from an aerospace ground equipment plan to a weight and balance control plan. Included were a personnel subsystem plan (covering the types of Air Force technicians required to operate and maintain the equipment, the training needed, and a plan for their schooling, including course outline and required training equipment), a technical data plan, a safety program plan, and other special plans. These were in addition to the fundamental technical development specification and plan, and the business plan. Each required schedules, work statements, and costs; each had to be keyed to the development, test, and production of the equipment. The combination and integration of these individual elements into one overall program plan meeting the required delivery schedule, together with a supporting PERT/cost plan, become the baseline for program conduct.

Defense proposals of this major-systems type are not now educated guesses at how a job might be handled; the preparation of the baseline for the proposal is in itself a thorough model, or simulation, of the job to be done.

DECISION MANAGEMENT

If a job is completely and thoroughly planned as required by the USAF 375 series, and if it proceeds exactly according to plan, no further management action is required (in the sense of revising plans, reversing earlier decisions, etc.). The job proceeds from baseline to baseline as scheduled; circuits work as planned and assemblies mate together; in short, specifications are met. Only when the job departs from its planned course is further management effort, as distinguished from engineering effort, required. When there is a plan for changes and a procedure for handling them as detailed in the 375 series, the problem of managing changes has been reduced to one of managing decisions, or *decision management*. The use of baselines and baseline control procedures delineates the areas within which decisions are restricted so that the ultimate aim of the job is advanced. The formalized system management process, if followed correctly, will not assure that the right decision is always made, but it will assure that a decision *is made* on the *right subject*—i.e., that the decision maker is attacking the right problem. Under these rules, the correct decision is almost unnoticed, but the incorrect decision is highlighted and the decision-maker is identified. Nor can one decide to temporize and do nothing, for the absense of decision is also highly visible.

DECISION-MAKING ROLE OF THE ENGINEER

With the imposition of the requirement for detailed documentation that ". . . will be the basis for, evolve in consonance with, and ultimately become the product of, the design process,"[1] the management role of the engineer is brought into sharp focus. The systems engineering process is guided by the requirements of sequential activity and functional flow diagrams which formalize the techniques of operations research. These diagrams display the full range of decision allowable on any question, as well as its constraints, and they permit traceability back to the fundamental system requirements baseline. The use of these functional flow diagrams highlights the essential high-cost decisions and pinpoints accountability for the decision. In any complex engineerng task there are a number of decisions that have a tremendous impact on the total cost of the system or subsystems. Such decisions must not be drifted into, nor made at a level incommensurate with the consquences of the decision.

[1] AFSCM 375-5, Paragraph 13

The formalized procedures in the Air Force's 375-5 document endeavor to give maximum visibility to all significant technical decisions and to expose their logical consequences and antecedents. Such technical decisions are properly made by the systems engineer. The 375-5 philosophy recognizes that this management role has almost always been played by the engineer as he seeks out the detailed technical solution to a problem.

To a great degree, the effective technical review of a program is done at the level of the first-line engineering supervisor. In effect, he authenticates the decisions made by the engineer. The remainder of the management structure is responsible for supplying the business integration, coordination, and administration that engineering needs and for providing the resources it requires. This type of operation strengthens the decision power and importance of first-line supervision, and diminishes the need for a multilayered management structure between first-line and top engineering management. The result is decision-making efficiency on many detailed technical matters by those closest to the job, accompanied by more efficient vertical control and communications for the chief engineer.

EFFECTS ON THE ORGANIZATION

To meet the requirements of these analyses most effectively, the contractor must set up his organization in such a way that: 1) costing is on a hardware-element (or end-item) basis, not on an organizational basis; 2) the organizational approach of the Military Service's project office is reflected in the contractor's own organization; and 3) the division of labor extends down to intensively specialized skill groups, each with a degree of creativity that matches the scope of the function encompassed by that group.

The DoD has set up a program office to manage the job in depth and to achieve the goal of a useful operational system that meets its performance requirements at the lowest overall cost to the Government. Data is required from contractors to monitor progress and/or to make decisions involving the integrity of the baseline. The data required will often not be of equally direct use, in a business sense, to the contractor who has a different goal—the delivery of equipment which meets the contractual obligation and the earning of a fair return on invested resources in the process. A third party, the eventual user, requires another kind of data—that which is needed to operate and maintain the equipment. The efficient compromise of these somewhat conflicting requirements is resulting in the training of a new group of specialists called *data managers*.

CONCLUSION

The emphasis in the new business environment on the management and administrative process recognizes that shortcomings in technical management and not technology are the limiting factors in systems acquisitions. The product is still uniquely the result of the engineer and the engineering process. In a highly competitive market place, the customer is carefully evaluating and buying the best solution to a national defense objective. This consists of the acquisition of a defined level of performance and capability—available when needed and at the lowest possible cost. Such a procurement may involve combining a receiver that incorporates the latest state-of-the-art developments with off-the-shelf processors and a magnetic recorder from "that system we developed last year." The challenge to the engineering-management process is to channel its creativity and competence to the achievement of the *best solution*—the intimate combination of technical and business judgment.

HISTORY AND MANAGEMENT OF THE LEM PROGRAM IN RCA

A brief history of RCA's participation in the LEM program is presented. Successful and seasoned techniques utilized during the LEM proposal effort and after contractual go-ahead are described. Some of the pitfalls and difficulties encountered are also discussed.

F. J. GARDINER, Mgr.

LEM Program, Aerospace Systems Division, Burlington, Mass.

Before the end of this decade, three Americans will embark upon the greatest voyage of the twentieth century—a manned flight to the moon. The National Aeronautics and Space Administration, commissioned by the Government to perform this epochal feat, has mobilized over 5000 industrial firms to assure success.

The Apollo vehicle, which will carry the three astronauts to and from the moon, comprises three modules: the Command Module housing the astronauts; the Service Module containing the translunar rocket power; and the Lunar Excursion Module (LEM). The LEM vehicle will descend to the surface of the moon and ascend to rendezvous with the Command-Service Module (CSM). The astronauts will transfer to the CSM for the return journey to earth.

Electronics will play a vital role in this mission. In the LEM vehicle, electronics will be utilized for navigation and guidance, communications, and maneuvering control. These electronic functions of the LEM are RCA's primary concern in the Apollo program.

RCA'S HISTORY IN PROGRAM

In many respects the early history of the LEM Program represents a classic approach to a large systems contract. This history has been documented and reviewed many times and, hopefully, it will be utilized to advantage in other instances.

Late in 1961, NASA awarded the Apollo contract to North American Aviation, and industry confidently expected that a procurement for the lunar landing stage would soon follow. This stage was to be an unmanned propulsion stage designed to land the Apollo manned spacecraft on the moon. Earth orbit rendezvous (EOR) was an essential step in this plan.

At RCA, the Astro Electronics Division had an impressive background in space satellites and electronic hardware. The Major Systems Division and the Missile and Surface Radar Division had extensive experience in ground tracking, trajectories, and operations of large systems. In addition, the Aerospace Systems Division was working intensively on the P-706 project which involved EOR techniques. By combining the capabilities of these four divisions, RCA could make a major contribution to the Apollo Program.

Final manuscript received December 21, 1965

Early RCA Apollo Studies

Marketing responsibility was assigned to the Astro-Elctronics Division and technical coordination to the Major Systems Division. It was decided to make an in-house study of an unmanned experimental EOR concept to simulate the problems of orbital refueling. Results of this study, presented to the NASA Marshall Space Flight Center, Huntsville, Ala., aroused considerable interest. Shortly thereafter, an unsolicited but well-coordinated proposal to fly such experimental vehicles was submitted. By the time the bulk of the technical work for this proposal had been completed, a new and fascinating approach was evolved by Dr. John Houbolt at the Langley Research Center of NASA. Late one evening in January 1962, Dr. Matson and the author made some calculations confirming that lunar orbit rendezvous (LOR) was the most effective technique. That was the turning point for RCA. Although the unsolicited proposal for the experimental unmanned EOR concept had been submitted to NASA, the bulk of the technical work was swung over immediately to studies of the new LOR technique, requiring the LEM vehicle for lunar landing. The further the study progressed, the more convincing the evidence appeared in favor of lunar orbit rendezvous. Both the EOR and LOR techniques are described in greater depth in a companion paper by Dr. L. E. Matson.

Later in 1962, NASA let a study contract for the LOR technique to Ling-Temco-Vought. Nevertheless, RCA was convinced that this approach would succeed, and RCA engineers were obtaining an increasing familiarity with the problem, and they were beginning to get a feel for this new and foreign environment, the moon, and the orbits and trajectories which the LEM must follow.

An Independent Study

In parallel with the RCA and the NASA in-house effort on LOR, the Grumman Aircraft Engineering Corporation had come to the same conclusions and was thus in a similar position. Grumman asked RCA to join in a study of the LEM vehicle, paralleling the NASA contract. RCA agreed and made available a team of specialists in the electronic and system analysis areas to work with Grumman. This team, located at Bethpage, N. Y., worked as an integral group with Grumman engineers. Management arrangements were simple and informal. The group worked together without real distinction of organization; the author was manager and coordinator for the RCA team and worked directly with the head of the Grumman preliminary design group. As before, the effort was a combined pool of RCA talent from each of the cooperating divisions, each funding its own effort at the request of and in coordination with the Major Systems Division.

1962 Design Report

A complete design report giving a thorough analysis of the Apollo mission and the LEM vehicle was issued in June 1962. Many features of the present LEM vehicle were identified and correctly designed. In general, the vehicle proposed at that time was somewhat less sophisticated and considerably lighter.

FRANK J. GARDINER received his BS degree in Aero-Thermodynamics from the Massachusetts Institute of Technology in 1943. After graduation he was commissioned in the U. S. Navy and served with the Pacific Fleet and later with the Bureau of Aeronautics in Washington. In 1947 he became Chief Engineer of Special Products Division, ITE Circuit Breaker, Philadelphia; principal products were microwave antennas and devices for both radar and communication systems. As a result of the growth of the Engineering Department, a separate division was set up in 1955 to market, design, test, and produce these devices. Mr. Gardiner managed that operation. In 1961 he joined RCA, Major Systems Division, Engineering Department and in a few months was assigned responsibility for space systems activities in that division. During 1962 an initial study was made of the lunar orbit technique; after that date the LEM effort was started. Mr. Gardiner was study and proposal manager until August 1962, when the Grumman proposal was submitted. After contractual go-ahead, as Manager, LEM Program, he moved with the LEM Program Office to the Aerospace Systems Division, Burlington.

The basic mission and trajectories have changed little since then, but have been considerably refined.

This design report was presented to NASA at various joint meetings, with both Grumman and RCA engineers participating. This study was the only complete one done by industry independently of NASA. The study concluded that the LEM vehicle and the LOR mission were distinctly superior to the original EOR concept. Grumman and RCA therefore strongly recommended to NASA that the official approach be changed from EOR to LOR. After considerable debate, LOR was adopted by NASA, and an RFQ for the LEM vehicle was issued by NASA in July 1962.

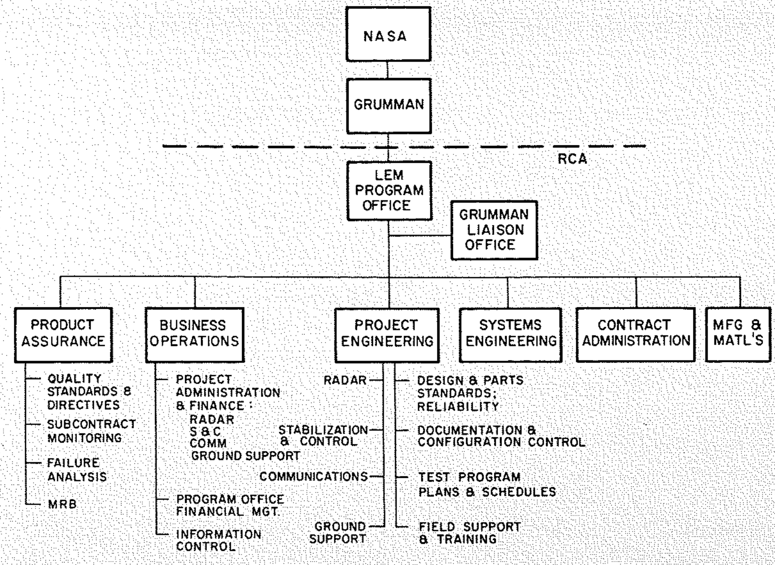


Fig. 1—Functional organization chart.

The Request for Quotation

Grumman and RCA were well prepared for this RFQ, which centered on several essay-type questions and which required a short and concise presentation. The final version of the proposal was edited jointly by the Grumman and RCA program managers. Although NASA stated that it could not be committed to team arrangements, the close working arrangement between Grumman and RCA had made it essential to follow through in a cooperative fashion. The proposal was filed in August and negotiations commenced in November 1962. Grumman received the prime contract in January 1963, and a subcontract to RCA followed in several weeks.

The Grumman-RCA approach to the LEM Program is called a *classic approach* for the following reasons:

1) The approach succeeded.
2) Both companies were well prepared.
3) Both companies had excellent technical backgrounds.
4) The target had been clearly identified well before any RFQ was received, in fact well before the Government officially adopted the LOR technique for the Apollo Program.
5) There was a continuous contact of a friendly and mutually beneficial nature between Grumman and RCA, and jointly with the customer.
6) Both companies were clearly identified with the LEM vehicle and obviously had the capability and resources to execute its design and fabrication.

RCA's Initial Assignments

RCA's initial contractual assignments consisted of several areas of system engineering, as well as preliminary engineering on electronic subjects. Work was considerably hampered by uncertainty of assignment to RCA of the original scope of work. It was hoped that major electronic hardware could be specified in detail before work would commence. In retrospect, one could second-guess this process and conclude that this period was not as effective as it could have been if preliminary design had been energetically pushed and organized trade-off studies had been performed. Thus, some key parameters were specified without adequate background; some have since been corrected, others were proved correct, and still others were found to be erroneous, but too late to permit correction.

RCA'S MANAGEMENT OF PROGRAM

Considering the history of the approach to the LEM Program and the key personnel involved, it was natural that RCA's management of the program would be based on the use of RCA skills from several divisions with a small central program office. Since the Aerospace Systems Division at Burlington was to receive the largest share of the work assigned to RCA, it was decided to move key personnel from Moorestown to Burlington. The remainder of the work was to be subcontracted and performed by other RCA divisions. A matrix type of project organization was established at the start of the first study (Fig. 1).

The LEM Program Office is responsible to Grumman in the following areas:

1) System engineering support
2) Landing radar, rendezvous radar, and associated ground support equipment
3) Communications subsystem and associated ground support equipment
4) Stabilization and control electronics.

The program office manages 12 different contracts, including activities at four RCA divisions, the RCA Service Company, and five major subcontractors.

Management Techniques

1) *The program office should not be directly involved in the design or manufacture of any hardware.* Further, all studies pertaining to hardware should be performed by the designing activity. However, the program office must have sufficient technical capability to monitor and make judgments independently of the design activities and subcontractors. Thus, a small systems group is appended to the program office, and specialized technical consultant services are supplied by several RCA activities.

2) *The identification of a project engineer who is solely and completely responsible for a given subsystem, black-box, or component;* other activities are identified to support him (Fig. 2). Supporting activities include standards engineering, PERT, financial, packaging, reliability engineering, quality control, etc. The responsible project engineer has full authority to apply inputs from these groups as he sees fit and to direct the support activities to achieve his specified goal. However, his actions are subject to review by higher authority, and his judgment is tempered by this knowledge. He must possess the final authority for the portion of the system assigned to him. Managing the development of sophisticated space age systems demands technical knowledge and expertness in many disciplines, and judgment that combines sensitivity to schedules and business acumen. The availability of project engineers with the required interests and inherent ability is basic to the success of the project engineering management approach. This availability factor is the weakness of the *Single Point of Responsibility and Authority* approach, yet no better scheme has been found. This approach has been preferred by the NASA Manned Space Flight Center, and it has been the cornerstone of RCA's management technique.

3) *Major subcontracts must be managed by the program office directly.* This group specializes in the management of projects and, therefore, can bring to bear the appropriate skills and assure the necessary cross-fertilization and ease of communication.

To achieve this the program office contracts for an integration activity which at first concerns itself with specifying the various black boxes or large components that are to be purchased. These specifications are furnished and continuously updated and reviewed by the integrating activity and submitted to the program office for approval and implementation.

4) *Level of responsibility and commensurate authority.* Efficient program management must assure that all echelons are working toward the same objectives as the program manager. The first step toward this goal is to be sure that the subcontractor management organization or the design organizations employed have a clear-cut management responsibility and authority. The program office must accurately specify the task in technical as well as financial and schedule terms and then must monitor the progress.

As used here, monitoring means making sure that the assigned group is acutely aware of its function and authority. Some project engineers try to manage the project details themselves and do not allow the assigned line management team to perform its function. The monitor must not over-direct and solve problems for the regular line management. If he does, the regular management group will feel ineffective and will tend to stand aside, or perhaps even obstruct, whereas their authority and responsibility must in fact be continuously pointed out to them.

The project engineer must also be sure that he specifies the end result desired and not the means of achieving it. Often a project engineer will specify a circuit or a design instead of carefully stating the desired performance independent of the means. Usually the performance is more difficult to state since it is a step toward generalization. But if the problem is understood, the designing activity will get to work to find the best solution. Only in this manner will the objective be achieved of getting many people to work at peak creativity and productivity instead of executing motions to another's commands.

Management Observations

One of the most difficult areas of program management has been the continuous flow of changes imposed by the customer. The number of contract changes have averaged six per week. In part, this is due to the complexity of the mission and the degree of refinement required in the hardware. These changes require a continuous reorientation of the program, invalidate plans and estimates, and make control of the project increasingly difficult. It is fundamental that performance be measured against a plan, but if this plan is continuously made obsolete by changes, the project engineer loses his standard of reference. In addition, he must devote a great deal of time to the change order itself, thereby distracting him from his original function. There is no clean-cut solution to this change-order problem in space-age hardware; however, it does point out again the need to specify only those things that truly must be specified. Each specification item and contract requirement proposed is a potential source of changes. Therefore the ideal specification accurately defines performance and interfaces only.

A lesson that has been forcibly learned is the ineffectiveness of incentive contracts in such an environment of continuous changes. Relatively slight variations in performance spell the difference between success and failure in an incentive contract; thus an incentive fee pattern may be designed to inspire desired performance in the contract so as to control the last 10% of cost or to assure delivery in a 2-year program within plus or minus 1 month. However, when changes affect contract targets significantly, incentive success or failure is profoundly affected. Rapid negotiation of changes is vital in incentive contracts; when this cannot be done by the parties involved, incentive targets become nebulous and meaningless. Current emphasis on incentive contracts has already revealed inherent weaknesses and should result in improved application of the incentive concept.

With the advent of the space age, new challenges in management, as well as in technical areas, have arisen. The technical problems of further miniaturization, greater reliability, and higher performance have been identified and discussed in many publications by many experts. However an additional and perhaps more fundamental problem of the challenge to management should be posed. Whenever engineering progress is made, there is a yardstick for measurement, i.e., the new machine is lighter, smaller, more reliable, or faster.

In management the measurement of success is more difficult. What is the yardstick? How are management approaches determined as better or weaker? One well-tested answer is competition, the very essence of our free enterprise system; but, this has been obscured by cost-plus defense contracts.

Yet, within a given technology and application, cost is still the fundamental management challenge; that is, total cost, not fee earned. One must find means of using this criterion more effectively. The LEM Program Office has devised several cost-measuring yardsticks which are being used as criteria. However, the effort is only in its infancy and will need much more data and thought.

CONCLUSIONS

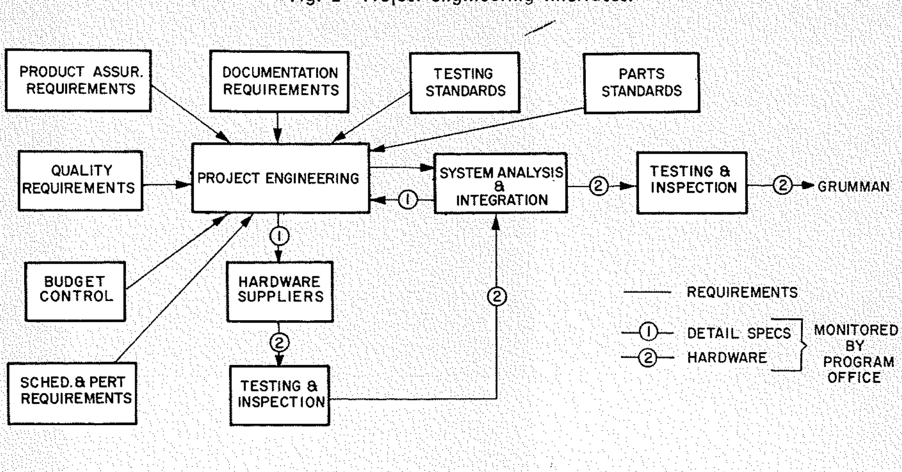
Starting with the inception of the customer's needs for LEM, RCA established a small project organization which conducted a successful proposal approach along the following guidelines:

1) Pooled needed skills from several divisions.
2) Organized and led the in-house effort prior to the RFQ.
3) Selected correct technical approach.
4) Convinced customer of ability to perform.

Following the award of contract, the following factors have been found to be important to successful operation:

1) Continuity of the project organization and personnel.
2) Management by small project organization.
3) Assignment of full authority and responsibility to project engineer with other activities in support of this assignment.
4) Delegation of design engineering and manufacturing functions.
5) Specification of performance requirements, rather than design details.
6) Delegation of management authority along with responsibility.

Fig. 2—Project engineering interfaces.



SYSTEMS CONSIDERATIONS FOR LANDING A MAN ON THE MOON

This paper describes the evolution of the Apollo mission in broad terms. Some of the more interesting factors studied by NASA and the Apollo contractors which have led NASA to choose the basic flight profile are discussed. Particular reference is made to the lunar descent, landing, takeoff, and rendezvous operations performed by the Lunar Excursion Module.

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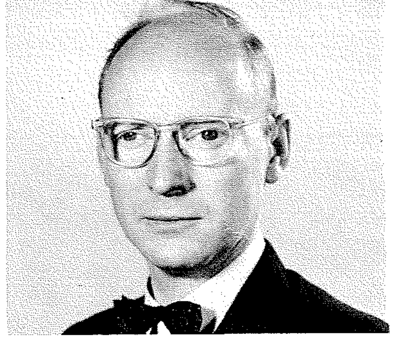

LESLIE E. MATSON received his BSE degree in Physics from the University of Michigan in 1942. He received an MSEE degree in 1955 and a PhD degree in Electrical Engineering from the University of Pennsylvania in 1961. He has been employed by RCA since 1942. Early experience included the design of radar equipments, and the system engineering of guidance and control equipment and radar data processing and decision equipments. From 1960 to 1963 he was with the Major Systems Division and subsequently with SEER as Manager of Systems Analysis. As such he was responsible for: analyzing radar surveillance system performance, specifying the overall data processing mathematics for BMEWS, and system engineering in space vehicle trajectory and guidance work and mission analysis leading to the LEM contract. As Manager of Space Systems Analysis, Aerospace Systems Division, he is presently responsible for systems engineering required to establish design requirements of LEM equipment, and for systems analysis tasks under an engineering assistance contract.

THREE basic mission profiles were considered for the Apollo mission. They include: direct ascent, earth orbital rendezvous, and lunar orbital rendezvous. Each mission profile is discussed briefly in subsequent paragraphs.

BASIC MISSION PROFILES

The earliest plan was based on a simple overall mission concept: the direct flight of the crew in the Apollo Command Module (CM) from the launch pad on earth successively to an earth park orbit, a lunar park orbit, a landing on the moon, and (after launching into a somewhat different lunar park orbit) a return trajectory leading directly to re-entry into the earth's atmosphere. The CM itself is the only unit that the crew occupies. The CM has the heat shield for re-entry, but the rocket propulsion for all thrust periods is supplied by a succession of units which are discarded along the way. The trajectory profile in Fig. 1 illustrates the travel from the four basic locations as a function of time which proceeds from left to right. It can be seen from the figure that several stages of the original launch vehicle are discarded on the way to the lunar park orbit. The configuration that lands on the moon consists of the Lunar Landing Module (LLM), the Service Module (SM), and the CM. The function of the LLM is to land the Command and Service Modules (CSM) on the moon; the LLM would be left there. For the return journey, the SM would lift the CM into the lunar park orbit and then insert it into the trans-earth trajectory. When the CM is precisely on the proper path of atmospheric re-entry, the SM would be separated from it and the CM, containing the three astronauts, would re-enter the earth's atmosphere. The weight at launch required for this mission profile was more than the capability of the Saturn-V launch configuration. Therefore, rather than delay the Apollo program until the more powerful Nova launch vehicle could be developed, other mission profiles were considered.

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The earth orbital rendezvous (EOR) mission profile was planned by NASA to utilize two Saturn launchings and combine their payloads after rendezvous in earth park orbit. Once the payloads were combined, the vehicle would have the same configuration as the one described previously for the direct translunar flight. Thus, the mission shown in Fig. 2 would be essentially the same as before, except that two large assemblages would have to be connected in earth orbit, either to assemble the translunar configuration itself or to transfer fuel to it. This docking operation impressed many persons as being a dangerous operation; but after careful study, it became apparent that the rendezvous and docking operation would be much easier than the landing operation on the moon. Therefore, the EOR approach was accepted as a valid concept which would permit the use of the Saturn-V launch configuration.

Another basic mission profile was developed which further reduced launch weight requirements by not taking the return vehicle with its propulsion system to the surface of the moon. In this procedure, called lunar orbital rendezvous (LOR), the CSM is parked in lunar orbit (Fig. 3) and a separate vehicle, the Lunar Excursion Module (LEM), takes two astronauts down to the landing site and returns them to rendezvous with the CSM. The LEM is built in two sections: the descent stage, which is left on the lunar surface, and the ascent stage with crew quarters, which is left in lunar orbit after rendezvous. With this particular mission plan, the launch configuration consists of a single Saturn V.

One complication of the LOR plan that makes it seem difficult is the *turn-around* maneuver which is required on the way to the lunar park orbit. This arises because the escape tower must be temporarily attached to the top of the CM at launch to provide an escape in case of very early launcher malfunction; also, the SM must be immediately below the CM to permit recovery from any subsequent launcher malfunction. Thus, the LEM must be carried below the SM during launch, but must be attached to the top of the CM when the SM provides thrust for guidance to and insertion into the lunar park orbit. Therefore, during the translunar coasting flight, the CSM must disengage from the LEM, turn around, attach its top end to the LEM, and then finally separate itself and LEM from the S-IV stage which by that time has served its purpose. Although the turn-around seems complicated, there is adequate time for careful execution. The only critical phase is docking, a technique which must be perfected in any event.

In comparing these three overall plans, it was clear that the LOR mission required the least total launch weight. However, this was only one of a number of considerations. The direct ascent flight plan was abandoned because of the late development timetable for the Nova. Therefore, the comparison centered on the EOR and LOR plans. The LOR turned out to be more satisfactory on several counts. The rendezvous and docking operations initially appeared to favor the EOR plan because they occurred near the earth where earth measurement of orbits was more precise. However, it was recognized that the LOR docking maneuver would be easier because the docking vehicles are smaller. In addition, the earth-based measuring systems are also quite capable of assisting the early phases of a lunar rendezvous. In both EOR and LOR, the final critical stages of approach and docking must be controlled by on-board systems and the crew. Therefore, the mechanical problems of docking the larger units or transferring propellants in orbit as required in EOR tend to favor the LOR mission.

A second major difference between the EOR and LOR plans is that, although both require landing modules, the LEM development should be much easier and less uncertain than that of the much larger LLM which must support both the CM and the SM. In the case of LOR, the entire landing configuration could be optimized for the most critical mission phases of lunar landing and takeoff without necessitating undesirable trade-offs for the sake of other phases. Consequently, it was decided that the LOR approach would be less expensive, much easier to plan, and more likely to succeed than the EOR approach.

LEM GUIDANCE REQUIREMENTS

The primary navigation and guidance equipment for Apollo consists basically of a three-axis inertial platform called the Inertial Measurement Unit (IMU), a general-purpose digital computer, and optical equipment for measuring angles from stars to horizons or landmarks of the earth or moon and for aligning the IMU to a stellar reference.

It was decided that the Primary Guidance, Navigation, and Control System for the LEM should consist of the same basic computer design and IMU as the CSM. The sensors for the LEM, however, must be considerably different because of the special requirements for lunar landing and for rendezvous.

A number of major trade-off studies were conducted on the various sensor requirements, and several of the more interesting ones are treated herein along with certain other details of the LEM mission profile.

LUNAR DESCENT ORBIT

One of the major problems in the mission design has been to provide alternate hardware systems and alternate mission profiles in order to maintain a very high probability of safe return in addition to a high probability of complete mission success. An interesting feature was the choice of the LEM lunar descent coasting path. Since the moon has no atmosphere, the landing must be done entirely by the use of rocket thrust. The most efficient method of descent from the 80-mile altitude of the CSM parking orbit is to execute first a short *insertion* burn. This maneuver would change the trajectory from a circular orbit to an elliptical orbit whose highest altitude would be at the CSM orbit and whose lowest altitude would be close to the lunar surface (about 50,000 feet is usually chosen). Near the low-altitude point, the major thrusting period would be initiated and in one burn the vehicle would be slowed down and landed. Accurate control is needed for the landing phase, and, therefore, the descent engine must be throttleable. This coasting path, called a Hohmann descent, is shown in Fig. 4.

It was observed that if, for some reason, it was decided not to perform the landing maneuver, the LEM could coast back up to the orbit altitude of the CSM. However, even though it would arrive back at the CSM altitude at the same point in space at which insertion occurred, it would get there about 6 minutes sooner than the CSM and would, therefore, be more than 300 miles away from it. If the descent coasting path could be chosen so that the period of the descending orbit equaled that of the CSM, then the two would return to the insertion point at about the same time, permitting an easier rendezvous. Such a descent orbit is called a synchronous descent and is shown in Fig. 5. It can be seen that this descent occupies only one-quarter of an orbit and the so-called synchronous return, which would be followed if the powered descent were not attempted, would occupy three-quarters of an orbit. Note that the first crossing of the synchronous return path with the CSM orbit is not used, since the two vehicles arrive at different times.

The basic trade-off parameters between these two flight paths are mission safety and propellant weight. The synchronous descent would appear to be safer because it offers an easy abort capability, as described previously. However, this feature must be evaluated in the light of the probability of this procedure being required, the question of whether this procedure is actually much easier than the abort procedures from the Hohmann path, and whether the use

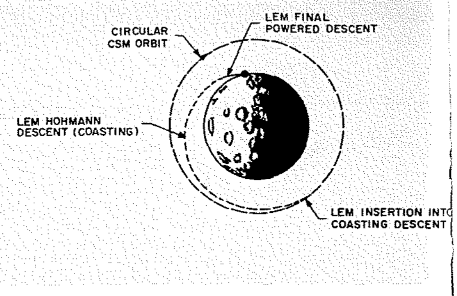

Fig. 4—Hohmann descent trajectory.

of the synchronous descent introduces other possible dangers. For instance, if in a synchronous descent the amount of insertion thrust were correctly controlled but aimed slightly in the wrong direction, it could put the LEM on a path which would impact on the moon. In contrast, no matter how the angle of a Hohmann insertion thrust is changed, the error can only raise minimum altitude. Basically, the only emergency situation which would show an advantage for the synchronous descent would be a failure of the primary navigation system; but this system is backed by both an on-board abort guidance system and by the earth-based tracking and computation networks. Since the approach speed for the synchronous return is several times as high as for the standard and abort rendezvous approaches, rendezvous from the synchronous return is somewhat more difficult. Therefore, on closer examination, the synchronous descent is not necessarily safer than the Hohmann descent.

The propellant weight trade-off is based on a more tangible fact: the synchronous descent would require in the order of 400 feet per second more engine capability than the Hohmann. The propellant needed to provide this additional capability weighs over 1000 pounds. Thus, the synchronous orbit would actually require the sacrifice of a large amount of real payload. Although the initial plans provided the capability to execute a synchronous descent, better uses have been found for this weight in structure, propulsion system, and payload.

LUNAR LANDING SENSORS

Many types of sensors have been considered for providing accurate information to the guidance system for the landing operation. One plan involved the use of a monopulse-terrain-avoidance type of radar. Another would use a laser radar to measure the range to the lunar landing point selected by the pilot

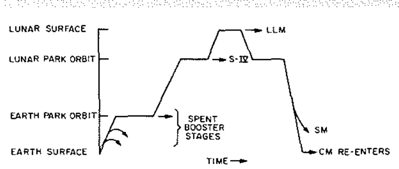

Fig. 1—Direct-flight lunar mission plan (one Nova launch).

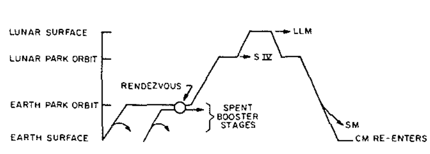

Fig. 2—Earth orbital rendezvous mission plan (two Saturn-V launches).

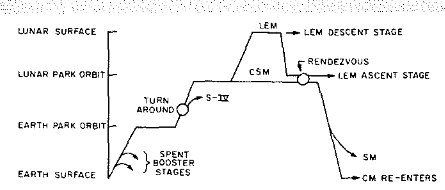

Fig. 3—Lunar orbital rendezvous plan (one Saturn-V launch).

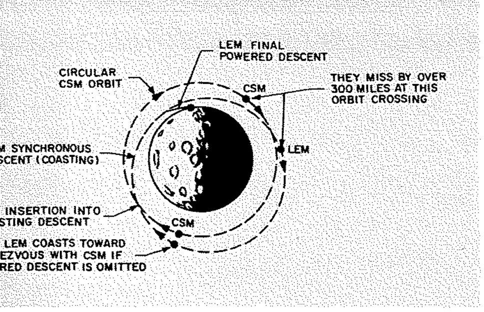

Fig. 5—Synchronous descent trajectory.

with the aid of an optical sight. Other basic approaches included various types of doppler radars and radars for tracking a transponder previously placed at the landing site. A multibeam doppler radar altimeter was chosen because it permits day or night landings, does not depend on prelocated landing aids, allows unmanned landings, and supplies data directly to displays, making it possible for the crew to land under completely manual control. Since the landing radar is located on the LEM descent stage, which will be left on the lunar surface, its weight does not penalize the ascent phase.

The selection of a safe touchdown point is vitally important. The Surveyor program is expected to obtain information both on evaluation of the possible dangers and the certification of specific sites. In order to guide the LEM to a certified site, it is planned that Surveyor will place a marker of some sort near the site. If the marker is a transponder, the LEM rendezvous radar (discussed below and in a companion paper) will track it during the latter portion of the descent.

A surface mode was originally designed into the rendezvous radar as a backup landing sensor with potential usefulness also in the ascent phase, but since it has not proved to be necessary, it has been deleted.

SENSORS FOR LUNAR SURFACE ALIGNMENT OF THE GUIDANCE SYSTEM

The alignment optical telescope (AOT) will be used to make star sightings to align the inertial equipment. Alignment will be assisted by measuring the lunar gravity direction with the inertial system. However, it is necessary to track the CSM to provide an independent check of the orbit relative to the actual landing point. The rendezvous radar is well suited to this function; the only special requirement imposed by this phase is the need for coverage over the majority of the hemisphere above LEM.

SENSORS FOR RENDEZVOUS

The basic sensor for rendezvous is the rendezvous radar. In the early part of the program it was decided to provide a backup for this function, installing rendezvous radar and transponders both on LEM and on the CSM. Either one of these could make the measurements required, and if the LEM rendezvous radar should fail, the CSM could make the computations and communicate the control order to the LEM. Also, the CSM propulsion system has the capability to rendezvous with the LEM. As was the case with the trade-offs between the Hohmann and synchronous descent paths, weight became the deciding factor. Since the earth-tracking and computing networks could back up the LEM rendezvous radar, the CSM rendezvous radar was not actually necessary and, hence, was deleted. Manual rendezvous methods have been studied extensively and these studies were very significant in establishing early that rendezvous is not basically an extremely dangerous or difficult procedure. A number of studies of this problem showed that by providing displays to the crew indicating the range, closing rate, and the inertial angular rates of the line of sight to the CSM, the LEM pilot could effect a rendezvous whether he could see the CSM or not, and he could do this without assistance from either primary or backup guidance equipment.

CONTINUING TRADE-OFF AREAS

As mentioned previously, a wide variety of technical solutions exist for each of the basic electronic requirements of LEM. As this is written, for instance, it is still being considered whether an optical tracker should be used in place of the rendezvous radar and the AOT. Also, parallel developments on lasers continue, with an eye toward more distant future applications. Considerable weight reduction in the radar equipment could also be obtained, but this would delay the schedule too much to be considered at this point in the program.

From the evolution of Apollo it can be seen that the three most tangible parameters in system considerations are schedule, cost, and weight. Many other parameters that would be expected to strongly influence overall systems decisions have not been as critical as the three mentioned. Some of these other considerations are discussed below.

Accuracy has always been a very real criterion in specific hardware designs, but it has not been critical in forming system decisions because basically different implementations can meet mission accuracy requirements with appropriate modification of details of the mission profile. Reliability has also remained largely a design implementation requirement rather than a critical decision parameter. It is a factor in design decisions, such as the use of integrated circuits, but some policy fluctuations have been permitted, such as allowing or inhibiting the use of various vacuum-tube devices.

The provision of manual modes of operation for monitoring and backup functions has not appeared to be the primary consideration in the design of LEM navigational and guidance equipment. The approach has tended to shift toward providing a high-performance, automatic navigation system and specifying the major crew requirements to cover any deficiencies of the automatic system, rather than providing manual aids to permit the crew to do all that is believed to be consistent with human capabilities. The automatic trend has resulted from a growing confidence in equipment reliability and a desire to keep the complexity of the crew's duties to a minimum. Also, providing manual modes increases cost and weight. Furthermore, while it is possible to calculate high reliability estimates for equipment, the probability of success of critical crew operations is hard to estimate. A major factor in Apollo system evolution, particularly with regard to backup system provisions, flight monitoring, and in-flight decisions, has been a growing dependence on the capability of the Manned Space Flight Network of earth-based radio-tracking and computing equipment to perform these functions.

POST-APOLLO PLANNING

As the Apollo Program nears the point of settling on a specific detail hardware configuration, it should be recognized that the overall space program of which Apollo is a part is aimed at more than just landing a man on the moon. The achievement of that objective by Apollo will raise more questions than it will settle. The technological advances made in this specific program will provide the means for further exploration of space, and the current progam must be viewed with the post-Apollo future in mind. In this context the major trade-off parameters will become mission cost and mission value; schedule, weight, equipment performance, reliability, and power requirements will be important secondary parameters in the design and choice of individual equipments. The question of balance between manned and unmanned missions will not be settled until more is known about the real value of having men in a space vehicle. The permitted spending rate and cost is bound to have very real and fluctuating limits. So the problem of mission planning and hardware selection will hinge on maximizing the results which can be obtained, consistent with discussions as to how much overall effort should be devoted to space exploration.

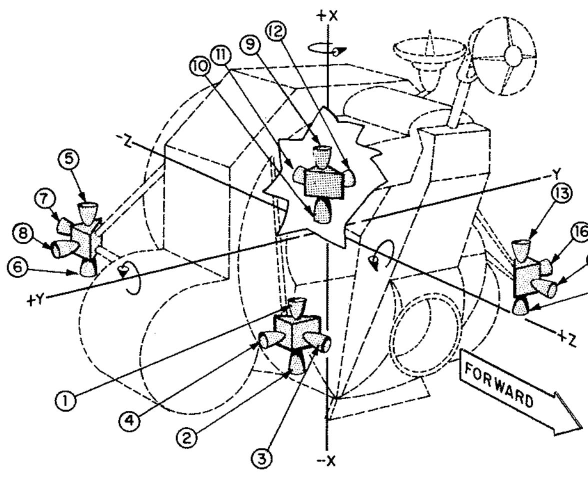

Fig. 1—LEM ascent stage.

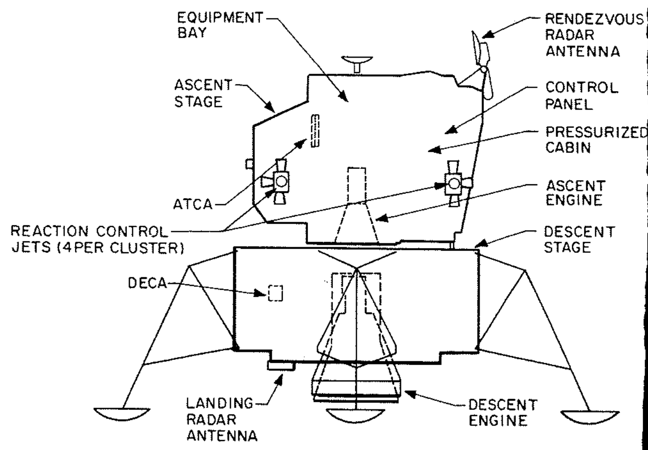

Fig. 2—LEM vehicle.

ATTITUDE, TRANSLATION, AND DESCENT ENGINE CONTROL OF LEM

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The attitude and position of the Lunar Excursion Module (LEM) are controlled by engine commands from the stabilization and control subsystem. This equipment includes the attitude and translation control assembly and the descent engine control assembly designed and built by RCA. Reliable and efficient operation of these assemblies is essential for Apollo mission success. Both units are discussed herein with emphasis on significant theory and design.

The LEM vehicle stabilization and control subsystem controls all 18 LEM engines and is used whenever any vehicle attitude or position change is desired. RCA is supplying the attitude and translation control assembly (ATCA) and the descent engine control assembly (DECA) for the LEM stabilization and control subsystem. The ATCA is mounted on the ascent stage and commands the 16 attitude and translation control engines (reaction control jets) located on this stage (Fig. 1). The DECA, mounted on the descent stage, controls the gimballed, variable-thrust engine located on the descent stage (Fig. 2). One ascent engine of fixed thrust is located on the ascent stage (Fig. 2). Signal flow of the LEM stabilization and control subsystem is shown in Fig. 3.

LEM STABILIZATION AND CONTROL

Optimum placement of the 16 reaction control jets provides as much redundancy as possible; for example, clockwise rotation about the Y-axis can be accomplished by firing jets 6 and 1 or 10 and 13 (Fig. 1). Similarly, translation upwards along the X-axis can be accomplished by firing jets 2 and 10 or 6 and 14. All four jets can be simultaneously fired for added thrust. Thus, vehicle rotation (attitude) about all axes is controlled by proper selection of jet pairs to produce couples. Vehicle translation along all axes is controlled by proper selection of jet pairs to produce linear motion.

The LEM is one of three modules comprising the Apollo spacecraft which will be placed in orbit around the moon. The stabilization and control subsystem will be used throughout the entire LEM portion of the Apollo mission. When two of the three astronauts have entered the LEM, it will be detached from the Command and Service Modules (CSM) at the desired position for separation. The 16 reaction control jets will position the LEM along the desired descent engine thrust vector. Then the throttleable descent engine will be fired under computer control to de-orbit the LEM and bring it into a programmed descent path toward the lunar surface. As the LEM nears the surface, the descent engine and reaction control jets will be fired to bring the vehicle to a level hover point directly above the desired landing site and then lower the LEM gently onto the lunar surface.

When the engineering and scientific mission is accomplished (in approximately 24 hours), the LEM ascent stage will be launched, leaving the descent stage behind. The ascent engine and the 16 reaction control jets will place the LEM ascent stage into an orbit close enough to allow rendezvous with the CSM. Final rendezvous and docking will be accomplished under astronaut control, using the 16 reaction control jets for translation and rotation. The two astronauts will then re-enter the Command Module for the earth-bound trip, leaving the LEM ascent stage in permanent orbit around the moon.

The ATCA and DECA are capable of operating in both the prime and backup (abort) modes of system operation. In addition to automatic control of the reaction control jets and descent engine, the ATCA and DECA provide for astronaut control as a further backup of the prime and abort modes. The ATCA and DECA also supply many inputs to the astronauts' displays and thus increase their ability to make correct decisions. The stabilization and control subsystem can handle many combinations of equipment failures with backup modes and astronaut assistance, and this flexibility assures mission safety and success.

RCA has been performing on the ATCA and DECA contracts since 1964. Both assemblies perform many varied functions and possess many interesting technical features. The performance of

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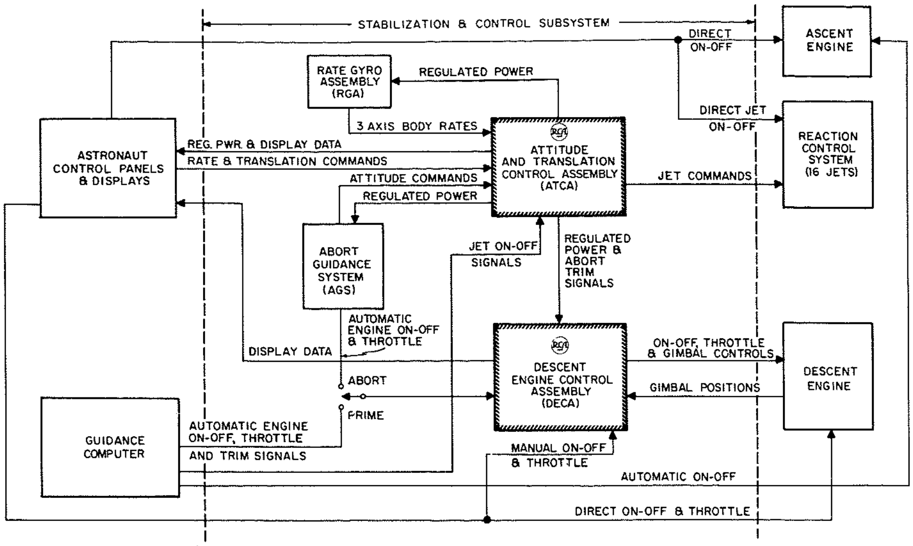

Fig. 3—Block diagram of stabilization and control subsystem.

both assemblies is discussed in subsequent paragraphs.

ATCA

The ATCA controls the logical time and sequence for firing the 16 reaction control jets for both attitude and translation control of the vehicle. ATCA also provides automatic trim signals for the gimballed LEM descent engine, and regulated AC and DC power for other LEM assemblies such as the DECA, rate gyro assembly, and abort guidance system.

Analog Amplifier

The functional block diagram of the ATCA (Fig. 4) shows that attitude control inputs for all three axes pass through signal limiters and then combine with the corresponding rate signals from an external rate gyro assembly to provide vehicle rate control and damping. Provision must be made for the great difference in vehicle dynamic response characteristics in the ascent and descent modes, which is caused by the absence of the descent stage in the ascent mode. The gain of the summing circuits can be adjusted to compensate for this difference. Attitude-hold capability is provided whenever the attitude control inputs are zero, since any vehicle rates will be sensed by the rate gyros and the ATCA will turn on the appropriate jets to eliminate the undesired rates.

In addition, the astronaut can introduce rate commands into the ATCA from his controller. The resultant 800-Hz (c/s) signal is then demodulated and passed through or around a 4.7° deadband. The 4.7° deadband is switched in or out by external control. When the deadband is switched in, any output is inhibited unless the error signal is greater than the voltage equivalent of a 4.7° error. In the pitch and roll axes only, the demodulated signal prior to deadbanding is also fed to the DECA where the signal is used to control the gimballing of the descent engine. After further DC amplification, the signal passes through a 0.3° deadband to assure that the vehicle will not respond to errors too small to affect performance and, therefore, waste fuel. An external mode switch allows the varying DC signal, or a fixed DC level that is set to provide a known output (pulse mode rate command) of the pulse ratio modulators, to pass into the logic portion of the ATCA.

Logic

The ATCA logic is implemented with digital integrated circuits which route rotation and translation commands to the appropriate jet pairs. Since many reaction control jet combinations are possible, extensive logic circuitry is required to assure efficient and exact selection of jets. For example, when counterclockwise rotation about the X axis and translation in the −Z axis direction are required at the same time, jets 7 and 15 (Fig. 1) can produce the desired rotation and jets 15 and 3 can produce the desired translation. The combination of these two commands would have jets 15, 7, and 3 firing at the same time. However, jets 7 and 3 point in opposite directions and thus would cancel each other out. The logic circuitry, therefore, not only determines which jets to fire when a rotation or translation is called for, but also prevents opposing pairs of jets from firing simultaneously, thus preserving fuel.

Pulse Ratio Modulator

The output of the ATCA is quasi-linear bang-bang control with variation in both duty ratio and repetition rate, utilizing a pulse ratio modulator with characteristics as shown in Fig. 5. Note that below the threshold no output is obtained. As the threshold is just exceeded, a minimum impulse bit is generated which is 13 milliseconds wide and occurs about every 2 seconds. As the error voltage increases, the pulse frequency also increases while the pulse width increases at a very low rate. However, as the error increases further, the pulse width rises exponentially to 100% *on* time while the pulse frequency goes through a peak pulse frequency of approximately 5 pulses/sec and then rapidly drops to zero as the pulse *on* time reaches 100%. There-

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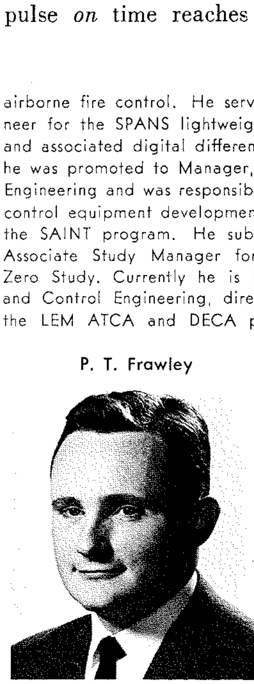
STANLEY S. KOLODKIN graduated from Massachusetts Institute of Technology with a BSEE degree in 1954 and an MSEE degree in 1955. Since joining RCA in 1955, he has been responsible for programs related to guidance and control problems in the fields of missile and space systems and airborne fire control. He served as project engineer for the SPANS lightweight inertial platform and associated digital differential analyzer. Later he was promoted to Manager, Control Equipment Engineering and was responsible for guidance and control equipment development and evaluation on the SAINT program. He subsequently served as Associate Study Manager for the SAINT Phase Zero Study. Currently he is Manager, Guidance and Control Engineering, directing the design of the LEM ATCA and DECA projects.

P. T. Frawley



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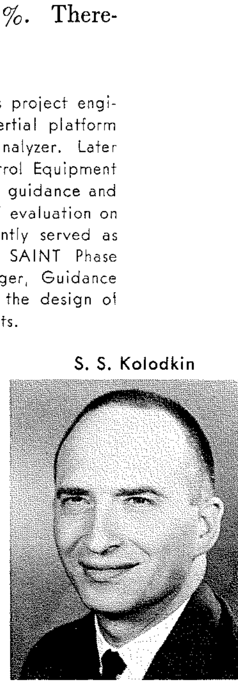

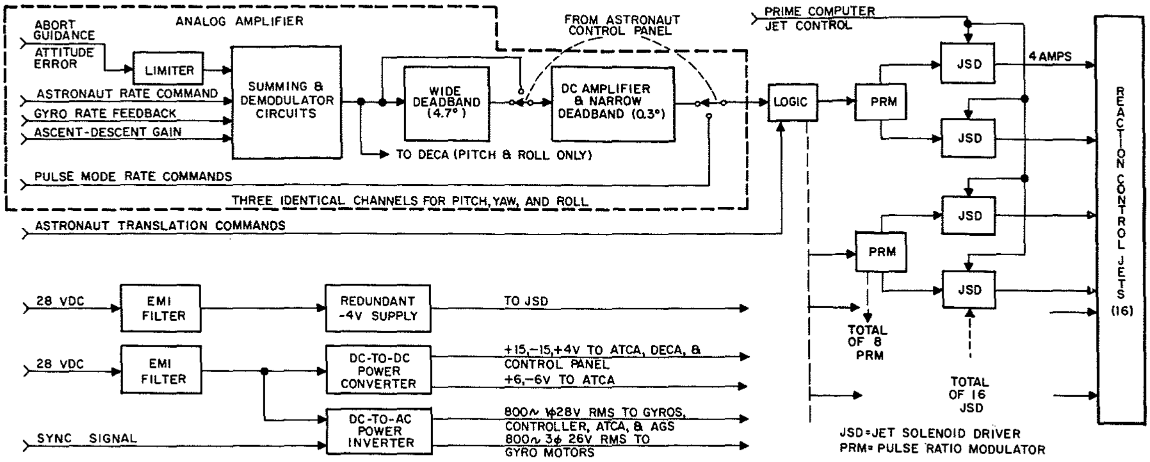

Fig. 4—Block diagram of ATCA.

fore, the pulse ratio modulator provides a dynamic range of duty cycle from 0.65% (13 ms every 2 seconds) to 100% while keeping the number of firing pulses minimal. Thus, the pulse ratio modulator characteristics optimize vehicle performance and fuel usage.

Jet Solenoid Driver

The output of the pulse ratio modulator operates the jet solenoid drivers that switch the 4-ampere current needed to open the propellant valves and fire the reaction control jets. Active arc suppression is used to minimize electromagnetic interference (EMI) problems. In the prime mode the jet solenoid drivers are driven directly from the LEM guidance computer and are completely independent from all other parts of the ATCA, including the power supply (a redundant −4 volt supply is provided for this purpose). In the abort mode the pulse ratio modulators feed the jet solenoid drivers to obtain the proper output.

Power Supply

The ATCA power supply provides regulated power (+15, −15, +6, −6, and +4 volts) for the stabilization and control subsystem as shown in Fig. 4. It consists of two sections, a DC-to-DC converter and a DC-to-AC inverter. The DC-to-DC converter has an input of 28 volts DC from the primary supply, and uses step-width regulation for minimum power dissipation over a wide range of input voltage. The oscillator frequency of the unit is set at 20,000 Hz. This high frequency has resulted in significant weight savings in the magnetic components and filters. Specially developed 20,000-Hz power transformers and inductors were developed for this application. The supply has complete short-circuit protection with automatic load sampling. In the event of a short circuit or overload sensed by a magnetic current sensor on the output lines, all voltages are automatically set to zero by turning off the primary oscillator. When an overload occurs, the load is automatically sampled at short intervals. The power supply resumes operation automatically once the short has been cleared. EMI filters are an integral part of the power supply.

The second section of the power supply, the DC-to-AC inverter, also utilizes step-width regulation. It features a ± 2° phase lock with an external sync input, and a backup free-running mode in the event of loss of sync signal. The basic frequency is 800 Hz; the backup frequency is 800 ± 8 Hz. Single- and three-phase outputs are provided using two independent channels and a Scott-T output.

Special Features

The ATCA utilizes analog integrated circuits of the operational amplifier type for voltage comparators. These units, constructed on a single chip, provide DC amplification greater than 1,000 with less than 5 millivolts offset. Each integrated circuit amplifier replaces more than 15 discrete parts.

A parameter trim capability assures maximum mission flexibility and allows for future vehicle dynamics changes. This feature permits easy access to various gain and deadband parameter components, thus allowing ATCA performance to be tailored to a wide range of foreseeable missions.

DECA

The DECA provides complete control of the descent engine including on, off, and throttling of the engine thrust, and gimbal control of the engine thrust vector. Fig. 6 illustrates in block diagram form the functioning of these controls.

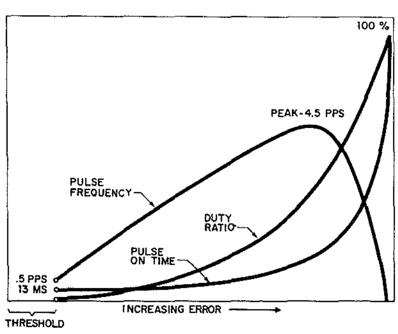

Fig. 5—Plot of pulse ratio modulator characteristics.

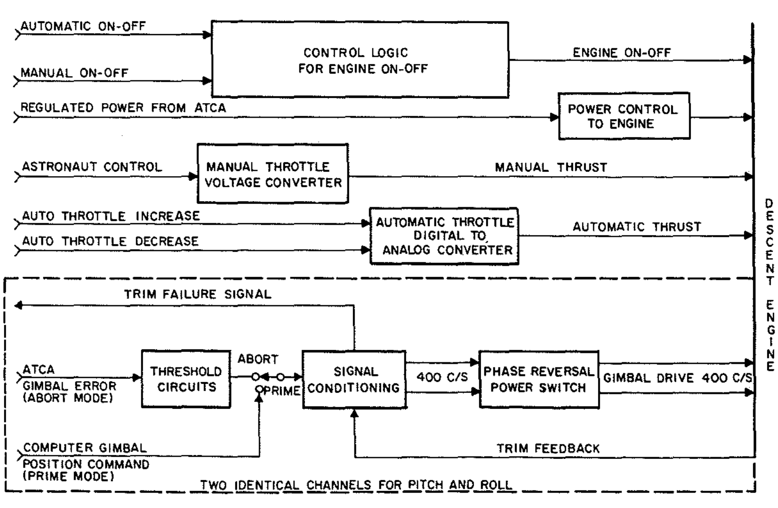

Fig. 6—Block diagram of DECA.

Engine On-Off Control

The DECA receives engine *on* and *off* commands on two lines. An integrated circuit gate in the control logic is set whenever an engine *on* command is received and is reset upon receipt of an engine *off* command. The gate drives a relay that provides a voltage level to the engine as an *on* command. The design of a subminiature high-current relay for this application has been a problem, since about 16 amperes of inductive load must be switched by this relay. In addition to this automatic switching, the astronaut has manual backup capability.

Engine Throttle Control

The automatic throttle consists of a digital-to-analog ladder converter using integrated circuits. The signal input is received as pulse trains on two lines. One line carries pulses for throttle decrease and the other line carries throttle-increase pulses. The throttle circuit supplies a precision analog output to the descent engine which varies as the net difference between the two 3200-Hz pulse trains. The descent engine uses the precision analog voltage to provide engine thrust control from 10% to full thrust. As backup to the automatic throttle capability, a manual throttle is available under astronaut control.

Engine Gimbal Control

The descent engine is located on a line through the calculated center of gravity of the vehicle. However, since engine thrust misalignments and small errors in the calculated center of gravity cause the actual engine thrust to lie along a line that does not run through the actual center of gravity, a small rotational component is introduced whenever the engine fires. The proper reaction control jets could fire so as to cancel this effect, but this would be costly of fuel. Consequently, the descent engine is gimballed so that it can align its thrust vector through the actual center of gravity.

Thrust vector about the astronauts' roll and pitch axes is controlled with two identical circuits as follows. In the primary mode the computer sends gimbal angle correction discrete commands that turn on power gates to supply 400-Hz power for driving the gimbal motors. In the abort mode the ATCA provides an analog trim error signal for each of the two axes. The error signal feeds two analog integrated circuit comparators of opposite polarity. Whenever the analog error signal exceeds either the plus or minus comparator thresholds, the appropriate power gate is opened to drive the gimbal motor. The phase of this 400-Hz gimbal motor power is dependent upon whether the plus or minus threshold is exceeded. Thus, in the abort mode the motor turns so as to reduce the thrust vector error below the DECA comparator threshold; in the primary mode the motor turns until the computer determines that the thrust vector error is negligible. In addition, a position transducer on the descent engine gimbal motor sends position signals to the DECA. By differentiating this signal to obtain gimbal motor speed, the DECA determines whether the motor is running in accordance with a primary or an abort trim error command. If it is not, the DECA automatically disables the gimbal motor. This disable signal can be overridden by the astronaut.

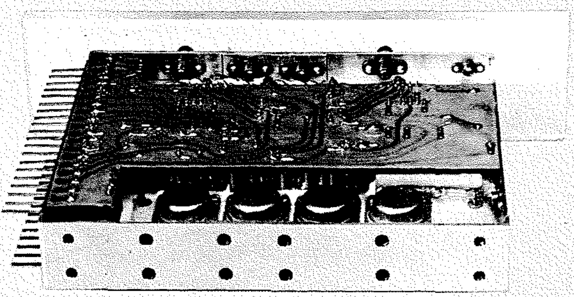

Fig. 8—Typical ATCA subassembly.

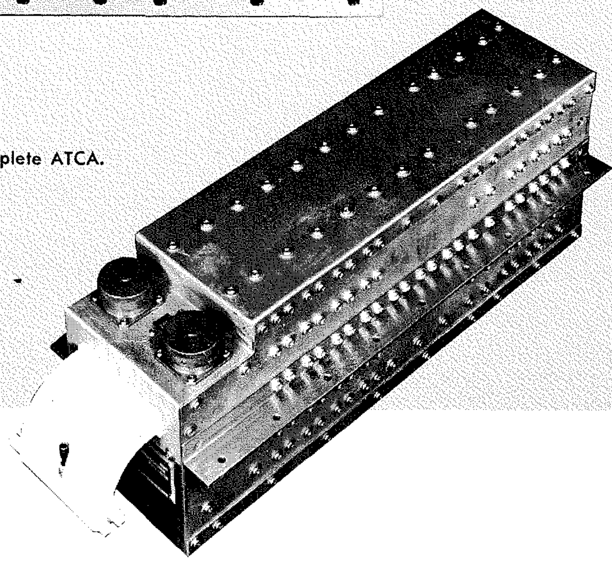

Fig. 7—Complete ATCA.

The DECA also controls the 28-volt prime power and B+ power for arming and operating the descent engine.

ATCA AND DECA PACKAGING

The ATCA and DECA are designed to meet different environmental conditions. The ATCA is mounted in the ascent stage aft equipment bay, which is not pressurized; however, cooling is provided by cold rails that maintain the ATCA heat sink flange between 35°F and 135°F. The ATCA is $17\frac{3}{4}$ inches long, $7\frac{7}{16}$ inches high, and $5\frac{1}{8}$ inches wide. It weighs 25 pounds and has over 3000 parts, including 26 analog and 36 digital integrated circuits (Figs. 7 and 8).

The DECA is mounted on the inside of the descent stage, which is not pressurized and which does not contain cold rails. Consequently, the DECA must provide its own cooling in the form of thermal inertia, that is, depend on its own mass to keep the final temperature of all parts below 160°F with a maximum starting temperature of 120°F. All small DECA parts are in cordwood modules, just like the ATCA; the large parts are packaged in planar form. The DECA is approximately 4 by $7\frac{1}{2}$ by $5\frac{1}{2}$ inches, and it weighs 8.5 pounds. It contains over 900 parts, including 16 analog and 85 digital integrated circuits.

CONCLUSION

Through the use of the ATCA and DECA in the stabilization and control subsystem, the LEM vehicle is provided with a lightweight control system that is optimized for the vehicle dynamics of the present mission and is sufficiently flexible for use on alternate future missions. The combination of built-in primary/abort features and astronaut manual override assure maximum mission safety.

LEM ELECTRONICS RELIABILITY

A brief description of the wide range of reliability tasks implemented under the Lunar Excursion Module (LEM) reliability program illustrates the vital role of reliability in all phases of the program, from conceptual design of a circuit to delivery as flight hardware. Analytical techniques and hardware aspects of reliability are discussed.

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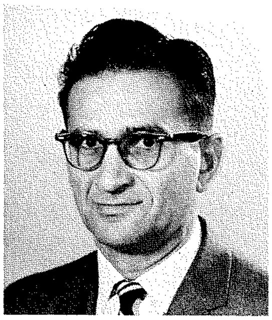

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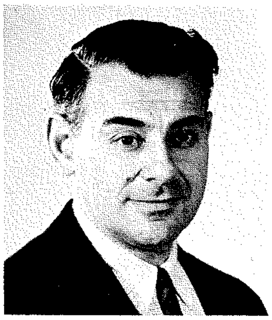

P. Marcellos

J. J. Landers

JEROME B. FRIEDENBERG received his BS degree in Aeronautical Engineering from the University of Michigan in 1939. Early experience included the preliminary design, installation, and testing of aircraft and rocket engines. With Bell Aircraft Corporation from 1950 to 1961, he was lead engineer for the in-plant test of the Shrike and Rascal rocket-powered, air-to-surface missiles. He was also program manager of the Dyna-Soar third-stage booster and project engineer on the Bell Aircraft-General Electric study for the moon landing vehicle and lunar life support complex. Upon joining RCA in 1961 he became responsible for the planning and organization of all RCA-conducted test programs (including subcontracting) for Program 706. As project engineer in the LEM Program Management Office, he is currently responsible for LEM test programs.

PETER MARCELLOS is a graduate of London University, England, where he received his BSc (Eng) degree in Mechanical Engineering in 1953. While employed by VAC Ltd. and later Sperry Gyroscope, in England, he was responsible for the analytical investigation and development of the fluid support of a spherical gyroscope for a long-range missile. In 1957 he emigrated to Canada where he was employed by A. V. Roe as a system engineer on the development of the CF-105 supersonic interceptor. He joined RCA Victor, Montreal, Canada in 1958 as Supervisor of Reliability Engineering. Following cancellation of the Astra fire control system, he transferred to RCA, Moorestown. There he was assigned to the Design Integration activity with responsibility for design reviews, design standardization, and development of advanced packaging techniques. Since joining the LEM Program Management Office in 1963, he has been responsible for reliability, standards, test, documentation, and configuration control.

JOHN J. LANDERS received his BSEE degree from Worcester Polytechnic Institute in 1945. Following graduation he joined the General Electric Company as a quality maintenance engineer. As Manager, Quality Control Ordnance Department for 6 years, he was in charge of the quality control activities on the Polaris fire control equipment, Talos missile shipboard handling system, and the AN/SPS-2, AN/SPS-8, and AN/FPS-6 radars. In 1960 he joined the Nortronics Precision Products Department and became Manager, Reliability and Quality Control. There he directed the reliability and quality control activities for prototype and production quantities of integrating and rate gyroscopes. He joined RCA in 1962 and is presently assigned to the LEM Program Management Office, where he is responsible for all product assurance phases of the LEM program. He is a member of Tau Beta Pi, Sigma Xi, IEEE, and the American Society of Quality Control.

The LEM vehicle is a most sophisticated mechanical-electrical system having mission requirements that are extremely complex and known environments that are exceptionally rigorous. However, there are large gaps in our knowledge of the total cislunar environment (true also for all spacecraft which venture outside the earth's atmosphere and gravity field).

The alien characteristics of the space environment are of much greater significance for the LEM vehicle than for earth satellites or even the low-altitude, limited-orbit Mercury and Gemini vehicles. The reasons for this added significance are: 1) the LEM is a manned vehicle, and 2) it must operate 100% successfully for as much as two weeks in this alien environment. Consequently, it is mandatory that an extremely high reliability level be attained in the equipments comprising the vehicle, as well as in the total operating system. Failure or malfunction of a single part or component may cause the termination of a mission that was the culmination of a vast investment of human effort and physical resources. Man's participation makes the success of such space missions of paramount importance. Preventable failure that would endanger human life is intolerable; equipment reliability must be assured to the maximum limits attainable.

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LEM RELIABILITY PROGRAM

The National Aeronautics and Space Agency, in its vital concern for the reliability and quality of Apollo space equipment, has imposed special quality and reliability documents as an integral part of the contractual requirements. The RCA-LEM quality effort is guided by NASA Quality Publication NPC 200-2, entitled "Quality Program Provisions for Space System Contractors." This document requires that material, component, and part suppliers follow NPC 200-3, "Inspection System Provisions for Suppliers of Space Materials, Parts, Components and Services." NASA documents that are implied, although not contractually imposed, are also available for use as space standards. These standards are used as applicable. In any event, the minimum acceptable quality is defined by existing military specifications.

Specification NPC 200-2 is a demanding, detailed, and costly quality requirement. From a management point of view, it emphasizes an organized approach to achieving quality through all phases of contract performance: preliminary engineering design, development, fabrication, processing, assembly, inspection, test, checkout, packaging, shipping, storage, maintenance, field use, flight preparations, flight operations, and flight analysis. The quality system must provide for early and prompt detection of actual or potential deficiencies, system incompatibilities, marginal quality, and trends or conditions that could result in unsatisfactory quality. There is tremendous emphasis on planning, determination of quality characteristics, documentation, traceability, purchase material control, fabrication control, and corrective action.

ENGINEERING RELIABILITY

Early in the design, before any circuit concept or equipment configuration is frozen, trade-off studies are performed to ensure that all aspects of reliability are considered and that reliability is given proper emphasis when compared with other considerations. The assurance of maximum reliability is made difficult by conflicting system requirements. The equipment must have maximum reliability, but it must also have minimum weight and power consumption. Further, it must be designed, tested, and delivered within a tight schedule. Reliability studies must determine the optimum design decision after careful evaluation of each trade-off system requirement.

Trade-off Studies

With such conflicting requirements, trade-off compromises are inevitable. Ingenious circuit and hardware design, improved component performance, and the use of redundancy in critical areas can be made to yield high reliability benefits with minimum weight or power. For example, the decision to use separate power supplies for the rendezvous radar and transponder subassemblies was based on a large increase in reliability versus a relatively small increase in weight (Fig. 1).

Normalized Failure Rates:

Rendezvous radar	$= \lambda_{RR}$	$= 21.0 \times 10^{-6}$
Transponder	$= \lambda_{T}$	$= 3.5 \times 10^{-6}$
Separate rendezvous radar power supply	$= \lambda_{RRPS}$	$= 2.5 \times 10^{-6}$
Separate transponder power supply	$= \lambda_{TPS}$	$= 2.0 \times 10^{-6}$
Common power supply	$= \lambda_{PS}$	$= 2.5 \times 10^{-6}$

Probability of Failure (Q) where $Q = 1 - P_S$ and P_S = Probability of Success:

Case A two-unit:

$Q_A = Q_1Q_2$ (1 and 2 indicate parallel branches)

$$\approx t^2(\lambda_{RR} + \lambda_{RRPS} + \lambda_T + \lambda_{TPS})^2$$

$$\approx 8.4\, t^2 \times 10^{-10}$$

Case B one-unit:

$$Q_B = 2Q_{PS} + (Q_{RR} + Q_T)\ (Q_T + Q_{RR})$$

$$\approx 2t\, \lambda_{PS} + t^2(\lambda_{RR} + \lambda_T)\ (\lambda_T + \lambda_{RR})$$

$$\approx 5t \times 10^{-6} + 6t^2 \times 10^{-10}$$

For a typical mission time (t) of 10 hours, $Q_A = 0.084 \times 10^{-6}$ and $Q_B = 50 \times 10^{-6}$. This improvement of approximately 600 times in the probability of success more than justifies the increased number of parts and the resultant minor increase in weight of the overall configuration. Hence, the decision was made to implement the design providing separate power supplies for the rendezvous radar and the transponder. Similar trade-off studies led to the choice of a redundant gyro configuration in the rendezvous radar to offset high present and projected gyro failure rates.

Parts Selection

To minimize component parts failure, the LEM reliability program places heavy emphasis on proper selection of parts. A preferred parts list, developed early in the program, lists qualified parts and serves as the prime reference for selection. Parts with adverse reliability history are eliminated from a design and replaced by acceptable alternates. Parts with incomplete reliability histories or which are in the developmental stage are usually excluded from consideration.

When the use of a nonpreferred part

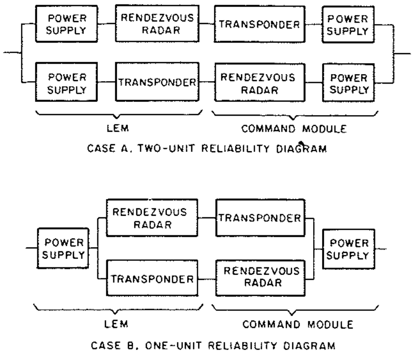


Fig. 1—Power supply trade-offs.

is essential to meet performance requirements, the part is carefully scrutinized to establish inherent and/or projected reliability on the basis of the materials and processes used in its fabrication. The part is also subjected to feasibility testing to check and verify the stability and adequacy of its performance in the LEM environment.

Cost and schedule considerations have not permitted the implementation of an extensive parts improvement program. However, all proposed parts are closely scrutinized, and maximum use is made of existing devices with a known reliability history.

Parts Application

The application of each part is monitored to verify the reliable utilization of each part and the implementation of adequate derating. To facilitate evaluation, all parts application data, including the stress and environmental conditions associated with each application, are tabulated in a reliability data list by subassembly.

The established derating policy limits the surface temperature of all parts in electronic assemblies to 71°C, and the permissible maximum stress level, in general, is limited to less than 50% of the rated level. Maximum permissible limits were established for semi-conductor junction temperatures (100°C for power, 112°C for general circuit application), and voltages, leakage currents, and other factors are controlled to meet the derating requirements. Heavy emphasis is placed on controlling the operating temperatures. Low temperature gradients within the hardware are maintained by extensive use of conductive coatings for parts mounting and packaging.

Parts Procurement and Qualification

The best parts available are used in the LEM program. These parts, known as *high-reliability* (HI-REL) parts, are procured to individually approved, high-reliability specifications which are especially developed for the LEM program. In addition to normal part procurement requirements, the high-reliability specifications require specific screening and burn-in testing, rigid quality control standards, and source traceability identification requirements. Most of the parts used for the LEM program were developed totally or in part on previous HI-REL programs and are preferred parts.

When HI-REL parts are not readily available, the best available existing part is used as a basis for upgrading by additional testing, screening, and burn-in (burn-in is an operational test at a specified temperature for a specified period of time). Testing techniques are used which take into consideration the existing military specification requirements and the LEM environmental requirements. These selective tests, if properly applied, eliminate parts whose characteristics indicate potential failure proneness. Consequently the residual failure rate of the parts remaining after testing is lower than it would have been had the marginal parts not been eliminated. RCA has found that this burn-in, in addition to eliminating the high failure rates experienced in the early life (debugging period) of the parts, also significantly improves part reliability.

All parts for flight hardware are subjected to 100% screening and burn-in. The parts will also have tightened quality control and inspection procedures. Traceability requirements extend these controls to the identification and control of the materials and processes used in the part fabrication. Traceability also requires accurate recording of test data so that the performance and quality of delivered parts can be verified.

The extraordinary controls required for space components are costly and tedious. It is obvious, however, that attention to detail in the basic equipment building blocks is fundamental for ultimate mission success.

Reliability Estimates

The high reliability goals for LEM hardware make verification of the mean life of individual assemblies an impractical task. To verify mean-time-between-failures performance with any reasonable degree of confidence, an inordinately long and expensive test program would be required. Hence reliability estimates based on part counts and established failure rates are used extensively. Failure-rate data on high-reliability parts from the Minuteman and similar programs were carefully evaluated, and calculated failure rates were established (see Tables I and II). These rates were modified for the LEM application and used as a standard of reference for evaluation of trade-off studies and reliability comparisons. They provide a preliminary reliability estimate based on average or approximate stress and environment. As the design progresses and the hardware is fabricated, actual stress and environmental conditions will be used to update failure rates and to estimate mission success.

Reliability Analyses

Analytical investigations form an integral part of the LEM reliability program; they take the form of detailed evaluations of the performance and limitations of circuits and component parts. The objectives of these analyses are: 1) to continually assess the reliability of the design; and 2) to uncover critical performance areas for the application of corrective action. Some of the more significant of these analyses are: 1) *Circuit Analysis*, 2) *Failure Effects Analysis*, and 3) *Failure Mode Prediction Analysis.*

MANUFACTURING FOR MAXIMUM RELIABILITY

The manufacturing process begins with the first purchase order that is placed. It is important at this point that:

1) The component specification is complete.
2) The performance history of the supplier is available.
3) The supplier understands the requirements of the purchase order.
4) The supplier has an organized approach toward meeting the requirements.

Design and standards engineers are the keys in obtaining a reliable component at this stage; they must make certain that:

1) The specification is complete.
2) Quality characteristics are designated in terms of critical, major, or minor.
3) Environmental and qualification levels are clearly specified.
4) Acceptance criteria are established and objective evidence of results is requested.

Exotic components often require more than mere functional performance and testing for proper control and assurance. Detailed control of raw material, intimate knowledge and control of the effect of processes, environmental controls, and numerous other measurable factors must be held within acceptable limits. In spite of intensive methodology, there often exists such a multitude of imponderables facing the design and industrial engineers that production yield is extremely low.

The low-yield component is the nemesis of the reliability and quality engineer. It is axiomatic that failures encountered in the supplier's manufacturing cycle accurately predict future field problems. Sometimes trouble begins when a supplier releases advertising on the virtues of its latest widget. This release is sometimes based on test results of three development units and the hope of improved performance with additional experience. Incomplete specifications are prepared, a qualification program is developed, and an attempt is made to fulfill the promises made. In the meantime, the unwary design engineer decides to use this new component in his design. Astute monitoring by the user at this stage can often spell the difference between success and failure. If the supplier has carefully developed a program with well-defined milestones, and if he has utilized balanced talent for attaining improved performance and for methodizing the known variables, a new space-rated component may be born. The manufacturing yield is the key to the degree of assurance. If the process is mechanized and all variables controlled, the yield should be 100%.

Undoubtedly, the greatest variable in any manufacturing process today is the human variable. RCA is making an intensive effort on the LEM program to select individuals with the right temperament for space work, to provide the right work environment and training, and to ensure constant inspection and monitoring of the work. For example, special emphasis must be placed on the fabrication of soldered connections. The LEM program requires that all soldered connections be made by operators certified in the techniques and standards outlined in Marshall Space Flight Center Procedure MSFC-PROC-158. To attain these standards, RCA personnel are trained in NASA soldering methods. The student receives 40 hours of training in the techniques of hand soldering electrical connections, and he is certified only after his sample board (containing 50 solder connections) is approved. The disciplines taught, the control over environmental conditions, the cleanliness of parts to be soldered, and the required tools and equipment are all part of the training required to assure the most reliable electrical connections.

Other processes, such as welding, encapsulating, brazing, plating, and heat-treating, are also controlled to ensure the functional, thermal, and mechanical integrity of LEM equipment. The LEM program requires that all process specifications be prepared and approved prior to use. Process control procedures supplement the specifications where necessary to provide detailed performance and control methods. Records are maintained on the results of evaluations. The proficiency, capability, and adequacy of personnel performing process certification are subject to verification and

TABLE I—Established Generic LEM Failure Rates for High-Reliability Parts

All rates are in failures/10^6 hours

Part Type	Calculated Failure Rate	Observed Data	Failure Rate for LEM Application
Capacitors, *glass	0.008	0/88	0.012
Capacitors, mica	0.019	2/140	0.003
Capacitors, solid tantalum	0.018	2/147	0.038
Capacitors, foil tantalum	0.024	0/29	0.039
Capacitors, Mylar	1.250***	24/19***	0.024
Resistors, film	0.004	5/1412	0.005
Resistors, composition	0.0018	**	0.005
Resistors, *WW accurate	0.019	**	0.026
Resistors, WW power	0.014	0/51	0.013
Diodes, general	0.031	2/85	0.031
Diodes, switching	0.016	9/576	0.016
Diodes, Zener	0.068	4/69	0.068
Diodes, power and rectifier	0.100	Estimated from power transistors	0.100
Transistors, general	0.057	3/64	0.057
Transistors, switching	0.029	6/232	0.029
Transistors, power, low-frequency (<100 MHz)	0.153	3/24	0.153
Transistors, power, high-frequency (>100 MHz)	0.400	Estimated	0.400

* Add 0.10 for variable devices.
** Minuteman OGE, F.D. Pace, Proceedings of the 11th National Symposium on Reliability.
*** Under accelerated test conditions.
MIL-HDKB-217 is used in all cases where parts do not meet the high-reliability definition.

TABLE II—Preliminary LEM Generic Failure Rates*

All rates are in failures/10^6 hours

Part Type	Calculated Failure Rate	Observed Data	Failure Rate for LEM Application
Transformers, chokes, and coils	0.044	2/59	0.050
Diodes, Zener (temperature compensating)	0.200	Estimated	0.200
Diodes, varactor, high-frequency, power	1.000	Estimated	1.000
Diodes, variable capacitance	0.200	Estimated	0.200
Integrated circuits, digital	0.430	16/37	0.100
Integrated circuits, analog		Estimated	0.300
Solder joints	0.004	GAEC	0.004**
Resistance weld joints	0.003	GAEC	0.003**
Crimp joints	0.016	RADC-TDR-64-46	0.016**
Wire wrap joints	0.000004	RADC-TDR-64-46	0.000004**

* To be revised and substantiated when specifics are available.
** Preliminary estimates based on approximately 2.8 connections per part.

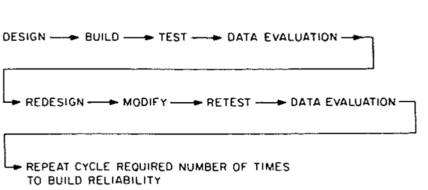


Fig. 2—Reliability test cycle.

approval by the cognizant NASA representative.

It is recognized that in-process and test failures will occur. However, a program of aggressive failure reporting, failure analysis, and corrective action can be an effective means of reliability improvement. Several models of equipment are built before flight hardware is developed, and it is by actively pursuing newly acquired knowledge and using controls during the early stage that maximum reliability is attained for the flight hardware.

TESTING FOR MAXIMUM RELIABILITY

In most ways, the test philosophy relative to LEM equipment is based upon proved methods. For instance, confidence in aerospace hardware has generally been achieved by doing the best possible job of simulating environments and operating the equipment through various aspects of the mission sequences and duty cycles therein. LEM test philosophy is similarly based, but is extended further by special applications of test technologies which, in themselves, are somewhat embryonic at this stage.

For LEM, the simple and well-known principle outlined in Fig. 2 has been recognized, and a well defined program has been prepared on that basis. The test program is divided into three major phases: design feasibility, design verification, and qualification. The cycle of design-build-test-evaluate is included in each phase, with information from the early phases feeding into subsequent phases (Fig. 3 shows the overlap between the test phases). It would be better to relate the phases in series, but that is usually an ideal situation which must be compromised because of scheduling considerations. However, the overlap between phases is carefully controlled by a program constraint mechanism: the start of major test activities in one phase is constrained by the completion of major activities in the preceding phase. The constraints between phases are monitored and controlled through the application of PERT methods.

The amount of testing in the LEM program is considerable, and the planned environmental exposures are many and varied. The hardware that is RCA's responsibility is scheduled to be installed both inside the LEM and on the exterior. The interior-mounted equipment will be installed in an equipment bay which will not have controlled pressure and temperature and which will be open to the space environment. Thus, whether installed inside or outside the LEM, the RCA hardware will be exposed to the hostile environments of cislunar space. Since the equipment will be immersed and operating in this environment for long periods of time—the Apollo mission from earth to lunar surface and back to rendezvous can extend to over a week—a large number of environmental tests, both nonoperating and operating, are required during a given mission simulation on one piece of hardware.

The test program (Fig. 3) is conducted on a set of equipment models which are used solely for these tests. When the various test phases are completed, the models are considered "dead," and no further activities are planned for them in the LEM program. An example of the number of units subjected to this test program is shown in Table III.

Actual flight hardware must undergo testing prior to delivery to Grumman. This testing consists of low-level, short-term electromagnetic-interference (EMI), vibration, and thermal-vacuum tests, which form the basis for customer and government acceptance.

The types of hardware and environments employed in the various test categories are presented in Tables IV and V.

Testing is exhaustively conducted at all levels of build. Painstaking testing, similar to that previously described for the parts and components test/reliability relationship, is performed on all subassemblies, assemblies, and higher levels of build as required. In addition, the equipment is scheduled to be tested by Grumman on the system level in a sophisticated vehicle ground and flight test program. Thousands of hours of testing-redesign-modification-retesting are being conducted on each LEM hardware design, and the compilation, analysis, and thorough evaluation of the huge mass of test data will provide a firm basis for confidence in the reliability of the model that will be on the first manned LEM flight.

Design Feasibility Testing

In the feasibility program much testing is done on circuits and sophisticated breadboards. This testing is largely electrical in nature and is performed on the bench under ambient conditions. Some of the units are subjected to temperatures deemed critical for stable operation. These are essentially engineering design tests, and the information gathered is used as the basis for design of the first packaged units.

As part of the feasibility phase, the first packaged units are subjected to a series of tests under environments defined as "critical" by engineering. The equipments or major portions are tested in such environments as shock, vibration, thermal-vacuum, humidity, and ultra-high vacuum. These critical environmental tests start at low levels but gradually increase to higher levels, with qualification test levels or higher as a goal. The type of unit used in the critical environmental test portion of the design feasibility test program is a preproduction model. In these models, certain liberties can be taken by the designers with regard to the type of parts to be used, as well as with the configuration.

The general objectives of the feasibility phase are:

1) To prove that the electrical design is capable of performing in accordance with the specified requirements
2) To accumulate data on electrical operation of the design when packaged densely in a configuration representative of the flight configuration
3) To perform structural and thermal tests on the packaged unit sufficiently early in the program to permit incorporation of the acquired data in the actual flight-type configurations.

Critical environmental tests are performed on sets of subassemblies, as well as on the complete electronic replaceable assembly, with the data from the former feeding into the design of the latter. Prior to the start of testing, comprehensive and detailed test plans and procedures are prepared by RCA and reviewed by the customer.

In parallel with the breadboard electrical feasibility tests, a program of mock-up tests, both thermal and dynamic, is undertaken. These mock-ups (thoroughly instrumented and closely representative of the form factor, stiffness, material, moment of inertia, and center of gravity) undergo temperature, thermal-vacuum, and vibration tests. Data from these tests are used to correct the design of the flightweight units which are used in the design verification tests.

Design Verification Testing

This phase of testing begins with a mission simulation sequence that includes tests under environmental conditions, such as: humidity and temperature, representing the prelaunch period during countdown; the vibration and temperatures of launch and boost; and the shocks of booster separation. Tests continue under environments simulating space flight, in-

TABLE III—Test Program for Rendezvous Radar

Test Category	Number of Units: Electronic Assembly	Antenna	Transponder
Design Feasibility	2	2	2
Design Verification	1	1	1
Qualification	2	2	2

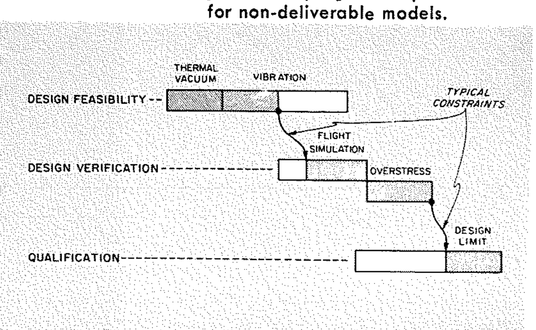
cluding: 1) combined thermal-vacuum, with the temperatures reaching a low of −300°F and a high of +250°F, while the pressure remains at 10^{-5} torr; and 2) combined temperature-vibration, in which the vibrations expected from the rocket motor during lunar landing and take-off operations are combined with appropriate temperatures. The landing shock is simulated, and an immersion is made in ultra-high vacuum of 10^{-9} torr to simulate the lunar pressure. During these environmental exposures, the equipment must operate as dictated by the actual mission duty cycles. During this portion of design verification testting, the levels of dynamic environmental stresses are at expected mission levels plus 15% safety factor. A more detailed presentation of applied environments is given in Table V.

Design verification testing ends with an overstress test, which is designed to uncover and pinpoint the weakest link in the hardware design. In this test the unit is subjected to environmental conditions which are raised in steps until the severity of the environment reaches the point at which equipment failure results. The objective of this overstress test is to force a failure, and an attempt is made to simulate the environmental conditions which represent the mission environment that will most probably cause failure. In the actual mission the environment which will create the greatest stress will be a complex condition in which no single environment will be present.

What combination of conditions will be a highly probable cause of failure? The answer to this question is derived from the failure mode analysis and prediction which designates the combination of environments and/or internal loads used in the overstress test.

The conditions for overstressing may, for example, be a combined temperature-vibration-voltage test, with the levels of each being raised in stepped fashion until failure appears. This type of overstress test places the hardware under the closest possible simulation of the actual mission conditions under which it is expected that failure is most probable, and then raises the operating loads and environmental levels until the failure appears. Thus, under the most severe conditions, any design *weak link* is exposed. The data are then used to redesign the equipment so that the failure condition will not appear until even higher levels of combined environments are reached, thereby raising the level of confidence in the ability of the equipment to operate under exceedingly adverse conditions.

Fig. 3—Test program sequence for non-deliverable models.



Qualification Testing

At the qualification stage of the program, the reliability of hardware and confidence in its capability are established to the point where the equipment can be qualified for use in manned flights. Prior to qualification, equipment is delivered to the customer, but not for use in manned Apollo missions. Initial deliverable production equipment is used in the Grumman and NASA ground test programs. However, the NASA requirements for manned flight equipment include the completion of a series of formal qualification tests at high levels of environmental stress, and under endurance conditions which essentially test the long-life capabilities of the flight equipment.

Specifically, the LEM equipment is subjected to a two-phase qualification:

Phase 1—Qualification testing, in which design limit levels are used on one unit, and endurance testing is conducted on a second unit.

Phase 2—Post-qualification testing, in which overstress testing is performed on the first unit, and repetitive flight simulations are conducted on the second.

The reason for the concurrent Phase 1 and Phase 2 tests is that a certain number of qualification test sequences must be successfully accomplished by the time the initial unmanned flight vehicles are delivered by Grumman to the John F. Kennedy Space Center. Thus, even before any on-pad activity takes place, the flight equipment must be qualified, and a high degree of confidence must exist regarding the equipment reliability.

CONCLUSIONS

A planned reliability program which permeates and influences the development of the LEM equipment is underway. This program is effective from the beginning of the engineering design through the fabrication of production equipments to the qualification of the fabricated flight hardware.

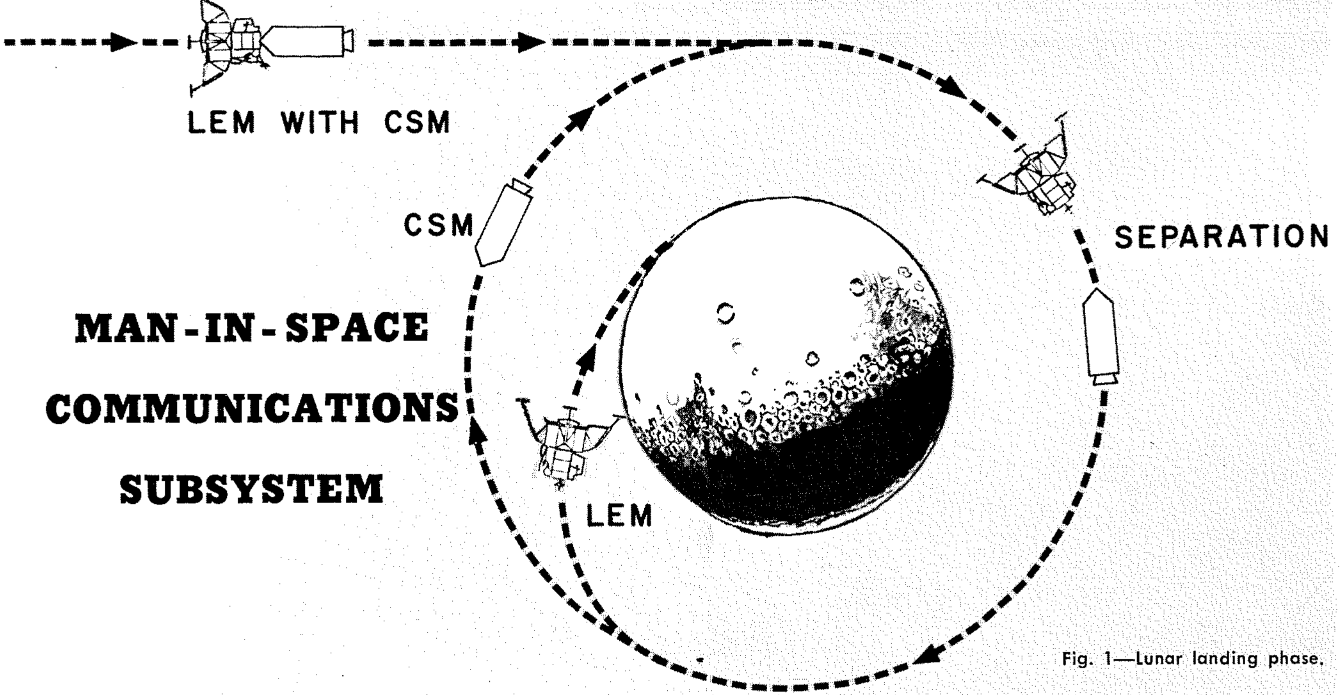
Repetitive and overstress testing of individual parts through assembled equipments in simulated space environments is designed to reveal all weaknesses. By evaluation of the large quantities of test data, all weaknesses are corrected, and the design is qualified at a very high stress level. In this manner, a high level of confidence in the reliability of the equipment is assured prior to the LEM flight.

TABLE IV—Type of Test vs. Equipment Build Level

Equipment Build Level	Ambient Functional	Structural Vibration	Critical Environment	Design Verification	Qualification
Circuits	X				
Breadboards	X				
Cordwoods	X	X			
Mechanical Mockups		X			
Preproduction Flightweight Subassemblies	X	X			
Preproduction Flightweight Assemblies	X		X		
Production Flightweight Assemblies	X			X	X

TABLE V—Environments Used in Various Test Categories

Environments	Test Category—Assembly Level: Design Feasibility Critical Environ Tests	Design Verification Tests	Qualification Tests
Temperature		Prelaunch hot and cold temp.	Prelaunch hot and cold temp.
Shock	15g sawtooth	15g sawtooth	15g sawtooth
Humidity	MIL-STD-810	MIL-STD-810	MIL-STD-810
Acceleration		Up to 5g	Up to 7g
Vibration	From 1g up to failure	Sine and random, 3 axes. Up to 50g	Sine and random, 3 axes. Up to 50g
Thermal-Vacuum	High and low temp. at 10^{-5} torr.	Up to +250°F and −300°F at 10^{-5} torr.	Up to +250°F and −300°F at 10^{-5} torr. 8 days.
Vibration and Temperature		Sine and random, 3 axes plus temp. up to ±260°F.	Sine and random, 3 axes plus temp. up to ±260°F.
Ultra-High Vacuum	10^{-9} torr	10^{-9} torr	10^{-9} torr, 8 days.
EMI	Per customer spec	Per customer spec	Per customer spec
Sand and Dust			MIL-STD-810
Salt Fog			MIL-STD-810
Explosion-Proof			MIL-STD-810



MAN-IN-SPACE COMMUNICATIONS SUBSYSTEM

Fig. 1—Lunar landing phase.

Reliable communications are essential to success of the Lunar Excursion Module (LEM) mission in the Apollo program. This paper describes the communications subsystem being designed and fabricated by RCA to provide the communications necessary for both in-flight and lunar-stay modes of operation. Features of the S-band transmission link between earth and the LEM vehicle, and the VHF transmission link between the Command Module and the LEM vehicle are discussed. The signal processor, S-band and VHF transceivers, S-band power amplifier, and steerable and erectable antenna assemblies are described.

RODGER E. DAVIS
LEM Program Management Office
Aerospace Systems Division, Burlington, Mass.

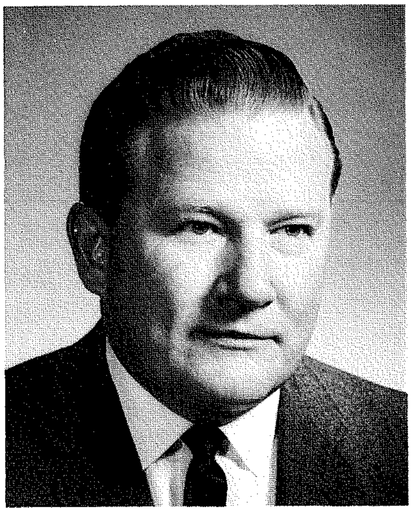
A COMMUNICATIONS subsystem is being built for the Lunar Excursion Module (LEM) by RCA under contract to Grumman Aircraft Engineering Corporation. This subsystem will provide communications links between the LEM and earth, between the LEM and the orbiting Command Module from which the LEM will descend to the lunar surface, and between the LEM and the astronaut walking on the moon. These links involve the transmission and reception of voice communications, television, telemetry, ranging, and biomedical data.

The design of the LEM communications subsystem makes maximum use of prior developments of the Apollo program as well as experience gained by RCA from previous aerospace communications systems. RCA divisions with major responsibilities are: 1) Aerospace Systems Division—Program Management Office, 2) Communications Systems Division—subsystem integration and VHF transceivers, and 3) Missile and Surface Radar Division—erectable S-band antenna. Major subcontractors to RCA on this program are: Collins Radio Co.; Motorola, Inc.; Dalmo Victor Co.; and Raytheon Co.

Final manuscript received December 15, 1965.

LEM SYSTEM DESIGN CONSIDERATIONS

The Apollo spacecraft that will be placed in orbit around the moon will consist of the LEM and the Command and Service Modules (CSM). During the moon orbit, two of the three astronauts will pass from the CSM into the LEM. When the desired position for separation is reached, the LEM will be detached for descent to the moon's surface (Fig. 1). Following a successful landing, the astronauts will relay data to earth using an erectable antenna. After approximately 24 hours, when the mission's engineering and scientific tasks have been completed, the LEM will be launched from the moon for rendezvous with the orbiting CSM. The two astronauts will re-enter the CSM for return to earth, and the LEM will be left to circle the moon as a permanent satellite.



RODGER E. DAVIS received his diploma in Physics from the University of Rochester in 1940. Since then, he has had wide experience in the development, installation, and flight testing of electronic control and communications systems for airborne applications at Wright Field, Sperry Gyroscope, and RCA. Among these projects were the development of steering adapters for coupling bombsights to automatic pilots, the installation and flight testing of radio and telemetry equipment of EQT-33 drones, and the development of the air-speed and mach control system for the B-47 aircraft. At Sperry, he was responsible for the development of the remote control system for the MB-29 and the coupling to navigational equipment. He was also project manager on the development of a microwave command-guidance weapon system using a two-way time-division data link. Since joining RCA in 1958, he has served successfully in the technical coordination of a military communications system, as Project Manager for the Automatic Ground/Air Communications System, and as Manager, Air Traffic Control Projects. Presently, he is in the LEM Program Management Office, managing the LEM communications subcontract for RCA. He is a senior member of the IEEE and a past chairman of the Transportation Division of the New York Section of the AIEE.

Communications Requirements

The functional requirements for the LEM communications subsystem are listed below. These functions must operate in the basic modes of the mission: in-flight and lunar-stay.

1) *Voice Communications*—A capability must be provided for voice communications between: the LEM and Command Module during line-of-sight phases of mission; the LEM and the earth (and relay to Command Module); the LEM and a roving (extra-vehicular) astronaut at a radial distance up to 3 nautical miles from the LEM; and astronauts within the LEM.
2) *Telemetry*—Data supplied to the LEM operational instrumentation system is time-shared pulse-code-modulated (PCM) data which may be transmitted simultaneously with voice and biomedical data.
3) *Television*—Video output from a portable television camera used by an extra-vehicular astronaut on the moon must be relayed to the earth.
4) *Range Information* — Coherent transponders must be provided to permit ranging to the LEM from the earth.
5) *Biomedical Data* — Hardline biomedical signals from transducers on an astronaut's body must be relayed to earth.

In-flight Communications

During the in-flight communications mode, the LEM will be either in the descent phase from the Command Module to the lunar surface or in the ascent phase from the lunar surface to rendezvous with the Command Module. Communications traffic during the in-flight mode will be concerned chiefly with an accounting of the progress of the descent or ascent phases.

Communications between the LEM and the Command Module will be provided by a VHF link (Fig. 2). Voice signals will be transmitted to the Command Module and voice signals will be received over the return path.

Communications between the LEM and the ground station will be provided by an S-band link. Voice signals and range interrogations will be received by the LEM on a carrier frequency of 2101.8 MHz (Mc/s). The LEM will relay back the range code and transmit voice signals, telemetry data, and biomedical data on a carrier frequency of 2282.5 MHz, which is phase coherent with the received signal.

Emergency keying of the carrier is provided as a back-up mode of communication in the event that voice transmission from the LEM is not possible. A steerable antenna on the LEM automatically maintains alignment with the LEM-earth line-of-sight path to minimize transmission losses.

Lunar-stay Communications

During the lunar-stay communications

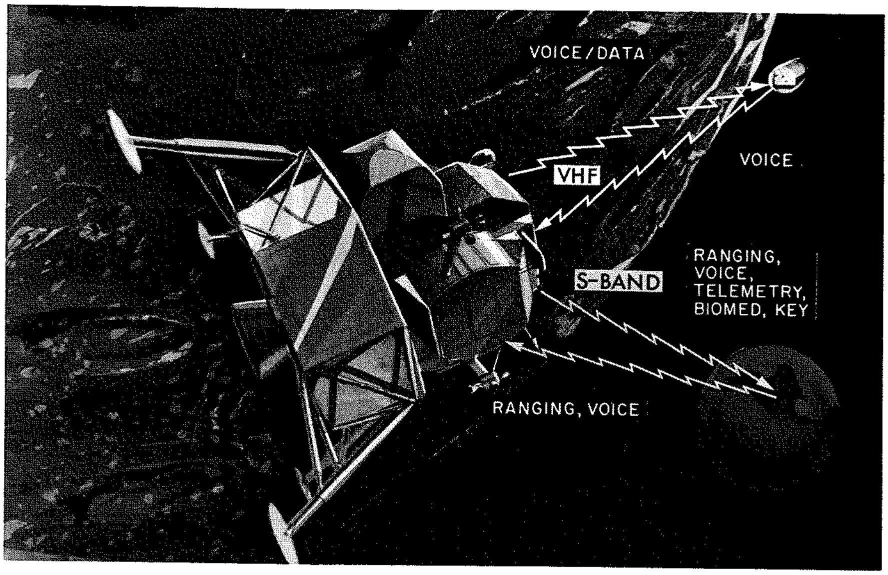


Fig. 2—In-flight communications.

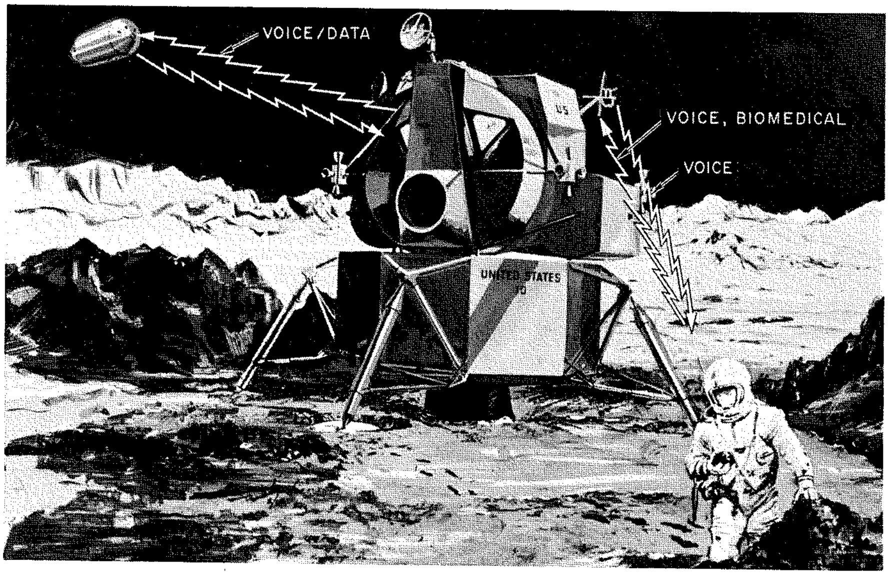


Fig. 3—VHF lunar-stay communications.

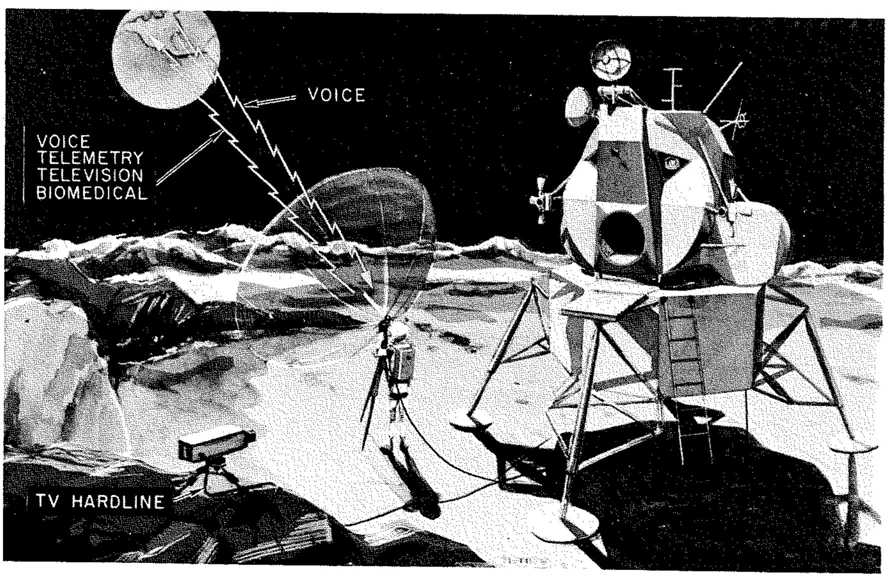


Fig. 4—S-band lunar-stay communications.

mode, the LEM will be resting on the lunar surface (Fig. 3). The two astronauts will alternate in leaving the LEM vehicle to explore the moon for 1-hour periods. They will collect specimens, take photographs, and emplace instruments which will relay scientific data to earth after they leave.

The extra-vehicular astronaut will be in constant voice communication with the LEM through a VHF link. This link will also transmit biomedical data on his physical condition. Another VHF link (the same as that for in-flight communications) will be used to transmit and receive voice signals between the LEM and the Command Module.

Communications between the LEM on the moon and the ground station will be provided by the S-band link. In this case, one of the astronauts will set up an erectable antenna on the lunar surface (Fig. 4). He will unfold the antenna much as one unfolds an umbrella and aim the antenna at the earth. This erectable antenna will improve power transmission by 6 dB over that obtainable with the steerable antenna on the LEM vehicle.

The activities of the extra-vehicular astronaut on the moon and views of the lunar terrain will be televised by a portable television camera. The camera will be set up and controlled by the extra-vehicular astronaut. A hardline (cable) will connect the camera to the LEM S-band link. The LEM S-band communications link will transmit voice signals, telemetry data, television video signals, and biomedical data to the ground station. In turn, voice signals will be received by the LEM from the ground station.

SUBSYSTEM DESCRIPTION

The communications subsystem (Fig. 5) contains the following major assemblies: signal processor, VHF transceivers, S-band transceiver, S-band power amplifier, steerable antenna, and erectable antenna. All subsystem assemblies make maximum use of advanced solid-state circuits to obtain extremely lightweight and highly reliable equipment.

The heart of the communications subsystem is the signal processor assembly. This assembly accepts input signals and sorts, processes, assigns priority, and controls the automatic operation of the subsystem.

Redundancy has been built into the assemblies to ensure highly reliable operation. For example, two separate VHF transceiver assemblies are available to the astronauts. The redundant receiver circuits, phase modulators, and transmitter channels incorporated in the S-band transceiver assembly are available through the use of switches and passive summation networks. The parallel redundant transmitter channels and redundant S-band power amplifiers are connected in a series configuration so that if either should fail, signals would be fed directly through the failed component with only a small insertion loss.

Signal Processor Assembly

The signal processor assembly (Fig. 6) functions as a premodulation processor and audio center in processing signals from the pulse-code-modulation telemetry equipment (PCMTE), voice and biomedical signals from the astronauts, and signals from certain communications and data subsystem transmitters and receivers. The following capabilities are provided:

1) Modulation and demodulation.
2) Processing of data from the operational instrumentation subsystem.
3) Emergency code keying for transfer of priority information in the event of a voice transmission failure.
4) Processing, switching, and mixing of voice, TV video signals, and biomedical data so that the correct intelligence corresponding to a given mode of operation is transmitted.
5) Utilization of the LEM communications subsystem as a relay station between the astronaut(s) on the lunar surface, the earth, and the Command Module.
6) Isolation, switching, and amplification of microphone and receiver audio inputs.

Premodulation Processor Functions—The data AM limiter receives PCM-NRZ data from the PCMTE at a rate of 51.2 kilobits per second or 1.6 kilobits per second. After processing by the data AM limiter, this data is fed to the biphase modulator where it shifts the phase of the 1.024-MHz sine wave from the frequency doubler by 180° ± 10°. The output of the biphase modulator passes through the bandpass filters (depending on the mode selected) and then to the PM or FM mixing network, depending on the mode.

When the emergency key-enable control is selected, the output of the 512-kHz tuned amplifier may be gated by the emergency key control, resulting in 512 kHz at the PM output terminal.

The 512 kHz from the tuned amplifier is also used as an input to the balanced mixer, where it is mixed with the output of the 113-kHz voltage-controlled oscillator (VCO) to provide a 625-kHz frequency-modulated signal at the input to the 625-kHz tuned amplifier. The 113-kHz VCO will provide a 113-kHz signal deviated 13.125 ± 1.3125 kHz at the input to the balanced mixer.

The 625-kHz FM signal is multiplied by the doubler to provide a 1.25-MHz carrier deviated 26.25 ± 6.625 kHz. This signal may be used as an input to either the FM or PM mixing networks to be mixed with the PCM-NRZ (non-return to zero) phase-modulated subcarrier.

The input to the VCO is from the isolation and mixing amplifier, which has as its inputs VHF-received voice-biomedical data or voice from the audio center (AC) and biomedical data from either astronaut in the LEM. The biomedical data from the LEM astronauts is on a 14.5-kHz subcarrier from the subcarrier oscillator (SCO). These signals may also be fed directly to the FM mixing network through the second isolation and mixing amplifier for use on baseband when the proper mode is selected.

Fig. 5—Block diagram of communications subsystem.

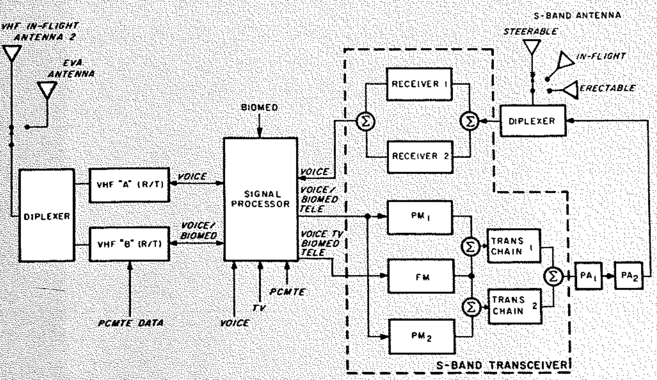
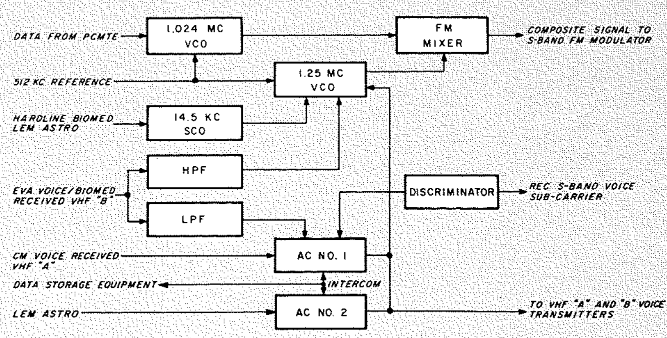


Fig. 6—Block diagram of signal processor assembly.



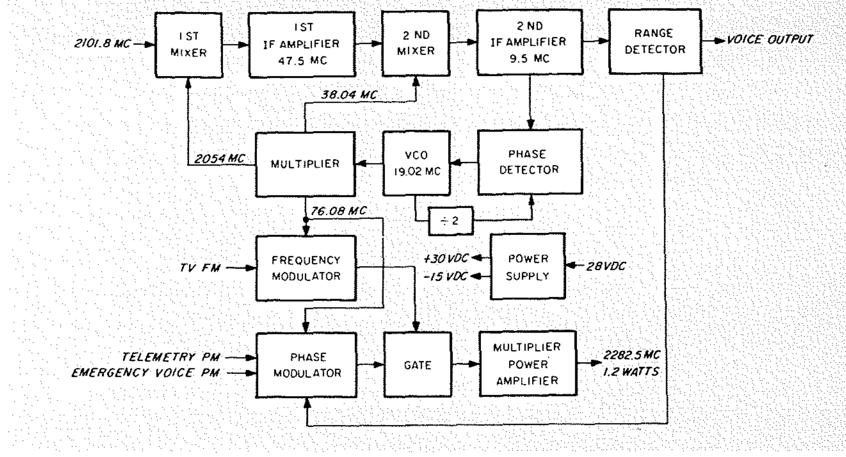


Fig. 8—Block diagram of S-band transceiver.

A TV video amplifier provides TV signals at the FM mixing network output. The TV or composite voice-biomedical signals do not appear at the FM output at the same time. The up-voice discriminator demodulates the S-band 30-kHz subcarrier and provides the required output to the AC headset amplifiers.

Audio Center Functions—VHF and S-band signals are fed to resistive isolation attenuators (pads) of each astronaut's headphone-amplifier input circuit. Diode switches, controlled from the astronaut's audio control panel, switch the selected signals to the headphone amplifier input. When more than one input is selected, the signals are combined at the headphone amplifier input.

The microphone signals are also fed through a diode attenuator in the voice operated transmit (VOX) circuitry. This variable attenuator functions as a remotely controlled VOX sensitivity control with approximately 25 dB of range. The VOX circuitry consists of an audio amplifier, rectifier, trigger, DC amplifier, and keying circuit. The VOX release time is adjustable from 1.2 to 6 seconds and is set to a prescribed value at the factory during manufacture.

Attenuators and an amplifier (intercom circuit pads and amplifiers) provide signals for the headphone amplifier input. A sidetone intercom signal is supplied which is down approximately 12 dB from the maximum output level of the headset amplifiers.

The various inputs to the headphone amplifier are the VHF and S-band receive signals, the signals from the intercom bus, and sidetone from the output of the microphone amplifier.

The headphone amplifier contains an AGC circuit which will maintain an output level constant within 4 dB to a point approximately 20 dB above threshold. The sidetone pads are designed for a sidetone level approximately 12 dB below the maximum output signal level.

Unbalanced microphone signals from the premodulation processor are fed to the microphone amplifiers. These amplifiers are similar to the headphone amplifiers and contain AGC circuitry. Each microphone amplifier delivers its signal to isolation pads through diode switches similar to the ones in the headphone amplifier input circuitry.

VHF Transceiver Assembly

The LEM VHF transceiver assembly (Fig. 7), an all-solid-state device, will be used as a voice communication link between the LEM and the Command Module, or between the LEM and the extra-vehicular astronaut, on a time-shared basis. The transceiver is capable of duplex operation, transmitting at 259.7 MHz and receiving at 296.8 MHz, or vice versa. Voice transmission is by infinitely clipped speech modulation. The receiver is capable of receiving AM voice from the Command Module or AM voice and biomedical data from the extra-vehicular astronaut.

The transmitter consists of a crystal-stabilized oscillator frequency source which is tripled to the final signal frequency. A chain of class C stages amplifies the final signal frequency to a level of approximately 15 watts. The output feeds through a bandpass filter, delivering about 12.5 watts of final carrier signal at the transmitter output terminals.

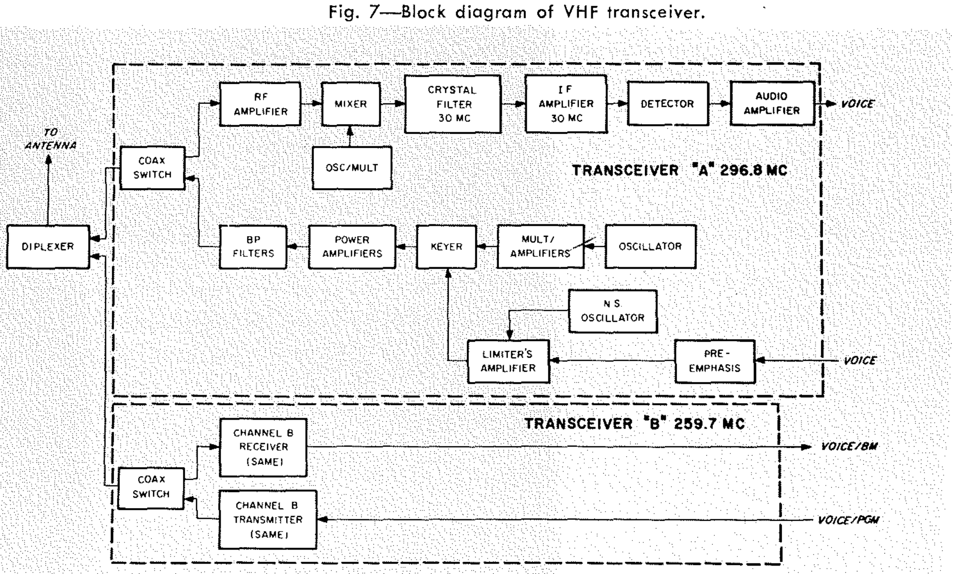
In the infinitely clipped speech modulation, the voice signal input to the modulator is alternately clipped and amplified to produce square waves representative of the signal input audio frequency. The square-wave output of the modulator is applied to the keyer, which keys the CW source on and off at the modulation rate. The RF carrier results in a constant amplitude envelope of rectangularly modulated RF bursts with a 50% duty cycle.

A noise-suppression oscillator, contained within the modulator, generates a supersonic signal (approximately 27 kHz) which is applied continuously to a limiter in the modulator. The noise-suppression signal, approximately 20 dB below a 0-dB modulation signal input, is overridden during the presence of voice. During intersyllable pauses, the noise-suppression signal modulates the carrier with an inaudible tone to suppress noise at the receive end of the communications link.

The receiver, a single-conversion type, uses an input center frequency of 296.8 MHz. A two-stage RF amplifier provides sufficient gain for a noise figure of better than 6 dB. A crystal-controlled oscillator feeds a transistor frequency tripler which multiplies the oscillator frequency to 266.8 MHz. The received signal and multiplied oscillator signal are applied to a transistor mixer. The intermediate frequency is passed through a 30-MHz bandpass crystal filter and fed to the IF amplifier.

The IF strip consists of a three-stage amplifier, audio-detector, squelch detector, and AGC detector. The two RF amplifiers and first two IF amplifiers are AGC-controlled. The squelch and audio signals are independently amplified and fed to a Schmidt trigger. The received

Fig. 7—Block diagram of VHF transceiver.



audio intelligence is then amplified sufficiently to drive the audio power stage. The output of the receiver is a nominal 10 mW.

S-Band Transceiver Assembly

The LEM S-band transceiver assembly (Fig. 8), a completely solid-state device, permits ranging to the LEM by a ground station. The transceiver is capable of receiving voice and digital data, and of transmitting PCM data, voice, biomedical information, and wide-band TV data.

The S-band transceiver assembly consists of a coherent phase-locked receiver, a coherent phase-modulated transmitter, and a noncoherent frequency-modulated transmitter. The receiver is capable of coherently detecting and tracking an up-link carrier transmitted from the ground station. Additional capability includes the coherent detection of the pseudo random noise (PRN) signal coded for turn-around ranging, and the detection of voice and digital information for further processing external to the transceiver. The down-link carrier can be either a coherent retransmission of the up-link, or an internally-generated noncoherent carrier. The down-link carrier can contain either phase-modulated (PM) or frequency-modulated (FM) signals controlled by the premodulation processor assembly. PM signals can consists of narrow-band information (voice or PCM data), the turn-around ranging signal, or a combination of all three. FM signals can be TV data or, in the event of failure of the PM mode of operation, narrow-band information.

For reliability, the receiver, the power converter, and the phase modulator and output chains of the transmitter are redundant. The down-link information can be phase or frequency modulated on one of two redundant transmitter chains; the signal output of the transmitter chain is selected in the output circuits before being applied to the output terminal.

S-Band Power Amplifier Assembly

The S-band power amplifier assembly consists of a DC-to-DC converter power supply, Amplitron tube, input isolator, and output circulator. (The redundant configuration requires an additional Amplitron and power supply.)

The DC-to-DC converter power supply employs pulse-width, closed-loop regulation techniques to provide anode and heater currents to the Amplitron tube. Automatic control of the heater warmup and recycling functions is incorporated in the power supply.

The amplifier is turned on by application of 28 volts DC. When 0.25 watt or more of RF power is present at the input, 20 watts or more of RF power is delivered to the output. RF output power and reflected power are automatically monitored.

The equipment has several modes, or states, of operation. When the power amplifier is turned off, it provides a low RF insertion loss path of 2.0 dB. This *feedthrough mode* serves as a fail-safe feature, since the low power of the driver (S-band transceiver) is fed through to the antenna. It is also a primary low-power mode for narrow-band use.

When both primary and RF drive power are applied, the unit automatically warms up the heater by applying a higher regulated heater current, and it simultaneously suppresses the high voltage for a timed interval. At the end of the interval, heater power is reduced and high voltage applied. If *lock* or amplification is not achieved, this cycle is repeated. The repetition of the warmup cycle is the *recycling* state.

Steerable Antenna Assembly

The steerable antenna assembly will be used to maintain line-of-sight S-band communications between the LEM and the earth, from occupancy of the vehicle through lunar orbit and descent until the erectable antenna assembly is placed in operation by the LEM crew. It will also serve as a standby link to earth during the lunar-stay phase. The steerable antenna will be activated again during pre-ascent checkout and will operate throughout the lunar ascent, rendezvous, and docking of the in-flight phase.

To maintain continuous line-of-sight from the LEM to the earth during all mission phases and vehicle attitudes, an earth-sensing RF system is utilized. The antenna assembly is designed to maintain the required operational pointing accuracy during the 30-second impingement from the LEM reaction control system (RCS) plume and the 20 ms/hr CSM RCS plume. The antenna assembly is sufficiently insulated to withstand the heat flux, and sufficient drive capability is provided to counteract plume-induced torque.

The steerable antenna assembly is a self-contained unit consisting of reflector, feed assembly, gimbal and drive system, earth tracker, and electronics. It is mounted externally at the end of a Grumman-supplied boom approximately 4 feet in length. The reflector is a heat-resistant paraboloid 26 inches in diameter, having a revolution focal length of 9 inches, and illuminated by a crossed-dipole circularly polarized feed at the end of a tapered pylon mounted to the reflector. Rigid coaxial line and rotary joints carry the signal from the feed through the axis to the RF coaxial connector at the boom interface. Cable wrap-ups at the axes permit transposition of power and control wiring without the use of slip rings.

Earth tracking by RF sensing is accomplished by a lobing difference pattern at the receive frequency. This operation utilizes a four-slot and plane aperture, the required hybrids and phase shifter used in conjunction with the crossed dipole transmit feed, and the AGC signal from the transceiver.

The servo system electronics are in a thermally protected enclosure which acts as a counterweight for the reflector around the Y_g axis. The servo provides corrective tracking inputs to the drive system from error signals derived from the earth-tracking system; it also supplies gimbal position information to the cabin instrumentation and displays. The antenna system can be manually positioned by the astronauts for initial earth acquisition. An automatic track mode maintains track on the communicating earth station.

Erectable Antenna Assembly

The erectable antenna assembly will be used for S-band communications from the lunar surface to the earth during the lunar-stay phase. A manually unfolding assembly, it consists of the reflector, feed assembly, limited alidade, tripod, and RF connection designed for operation on the lunar surface. The assembly will be transported from earth in a container (10 inches diameter by 39 inches long) in the outer equipment compartment of the LEM descent stage.

When erected the antenna is a 10-foot-diameter paraboloidal reflector, illuminated by a pylon-mounted vehicle feed system. The reflector, which is supported on an extendable tripod, is a flexible membrane attached to 21 folding, radial, spring-loaded parabolic ribs. A spring-loaded deployment release is actuated by the astronaut to unfurl the reflector after he has opened and rough pointed the tripod. The feed pylon is of trombone construction, and the tripod is hinged and collapsible.

All mechanisms and controls are designed for operation by the extra-vehicular astronaut under lunar environment. The antenna assembly incorporates a sighting device and limited azimuth-elevation adjustments to aid the astronaut in orienting the antenna's line-of-sight to the earth. A soft, deployable RF cable will connect the LEM vehicle to the erected antenna during the lunar-stay phase. Since the erectable antenna will remain on the moon, no provision has been made for collapsing and re-stowing the assembly.

AN ERECTABLE ANTENNNA FOR SPACE COMMUNICATIONS

This paper describes the engineering considerations involved in the design of an erectable antenna for S-band communications between the lunar surface and the earth during the lunar-stay portion of the Apollo mission. Detailed electrical and mechanical characteristics are given and the antenna erection sequence is illustrated.

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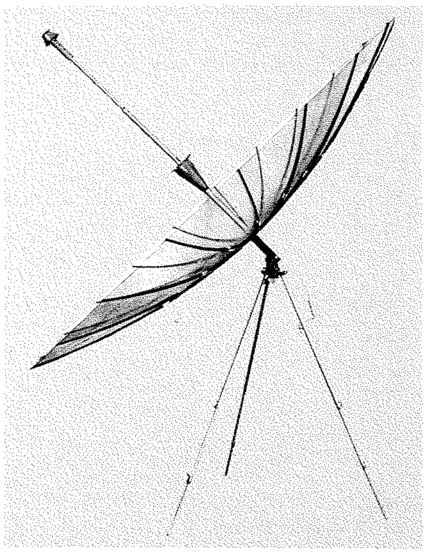
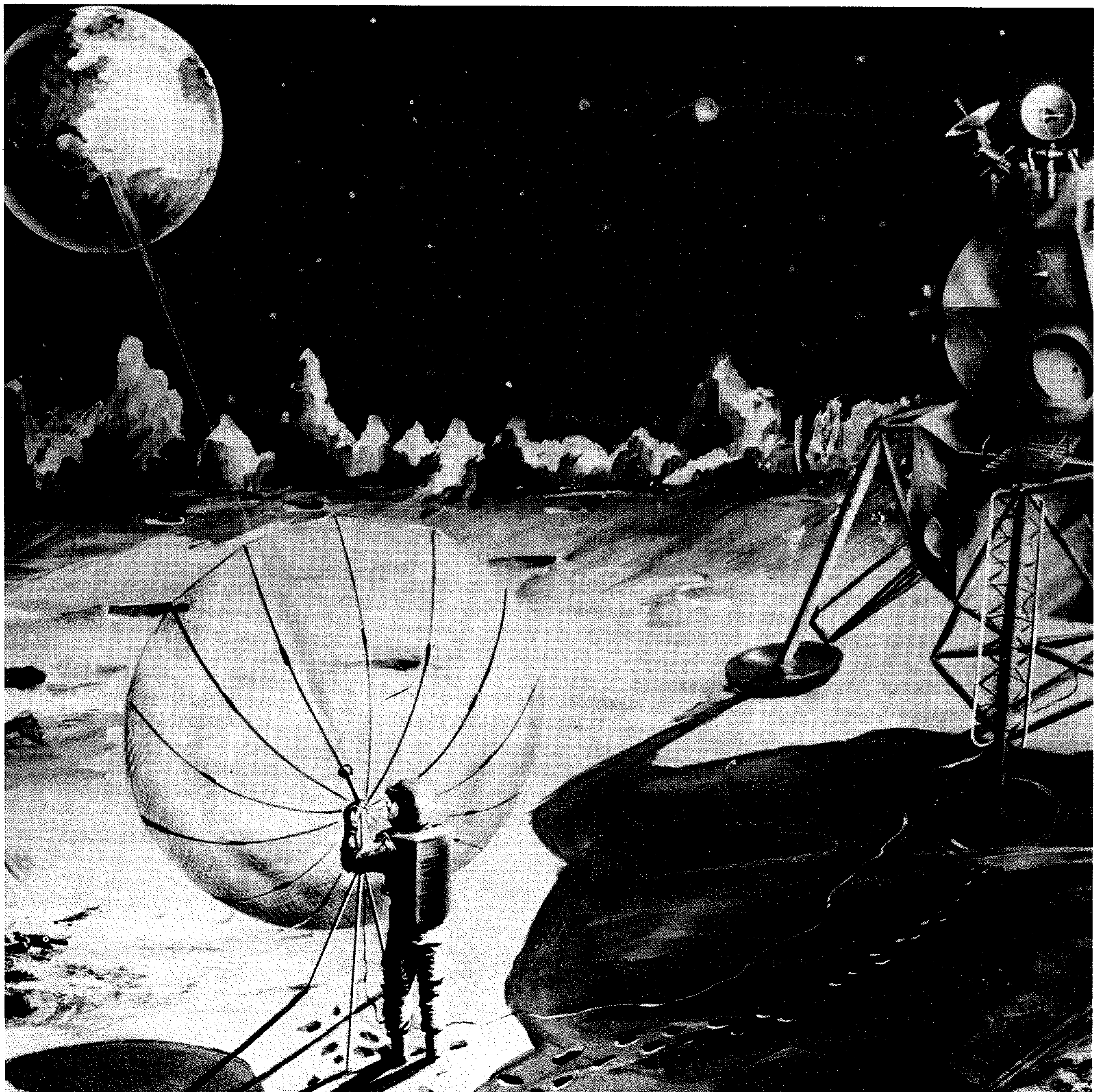


Fig. 2—Antenna fully erected, showing wire mesh, rib structure, and antenna contour.

Fig. 1—Artist's conception of erectable antenna in S-band communications link between the LEM and earth.



A UNIQUE antenna is being developed by RCA's Missile and Surface Radar Division for use on the lunar surface in the Apollo program. This unit will be utilized in the S-band communications link between the lunar surface and the earth station (Fig. 1). The design of this antenna involves the application of engineering approaches that will guarantee safe and easy erection of the antenna by the astronaut and will ensure high reliability in the lunar environment.

Human factors considerations incorporated in the design will permit the antenna to be set up and operated with a minimum of gross body movements by the astronaut. Since the astronaut's hand motion is limited to the area between his knees and his head, the erection procedure is designed to fit these conditions. No tools are required and no loose pieces need be attached. The antenna is deployed through the release of stored energy in leaf-type springs at the joints of the reflector rib sections.

To assure maximum signal on the earth's surface, the operating performance requirements for the antenna are as stringent as the set-up specification. A gain of 32.0 dB is specified for the transmit frequencies over the angle illuminating the earth. This angle at perigee is calculated to be 2.07°; since 0.50° must be allowed to account for errors in pointing the beam, the total angle over which the gain must be achieved is 2.57°. The radiation will be in the S-band and will be circularly polarized. The power-handling capability will be 10 watts CW.

ANTENNA DESIGN

The 32-dB gain required and the physical limitations on antenna size dictated an antenna of relatively high aperture efficiency. A parabola of revolution with an aperture diameter of about 10 feet was chosen as the most practical reflector for the following reasons: 1) it has a relatively high aperture efficiency; 2) the antenna must be capable of being pointed parallel to the lunar surface; and 3) the physical limitations imposed by the space suit and the 1/6-g lunar environment make it necessary for the astronaut to work at the center of the reflector during erection and alignment of the antenna.

A parabolic reflector type of antenna with a folding capability that will allow packaging in the required shape and size can be constructed by stretching a reflective membrane between ribs. The resulting reflector is much like an ordinary umbrella in appearance (Fig. 2). The desired parabolic contour can be obtained either by suitably loading flexible ribs or by using relatively rigid ribs which have been properly shaped. For this antenna RCA has chosen the membrane/rib approach with ribs that are relatively rigid in construction. A reflector of this design has a more predictable and accurate contour than is possible with flexible ribs.

Practical antenna design is derived from a theoretical model which consists of a circular aperture having a Gaussian illumination distribution of

$$10^{-\left(\frac{Nr^2}{20}\right)}$$

where r is the normalized radius ($r = 1$ at the edge) and N is the edge taper in decibels. The total energy from the illuminator falls mostly within the aperture area for reasonable taper values. The amount falling beyond the edge corresponds to the spillover. Patterns and gain characteristics for this model are known for the normally used ranges of N.

The gain of the theoretical model is a function of aperture size with taper as a parameter. It can be shown that at $D/\lambda = 23$, corresponding to a 10-foot diameter at 2265 MHz (Mc/s), the gain is almost constant at about 34 dB for tapers of 10, 15, and 20 dB. The RCA design utilizes a 15 dB taper.

The practical antenna will have losses that are not present in the theoretical model. Semiempirical data indicates that these losses will be 2 dB. Some of the factors which contribute to these losses are as follows:

1) Aperture blockage
2) Feed phase error
3) Feed dissipation
4) Feed backlobe
5) Reflector dissipation and transmission
6) Feed reflection
7) Feed phase center error
8) Cross-polarization
9) Polarization
10) Surface deviations

In order for a reflector antenna to produce a highly collimated beam of energy, the phase distribution over the aperture must be uniform. Deviations in the uniformity of the phase distribution will reduce the intensity of the beam. These deviations in phase are caused by:

1) Deviation of the reflector from a true

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F. S. WEZNER received his BSME from the University of Pittsburgh in 1949 and his MBA from Drexel Institute of Technology in 1962. He joined RCA's Special Devices Engineering section in 1949, where he designed and developed servo-gear trains, navigational computers, and infrared devices for shipboard and airborne use. Reassigned as mechanical project engineer to Missile and Surface Radar Division in 1955, he was in charge of the general engineering effort on Talos land-based equipment. Promoted in 1957 to Leader, Mechanical Microwave Development and Design, he directed work on communication antennas for RELAY, SERT, Project L, and Project 706. He is presently in charge of the LEM Antenna Group, with responsibility for the lunar erectable antenna and the design of the microwave/antenna subsystem of the rendezvous radar. Mr. Wezner holds a patent on a reset mechanism; he has filed five patent disclosures on mechanisms and erectable antennas.

R. J. MASON received his BS degree in Mechanical Engineering from the University of Nebraska in 1950 and his MS degree in Mechanical Engineering from Villanova University in 1964. He joined RCA in 1950 and was employed as a design engineer responsible for the mechanical development of microwave components for such projects as: Bumblebee, Terrier, SPS-12, TV Relay, Talos, and BMEWS. More recently he was responsible for the mechanical design of the microwave system in the MIPIR radars. In 1962 and 1963 he was engaged in a jungle communications study which required the development of lightweight man-pack antennas and deployment devices. Mr. Mason is presently the lead mechanical engineer on the LEM erectable antenna.

Fig. 3—Change in gain vs number of ribs.

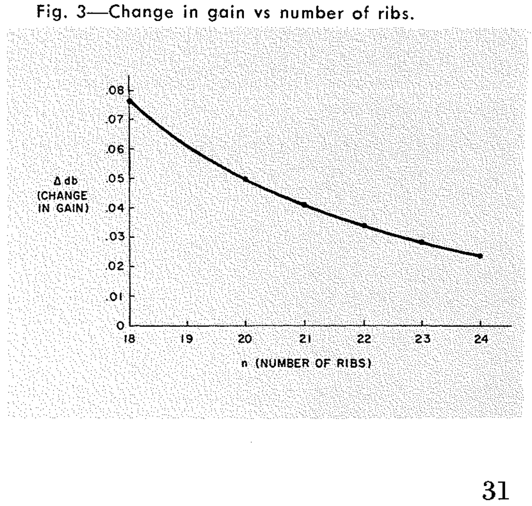


Fig. 4—Antenna reflector partially unfolded.

parabola (i.e., geometric errors which are a function of the number of ribs, saddle effect of the membrane, and total reflector droop).

2) Displacement of the feed center from the focal point of the reflector.
3) Deviation of feed wavefronts from a spherical shape.

Surface deviation losses were budgeted at 0.57 dB. It can be shown from the expression:

$$\alpha \text{ in} = \frac{0.452}{f} (\Delta \text{dB})^{0.5}$$

which states that the RMS deviation from a true surface must be limited to 0.15 inch to prevent the loss in gain from exceeding 0.57 dB. This requirement then becomes fundamental and of prime importance in the design of the antenna.

Although the surface formed by stretching a membrane between ribs is not a true paraboloid of revolution, the effect on gain is small (Fig. 3). In addition to this stretched-membrane effect, the total surface error is composed of a saddle effect due to radial tension in the membrane, the effect of droop in the gravity field, thermal distortion, wrinkles in the membrane, fabrication tolerances, and erection tolerances. The RMS of these errors must not exceed 0.15 inch, as previously stated. In general, the greater the number of ribs the more accurate the contour; however, the number of ribs is limited by weight and the space available. The RCA antenna has 21 ribs which are fabricated of 0.010-inch-thick aluminum brazing alloy formed into a tapered box beam and electron-beam welded. The curvature of the formed ribs provides the parabolic contour. A relatively flat reflector (F/D = 0.54) minimizes the load on the ribs and facilitates folding it into a cylindrical package.

Each rib must fold in two places to limit the length of the package to 39 inches. A 90° fold at the base of each rib and a 180° fold at approximately the mid-point allows the reflector to collapse neatly around the feed support (Fig. 4). The method of folding the ribs employs curved metal strip springs which are positioned to serve as a hinge in the folded postion and provide a *built-in* self-locking feature in the erected position. (Fig. 4) These springs, which look like pieces of a rolled-up steel carpenter tape, provide the energy necessary to erect the antenna automatically when the ribs are released. Each spring is coated with a material which prevents cold welding in the space environment. Springs have been operated by M&SR engineers in liquid-nitrogen baths and at elevated temperatures with no adverse effects.

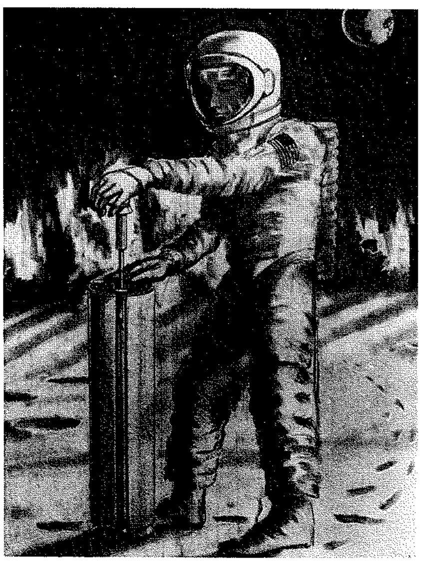
A special wire mesh was developed for the reflector surface. To fulfill its function, the reflector surface must:

1) Have a voltage reflectivity of 98%.
2) Be lightweight.
3) Fold and unfold at least 100 times without damage.
4) Be flexible at —420°F.
5) Withstand temperatures of +260°F.
6) Be dimensionally stable.
7) Pass as much solar energy as possible.
8) Resist ultra-violet radiation.
9) Not hold a static charge.

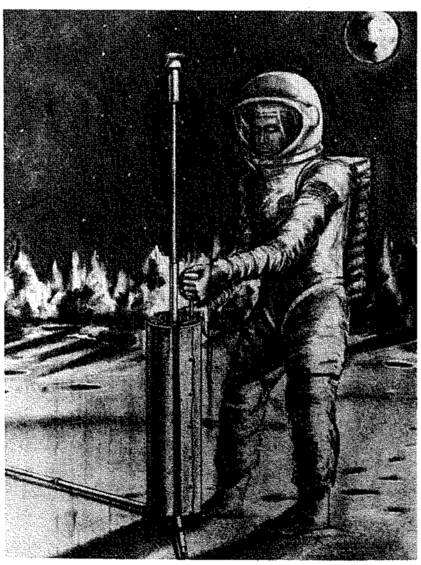
Organics and glass materials were first considered for this application; some were tried experimentally, but were discarded for various reasons. Although it is very expensive, the wire mesh fulfills all the requirements. The wire mesh, a tricot-knit fabric similar in appearance to mesh hose, is constructed of yarn composed of 14 filaments of 0.0005-inch-diameter nickel chromium wire. There are 38 miles of wire weighing 1.4 lbs. in each antenna. The fabric is coated with 0.000005-inch-thick, immersion-plated gold to obtain the required reflectivity. The mesh is comparable in flexibility to ordinary cloth

Fig. 5—An artist's conception of the antenna erection and aiming sequence is shown in a) through f) below.

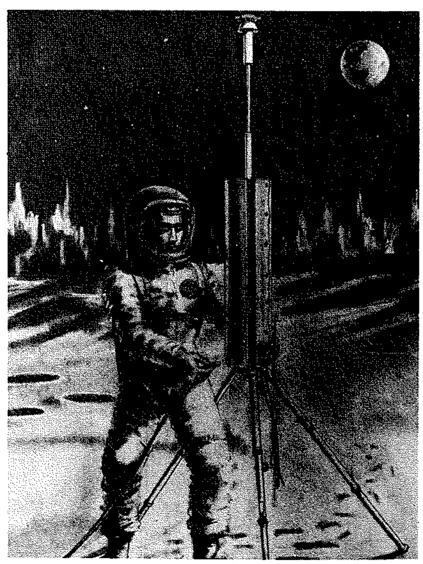
a. The astronaut sets the 39- x 10-inch antenna cylinder on the lunar surface and releases the telescoping feed.



b. The feed and telescoping tripod legs are extended.



c. The antenna is electrically connected to the LEM.



at room temperature, and at low temperatures it is far more flexible than any of the organics tested.

The wire-mesh fabric is cut into triangular sections and joined with very small rods which are threaded through the mesh openings. The rods are then fitted into grooves in the contoured edge of the ribs.

The antenna feed is supported on the end of a boom extending along the reflector axis. Packaging requirements dictated a telescoping boom that would be structurally rigid when extended to the exact final position required for the feed. In addition, it was determined that electrical losses could be minimized by using the support boom as a coaxial transmission line. The final result is a telescoping, 50-ohm, coaxial-feed support having two sliding-choke joints. The coaxial input to the antenna passes through the elevation axis and connects to the transmission line through a right-angle transformer.

The antenna feed is a single-element, end-fire helix with a cup-shaped reflector that reduces side-lobe and back radiation. The pitch of the outermost turn of the helix was adjusted experimentally, to obtain low axial ratios. The helix is electroplated on a hollow fiberglass cylinder through which the end of the support boom passes. A strip-line transformer on the back of the cup reflector matches the feed to the transmission line.

Since the RF beam must be centered on the earth, regardless of the position of the earth with respect to the moon, the effect of the reflector droop must be compensated by a similar droop of the feed support. This requirement was met by selecting a telescoping-boom diameter that would provide the proper flexibility. Factory adjustment of the unsupported length of the boom allows the droop of the boom to be changed if necessary.

The choice of structural materials was limited to those which are relatively thermally conductive, since uneven heating of elements such as the ribs or feed support could result in considerable distortion if the heat were not distributed by conduction. The temperature of the elements of the antenna can be controlled somewhat by the surface coating.

The reflector is mounted on a tripod consisting of telescoping tripod legs and an azimuth/elevation adjustment. The astronaut points the antenna by turning a crank. An azimuth travel of 360° and an elevation travel of 60° from zenith is provided. The elevation travel may be extended to 90° from zenith for certain mission requirements. The tripod legs fold around the antenna in the stowed condition and contribute to the structural rigidity of the stowed antenna. These legs are adjustable to compensate for a 5° slope of the lunar surface, and they are spread so that the center of gravity of the antenna always falls within the leg triangle.

The astronaut uses an optical sight to center the RF beam on the earth. The sight consists of a ring sight and a mirror which allows him to maintain a sight angle perpendicular to the lunar zenith as the antenna is pointed through various angles of elevation. The ring sight subtends a small portion of the field of view through the mirror. The earth is first located using the mirror. Then the antenna is rotated in azimuth and elevation until the earth is brought into the field of view of the ring sight, after which the aiming is with the ring sight. Breadboard tests indicate that pointing accuracies of 0.085° are easily obtained with this arrangement.

The antenna is completely folded into a cylindrical package for transportation to the moon. Two covers are provided for the package. The outer cover protects the antenna from dust in the earth environment and is removed prior to launch. The inner cover, which serves as a thermal shield against solar radiation, is removed prior to deployment of the reflector.

The antenna erection and aiming sequence is visualized in Fig. 5.

CONCLUSION

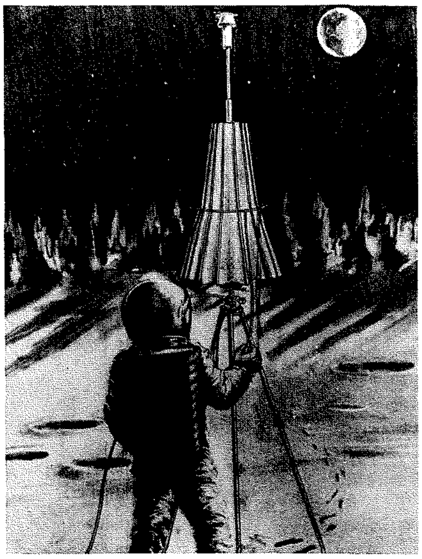
The relatively simple problem of designing a high-gain antenna becomes quite complex when weight, space environment, and human factors requirements are added. The detailed engineering considerations described in this article illustrate the extent of design effort required for a relatively simple end use. Even the smallest piece of hardware requires tremendous engineering analysis as well as ingenuity when the reliability requirements of a mission such as Apollo are imposed.

ACKNOWLEDGEMENTS

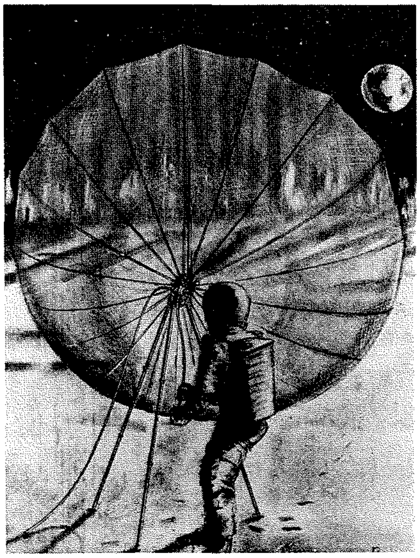
The authors wish to express their appreciation for the contributions of Dr. R. C. Spencer and D. F. Bowman to this project.

d. A protective cover (thermal shield) is removed before the reflector is deployed.

e. When the astronaut squeezes the release trigger, the package unfurls into a 10-foot-diameter parabolic reflector.



f. The astronaut uses an optical sight to center the RF beam on earth; he points the antenna by turning a crank.



LUNAR EXCURSION MODULE RENDEZVOUS RADAR & TRANSPONDER

The Lunar Excursion Module (LEM) carries a rendezvous radar for tracking a transponder located on the lunar surface or on the Apollo Command Module, and for tracking the lunar surface. This radar must make precise measurements of angle, angle rate, range, and range rate along the line of sight. These measurements will provide the data required for successful guidance of the LEM to a rendezvous with the Command Module, which will terminate the lunar excursion part of the Apollo mission. The rendezvous radar and transponder are designed to provide the required accuracies under the widely varying conditions of space flight with high reliability and minimum weight.

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THE rendezvous radar is a versatile general-purpose tracking device which furnishes the LEM with accurate relative measurements of position and velocity. Relative measurements may be made to a transponder located on the Command Module to provide the navigation fixes needed to accomplish safe rendezvous. They may also be made to a transponder functioning as an active homing device on the lunar surface, in order to achieve a precise lunar landing. Such relative navigation fixes are used both during the descent and ascent of the LEM vehicle and during the LEM's stay on the lunar surface. The radar also provides continuous relative navigation data throughout the mission. For instance, during the descent to the lunar surface, the radar tracks the Command Module and, by using it as a reference point, assists in the accurate deceleration and landing on the surface.

The radar can also make range and doppler measurements to the lunar surface without the benefit of a transponder. During the terminal landing manuevers, the velocity of the LEM relative to the lunar surface can be determined from the doppler data, and the LEM's altitude can be determined from the range data. In this mode, the rendezvous radar can function as an alternative to or as a monitor of the landing radar.

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PERFORMANCE REQUIREMENTS

The performance requirements for the rendezvous radar/transponder are shown in Table I in terms of the required accuracy of output data. Due to the manned space-flight aspect of the LEM mission, the reliability requirements are very high.

TABLE I—Rendezvous Radar/Transponder Accuracy Requirements*

Range	— Less than 1% error
Range Rate	— Less than 1 foot/second error
Angle	— Less than 1/8° error
Angle Rate	— Less than 0.3 milliradian/second error

* Exact figures classified

The rendezvous radar/transponder must operate in the vacuum of space (10^{-10} mm of Hg) and under the vibration conditions associated with the thrust of the main rocket engines of the LEM. The antenna assembly mounted on the LEM body must operate in an external temperature range of −300°F to +250°F, corresponding to the lunar night and lunar day. In certain positions the antenna is exposed to the hot gases expelled by the reaction control jets; these jets operate intermittently during space flight, and the radar must maintain full accuracy during their operation. All the above performance requirements are to be met with a radar and transponder whose total weight is less than 80 pounds.

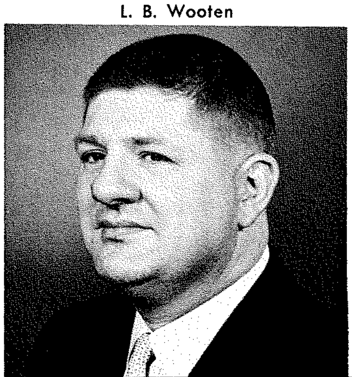
Table II contains a list of rendezvous radar parameters, and Table III includes the transponder parameters.

TABLE II—Rendezvous Radar Parameters

Radiation Frequency (Classified)	X-band
Radiated Power (Classified)	Less than 1 W

Dr. W. C. Curtis

L. B. Wooten



WILLIAM C. CURTIS received his BS degree in Electrical Engineering in 1934 and his MS degree in Electrical Engineering in 1935, both from the University of Illinois. He joined the Industrial Education Department of Tuskegee Institute in 1935 as an instructor of electrical design, and in 1940 became Director of the School of Mechanical Industries. In 1945 he left Tuskegee to attend Harvard University, from which he received an MS degree in Communications Engineering in 1945 and a PhD degree in Engineering Sciences and Applied Physics in 1949. While at Harvard, he was employed at the Raytheon Company where he was in charge of frequency modulation engineering for commercial transmitters. He returned to Tuskegee Institute as Dean of the School of Engineering in 1949. He joined RCA in 1954 and has since been responsible for the direction of theoretical and experimental analysis of new radar techniques. He is Manager, Radar Systems, in Radar Engineering. Dr. Curtis has made patent disclosures on circuits to detect ground intercept of monopulse beams, on techniques for optical pulse compression, and on new film recording techniques for radars. He published one paper on "Time Delay of Variational Current in Glow Discharge Tubes."

LYNN B. WOOTEN received his BSEE degree from Tulane University in 1949. He worked as a broadcast engineer until he joined the U.S. Army, where he was engaged in field testing of fire-control radars and radio-controlled target aircraft. After receiving his MSEE degree from Tulane University in 1955, he joined RCA's Airborne Systems Division in Camden, N.J. There he designed aided-lock-on circuits for the MG-3 airborne radar, an automatic ranging modification for the MA-7 airborne radars, and a sampled-data range tracking system for a special counter-countermeasures technique for air defense aircraft. He began systems work in radar and electronic countermeasures in 1957 on the ARIES and ASTRA airborne fire-control radars. He joined the RCA Systems Engineering Program at the University of Pennsylvania and received an MS degree in Systems Engineering in 1959. He was design engineer on the automatic target detection and acquisition circuits for the AN/FPS-16 radar digital ranging modification, systems engineer on the AN/ALR-19 countermeasures receiver, and project engineer on the "Decision Synthesis" automatic ECM control system. Since 1964, he has been systems engineer on the receiving, frequency tracking, and range-tracking subsystems for the LEM rendezvous radar. He is a member of the IEEE.

Table II Cont'd

Antenna Design	Cassegrainian
Amplitude monopulse Tracking Method	
Antenna Diameter	24 in
Antenna Gain	32 dB
Antenna Beamwidth	3.25° - 4.0°
Antenna Sidelobe Level	15 dB adjacent to main lobe
Angular Coverage	± 70° x 225°
Number of Gyros	4 (2 redundant)
Modulation (Transponder mode)	PM by 3 tones: 200 Hz, 6.4 kHz, 204.8 kHz
Modulation (Surface mode)	FSK, 50% duty cycle, 6 kHz - 480 kHz
Receiver Channels	3
Receiver Noise Figure	10 dB max
Receiver IF Frequencies	40.8 MHz, 6.8 MHz, 1.7 MHz
Maximum Range (Classified)	Several hundred miles
Minimum Range	50 ft
Maximum Range Rate	± 4900 ft/s
Minimum Range Rate	0 ft/s

TABLE III—Transponder Parameters

Received Frequency	X-band
Radiated Frequency	Received frequency minus 40.8 MHz
Radiated Power	Less than 1 W
Modulation	PM by 3 tones: 200 Hz, 6.4 kHz, 204.8 kHz
Receiver Noise Figure	10 dB max
Receiver IF Frequencies	40.8 MHz, 6.8 MHz

RENDEZVOUS RADAR

The rendezvous radar is basically an X-band, space-stabilized, CW tracking radar designed to track a cooperating transponder. Since the radar and its transponder each utilize solid-state varactor multipliers as transmitters, transmission and reception are on a high-duty-cycle CW basis. Gyros located on the radar antenna stabilize the line of sight against the effects of LEM body motions and permit accurate measurements to be made on the line-of-sight angular rate. Angle tracking uses the technique of amplitude-comparison

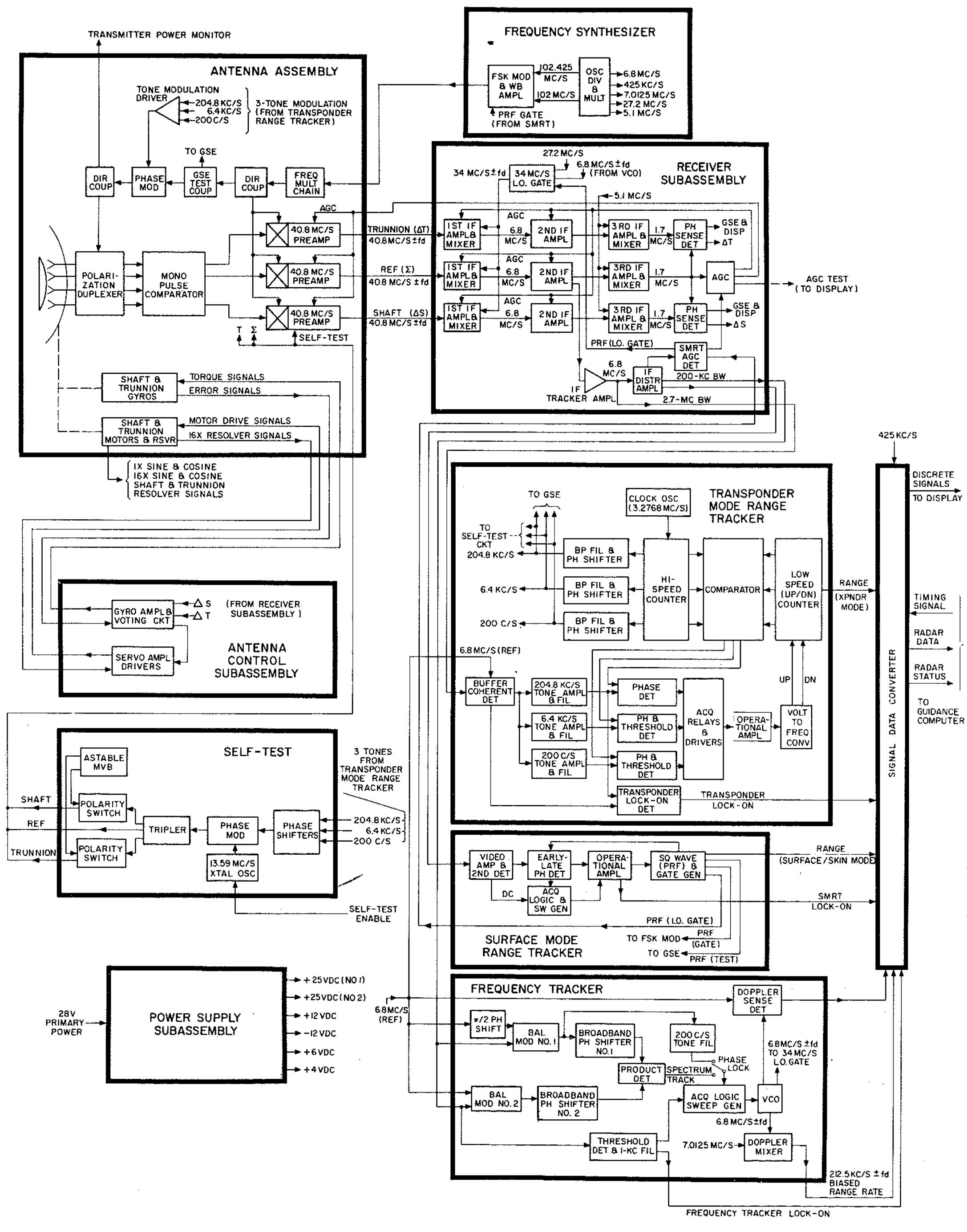


Fig. 1—Detailed block diagram of rendezvous radar.

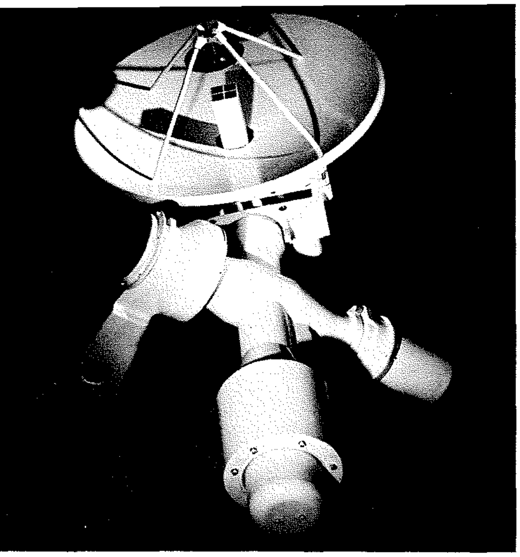


Fig. 2—External view of radar antenna.

monopulse (or simultaneous lobing) to obtain maximum angular sensitivity and boresight accuracy. Range-rate is determined by measuring the two-way doppler frequency shift on the signal received from the transponder. Range is determined by measuring the time delay between the transmitted signal modulation waveform and the received signal waveform. The modulation used during the transponder tracking mode is multitone phase modulation; during the surface mode, the modulation is variable-PRF FSK. The FSK modulation permits the use of a single antenna for both transmission and reception during the surface mode, where the transponder frequency side-step action is not present. A block diagram of the rendezvous radar is shown in Fig. 1.

Antenna Assembly

The radar antenna assembly includes the usual microwave radiating and gimbaling elements and many other internally-mounted electrical components, such as gyros, resolvers, multiplier chain, modulator, and mixer-preamplifiers. The antenna location of the multiplier chain transmitter and the receiver mixer-preamplifiers eliminates the need for a large number of microwave rotary joints and permits the use of flexible low-frequency coaxial cables to connect the outboard antenna components to the inboard electronics assembly. A flexible cable wrap-up system is used at each of the rotary bearing points.

The antenna is a four-horn, amplitude-comparison, monopulse type having a cassegrainian configuration to minimize total depth. The antenna transmits and receives circularly polarized radiation to minimize signal variations resulting from attitude changes of the linearly-polarized transponder antenna. Fig. 2 is an external view of the antenna assembly. Components are distributed inside the antenna to achieve balance around each axis. Each axis is controlled by a brushless servo motor driven by pulse-width modulated drive signals.

Four rate-integrating gyros are used for line-of-sight space stabilization and line-of-sight inertial angle-rate measurement. These gyros in the lower section of the trunnion axis act as a counterweight. Only two of the gyros are used at any one time. and a voting logic system (not located on the antenna) is utilized to transfer control to the other two gyros in the event of a failure in either of the two gyros being used. A two-speed resolver is mounted on each axis for high-accuracy angle-data pickoff for the guidance computer and for display.

The multiplier chain, phase-modulator, and mixer-preamplifiers are mounted internally behind the antenna dish. The multiplier chain supplies X-band power for radiation and local oscillator excitation, which is feasible because the transponder replies with a frequency side-step equal to the radar first IF frequency. The heat dissipated by the multiplier chain is radiated into space by the dish. The phase modulator uses a ferrite rod inside a waveguide and a solenoid for varying the magnetic field inside the rod. The ranging tone signals are applied to the solenoid, varying the electrical length of the rod and providing phase modulation of the X-band carrier. Three balanced mixers and three preamplifiers are included: one for the reference channel, one for the shaft error channel, and one for the trunnion error channel.

Servo Electronics

Included in the antenna servo electronics are amplifiers for driving the antenna shaft and trunnion axis servo motors, amplifiers for driving the gyro torquer coils, and voting logic for selecting the correct gyro pair. The servo electronics, in connection with the antenna components and radar receiver, form an inner and outer closed loop for each axis. The inner, or stabilization, loop keeps the antenna boresight axis fixed in inertial space in the presence of body motions. The outer, or tracking, loop directs the antenna boresight to the target, using tracking error signals from the monopulse receiver.

In the automatic mode the guidance computer will designate the antenna boresight to within one degree of the target and command the tracking loop to close. The antenna will then continuously track the target by maintaining the monopulse receiver angle error signals at null. The antenna may also be manually slewed at fixed inertial rates.

The antenna shaft and trunnion motors are 32-pole, brushless, permanent-magnet rotor types driven by pulse-width modulated drive signals applied to sine and cosine windings of each motor. The direction of rotation is changed by reversing the motor windings which are excited by a pulse-width modulated drive voltage obtained by on/off switching of the 28-VDC power at a 1.8-kHz (kc/s) rate.

A gyro voting system consisting of performance comparison and logical switching circuits automatically detects and removes a malfunctioning gyro. Of the four gyros, two are used to stabilize the antenna and two are used to monitor the performance of the controlling gyros. Each pair can perform either the control or the monitoring function. The voting system determines whether either pair contains a failed gyro and ensures that that pair is not used to stabilize the antenna.

Receiver

The receiver is a three-channel, highly stable, triple-conversion superheterodyne which has intermediate frequencies of 40.8, 6.8, and 1.7 MHz (Mc/s). The bandwidth of the first and second IF amplifiers is approximately 3 MHz, and the bandwidth of the third IF amplifier is approximately 1 kHz. Two channels are provided for amplifying the shaft and trunnion axis error signals and one channel for amplifying the sum or reference signal. The receiver also includes phase-sensitive detectors for generating angle error signals, an AGC circuit for controlling the gain of the three receiver channels, an IF distribution amplifier unit for supplying reference channel signals to range and frequency trackers, and a gated local oscillator mixer for generating the second local oscillator signal. The second local oscillator frequency is obtained by beating the output of the frequency tracker VCO (voltage-controlled oscillator) with a reference frequency to produce a sum frequency exactly 6.8 MHz lower than the incoming 40.8-MHz doppler-shifted frequency. After the second mixer, the doppler frequency shift is removed, and all subsequent signal processing is accomplished at fixed carrier frequencies. The most stringent requirement on the receiver is that the three channels must gain-track within ±2.5 dB and phase-track within 27° over a dynamic range of greater than 110 dB, and over a temperature range of 70°C.

Frequency Synthesizer

The frequency synthesizer generates all of the fixed frequencies required for coherent signal transmission and reception. A single 1.7-MHz stable crystal oscillator and a system of multiplication, division, and mixing produce the required frequencies. During the transponder mode, a CW output signal is generated for excitation of the transmitter multiplier chain. During the surface mode, a variable-PRF FSK-modulated excitation is generated. The synthesizer also generates various receiver local oscillator, clock, and reference frequencies used by the receiver, the signal-data converter, and the trackers.

Frequency Tracker

The frequency tracker tracks either the coherent narrow-line spectrum received from the transponder or the wide spectral distribution received from the lunar surface. During the surface mode the tracker generates a VCO sine wave which tracks the center of power of the received signal spectrum. During the transponder mode, the tracker is switched to phase-lock the VCO with the incoming narrow-line spectrum. Note that the phase detector for the phase-locked loop uses a 6.8-MHz signal from the frequency synthesizer as a reference. The error signal drives the VCO to a frequency that, when mixed with a 27.2-MHz synthesizer signal and used as the local oscillator signal for the second IF mixer, removes the doppler frequency shift from all signals in succeeding IF stages. Thus passage of the 1-kHz-bandwidth signal through the 1.7-MHz filters is assured. The tracker utilizes a frequency sweep circuit for sweeping the VCO frequency across the doppler frequency range (± 100 kHz), searching for the received signal. A threshold circuit senses the presence of the carrier signal within locking range, stops the sweep, and permits the VCO to phase lock.

Transponder Mode Range Tracker

The transponder mode range tracker determines the range to the transponder by measuring the phase angle between the transmitted tones and the received tones. The signal received from the transponder (at 6.8 MHz) is demodulated in a coherent product detector which uses a 6.8-MHz quadrature reference. The individual sine-wave tones are extracted from the receiver noise using bandpass filters tuned to the tone frequencies. Range phase-delay is measured independently on each of the three tones in a closed tracking loop. Three reference square waves are generated locally, each having variable phase with respect to the transmitted tones. This phase delay is adjusted until the reference square waves have matching phase with respect to each of the received tones. The reference square waves are produced digitally by comparison between a running high-speed counter and a low-speed up-down range counter. The low-speed range counter is driven up or down until a phase null is achieved in each of three phase detectors. The range counter is driven up or down by incremental range pulses obtained from a DC-to-PRF converter controlled by weighted integration of the three-phase detector error signals.

Surface Mode Range Tracker

The surface mode range tracker controls the PRF of the frequency-shift-keyed CW transmitted signal. The PRF is automatically adjusted to the value which will cause the returned signal from a transmitted pulse to be centered in time between that transmitted pulse and the next transmitted pulse. Under these conditions the period of the PRF is twice the radar signal transit time.

Signal Data Converter

The signal data converter accepts range and range-rate data from the range and frequency trackers, converts it to 15-bit serial format, and shifts it out to the guidance computer as requested by the computer. The signal data converter also sends various discrete radar status indications to the computer, selects radar modes, and processes display data for activation of the astronaut display panels.

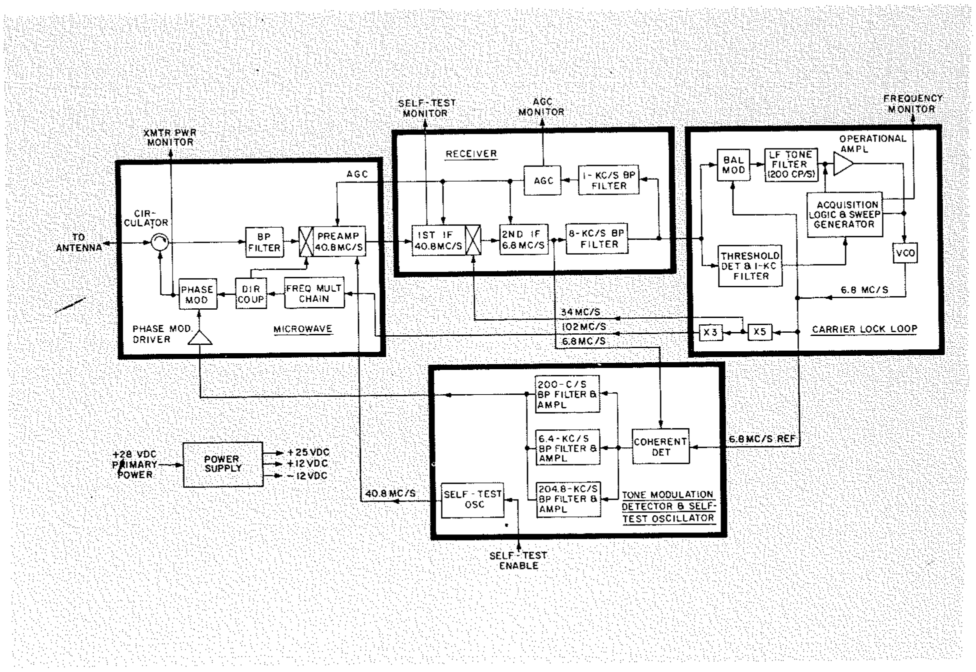
Self-Test

Radar self-test circuits in the frequency tracker subassembly permit testing of the radar without the use of a cooperating transponder. The self-test circuit checks transmitter power, phase-lock at minimum signal level, angle error detection, AGC action, and range and range-rate measurement. Insertion of single values of range and range rate permits quantitative checking by observation of the displays.

Power Supply

The radar power supply is basically a highly efficient DC-DC converter providing six regulated DC output voltages. The unit utilizes the method of switched-tap modulation for input regulation. After chopping, rectification, and filtering, series regulators are used at each output. The use of a 20-kHz chopping frequency makes it possible to minimize the weight of transformer and ripple filter components. Short-circuit protection circuitry senses overload current conditions on any of the output lines and deactivates the 20-kHz chopping oscillator for a preset period of time. If the overload is removed during this period of time, normal operation is resumed; if not, the deactivation cycle continues until the overload is removed.

Fig. 3—Block diagram of transponder.



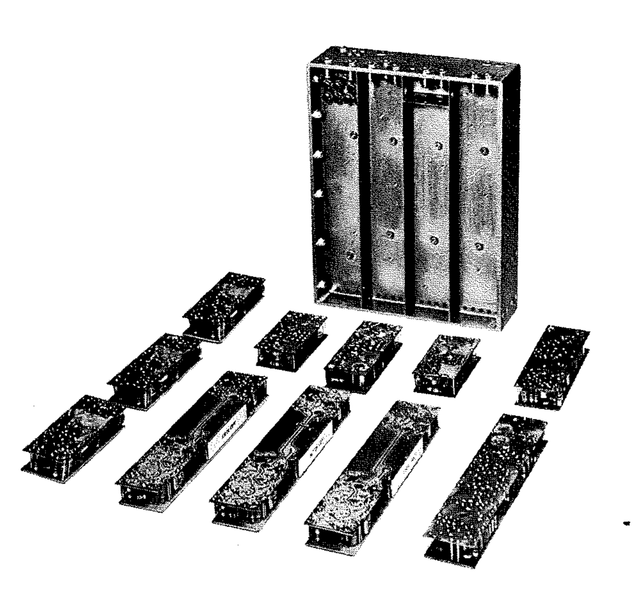


Fig. 4—Cordwood modules of segment No. 1 in radar receiver.

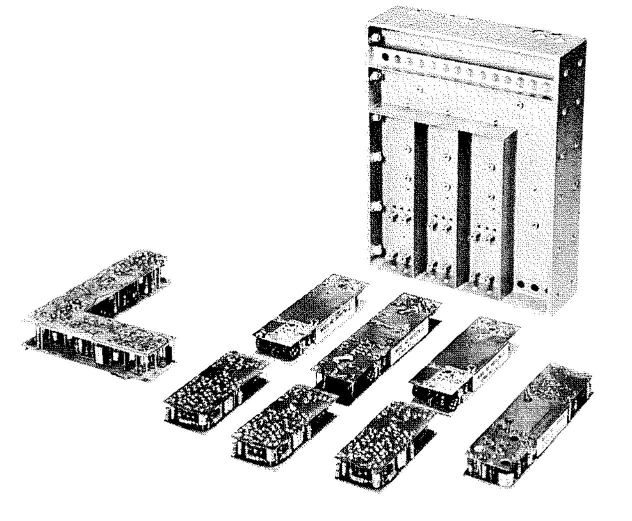


Fig. 5—Cordwood modules of segment No. 2 in radar receiver.

TRANSPONDER

The transponder, in connection with its antenna, receives the transmitted CW radar signal and generates a strong phase-locked reply signal for transmission back to the radar. The ranging modulation on the received signal is also turned around and sent back to the radar. The transponder, like the rendezvous radar, employs a single multiplier chain for both transmitter and local oscillator. This arrangement is made possible by designing the transponder to reply with a carrier frequency that is an exact integer ratio of the received signal carrier frequency; consequently, the transmitted frequency is 40.8 MHz lower than the received frequency. A small portion of the transmitter output is used for local oscillator excitation, and a first IF frequency of 40.8 MHz results. Since the transmitted and received frequencies are separated, the use of a diplexer permits operation with a single antenna. A block diagram of the transponder is shown in Fig. 3. (Refer to Table III for transponder parameters.)

The phase-lock operation of the transponder is as follows. The radar carrier signal is received and converted to the first IF frequency of 40.8 MHz. The signal is amplified and mixed with a 34-MHz second local oscillator frequency to produce a 6.8-MHz second IF frequency. A voltage-controlled oscillator is pulled in frequency in an APC loop to phase-lock the incoming 6.8-MHz IF carrier signal to the VCO signal. Multiplication of the VCO frequency by approximately 1400 produces the transmission (and first local oscillator) frequency. Acquisition is accomplished using a VCO sweep and threshold circuit similar to the one used in the radar.

The ranging tones are extracted from the 6.8-MHz received signal in exactly the same manner as in the radar. After bandpass filtering and amplification, they are applied to the phase modulator for retransmission back to the radar.

Self-test circuits are included to permit testing of the transponder without the use of the rendezvous radar. A test oscillator operating at a single frequency permits the transponder to phase-lock without an external input. The transmitter power and AGC action may also be checked for phase lock at minimum signal level.

ACQUISITION TECHNIQUE

The normal automatic acquisition sequence for the rendezvous radar and the transponder is as follows:

1) The radar antenna, under computer control, is designated in angle so that its transmitted CW radiation can be received at the transponder.
2) The transponder, which was previously sweeping in frequency, stops its sweep and phase locks to the received radar signal.
3) The radar receiver, which was previously sweeping in frequency, stops its sweep and phase locks to the received transponder signal.
4) The radar angle tracking loop is then closed and the angle error is nulled.
5) The radar activates ranging modulation and the range tracking error is nulled.
6) The radar indicates a *data good* condition to the computer.

PACKAGING OF ELECTRONICS

The electronic assembly circuitry is developed in two forms: 1) digital and analog integrated circuits using multilayer boards, and 2) coated (unpotted) cordwood packaging for discrete electronic parts.

Cordwood packaging (Figs. 4 and 5) allows a 2:1 reduction in size over the usual transistor circuit packaging methods. Egg-crate design of packaging cases provides shielding of high-frequency receiver circuits.

Cooling is obtained by bolting case flanges to a *cool* plate varying in temperature from +35°F to +135°F. The design is such that despite this variation, the temperature of an electronic part will not exceed +160°F. Conductive cooling of the electronic parts is achieved by sealing the bottom of a cordwood board to the subassembly web with a high-thermal-conductivity compound. Where required, beryllium oxide ceramic heat sinks are used to conduct excessive heat to the subassembly web.

CONCLUSION

The rendezvous radar/transponder provides the LEM navigation system with the high-accuracy tracking data needed for rendezvous or precise lunar landing. These accuracies are achieved under the widely varying conditions of space flight with high reliability and with minimum weight. The probability of mission success is enhanced through the use of operational modes which can serve as a backup for the primary modes.

CASSEGRAINIAN MONOPULSE TRACKING ANTENNA FOR SPACE RENDEZVOUS

This paper describes the development and design of an X-band tracking antenna assembly which will provide position and rate information on range and angle between the Lunar Excursion Model and the Command Service Module for navigation and guidance computations during the lunar-stay and rendezvous phases of the Apollo mission. Controlling factors such as performance requirements, environment, and size and weight limitations are outlined.

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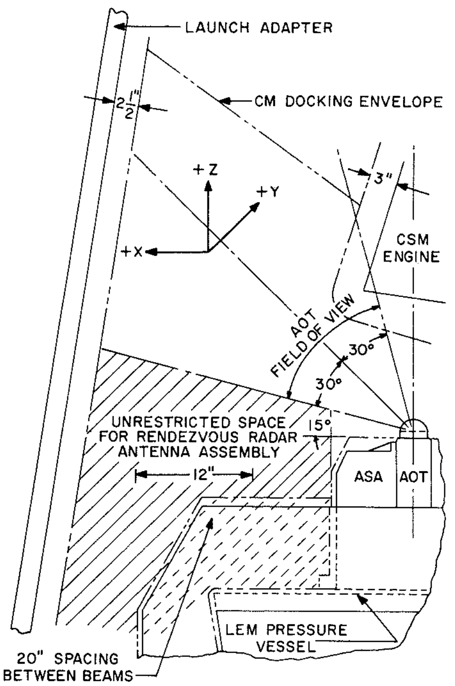


Fig. 1—Envelope restrictions

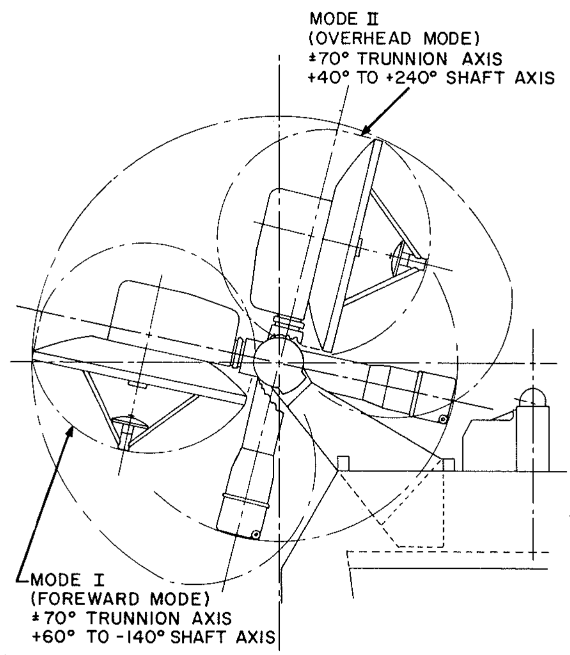
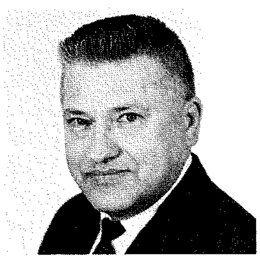


Fig. 2—Angular coverage



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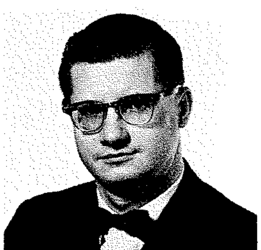
W. E. Powell



WAYNE W. CARTER received his BSME degree at Iowa State University in 1942. He was employed for 5 years by the Elliott Company, Jeanette, Pa., in research and development of air compressors and combustion chambers for large gas-turbines. From 1947 to 1950 he worked for Socony Mobil Oil Company in the research and development of fuels and lubricants for internal combustion engines. He joined RCA in 1950 as a member of the Government Radar Section. He contributed to the development of the AN/FPS-16 instrumentation radar antenna and the TALOS land-based missile launcher, and he was principal design engineer on the BMEWS tracking radar antenna. Recent activities have been concerned with the development of antennas for space use, and he is presently a member of the Advanced Radiation Equipment Group. He is a member of the American Society of Mechanical Engineers and the American Society for Metals.

WALTER E. POWELL received his BSEE degree from the University of Pennsylvania in 1951. From 1951 to 1958 he was employed as an electronic scientist at the Naval Air Development Center, where he was engaged in the design and development of radomes and radome materials. He joined RCA in 1958 and was assigned to the design of antenna components for the BMEWS tracking radar. Other assignments included studies of the electrical properties of the BMEWS radome and the TRADEX antenna concepts. In 1960 he became Leader of the Radar Antenna Group, where his responsibilities included supervision of the design and development of the TRADEX antenna microwave components, the FPQ-6 radar Cassegrainian antenna feed system, and a low-noise temperature antenna study. In 1964 he became responsible for the antenna microwave design of the LEM rendezvous radar antenna assembly. Mr. Powell is a member of the IEEE and the Franklin Institute.

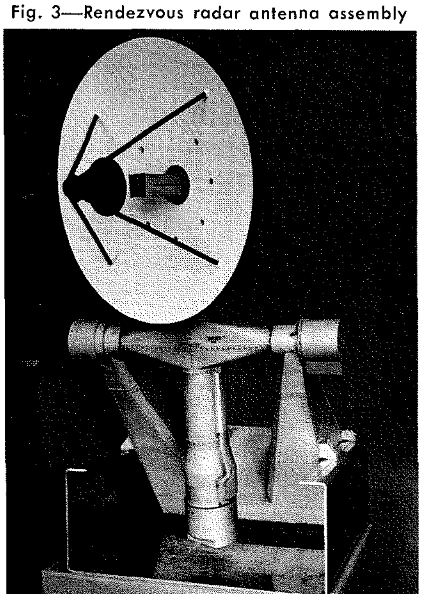
THE rendezvous radar antenna assembly, a major subassembly of the rendezvous radar[1], will provide range, range-rate, angle, and angle-rate information for the rendezvous of the Lunar Excursion Module (LEM) with the Command Service Module (CSM) during the manned lunar landing mission. The antenna assembly, mounted externally on the LEM structure, provides either primary or back-up functions during the descent, lunar stay, ascent, and rendezvous phases of the LEM mission. The two-axis antenna assembly includes: a Cassegrainian antenna with monopulse feed, transmitter, and receiver preamplifiers to generate line-of-sight (LOS) angle-error signals for angle tracking and received sum signal for range tracking; on-mount gyros to generate LOS angle-rate data relative to inertial reference; and resolvers to generate LOS angle position data relative to the LEM.

REQUIREMENTS AND CONSTRAINTS

In addition to such considerations as high launch-vibration levels and high vacuum environment typical of space mission equipment, the design and development of the rendezvous radar antenna assembly was subject to a number of system requirements and constraints. First, the assembly must provide the widest possible angular coverage with limited space, weight, and electrical power. Second, high levels of reliability, antenna gain, and pointing accuracy must be maintained under all mission conditions, including vibration effects from the ascent and descent main propulsion engines, and exhaust plume effects of the reaction control steering engine. Third, the antenna assembly must be compatible with other system components with axes orientation, temperature levels, and motion of parts dictated by other system requirements. Fourth, the design must be adaptable to changing requirements as finer details of the various phases of the overall mission or *mission profile* evolve.

Final manuscript received December 27, 1965

Fig. 3—Rendezvous radar antenna assembly



EVOLUTION OF DESIGN CONCEPT

Initial systems analyses and trade-off studies established the need for a 24-inch-diameter Cassegrainian reflector and monopulse feed arrangement with on-mount transmitter and receiver preamplifiers to minimize power losses and on-mount redundant gyros to provide line-of-sight angle-rate data. Compatibility with other navigation instrumentation and nomenclature required the use of a gimbal arrangement with a *shaft* axis parallel to the LEM Y axis and an orthogonal *trunnion* axis providing antenna motion outward to each side of the LEM X-Z plane (the shaft-trunnion axes correspond, respectively, to the more commonly known elevation-traverse axes). Angular coverage specifications defined the 0° reference as looking along the LEM Z axis and required a shaft axis angular coverage from −70° to 155°, a total travel of 225°, and a trunnion axis coverage from −70° to 70°, a total travel of 140°.

The space available on LEM for the antenna assembly is shown in Fig. 1, which defines principal space envelope restrictions and location of adjacent components. Extensive design layout studies were conducted using small high-speed-drive motors with gear reducers and offset gimbal axes. These studies indicated that the required range of travel could not be obtained within the available space and envelope constraints without the use of a separate deployment device to move the antenna from a stowed to an operating position. Furthermore, accuracy requirements under main propulsion engine thrusting conditions and avoidance of principal LEM structural resonant frequencies indicated the need for higher first-mode antenna resonant frequencies, with 60 Hz (cps) as a goal.

A review of the angular coverage requirements for different parts of the lunar mission indicated that shaft-axis coverage requirements occur in two conical zones, one centered along the LEM Z axis and the other centered along the LEM X axis. A new gimbal arrangement was conceived with intersecting gimbal axes and an offset antenna reflector which is counterbalanced by the gyros and trunnion axis drive components on the opposite side of the shaft axis. Angular coverage (Fig. 2) is obtained in two modes. Mode I provides shaft axis coverage from 60° to −70° and beyond. Mode II, obtained by rotating the trunnion axis an additional 180°, provides line-of-sight coverage from 40° to 155° and beyond, assuring a 20° overlap between Mode I and Mode II coverage. This arrangement could potentially provide complete spherical angular coverage. Useful angular coverage is presently limited only by gimbal-lock conditions near the poles and by blockage from the LEM structure. Significant additional features of this arrangement are: 1) the incorporation of direct-drive brushless torque motors, 2) precision dual-speed pancake resolvers, 3) use of clock-spring cable wraps, and 4) elimination of all sliding or rolling contact except for bearings and seals, with resultant increased accuracy and reliability.

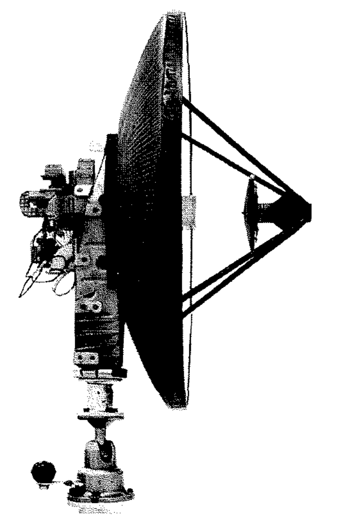
DESCRIPTION OF ANTENNA ASSEMBLY

The Flight Weight Breadboard Antenna Assembly (shown without heat shields in Fig. 3) is essentially a prototype model used for radar system debugging and preliminary evaluation. The antenna assembly includes two functional subassemblies: the RF subassembly, which includes all of the antenna, transmitter, and receiver components related to RF radiation; and the gimbal subassembly, which includes all of the components necessary to support and position the RF subassembly.

RF Components

The RF subassembly (Fig. 4) includes the 24-inch-diameter Cassegrainian reflector components, a solid-state frequency-multiplier transmitter and subassembly[2], a modulator driver, and a microwave subassembly. The microwave subassembly (Fig. 5) includes the feed, comparators, directional coupler, and waveguide components; all items are fabricated of 40E aluminum alloy by precision investment casting and joined by dip-brazing. Also included in the microwave subassembly are three mixers with solid-state preamplifiers, a

Fig. 4—RF subassembly



phase modulator, and the LO distribution system.

A unique feature of the microwave subassembly is the polarizer-duplexer, which provides for separation of the transmit and receive signals at the feed horn (Fig. 6). The polarizer-duplexer consists of a polarizer element and a dual-mode transducer which mate with each of the four radiating horns making up the four-horn monopulse feed system. One port of the dual-mode transducer connects to the transmitter by way of the transmit power-divider. The orthogonal port of the transducer is connected to the receiver via the monopulse comparator. These two ports of the transducer couple through two orthogonally polarized modes into the polarizer element. The two ports are isolated from each other by greater than 50 dB, due to the orthogonality of the ports and the transducer. The polarizer element converts linearly polarized inputs into circular polarization. Orthogonal linear signals are converted to orthogonal circular signals. The transmit signal is converted into right-hand circular polarization and the receive channel receives left-hand circular polarization.

Although the inherent isolation of the dual-mode transducer is greater than 50 dB, the isolation of the polarizer-duplexer of the antenna is limited by the reflections from the feed horn aperture and the subreflector. When a circularly polarized wave is reflected from a symmetrical reflector, its sense is reversed. Therefore, reflections of a circularly polarized transmit signal tend to cross couple into the receive channels, degrading the inherent isolation of the transducer. Due to the proximity of the subreflector to the feed horn, the level of the reflection from the subreflector is extremely high. Considerable development effort was required to substantially reduce reflections from the subreflector without seriously degrading the antenna radiation pattern. A vertex matching plate on the subreflector was used to reduce subreflector reflections.

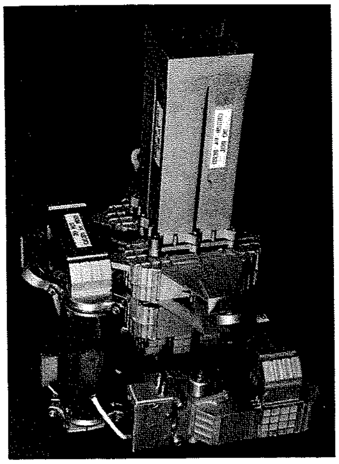


Fig. 5—Microwave subassembly

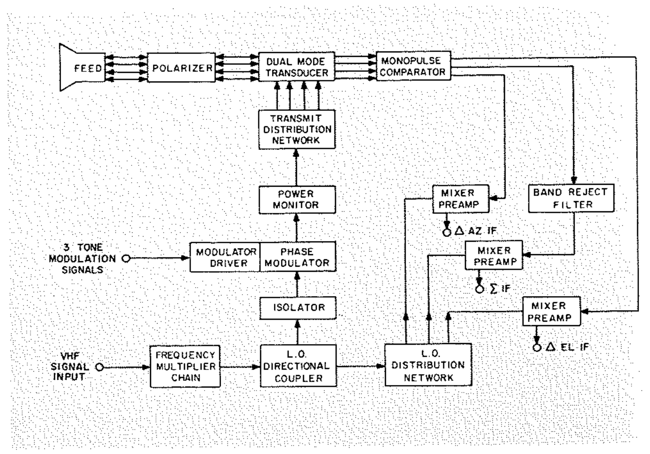


Fig. 6—Microwave subassembly block diagram

Gimbal Subassembly

Detail features of the gimbal subassembly are shown in Fig. 7. The two axes utilize similar parts which differ only in size and arrangement. The keynote of the design is mechanical simplicity, with sliding contacts eliminated wherever practical.

The direct-coupled brushless torque motors used in the angle drives eliminate gear backlash and gear compliance from the drive system, reduce the number of mechanical parts and cable-wrap circuits, provide improved heat transfer for heat dissipation from the motor, and increase reliability. Motor commutation signals are derived from the 16-speed winding of the dual-speed resolver (required for angular position readout) without disturbing the data function of the resolver. In similar fashion, signals can be taken from the one-speed cosine winding of the trunnion axis resolver to derive a *secant* function to aid in maintaining constant shaft-axis servo-loop gain. Angle-rate readout of LOS angle relative to inertial space is derived from two pairs of redundant gyros mounted on the trunnion rotating assembly. The gyros are positioned to counterbalance the offset antenna reflector.

Electrical signals are carried to and from the rotating portions of the antenna by means of spiral *clock-spring* cable-wraps utilizing flat Teflon-woven straps containing a combination of coaxial lines and single, double, and triple twisted leads, with and without shields. The cable-wrap avoids the use of sliding contacts and greatly reduces the number of components, thereby increasing reliability.

The drives for each axis have eliminated the need for any bearings other than the main gimbal bearings. The shaft axis utilizes two deep-groove ball-bearings with one bearing axially fixed and the other free to slide. The trunnion axis, being more rigid in the axial direction, utilizes a pair of angular-contact ball-bearings with the contact angle and spacing selected to minimize differential expansion effects. All four bearings are otherwise of similar design, utilizing balls and races of modified 440C stainless steel with a burnished coating of molybdenum disulfide, and ball retainers of reinforced Teflon impregnated with molybdenum disulfide. The bearings on each axis are protected from exterior contamination by two low-friction, bellows-supported, face-type seals utilizing Teflon faces rubbing on stainless steel.

Thermal Control

Features of thermal control are discussed separately in a related article.[3]

SUMMARY OF FEATURES

Briefly, the most unusual features of the rendezvous radar antenna assembly are:

1) Use of a Cassegrainian reflector system with 20-wavelength aperture.
2) Use of subreflector spoiler to obtain high transmit-to-receive signal isolation.
3) Essentially complete spherical angular coverage.
4) Use of only four bearings.

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2. E. Bliss and M. Fromer, "Design of Solid-State Frequency Multipliers for the LEM Radars," RCA ENGINEER, *this issue*.
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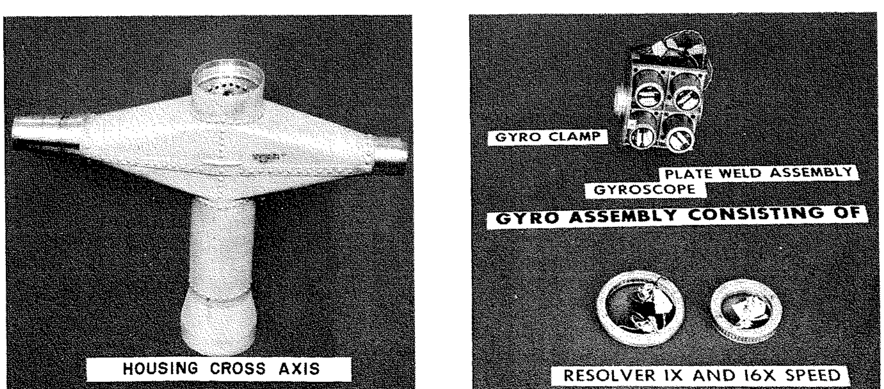
Fig. 7—Gimbal subassembly details



DESIGN OF SOLID-STATE FREQUENCY MULTIPLIERS FOR THE LEM RADARS

The design of all-solid-state frequency multipliers for satisfactory performance in translunar space or on the lunar surface poses many problems. This paper discusses the design considerations involved in the development of a highly reliable and sophisticated package which will function as a velocity sensor and altimeter for a moon-landing system, and as a radar transmitter and transponder in a rendezvous-for-return system. The discussion covers the integrated electro-mechanical design of the basic unit, including typical performance parameters. Packaging advances and the solution of thermal problems also are described.

E. BLISS and M. FROMER

Electronic Components and Devices
Harrison, N. J.

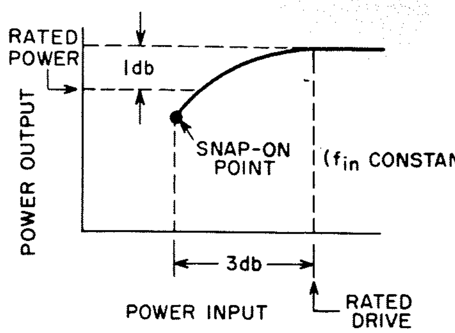


Fig. 1—Dynamic range characteristic.

THE most important considerations in the design of the frequency multiplier (transmitter) units for the Lunar Excursion Module (LEM) radars were performance, reliability, efficiency, and weight. Each of these considerations is briefly discussed in general and then described as it specifically applies to the design of the individual modules.

PERFORMANCE

Certain performance requirements were mandatory for the multiplier to survive its environment and to serve the needs of the system without interfering with other parts of the system. These requirements included shock and vibration resistance, freedom from microphonics, and minimum electro-magnetic radiation interference (EMI).

Since the frequency multipliers will be mounted on systems structures that have magnified mechanical transmissibilities, they must be capable of surviving the most severe shock, acceleration, and acoustical-random and sinusoidal vibrations that will accompany both the launch and the lunar descent.

The unit must remain remarkably free from microphonics (more than 100 dB below carrier) in spite of the performance-degenerating vibrations that accompany the operation of the landing jets; otherwise, the spurious outputs would result in inaccurate determinations of altitude and landing velocity. The virtual elimination of microphonics is a major objective of the program.

Another major performance requirement is the reduction of EMI to a minimum. To avoid interference with other radars and other systems that will be operating during the mission, spurious signals from the frequency multiplier output must be 80 dB down from carrier. More than 12 intermediate frequencies are generated in frequency multiplicaton from VHF to X-band, and these frequencies must be *tightly contained* within the packaged unit to prevent leakage to and interference with other systems used in the LEM. In addition, the electrical inputs, such as DC power, must be sufficiently filtered that externally generated signals will not affect the operation of the multipliers.

A system demand that affected the design of the multiplier chain was the alternate shifting of the input signal between two frequencies several hundred kilohertz apart at rates approaching 500 kHz (kc/s). To shift at this rate and overcome inherent circuit switchover times in the order of 100 nanoseconds, a minimum bandwidth of approximately 20 MHz was required for all of the tuned circuits. Although the bandwidth is relatively easy to attain near the output end of the chain (at S-band or X-band), it becomes a major achievement in the transistor amplifier where 20% bandwidth is required without reduction in efficiency.

Discussion of Performance Characteristics

Table I lists the characteristics of a typical frequency-multiplier package. Typical performance characteristics for this family of multipliers are shown in Figs. 1 through 5.

The dynamic range characteristic (Fig. 1) illustrates the effect of input drive on output power. The multiplier shows no output power for small values of input drive until it reaches the *snap-on point*, which occurs approximately 3 dB below rated drive. From the snap-on point to the rated input drive point the multipliers exhibit rapid transition to flat power output.

The bandwidth characteristic (Fig. 2) is entirely a function of system requirements and is implemented by means of the output filter. Greater bandwidths are readily achievable with

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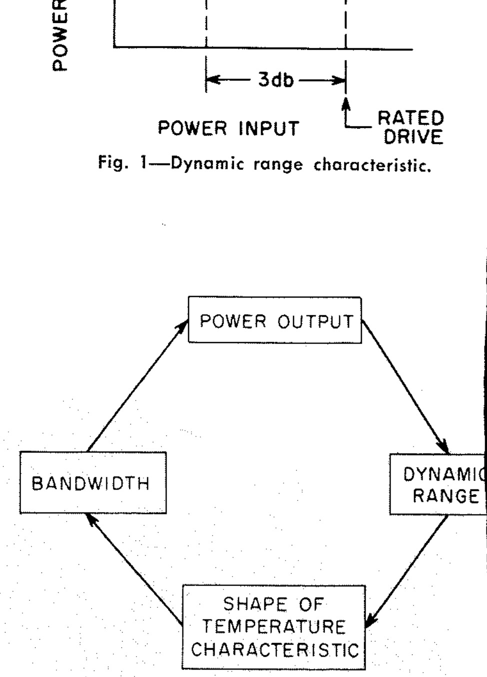


Fig. 5—Block diagram of characteristics trade-off.

TABLE I—
Frequency Multiplier Characteristics

Characteristics	Approximate Values
General	
Overall frequency multiplication	96
Electrical	
Input Data	
RF power drive*	less than 20 mW @ VHF
Impedance	50 Ω
DC voltage required	25 V
DC power demand	25 W
Output Data	
Frequency	X-band
Power	Approx. ½ W
Spurious	More than 75 dB below carrier
Bandpass	1% (limited by output filter)
Mechanical	
Dimensions	5 x 5 x 2 in.
Weight	2 lb
Volume	50 in³
Lowest mechanical resonant frequency	greater than 250 Hz
Reliability	
Rated failure rate**	10 failures/1 million hours
Thermal	
Method of cooling	Conduction via heat sink
Required heat-sink temp. range	−26° to +63° C
Thermal figures of merit	
Dissipation into heat-sink area	1 W/in² av.
Volumetric	½ W/in³ of package
Weight	12.5 W/lb
Heat sink interface	Approx. 5 x 5 in. flat within 0.003 in.; polished to 8-μin. finish

* Some units contain an integral crystal- controlled oscillator/buffer amplifier in the same size package.

** Performance degradation in any component as well as the total multiplier that exceeds its rating limit is deemed a failure.

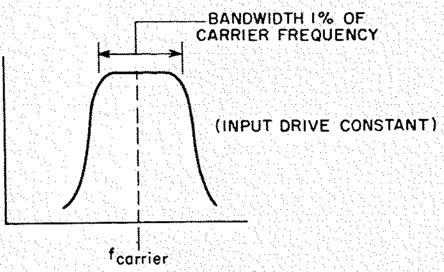


Fig. 2—Power output as a function of frequency.

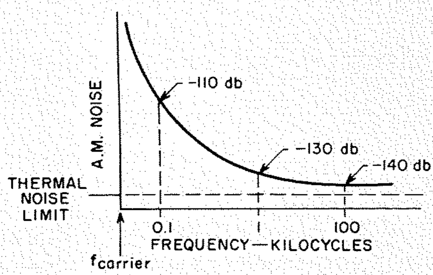


Fig. 3—Amplitude-modulated noise as a function of frequency difference from carrier.

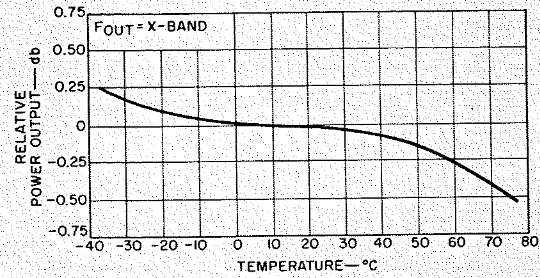
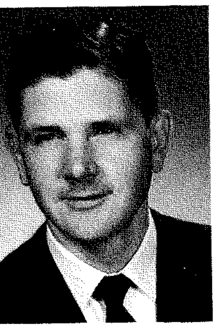


Fig. 4—Power output as a function of temperature for a typical X-band varactor frequency multiplier. Power variation is less than ± dB over temperature range shown.



E. Bliss

M. Fromer

EDWARD E. BLISS received his BS degree in Physics from St. Lawrence University in 1952. He joined RCA Microwave Tube Operations in 1953 as an engineer in traveling-wave-tube design and development. He was project engineer for the development of medium-power traveling-wave tubes for use in high-definition microwave radio relay systems. He was promoted in 1958 to engineering leader. In 1963 he was assigned to the design and the development of frequency multipliers for a missile-tracking system, and he later designed C-band frequency multipliers for use in experimental satellite communications systems. He is currently a senior design engineer on the LEM Project. Mr. Bliss holds several patents, including one on temperature compensation of traveling-wave-tube focusing structures.

M. FROMER received his BSEE from the Newark College of Engineering in 1950. For 8 years he worked on the design and development of industrial instruments, servos, and computer machinery. He joined the RCA Microwave Tube Operations Department in 1959 as an equipment development engineer. He was appointed Engineering leader, Electrical Equipment Development, in 1961. In 1962 he was a system engineer in the Data Systems Development group, and in 1964 became Engineering Leader of the Solid-State Engineering Mechanical Design group. Mr. Fromer holds a patent for his work on ultra-precision servo systems.

this type of solid-state frequency multiplier depending upon application sensitivity to spurious responses.

The noise characteristic is a function of departure from the carrier frequency (Fig. 3). A 1/f characteristic, it has one asymptote at the carrier and the other close to the thermal noise limit (−140 dB). At the X-band frequency this fractional-watt-output noise level is lower than that of the best-known detector crystal.

The power output scale in Fig. 4 has been expanded to show the typical shape of power output sensitivity with temperature. The curve also illustrates the relatively independent operation over wide temperature excursions.

The interdependence of various characteristics of the system are shown in Fig. 5. Because the characteristics are a function of tuning, primary performance for a given application may be peaked up with a change in secondary requirements.

Comments on Practical Performance

The applications for these multipliers, of necessity, make them a part of the actual payload where volume, weight, performance-effectiveness, and power demand are but a few of the considerations influencing the design specifications. Since this equipment is competing for space and weight with the astronauts, the performance is viewed accordingly. A list of interesting returns-for-the-investments follows:

RF Power Output (X Band)	200 to 300 mW/lb 4 to 6 mW/in^3 of volume
Power Gain	6.5 to 8 dB/lb 0.26 to 0.32 dB/in^3
Conversion Efficiency	16 to 23 mW output/DC watt input
Reliability	5 failures/lb/ 1 million hours

To get an idea of the *talk power* of these transmitter units, consider that it takes less than ½ watt at C-band to transmit effectively from a communications satellite with a range of about 20,000 miles. On this basis if the range requirement were only 20 miles, the *talk power* could be expressed as 10 miles per pound and 0.4 miles per cubic inch.

RELIABILITY DESIGN REQUIREMENTS

To assure reliability, the following practices were observed:

1) Parts were selected from a special list of approved parts for the LEM program; each part was assigned a failure rate and a derating schedule.
2) The surface operating temperature of all components was limited to 71°C.
3) The preferred maximum junction temperature for semiconductors was limited to 100°C; an absolute maximum of 125°C was allowable where reliability could be demonstrated. (For example, consider a circuit in which a single varactor operates at a function temperature of 120°C and with an assigned failure rate of 1.2. If two varactors were parelleled, the junction temperature would then be approximately 95°C but the total failure rate would be 2.0. Thus the single varactor operating at the 120°C junction temperature has greater reliability and its use would be justified.)
4) An extensive quality assurance program was applied, including inspections, training of assembly technicians, and conditioning of parts.

The limiting of surface temperatures to 71°C and junction temperatures to 125°C coupled with a relatively high heat-sink temperature limit of 63°C was responsible for some of the most sophisticated design work performed on these units.

Efficiency

DC power is always at a premium for space applications and no less so on a manned lunar mission. The general approach for maintaining the maximum obtainable efficiency was to use resonant circuits having unloaded Q's as high as possible and then to load the circuits heavily so as to reduce the loaded Q and thus the circuit losses. In addition, the best available semiconductor devices were used to maintain high efficiency. For example, the transistor proposed and used in the output stages of the transistor amplifier was not on the approved list. The 2N3375, which represents a breakthrough in the semiconductor art, was chosen for this stage because of its outstanding performance. It is now undergoing an extensive qualification program.

Weight

Weight is an equally important factor for the space application of a frequency multiplier. In general, the weight decided upon was a compromise between the mass required to conduct the heat away from centers of high thermal dissipation, and the structural rigidity required to withstand the shock and vibration of launch. Functions were combined throughout the design, and the practice of limiting design was employed. For example, a casual examination of one of the modules might indicate that it could have been made lighter. In all probability the justification would be that it is part of a laminated structure that has been thermal-shaped for controlled heat distribution and has a natural resonant frequency of more than 1000 hertz (c/s).

DESIGN FEATURES

To best show how the objectives influenced the electrical and mechanical design of the multiplier chain, the equipment is discussed below on a module-by-module basis. Fig. 6 shows a typical frequency multiplier with the cover in place. Fig. 7 is a composite block diagram and photograph of the frequency multiplier less the cover and DC power connector.

Crystal Oscillator and Buffer Amplifier Unit

This unit is the heart of the system; it produces the approximately 100-MHz signal that drives the entire chain. This frequency is stable to two parts in 10^5 over a temperature range of $-26°$ to $+63°C$. No oven is used with the crystal. The buffer amplifier provides approximately 20 milliwatts of output to drive the succeeding stage, the transistor amplifier. Since this unit operates at low power, no heat-dissipation problem exists, and it can be densely packaged. A combination of cordwood-and-deck construction is used. Note that the tubular glass capacitors also serve as standoffs for the upper deck. A beryllium-oxide cup cemented with silver epoxy between the transistor case and the chassis provides the electrical insulation necessary and facilitates thermal grounding to the chassis. The collector of the 2N3118 transistor used in this module is connected to its TO-5 case. The crystal case is cushioned with silicone rubber cement on the chassis to avoid vibration-modulation of the 100-MHz signal.

Transistor Amplifier Unit

The transistor amplifier unit (Fig. 8) presented one of the greatest challenges to the designer. All the RF power gain needed to drive the entire chain must be generated in this module; therefore, the efficiency of this unit is all important. Because nearly 40% of the power consumed by the frequency multiplier is dissipated in the transistor amplifier, the thermal problem is one of the most severe in the entire package.

This unit amplifies by 30 dB the 100-MHz signal produced by the oscillator section; that is enough power at this frequency to span the globe. The use of RCA 2N3375 transistors in this three-stage amplifier made possible a conversion efficiency of better than 60% while maintaining a 20% bandwidth. The 2N3118 input transistor is the same type used in the oscillator section, and it is thermally grounded to the chassis in exactly the same manner. This stage has about 7 dB gain. The second stage, using the stud-mounted 2N3375 transistor, contributes about 12 dB gain. The output stage of the amplifier uses two 2N3375 transistors in parallel to produce the full output power, for a total overall gain of 30 dB. The mounting and soldering of the 2N3375 transistors to the printed circuit board is conventional, but the thermal grounding is not; the bonds between the transistor studs and the chassis are made with silver epoxy. Admittedly this construction does not make for a readily repairable unit, but the unit is not expected to be repaired in service and, in addition, minimum thermal resistance is obtained. Tests show that the chassis-to-transistor case temperature difference under full rated load is 4°C. These test results indicate that the transistors have essentially become a part of the chassis.

Although the printed-circuit design shown in Fig. 8 is conventional practice in low-frequency applications, it was an unusual achievement for this high-frequency unit. Notice that no compartments separate the three stages and no shielding is used between them. Since the *shielding* is provided through controlled proximity, this design concept demands the highest degree of technical cooperation between the circuit and packaging designers. The extra design effort expended resulted in a lightweight device that is immune to the effects of vibrating shields.

First Multiplier Module

The quadrupler shown in Fig. 8 utilizes a lumped-circuit configuration to multiply the approximately 100-MHz output of the transistor amplifier to a 400-MHz signal at an efficiency of approximately 55%. To accommodate the system-required frequency-shift-keying-signal mode, the total bandwidth of this unit at the output frequency is approximately 20 MHz. Because several watts are dissipated in the varactor in this stage, thermal grounding is especially important. The circuit components are mounted on a double-clad printed-circuit board. Box construction is used for structural reasons. The metal-foiled surfaces of the board act as shields between the multiplier and the amplifier mounted below it. The thermal and RF grounding of the varactor posed a rather unique packaging problem. Since the quadrupler is mounted above the transistor amplifier (Fig. 6), the varactor had to be thermally grounded to the chassis and RF grounded to the quadrupler chassis. Thus the thermal and RF grounds were about ½-inch apart. In addition, the varactor passed through the transistor-amplifier board, and this raised the possibility of loop feedback. The solution to this problem is as follows. The varactor was thermally grounded through a split chuck welded to the chassis and press-fit to the varactor. A copper tube, slipped over the chuck and screwed to it, was soldered (at its other end) to the ground foil of the quadrupler circuit board. This arrangement resulted in a tight RF-ground path, provided an excellent RF shield, and satisfied the heat dissipation problem.

Second Multiplier Module

The tripler circuit (Fig. 6) multiplies the frequency of the 400-MHz output of the preceding quadrupler to a 1200-MHz signal at an efficiency of approximately 50%. In addition, this tripler performs a filtering function, since the output cavity suppresses the unwanted 100- and 400-MHz harmonic components.

The input circuit of the tripler and the intermediate, 800-MHz idler circuitry are lumped/distributed parameter configurations similar to those used in the quadrupler. The output circuit, a coaxial cavity (actually the first truly microwave section of the multiplier chain), narrows down the bandwidth to about 36 MHz at the 1200-MHz output frequency.

The tripler chassis is an aluminum extrusion that satisfies both the structural and thermal requirements. The cold working gives the extrusion a remarkable strength-to-weight-ratio and the mirror-like finish required for this project. The sides and top of the box are copper-clad circuit board similar to that used in the quadrupler. The varactor is thermally grounded to the chassis.

Third Multiplier Module

The quadrupling function performed by this module is accomplished in two steps; no single varactor is available that can operate at this frequency range with sufficient efficiency and power-dissipating capacity. The two varactor doublers (Fig. 6), operating in cascade, multiply the 1.2-GHz (Gc/s) output of the tripler module to produce an output signal at 4.8 GHz; each varactor dissipates approximately 1 watt. The low-frequency doubler, mounted on the extruded aluminum cover, consists of three strip-line resonator bars. These resonator bars have heavy capacitive loading which permits a significant reduction in their mechanical lengths. The capacitors also serve as matching devices for the doubler input and output circuits.

The medium-frequency doubler, the other half of this module, is a resonant cavity whose input is capacitively coupled from the low-frequency doubler. The input circuit of this second doubler is tuned to 2.4 GHz by the inductance of an input probe, the capacitance of the varactor, and the distributed capacitance (also tunable) to the cavity walls. The cavity, heavily copper plated to increase its Q, is tuned to 4.8 GHz through capacitive loading at its center. The extrusion conducts the heat from the varactors to the tripler housing and through six parallel paths to the chassis. Silver epoxy is used to reduce the thermal interface between the extrusion, the tripler, and the heat-sink ground.

Final Multiplier

The final unit (Fig. 6) consists of a varactor doubler, a ferrite isolator, and an output-waveguide impedance-matching transformer/filter. Operating between 35 and 40% efficiency, the doubler produces a fraction of a watt at 9.6 GHz. It is a tribute to the design that this module has produced a full watt of RF power output at X-band at over 30% efficiency.

The 4.8-GHz input to the doubler is coupled from the output cavity of the medium-frequency doubler through a coaxial line which terminates in a probe in the cavity. A choke in the coaxial section prevents the X-band signal generated by the varactor in the waveguide section from feeding back through the input. Tuning screws in the waveguide adjust the input resonant frequency, the output resonant frequency, and the output matching. An aluminum leg that is part of the dip-brazed housing is the heat-sink path to ground for varactor heat dissipation.

From the output doubler, the signal passes through a fairly conventional ferrite isolator and an output filter. The total insertion loss of the isolator and filter is approximately 0.6 dB; the bandwidth of the filter is 200 MHz. The cutoff frequency of the waveguide and the stop bands of the filter combine to eliminate the harmonics of the 1200-MHz signal in the output.

Chassis

A typical chassis for the LEM frequency multiplier uses a box-beam form having 3/8-inch-high sides and a 0.050-inch-thick bottom plate. Pads, bosses, and ribs are brazed to this plate to accommodate the RF stages. In addition to adding structural strength, the sides serve as a gasket face for the RF- and humidity-sealing cover. The chassis serves both as a mounting surface and as a thermal spreader approximating an isothermal source to the LEM structural heat sinks. The many modules bolted and bonded to the chassis are structural members that contribute considerable strength and stiffness to the package. In areas where modules are not mounted on the chassis (e.g., in the area under the high-frequency doubler-isolator-filter), an added rib stiffens the bottom plate and provides shielding for the adjacent transistor-amplifier unit.

Cover

Even the cover for this project presented an engineering problem. Its function is to shield the circuitry, prevent EMI, and humidity-seal the multiplier. If designed arbitrarily, the thickness of the cover would have presented an intolerable weight problem for its function. Controlled-leak devices were considered and rejected because they represent possible sources of noise or failure due to vibration. The ribbed aluminum cover, as finally designed, is both light in weight and structurally sound, especially when bolted to the box-constructed chassis.

CONCLUSION

An efficient and reliable all-solid-state frequency multiplier has been designed for the LEM radars. The integrated electro-mechanical design provides for resistance to shock and vibration, freedom from microphonics, minimum EMI, and controlled heat dissipation.

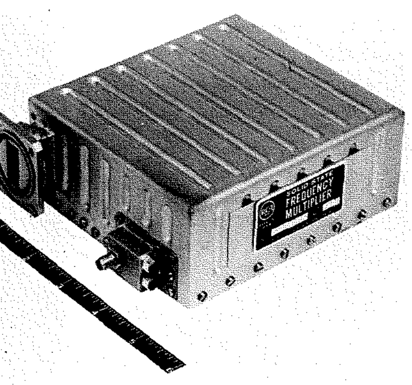


Fig. 6—Typical LEM frequency multiplier. The waveguide output is at the left. The doghouse on the right contains two feedthrough capacitors to filter DC input power, and a coaxial connector for modes requiring external RF drive.

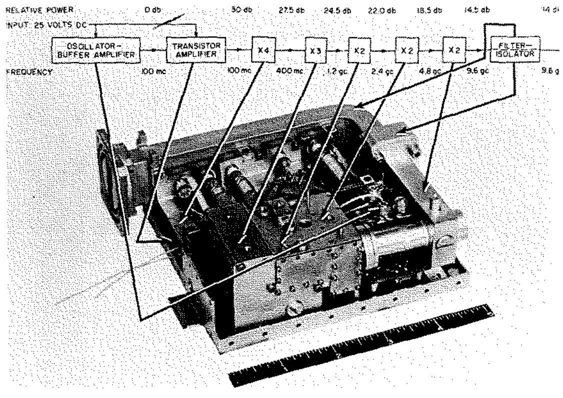


Fig. 7—Composite block diagram and photograph of LEM frequency multiplier (less cover and power-input connector).

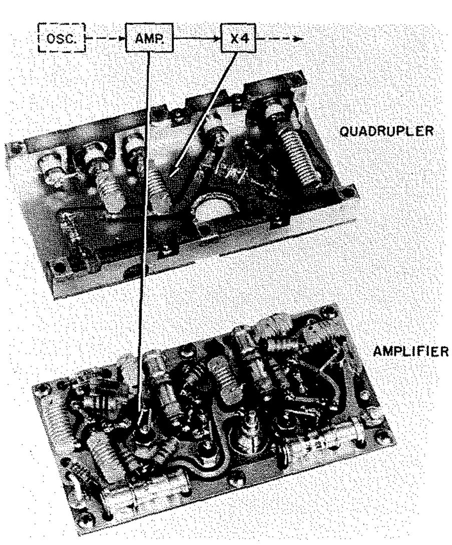


Fig. 8—Exploded view of transistor amplifier and quadrupler. →

LUNAR EXCURSION MODULE RADAR RECEIVERS

This paper describes the receivers of the Lunar Excursion Module (LEM) rendezvous radar and transponder. The radar, a continuous tracking type, provides range, range rate, angle, and angle rate information to the computer. It is a simultaneous lobing or monopulse system which supplies an error signal to the servo mechanism for angular control of the antenna position. The radar receiver obtains range information by a three-tone phase-shift technique; range rate is derived from the doppler frequency shift.

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THE rendezvous radar and the transponder receivers are superheterodyne types of all-solid-state design. The rendezvous radar receiver, with three intermediate frequencies and three channels, is a typical amplitude-comparison monopulse system for two-coordinate (trunnion and shaft) angle data. The single-channel transponder receiver has two intermediate frequencies.

Although not packaged with the receivers physically, a preamplifier is associated with each IF channel. In the rendezvous radar, the preamplifiers and the associated X-band mixers are located at the antenna. In the transponder, the preamplifier is in the microwave portion of the system. Antenna control accuracy requires receiver interchannel phase tracking of 20 degrees between the reference (sum) channel and either difference channel (trunnion or shaft), and amplitude tracking of ±2.5 dB over the temperature range of 0°C to +70°C and over the full dynamic range of 96 dB. After initial boresight, performance can be maintained over the temperature range for 10 days without adjustments. The overall gain of the radar receiver is 123 dB; the output level of the reference channel is constant to ±0.5 dB over the dynamic range.

The first and second IF amplifiers use broadband (>100-MHz (Mc/s)), transformer-coupled, common-base stages with lumped filters. AGC is provided by shunt diodes which are DC-coupled to the emitters of the common-base stages. The AGC scheme provides a net overall loss of 20 dB per gain stage for the first and second IF amplifiers at the upper end of the dynamic range. (The third IF amplifiers do not have AGC.)

Size, weight, and long-term stability requirements dictated a design with an absolute minimum of tunable components and potentiometers. Untuned, broadband, double-balanced second and third mixers reduce internal coherent spurious problems.

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RENDEZVOUS RADAR RECEIVER

The rendezvous radar receiver (Fig. 1) provides an intermediate signal path between the antenna and the antenna control servos and the three trackers. The subassemblies include a frequency tracker, a three-tone range tracker, and a surface-mode range tracker (SMRT). The receiver AGC maintains constant signal output to the subassemblies which is unaffected by variations in receiver signal input.

Each three-channel IF amplifier (Fig. 2) consists of three separate conversion frequency stages, including a 40.8-MHz first IF stage, a 6.8-MHz second IF stage, and a 1.7-MHz third IF stage. The complete unit has 14 circuit modules of cordwood construction, which, in addition to the 9 IF amplifiers, include a 34-MHz gated local oscillator (LO) mixer and amplifier, a 6.8-MHz tracker amplifier, a 6.8-MHz tracker distribution amplifier, an angle error detector and AGC amplifier, and a SMRT AGC detector.

The receiver is fed the sum signal and the two difference signals from the antenna assembly. Each of these signals, representing an output at 40.8 MHz of each of the three microwave mixer-preamplifiers, is an input to an IF amplifier channel in the receiver. In each channel, the 40.8-MHz signal is amplified in the first IF stage and converted to a 6.8-MHz signal in the second mixer. This signal is amplified in the second IF amplifier and fed to the third IF amplifier, which converts it to a 1.7-MHz signal and then amplifies it for an output at this frequency. Each IF difference channel output drives a separate input to the angle error circuitry, and the IF sum channel supplies the reference to the angle error phase detectors as well as to the AGC detector and amplifier. The angle error output consists of two DC voltages which feed the servo loops controlling the antenna. The AGC output, a DC voltage, controls the gain of the first and second IF amplifiers of all three channels and that of the preamplifier in the antenna assembly. A 6.8-MHz output from the second IF amplifier of the sum channel is supplied to a 6.8-MHz tracker amplifier. The tracker amplifier feeds the three-tone range tracker, and a tracker distribution amplifier with outputs to the frequency tracker and the SMRT.

Inputs are also supplied to the receiver from the frequency synthesizer and the frequency tracker. The frequency synthesizer provides a 27.2-MHz input to the mixer in the 34-MHz gated LO mixer and a 5.1-MHz input to the third mixer in the third IF amplifier. The frequency tracker supplies an input signal to the 34-MHz gated LO mixer and amplifier. This signal is nominally at 6.8 MHz but deviates from this value by the frequency of the doppler. The 34-MHz gated LO mixer feeds the second mixer in the first IF amplifier, thereby producing the 6.8-MHz second IF.

The first IF amplifiers for the sum and difference channels are identical and are constructed with matched transistors and diodes. Fig. 3 shows the approximate distribution of gains; the location of the 10-MHz bandwidth lumped filter, which sets the bandwidth of the first IF; the stages controlled by AGC; and the second mixer.

The grounded-base amplifier stage (Fig. 4) is typical of all amplifier stages in the first IF, the second IF, the tracker amplifier, and the distribution amplifier. AGC components include *CR*1, *R*3, *R*4, *C*4, and *C*5.

The grounded-base configuration was selected because of the stringent phase-tracking (±20°) requirements of the monopulse receiver. Using a transistor having a high gain-bandwidth product and wideband (≈100-MHz) bifilar-wound autotransformers, it is possible to achieve low phase slope (about 0.5°/MHz) per stage.

Diodes matched to 3 millivolts over the temperature and current range are used cross channel for AGC tracking. Computations indicate that for transistors in the AGC-controlled stages, DC emitter voltage (V_{BE}) matching to 10 millivolts cross channel is adequate for gain tracking (±2.5 dB).

The gated 34-MHz local oscillator supplies a signal which is mixed with the 40.8-MHz signal in the second mixer, yielding the 6.8-MHz second IF signal. The gating oscillator supplies the 34-MHz signal to the second mixer only during the interval when radar returns are being received. The 34-MHz signal to the second mixer is cut off during the transmit interval because the transmitter alternately transmits two frequencies, the transmit frequency and the receiver LO frequency. If the 34-MHz signal were not inhibited, the receiver would respond to the radar returns generated by the transmission of the LO frequency.

The third IF amplifier and third mixer convert the 6.8-MHz signal from the second IF amplifier to 1.7-MHz and provide the remainder of the gain necessary for proper dynamic range of the receiver. The third IF amplifier contains a 1-kHz (kc) bandpass crystal filter which reduces the noise in the outputs to the angle error detector and which also removes the undesired mixer products. Two integrated circuits in a differential amplifier configuration provide approximately 60 dB of gain in this stage at 1.7 MHz.

The balanced mixer in this stage employs a diode bridge having closely matched electrical characteristics and low junction capacitance. Bifilar- and trifilar-wound transformers in the input and output of the mixer ensure a high degree of balance and, consequently, high port-to-port isolation.

Integrated circuit amplifiers in the third IF stage ensure a constant voltage output which is particularly critical because this stage is not in the AGC loop. Temperature tests from 0°C to 71°C indicate a variation of less than 0.1 dB.

Initial channel phase correction is assured by a phase-shift configuration that provides 120° of phase shift with a minimum of amplitude variation. Actual tests show less than 0.2 dB variation in amplitude over the 120° range.

Identical shaft and trunnion axis phase-sensitive detectors supply the DC error signal to the antenna servos. The detectors consist of a buffer stage, two peak detectors, and an operational amplifier.

High filter impedance and the use of matched diodes make the peak detectors insensitive to temperature. The diodes are matched to within 3 millivolts over the temperature range of −55°C to +100°C and over the current range from 10 microamperes to 1.0 milliampere.

The difference in output voltage of the two peak detectors is taken by an inte-

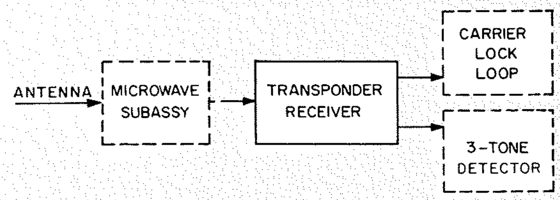


Fig. 1—Functional block diagram of radar receiver.

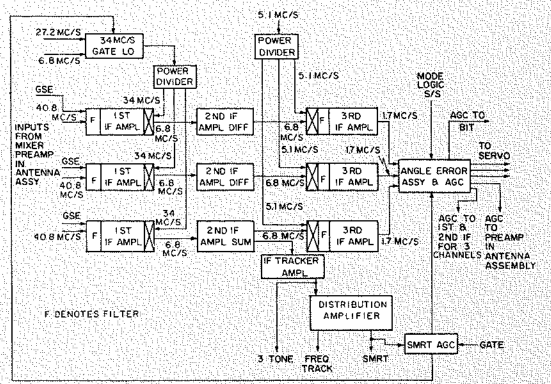


Fig. 2—Detailed block diagram of radar receiver.

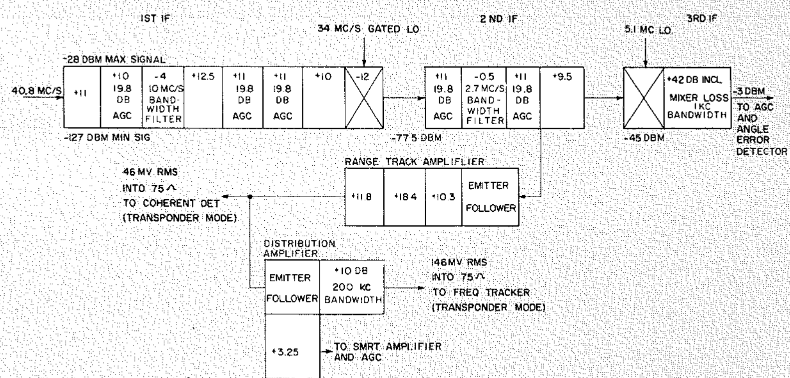


Fig. 3—Signal gain distribution along radar receiver sum channel.

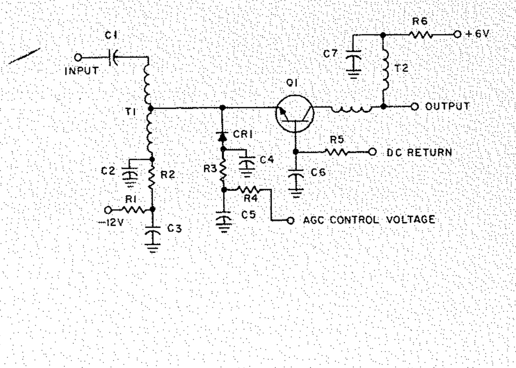


Fig. 4—Grounded base amplifier stage.

N. ARON received his BSEE degree from Northeastern University in 1940 and his MEE degree from the Polytechnic Institute of Brooklyn in 1954. He worked for the Signal Corps and was in charge of a quality control group at Western Electric Co. For several years he taught electronics, optics, physics, and mathematics at City College, N. Y. and at the RCA Institutes. Later he worked with the Electronic Computer Division of the Underwood Corporation as a development engineer in computer circuitry and logic and with the Sylvania Electric Waltham Labs as senior engineer, computer development. He returned to RCA in 1956, with responsibility for development of digital-to-analog output equipment for a solid-state airborne computer. He has since been responsible for the development of several analog-to-digital conversion units using solid-state devices exclusively. He directed the development of a complete PCM telemetry system for small-missile applications and the development of an infrared missile seeker using television techniques. Later, he was program manager of the Vidicon Strike Reconnaissance research program. As Leader, Technical Staff, Radar Engineering, he was responsible for the electronic design of the rendezvous radar and transponder receiver subassemblies for the LEM Program.

grated circuit operational amplifier, which also provides a differential gain of 2.37 to adjust the overall scale factor of the phase-sensitive detector to 1-volt DC output for 1-volt peak-to-peak AC input.

The AGC detector and amplifier consist of a buffer, a peak detector, and an integrated circuit operational amplifier. The buffer stage, a Darlington pair connected as a common collector amplifier, provides the reference drive to the phase-sensitive detectors of the angle error circuitry as well as the input to a peak detector for the AGC.

The peak detector output is summed with a reference voltage derived from the power supply by a resistive divider. The peak detector is temperature compensated by a circuit which causes the reference output to track the peak detector output with temperature. The output of the peak detector is amplified by an operational amplifier with a voltage gain of 60. The operational amplifier consists of an integrated circuit chip and an output common collector amplifier. It is operated in the noninverting configuration to provide a high input impedance. The output common collector amplifier provides a high current output to the first and second IF amplifiers. The normal AGC operating range is from 0 to 4 volts.

The preamplifier AGC drive requires from 0 to 2 volts and is taken from the output of the operational amplifier by a resistive divider. This divider action produces a delay in the preamplifier AGC to prevent impairment of the noise figure of the receiver at long range.

In the surface mode, a relay operated by a logic level applied to the relay driver connects the SMRT AGC circuit output to the input of the normal AGC operational filter. The input signal to the SMRT AGC circuit is derived from the 6.8-MHz wideband output (2.7-MHz bandwidth) of the distribution amplifier instead of from the 1.7-MHz output of the third IF amplifier. Use of this wideband input improves the AGC response time for the pulsed operation during the surface mode tracking. The SMRT AGC circuit supplies a DC level via the relay to the normal AGC unit to control the receiver and preamplifier gains.

TRANSPONDER RECEIVER

The transponder receiver (Figs. 5 and 6) has a single IF channel consisting of a 40.8-MHz first IF amplifier and a 6.8-MHz second IF amplifier. These two circuits are similar in design to those in the radar receiver. The 6.8-MHz output of the second IF amplifier feeds a carrier lock loop amplifier and AGC detector and a three-tone coherent detector. The carrier lock loop amplifier supplies a 6.8-MHz narrow band signal to a crystal-controlled oscillator in a phased locked loop circuit; the 6.8-MHz wideband (2.7-MHz bandwidth) signal to the three-tone coherent detector is used to demodulate the received three-tone signal for later remodulation and retransmittal.

The AGC for the transponder receiver is developed in a manner similar to that used in the rendezvous radar. The overall gain and the stage gains of the transponder receiver are shown in Fig. 7.

CORDWOOD DESIGN CONSIDERATIONS

Weight reduction and miniaturization were obtained primarily by use of cordwood construction. However, careful thought was given to: 1) the use of high-reliability miniature parts for standard resistors, capacitors, and inductors; 2) the use of integrated circuits wherever feasible; and 3) the development of miniaturized components, particularly power dividers, high-frequency wideband transformers, and filters. Fig. 8 shows the dramatic size reduction achieved in the miniaturization of power dividers. Size reduction of the wideband transformers used extensively throughout the receiver resulted in further reductions in the size and weight of cordwood assemblies (Figs. 9 and 10). The redesigned wideband transformer uses a ferrite core of the size found in computer memory arrays.

The cordwood configuration necessitated careful layout of the printed circuit boards, particularly for the 40.8-MHz first IF amplifier and for the 34-MHz gated local oscillator and mixer. In each case, the balanced mixers had separate shields inserted between the printed circuit boards to increase electrical isolation and reduce cross-coupling. The higher frequency circuitry required some initial layout changes before satisfactory performance was achieved.

The radar receiver with all cordwood modules removed is shown in Figs. 11 and 12. The transponder receiver is similarly shown in Fig. 13.

The mechanical packaging of the modules requires that each module be mounted in a separate compartment of the basic receiver section. Feedthrough capacitors and filters are provided within the structure to isolate the modules from one another and from the external wiring.

The reliability of the modules has been assured by the operation of all components at the recommended stress levels. To maintain compatibility with the overall module height of 0.4 inch, resistors have been included in parallel combinations. In certain cases, such parallel combinations have been used where it has not been possible to obtain the appropriate single, high-reliability component.

The radar receiver weighs 2.82 pounds and dissipates 6.5 watts; the transponder receiver weighs 0.94 pound and dissipates 2 watts. Both units operate from +12- and −12-volt power supplies. The radar receiver also requires +6-volt power.

CONCLUSION

Solid-state circuit design implemented with miniaturized high-reliability components and careful attention to packaging has resulted in the development of small, lightweight monopulse radar and transponder receiver subassemblies having low power dissipation. The receivers are especially suited for aerospace use; their performance is comparable to, and in many instances exceeds, that of present-day ground-based tracking radars.

ACKNOWLEDGEMENTS

Contributors to the design of the receivers described in this paper include H. K. Schlegelmilch, H. L. Slade, J. Aldwinckle, E. LeBlanc, and L. Blundell for the circuit design, and J. Way for the packaging and mechanical design.

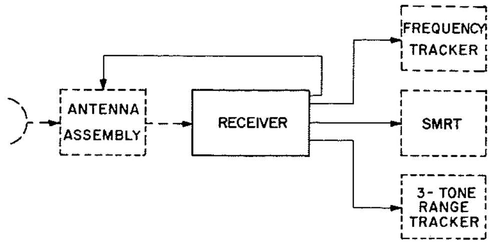


Fig. 5—Functional block diagram of transponder receiver.

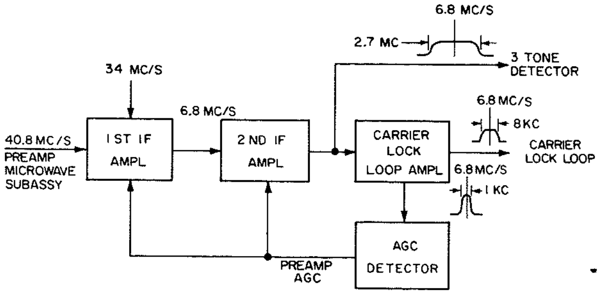


Fig. 6—Detailed block diagram of transponder receiver.

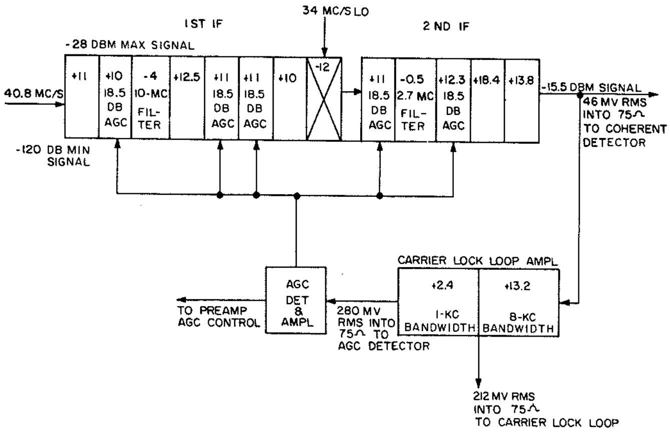


Fig. 7—Signal gain distribution of cordwood transponder receiver.

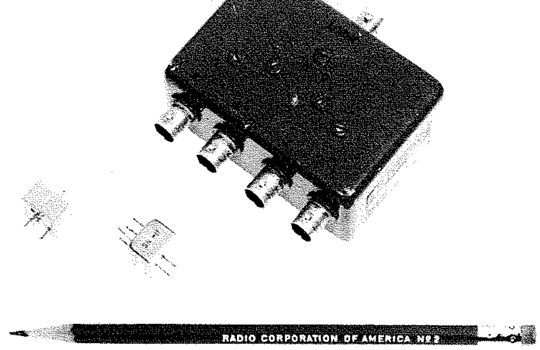


Fig. 8—Comparison of standard and miniaturized power divider.

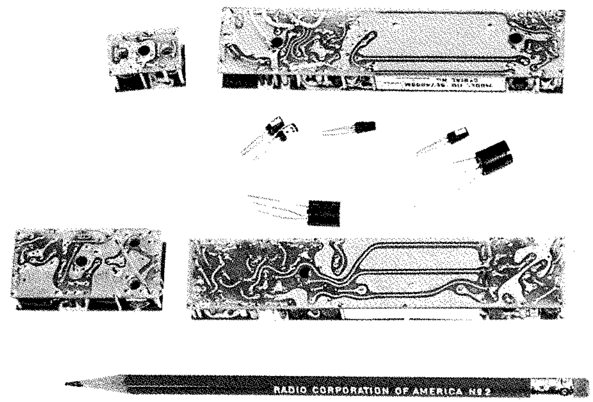


Fig. 9—Reduced size of first IF amplifier (top) was achieved through miniaturization of wide-band transformers (compared in center of photo with original transformers). Original amplifier is shown at bottom for comparison.

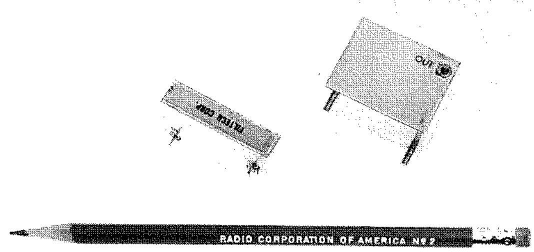


Fig. 10—Typical crystal filter (right) and miniaturized cordwood-mounted version.

Fig. 11—Cordwood modules of segment No. 1 in radar receiver.

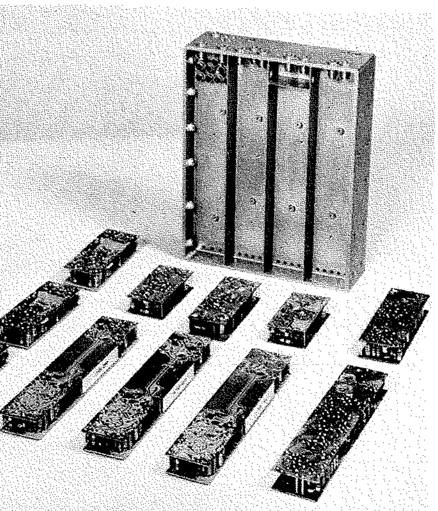


Fig. 12—Cordwood modules of segment No. 2 in radar receiver.

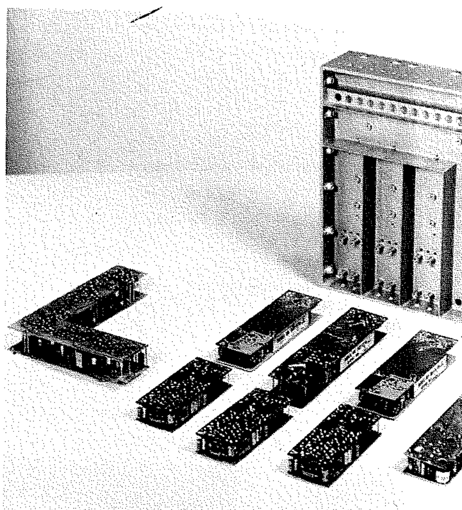
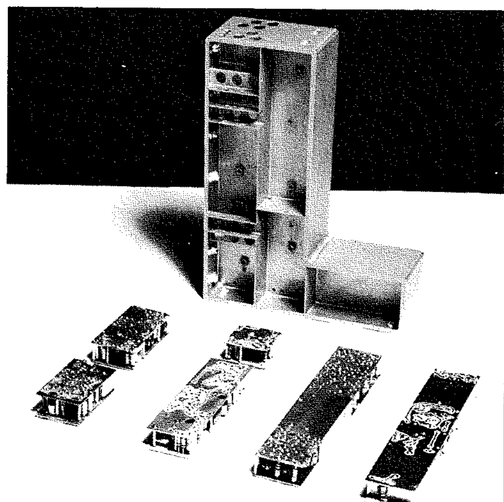


Fig. 13—Cordwood modules in transponder receiver.



PACKAGING THE LEM RENDEZVOUS RADAR AND TRANSPONDER

The high-frequency and heat-dissipating circuits in the LEM rendezvous radar and transponder imposed special requirements on the packaging design. In addition, extremely efficient integrated circuit connections were required for the integrated range-tracking digital circuits. This paper describes the packaging techniques used to produce a small, lightweight rendezvous radar and transponder that will operate in space with high reliability.

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THE ability to pass vibration tests is often the limiting item in the development of an aerospace electronic system. In this area specifications usually require that an equipment continue to perform its principal functions during and after a vibration test and before and after a shock test. To obviate malfunctions due to physical displacements, rigidized *hard* wiring is used, and supporting structures for parts are specially designed. The latter technique involves maximizing both the natural frequency and the ratio of damping to critical damping.

One of the most critical items to be considered in designing equipment for operation in a space environment is minimum weight. Another criterion is reliability, which is influenced by maximum operating temperatures of electronic parts. Since the transfer of heat in a vacuum is primarily by conduction, the design must provide minimum conductive path lengths for high-heat-dissipating parts. Other critical items are humidity prior to launch, electromagnetic-interference (EMI) shielding, vibration and shock, and reduction of out-gassing or release of toxic gasses under vacuum conditions. All of these effects were considered in the mechanical design of the LEM equipment.

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PACKAGING CONCEPT

The cases for the rendezvous radar and transponder were designed to achieve the lowest possible weight structure. Ultra-light alloys, electron-beam welding, and chemical milling techniques were utilized. The choice of material for each structural part was based on such criteria as thermal conductivity and stiffness. Aluminum alloy 2014-T651 was used for the cases because it can be electron-beam welded and because of its strength and high thermal conductivity. Titanium alloy (6AL-4v) fasteners were used because of their high strength-to-weight ratio.

Structural Design

The electronics assembly of the rendezvous radar consists of a case that houses the various electronic subassembly segments, the wiring subassembly, and the cabling subassembly (Fig. 1). The multifunction design of the case provides structural support for the subassemblies, an EMI shield, and conductive heat transfer to the cold plates on which the case is mounted in the LEM vehicle. The wiring subassembly is a multilayer printed circuit board that interconnects the subassemblies within the case; connections to the board are split-pin wire-wrap types. The cabling subassembly is the cabling transition from the wiring subassembly and the external radar electrical connection to the LEM vehicle cabling.

The radar circuits are grouped in functional electronic *blocks* or subassemblies. Subassembly frames provide the structural support, conductive heat transfer paths, and EMI shielding for the subassemblies (Figs. 2 and 3).

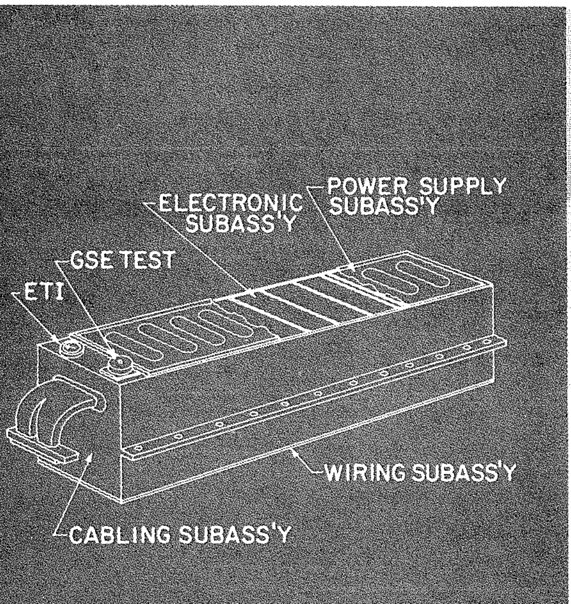


Fig. 1—Rendezvous radar electronic assembly.

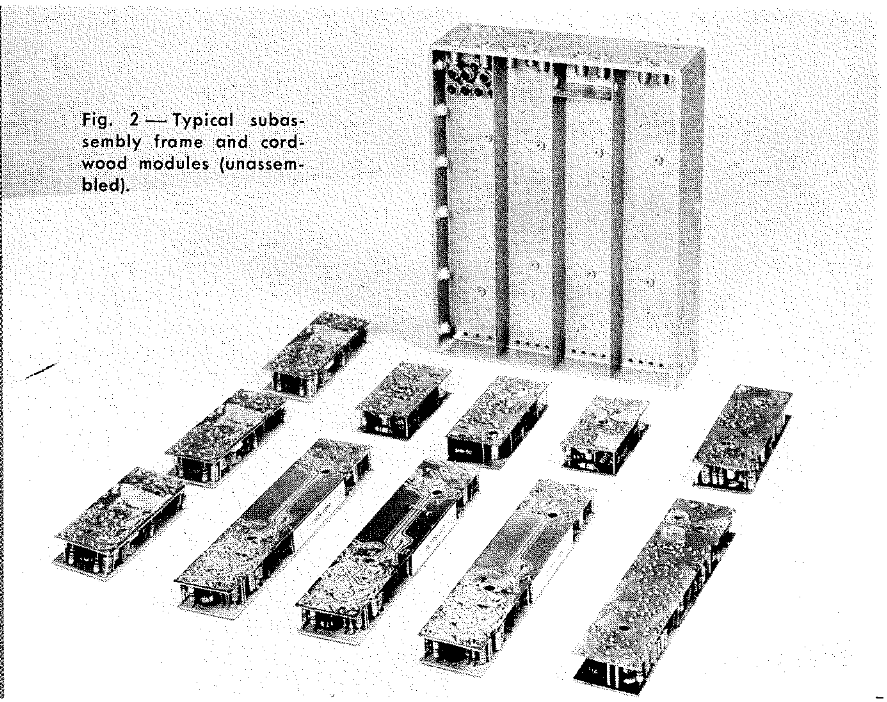
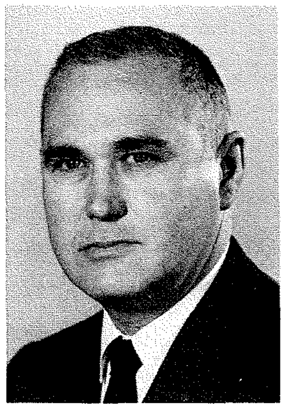


Fig. 2—Typical subassembly frame and cordwood modules (unassembled).



JOSEPH I. HERZLINGER received his BSME degree from Newark College of Engineering in 1940 and his MS degree in Mechanical Engineering from Drexel Institute of Technology in 1961. He joined RCA in 1940 and for six years was engaged in the mechanical design of shipboard radar equipments and television transmitter and antenna equipment. Since 1946 he has had project responsibility in the mechanical design of Shoran equipment and airborne-search and fire-control radars. He contributed to the mechanical design of the Vernier I and Vernier II high-resolution radar systems and an advanced, high-speed tape transport. He is presently Leader, Technical Staff, Radar Engineering and is responsible for the packaging design of the rendezvous radar and transponder equipments for the LEM program. He has two U.S. patents and is a licensed professional engineer in the State of New Jersey.

MILES J. KURINA received a BSME degree from Purdue University in 1956. Following graduation he joined the Visking Corporation as a mechanical engineer and was responsible for the design of a high-speed printing press, gas-diffusion test apparatus, and atmospheric test equipment. At ABMA, Huntsville, Ala. he was involved in the design and stress analysis of the supersonic test section and missile model design for wind tunnel testing. At Hughes Aircraft Company, in the Design Integration Section of the Guided Missile Laboratory, he participated in the design and development of new Falcon air-to-air missiles. As Senior Design Engineer at Gilfillan Corp., he was engaged in the design and packaging of the prototype digital computer, servo mechanisms, and associated units of a height-finder radar for shipboard use. Since joining RCA in 1962, he has been responsible for the mechanical design of an automatic satellite detection equipment, the 4F radar transmitter, and the LEM rendezvous radar and transponder equipments.

A. W. SINKINSON received his BSME degree from Northeastern University in 1952. He was engaged for several years in the product design of industrial controls and instrumentation. As Chief Mechanical Engineer at Francis Associates from 1958 to 1962, he was responsible for design evaluation and consultation in the field of high-reliability and high-density electronic packaging for the Polaris guidance computer and flight control, transit command receiver, USD-7 computer, Dynasoar telemetry subsystem, Typhon, and Sidewinder electronics. Since joining RCA in 1962, he has developed packaging techniques for an advanced airborne computer and for the LEM rendezvous radar and transponder. He is a professional engineer in the states of Massachusetts and Vermont and is a member of Tau Beta Pi, Pi Tau Sigma, American Society of Mechanical Engineers, and American Association for the Advancement of Science. He is a joint holder of patents for an infrared analyzer and for electronic packaging.

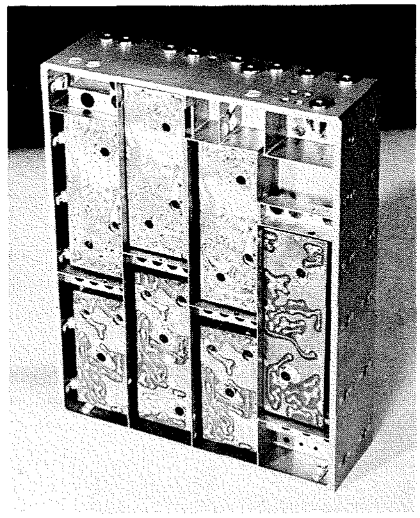
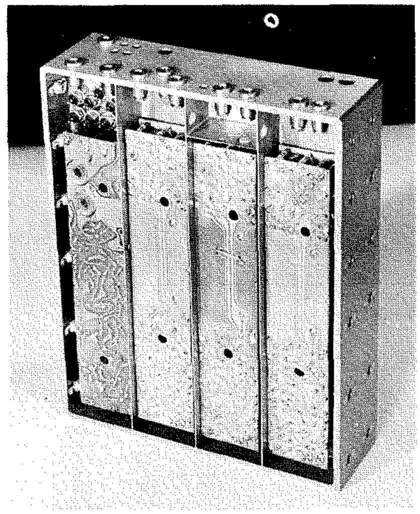


Fig. 3—Two views (above and below) of typical cordwood modules assembled as radar circuit blocks in a common frame.



Discrete Electronics Packaging

Subassembly frames of the rendezvous radar and transponder are of *modular* design (i.e., parts are arranged in cordwood fashion between printed circuit boards in a functional circuit or modular grouping). Modules are conformally coated and bonded to both surfaces of a metallic heat-conducting plate within the subassembly. The dip-brazed frame has a cellular eggcrate type of design that provides complete isolation for each module.

The use of a conformal coating instead of encapsulation resulted in substantial weight savings. Preliminary vibration testing of the modular design beyond LEM environment levels with no destructive failures confirmed the validity of this concept.

Cordwood packaging of high-frequency circuits operating beyond 100 MHz (Mc/s) has been successful. Careful attention to part arrangement was required, and the use of the space etch technique on the printed circuit boards eliminated ground plane difficulties.

Integrated Electronics Packaging

The range tracker in the rendezvous radar uses digital, monolithic-silicon integrated circuits in flat-pack form. The routing of wiring for voltages, grounds, and clock pulses is particularly critical because of the high-speed pulses involved, since the cross-talk and loading-to-ground effects of any capacitive coupling increases as frequency increases. Multilayer circuit boards (Fig. 4), made by the *built-up* process, are used in packaging the integrated circuits; these boards satisfy all requirements including minimum weight.

Each circuit-board conductor is a single, three-dimensional network of solid, electrolytically pure copper, mechanically and metallurgically homogeneous. Layer-to-layer and layer-to-surface junctions are integral with the conductors on each plane; each junction has a fillet in both width and thickness dimensions to provide greater cross section, strength, conductivity, and reliability at horizontal-to-vertical transitions. The conductor network is completely surrounded by a dielectric equivalent to G11 epoxy glass (per Specification MIL-P-13949C); no other adhesive is used.

Blind layer interconnections can be made completely within the circuit board without extension to either surface. Conductors can be run on layers directly over and under the internal connections. This approach permits great layout freedom and greater conductor and component densities than are possible with other types of circuit boards. Elimination of unnecessary

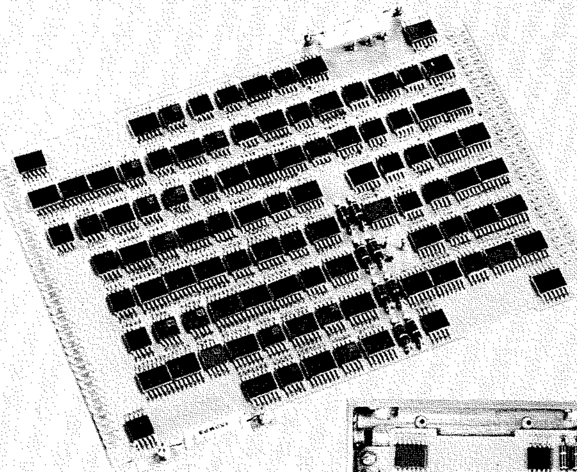


Fig. 4—Multilayer board with integrated circuits.

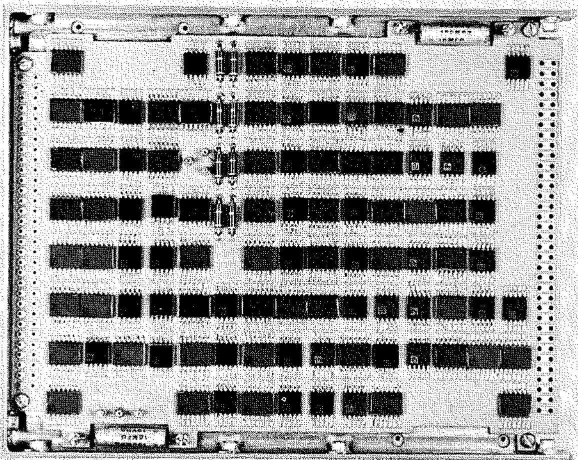


Fig. 5—Typical integrated circuit subassembly.

layers reduces cost, size, and weight, and improves reliability.

Internal conductors are brought to the surface of the board only where desired for component attachment and connector terminal mounting. No conductor lines are on the surface; only solder pads are exposed.

The 0.003-inch conductor thickness plus 0.005 inch of dielectric between each plane results in a total layer thickness of 0.008 inch. The total thickness of a 4.5-inch by 6-inch board interconnecting over 100 integrated circuits is 0.050 inch. Conductors are centered in the dielectric material; thickness is accurately controlled to provide constant, uniform electrical capacitance. The 0.005-inch interlayer thickness was selected as the best weight/interlayer-capacitance compromise. Capacitive coupling, usually troublesome, is rendered insignificant by judicious arrangement of conductor patterns. The following conventions are observed:

1) Orthogonality of voltage conductors and clock-pulse conductors wherever possible,
2) Restriction of the length of a clock-pulse conductor parallel to a voltage conductor to no greater than their distance apart,
3) Restriction of clock-pulse circuitry to the top layer, voltage circuitry to the bottom layer, and ground circuitry to the next-to-bottom layer.
4) Interposition of a wide ground conductor between parallel runs of clock-pulse and voltage conductors if the length exceeds their distance apart.

Support is provided for the board and the heat conductive path by fastening the circuit board to a subassembly frame (Fig. 5). For piece-part dissipation greater than the critical value, an aluminum slug is buried in the board to provide close thermal coupling to the frame. One side of the board contains split-pin, wire-wrap terminals for connection to the wiring subassembly.

Each solder pad on the board is the end of a solid copper pillar to which an integrated circuit lead is attached by resistance soldering with programmed energy. Solder on pretinned integrated circuit leads and the solder-coated circuit board is melted into a homogeneous joint using parallel-gap electrodes in a precision weld head, and a specially designed power supply. Such parameters as force, length, and energy of the electrical power pulse are adjusted to optimize the soldering process.

Integrated circuits are cemented to the board to provide thermal conduction; conformal coating eliminates connection stress and strain.

Subassembly Interconnections

The most advanced and reliable techniques are used for the connections and cabling of the LEM radar equipment. This portion of the electronics is made as *permanent* as possible to increase reliability. The accompanying decrease in maintainability is a reasonable compromise for an overall increase in system reliability.

Two interconnection areas are ruggedized within the individual electronic packages: the interconnecting wiring (between subassemblies) and the separable connections (between the subassemblies and the interconnecting wiring). To strengthen the interconnecting wiring, flexible or *loose* wiring is replaced with multilayer circuit boards of the type used for interconnecting integrated circuits (Figs. 6 and 7).

The immediate reliability value is evident; wires are not subjected to vibration, flexure, or other stresses. To further increase subsystem reliability, piece-part subassemblies are connected to the interconnecting wiring subassembly by gas-tight, wire-wrap connections. The elimination of friction-type, plug-in connections increases subsystem reliability with a limited sacrifice in ease of removal for maintenance.

A basic design criterion was that all electrical connections emanating from a subassembly should be in the same reference plane. Such an arrangement provides maintenance accessibility and permits all structural-thermal subassembly interfaces to be aligned on the perpendicular axis, thus preventing interference between the interfaces.

Each interconnecting board can be electrically checked independently and removed from the vehicle for maintenance. These boards are thinner and lighter than welded-wire-matrix wiring subassemblies, and considerable savings in volume and weight are obtained as compared to standard back-panel cabling methods.

The split-pin wire-wrap connection increases reliability by two orders of magnitude over plug-in connectors.

HEAT TRANSFER

Conduction is the principal means of heat transfer for the LEM electronics. Heat paths are provided from the heat-dissipating electronic parts to the mounting flanges of the electronic assemblies and then through an interface into the mounting rails (Figs. 8 and 9). A mixture of ethylene glycol and water circulating through the rails transfers the heat to a heat exchanger where it is radiated into space or absorbed by evaporating water.

The allowable heat flux per unit area is controlled to limit the temperature gradient at the equipment flange-mounting rail interface. Provision is made in areas of high heat flux density for lateral heat transfer to restrict the heat flux density to allowable limits. For reliability, the maximum surface temperature of all electronic parts is limited to 160°F. This specification dictates careful heat-transfer calculations supported by thermal-vacuum temperature tests to obtain the minimum weight for equipment which is cooled by conduction. It should be noted that careful parts layout was required to ensure short conductive paths.

Transistors or diodes used in the power supplies and servo amplifiers which dissipate power in the order of 0.5 to 10 watts (or more) are mounted to the subassembly structure by integral studs or high-conductivity cement. High-dissipation resistors are flat-mounted to the structure with high-conductivity cements.

In the modular design the heat is conducted from the leads through the epoxy insulating material to the subassembly web. Where required, beryllia heat sinks are cemented to transistors, and additional heat-conducting wires are soldered to pads adjacent to resistor leads to keep the surface temperatures of parts within specification.

The heat-transfer analysis of the electronic parts on each subassembly considered two-dimensional heat flow under steady-state conditions. Nodal points were established on each subassembly web. By the use of heat inputs into each node and the thermal resistance of the heat flow paths, a matrix was established to determine the temperature drop from each nodal point to the mounting flange of the assembly housing; this was assumed to have a maximum temperature of 135°F. The resistances of the paths at the subassembly mounting bolts were considered. It was assumed that there was no heat flow through the interface except at the bolts.

It is extremely difficult to compute the temperature drop from the electronic part to the subassembly web, since it is a function of heat distribution in the part and of the part design. The temperature drops across all of the critical heat-dissipating parts in the equipment were determined experimentally for various mountings, and these results were added to the temperatures at the applicable nodal points to determine part surface temperatures.

The final heat transfer computation considered the three-dimensional flow on an overall assembly basis to allow for the effects of lateral heat transfer. This computation was followed by an experimental program to verify the temperatures by test.

CONCLUSIONS

The critical areas of mechanical design have been concerned with minimum weight, efficient conductive cooling, humidity, vibration, shock, outgassing, and release of toxic fumes. Each of these items has been considered in the mechanical design, and all tests and analyses performed so far indicate that the mechanical design satisfies the requirements.

Fig. 6—Typical split-pin wire-wrap joints.

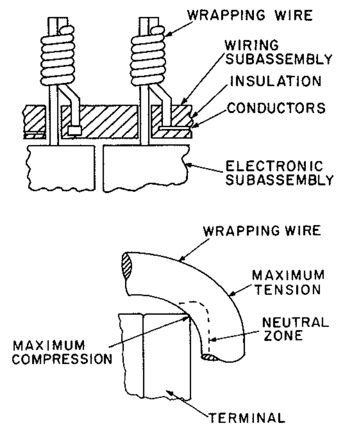


Fig. 7—Typical split-pin wire-wrap connections to wiring subassembly.

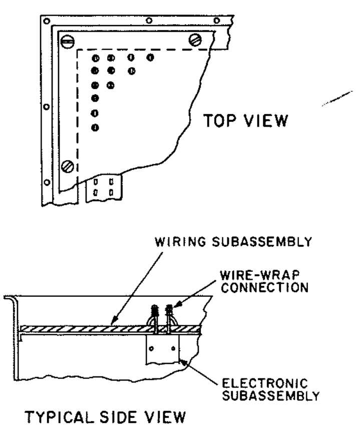


Fig. 8—Assembly of typical subassembly to case.

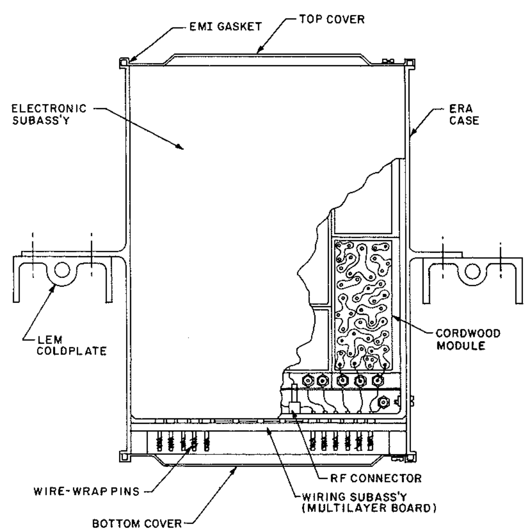
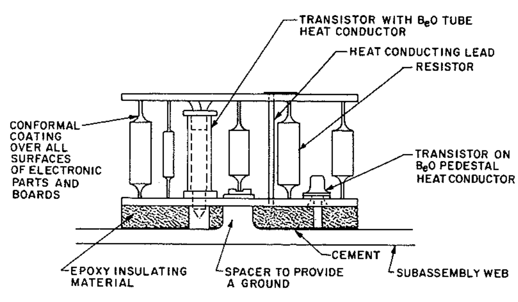


Fig. 9—Typical module heat sinks.



DIGITAL VERSUS ANALOG TELEVISION TRANSMISSION FROM SPACECRAFT

Transmission of television in digital form offers certain advantages over conventional analog transmission for many space missions. The efficiency of digital TV transmission systems can be increased through the use of bandwidth-reduction or data-compression techniques. Two new techniques are discussed and pictures are presented showing the results of a 2:1 data compression. Each technique is practical for use in present-day spacecraft, and one shows promise of achieving about a 10-fold saving of time or bandwidth (or power) after further development.

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TELEVISION has many applications in space missions.[1] In some of these applications, such as in meteorological satellites, the video information has generally been transmitted in analog form. In others, such as deep-space probes, the mission objectives can be better satisfied by transmitting the TV data in digital form. Although the analog approach is usually the most straightforward, there are a number of advantages to digitizing the video signal before processing, storage, and transmission. Therefore, although the basic system requirements may not dictate the use of digital techniques, the use of these techniques may provide a more desirable system in terms of operating accuracy and reliability. For example, in the case of deep-space probes, where information must be sent at extremely low rates (due to the immense transmission ranges involved and to the limitations on transmitter power), the data can be processed and transmitted more practically in digital form. Also, for reconnaissance-type missions, where high accuracy and resolution (and possibly encryption) are required, digital TV can provide high accuracy with less transmission power and bandwidth (and encryption with more simple coding) than analog TV. Even in the case of near-earth, lower-accuracy systems, such as meteorological satellites, where the signal can be readily transmitted in analog form, the use of digital TV is made highly desirable by: 1) the requirement for multiplexing a number of video channels, 2) the requirement for on-board storage and data reduction, or 3) the possibility of regenerating, and the ease of handling, the *yes-no* digital signal. As digital memories capable of storing millions of bits become practical for use in space, they will replace the troublesome magnetic-tape recorders presently used in many applications.

Final manuscript received June 25, 1965

ANALOG TV

In conventional television practice, the scene which has been imaged by the TV sensor or camera is scanned in a rectilinear fashion and converted into an electrical signal whose amplitude is a continuously varying representation of the light intensity throughout the scene. The maximum video frequency that must be transmitted is determined by the required frame rate and the spatial resolution; these, in turn, are dictated by the motion or rate of change of information and by the size of the detail in the field of view.

To obtain the required video signal-to-noise ratio (SNR) in the received signal with the limited transmitter power available in spacecraft, FM rather than AM is normally used in order to trade greater transmission bandwidth for higher SNR.

DIGITAL TV

If the original analog signal from the video sensor is sampled in time (at or above the Nyquist rate), quantized into a finite number of amplitude levels, and coded into digital words, the result is a digital TV signal. This signal may now be transmitted and received in the form of a stream of digital bits, decoded to the corresponding analog levels, and displayed as a normal TV signal. For increased linearity, the deflection waveforms can be digitally derived (instead of operating the TV camera in the conventional manner) by counting down from the basic clock rate and obtaining staircase-type waveforms from digital-to-analog conversion. For increased video SNR, the discretely indexed read-out beam can be pulsed *on* for direct sampling of each picture element. These techniques are particularly applicable to slow-scan systems.

The new digital *baseband* signal has a bandwidth determined by the original analog frequencies (or the number of picture samples per unit time) and the desired intensity resolution; this bandwidth is greater than that of the conventional analog signal. Although the transmission bandwidth required for the digital signal may not be greater than that for the analog (e.g., if FM is used),[2] the storage and transmission of the information will be more efficient if the number of bits required to describe each frame can be reduced.

The most efficient method of transmitting digital data is by phase-shift-keying (PSK).[3] A binary pulse-code-modulation (PCM) system is used to convert the original signal into a serial bit train of *1's* and *0's*. The information is then represented as one of two states of an RF carrier. In PSK, the binary pulses switch the phase of the RF carrier 180°.

DIGITAL VS ANALOG TRANSMISSION

A comparison of information transmission in analog form by FM and in digital form by PCM-PSK, on the basis of relative accuracy, power, bandwidth, and complexity, indicates that the analog system is generally simpler whereas the digital system is capable of achieving greater accuracy at higher efficiency.[2]

Transmission Power and Bandwidth vs Required SNR

Both the analog-FM and the PCM-PSK transmission systems are wide-band, SNR-improvement systems. Above a certain threshold value of received RF carrier-to-noise ratio (CNR), the FM system will provide a higher demodulated SNR (in accordance with the standard FM improvement formula) if the frequency deviation of the RF carrier is increased. By employing a greater number of bits to represent each sample or picture element, the digital system quantizes the original analog signal more finely into a greater number of amplitude levels. Interpreting the errors made in quantization as an effective noise, the signal-to-quantization-noise ratio of the reconstructed signal is increased as the number of bits per picture sample is

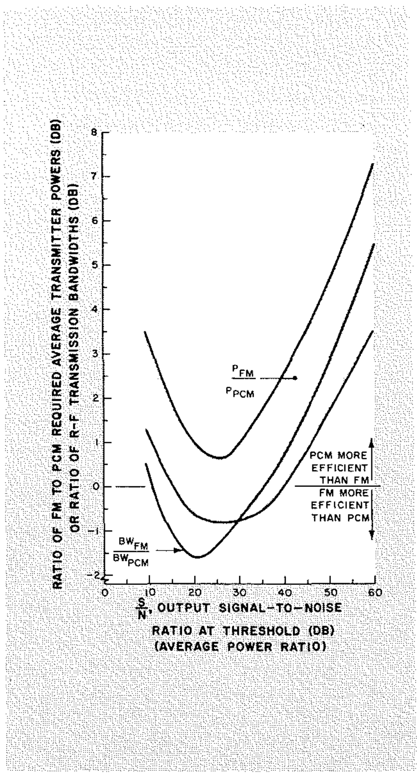


Fig. 1—FM-to-PCM ratios of required average transmitter powers, and RF bandwidths as functions of output SNR at threshold for analog-FM and PCM-PSK systems.

increased. Therefore, the resultant video SNR is higher as long as the received CNR is high enough to assure that the number of errors made in detecting the received bits is negligible. Here, the rapid decrease in bit error rate, as the CNR is increased, represents the system threshold.[3]

The relative digital and analog system efficiencies are shown in Fig. 1 in terms of the transmission bandwidth required to provide a given SNR at threshold, and the transmitter power required to attain threshold in this bandwidth. A wide region is used, rather than a single curve, to represent the variation possible, depending on the particular threshold definition employed and the manner of PSK detection.

The general conclusion drawn from this comparison is that for the RMS video SNR's normally employed in television (20 to 40 dB), the digital and analog systems are fairly equivalent (within 1 or 2 dB) in terms of required transmission power and bandwidth. (The peak-to-peak, black-to-white, video-signal-voltage to RMS-noise-voltage ratio is considered to be 9 dB above the RMS voltage or average power ratio.)

The efficiency of analog transmission can be improved by preemphasis and deemphasis, and by such threshold-reduction techniques as phase-locked receivers and FM feedback. By using preemphasis and deemphasis, the required output video SNR at threshold can be achieved with a lower deviation or modulation index. Since a system with a lower index requires a narrower transmission bandwidth, less power is needed to reach threshold in this bandwidth. Since the demodulated SNR increases more rapidly with increased deviation ratio than does the required transmission bandwidth (and therefore the noise, assuming a flat noise spectrum), a higher deviation ratio can be used to achieve the required output SNR at the lower input CNR threshold, if the system threshold can be reduced. Although the required transmission bandwidth is wider for the higher-index system, less power is required to achieve the lower threshold in the wider bandwidth than is needed to achieve the normal threshold in the narrower bandwidth of the lower-index, conventional system.

In addition to optimizing the transmission waveforms, synchronization, detection scheme, and general transmission link parameters, the efficiency of information transfer in digital transmission can be increased by coding the original data so that fewer bits will be needed to convey the essential or significant information to the receiver. Bandwidth-reduction (or more generally, data-compression) techniques can be applied to TV data to reduce the total number of bits required to delineate the scene, since most pictures have much redundant data in the form of large areas with no significant gray-level variation. If fewer bits are transmitted in the same frame time, the transmitted bit rate (and, therefore, the transmission bandwidth) can be decreased and threshold can be achieved with less transmitter power, since less noise power will be encountered in the narrower bandwidth.

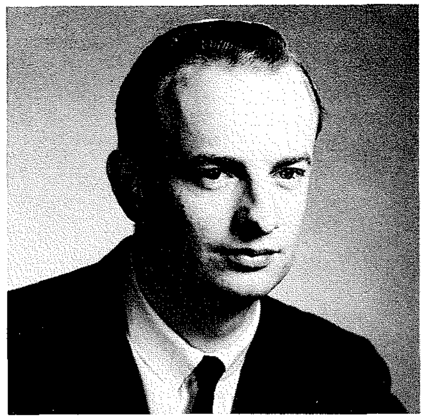
Advantages of Digital Transmission

For any spacecraft transmission system, the analog-FM technique is usually the most straightforward approach; however, the information may be transmitted in digital form to take advantage of one or more of the following factors:

1) Transmitter power savings over conventional analog-FM transmission for high-accuracy systems (those requiring high SNR in the output)
2) Ability to regenerate the digital signal
3) *Solidity* with which the information is known when digitized
4) Ease of handling *yes-no* or *on-off* signals
5) Ease of multiplexing digital signals
6) Ability to encrypt the digital signal
7) Practicality of processing and sending information at extremely low rates, as from deep space, when in digital form.

DIGITAL TV BANDWIDTH REDUCTION

Although the transmission power and bandwidth required to transmit information in digital form may not exceed the requirements for analog transmission, representation of even a few video frames in digital form requires an extremely large number of bits. For example, each cycle of analog video information requires about 12 bits of information when coded in digital form. A digital TV counterpart to the commercial TV video bandwidth of 4 MHz (Mc/s) would involve a bit rate of about 48 megabits/second, a substantial increase in information bandwidth. Each conventional TV frame requires more than 1.5 million bits when represented in digital form; this number is beyond the capability of existing aerospace solid-state storage systems. Each picture or frame in commercial TV takes 1/30 of a second to transmit in analog form; each picture of Mars taken by the Mariner IV spacecraft took about 8-2/3 hours to transmit in digital form because of the limited transmitter power and the extremely long range. Only about 20 frames were transmitted as the result of the limited bit-storage capability of the data-rate slow-down equipment. A reduction in the number of bits required to describe this data would have allowed more pictures to be trans-



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mitted in the same time, or the original pictures could have been transmitted in less time, thus increasing the reliability of the mission. Alternatively, the existing 200-scan-line resolution (compared to 525-line commercial TV) could have been increased (40% increase for a 2:1 data compression). Therefore, it is desirable to reduce the bandwidth of the digital TV signal or to compress the amount of digital data required for adequate pictorial representation.

If the detail in the original scene or scanned signal is to be preserved, the sampling rate must be at least twice the maximum video frequency to maintain spatial resolution (one sample per picture element). The actual sampling rate may have to be higher in a practical system to prevent signal components that are higher than the nominal maximum video frequency from interfering with the lower frequency information, since the sampling theorem applies only to perfectly band-limited signals. This interference effect is often called aliasing error. A Kell factor can be applied to the interline sampling, as is done for the sampling of the image by the horizontal scan lines; in this way the probability of relative alignment of detail and sampling points is taken into account. Since a sampling rate of about three times the maximum video frequency to be reproduced is often used in practice, and since a Kell factor of about 0.7 is commonly applied, although the aliasing and Kell effects differ, compensating for one tends to compensate for the other.

The number of quantization levels used to maintain the intensity or gray-scale resolution determines the number of bits required to describe each sample. As the number of bits used to represent each picture element is decreased, the accuracy of the digital representation decreases and an intensity contouring effect becomes noticeable to the human eye. If 6 or more bits are used per picture element and 64 or more different intensity levels are represented, the contouring effect is not noticeable.[4] The accuracy of a 6-bit system is about 1.6% of full-scale. Considering the errors encountered in quantization as effective noise, with respect to the signal amplitude before quantization, this system has an RMS-signal-to-RMS-quantization-noise ratio of 37.8 dB.[2,5] Therefore, the 6-bit picture is generally employed as a reference, since it is equivalent for all practical purposes to the original analog. Bandwidth-reduction techniques are used to eliminate contouring, or to reduce the number of bits required per picture in some other way, while the 6-bit picture quality is maintained in the output.

Redundancy in Pictures

Digital TV data compression is possible because most pictures contain redundant information that does not have to be transmitted. The detail represented by the system resolution capability is not always present; therefore, the average video frequency is considerably less than maximum. The objective of most data-compression techniques is to eliminate this redundancy or use it to reproduce the vital information at the receiver, while transmitting a smaller number of bits. Some techniques go further than this and reduce the amount of information transmitted to the point where picture degradation occurs; however, such degradation is not readily noticeable to the human eye. Other techniques adjust the accuracy in accordance with the accuracy of the information presented by the sensor. For example, as the information frequency increases, the output of practical video sensors drops off. Since the noise spectrum is relatively flat, the high-frequency information is defined (in a particular system) less accurately than the low-frequency information. A technique using this principle can effect a saving by reducing the accuracy with which it represents high frequencies.

Types of Bandwidth-Reduction Techniques

Many different bandwidth-reduction techniques have been proposed and implemented to various degrees.[1] The technique to be used in any given system depends on: the subject matter to be transmitted; the end use for the data; the complexity tolerable at the transmitting and receiving terminals; the required saving in bit rate, transmission time, or storage; and the characteristics of the transmission channel. All of these techniques, however, can be divided into three general categories:

1) Techniques that transmit a reduced number of bits for each sample or picture element and rely on the redundancy in most pictures to extract a greater amount of information.
2) Techniques that accurately represent each picture element but which transmit only elements significantly different from those which came before; the total number of bits sent is reduced by extracting the redundant information through a time-buffering scheme (that is, the extraction of redundant picture-element samples and the variation of the picture read-out rate to maintain a constant transmitted bit rate).
3) Hybrid techniques that combine features of types 1 and 2.

Type 1 techniques *utilize* the redundancy in pictures, whereas type 2 techniques *remove* some of the redundancy. Non-time-buffering techniques can attain compression ratios of about 2:1 (that is, effectively 3 bits per picture element) while reproducing the pictures with reasonable fidelity. Time buffering offers various amounts of reduction depending on the complexity of the pictures involved. A saving of 4:1 is representative of pictures of average complexity. By employing both types in a hybrid system, a compression of at least 6:1 is feasible. Previous work in the digital TV field indicates that for pictures of average complexity, a compression of about 10:1 is theoretically possible.[6]

NEW DIGITAL TV DATA-COMPRESSION SYSTEMS

Two new data-compression techniques have been developed by RCA's Astro-Electronics Division in a company-sponsored independent research and development program. The techniques are non-time-buffering, although one of them is readily adaptable to time buffering. The one technique depends on averaging over a number of picture elements to obtain greater accuracy; the other can provide information of 6-bit accuracy for most of the elements in a picture. These new digital TV data compression techniques, the Improved Gray Scale PCM System and the Coarse-Fine PCM System, are described and evaluated in considerable detail in another paper.[7]

The Improved Gray Scale PCM System

The Improved Gray Scale (IGS) PCM System eliminates the intensity-contouring effect and provides nearly the accuracy of a 6-bit system for the low-frequency information in the picture by averaging over a number of picture elements. On an element-to-element basis (for the high-frequency information), IGS maintains 3-bit accuracy for most elements, with some being represented with slightly more than 2-bit accuracy. Although the peak-to-peak error is almost twice that of the 3-bit system, this technique merits consideration because of the simplicity with which it eliminates the contouring effect, and the fact that smaller intensity changes can be detected than is possible in the regular 3-bit system. The scheme consists of digitizing the original signal to 6 bits, transmitting and displaying the 3 most-significant bits, and retaining the 3 least-significant bits to be added to the intensity of the next sample or picture element (Fig. 2). The cumulative effect of the retained least-significant bits is to change the most-significant bits in such a way that the displayed levels average out to about a 6-bit-accuracy representation of the true intensity. If the input signal is a DC video level, the transmitted 3-bit words alternate over a range 1/8 full scale about the true level, and when the

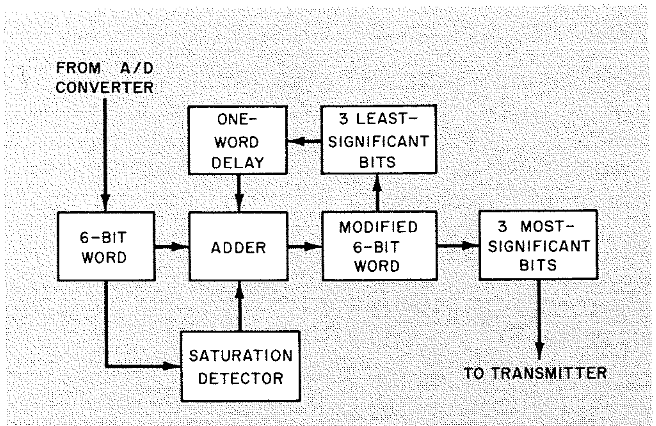


Fig. 2—Simplified logic diagram for Improved Gray Scale PCM processing.

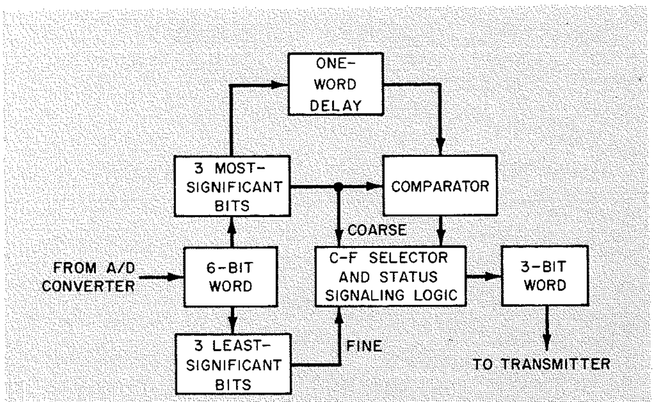


Fig. 3—Simplified logic diagram for Coarse-Fine PCM processing.

displayed intensity levels are averaged over no more than eight elements, the average intensity is equal to the original 6-bit representation of the true intensity. As the frequency of the input signal increases, the averaging becomes more approximate. Only eight different intensity levels are displayed. A different number of most- and/or least-significant bits might be used to trade off bandwidth reduction and resultant picture accuracy.

The Coarse-Fine PCM System

The Coarse-Fine (C-F) PCM system represents video information with 6-bit accuracy for low and high frequencies that vary within a range of 1/8 full scale; 3-bit accuracy is provided for large-amplitude, high-frequency variations. These latter variations rarely occur, since response of practical video sensors falls off with an increase in frequency. Hence, this system is capable of representing the video information with the accuracy of a 6-bit system on an element-to-element basis. The C-F system (Fig. 3) digitizes the original signal to 6 bits and transmits either the 3 most-significant bits (coarse information) or the 3 least-significant bits (fine information). If the original signal changes very rapidly over a range greater than 1/8 full scale, causing a change in the 3 most-significant bits at each sample (or picture element), then these bits are transmitted and displayed as eight *absolute* levels from black to white. However, let's assume that: the signal changes more slowly, or the swing is less than 1/8 full scale; the signal is not at a decision or threshold level between two adjacent coarse levels; and the 3 most-significant bits do not change for at least four samples. Then, the 3 least-significant bits are transmitted and displayed as eight *relative* levels, with respect to the most recently received coarse level (between this level and the next coarse level). It should be noted that 64 different intensity levels are actually displayed. A set of rules has been established to determine whether to send coarse or fine bits at the transmitter; the selection is made on the basis of a comparison between the coarse level of the present sample and that of the preceding element. An inter-word code or signaling relationship is employed, causing the decoder at the receiver to display the information as coarse or fine levels. The two basic rules are:

1) If the C-F decoder finds two successive 3-bit words to be identical, that occurrence will be accepted as a command to interpret the words following as fine information.
2) If during fine translation the C-F decoder finds that two successive 3-bit words differ only in their most-significant-bit position, that occurrence will be accepted as a command to revert to coarse translation.

In this way spatial resolution need not be sacrificed to inform the receiver of the C-F transitions.

A three-word memory is required at each end and three successive words are compared at all times. The encoder status signaling logic maintains at least a 3-bit accuracy for every sample (with one rare exception) and causes the relationship between any pair of words to signal the decoder whether any given word is coarse or fine. The exceptional case occurs when one course level differs by about 1/2 full scale from the preceding coarse level; when this happens, the least-significant bit of the second coarse level must be inverted to keep from inadvertently sending a code signal.

Pictorial Results

Although data-compression techniques can be theoretically investigated and analyzed, the actual processing of representative information should be performed before final conclusions are reached. An experimental digital-TV facility was assembled to evaluate various data-compression schemes. The present facility (Fig. 4) is composed of the flying-spot scanner portion of the RCA TV imagery simulator, a 6-bit analog-to-digital (A/D) converter, a 6-bit digital-to-analog (D/A) converter, various digital processing equipment, a kinescope display, and 35-mm reproduction facilities.

The original subject, in the form of a 35-mm transparency, is converted into an analog electrical signal by the flying-spot scanner. The video signal from the scanner is filtered, amplified, and presented either directly to the display to obtain an analog picture, or to the digital chain for processing.

In the digital chain, the A/D converter samples the video, holds the sampled level as it is converted into one of the 64 possible 6-bit digital words, and presents this 6-bit word to the output. This data

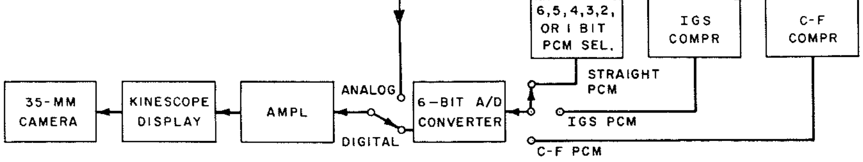


Fig. 4—Experimental digital television facility.

Fig. 5—Portrait picture processed by analog and various digital television techniques.

a. Analog   b. 6-bit PCM   c. 3- x 3-bit IGS   d. 3-bit PCM

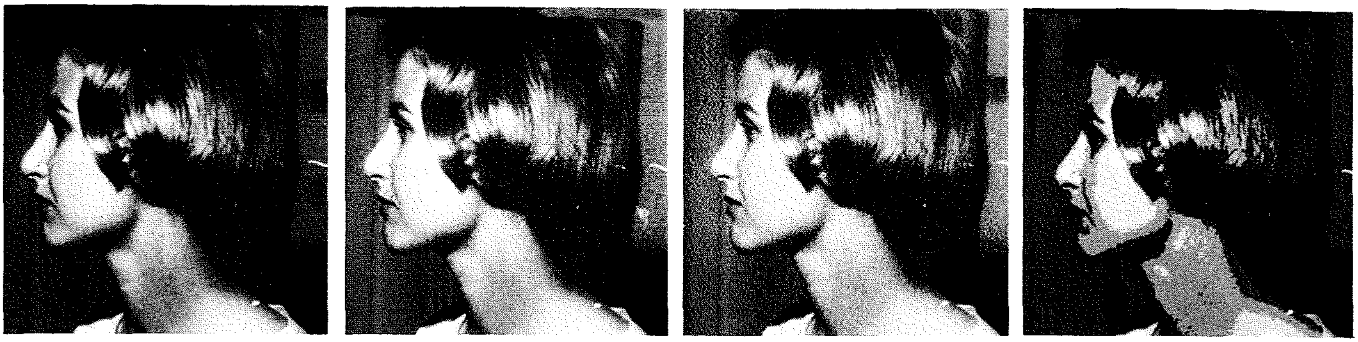


Fig. 6—Portrait picture processed by various digital television techniques (IGS and PCM).

a. 4- x 2-bit IGS   b. 2- x 4-bit IGS   c. 4-bit PCM   d. 2-bit PCM

Fig. 7—Portrait picture processed by various digital television techniques (C-F and PCM).

a. 3- x 3-bit C-F   b. 6-bit PCM   c. 3-bit PCM   d. C-F coarse data only

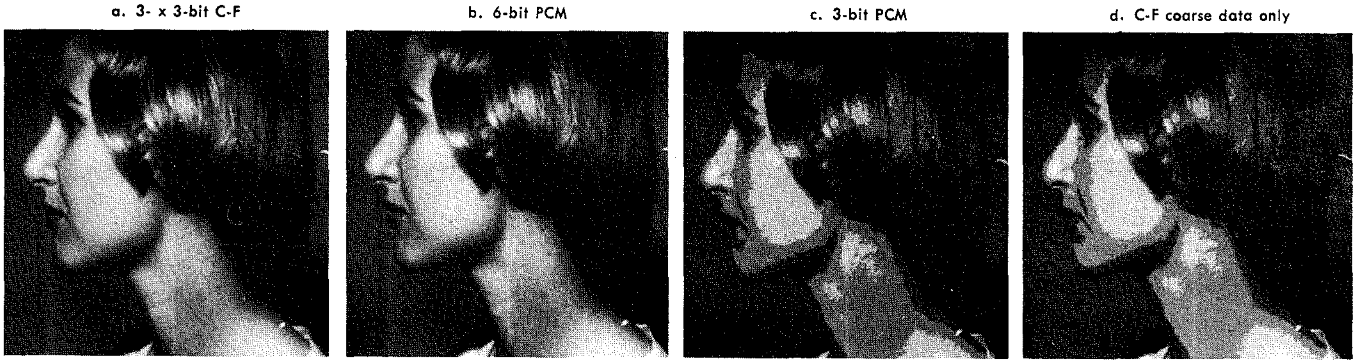


Fig. 8—Meteorological picture processed by various digital television techniques (C-F, IGS, PCM).

a. 3- x 3-bit C-F   b. 3- x 3-bit IGS   c. 6-bit PCM   d. 3-bit PCM

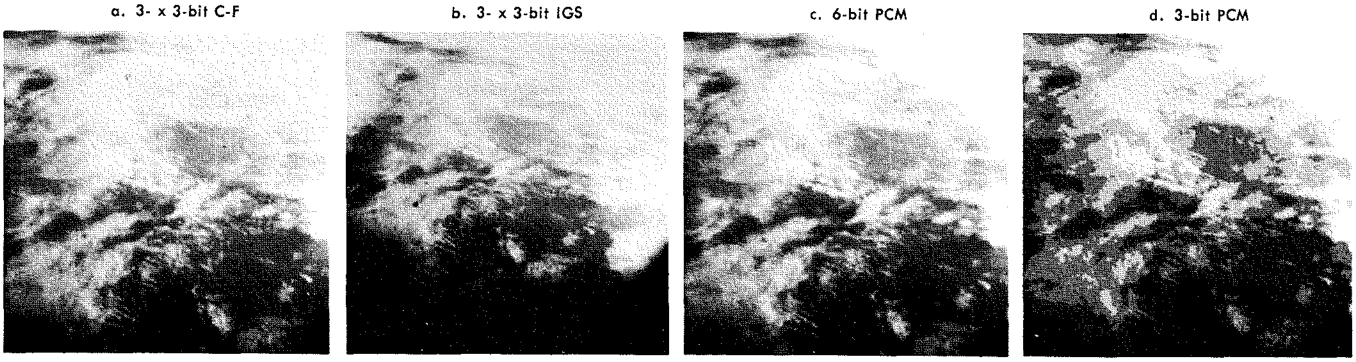
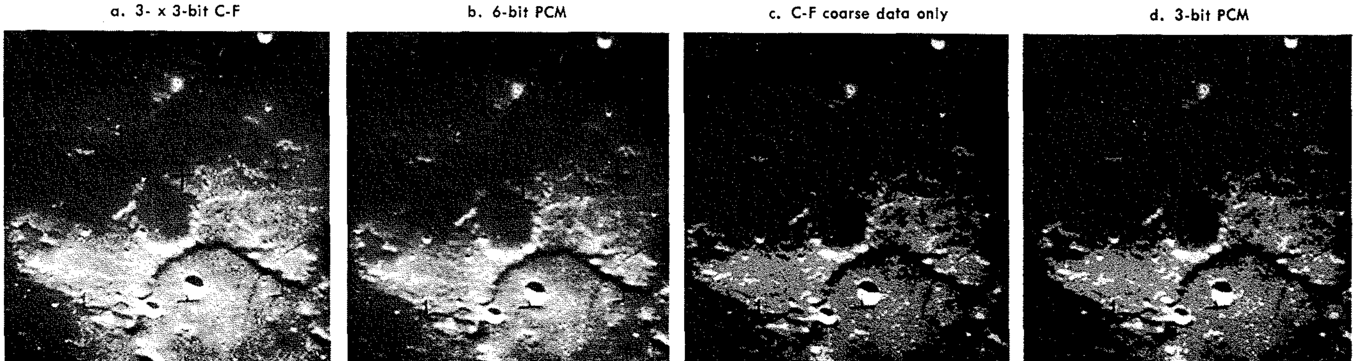


Fig. 9—Scientific picture processed by various digital television techniques (C-F and PCM).

a. 3- x 3-bit C-F   b. 6-bit PCM   c. C-F coarse data only   d. 3-bit PCM



is then switched to either a (straight) PCM chain, the IGS data compressor, or the C-F data compressor. At the *receiving* end, data from any one of the three channels is presented to the 6-bit D/A converter, which yields the corresponding analog output.

The equivalence of the analog and the 6-bit-PCM pictures is demonstrated in Fig. 5. This figure also compares 3-by-3-bit (3 most-significant bits transmitted, 3 least-significant bits retained for cumulative addition) IGS processing and 3-bit PCM pictures. (Figs. 5 through 9 are presented primarily for comparison purposes. Since some detail has been lost in reduction and reproduction, they are not ideal representations of the various transmission methods.) It can be seen that although the IGS system transmits the same number of bits as the conventional 3-bit system, it eliminates the contouring effect and permits the detection of smaller intensity variations in the original scene. Although the IGS system approaches the accuracy of the 6-bit system and requires only half the number of bits, an intensity dot pattern is noticeable in the IGS picture. By adding lighter gray levels to individual picture elements, the IGS system has improved the *large area* gray scale rendition over that of the 3-bit system, but the intensity variations are not completely averaged by the human eye. Certain applications might well use the IGS pictures without further refinement. However, additional processing of the data at the receiver could average the data in its electrical form before display. This processing would produce a more subjectively pleasing picture, but it would reduce the limiting spatial resolution of the system.

The tradeoff that can be made with the IGS system between bandwidth saving and resultant picture fidelity is shown in Fig. 6. If the original 6-bit word is separated into 4 most-significant bits and 2 least-significant bits so that 4 bits per picture element are transmitted and displayed (16 possible levels) and 2 bits are retained to supplement succeeding elements, the fidelity of the reproduced picture can be increased while realizing only a 1.5:1 saving. A 2:1 saving is provided by the 3-by-3-bit form of the IGS system. Alternatively, the 2-by-4-bit IGS configuration can provide a 3:1 compression with pictures that are less accurate, but which are substantial improvements over 2-bit pictures of comparable bandwidth.

The results of C-F system processing are shown in Fig. 7. While transmitting only half the number of bits, this system reproduces pictures which are almost as good as those of the 6-bit system. Shown for comparison with the 3-bit PCM picture is the picture resulting from the display of only the coarse data; i.e., the data was not refined with the 3-least-significant bits available during fine-data transmission. Of the more than 340,000 elements in the C-F picture, 80 to 90% are represented with fine information (6-bit accuracy) and the rest with 3-bit accuracy. The coarse elements can be distinguished from the fine by the received data, and a C-F overlay picture can be generated (e.g., by displaying black when coarse and white when fine) to aid in identifying the two accuracies.

Representative IGS and C-F meteorological pictures are compared in Fig. 8 along with straight 6-bit and 3-bit pictures. Although both the IGS and C-F systems require the same bandwidth (in the 3-by-3-bit configuration of each system), the C-F system reproduces a picture with greater fidelity. However, the C-F system is about three times as complex as the IGS system and employs more sophisticated data coding.

The C-F system processing of another type of subject matter is shown in Fig. 9. The *flecks* in the upper left-hand portion of the C-F picture are accentuations of small signal variations about the threshold level between two coarse quantization levels. These variations cause the system to remain in the coarse mode of operation. They could be eliminated by additional processing of the data at the transmitter before coarse-fine encoding to discriminate between *meaningful* signal variations and *noise*. In this picture the C-F system again represented 80 to 90% of the elements with 6-bit accuracy. Of the remaining elements, all but a few are accurate to 3 bits; these few were reduced to 2-bit accuracy to prevent an unwanted signal code from being transmitted. The probability of an intensity change of about one-half of the black-to-white range occurring from one element to the next is quite small; it occurred only a few times in the scene in Fig. 9 and did not occur at all in Fig. 7. These large-amplitude changes most likely occurred at the transition between a near-white area at the edge of the picture and the black (blanked) retrace interval whose encoding was not disabled.

CONCLUSIONS

Digital techniques can be used to advantage in many space-TV applications. For the video SNR normally required (in the range from about 30 dB to about 50 dB, peak-to-peak, black-to-white video-signal swing-to-RMS noise ratio), the transmission power and bandwidth required for analog-FM and PCM-PSK transmission are about the same. Compression of the digital data to increase the efficiency of digital-TV storage and transmission is possible.

Two new digital-TV data compression techniques have recently been developed at the RCA Space Center. Each provides a 2:1 compression over 6-bit PCM. One is an elementary technique (the IGS system) which provides fair pictures; the other (the C-F system) is a more elaborate but still relatively simple technique which provides excellent pictures. The 2:1 reduction in data permits a given digital storage system to store twice the number of pictures that could be stored using noncompressed data; similarly in any mission the same number of pictures can be transmitted in half the time, or twice as many pictures can be transmitted in the original time. Alternatively, spatial resolution can be increased 40%.

To obtain substantially higher compression ratios, time buffering must be employed. The development of a hybrid system employing the coarse-fine system with time buffering of the fine data is now being pursued. Initial measurements have indicated that this system can achieve a 10:1 data compression on the average for subjects like the lunar pictures shown in Fig. 9.

ACKNOWLEDGMENTS

Of the many who have contributed to this program, specific mention is due to William T. Bisignani who has conducted the second and third years of this program and who has performed most of the experimentation; to Gerald P. Richards who has accomplished the major portion of the digital logic design and who contributed the Coarse-Fine system idea; and to John Lowrance and A. John Vaughan for their ideas on the Improved Gray Scale System.

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TWENTY-FOUR-HOUR SATELLITE ORBITS

Several features of synchronous satellite orbits are explored and ground track plots are presented to illustrate the effects of varying orbit eccentricity and inclination. Graphs of subtended coverage angles are presented to indicate the portion of the earth within view and the viewing angle at the satellite. The analysis includes several values for the argument of perigee to indicate the effect on the ground tracks of moving the perigee of the orbit; examples are shown for perigee at the southern extreme of the orbit. Equations used in the computer program are presented and discussed.

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SYNCHRONOUS satellites are orbiting vehicles with rotational periods equal to the rotational period of the earth; such satellites are of interest as communication relays between points on the earth, or between other low-orbit satellites and ground stations. In the design of synchronous satellite orbits, it is useful to know the ground track for orbits that either are inclined or eccentric or both.

This paper provides a few illustrative ground-track plots for such satellite orbits and includes equations for computing other ground tracks. Further, the coverage and subtended angles for various orbits are illustrated and the equations are included. A full set of ground-track plots may be found in another paper.[1]

For most purposes, the graphic presentation provides the optimum balance between expedience and accuracy. Higher accuracy may be attempted by direct computation from the equations in this paper, or from equations of the analyst's choice. A more rigorous treatment may be found in another paper.[2]

PHYSICAL MODEL

For the purpose of this work, it is assumed that the earth is spherical and that neither the line of nodes nor the argument of perigee precesses. The line of nodes is the intersection of the orbit plane with the earth's equatorial plane. The argument of perigee is the angle between the line from the center of the earth to the perigee and the line of nodes. This angle is measured from the ascending node, the south-to-north equator crossing. It is further assumed that no perturbations appear as the result of drag, solar pressure, lunar attraction, or any other cause.

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Actually, the line of nodes and the argument of perigee do precess, partly because of the oblateness of the earth. The precessions are a combination of short-term oscillation and long-term steady drift, called secular motion. The following equations, which describe the approximate secular behavior of the orbit, show that these precessions are minor. For the precession of perigee,

$$\Delta\omega \text{ (in deg/rev)} = 0.5895\,(2-2.5\sin^2 i)\left(\frac{r}{a}\right)^2\left(\frac{1}{1-e^2}\right)^2$$

and for the precession of the line of nodes, $\Delta\Omega$ (in deg/rev):

$$\Delta\Omega = -\,0.5895\cos i\left(\frac{r}{a}\right)^2\left(\frac{1}{1-e^2}\right)^2$$

where r = radius of earth, a = semimajor axis of orbit (r and a are in the same units), e = eccentricity of the elliptical orbit, and i = inclination of the orbit.

For the synchronous orbit, $(r/a)^2 = 0.0227$. The precessions of a synchronous orbit for the range of possible eccentricity and inclination are shown by Figs. 1 and 2. For example, an orbit with eccentricity of 0.4 and inclination of 30° will precess in one year about 9.5° in argument of perigee and about 6° in line of nodes.

MATHEMATICAL MODEL

The ground tracks are calculated from Keppler's equation and a geometric transformation to account for the orbit inclination. The specific equations (1 through 8 below) used in the computer program are:

$$0.1309t = E - e\sin E \qquad (1)$$

Uniformly spaced time tics are obtained by taking time, t, as an independent variable, measured in units of half hours. Eccentricity, e, is taken as the parameter for each group of curves. The eccentric anomaly, E, is obtained by the Newton-Raphson method, which converges quite reasonably for eccentricity up to 0.9.

$$\omega = 2\tan^{-1}\left(\sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2}\right) + \omega_p \qquad (2)$$

The argument, ω, is found explicitly from the results of equation 1 and ω_p, the argument of perigee. In the set of ground tracks illustrated in this paper, $\omega_p = -90°$.

$$\lambda = \tan^{-1}(\tan\omega\cos i) - \tan^{-1}(\tan\omega_p\cos i) - 7.5t \qquad (3)$$

The geographic longitude displacement, λ, of the satellite from the longitude of perigee is computed from the following three expressions:

1) $\lambda_n(\omega) = \tan^{-1}(\tan\omega\cos i)$
   Longitude displacement of the satellite from the ascending node, measured in a stationary coordinate system (Fig. 3)
2) $\lambda_n(\omega_p) = \tan^{-1}(\tan\omega_p\cos i)$
   Longitude displacement of perigee. In the set of ground tracks illustrated in this paper, $\lambda_n(\omega_p) = \lambda_n(-90°) = -90°$
3) $7.5\,t$
   The motion of the perigee meridian.

$$L = \sin^{-1}(\sin\omega\sin i) \qquad (4)$$

The geographic latitude, L, of the satellite is obtained directly from ω and i (Fig. 3).

$$R = 22800\,(1 - e\cos E) \qquad (5)$$

The radius, R, from the earth center is computed for a semimajor axis of 22,800 nautical miles.

$$H = R - 3440 \qquad (6)$$

H is the altitude above a spherical earth with a radius of 3440 nautical miles.

$$-A_\varepsilon = \sin^{-1}\left[\frac{3440}{R}\sin(90+\varepsilon)\right] \qquad (7)$$

Angle A_ε is the half-angle subtended at the satellite by the area for which the elevation angle of the line of sight to the satellite is ε or greater (Fig. 4). Computations have been made for $\varepsilon = 5°$ to define communication coverage, and for $\varepsilon = 30°$ to define optical mapping coverage.

$$-G_\varepsilon = 90 - A_\varepsilon - \varepsilon \qquad (8)$$

Angle G_ε is the earth-centered half-angle subtended by the area defined for A_ε (Fig. 4).

BASE MAP

The plotted ground tracks are scaled to match the rectangular projection of the earth that constitutes the lower half of a 90° B-map. This choice makes an accurate reproduction master readily available. More important, the library of B-charts at SEER may be used to obtain various coverage boundaries rapidly.

B-charts and B-maps are projections representing real or virtual features of the earth's surface in a way that greatly simplifies the plotting and study of satellite orbits. The B-maps represent geographic features; the B-charts represent the coverage, or "visibility," of satellites from ground stations. A full discussion of B-charts and B-maps may be found in another paper.[3]

GROUND TRACKS

Five sets of ground tracks are illustrated for perigee at −90°, the southern extremity. Each set includes tracks for seven inclinations at one eccentricity. Inclination ranges from 0° to 90° in 15° steps, and eccentricity ranges from 0 to 0.8 in 0.2 steps. Intermediate values may be interpolated except in the transition region, where the figure-8 shape untwists into a cusp and then into a smooth, convex curve. In this region it may be wise to compute a few positions from the equations given earlier. The half-hour time tics permit rapid evaluation of coverage duration and physical spacing of satellites.

The map of the earth (Fig. 5) has a ground track transcribed upon it for $e = 0.4$, $i = 30°$, centered at 260° west longitude. The altitudes at apogee, perigee, and equator crossing are entered and the 6-hour time tics are emphasized. The $\varepsilon = 30°$ coverage

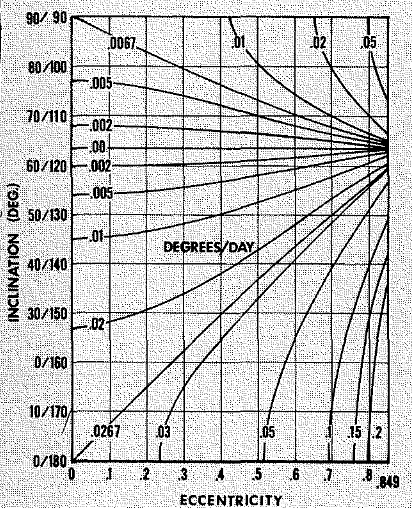

Fig. 1—Precession of perigee (synchronous orbit, secular component).

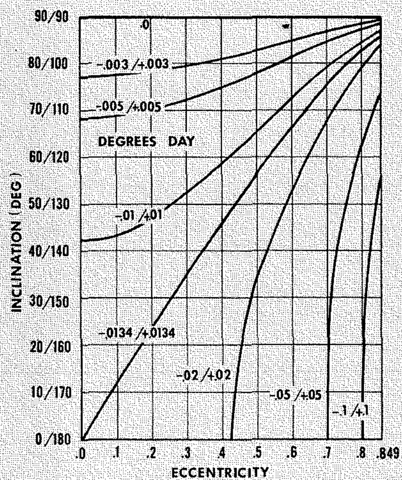

Fig. 2—Precession of line of nodes (synchronous orbit, secular component). Note that precessions are negative for posigrade orbits and positive for retrograde orbits.

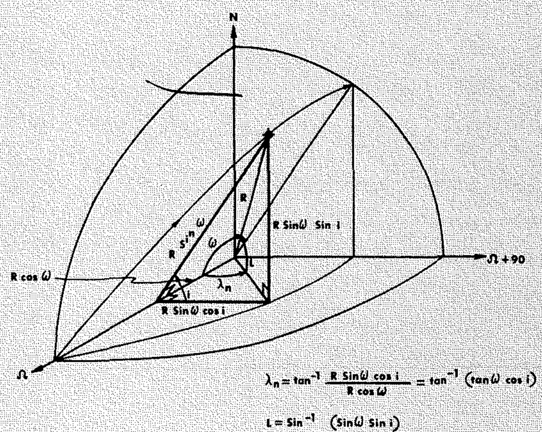

Fig. 3—Geometry relating latitude and longitude displacement of satellite to inclination and argument.

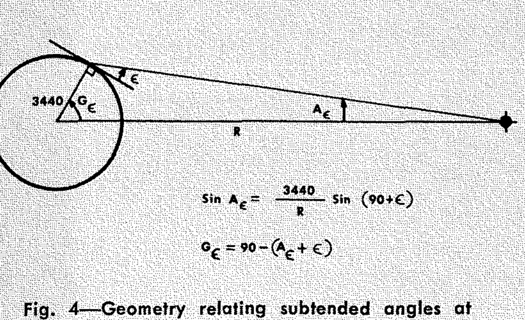

Fig. 4—Geometry relating subtended angles at satellite and at earth center to orbit radius and elevation angle.

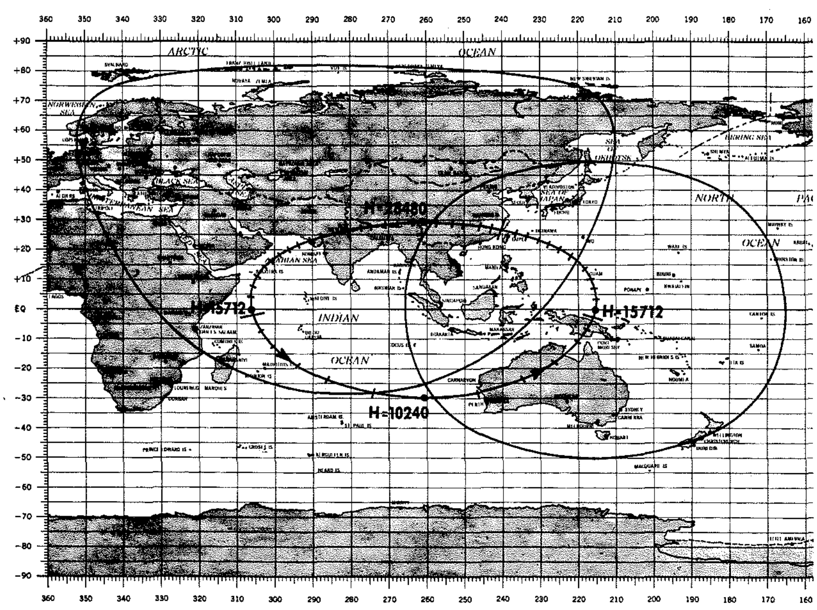

Fig. 5—Map of the earth; ground track is transcribed for $e = 0.4$ and $i = 30°$, centered at 260° west longitude.

boundaries (Eq. 8) are transcribed from a B-chart for a satellite at the ascending node and at the half-day opposition point (approximately 280° W longitude, 27° N latitude).

The ground track sets for perigee at $\omega = -90°$ are shown in Figs. 6 through 10. A more complete set of ground tracks is available at SEER and in reference 1.

SUBTENDED ANGLES

As a satellite moves around an eccentric orbit, its altitude changes from minimum altitude at perigee to maximum at apogee. As the altitude changes, so do the angles subtended at the earth's center and at the satellite by the boundary of the zone of coverage. The geometry is illustrated in Fig. 4. The actual values of the subtended angles throughout the orbit are shown in Figs. 11 and 12.

APPLICATION

The ground tracks and corresponding coverage boundaries have been used to design the orbits for a satellite surveillance and communication system. Through the use of these curves, it is possible to examine a large number of possible orbits very rapidly and select those best suited to the satellite's mission.

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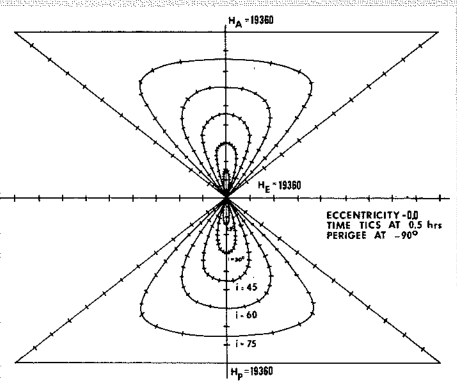

Fig. 6—Ground track sets of inclined synchronous satellite for perigee at $\omega = -90°$ and eccentricity of 0.0.

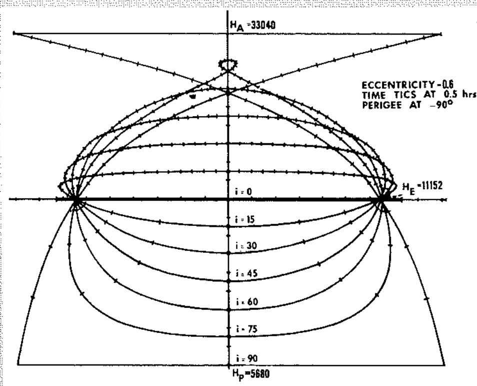

Fig. 9—Same as Fig. 6 except for eccentricity of 0.6.

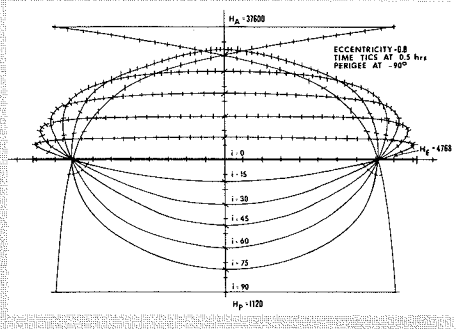

Fig. 10—Same as Fig. 6 except for eccentricity of 0.8.

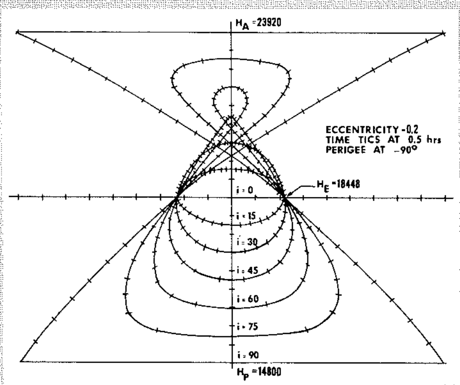

Fig. 7—Same as Fig. 6 except for eccentricity of 0.2.

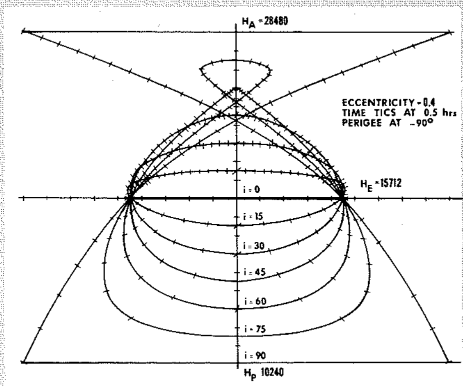

Fig. 8—Same as Fig. 6 except for eccentricity of 0.4.

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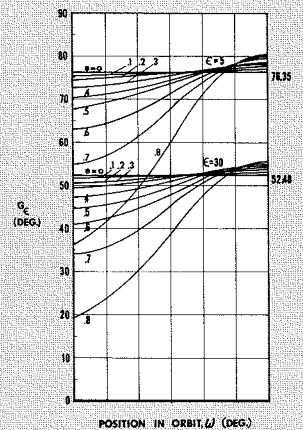

Fig. 11—Earth centered half-angle G_ϵ subtended by coverage zone.

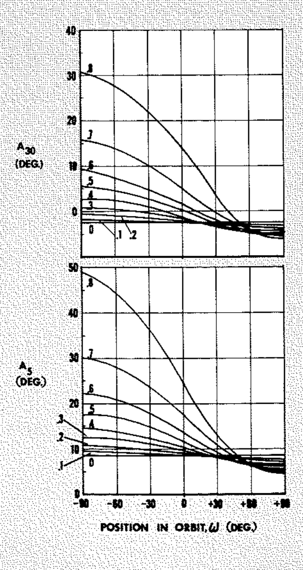

Fig. 12—Half-angle A_ϵ subtended at satellite by coverage zone.

ANTENNAS IN MAGNETO-PLASMAS

This paper describes some of the more interesting, albeit complex, characteristics of propagation in magneto-plasma. Antenna impedance is discussed and antenna patterns are examined.

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It is well-known that the near-earth environment (distances out to one or two earth radii) consists of a magneto-plasma and that both propagation and antenna characteristics in such a medium can be significantly different from those in free space. As the result of recent developments in satellite technology, the study of antennas immersed in magneto-plasmas is of considerable practical interest for all experiments involving antennas carried by space vehicles and operating close to or below the local gyrofrequency.

PROPAGATION CHARACTERISTICS IN A MAGNETO-PLASMA

By definition, a plasma is a fluid in which there are an equal number of free negative and positive charges. For purposes of this paper, the negative charges are assumed to be electrons, whereas the positive charges are assumed to be infinitely massive and, therefore, immobile. This approximation is satisfactory at frequencies that are high compared to the ion plasma and gyrofrequencies.

There are essentially four parameters associated with radio wave propagation in a simple, homogeneous plasma:

1) The number density, N, of free electrons. This number density is usually expressed through the parameter called *plasma frequency* where $\omega_p^2 = Ne^2/m\varepsilon_o$, e being the charge of the electron, m its mass, and ε_o the dielectric constant of free space.
2) The DC magnetic field, B_o. This field is usually expressed through the parameter called gyrofrequency or cyclotron frequency and is given by $\omega_B = e\,B_o/m$.
3) The collision frequency, ν, of electrons with the heavy ions or with neutrals.
4) The operating frequency.

First, we neglect the effect of collisions thereby eliminating the parameter ν. This is a very good approximation at altitudes above 150 km. Next, to normalize the plasma frequency and the gyrofrequency divide these by the operating frequency; this reduces the number of parameters needed to describe the radio properties of a plasma to two. Specifically, the normalized parameters used in the ionospheric literature when collisions are neglected are:

$$X = \omega_p^2/\omega^2 \text{ and } Y = \omega_B/\omega$$

Elementary, albeit elaborate, calculations[1,2] show that radio wave propagation in magneto-plasmas is radically different from that in isotropic media in several important details. First, at any given frequency there are two characteristic waves with two different refractive indices, n_1 and n_2, which can propagate in a simple magneto-plasma. Secondly, n_1 and n_2 are functions of direction measured with respect to the DC magnetic field.

Fig. 1, shows the X-Y^2 plane divided into regions with differing propagation characteristics. In regions of this plane where $n^2_{1,2}$ is positive, propagation of the corresponding characteristic wave is possible and vice versa; in regions where $n^2_{1,2}$ is negative ($n_{1,2}$ imaginary), the corresponding characteristic wave is cut off. The origin represents free-space conditions. Both characteristic waves propagate in regions 1, 3, 6, and 7, whereas in regions 2 and 8 only one mode can propagate, and in region 4 only the other mode can propagate. Neither mode can propagate in region 5. Furthermore, the refractive index for one of the modes becomes infinite for some direction of propagation in regions 3, 7, and 8. Under these circumstances, both the far field in some particular direction[3] and the radiation resistance of a point dipole become infinite. This author[4] has shown that assuming non-zero dimensions for the antenna will remove this *infinity catastrophe*.

Final manuscript received November 23, 1965.

ANTENNA IMPEDANCE

The theory of antenna impedance in magneto-plasmas is so involved[5] that very few, if any, useful analytic formulas are available. Electronic computers have to be used to calculate the impedance as a function of the many parameters involved. The important parameters include the antenna dimensions, antenna orientation with respect to the magnetic field, the operating frequency, and the plasma parameters such as plasma frequency, gyrofrequency, and collision frequency. Because of this situation, only preliminary and limited calculations have been made to date concerning this new and

Fig. 1—The X-Y² plane.

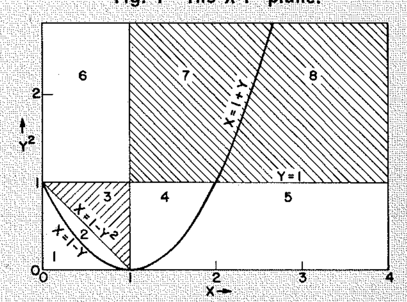
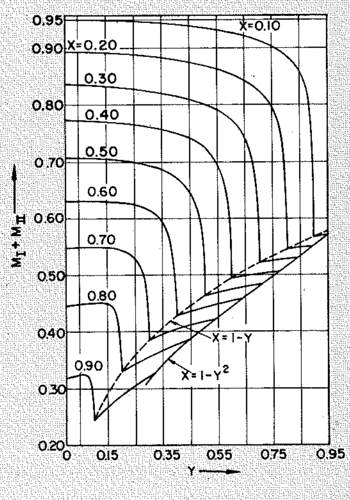
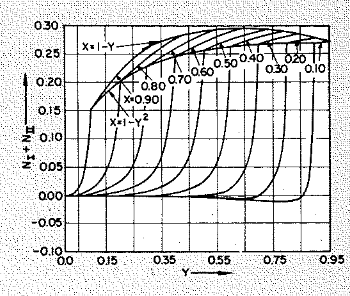


Fig. 2—Relative radiation resistance parameters for an electric dipole: a) $M_1 + M_2$ vs Y, and b) $N_1 + N_2$ vs Y.



(a)



(b)

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important area of research. The theory and calculations of the impedance of a linear dipole in the parameter range defined as region 8 in Fig. 1 have been described in a previous paper[4]. This region corresponds to VLF frequencies in the earth's ionosphere; it is of particular interest because it is well known experimentally[9] (the *whistler* phenomenon) that these frequencies not only can propagate in the ionosphere but can also penetrate the earth-ionosphere boundary and reach the surface of the earth. One of the major motivations for the work reported in reference 4 was to see whether or not it was feasible to excite this *whistler* mode with an antenna immersed in the ionosphere. Because of the complexity already alluded to, only a limited number of calculations were made (Tables I, II).

In regions of Fig. 1 where the *infinity catastrophe* does not occur, one can calculate the radiation resistance of a point dipole. Such calculations were reported by Weil and Walsh for both an electric dipole[6] and a magnetic dipole[7]. It should be noted that the radiation resistance of even point dipoles depends not only on the plasma parameters but also on the orientation of the antenna with respect to the magnetic field. The angular dependence can be expressed through the relation $R_A = M + N \cos 2\psi$ where R_A is the dipole antenna resistance and ψ is the angle between the dipole direction and the magnetic field. The quantities M and N depend on the ionospheric parameters, i.e., the magnetic field and the electron density. Calculations for electric and magnetic dipoles (loop antennas) are presented in Figs. 2 and 3.

Actually, the parameters M and N can be subdivided into two parts (e.g., $M = M_1 + M_2$) with the subscripts 1 and 2 designating the two different modes that can exist: the ordinary and the extraordinary. Thus, the relative power radiated into mode 1 is given by $M_1 + N_1 \cos 2\psi$, whereas the relative power radiated into mode 2 is given by $M_2 + M_2 \cos 2\psi$. Details are given in references 6 and 7. A comparison of magnetic and electric dipole radiation resistances, although generally similar in nature, shows significant differences. For example, in the case of the isotropic plasma ($Y = 0$) the radiation resistance varies as $(1 - X)^{1/2}$ for the electric dipole but as $(1 - X)^{3/2}$ for the magnetic dipole when $X \leq 1$. Consequently, the derivative with respect to X, as $X \rightarrow 1$ from the left, is infinite for the electric dipole but zero for the magnetic dipole. Thus, for the electric dipole the condition $X = 1$ when $Y = 0$ is sharply defined by a radical change in its radiation resistance. For the magnetic dipole, this condition is not nearly so sharply defined. When $Y \neq 0$, the equations become more complicated; however, Weil and Walsh[7] have shown that here, too, the radiation resistance of the electric dipole changes much more radically at $X = 1 - Y$ than does the magnetic dipole. Thus, it appears that the electric dipole would be a much more sensitive probe of plasma parameters, but the magnetic dipole may be a more desirable transducer for transmission or reception of radio signals because it is less sensitive to the local environment. It should be noted that this discussion applies to frequencies around $X = 1$ which is at MF or low HF. This discussion does not apply to UHF or microwaves.

TABLE I—Antenna Impedance when Dipole is Aligned with Magnetic Field

$f = 5$ kHz $\quad f_B = 1.4$ MHz

$f_p = 9$ MHz $\quad \nu = 0$

MKS units throughout

Radiation Resistance

w \ l	3×10^{-2}	3×10^{-1}	3	30	300
3×10^{-2}	0.09	9.4	816	2.5×10^3	280
3×10^{-1}		9×10^{-3}	0.94	82	245

Reactance

w \ l	3×10^{-2}	3×10^{-1}	3	30	300
3×10^{-2}	+6.2	+78	$+2 \times 10^3$	$+6 \times 10^3$	$+2 \times 10^3$
3×10^{-1}		+0.6	+7.0	+162	+380

TABLE II—Antenna Resistance when Dipole is Perpendicular to Magnetic Field

$f = 5$ kHz $\quad f_B = 1.4$ MHz

$f_p = 9$ MHz $\quad \nu = 0$

MKS units throughout

w \ l	3×10^{-2}	3×10^{-1}	3	30	300
3×10^{-2}	1.5×10^3	5×10^2	94	14	3
3×10^{-1}		150	50	9.4	2.7

THE RADIATION FIELD AND ANTENNA PATTERN

To understand the very complicated far-field patterns that can result in magneto-plasmas, it is desirable to begin with a discussion of dispersion and the relation between wave-normal direction and ray direction. Dispersion refers to the relation between the propagation constant, k, the frequency of propagation, $\omega/2\pi$, and direction (α,β) with respect to a given coordinate system. In magneto-plasmas, the DC magnetic field is usually taken to be along the z-axis. With this orientation of the coordinate system and at an assumed constant frequency, the propagation constant, k, becomes a function of the polar angle, α, and is independent of the azimuthal angle, β. Each of the possible modes (ordinary and extraordinary) can then be represented by the relations $k_1(\alpha)$ and $k_2(\alpha)$. Either or both of the modes can be real or imaginary functions of α. When real, these dispersion relations can be plotted on a polar diagram. Two general types should be distinguished (Fig. 4). Either of the two modes can be of either general type.

The figure of $k(\alpha)$ versus α on the polar diagram must be symmetrical

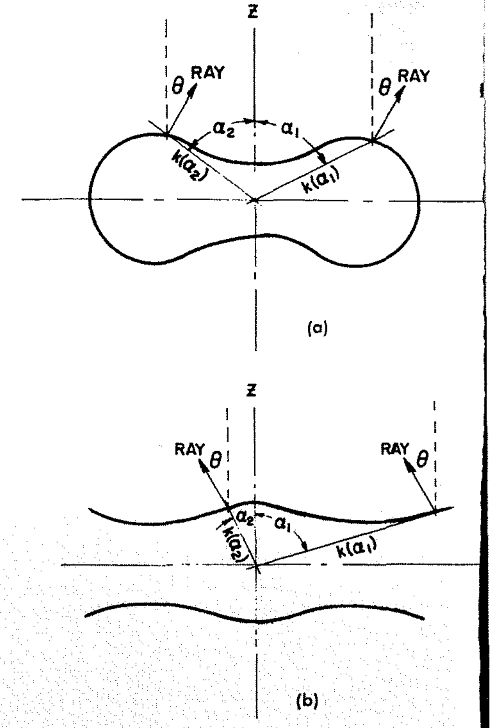


Fig. 4—The two general classes of dispersion curves in magneto-plasmas: a) closed surface, and b) two-branched open surface.

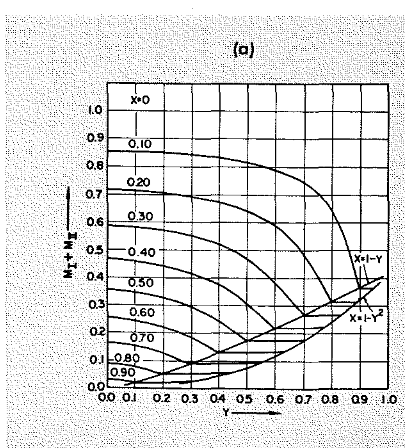
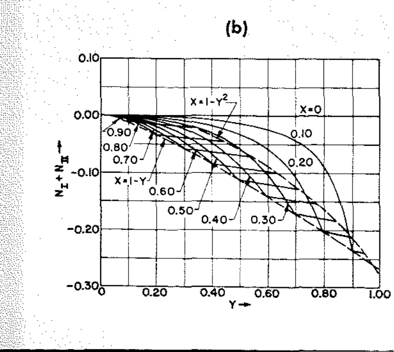


Fig. 3—Relative radiation resistance parameters for a magnetic dipole (loop antenna): a) $M_1 + M_2$ vs Y, and b) $N_1 + N_2$ vs Y.



with respect to both the z-axis and the x-y plane. Fig. 4(a) shows a closed surface, and Fig. 4(b) shows a two-branched open surface. In the second case, of course, $k \rightarrow \infty$ for some particular direction α. For isotropic media, the dispersion curve would be a circle, i.e., k would be the same in all directions. It can be shown that the direction of ray (or energy) travel is perpendicular to the dispersion curve. Fig. 4(a) shows that in a given direction θ (with respect to the magnetic field) from a source, there are two rays traveling. Each of these rays will locally look like a plane wave, but the wave normal will not be along the ray. Instead, one wave normal will be along the direction α_1 and the other along α_2. The propagation constants would be $k(\alpha_1)$ and $k(\alpha_2)$, respectively. The same general situation holds for Fig. 4(b); however, two very interesting characteristics of the two-branched dispersion curve are shown in this figure. First, not all directions, θ, are possible directions along which rays (energy) can travel. It should be clear from Fig. 4(b) that it is not possible to propagate energy close to the direction transverse to the magnetic field (i.e., $\theta = \pi/2$). This is the type of dispersion curve that applies to *whistler* frequencies in the ionosphere, and in that particular case the propagating energy is confined within a cone of about 20° from the magnetic field, the apex of the cone being at the source. The second distinctive feature of the open-branched dispersion curve is that for point dipole sources, one seems to get infinitely far fields in the direction where $k(\alpha) \rightarrow \infty$. (The direction along which $k = \infty$ is referred to as the resonant direction.) As mentioned previously, this *infinity catastrophe* is a mathematical difficulty only. The infinity disappears as soon as one considers dipoles of non-zero dimensions. It must be admitted, however, that for reasonable-sized dipoles at sufficiently low frequencies, the fields can be extremely high near the resonant direction. In isotropic media where the dispersion curve is a circle, θ is identical with α and the energy travels along the wave normal.

This discussion was designed to emphasize three salient points:

1) There are, in general, two modes which must be considered in magneto-plasma propagation.
2) Each mode may give rise to several rays traveling in a given direction, each ray having a different wave-normal direction.
3) The fields may become infinite when considering point dipole sources.

It should, therefore, be understandable why the far-field antenna pattern should be extremely complicated to present. In fact, because of the multiplicity of rays that may be propagating, the far-field power flow may not be radially out from the source. This possibility suggests that receiving antennas should not necessarily be pointed toward the source to get maximum signal. It may be interesting to examine some of the complicated antenna patterns presented by Arbel and Felsen[8].

Luckily, there is one region of ionospheric parameters in which the far-field pattern description becomes reasonably tractable. That occurs under the assumption that the DC magnetic field approaches infinity. The results are presumably valid when $Y^2 >> \max(X,1)$, where $\max(X,1)$ stands for the larger of the two quantities, X and 1. This, unfortunately, is not the case for *whistlers* in the ionosphere; the parametric region for *whistlers* is described by $X > Y^2 >> 1$.

Returning to the case of the infinite magnetic field, Kuehl has shown that the antenna pattern for a point dipole in the x-direction (remembering that the magnetic field is in the z-direction) is given by

$$\Phi = \sin^2 \varphi + \frac{(1-X)^2 \cos^2 \varphi \cos^2 \theta}{(1 - X \sin^2 \theta)^{3/2}}$$

and the pattern for a point dipole directed along the magneto-static field is given by

$$\Phi = \frac{\sin^2 \theta}{(1 - X \sin^2 \theta)^{5/2}}$$

For $X < 1$, the antenna patterns are well behaved, and a plot of these is shown in Fig. 5. However, for $X > 1$, the power flux density becomes infinite at that angle for which the $\sin \theta = 1/\sqrt{X}$. This writer's work shows that when dipoles of non-zero dimensions are considered, the far-field pattern for the x-directed dipole becomes (approximately)

$$\Phi = \sin^2 \varphi + \frac{(1-X)^2 \cos^2 \varphi \cos^2 \theta}{(1 - X \sin^2 \theta)^{5/2}} A^{-4}$$

$$A = 1 + k_o^2 \times \frac{w^2 \cos^2 \theta + (1-X)^2 \sin^2 \theta \, (w^2 \sin^2 \varphi + l^2 \cos^2 \varphi)}{1 - X \sin^2 \theta}$$

whereas for the z-directed dipole, $\Phi =$

$$\frac{\sin^2 \theta}{(1 - X \sin^2 \theta)^{5/2} \left[1 + \frac{k_o^2 \, l^2 \cos^2 \theta}{1 - X \sin^2 \theta} \right]^4}$$

In the above, $k_o = 2\pi/$free space wave length, while w is the half-width and l is the half-length of the antenna. While the above functions are never infinite, they can be very large indeed. It should be explicitly noted that the power patterns given above are valid for $0 \leq \sin \theta \leq 1/\sqrt{X}$ and are identically 0 for for larger angles.

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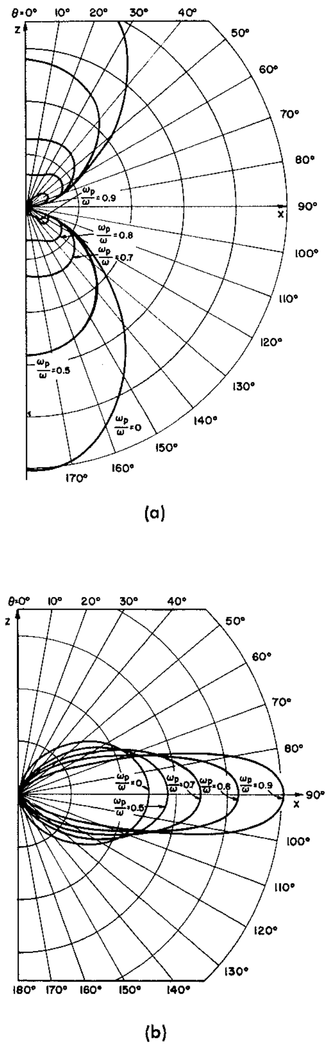

Fig. 5—Time average Poynting vectors in the half plane $\phi = 0$: a) for an x-directed dipole and infinite magnetostatic field, and b) for a z-directed dipole with $\omega_p/\omega < 1$ and an infinite magnetostatic field.

ARMY AUTOMATIC TEST EQUIPMENT: CURRENT STATUS

A Progression of Automatic Test Equipment Design

O. T. CARVER and D. B. DOBSON

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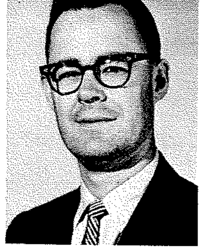
The automatic test equipment briefly described and pictured in this article evolved from earlier test systems developed for the Army and described in RCA Engineer, Volume 8, Number 2, August-September 1962. Refer to that issue and to *Computer-Controlled Automatic Testing—A Review* by B. T. Joyce and E. M. Stockton, Volume 10, Number 5, February-March 1965 for coverage of design work leading to the systems described in this article.

O. T. Carver



D. B. Dobson

Editor's Note: Since the subject of Army Automatic Test Equipment has been the topic for previous papers published in the RCA Engineer, the author engineers O. T. Carver and D. B. Dobson volunteered to provide our readers with the brief pictorial review contained herein. Both authors have been frequent contributors to the RCA Engineer since its inception in 1955. In addition to these efforts, David Dobson, RCA Engineer Editorial Representative, served as coordinator in planning this issue.

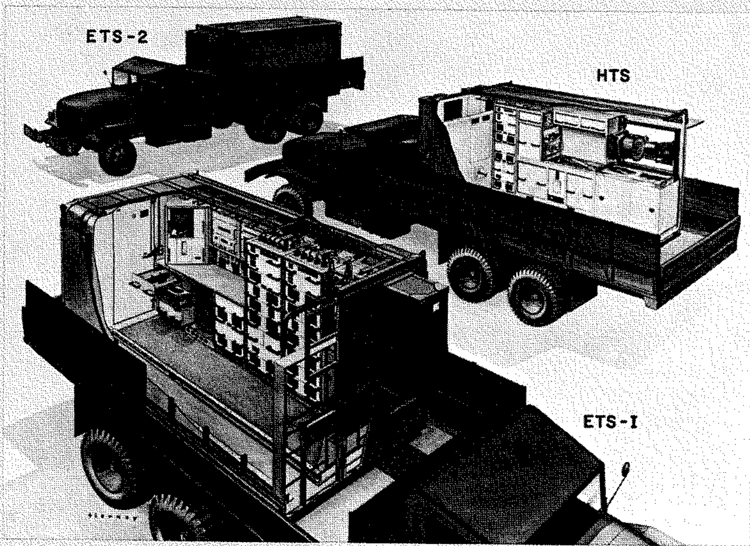


Fig. 1—The MTE (Multisystem Test Equipment) Developmental Model, consisting of Electronic Test Set No. 1 (ETS-1), Electronic Test Set No. 2 (ETS-2), and the Hydraulic Test Set (HTS), culminated a 2-year development program started in 1962. The MTE system is designed to provide field maintenance support for complex missile systems. The division of work load and the ranges of stimuli and measurements were determined by a study of the test requirements of a number of Army missile systems. The complexity of missile microwave and hydraulics equipment dictated the development of three independently operated test sets, with portions of each set duplicated in the other two sets.

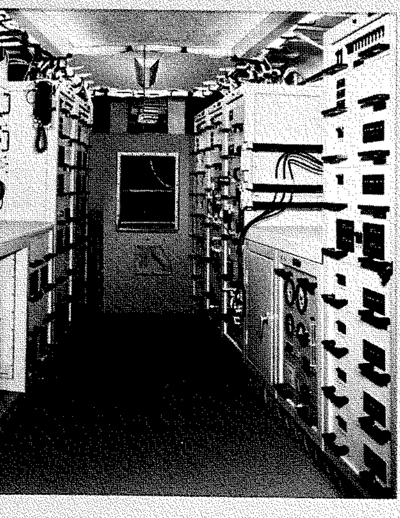


Fig. 2—ETS-2 is used for testing microwave units. The unit is placed on the work surface of the operator control console (shown at the left) and is connected to the test set.

Final manuscript received September 1, 1965

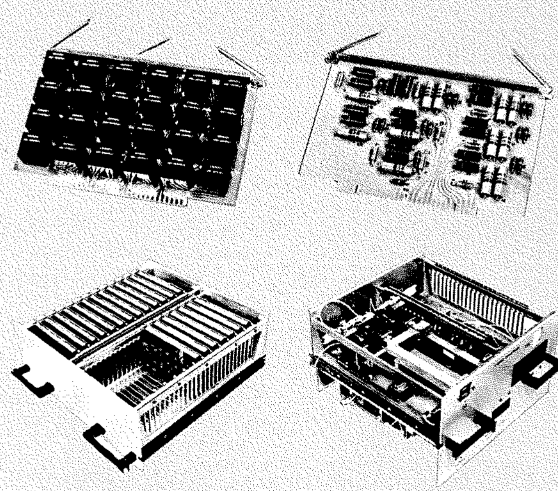


Fig. 3—Each test equipment consists of *building-block* assemblies. The assemblies are composed of solid-state components on standardized boards and special components mounted on specialized boards. Standard and specialized chassis, all to the same form factor, fit into standard racks. The flexibility of this design permits the reconfiguration necessary to accommodate new test requirements.

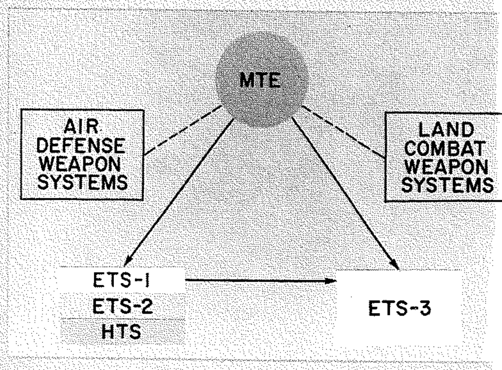


Fig. 4—The division of Army weapon systems into air defense and land combat systems made necessary another category of equipment, Land Combat Support Systems (LCSS), to handle the Shillelagh, Lance, and TOW missiles. These missile systems do not contain microwave or hydraulic units but do include electro-optical equipment. The test system configuration for LCSS is called Electronic Test Set No. 3 (ETS-3).

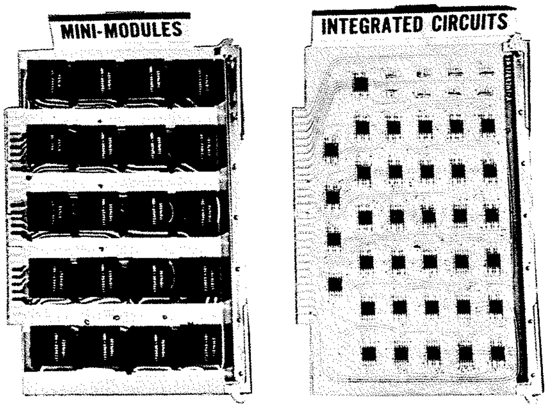
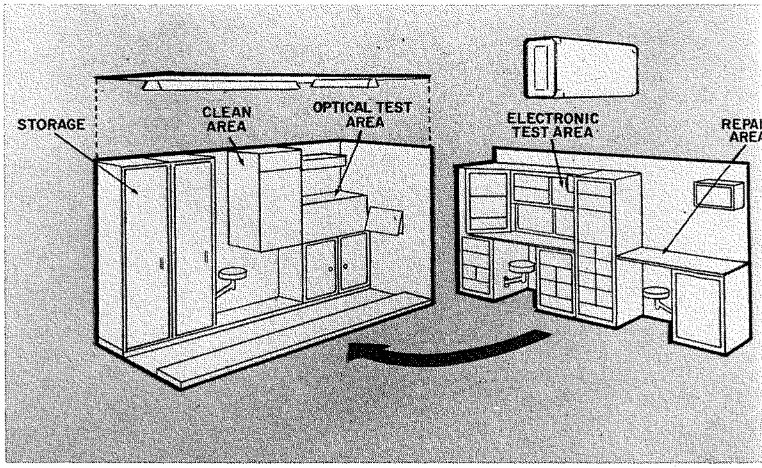


Fig. 5—Integrated circuits will replace the present transistorized minimodules for all digital functions. Although the integrated circuits will be mounted on standard MTE boards, the use of integrated circuits will reduce the number of assemblies required for ETS-3 from 19 to 9.5.

Fig. 6—ETS-3 consists of Electronic Test Group 3, a generator, and associated cables, and is housed in a shelter which may be transported by truck or helicopter. The shelter contains two test stations and one repair station. A perforated tape input controller commands the stimulus and measurement subsystem and evaluates measured values. Adapters under programmed control stimulate optical detectors and measure the characteristics of optical radiators.



ig. 7—RCA started construction of the DIMATE (Depot Installed Mainteance Automatic Test Equipment) in June 1962. DIMATE, now installed at obyhanna, Pennsylvania Army Depot, far exceeds the overall capability f the earlier DEE (Digital Evaluation Equipment), which RCA installed at obyhanna in 1961 (shown at top right).

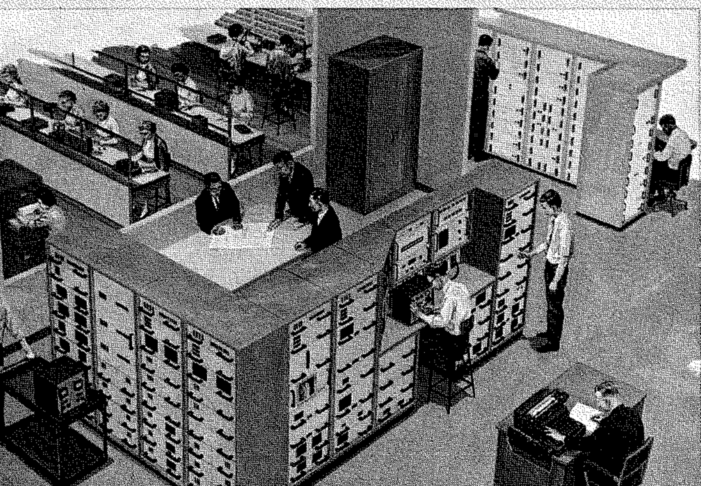


Fig. 8—The detector-adapter used to test infrared (IR) detectors, supplies calibrated; collimated IR energy whose characteristics are controlled by programmed commands. A source adapter operates as an electrical-optical transducer for the radiating unit under test (UUT).

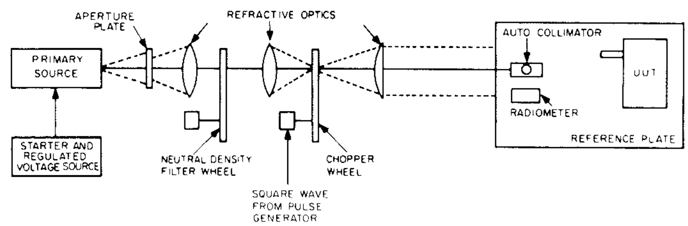
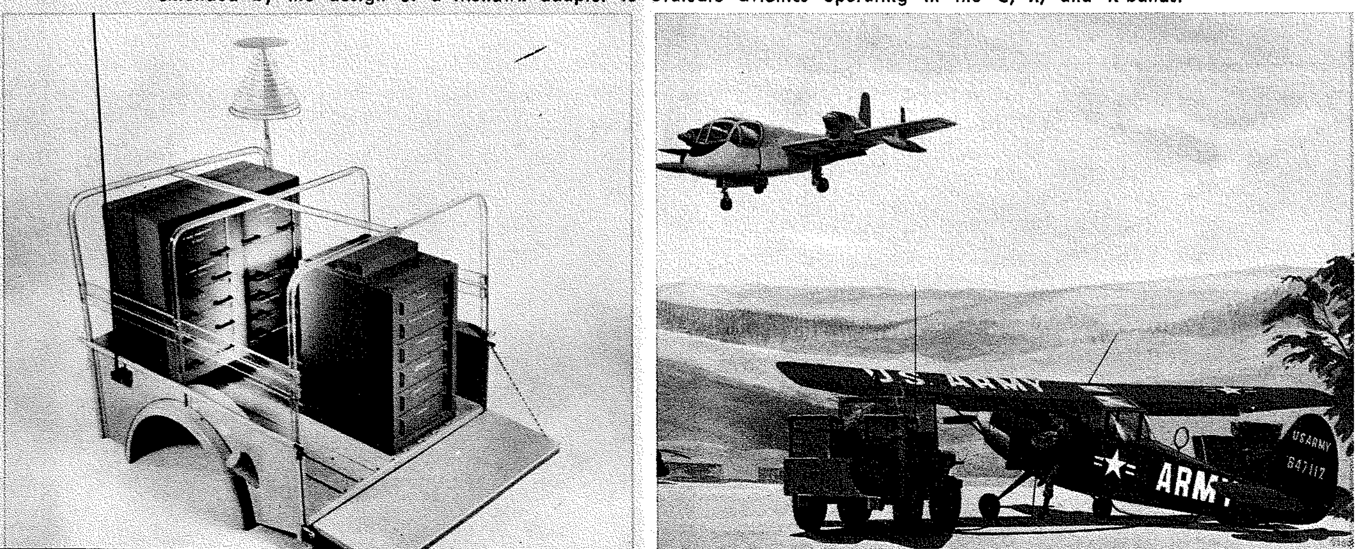


Fig. 9—The latest version of the Preflight Test Set, now known as the AN/ASM-88, is shown in model form and as the artist visualized its use in checking out avionics on an Army aircraft. (See article by Mergner, RCA Engineer, Volume 8, Number 2.) Four units have undergone field evaluation trials, and capability has been extended by the design of a Mohawk adapter to evaluate avionics operating in the C, X, and K-bands.



GAIN NONLINEARITY AND BISTABLE INSTABILITY IN PARAMETRIC CONVERTERS

The subject of the large-signal operation of parametric devices has been discussed in several papers.[1-6] In most of these analyses, the actual dynamic range response has not been clearly defined with regard to the variety of possible impedance-match conditions. This peculiar property of coupled nonlinear circuits yields impedances which are functions of the power levels at which the device operates relative to the maximum achievable output power. In addition, a bistable operation condition might occur, where the output would switch between two possible power levels. This bistable operating point will be shown to be a function of the relative levels of the circuit resistances. Consequently, a maximum power level to prevent relaxation will be shown to be a function of the loaded diode Q's.

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The most popular method of achieving medium power generation, with solid-state devices, at frequencies above 1 Gc/s, is to utilize the low-loss, nonlinear reactance property of varactor diodes. These diodes have been used as frequency multipliers (i.e., doublers, triplers, etc.),[1-6] low-noise amplifiers, and efficient frequency converters.

The mechanism for varactor power generation relies upon the nonlinear relation between the voltage and charge of the diode. In the case of a square-law varactor (abrupt), the voltage across the diode terminals is proportional to the square of the total applied charge, $V = Q^2 = (\int I dt)^2$. If a particular source at ω_o is connected to the varactor by means of the necessary impedance matching and filter networks, a current will be induced to flow, at $2\omega_o$. By means of filters these two currents may be isolated and thus restricted to circulate in their respective meshes.

In microwave varactor circuits, the primary loss mechanism loss is the series loss resistance of the particular diode used. Additional losses are due to filter insertion losses and reflections due to impedance mismatch. The series loss resistance is usually considerably smaller than the diode reactance at the operating frequency and, therefore, results in minimum loss between the source and the desired output.

The high-level upconverter, a three-frequency device, uses a source of power known as the pump, and a low-frequency signal source, to produce an output at the sum frequency (Fig. 1).

Several design techniques have shown,[1-5] that the conversion mechanism between the pump and sideband output may be maximized by proper choice of operating parameters. By tuning the low-level signal source, a variable frequency source of power is achieved at the sum frequency. The pump source needs no significant bandwidth for this application, and may easily be derived from the combination of a VHF transistor power source and an appropriate narrow-band, high-efficiency varactor multiplier chain.

Several interesting aspects of this device have often resulted in undesirable modes of operation. The phenomenon of gain saturation is of little significance when using the converter as a high-level, unmodulated source. The introduction of a modulated signal into the converter, operating at high conversion efficiency, would result in a distorted output, a function of the type of modulation and degree of gain-nonlinearity. The basic mechanism which creates this intermodulation distortion will be analyzed and shown to be a function of the output power and power-sensitive input impedances.

Another troublesome problem associated with these devices is due to the nonlinear stored charge.

If the proper levels of impedance, as well as bias, are not established, a bistable operating condition might result. This condition is characterized by a signal power level which results in a multivalued output. The result is a relaxation between these levels, hence instability. This problem will also be examined with regard to safe drive power levels as well as several procedures to minimize this condition.

THE CURRENT-PUMPED MODEL

It has been shown[2,5,6] that the *current-pumped, abrupt-junction* converter is characterized by a perfect square-law relationship between the diode terminal voltage and the reactive charge. Although the truly abrupt diode may appear to be a somewhat idealized model, many diodes may be found to exhibit this square-law characteristic over a large portion of their reverse voltage *C-V* characteristic. In fact, junction exponents in excess of 1/2 are conceivable, considering the recent advance in diode technology.[8,9]

The necessity of a current-pumped network, where the individual currents are independent, may be justified by considering the impossibility of truly achieving voltage pumping.[2,5] If one were to assume, for an arbitrary varactor, that the capacitance varied as a first-order function of the voltage, excluding all higher-order terms, one would derive the identical equations with respect to large-signal dynamic saturation, as with the analysis included herein. However, since the former analysis assumes voltage pumping as well as excluding higher-order nonlinearities in the initial reactance expansion, the results would not be characteristic of the physical device.

The present analysis will, therefore, assume current pumping is achieved in a particular circuit design. The square-law, abrupt-junction diode will be used as a model. However, to approximately a first order, the results may be applied to any varactor, regardless of the junction exponent.

GAIN SATURATION

The phenomenon of gain saturation in any parametric device is the result of the interaction between the pump and

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signal circuits. The pump circuit may be characterized by a coupling impedance, R_{op}, which is proportional to the signal current.[5] This effective impedance couples pump power, proportional to the signal current input to the output circuit.

Fig. 2 represents the coupling between the three circuits. The transfer (coupling) impedances are defined as:

$$R_{op} = \frac{m_1^2\, \omega_c^2\, R_s^2}{\omega_i\, \omega_p\, R_{Ti}} \qquad (1)$$

$$R_{os} = \frac{m_2^2\, \omega_c\, R_s^2}{\omega_s\, \omega_i\, R_{Ti}} \qquad (2)$$

In the above:

$$R_{Ti} = R_L + R_s + R_{ci} \qquad (3)$$

where R_L = idler load, R_s = diode loss, and R_{ci} = other idler losses. Also:

$$m_1 = \frac{i_s}{Q_m \quad \omega_s}$$

$$m_2 = \frac{i_p}{Q_m \quad \omega_p}$$

Eq. 3 represents the normalized currents (signal and pump) referred to the maximum diode charge Q_m and their respective frequencies.

As the signal power increases, the normalized current m_1 increases, resulting in a power sensitive variation in R_{op}. The resulting change in m_2 effects a change in R_{os}, the signal-to-idler transfer impedance, as seen in Eq. 1. Eq. 4 represents the current gain between the signal current i_s and the idler i_o:

$$\frac{i_o}{i_s} = \frac{m_2\, S_m}{\omega_s\, R_{Ti}} = K_o\, i_p, \qquad (4)$$

where K_o represents a normalized small signal-gain, with respect to i_p. The cumulative effect of detuning R_{os} with respect to a constant source impedance results in a nonlinear rise of m_1 with increasing signal power. For small signals, m_2 $(\sim i_p)$ remains constant, whereas large signals result in a variation in m_2 (i_p) as indicated by Eq. 5. This effect results in a decrease in the conversion gain between signal and idler circuits as power is increased.

The variation of m_2^2 with sideband power is represented by Eq. 5.

$$m_2^2 = \frac{P_p\, R_{gp}}{R^2_{Tp}\, Q^2_m\, \omega^2_p} \Psi \qquad (5)$$

where:

$$\Psi = 1 - \frac{1}{2}\,\frac{P_o}{P_{om}} \pm \sqrt{1 - \left(\frac{P_o}{P_{om}}\right)} \qquad (6)$$

The term Ψ represents the nonlinearity in the variation of m_2^2 with output power. The output P_o has been normalized to the maximum attainable output power P_{om} (maximum operating efficiency) where:

$$P_{om} = P_p\left(\frac{\omega_3}{\omega_2}\right)\left(\frac{1}{1+\varepsilon_p}\right)\left(\frac{1}{1+\varepsilon_i}\right) \qquad (7)$$

$$\varepsilon_p = \frac{R_s + R_{cp}}{R_{gp}} \qquad \varepsilon_i = \frac{R_s + R_{ci}}{R_L} \qquad (8)$$

The terms R_{cp} and R_{ci} represent pump and output circuit losses.

When the device is operating, saturated, at maximum output (P_{om}), the term m_2 assumes its smallest value m_{2m}. Fig. 3 demonstrates the variation of m_2^2 normalized to m_{2m}^2 as the output power ratio P_o/P_{om} is varied. It is readily seen that the small signal value of m_2^2 (which may be referred to as m_{2s}^2) is four times the large signal value m_{2m}^2, corresponding to P_{om}. This variation in m_2^2 with output power is the cause of the variation of the input transfer impedance R_{os}, and consequently results in a saturation of the signal conversion gain.

In the case of an upper sideband converter, the output power P_o at ω_i may be written as:

$$\frac{P_o}{P_S} = 4\left(\frac{P_{om}}{P_{Sm}}\right)\left(\frac{y}{(1+y)^2}\right) \qquad (9)$$

$$\frac{P_S}{P_{Sm}} = \left(\frac{P_o}{P_{om}}\right)\left(\frac{(1+y)^2}{4y}\right) \qquad (10)$$

where P_{sm} = signal power P_s at ω_s to give output P_{om} at ω_i, and where:

$$y = \frac{R_{os}}{R_{Ts}}$$

$$= \frac{\textit{(input signal transfer impedance)}}{\textit{circuit impedance at } \omega_s} \qquad (11)$$

$$= 2\,\Psi\,\frac{m_{2m}^2\, R_s^2\, \omega_c^2}{R_{Ts}\, R_{Ti}\, \omega_s\, \omega_i}$$

It may readily be seen that the match condition for maximum efficiency requires $y \rightarrow 1$, regardless of power level. Since y is an active function of input power, variable matching networks must be provided to control the necessary variables in order to maintain an impedance match if ultralinear performance is desired. For two or more signals at different power levels, saturation effects cause intermodulation distortion, since linearity can only be achieved with respect to one signal. Fig. 4 demonstrates the gain-saturation characteristics obtained by specifying a variety of match conditions. The ranges indicated represent the power levels for which the device was matched. A comprehensive study of the amount of intermodulation distortion characteristic of these devices has been performed.[11] (See ref. 11, at end.)

A value of the saturation variable Ψ has been computed for a particular normalized efficiency P_o/P_{om} using Eq. 6. The impedance R_{Ts} is adjusted to provide an impedance match for a particular power level. Since m_2^2 determines the impedance level at a particular power output, assuming the load impedance is held constant, the input

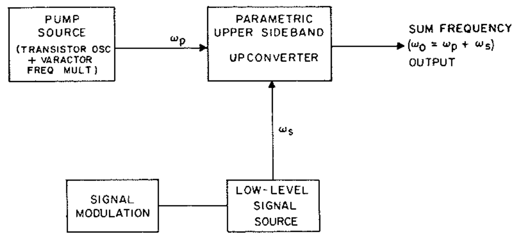


Fig. 1—Solid state parametric varactor upconverter.

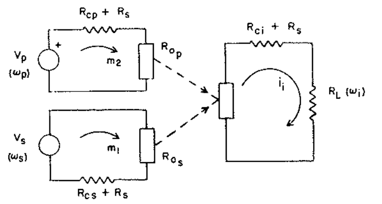
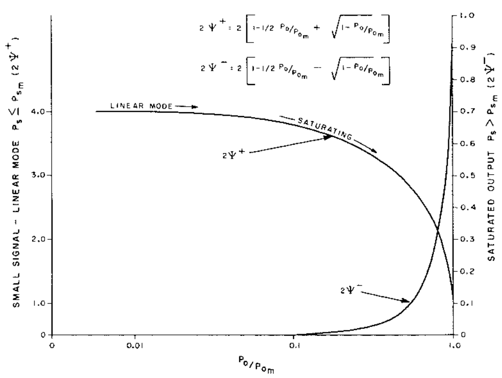


Fig. 2—Coupled parametric circuits.

Fig. 3—Saturation variable $m_2^2/m_{2m}^2 = 2\,\Psi$ as a function of output power.



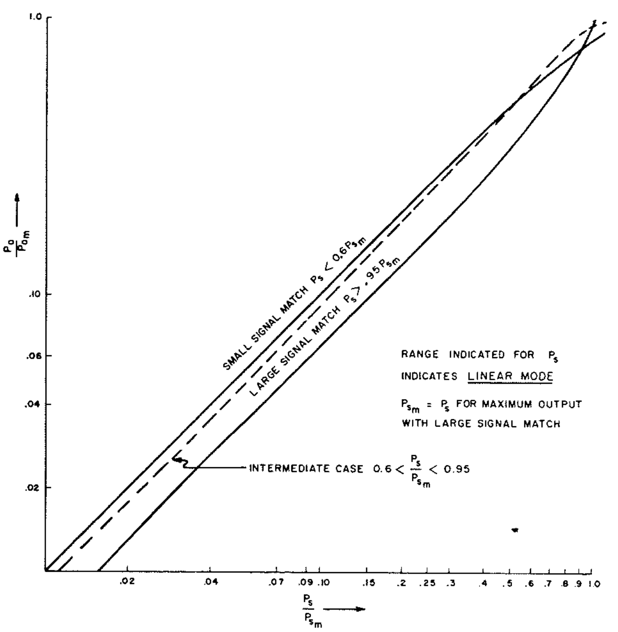


Fig. 4—Nonlinear power saturation due to variation in primary transfer impedance match with output power.

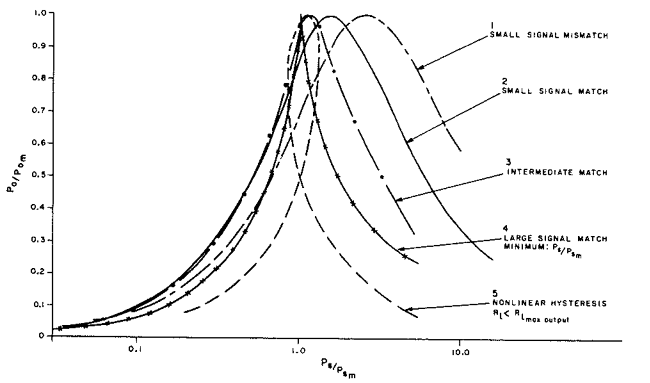


Fig. 5—Complete nonlinear saturation due to impedance mismatch in signal circuit.

impedance will vary from a nominal value R_{Ts}' ($y = 1$) to 1/4 R_{Ts}' as the signal is increased to a maximum. Likewise, if a match is maintained at P_{om}, the impedance varies from R_{Ts}'' corresponding to $y = 1$, to 4 R_{Ts}', as the signal output is decreased to small signal levels.

For small signal operation: Linear operation, ($y = 1$) corresponding to Eqs. 5 and 11.

$$y = \frac{m_2^2}{m_S^2} = \frac{1}{2}\Psi \qquad (12)$$

For a large signal match: High conversion efficiency, $y = 1$,

$$y = \frac{m_2^2}{m_{2m}^2} = 2\,\Psi \qquad (13)$$

For an intermediate tuning condition (arbitrary),

$$y = \frac{m_2^2}{m_{2I}^2} = \Psi \qquad (14)$$

Solving these equations for y as P_o/P_{om} is varied enables one to obtain P_S/P_{Sm} from Eq. 10. This data is used to plot Figs. 4 and 5. If the number of diodes is increased, P_{om} and P_{sm} are increased accordingly, the amount of non-linearity for a particular output power is thereby decreased by use of multiple diode networks.

CRITERIA FOR RELAXATION PHENOMENA —BISTABLE MODE

In order to demonstrate possible instabilities, characteristic of nonlinear devices as characterized by the so-called *Duffing Equation*,[10] the parameter y is set equal to a quantity greater than 2Ψ. Fig. 5 demonstrates the condition $y = 4\Psi$ which would result if R_{Ti} were reduced to 1/2 the level corresponding to $y = 2\Psi$. The looping effect shown indicates the possibility of a multivalued output or bistable condition where the output power will "relax" between two levels. In addition, the output power resulting from an increasing input level will not be the same as the output resulting from a decreasing input due to hysteresis.

The condition corresponding to a maximum output match, curve 4, is characterized by a minimum value of $P_S/P_{Sm} = 1$, which is defined at this point. This curve possesses a saddle point at its peak. This condition would result in an output power which was very sensitive to changes in signal level and function of all the circuit parameters. By sacrificing some input signal circuit efficiency with a minor degree of real impedance detuning, the maximum output condition may be attained with a minimum amount of peak output drift. These results are shown in Fig. 5 where the change in characteristic from curve 4 to curve 1 corresponds to a continuously decreasing input source impedance. Curve 1 is an example of the case where the input source impedance is adjusted to be twice its small signal match value.

From Eq. 11, in order to prevent an unstable mode, the following quantity should always be less than unity.

$$\frac{m_{2m}^2 R_S^2 \omega_c^2}{R_{Ts} R_{Ti} \omega_s \omega_i} \leq 1$$

The maximum value for the function occurs at a large signal match, curve 4, where it is equal to unity. As has already been indicated, the curves 4, 3, 2, and 1 correspond to $y = 1$ for decreasing input power levels. The above variable is effectively decreasing due to an increasing level for R_{Ts} required to maintain a match condition at the reduced levels. For instability to occur (curve 5), the indicated variable must be greater than unity. The threshold condition may be represented as:

$$\frac{m_{2m}^2 R_S^2 \omega_c}{\omega_s \omega_i R_{Ts} R_{Ti}} = 1 \qquad (15)$$

This corresponds to the condition where the device is tuned for $P_s/P_{sm} = 1$ (high efficiency conversion in all circuits).

In general, substituting for m_{2m}^2 in Eq. 15,

$$\frac{1}{8}\frac{P_p}{P_N}\left(\frac{\omega_c^4}{\omega_s \omega_p^2 \omega_i}\right)\left(\frac{R_S^3 R_{gp}}{R_{Ts} R_{Ti} R_{Tp}^2}\right) \leq 1 \qquad (16)$$

$$P_N = \frac{V_B^2}{R_S}$$

After minimizing losses, a conservative estimate of the maximum allowable pump power before instability (maximum pump power to prevent oscillation for high level tuning) becomes:

$$\overline{P_{pm}} = 8\,P_N \left(\frac{\omega_s\,\omega_i\,\omega_p^2}{\omega_c^4}\right) \left(\frac{R_{gs}\,R_{gp}\,R_L}{R_s^3}\right) \quad (17)$$

$$= 8\,P_N \left(\frac{1}{Q_p\,Q_{pL}\,Q_{sL}\,Q_{iL}}\right) \quad (18)$$

But:

$$Q_p = \frac{\omega_c}{\omega_p} \qquad Q_{pi} = \frac{\omega_c}{\omega_i}\,\frac{R_s}{R_{gi}} \quad (19)$$

$$Q_{pL} = \frac{\omega_c}{\omega_p}\,\frac{R_s}{R_{gp}} \qquad Q_{ps} = \frac{\omega_c}{\omega_s}\,\frac{R_s}{R_{gs}}$$

Or:

$$\overline{P}_{pm} = \left[8\,V_B^2\,C^2_{min}\,(R_{gs}\,R_{gp}\,R_L)\,(\omega_s\,\omega_i\,\omega_p^2)\right] \times 10^{-12} \quad (20)$$

where C_{min} is in pF, ω's are in Gc/s. For example, let $V_B = 100$ volts, $(R_{g1}\,R_{g2}\,R_L) = 1.25 \times 10^5$ (50 ohms each), $C_{min} = 1$ pF, and $\omega_1\,\omega_2^2\,\omega_3 = 70$, then $\overline{P_{pm}} = 0.875$ watts per diode.

To prevent relaxation oscillations while maintaining a near match at large signal levels, the circuit impedance must be made sufficiently high. In addition, the operating signal frequency should not be too far removed from the pump frequency (high Manley-Rowe gain), in order to operate at optimized high power levels for a given diode, V_B and C_{min}. For the example shown, the diode characteristics are nominal, with 50 circuits, excluding losses. With increasing circuit loss, the acceptable operating level P_{pm} would be correspondingly increased.

Mismatching the input circuit will increase the threshold power P_{pm} by a factor equal to the amount R_{Ts} is decreased corresponding to the condition $\gamma = 1$. For instance, if the device is tuned at small signal levels, $R_{Ts}' = 4\,R_{Ts}''$ (maximum output), $P_{pm}' = 4\,\overline{P_{pm}''}$; $P_s/P_{sm} > 1$. The dynamic range is thus extended, regarding instabilities, by sacrificing input-signal circuit efficiency at the low IF frequencies in favor of high power conversion between the pump source and output upper sideband. It must be emphasized that the lower sideband must be effectively suppressed by the appropriate filter networks.

The use of multiple diode structures would enable the device to handle large powers while maintaining a reasonably high conversion efficiency (C_{min}) is minimized for power conversion applications, with a minimum amount of instability. Assuming balanced networks are used, each diode shares the total power equally, thereby increasing the operating level of P_{pm} to $N\,P_{pm}$, where N is the number of diodes. These structures are also characterized (i.e., push-pull configuration) by a large degree of isolation between the pump and output ports, reducing the need for loss of filter networks, especially when the frequency separation is quite small.

CONCLUSION

The varactor diode may be used to convert power efficiently from one frequency to another. The nonlinearity associated with the process of gain saturation gives rise to intermodulation distortion products in the output, their relative magnitude being a function of the relative output P_o/P_{om}. The amount of distortion present may be found as a function of the nonlinearity of the operating point. Since the varactor converter is capable of higher drive powers (i.e. pump) compared with resistive devices, the amount of distortion for comparable outputs is far less for the reactive converter. The use of multiple diode structures does not altar the shape of the gain curve; however, the maximum output is extended proportional to the number of diodes used. Hence, the relative operating power level for each diode is similarly reduced, resulting in a decrease in nonlinearity associated with each individual diode (i.e. when the combined power output is equal to that power achievable from *one* diode).

The nonlinear charge associated with this device, permits the possibility of a bistable operating condition. As a power source, the converter is required to be stable, and thus all forms of instability must be avoided. It is shown that proper choice of impedances, bias voltages, and diode configuration (number of varactors), eliminates the problem of relaxation oscillations.

ACKNOWLEDGEMENT

The author is grateful for the technical assistance rendered by his Group Leader, B. B. Bossard, in the writing of the paper. In addition he would like to thank Stuart Perlow for his aid in the performance of the laboratory experiments which confirmed the operating characteristics of the device discussed in the paper.

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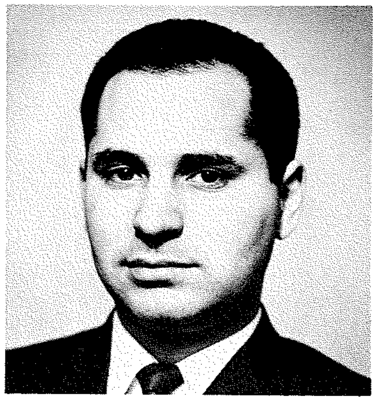

B. S. PERLMAN received his BEE degree from CCNY in 1961, and an MSEE degree from the Polytechnic Institute of Brooklyn in 1964. In 1961, he joined RCA as a specialized trainee in DEP Applied Research where he was introduced to concepts of signal processing. Later in 1961, at Moorestown and Burlington, he worked on radar receivers, and parametric amplifiers. Then in late 1961 he moved to the DEP-CSD Systems Laboratory in New York where work was continued in the development of active, low-noise and broadband reactive devices. He developed several high-power varactor devices, among which was a 5-Gc/s converter with 50% efficiency for use in all-solid-state relay equipment. In 1963, Mr. Perlman studied various aspects of lasers at the RCA Laboratories, and returned to New York to develop a laser communication system; of primary interest was the development of efficient optical modulators. He has recently been concerned with intermodulation distortion in amplifiers, the development of broadband reactance devices, and a comprehensive study of parametric circuits. Mr. Perlman has published numerous papers related to his work and has several patent disclosures; he is a member of IEEE, IEEE G-MTT and NYSSPE.

AUTOMATIC CHECKOUT AND MONITORING OF LARGE COMPLEX SYSTEMS

Techniques are described for automatic checkout and monitoring whereby equipment faults may be isolated down to the smallest removable assembly level. All checkout and monitoring functions are performed by commands from the system computer which also evaluates the test results obtained. Experimental checkout and monitoring equipment is discussed. This equipment was constructed as part of a phased-array radar development program to make phase and amplitude measurements on receivers and to simulate target error signals for evaluating system performance. A phase detector developed as part of this program is described.

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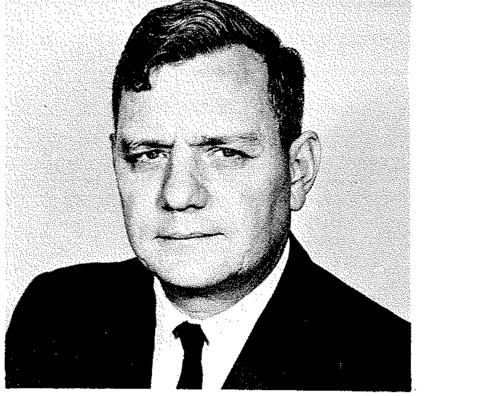


HERBERT BROCKMAN received his BS in Electrical Engineering from the University of Maryland in 1950. He worked on display and display-control equipment for airborne fire-control radar at Westinghouse prior to joining RCA in 1959. He has specialized primarily in the design of automatic checkout and monitoring equipment for radar systems at RCA. He was Design Project Engineer on the checkout target simulator and system signal simulator equipment used for automatic checkout and monitoring of BMEWS. He was also responsible for the design and development of prototype automatic monitoring equipment for the Terrier radar in a program aimed at improving system **up** time. During the past 18 months he has been assigned to the SAM-D program, where he has been responsible for system concepts and evaluation of hardware developed to demonstrate feasibility of automatic checkout equipment for large systems.

With the trend toward more sophisticated radar and communications systems, built-in checkout and monitoring (CAM) equipment has become essential for maintaining equipment and minimizing system *down* time.[1]

This paper describes techniques that help automate the CAM functions so that faults can be isolated down to the smallest removable assembly or module level automatically. In this way semiskilled technicians can maintain the equipment simply by replacing defective modules, thus minimizing system *down* time.

DESIGN APPROACH

The basic functions required in any automatic monitoring system are as follows:

1) Establish appropriate timing of signal monitoring which does not interfere with normal system operation.
2) Generate appropriate test signals to stimulate the circuit to be monitored.
3) Select the signal to be monitored and provide isolation between the monitoring circuit and the signal output.
4) Evaluate test results of signals monitored and set threshold for out-of-tolerance condition on each signal.
5) Provide visual identication of faults located.

In large complex systems, these functions are most easily performed by using the system's computers.[2] The computer actively controls the sequence of events in the entire system, and performs system computations in such a way that the CAM functions are simply an extension of its normal system duties.

The interface of CAM with a computer and radar (Fig. 1) illustrates techniques employed for automatic checkout and monitoring in large systems. Digital command data goes to CAM from the computer and controls all checkout and monitoring functions in the same manner that command data to the radar controls its functions. Command data to CAM may contain the following information:

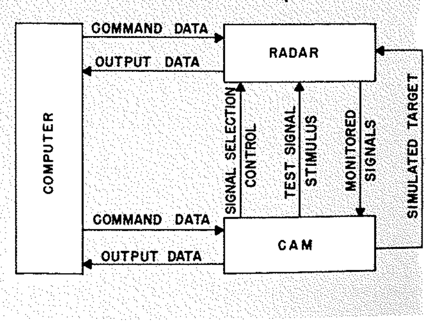
1) Radar mode of operation.
2) Location of signal to be selected for monitoring.
3) Location and type of test signal stimulus required for monitoring.
4) Target parameters for simulated check-out target signals.

Using such data, CAM selects a particular point to be monitored, generates appropriate test signals, stimulates the circuit in a realistic manner, and processes the monitored signal so that the test results can be fed back to the computer for evaluation. Monitored signals are usually processed by converting the signal to a DC or video amplitude, normalizing the signal amplitude, converting the signal to digital form in an analog-to-digital (A/D) converter, and transmitting the signal to the computer over the output data bus. This technique lends itself to sequential monitoring of a large number of points in the system.

Simulated checkout target signals, generated from target parameters in the command data, are fed into the front end of the radar to exercise the overall system for performance evaluation and operator training. Realistic dynamic targets can be generated by using prerecorded magnetic tape in conjunction with the computer to simulate targets of various threat levels in a manner similar to that of BMEWS.[3] The point made here is that although the function of system checkout is not directly related to automatic monitoring, it can be easily mechanized with little additional hardware.

Test results obtained from CAM by the computer are compared with expected values stored either directly in the computer memory or in some external memory device (such as a magnetic tape or drum) that is easily accessible to the computer. The deviation of the measured value from the expected value is compared with preset limits to establish a *go* or *no-go* condition. When monitoring several signals having the same characteristic, it is often desirable to compare the measured value of each signal with the average of all the measured values to establish an out-of-tolerance condition. In this case, the computer performs an additional function by computing the average and storing it in memory as the expected value. When the computer determines that a *no-go* condition exists

Fig. 1—Interface of CAM with radar and computer.



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on any signal monitored, the location of the fault is determined and displayed on a visual readout, such as a hard-copy printer. Should the fault location be remote from the printer, a remote nixie readout display may be located near the equipment monitored. Along with the nixie readout display, a momentary *fault acknowledge* switch is provided so that the operator may acknowledge receipt of the message and reset the nixie readout to accept other readout messages. Remote nixie readouts are controlled directly by the CAM equipment using the normal CAM/computer interface for command and control, since CAM is more intimately associated with the hardware than the computer.

MONITORING OF DIGITAL CIRCUITS

Each element in a typical digital circuit has only two stable states, (i.e., a logical *1* or *0*); therefore, it is theoretically more reliable than the analog circuit with its *infinite* number of states. However, in any large system involving complex logical functions, individual digital circuits are so large that faults can be very difficult to isolate; thus, overall reliability can be adversely affected more by the preponderance of digital circuits than by the purely analog subsystems.

The standard diagnostic and parity checks used to troubleshoot computers do not preclude the need for highly skilled technicians to maintain the equipment. To alleviate the maintenance problem, several avenues of approach may be required:

1) Reduce the number of points to be monitored by packaging logic on a circuit function basis.
2) Design self-checking features in the logic to aid in pinpointing faults.
3) Extend the use of diagnostic and parity checks to further pinpoint faults.
4) Provide redundant logic in critical areas to improve reliability.
5) Develop a simple troubleshooting chart, listing all possible removable assemblies which could cause a fault.

The approaches listed above are determined by the type of logic and the degree of complexity of the subsystem. Development of an effective fault-isolation system must be well planned early in the development stage of the system. However, an effective fault-isolation system offers two advantages: 1) equipment *down* time is held to a minimum, and 2) only semiskilled maintenance personnel are required to maintain the equipment.

Although no development work was conducted on automatic monitoring of digital equipment, another paper[4] describes techniques employed in a telephone dial test set which was developed to perform a 100% self-check on a 555-transistor digital system. In this small system, the increase in transistor circuits required to perform the self-check was 18.2%; two other systems, designed on paper only, require only 5% and 10% increase, respectively, in circuits for checkout.

TECHNIQUES FOR ACHIEVING HIGH ACCURACY

In the sequential monitoring system, high accuracy can be achieved by minimizing DC offsets, by converting RF signals to low-frequency video or DC in a peak detector, and by converting measured values to digital form. The basic elements affecting accuracy in the monitoring chain are the peak detector, the selector switch, the A/D converter, and the transmission line between the circuit to be monitored and the A/D converter in the CAM equipment. Attenuation and noise in the transmission line can be minimized by limiting the frequency spectrum of the video signal and by making the signal level several orders of magnitude greater than the noise. A/D converters of only moderate complexities exist with accuracies exceeding one part in 10^4. Since only one A/D is required per system, its complexity is easily afforded.

Essentially zero DC offset can be obtained by using a field-effect transistor (FET) or a dry-circuit reed relay as the selector switch. The inherent zero DC offset characteristic of the FET and its moderate saturation resistance of approximately 100 ohms make it suitable for monitoring signals in the frequency range from DC to at least 1.0 MHz (Mc/s). In a few cases, however, a mechanical switch is required because of its lower contact resistance, higher current and voltage capability, and greater isolation at high frequencies. A hermetically sealed miniature glass reed and a complete reed relay packaged for printed circuit application are shown in Fig. 2. This particular Clare Co. relay is a dry-circuit type with a contact resistance of less than ¼ ohm and an average life in excess of 100 million operations. Operating time of the relay, including contact bounce, is 1 millisecond maximum; the coil dissipation is less than ½ watt. The capacitance of the normally open contacts is 1 pF; since the capacitance to the coil and shield is also 1 pF, the relay is ideal for switching frequencies up to 30 MHz.

HARDWARE DEVELOPMENT

Experimental CAM equipment was developed in conjunction with a phased-array radar to demonstrate the feasibility of automatic checkout and monitoring of large systems. The primary functions of the CAM equipment are: 1) measure relative phase and amplitude variations of a test signal through each of a large number (N) of radar receivers for fault isolation, 2) generate dynamic target error signals to check the performance of the radar signal processor, and 3) demonstrate the practical aspects of performing these functions automatically under computer control. The CAM interface with the phased-array radar is shown in Fig. 3. Note that the CAM interface here is quite similar to that with the radar and computer shown in Fig. 1. The major difference is a more detailed breakdown of the radar and CAM interface in the latter; the monitoring approach described earlier is applied.

To make phase or amplitude measurements, command data is sent to CAM from the computer. Such data defines the type of measurement, selects the appropriate receiver to be monitored, and generates the test signal to stimulate the receivers. Since the same measurements are made on all receivers, the same test signal is applied to all receivers simultaneously; however, the signal output from each receiver is monitored one at a time. Test signals are fed into the receivers on a noninterference basis with the normal radar signals by gating an IF switch and then mixing the signal up to the receiver RF frequency in a single-sideband mixer. The LO signal used in the mixer is the same as supplied to each of the receivers. A passive power divider provides multiple outputs for all receivers, and the test signal is fed into the front end of each receiver via a directional coupler. The IF output from each receiver is fed via a directional coupler to a switch matrix where each receiver output may be selected individually for monitoring. Particular care is exercised to maintain equal electrical length on each set of input and output cables, and to maintain equal phase shifts through each set of input and output directional couplers and each output port of the power divider to minimize variations in phase shifts in each line.

The switch matrix is arranged symmetrically like a circular commutator to maintain equal electrical length of each receiver output. Reed relays (similar to those of Fig. 2 except that the leads are axial, not out of the bottom) are used for signal selection because of their low capacitance and fast operating speed. Since the switch matrix is located near the receivers but is remote from the central CAM equipment, an IF amplifier is provided. This unit amplifies the selected receiver signal before sending it to CAM to minimize noise pickup on the long line.

The gated IF receiver output selected by the switch matrix is converted to video by a peak detector for amplitude

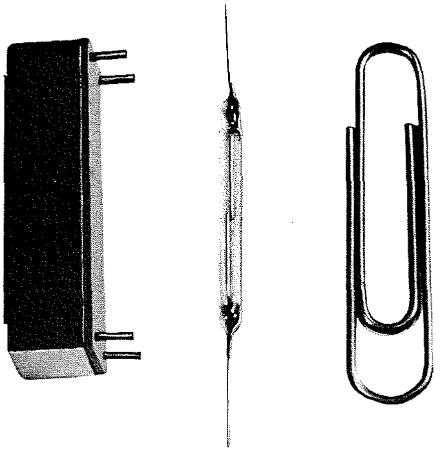

Fig. 2—Miniature glass reed and complete relay size compared to paper clip.

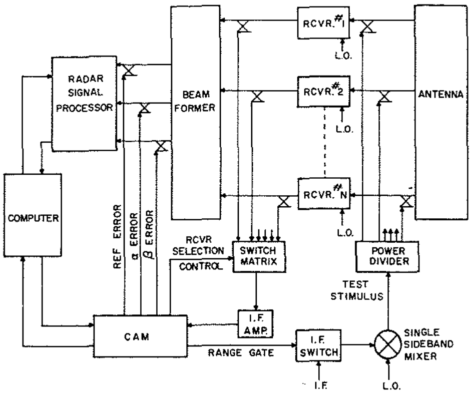

Fig. 3—Block diagram of CAM interface with phased array radar.

measurements. To make phase measurements, the gated IF signal is mixed down to approximately 2.5 MHz in the central CAM equipment where more accurate phase measurements can be made on a pulsed basis than at IF. The output of the phase detector (discussed later in this paper) is also a video pulse. When making either phase or amplitude measurements, the video is digitized in an A/D converter and sent to the computer via the data output bus for evaluation. As outlined earlier, the computer determines the average value of all amplitude or phase measurements and compares each measured value with the average value to establish either a *go* or *no-go* condition on each signal measured. The computer prints out a hard copy of the deviation of each measured value with respect to the average, and specifies the fault location of any receiver that may be out of tolerance in either phase or amplitude. The fault location is displayed on a nixie readout in the CAM equipment.

PHASE DETECTOR

To monitor the relative phase shift of a test signal through each of the receivers in an operational system, a phase detector having a linear response and capable of pulsed operation is required. In the system under development, the out-of-tolerance limits on the relative phase shift of each receiver with respect to the average was preset by the computer at ± 5.0°. The resolution and phase stability of the phase detector should be at least an order of magnitude smaller, or less than 0.5°. In addition, the phase detector should be relatively insensible to changes in signal amplitude.

Twin gated differential amplifiers are used in the phase detector (Fig. 5) for the following reasons:

1) The inherently high input impedance of differential amplifiers minimizes phase distortion.
2) Differential amplifiers can be operated as high-gain, nonsaturating squaring amplifiers, thereby eliminating distortion caused by the inherent storage time delay of transistors when driven out of saturation.
3) Push-pull operation is easily obtained with single-ended input signals.
4) As the result of the high gain obtained, only relatively low-level sinewave input signals are required.

Although the output frequency of the receivers is at IF, phase measurements are made at approximately 2.5 MHz; at this frequency the gain-bandwidth of the transistors is less critical and higher overall performance can be obtained. The input signal to be measured is a burst of about 2.5 MHz sine waves with a duration of 35 microseconds; the reference signal is a coherent CW sine wave of the same frequency. The input signal is fed to the two differential squaring amplifiers composed of $Q1$ and $Q2$. The reference signal is fed to differential squaring amplifier $Q3$, which gates $Q1$ *on* during the positive half cycle of the reference, and $Q2$ *on* during the negative half cycle. Since the collectors of $Q1$ and $Q2$ are connected, the signals are additive during both half cycles and push-pull operation is provided.

In effect the circuit is a digital *and* circuit for two symmetrical square waves composed of the 2.5-MHz square-wave signal and reference waveforms. As the phase varies between the two waveforms, the average DC level of the output varies linearly (see dashed-line ramp function in Fig. 4). Since the average DC level of the RF pulses is the desired function, the two outputs in the collectors of $Q1$ are filtered by $C1$ and $C2$ to remove the RF components of the signal. The double-ended signal is then converted to a single-ended signal in the differential amplifier composed of $Q4$ and $Q5$.

Since the input signal is an RF burst rather than CW, the output is a video pulse rather than DC. When the input signal is absent, both halves of each differential amplifier conduct equally, thereby establishing a zero reference level which corresponds to a phase angle of 90° on the ramp function. To obtain high phase sensitivity, the gain of the differential amplifier composed of $Q4$ and $Q5$ is adjusted for saturation at a phase angle of about 120° and the amplifier is cut off below about 80°; the resulting response curve is as shown by the solid-line function in Fig. 4. The full dynamic range of video output is limited to phase angles between 90° and 120° or 240° and 270°, since only positive video can be handled by the A/D converter. However, the phase limits preset by the computer are only ± 5.0°, and the initial phase is adjusted so that the video falls in the mid-range of the response curve.

For a period of 200 microseconds prior to the application of video, the capacitance-coupled video output is clamped to ground at the base line by transistor $Q6$; this eliminates problems of DC drift inherent in DC coupling. A 2N2432 chopper-type transistor, operated in the inverted collector connection, is used to maintain a maximum DC offset of 1.0 millivolt in the clamp gate. Type MD1122 dual transistors in the phase detector minimize unbalance of the differential amplifiers caused by variation in the base-to-emitter forward voltage drop of the two transistors in each differential amplifier; the MD1122 housing has two transistors in one can with the base-to-emitter forward voltage drops matched to within 5.0 millivolts.

To obtain adequate filtering of the RF pulses, the capacitance of $C1$ and $C2$ must be quite large, which affects the rise time of the output video. However, the accuracy of amplitude measurement is not impaired, since the video amplitude is sampled approximately 3.0 microseconds from the end of the video pulse. This sampling is done by the A/D converter where the slope of the video is essentially zero. Since the operating range of the video is 30° and the A/D converter contains 8 binary bits, the phase can be resolved to within ± 0.12 degree approximately.

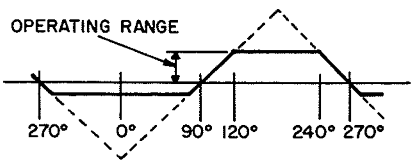

Fig. 4—Phase detector response curve.

DYNAMIC TARGET SIMULATOR

As part of the radar development program, a dynamic target simulator (Fig. 6) was designed to generate target error and reference IF signals to check the tracking performance of the radar signal processor. These signals must be capable of varying dynamically in range, amplitude, and doppler. Each variable parameter making up the target signals is obtained from the computer via the CAM digital control equipment.

The range of the target signals is determined by a range-gate generator having a counter for coarse range and a delay line for fine range. Ten bits of range designation are strobed into the range counter; zero time is established by a *0 time* trigger which is phase coherent with the 5.0-MHz clock pulse. The range counter begins its run down at zero time. When the counter reaches zero, the count is decoded and a narrow *start gate* is generated; a finite time later a narrow *end gate* is generated which shuts off the range counter. The start gate and end gate are then fed through an *or* circuit to the *fine range delay line*, where the target range is resolved to within 4 yards by controlling the delay of the two gates through the delay line with a 3-bit fine range designation. The target range gate is generated by stepping a 1-bit counter with the delayed start and end gates.

A 9-bit digital oscillator is used to generate target doppler (f_d) on a 30-MHz carrier. The 30-MHz + f_d is gated by the range gate in an IF switch and fed to an MGC (manual gain control) amplifier to obtain the proper signal level. The gain of this amplifier is controlled by a 4-bit digital-to-analog (D/A) converter which establishes the power level of the target reference signal over a 35-dB dynamic range. In a monopulse radar system, the α and β error signals are either in phase or 180° out of phase with the reference signal, depending on the quadrant the target is in with respect to the center of the beam. The power levels of the error signals are related to the power levels of the reference signals but are always smaller than the latter. Therefore, both the α and β error signals are derived from the reference signal. The reference signal is fed to an α and β polarity switch, which is controlled by the α and β sign bits, respectively, to obtain either an in-phase or 180° out-of-phase error signal. The outputs of the polarity switches are fed to voltage controlled attenuators (VCA) where the attenuation of the error signals is controlled over an additional 30-dB range by a 4-bit D/A in each channel. Thus, the generated error signals can be controlled over a 65-dB range, including the 35-dB range of the reference signal. These three error signals are connected, respectively, to the input of the radar signal processor at the same points as are the target signals from the beam-forming networks.

In the radar development program the computer is programmed to vary only one of the target parameters at a time for performance evaluation. In the final system, however, all parameters could be varied simultaneously to generate realistic dynamic targets by using prerecorded digital magnetic tapes. These tapes would be generated by another computer programmed to simulate aerial raids of any realistic threat level. In addition to providing a means of checking overall system performance, dynamic target simulation can be used for operator training and for increasing user confidence.

CONCLUSIONS

Although the experimental CAM equipment developed in the phased-array radar program was limited in scope, the overall system approach and design techniques used are directly applicable to the automatic checkout and monitoring of large systems. In the development program, CAM reduced equipment *down* time by keeping a constant surveillance on the radar receivers to note performance degradation. CAM also proved useful in the initial debugging phase of the development program where it was used to check the interface between several of the subsystems.

Some general conclusions regarding automatic checkout and monitoring follow:

1) Automatic fault detection and isolation of the smallest removable assembly can be accomplished most economically in large systems by using the central control computer for evaluating test results.
2) In large systems the cost of hardware for CAM functions may be less than 10% of the cost of the overall system.
3) To be effective, checkout and monitoring should be considered in the initial design phase of system development.[5]
4) The reliability and accuracy of CAM should be an order of magnitude better than the individual components of the system.
5) The additional cost of automatic CAM equipment is more than offset by the saving in system maintenance cost, not to mention the vast improvement in system *up* time.

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Fig. 5—Phase detector for pulsed RF signals.

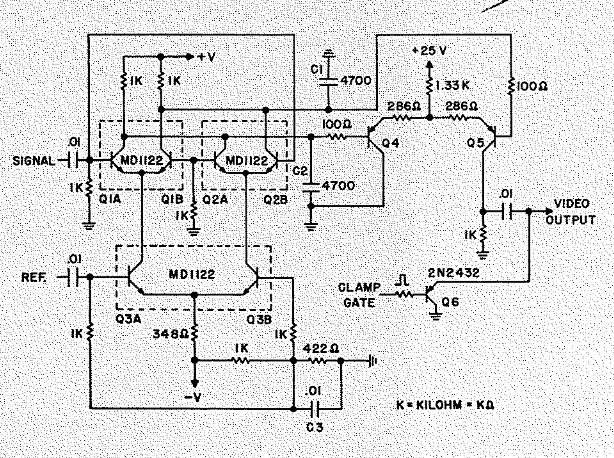
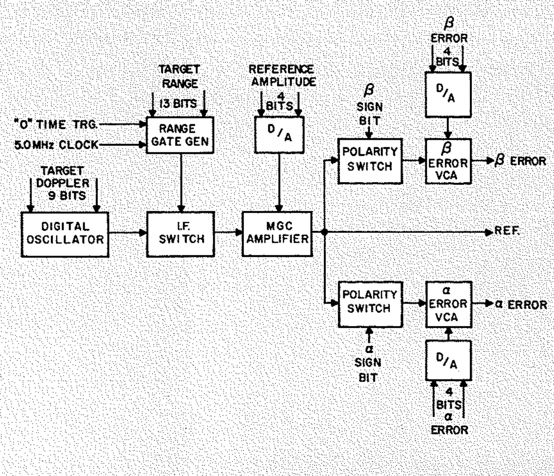


Fig. 6—Block diagram of dynamic target simulator.



DIELECTRIC-TO-METAL COMPRESSION-BAND SEALS

This paper describes the results of a study program aimed at improving dielectric-to-metal sealing techniques used in the fabrication of output windows for high-power microwave tubes. Output windows for high-power tubes must maintain a vacuum-tight enclosure and pass the microwave energy produced by the tube with minimum losses. Vacuum tightness must be retained through the high-temperature bakeout phases of tube production, through operating temperature cycles, and through atmospheric-pressure changes.

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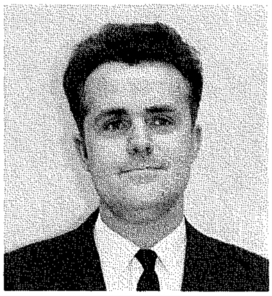

F. J. Hoffman

A. C. Grimm

E. TENO received his BSEE from Penn State University in 1953. While employed by Sylvania Electric Company from 1952 to 1961, he was involved in the design and development of vacuum tube components, manufacturing processes, and mechanical and electrical evaluation testing. He also designed miniature vacuum tubes for guided-missile applications. Since joining RCA Electron Tube Division at Lancaster, Pennsylvania in 1962, Mr. Teno has been employed as a super-power tube development engineer. His work at RCA includes assignments related to the electrical and mechanical design of large power tubes. In addition, he has recently completed an investigation of compression-band sealing techniques for microwave output windows. He is presently working on the electrical design of a broadband coaxitron microwave amplifier tube. He is a member of Eta Kappa Nu and the IEEE.

F. J. HOFFMAN spent five years in the U.S. Navy and the U.S. Coast Guard. During this period he spent approximately one and one-half years attending two U.S. Navy Electronic schools finally leaving the service as a chief electronic technician. Mr. Hoffman joined RCA Tube Division at Lancaster, Pa. in 1952 as an electronic technician. Initially assigned to the Regular Power Tube Design and Development Group, he was specifically concerned with application problems of both small and medium power tubes. In 1957 he joined the Super-Power Tube Advanced Development Group as an engineering technician. In this capacity he assisted in the development of the RCA ribbon-beam klystron, and the RCA developmental type A-1230D klystron for the Stanford two-mile linear accelerator.

A. C. GRIMM received his BSEE from Brooklyn Polytechnic Institute in 1940. Following graduation, he joined the RCA Tube Division and was assigned to the Tube Engineering Section, where he was engaged in the development of receiving and small power tubes. From 1951 to 1953 he directed the advanced development effort on the RCA color kinescope. He was promoted to Product Manager for the Color Kinescope Product Group in 1954. Named Manager, Advanced Development, Power Tube Group in 1955, he was responsible for the development of the RCA ribbon-beam klystron. He also directed the work on the RCA developmental type A-1230D klystron for the Stanford two-mile linear accelerator. He is presently Manager, Super-Power Tube Operations. Mr. Grimm holds five patents on electron tubes and associated devices, and he has published several papers on color kinescopes. He is a member of Tau Beta Pi, Eta Kappa Nu, and the IRE.

Nearly all present output windows use a high-alumina ceramic which is metalized and then brazed to a metal cylinder. Although windows of this type are generally reliable, the high dielectric constant of alumina ceramic and the RF energy losses caused by the metalized layer reduce tube performance. Many efforts have been made to eliminate these disadvantages by extending fabrication techniques to dielectric materials having lower losses and lower dielectric constants and by reducing losses in the metalizing layer. Because many of these substitute dielectric materials are more difficult to metalize and fabricate into window assemblies, these past efforts have only been moderately successful.

COMPRESSION-BAND SEAL

A completely different window design, known as the compression-band seal, was initially developed by RCA for the Atomic Energy Commission, and then extended to the sealing of various dielectric materials under an Air Force contract. The window consists of a dielectric disc, a seal sleeve, and a compression band (Fig. 1). No metalizing is required, and vacuum tightness is obtained by designing the dimensions of the parts so that the compression band exerts enough radial pressure on the seal sleeve to make it conform to the seal edge of the dielectric disc. By proper selection of the materials and design parameters, a compression-band window can be fabricated that will remain vacuum tight at high temperatures and through repeated temperature cycles. By means of this sealing technique, RF windows can be made with many dielectric materials that are difficult to metalize.

For this program many different materials were tested using the compres-

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Fig. 1—Compression-band window.

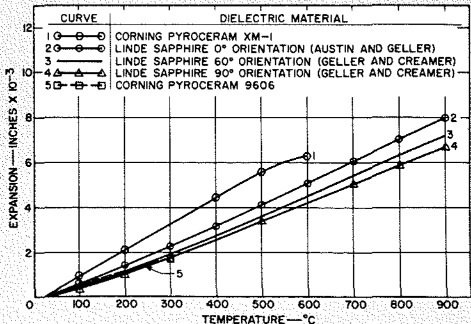


Fig. 2—Expansion as a function of temperature.

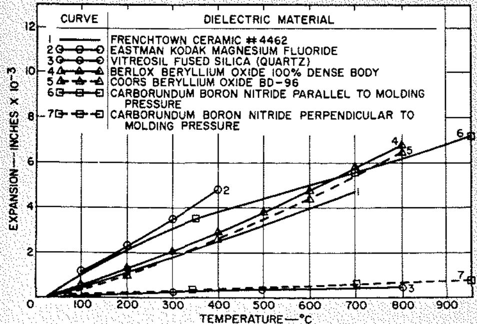


Fig. 3—Expansion as a function of temperature.

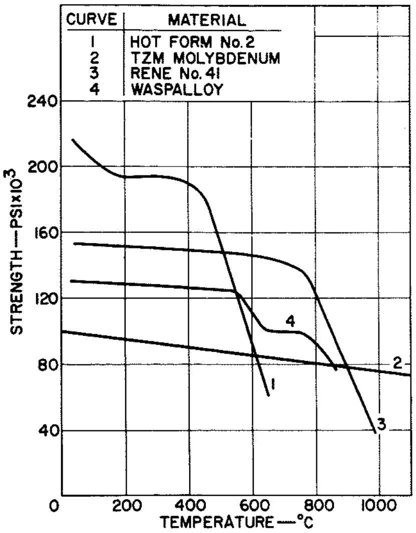


Fig. 4—Yield strength as a function of temperature.

sion-band technique. Beryllium oxide, Pyroceram 9606, and Frenchtown 4462 ceramics were used in windows that could be repeatedly baked to 700°C. The latter ceramic was used as the reference material. Windows fabricated from magnesium fluoride, sapphire, and boron nitride were reliable to 450°C. In all cases, after being bake-tested, these windows remained vacuum tight through a life test of 1,000 temperature cycles.

MATERIAL CONSIDERATIONS

Before compression-band seals can be mechanically designed, it is necessary to know the mechanical and physical properties of the three component parts. The most pertinent mechanical properties of the dielectric material are the compressive strength (Table I) and thermal expansion as a function of temperature (Figs. 2 and 3).

The properties of prime importance for the compression band are yield strength and thermal expansion as a function of temperature (Figs. 4 and 5). Physical and mechanical properties for the above materials were reviewed at operating temperatures up to and above 700°C. Rene 41, Waspalloy, and TZM molybdenum compression-band materials were chosen because their high yield strength and thermal expansions were similar to one or more dielectric materials being investigated. Hot Form No. 2 was used as a reference material for the tests conducted.

Copper was initially chosen as a sleeve material because of its successful use in the compression-band seals made by RCA for the Stanford Linear Accelerator klystrons. Other test seal sleeves evaluated used 304 stainless steel, Kovar, and nickel to avoid temperature and seal-pressure limitations. In all cases, the sleeves were 0.001-inch copper-plated. This copper plating provided sufficient "skin depth" for low-loss transmission at X-band frequencies and also served as a ductile gasket material to make the seal vacuum tight. Test window assemblies using 304 stainless-steel sleeves were vacuum tight at bake temperatures of 800°C.

DESIGN OF COMPRESSION-BAND WINDOWS

Since the physical properties of the materials to be used are known, it is possible to calculate the part dimensions necessary for a desired seal pressure and also to predict the maximum possible bake-out temperature for a given combination of dielectric, seal sleeve, and compression-band materials. In the analysis that follows, it is assumed that the diameter of the dielectric disc has been selected to meet specific electrical and frequency requirements. The equations for this calculation are shown in the *Appendix* at the end of this paper. Although dielectric thickness is primarily determined by electrical requirements, the minimum value must be determined from mechanical considerations to assure adequate strength.

In the *Appendix*, the stress at which a dielectric disc of a given thickness will buckle[1] is given by Eq. 1. The remaining design relationship to be derived is the size of the compression-band necessary for the required seal pressure. The relations[2] for the stress in a hoop subjected to internal pressure are given by Eq. 2 and 3 in the *Appendix*. By substitution of calculated dimensions, selected dimensions, and material physical properties in these equations, the unknown values for r_o, r_i and t_d can be derived. (See Fig. 6 for definition of these terms.)

Eqs. 4, 5, and 6 in the *Appendix* are the derived basic design relations for the compression-band seal. At elevated temperatures, the sealing pressure varies in accordance with Eq. 7. When the thermal expansion rate of the compression band is larger than that of the dielectric, the seal will fall apart at some elevated temperature. This point occurs when the term $r_d + t_s - D = r_i$.

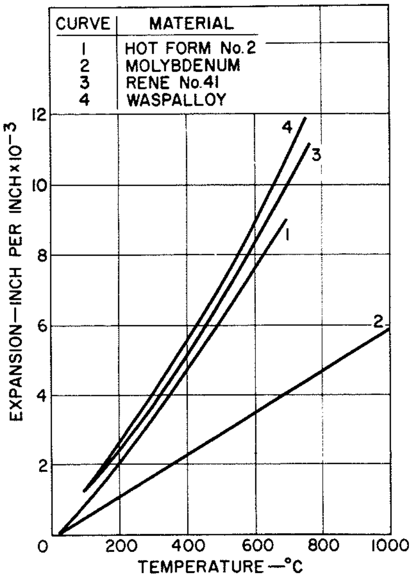


Fig. 5—Expansion as a function of temperature.

Fig. 7 shows the theoretical seal-pressure variation for Frenchtown 4462 ceramic and various compression-band metals. In all cases, a constant seal sleeve deformation of 0.001 inch was assumed. These curves make it apparent that the greater the difference in the expansion rates of the compression band and the dielectric, the less the temperature can be increased before zero seal-pressure and a leak results.

ASSEMBLY OF COMPRESSION-BAND WINDOW

The compression-band window is assembled by expanding the compression band sufficiently with inductive heating to pass over the copper sleeve and dielectric disc as shown in Fig. 8. The copper seal is kept cool by the use of a chill block immersed in liquid nitrogen. Upon cooling, the interference fit of the compression band exerts a seal pressure proportional to the design calculations. The following precautions must be observed in the assembly of compression-band windows.

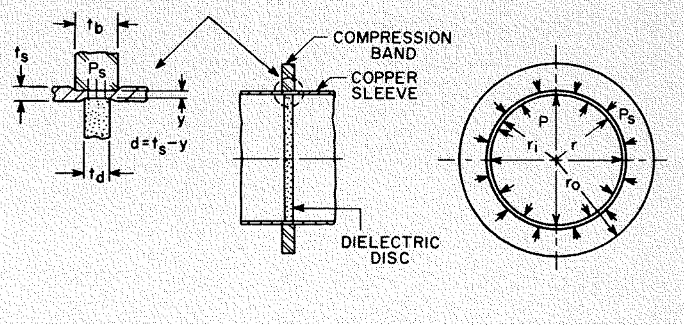


Fig. 6 — Cross-sectional view of compression-band window.

1) To prevent a reduction in yield strength, the temperature to which the band is heated should be below the recommended operating temperature for the compression-band material.
2) The assembly fixture must maintain perfect alignment between the band, seal sleeve, and dielectric disc.

Compression-band windows that are not completely vacuum tight after assembly usually become vacuum tight when baked at a temperature of 400°C.

WINDOW TESTS

Three environmental tests were used to evaluate the compression-band window assemblies. These tests consisted of: a high-temperature bake test under conditions similar to those encountered during tube production; temperature-cycle life tests which simulate the on-off operation of a vacuum tube; and shelf-life tests. Each test window was attached to a vacuum test fixture for these tests. Windows to be bake-tested were mounted in a double-vacuum bake-testing unit, which is similar to systems used to bake electron-tube devices. The windows were then leak-tested at the bake temperature by admitting helium at a partial pressure of 1,000 micrometers in the outer vacuum chamber and then detecting for helium with a mass spectrometer in the inner vacuum chamber.

The temperature-cycle life test was conducted with the window assembly under vacuum on one side and the temperature was varied from 20°C to 125°C every 15 minutes for a total of 1,000 cycles. In addition, shelf-life test results indicated that vacuum tightness remained satisfactory during the 6-month test period.

CONCLUSIONS

Compression-band assemblies have been successfully fabricated using dielectric discs having diameters of 1.25 and 3.50 inches. Window assemblies using a high alumina dielectric material can be consistently produced without failure. In general, the higher the compression strength of the dielectric material, the greater the chances for making successful window assemblies. A total of 63 vacuum-tight assemblies have been fabricated using the compression-band technique and dielectric materials evaluated during this study program.

On the basis of design relations and the mechanical properties of the materials used in the fabrication of the seal, theoretical calculations can be used to predict the maximum allowable sealing pressure, the minimum dielectric thickness, and the seal pressure at elevated temperature. Testing of window assemblies has shown that the degree of correlation between the calculated design and the measured actual seal pressure is primarily a function of the amount of deformation of the seal sleeve material. The higher the yield strength of the material, the better the correlation.

In addition, tests have shown that the practical minimum sealing pressure is within the range of 25,000 to 35,000 lbf/in². Vacuum-tight seals having lower seal pressures can be achieved, but the results at the present time are erratic. The environmental test results have shown that a 700°C bake test for 48 hours and a 1,000-cycle life test are practicable for compression-band assemblies which are fabricated from beryllium oxide, Frenchtown 4462 ceramic, and Pyroceram 9606. A 450°C bake test for 48 hours and 1,000-cycle life test are practicable for seals made with magnesium fluoride, boron nitride, and sapphire.

Results of sapphire-window bake tests at temperatures above 450°C have been encouraging, and it is believed that, after further development, a 700°C bake temperature should be possible. It is felt that the compression-band window, having low RF losses, high reliability, tolerance to high bakeout temperatures, ease of assembly, and low cost, will prove to be a major contribution to the manufacture of high-power microwave devices.

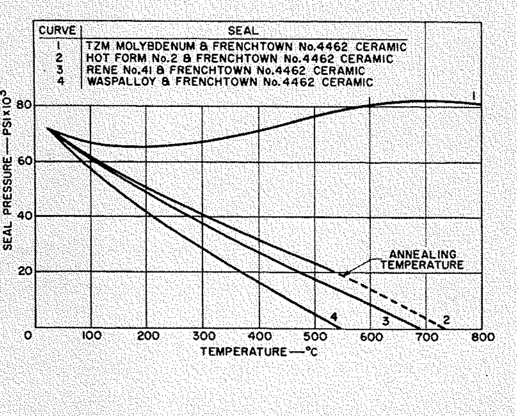


Fig. 7—Effect of temperature increase on pressure of seals made with Frenchtown 4462 ceramic and other different materials (Initial pressure was 72,000 lbf/in².)

TABLE I—Compressive Strength of Dielectric Materials

Dielectric Material	Compressive Strength Room Temperature, 10^6 lbf/in²
Frenchtown Ceramic 4462	425
Linde Sapphire 60° Crystal Orientation	300
Coors Beryllium Oxide BD-96	205
Vitresoil Quartz	160
Eastman Kodak Magnesium Fluoride	155
Carborundum Boron Nitride:	
(a) Parallel to Molding Pressure	50
(b) Perpendicular to Molding Pressure	35

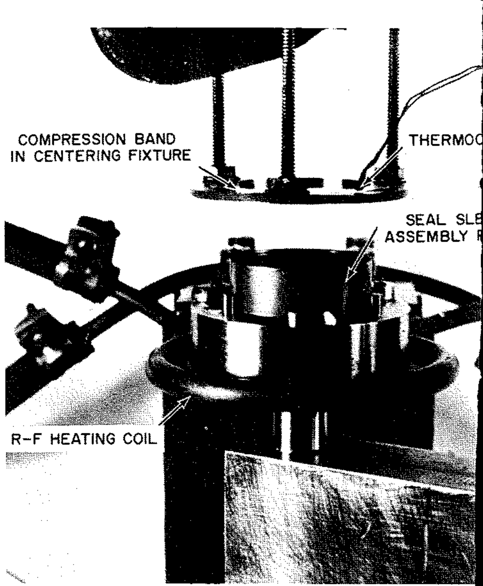


Fig. 8—Assembly fixture for compression-band window.

BIBLIOGRAPHY

1. S. Timoshenko, *Theory of Elastic Stability*, Engineering Societies Monograph, McGraw-Hill Book Company, Inc., New York, 1936.
2. S. Timoshenko, *Strength of Materials*.

APPENDIX
DESIGN EQUATIONS FOR COMPRESSION-BAND WINDOWS

$$\sigma\ buckling\ (P_S) = K \frac{E_d}{1 - v_d^2}\left(\frac{t_d}{r_d}\right)^2 \quad (1)$$

where σ *buckling* = maximum stress before buckling, E_d = Young's modulus, v_d = Poisson's ratio, t_d = disc thickness, r_d = disc radius, and K = empirically determined constant (0.35 to 1.22)

$$\sigma\ radial = \frac{r_i^2 P}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2 P}{r^2 (r_o^2 - r_i^2)} \quad (2)$$

$$\sigma\ tangential = \frac{r_i^2 P}{r_o^2 - r_i^2} + \frac{r_i^2 r_o^2 P}{r^2 (r_o^2 - r_i^2)} \quad (3)$$

where r = radius where stress is calculated, r_i = inside radius, r_o = outside radius, and P = internal pressure.

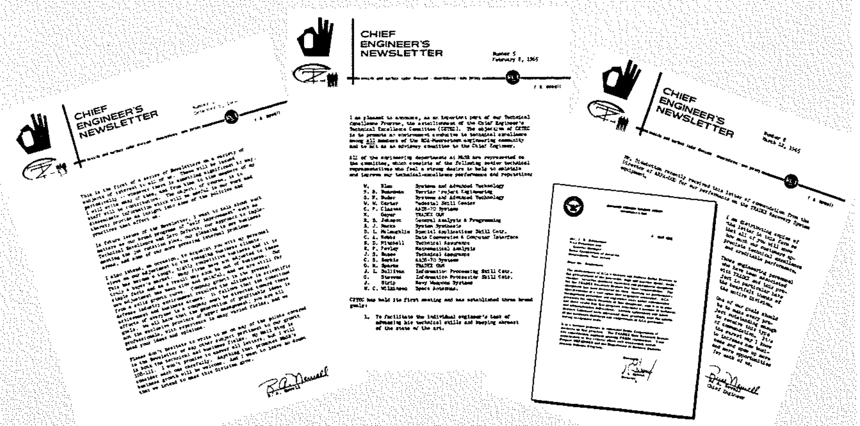
$$t_d = r_d \left[1.64\, P_S \left(\frac{1 - v_d^2}{E_d} \right) \right]^{1/2} \quad (4)$$

When $K = 1.22$ (see Fig. 1):

$$r_i = \frac{r_d + t_s - D}{\left(\frac{\sigma\ max + 1}{E_b} \right)} \quad (5)$$

$$r_o = r_i \left[\frac{\left(\frac{\sigma\ max}{P_S} \cdot \frac{t_b}{t_d} \right) + 1}{\left(\frac{\sigma\ max}{P_S} \cdot \frac{t_b}{t_d} \right) - 1} \right]^{1/2} \quad (6)$$

$$P_S = E_b \frac{t_b}{t_d} \left(\frac{r_o^2 - r_i^2}{r_o^2 + r_i^2} \right) \left(\frac{r_d + t_s - D - r_i}{r_i} \right) \quad (7)$$



Sample "Chief Engineer's Newsletters"

A PROGRAM FOR TECHNICAL EXCELLENCE

The current pressures of economics—keen competition, cost-effectiveness, and fixed-price contracts—make management and engineers extremely cost- and schedule-conscious. Programs for value engineering, increased documentation, and zero defects tend to make engineers forget that their prime contribution must always be technical. Consequently the engineer should constantly bear in mind that no slogan, no campaign, no emphasis on business factors should be allowed to impair his technical excellence. This paper describes the program developed and operating at M&SR to promote technical excellence.

M. W. NACHMAN

Zero Defects Administrator, Technical Assurance
Missile and Surface Radar Division
Moorestown, N. J.

THE emphasis today in defense procurement is on better technical management, cost-effectiveness, and careful assessment of schedules and costs. These considerations tend to deemphasize creativity, innovation, and technical performance. Many engineering managers have shown increasing concern for the actual and psychological effects this shift in emphasis has on engineering performance. John B. Campbell in a recent editorial in Space/Aeronautics said, ". . . The detailed RFP, the concept of cost-effectiveness, the documentation requirements, the value engineering clause, the zero-defects campaign—all of these have encouraged a more analytical approach to systems design and manufacture. But as performance parameters are spelled out in ever increasing detail, as documentation gets thicker, and as cost constraints are drawn ever more tightly, many engineers are finding that the creative part of their job has withered away.

"By now, most engineers have accepted the fact that engineering isn't what it used to be, and never will be again. But maybe it's time for someone to take a long, hard look at the psychological impact of the defense establishment on engineering today. The mind and energy of the creative engineer are priceless assets, and the country can ill afford to lose them."

The impact of these business problems has been and will continue to be felt by all of us. And survival in the defense business depends upon the satisfactory solution of these problems. In the solution of such problems, however, we must never let down in our pursuit of that elusive goal *technical excellence.*

In July 1964 the Engineering Department of the Missile and Surface Radar (M&SR) Division was reorganized. A major goal to be achieved in this and subsequent reorganizations was an emphasis on and an implementation of modern management methods for improved cost and schedule control. No less important was the goal to sustain, and even improve, technical excellence at the same time. Therefore, the need for a Technical Excellence Program was recognized and the decision to institute one was made.

THE PHILOSOPHY

Upon first consideration of the formal program, M&SR was faced with the compound task of developing a logical and workable approach to an idea that was hard to define. To excel means to surpass or outdo, and a program was needed that would motivate all in the pursuit of this excellence.

The Technical Excellence Program at Moorestown was conceived with motivation as the pivotal ingredient. It was recognized that the success of the effort would depend upon being able to motivate every individual (the entire organization) to become aware of the need, and to improve his desire and his ability to do a better job. Each has to perform his assignments in the most simple and direct manner, not only within the time and cost limits, but also in meeting performance requirements. This is technical excellence in its broadest sense.

THE RESULTS

All motivational stimuli rarely exist simultaneously at their fullest; they tend to dilute each other. Nevertheless, the M&SR Technical Excellence Program has produced most significant results. In describing these results, the implementation techniques and features of this program will be emphasized.

Organization

The reorganization of the Engineering Department in July 1964 produced at least three significant changes advancing the pursuit of technical excellence.

a) Each design activity employs a new skill-center concept, providing the motivational nucleus for focusing and building its technical strength. Every skill center is a small group of the more seasoned and experienced engineers which becomes the recognized technical leader (i.e., the consultant group) to the design and development and project engineers in their respective activities. Members of the skill centers do not concentrate their efforts on any one project. Rather, they provide broad coverage in developing and assuring the technical adequacy of new concepts (new business), in reviewing technical requirements to minimize technical risks, in acting as troubleshooters to resolve overall technical problems, and in spearheading the application of company-funded R&D programs. Not only are the talents and abilities of these skill-center engineers enhanced, they also train and guide others within the activity, pro-

Final manuscript received November 18, 1695

viding constant development of technological skills for future projects.

b) The second change arose from the establishment of a separate Technical Assurance activity reporting directly to the Chief Engineer. This new activity includes such functions as Design Review, Technical Verification, Value Engineering, and Zero Defects. The establishment of a separate Design Review group is not new, but by making the group responsible for determining the need for its services, the effectiveness of this important function was increased. Now, every phase of every project is reviewed as needed, but it is determined by the Design Review team rather than the individual design and development groups. This group of scientific and design specialists provides independent critical analyses of proposed designs to assure that the delivered products will meet contractual requirements. Also, a new Technical Verification function was established to administer a specification review program to assure the adequacy and compatibility of systems specifications prior to their release.

c) Finally, the Advanced Techniques group was established to concentrate effort on new techniques. This new group is responsible for achieving the strongest independent research and development (IR&D) and systems effort possible. They determine the current and anticipated technological growth of M&SR in various fields.

In all the instances cited above, the pursuit of technical excellence has been advanced not only by those assigned to these specialty functions, but by all technical personnel, because the existence of these functions raised the technical level of all endeavors.

Manpower Development

Effort was directed to the channeling and updating of existing skills and the development of new skills. A Competence (or Skill) Register, established in the latter part of 1964, provides rapid access to the available skills and indicates where other skills are needed. A sample of the form used to prepare the Skill Register is shown in Fig. 1. The Register, which is kept up to date, permits machine sorting and retrieval of the names of personnel having needed skills when required. This system permits the assignment of technical personnel to those tasks which maximize the application of their talents. When people can do jobs they like to do, the results are substantially better. The M&SR after-hours training program has been redirected to stimulate the updating of existing skills and the development of new ones. The courses offered now are more advanced than previous offerings and are of a type which cannot readily be obtained elsewhere. The courses are conducted on a more formal basis than previously, and instructors have been selected on the basis of their knowledge and teaching ability rather than on their availability. This increased emphasis on training spurs the pursuit of technical excellence.

Improved Communications

The need for improved communications as a motivational element in technical excellence was recognized from the beginning. Late in 1964 the first of a new series of *Chief Engineer's Newsletters* was issued to all personnel in the Engineering Department. Their purpose can be best explained by quoting from Issue No. 1, dated 18 December 1964.

> "In future issues of the *Newsletter*, I want to talk about such matters as our broad programs of self improvement such as Technical Excellence and Zero Defects, our approach to implementing the job-rotation plan, our planning in new business areas, and some of our more pressing internal problems."

These *Newsletters*, providing direct communication between the Chief Engineer and all his engineers, are not intended to bypass normal supervisory channels, but to supplement them.

Chief Engineer R. A. Newell has conducted departmental meetings on two occasions. At the first, held 11 September 1964 at a local theater, Mr. Newell explained his management philosophy

M. W. NACHMAN graduated from West Virginia University with the BSEE degree in 1950 and joined Philco Corporation's TechRep Division, where he became supervisor of special projects in the Engineering Writing Department. In 1955 Mr. Nachman joined RCA as a project engineer on the Talos system, preparing engineering and test reports. He was promoted to Leader and then Manager of the engineering writing activity for BMEWS; later, he was responsible for the product-improvement group on that project. Mr. Nachman has served as chairman of the Zero Defects Program Committee at Moorestown since its inception in 1964. He also contributed to the development of the Technical Excellence Program at Moorestown and DEP. He is presently responsible for configuration management on the SAM-D project. He is a senior member of the IEEE and has been a member of the public relations committee of the local chapter of the NSPE.

Fig. 1. Sample Skill Register form.

(1)

LAST NAME	FIRST	MIDDLE	EMPLOYE NO.	ACTIVITY NO.	OCC. NO.	DIVISION
Jones	Smith	Brown	47412	682	5433	M&SR

NOTE:
1. Read Instruction Book
2. The number in margin refers to section in instructions.
3. Print

DEFENSE ELECTRONIC PRODUCTS
MOORESTOWN, NEW JERSEY
RCA
COMPANY PRIVATE

PROFESSIONAL COMPETENCE REGISTER RESUME

FILL IN BLANKS OR CIRCLE APPLICABLE NUMBERED BLOCK

(2)

DATE OF BIRTH: MO. 12 / DAY 13 / YR. 20
U.S. CITIZEN: X [1] YES [2] NO
NUMBER OF DEPENDENTS: 5 (EXCLUDE YOURSELF)

CURRENT SECURITY CLEARANCE: [0] NONE
ARMED FORCES: [1] CONFIDENTIAL; X [2] SECRET; [3] TOP SECRET
AEC: [4] L; [5] Q; [6] LX; [7] QX

TEMPORARY ASSIGNMENTS: [0] NONE
DOMESTIC: [1] UP TO ONE MO.; [3] ONE TO 3 MO.; [5] THREE TO 12 MO.; [7] OVER 18 MO.
OVERSEAS: [2] X; [4]; [6]; [8]

PROF. LICENSE: [1] NO; [2] YES X; STATE OR TERRITORY: N.J.

FOREIGN LANGUAGE PROFICIENCY (LIST)
BEST: [0][9] French
OTHER: [1][0] German
OTHER: [ ][ ]

MILITARY STATUS

(3)

YRS ACTIVE SERVICE: 5
HIGHEST RANK: Cdr.

BRANCH OF SERVICE: [1] AIR FORCE; [2] ARMY; [3] COAST GUARD; [4] MARINES; X [5] NAVY; [6] OTHER (LIST)

PRESENT DRAFT STATUS: [1] I-A; [2] I-D; [3] II-A; [4] II-S; [5] III-A; [6] IV-A; [7] IV-F; [8] V-A; [9] X OTHER

RESERVE STATUS: [1] ACTIVE RESERVE; [2] INACTIVE RESERVE; [3] RETIRED REGULAR OFFICER

EDUCATION

(4)

CODE (LEAVE BLANK)	YR. OF DEGREE	DEGREE	COLLEGE / SCHOOL / UNIVERSITY EXCLUDE HIGH SCHOOL	MAJOR COURSE
	1940	AB	Yale University	Physics
	1950	Ph.D.	Univ. of Penn.	"

OTHER GRADUATE LEVEL COURSES TAKEN	WHERE TAKEN	YEAR	CREDIT YES	CREDIT NO
Advanced Math.	Univ. Penn.	1952	X	
Electromag. Theory	" "	1953	X	
Functions of Complex Variable	" "	1953	X	
Transients in Linear Systems	" "	1958	X	

ADDITIONAL INFORMATION

(5)

HONORS AND AWARDS

YEAR	LIST FELLOWSHIPS, MEDALS, HONORARY FRATERNITIES AND DEGREES
1940	Graduation with Honors, Yale University
1941	Bashley Fellowship - Univ. of Penn.
1946	Citation by Chief Bu-Ships - Research Report
1961	Elected Fellow - American Physical Society

SIGNIFICANT ACHIEVEMENTS

YEAR	LIST PAPERS, BOOKS, PATENTS, PROFESSIONAL SOCIETY ACTIVITIES, ETC.
1947	Co-author - Textbook "Electrical Acoustics"
1949	Chairman - Seminar "Undersea Acoustics"
1962	Nat. Chairman - Panel on Acoustical Electronics
	Acoustical Society of America

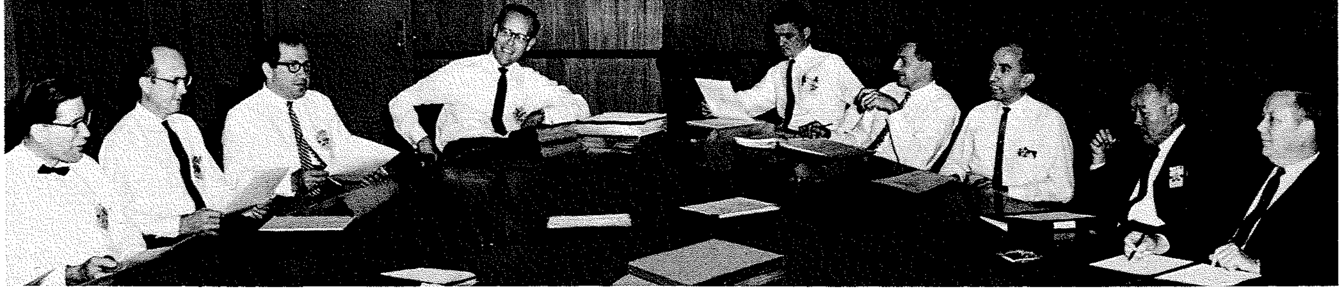


Fig. 2. The Chief Engineer's Technical Excellence Committee. Left to right: G. H. Stevens, S. H. Buder, J. S. Russo, R. D. Mitchell, G. M. Sparks, N. Lesso, J. Strip, Y. H. Dong, and C. A. Hobbs. Not shown: R. F. Pavley, R. S. Johnson, H. B. Boardman, W. W. Carter, C. P. Clasen, H. Geyer, S. J. Macko, D. L. McLaughlin, J. L. Sullivan, and W. C. Wilkinson.

and discussed current business problems and the plans to overcome them. The second, a dinner meeting held 24 May 1965, featured a discussion of internal and external business matters that were of concern to the engineers. Both of these meetings unquestionably improved the understanding of the goals set by the Chief Engineer.

A plan was developed for improving both the significance and frequency of staff meetings, another positive motivational element toward improved technical excellence. Upward communication is solicited and encouraged to make information transfer truly a two-way process.

Chief Engineer's Technical Excellence Committee (CETEC)

The establishment of CETEC in early February 1965 was the most significant single contribution to the Technical Excellence Program. After a thorough planning period, during which many approaches were considered, this body of senior technical representatives from every activity in the Engineering Department was formed. Committee members (Fig. 2) were selected on the basis of their acceptance by their peers. Each member has expressed a strong desire to help maintain and improve the technical excellence performance and reputation at Moorestown.

The primary objective of CETEC is to promote an environment conducive to technical excellence among all members of the RCA Moorestown engineering community and to serve as an advisory committee to the Chief Engineer in such matters. During its first meeting, CETEC established three broad goals:

a) To aid the individual engineer in advancing his technical skills and keeping abreast of the state-of-the-art.
b) To provide a mechanism for formally recognizing and publicizing individual technical achievements and advances.
c) To enhance the technical reputation of the M&SR Engineering Department in the community and in industry.

Shortly after its formation CETEC organized itself into four working subcommittees to concentrate on these goals. In addition to its many full committee meetings, each working subcommittee has met frequently to consider specific areas where problems are hindering the attainment of the broad goals cited above, or where specific activity, on the part of one or more of the subcommittees, will result in positive steps toward realizing these goals. Important areas considered thus far have included:

a) Manpower utilization and planning for technical excellence.
b) A variety of training programs for updating engineering skills.
c) Publications and publicity for engineering accomplishments.
d) Participation by M&SR personnel in the activities of professional technical societies.
c) Recognition and awards for notable achievements.

The efforts of CETEC to date have been very successful. Many recommendations have been implemented; a survey of the entire engineering community revealed the most pressing problems in the minds of the engineers, and these have been or are being resolved; and many discussions and lectures have been arranged on technical subjects of current importance to the engineers (these affairs serve as another path for communicating management philosophy and decisions on subjects of broad interest). CETEC has been a prime catalyst in the pursuit of technical excellence.

Recognition and Awards

To sustain the pursuit of technical excellence, recognition and reward must be given to the achievers. Under the M&SR Technical Excellence Program, two types of awards are made: Quarterly Activity Technical Excellence Awards and an Annual Technical Excellence Award. Multiple quarterly awards are made to individuals for achievements in the various activities of the engineering community. Once each year, the achievements of these individuals are evaluated by CETEC and the Chief Engineer to select the most outstanding case for the annual award.

Fig. 3. Plaque given by CETEC for Quarterly Activity Technical Excellence Award.

Achievements are measured against *standard* (throughout the engineering community) critria and *unique* (to the individual's work) criteria. Standard criteria include:

a) Outstanding accomplishments in connection with the individual's work made during the quarterly period, or outstanding accomplishments made over a longer period but which were culminated during the quarterly period.
b) Published or presented technical papers, engineering reports and memoranda, patent disclosures, etc., pertaining to the achievement.
c) Resourcefulness, creativeness, maturity, and diligence in carrying out the cited achievement.
d) Present and future value of the achievement to the activity, the engineering community, and RCA.
e) Professional affiliations (societies, committee memberships, professional groups, offices held, etc.).
f) Other professional and honorary awards.
g) Educational background (degrees received and when).

Recipients of the quarterly awards and their sponsors are honored in a private luncheon with the Chief Engineer and guests. Each person so honored receives a suitably inscribed plaque (Fig. 3) and a text or reference book of his own choosing (with a pre-established monetary upper limit). The nature of the annual award, which is of significant value, is determined by the Chief Engineer.

In addition to these formal awards, personal letters from the Chief Engineer are sent to all engineers who present or publish a paper, obtain a degree, or otherwise deserve recognition. Also, prizes are awarded to winners of engineering-related contests, such as cost break-throughs.

CONCLUSION

The M&SR Technical Excellence Program initiated in July 1964 has become a worthwhile program in which the entire engineering community is enthusiastically involved. Results to date have been good. Nevertheless, it is realized that the pursuit of technical excellence is a never-ending task that requires persistent application of extra effort.

AUDIO-FREQUENCY JUNGLE MESSAGE ENCODER-DECODER

E. R. SCHMIDT and E. D. SIMSHAUSER

Communications Systems Division

DEP, Camden, N. J.

THE Jungle Message Encoder-Decoder (JMED) described here is designed for use in tactical situations involving cooperating military forces from countries where language barriers exist. If the problems inherent in language inflections, dialects, and accurate translations from English to other languages are to be avoided, the military command and control functions in fluid tactical situations require some form of "universal" language. The JMED device solves part of this tactical communication problem. It has been delivered in quantity to the U.S. Army Electronics Command for evaluation test (Fig. 1).

The JMED meets a number of special operating requirements, as follows:

1) *silent operation*—In some tactical situations, voice communication would betray the user's position. The JMED is essentially silent in operation; under quiet circumstances only a slight clicking sound is audible. This sound is of the same order of magnitude as the rustling of clothing.

2) *language translation*—By providing message cards with the proper digital code imprinted, along with a message in one or more languages, language translation can be accomplished. Each user uses a card printed in his own language.

3) *unattended operation*—Because of the indefinite storage capability of the display modules, the JMED can be left unattended and will receive and retain an incoming message until reset by the attendant or the next message.

The JMED contains a visual readout of five binary-coded displays using combinations of + and *0*. These combinations allow a message content of up to 32 discrete possibilities. Of these, 30 possible coded messages can each represent a different military communication. Thus, uniform, accurate interpretation of any one message is achieved when the person receiving the coded message as a visual readout on the display of his receiver compares that readout to his own message-translation card. The remaining two of the possible 32 message formats are used for device control. An all-*0* readout indicates a *reset* or *standby* condition, while an all + readout signifies an error in the received message.

MESSAGE DISPLAY

The display module (Fig. 1, and Fig. 2 inset) can be read out for sending, or set by the received signal. This complete two-way device includes two display states (+ and *0*), electronic or manual setting of the display, and electrical or visual readout. For transmission, the coded message is set in manually and then read electronically from the display into the transmission system. In reception, the message code received sets the display electrically for the user to visually observe.

Electronic display setting requires a single pulse of 350-mW peak power of about 5-ms duration. Thus, the total set energy is about 1.6 mW·s, and set duration is conveniently low, which minimizes storage problems. Once the display is set, that state holds indefinitely without power. The set energy is low, being *at least five times lower than comparable devices*, a significant feature in battery-operated equipment.

The physical size of a single display module is about 1.2 x 0.8 x 0.8 inches, excluding mounting brackets. Electrically isolated coil leads are provided for *interrogate*, + *readout*, *0 readout*, and *set* coils.

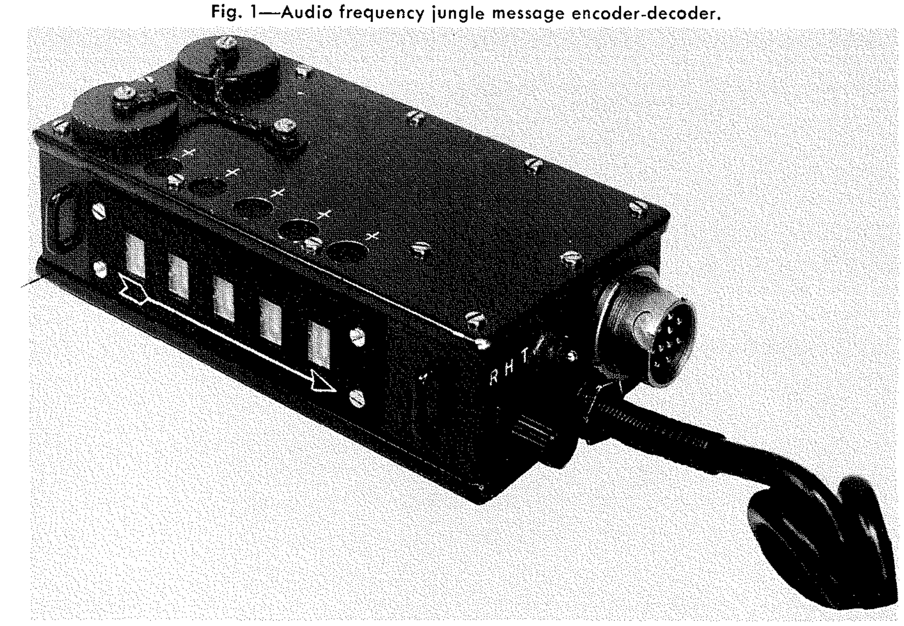
FIELD COMPATIBILITY

The JMED is designed to be compatible with the military man-pack radios used or expected to be used; it is also compact, lightweight, and capable of long life. The feasibility model described in this article uses discrete components and a few microelements. The self-contained nickel-cadmium batteries provide up to 200 operations during normal usage and up to 1,000 hours of capability on a standby basis. Adapters and plugs allow for operation over AN/PRC-10 radios using carbon (10-pin) handsets or AN/PRC-25 radios using dynamic (5-pin) handsets. Other military radios with similar input and output characteristics would be suitable for JMED operation with appropriate connections between the radio and JMED unit.

SYSTEM DESIGN AND OPERATION

The JMED measures 6.75 x 3.5 x 2 inches and weighs a little over three pounds. Besides the two batteries, it contains a selector mode switch for *receive*, *handset*, and *transmit*, and a

Fig. 1—Audio frequency jungle message encoder-decoder.



Final manuscript received October 12, 1965

ARRANGEMENT OF CIRCUIT MODULES

The bold-faced numbers below refer to the numbers shown on Figs. 2 and 3.

1 The bandpass filter amplifier is the input signal coupling stage. This module contains the turn-on signal limiter, the FM-signal bandpass filter stage with its limiter, and a single gain stage.

2 The discriminator amplifier module removes the carrier frequency and the resultant data-bit tones with necessary gain stages.

3 The oscillator filter provides these dual functions for the data-bit tones: a Q-multiplier design for the selective filtering, and by external switching, the capability to perform as data-bit oscillators with the audio-tone gates.

4 This module contains a dual rectifier, integrator, and high-impedance complementary emitter follower which are the data-bit detection stages.

5 The + and 0 detection stages consist of a complementary transistor latching configuration with output of drivers.

6 This module contains a carrier frequency multivibrator which is a voltage-controlled oscillator. The resultant output FM signal is taken directly from this stage.

7 The narrow bandpass filter, amplifier, and rectifier integrator for the start of message-signal detection.

8A The clocked flip-flop module contains the four microelement devices used in the JMED. These stages are connected for gated data-bit counts and + odd parity counts. Associated gates and the readout amplifier are also contained in this module, which constitutes the error circuit.

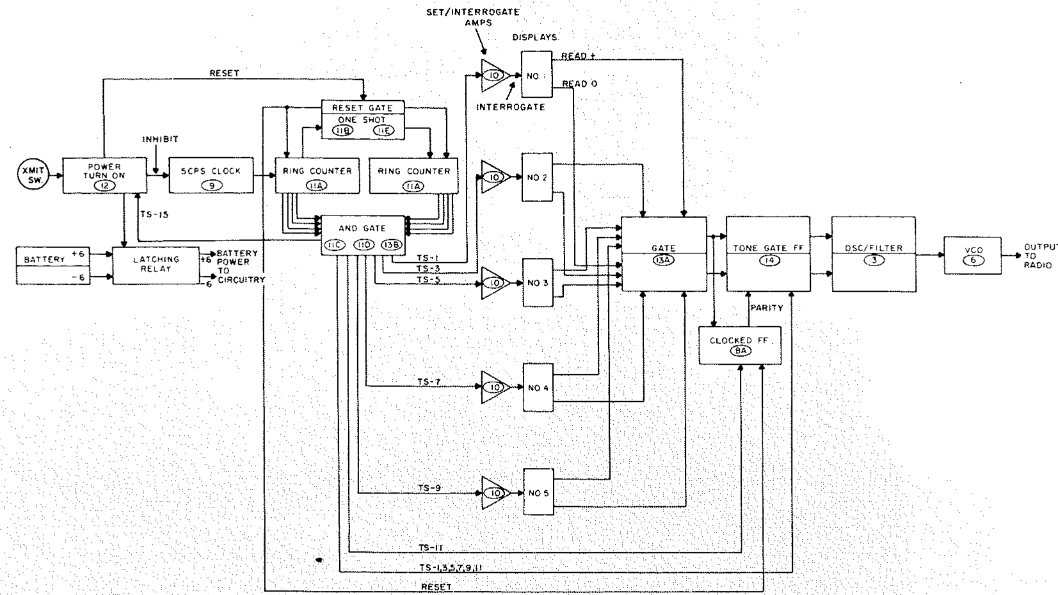
8B The error circuit output drivers which, when pulsed, will supply a set + pulse to all five display modules.

9 This is the most difficult and important module. The clock contains control stages and bias features which determine the astable multivibrator's basic frequency and control. Also included is the sync input stage necessary to the receiver synchronization for decoding the data bits from the time-sequenced transmission.

10 The set +, set 0, and the interrogation gated amplifier stages for each of the five display modules.

11A-11E These generate the 15 time slots required in the JMED time sequence data system. A four-by-four ring counter design made from the complementary latch transistor configuration is used.

12-14 The remaining modules constitute the control, inhibit, one-shot stages, and gate amplifier stages used in the time sequencer generator. The power turn-on module **(12)** contains a latch design for the power turn-on stage driver, and necessary gating steps for the time control to generate and detect the start of the message tone. Another module **(13)** is the display module readout pulse amplifier. Finally, the tone gate flip-flop stages **(14)** are used to provide the control to gate the data-bit tone to the VCO; these are capable of pulsed turn-on and pulsed turn-off.



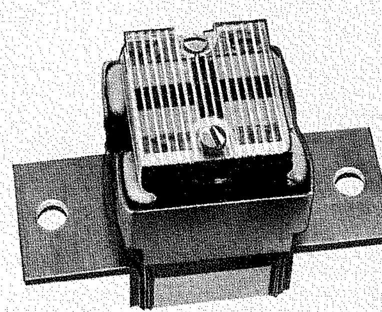


Fig. 2—Above: The jungle message encoder-decoder—transmit mode. Inset (left): The display module.

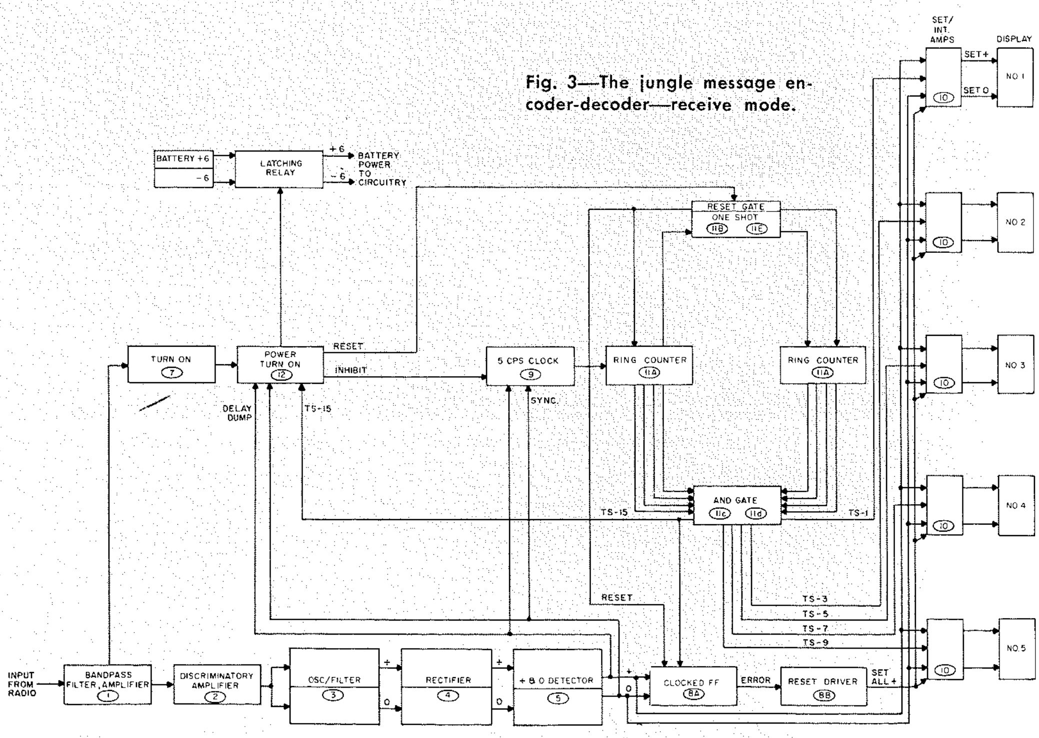


Fig. 3—The jungle message encoder-decoder—receive mode.

toggle switch for *transmit momentary-action.* When the mode switch is in the *handset* position, a handset plugged into the JMED is connected straight through to the radio and the handset operates normally with the radio. The JMED circuitry uses DC power switching to keep power consumption small. The use of complementary transistor pair circuits eased power requirements. These pairs form a device configuration using the flip-flop principle. Other configurations of the pair interconnections and usage provide for a latch effect similar to the silicon controlled switch. All circuit designs aimed for minimum current drain and essentially one-shot action.

TRANSMIT MODE

The transmission system (Fig. 2) is based on two low frequencies: 70 c/s for a *0* data bit and 130 c/s for a + data bit. These frequencies modulate an audio carrier tone of 1,500 c/s that has a required accuracy of ±100 c/s. Hence, the JMED may be used with single-sideband radios. The data-bit tones (70 or 130 c/s) are sent sequentially in a return-to-zero form of message transmission.

In operation, a message is manually inserted in the display by the sender; he then places the selector switch in the *transmit* mode and depresses the transmit toggle switch for a count of two (to warm up the transmitter output stages, where tubes are used). Internal power switching takes place upon release of this toggle switch. The power turn-on produces a carrier tone boost of about 500-ms duration by means of a resistance-capacitance timing circuit. This tone burst is used for the start of the message signal. After the tone generation, the timing generator produces time slot *1* (*TS1*); the *TS1*, through gates, drives an interrogation pulse into display module *1*. This interrogation is read out by a pulse amplifier signifying either + or *0* state within the display module. The first data bit to be sent, either a + or *0*, is a 1,550-c/s gated tone from the 70-c/s and the 130-c/s tone oscillators into the carrier voltage-controlled oscillator. The resultant frequency-modulated tone (representing the first data bit) with a deviation of ±300 c/s is then transmitted in *TS1*. Then, *TS2* sends only the carrier tone, while *TS3*, *TS5*, *TS7*, and *TS9* send data bit tones. Alternately *TS4*, *TS6*, *TS8*, and *TS10* send only the carrier tone. As the data-bit tones of the five displays are transmitted, a count of + odd is used to provide a parity-bit tone in *TS11*. At the completion of *TS11*, the pure carrier tone is generated continuously until the end of *TS15*. This tone is used to provide extra guarding against voice-noise simulation and a more reliable signal detection. A more detailed explanation of this combined system tone transmission will be given in the next section.

RECEIVE MODE

When a message is received by JMED (Fig. 3), the initial 500-ms carrier tone provides a selected discrete turn-on signal. Use of hard limiting, narrow-band-pass selection, and tone integration of this carrier tone guards against false turn-on by voice, noise, etc. The detected start-of-message tone turns on the DC power to the receiving JMED, provides clock inhibition, and reset-standby to the receiving circuits. The first data-bit tone is demodulated, fed to frequency-selective filters, rectified, and level-sensed. The resultant step response is gated with the receive-generated *TS1* which will have been enabled by the initial edge of data bit detection. The *and*ed signal is used to set the receive display module one into the proper + or *0* state.

The basic time used for transmitting time slots is 175 ms, consistent with reliable detection of the 70-cps tone with a low tone-to-noise ratio. The receiving time-slot clock is free running at a slower rate than the transmitting clock. Hence, each detected data-bit tone generates a pulse which synchronizes the longer-duration receiver clock with the transmitted data bits on a bit-by-bit basis.

Each detected data bit is counted in an error circuit. The correct count is six bits (five displayed, plus one parity). The + odd count is also performed. During the time corresponding to *TS12* through *TS14*, the error circuits remained enabled; if more than six counts or a + even parity is recorded, then an error is indicated. The sample time for the error readout is *TS15*. If an error is detected, then a *set error* pulse is generated, driving all five display modules to the + condition signifying a message received in error. The end of *TS15* is used to reset the DC power stage to an all-*off* condition.

CIRCUIT MODULES

Certain circuit functions are combined in the same module. Figs. 2 and 3 have accompanying text that keys the circuit functions to the 14 modules that are used.

These modules were fabricated in cordwood packaging concepts, using small components. The design was especially tailored to achieve minimum power drain. A hybrid approach to integrated circuit techniques could be used for further reduction in size.

ACKNOWLEDGEMENT

Work was sponsored by the Advanced Research Projects Agency under Contract DA-28-043-AMC-00090(E). The equipment is being evaluated by the Communications Automatic Data Processing Laboratory of the U.S. Electronics Command.

EDWARD R. SCHMIDT received his BSEE degree in 1955 from Purdue University. He joined ITT Federal Laboratories as a member of the technical staff in 1955 and worked on a transistorized oscillator and DC dialing for commercial telephones. In 1956 he joined the Stromberg Carlson Company and worked on electronic switching. In 1959 he joined RCA Systems Group in Tucson working on field army integration studies. He has worked on several digital-communications projects. In 1962 Mr. Schmidt joined Hughes Tucson Engineering Lab and worked on the electronic chassis of the GAR II AIM Missile. He returned to RCA in 1963 and was lead design engineer for the Tucson effort on the AN/FSQ and the JMED projects. Mr. Schmidt is a member of the IEEE, and he has had three patents issued.

ELVIN D. SIMSHAUSER graduated from Kent State Unviersity with a BS in Physics in 1951 and joined RCA in Camden, New Jersey at that time. After completing the engineering training program he was assigned to the Special Devices Section where he did development work on sound powered telephones, aircraft and submarine intercom systems, and miscellaneous transducers. After two years in the Army as a computer technician, he returned to RCA (Surface Communications Division) in 1956, working on headset and microphone development for the Air Force. In 1958 he was promoted to Leader and worked on several classified communications systems. He transferred to the RCA Tucson Plant in 1963 and since that time has been responsible for three programs, one of which is the Jungle Message Encoder-Decoder.

THREE RCA MEN ELECTED IEEE FELLOWS

The three RCA men cited herein have been honored for their professional achievements by being elected Fellows of the Institute of Electrical and Electronic Engineers. This recognition is extended each year by the IEEE to those who have made outstanding contributions to the field of electronics.

GERALD B. HERZOG

. . . for contributions to solid-state television and computer circuits

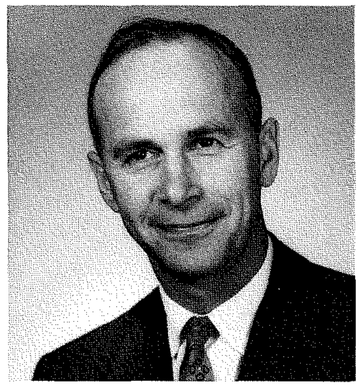
GERALD B. HERZOG received his BSEE and MSEE degrees from the University of Minnesota in 1950 and 1951, respectively. He has been active in semiconductor work since joining RCA Laboratories in 1951. He helped develop the first completely transistorized TV set in 1952, and later did research on transistorized color sets. In 1957 he began work on ultra-high-speed computer circuits and led a group working on microwave phase-locked-oscillators and tunnel diode circuits. As Head of the Solid-State Computer Devices group of the Computer Research Laboratory, RCA Laboratories, Princeton, N.J., he is presently concerned with the application of integrated circuits in computer logic and memory. Mr. Herzog is a member of Sigma Xi and Eta Kappa Nu. Prior to being named a Fellow of the IEEE, he was a senior member. He has received the David Sarnoff Outstanding Team Award in Science for his work on high-speed computers, as well as two Achievement Awards. He has published several papers on transistor and tunnel diode circuits, and he holds 20 issued U.S. patents.

HARRY R. WEGE

. . . for contributions to radar and weapons systems

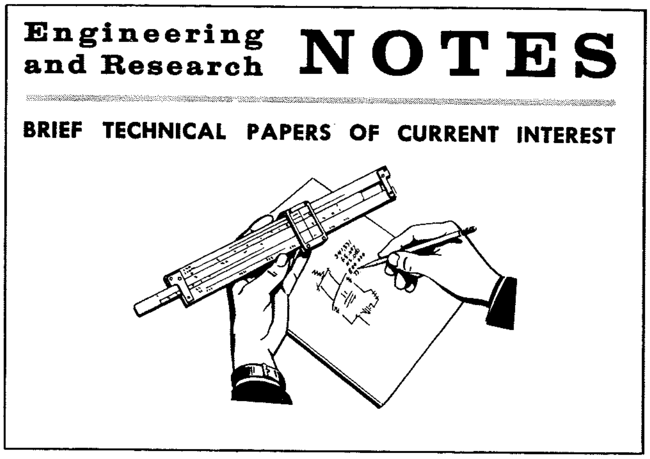
HARRY R. WEGE received his BSEE degree from Kansas State University. Since joining RCA in 1930 he has held numerous engineering and management positions, including design and development engineer, radar engineer, and Chief Engineer of Missile and Surface Radar Operations. In 1954 he received the RCA Victor Award of Merit for his outstanding contributions to radar and guided missile work. He was appointed Manager, M&SR Operations in 1955 and subsequently served as General Manager of the M&SR Division from 1956 to 1959. In 1961 he was named Vice President and General Manager of DEP's newly formed Data Systems Division. He is presently a Vice President of RCA and Director of the SAM-D Program (Surface to Air Missile—Development). Mr. Wege is a licensed professional engineer in the State of New Jersey and a member of Sigma Tau, the American Society of Naval Engineers, Armed Forces Communications and Electronics Association, American Ordnance Association, and Armed Forces Management Association. Prior to being named a Fellow of the IEEE, he was a senior member.

HANS K. JENNY



. . . for contributions to the development of microwave devices

HANS K. JENNY received his MSEE degree from the Swiss Federal Institute of Technology in 1943. As assistant professor with the Institute for two years, he did research on klystrons and the reduction of their noise figure. He joined RCA in 1946 and was given responsibility for the development of CW magnetrons and frequency-modulating schemes for magnetron oscillators. In 1950 he was promoted to engineering manager. In this capacity he was responsible for applied research and advanced development in support of traveling-wave tubes, microwave solid-state devices, pencil tubes, and power and super-power devices. As Manager, Advanced Development Engineering, Microwave and Power Devices Operations, his responsibilities cover activities based in Harrison, N.J., Lancaster, Pa., and Princeton, N.J. Mr. Jenny holds 12 patents in the fields of magnetrons, cavity tuning and modulation, crossed-field amplification and radar systems. He is the author of numerous publications pertaining to microwave devices. He was a senior member of the IEEE prior to being named as a Fellow.



High-Speed Film Processor and Quick-Access Display System

E. SCHWARTZ AND A. A. BLATZ,
Missile and Surface Radar Division,
DEP, Moorestown, N. J.

Fig. 1—The authors, Elihu Schwartz (left) and Andrew Blatz, inspect a film strip from the 35-mm Bimat-film processor developed while they were assigned to Advanced Systems Technology, Hydrospace Group, M&SR.

Several new high-speed film processors and a new high-resolution, quick-access display system have been developed by the DEP Missile and Surface Radar (M&SR) Division at Moorestown, N. J.

The 35-mm CRT recording camera/processor (Fig. 1) is a self-contained system that continuously records transient data from a CRT or other light source and prints out a high-quality positive and optional negative. The dry positive is available for analysis in less than 1 minute. The first in the industry to use the Eastman Kodak 10-second Bimat technique, this processor is an outgrowth of M&SR work on optical data-processing and display equipment for military applications.

The Bimat film, which consists of a support carrying a hydrophilic layer containing physical development nuclei, is supplied in a soaked, or chemically changed, condition. Bimat permits the use of silver halide films for the first time in systems requiring fast, dry image formation with a high packing density. Silver halide films have sensitivities at least 100 times greater than other dry recording processes and resolutions greater than 100 line pairs per millimeter, compared with resolutions of 3 to 5 line pairs for other dry processes.

High-speed Bimat processing potentially can be used in many areas for the recording, storage, and readout of optical information. M&SR engineers believe that the simplicity, cleanliness, and reduced handling of the Bimat film processors make them logical replacements for existing wet systems. For example, displays using wet processing or low-quality dry processing are employed now in space and military systems for command and control, side-looking radar, information storage and retrieval, air traffic control, and data processing. The use of photographic film for on-line computer readouts that permit high-resolution, continuous-tone, high-speed displays is now practical.

The basic processing technique of the RCA 35-mm camera/processor is illustrated in Fig. 2. The negative film is first exposed in the gate and then laminated to the processing film between the first laminating rollers. The laminate passes through the temperature-controlled oven, where it is processed in 10 seconds, and then the films are separated at the delaminating rollers. If desired, the tacky positive may be dried with warm air before handling. Base fog can be removed from the negative by relaminating it with a second processing film. After processing, the positive may be viewed or projected immediately and the negative stored for future analysis. Specifications for this camera/processor are shown in Table I.

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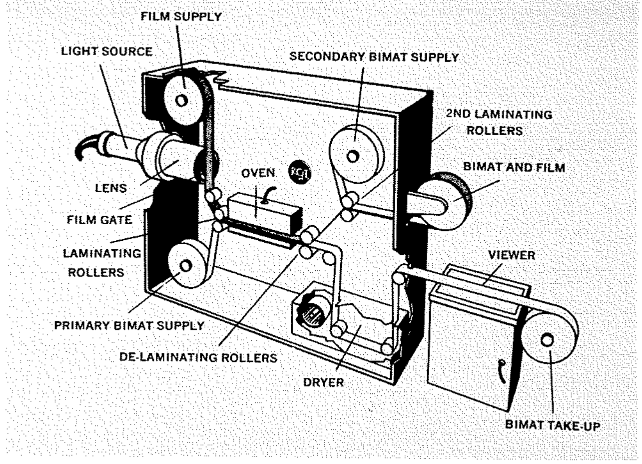


Fig. 2—Simplified schematic diagram of processing technique used in 35-mm CRT recording camera/processor.

TABLE I—Specifications for RCA 35-mm CRT Recording Camera/Processor

Display film	35-mm Bimat (SO-111)
Type of copy	Positive, continuous-tone print on polyester base; optional negative, continuous-tone print on acetate base
Film transport	Continuously variable from 0.3 in/min to 1 in/sec
Access time	Variable; dependent on transport speed
Construction	Suitable for mobile transportation and operation
Capacity	100 ft of film

The RCA 5-inch in-flight film display system is a self-contained, quick-access signal recorder that produces high-quality positives with minimum delay. The system includes the electronics, light source, camera, processor, and viewer. The use of silver halide recording provides extreme actinic sensitivity, high resolution, and high packing density. Specially fabricated polyurethane transport belts are used to drive the film, control the critical laminating pressure and temperature, and maintain the lamination for sufficient time to completely develop and fix the film (Fig. 3). This processing system minimizes the time from exposure to view, even for displays requiring slow transport rates. With this system it is possible to use high writing speeds and microscopic spot sizes to obtain high-resolution displays with access within seconds. Specifications for the RCA 5-inch in-flight film display system are presented in Table II.

Fig. 3—Simplified schematic diagram of processing technique used in 5-inch in-flight film display system.

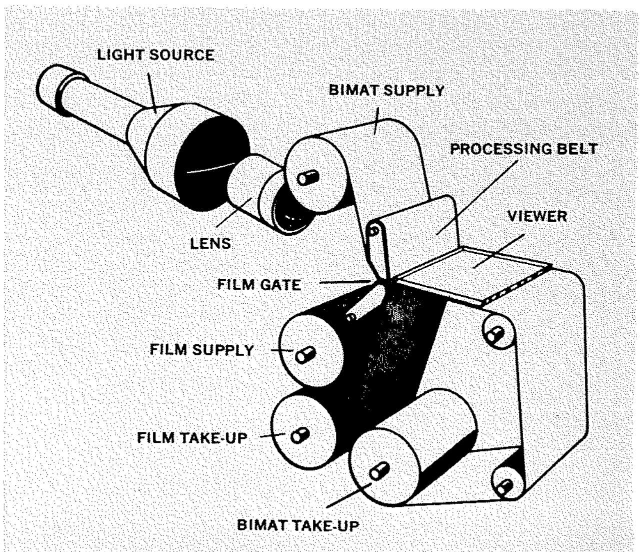


TABLE II—Specifications for RCA 5-Inch In-Flight Film Display System

Display film	5-inch Bimat (SO-111)
Type of copy	Positive, continuous-tone print on polyester base
Light source	P-11 phosphor spectrum or equipment
Film transport	Dual film rates, 0.3 in/min and 1.0 in/min
Access time	30 sec at 1 in/min transport speed (exposure to view)
Construction	Suitable for use in high-performance military aircraft
Capacity	8 to 24 hrs of continuous operation without reloading

In addition to the equipment described above, M&SR has developed another type of 35-mm processor and a 16-mm quick-access processor for use in optical data correlation. Additional information on any of these devices can be obtained from E. Schwartz, Radiation Equipment Product Design, or A. Blatz, Data-Processing Engineering Product Design, M&SR.

Pattern Generation Under Numerical Control

Dr. R. Rosenfeld
RCA Laboratories, Princeton, N. J.

Final manuscript received November 19, 1965

One of the manifestations of the trend toward automation has been the growing importance of numerically controlled machines for production purposes. The operation of such machines is controlled by a tape rather than by a human operator. These machines offer better accuracy and considerably greater speed than can be expected from a human operator, and they are less subject to error. The requirement for skill and know-how is not in the operation of the machine, but rather in the generation of the control tapes.

A numerically controlled coordinatograph (Fig. 1) has recently been installed at the David Sarnoff Research Center. This machine has a flat bed that can accommodate a photosensitive film measuring 48 by 60 inches. A carriage containing a light that projects a light spot on the film is mounted above the bed and can be continuously moved in both the x and y directions by motor-driven screws. In operation, a punched tape controls the size, intensity, shape, and position of the light spot. The output of the machine is a line pattern on a film transparency. Line widths as small as 0.005 inch, positioning accuracies of 0.001 inch, and repeatability accuracies of 0.0005 inch can be achieved. Such precision makes it possible to eliminate the optical reduction step that has been the common procedure in many applications. Photographic transparencies of the type generated by the machine have become essential elements in the fabrication of a wide variety of electronic systems. An identical table with a faster control system is in operation at Central Engineering in Camden. It is used primarily for generating patterns for back-plane wiring boards for the Spectra 70[1].

The generation of the control tapes by conventional methods is time consuming and requires considerable care. The desired pattern must be expressed as the x-y coordinates of every single point. The tracing of curves requires a very large number of points, since they must be made up of a series of very short, straight-line segments. Therefore, a special computer language has been devised at RCA Laboratories whereby the 601/301 Computer makes most of the tedious and repetitive calculations. With this language, tapes can now be generated very easily, even by inexperienced programmers. Besides providing for the systematic preparation of tapes, the computer carries out calculations necessary for making circles, scaling, repeating figures, and for blackening the entire interior of a polygon when only the boundaries are specified. In the initial use of this technique, several types of integrated circuit patterns and some highly repetitive patterns for display devices were produced.

1. G. H. Lines, E. A. Szukalski, and F. X. Thomson, "Photochemical Laboratory—Processes for Integrated-Circuit Multilayer Printed Wiring," *RCA Engineer*, October-November, 1965, page 38.

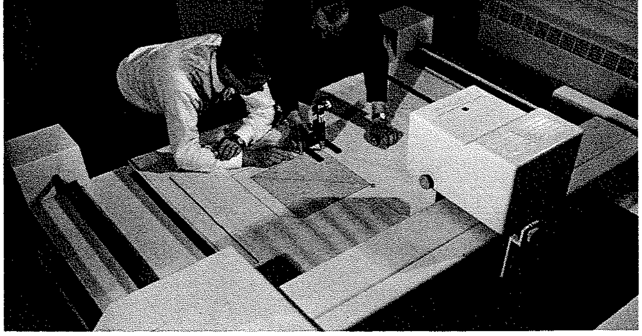


Fig. 1—This numerically controlled coordinatograph at the David Sarnoff Research Center has been used extensively in the preparation of precision patterns.

Automatic Continuity and Leakage Tester for Multilayer Printed-Circuit Boards

Nate Parks, *Applied Research, DEP, Camden, N. J.*

Final manuscript received December 21, 1965

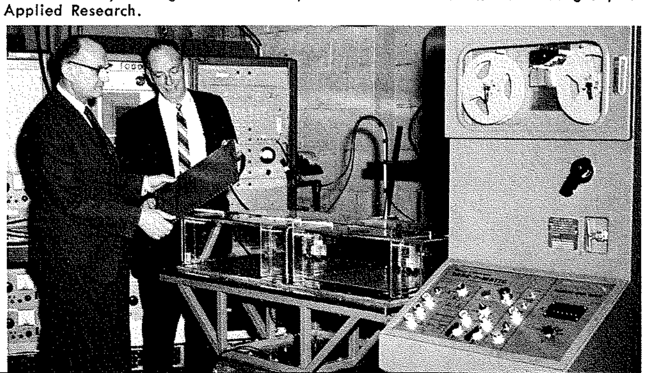
Multilayer printed-circuit boards, now being used extensively throughout the Corporation, have reached a high state of complexity. They may contain as many as 3800 conductor or copper paths, resulting in complicated interconnecting nets. A manual point-to-point check of such a board confronts an operator with about 16,000 check-point locations, consuming an estimated eight hours for full appraisal. Automatic test equipment capable of handling a task of this size is available on the market, but it costs between $160,000 and $300,000, with an additional cost of $30,000 to $50,000 for new interface and jig equipment each time a new board or wiring format is introduced. A simultaneous attachment of up to 9,000 electrical connections is required for this equipment, resulting in questionable reliability and requiring considerable programming by paper or magnetic tape.

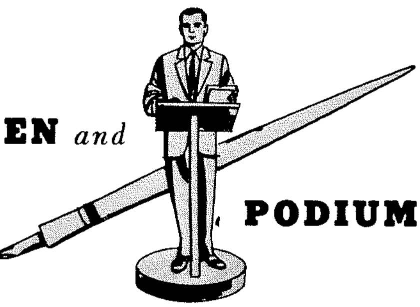
To meet RCA's need for a cheaper, faster, and more reliable way to check multilayer printed-circuit boards, Nate Parks of DEP Applied Research conceived and directed the implementation of the capacitive continuity tester (Fig. 1). The first tester, now in operation, cost $60,000 to construct. Three additional units are now being fabricated at an expected cost of $45,000 per unit. No programming is required for these units, and changing over to a different board or wiring format is a simple matter of adjusting the X and Y axis stepping increments. Reliability is greatly increased by the requirement for only two point contacts, instead of 9,000 electrical connections. With this equipment, a board as large and complex as the Spectra 70/45 back plane can be completely tested in less than 30 minutes.

Testing is accomplished with a pair of synchronized contacts mechanized for automatic and sequential connection on corresponding pads of both a standard pretested board of known quality and the board being tested. (The board to be tested is first prestressed by application of a high voltage to check for shorted conductors and to induce failure in borderline insulation.) In the point-by-point test, capacitance-to-ground is compared with the capacitance of the corresponding point on the standard board. Predetermined deviations from the standard are recorded in a manner that locates the faulty point for subsequent visual inspection and repair.

Mr. Park's design was developed to the point of proven application by J. Surina of Applied Research. It was then implemented by Anthony Pendino and Daniel E. Simpson of the Test Equipment Design group of CSD, who accomplished the final design and constructed the tester shown in Fig. 1. Three additional machines are now under construction.

Fig. 1—Nate Parks (right), Engineering Leader, Applied Research, discusses the operation of the multilayer printed-circuit-board tester, that he conceived, with Joe Brustman, Manager of the Computer Advanced Product Research group of Applied Research.





PEN *and* PODIUM

A SUBJECT-AUTHOR INDEX TO RECENT RCA PAPERS

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SUBJECT INDEX

Titles of papers are permuted where necessary to bring significant keyword(s) to the left for easier scanning. Authors' division appears parenthetically after his name.

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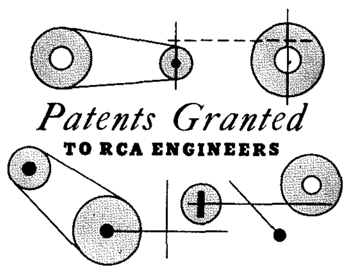

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Flow Gauges—K. N. Karol, I. Weiss (ECD, Hr.) *U.S. Pat. 3,224,270*, Dec. 21, 1965

Indirectly Heated Cathode—J. W. Hollingsworth, M. R. Horton (ECD, Lanc.) *U.S. Pat. 3,225,246*, Dec. 21, 1965

Transistor Circuitry Having Combined Heat Dissipating Means—R. Minton (ECD, Som.) *U.S. Pat. 3,226,564*, Dec. 28, 1965

Square Loop Molybdenum Modified Ferrites—H. Lessoff, E. G. Fortin (ECD, Needham) *U.S. Pat. 3,223,641*, Dec. 14, 1965

Power Transistor and Method of Manufacture—J. E. Wright, J. Shellick (ECD, Som.) *U.S. Pat. 3,223,902*, Dec. 14, 1965

Getter Assembly for Electron Tubes—J. J. Free, J. W. Gaylord (ECD, Lanc.) *U.S. Pat. 3,221,201*, Nov. 30, 1965

Sintered Metal Conductor Support—F. R. Ragland, Jr. (ECD, Lanc.) *U.S. Pat. 3,221,203*, Nov. 30, 1965

Logic Switching Circuit Comprising a Plurality of Discrete Inputs—B. Zuk (ECD, Som.) *U.S. Pat. 3,217,181*, Nov. 9, 1965

Variable-mu Electron Discharge Device—O. H. Schade, Sr. (ECD, Hr.) *U.S. Pat. 3,217,202*, Nov. 9, 1965

Apparatus for Testing Magnetic Materials—D. A. Kadish (ECD, Needham) *U.S. Pat. 3,229,195*, Jan. 11, 1966

BROADCAST AND COMMUNICATIONS PRODUCTS DIVISION

Wide Range Variable Frequency Free-Running Multivibrator—L. V. Hedlund (BCD, Cam.) *U.S. Pat. 3,222,617*, Dec. 7, 1965

Amplifier Including Momentary Gain Increasing Means—P. Dowhy (BCD, Meadow Lands) *U.S. Pat. 3,218,568*, Nov. 16, 1965

Contrast Control System—R. W. Voeckler (BCD, Cam.) *U.S. Pat. 3,217,100*, Nov. 9, 1965

Pulse-Width Discriminator—R. N. Hurst (BCD, Cam.) *U.S. Pat. 3,219,838*, Nov. 23, 1965

RCA VICTOR HOME INSTRUMENTS

Stereophonic Phonograph System—J. A. Tourtellot (H.I., Indpls.) *U.S. Pat. 3,225,146*, Dec. 21, 1965

Dampened Suspension Systems for Stereophonic Phonograph Pickups—R. P. Peterson (H.I., Indpls.) *U.S. Pat. 3,226,124*, Dec. 28, 1965

Parametric Frequency Converters—L. A. Harwood, T. Murakami (H.I., Indpls.) *U.S. Pat. 3,226,645*, Dec. 28, 1965

Remote Control System—T. C. Jobe, E. J. Evans (H.I., Bloomington) *U.S. Pat. 3,218,388*, Nov. 16, 1965

Magnetic Recording and Reproducing Apparatus—P. E. O'Connell (H.I., Indpls.) *U.S. Pat. 3,216,275*, Nov. 9, 1965

Television Tuner Switching System—R. D. Brand (H.I., Indpls.) *U.S. Pat. 3,219,933*, Nov. 23, 1965

Suspension Systems for Phonograph Pickups—D. R. Andrews, J. A. Tourtellot (H.I., Indpls.) *U.S. Pat. 3,228,700*, Jan. 11, 1966

Printed Circuit Push Button Switch Device with Cam Follower Contact Actuating Structure—T. D. Smith (H.I., Indpls.) *U.S. Pat. 3,229,053*, Jan. 11, 1966

Electrically Tunable Field-Effect Transistor Circuit—D. J. Carlson (H.I., Indpls.) *U.S. Pat. 3,229,120*, Jan. 11, 1966

RCA VICTOR RECORD DIVISION

Sound Signal Transforming System—D. L. Richter (Rec., Indpls.) *U.S. Pat. 3,229,038*, Jan. 11, 1966

DEFENSE ELECTRONIC PRODUCTS

Frequency Modulator Recording—H. R. Warren (DEP-CSD, Cam.) *U.S. Pat. 3,229,046*, Jan. 11, 1966

Field-Effect Transistor Circuit—L. Sickles, M. E. Malchow (DEP-AppRes, Cam.) *U.S. Pat. 3,229,218*, Jan. 11, 1966

Output-Follows-Input Pulse Amplifier Employing a Tunnel Diode Bistable Circuit Having an Inductor—R. H. Bergman (DEP-AppRes., Cam.) *U.S. Pat. 3,217,180*, Nov. 9, 1965 (assigned to U.S. Gov't.)

Apparatus for Providing Fluid Bearings—R. D. Scott (DEP-CSD, Cam.) *U.S. Pat. 3,228,014*, Jan. 4, 1966

Magnetic Transducer—H. R. Warren (DEP-CSD, Cam.) *U.S. Pat. 3,225,145*, Dec. 21, 1965

Monostable Pulse Generator Employing Delayed Switch Means Shunting Tunnel Diode for Controlling State Thereof—C. Neitzert (DEP-AppRes., Cam.) *U.S. Pat. 3,225,219*, Dec. 21, 1965

Information Translating Apparatus—E. D. Simshauser (DEP, Cam.) *U.S. Pat. 3,223,029*, Dec. 14, 1965

Positive Acting, Multiposition Detent Switch—R. R. Helus, F. J. Jansen (DEP-WCD, Van Nuys) *U.S. Pat. 3,222,466*, Dec. 7, 1965

Computer Circuits—W. J. Gesek, L. L. Rakoczi (DEP-CSD, Cam.) *U.S. Pat. 3,221,154*, Nov. 30, 1965

Memory Circuit Employing Negative Resistance Elements—M. M. Kaufman (DEP-AppRes, Cam.) *U.S. Pat. 3,221,180*, Nov. 30, 1965

Magnetic Reading Apparatus for Demodulating a Recorded Frequency Modulated Signal—H. R. Warren (DEP-CSD, Cam.) *U.S. Pat. 3,218,618*, Nov. 16, 1965

Gate Circuit for Providing Integral Pulses—H. Chin (DEP-ASD, Burl.) *U.S. Pat. 3,217,176*, Nov. 9, 1965

Logic Circuits—B. Walker (DEP-AppRes., Cam.) *U.S. Pat. 3,217,177*, Nov. 9, 1965

Wave Guide Connector—D. J. Newman (DEP-ASD, Burl.) *U.S. Pat. 3,202,946*, Aug. 24, 1965 (assigned to U.S. Gov't.)

Temperature-Stabilized Transistor Multivibrator—P. J. Anzalone, A. D. Mayer (DEP-CSD, Cam.) *U.S. Pat. 3,194,977*, July 13, 1965 (assigned to U.S. Gov't.)

Meetings

MARCH 2-4, 1966: **Scintillation & Semiconductor Counter Symp.**, IEEE, G-NS; Shoreham Hotel Wash., D.C. **Prog. Info.:** W. A. Higinbotham, Brookhaven Nat'l Labs., Upton, L.I., N.Y.

MARCH 21-25, 1966: **IEEE Intl. Convention**, IEEE, All Groups, TAB Comms.; Coliseum & New York Hilton Hotel, N.Y., N.Y. **Prog. Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

MARCH 22-23, 1966: **Biomagnetics Mtg.**, Amer. Phys. Soc.; Univ. of Illinois. **Prog. Info.:** M. F. Barnothy, Univ. of Illinois, 833 S. Wood St., Chicago, Ill.

MARCH 30-APR. 1, 1966: **Engineering Aspects of Magnetohydrodynamics Mtg.**, Amer. Soc. of Mech. Engrs., IEEE, AIAA; Princeton University. **Prog. Info.:** R. G. Jahn, Guggenheim Labs., Forrestal Res. Center, Princeton, N.J.

MARCH 31-APR. 1, 1966: **Conf. on Analysis & Synthesis of Networks**, IEEE W. German Section VDE; Stuttgart, W. Germany. **Prog. Info.:** H. H. Burghoff, 6 Frankfurt S10, Stresemann Allee 21, VDE Haus, W. Germany.

APR. 12-14, 1966: **Cleveland Electronics Conf.**, IEEE Cleveland Section, et al.; Cleveland, Ohio. **Prog. Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

APR. 12-15, 1966: **4th Quantum Elec. Conf.**, IEEE, G-ED, G-MTT, et al.; Towne House, Phoenix, Ariz. **Prog. Info.:** J. P. Gordon, Bell Telephone Labs., Murray Hill, N.J.

APR. 18-19, 1966: **1st Nat'l ISA Symp. on Maintenance**, ISA; Wilmington, Delaware. **Prog. Info.:** R. H. Miller, P.O. Box 7007, Wilmington, Delaware.

APR. 18-21, 1966: **Spring URSI-IEEE Mtg.**, IEEE-URSI; Natl. Academy of Science, Wash., D.C. **Prog. Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

APR. 20-22, 1966: **1966 INTERMAG (International Conference on Magnetics)**, IEEE, G-MAG, VDE, AF; Liederhalle, Stuttgart, Ger. **Prog. Info.:** Dr. E. W. Pugh, IBM Corp., 1000 Westchester Ave., White Plains, N.Y.

APR. 20-22, 1966: **Southwestern IEEE Conf. & Elec. Exhib. (SWIEEECO)**, IEEE, Region 5, Dallas Memorial Auditorium, Dallas, Texas. **Prog. Info.:** Dr. Robert Carrel, Collins Radio Co., Dallas, Tex.

APR. 26-28, 1966: **Spring Joint Computer Conf.**, IEEE, AFIPS, ACM; Boston Civic Ctr., Boston, Mass. **Prog. Info.:** Dr. H. Anderson, Digital Equip. Corp., Maynard, Mass.

MAY 4-6, 1966: **1966 Electronic Components Conf.**, IEEE, G-IGA, ASME-SAE; San Francisco, Calif. **Prog. Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

MAY 5-7, 1966: **7th Symp. on Human Factors in Electronics**, IEEE, G-HFE, Minneapolis, Minnesota. **Prog. Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

MAY 10-12, 1966: **Nat'l Telemetering Conf.**, IEEE, G-AES, G-ComTech, AIAA-ISA, Prudential Center, Boston, Mass. **Prog. Info.:** Dr. A. J. Kelley, NASA-ERC, 575 Tech. Sq., Cambridge, Mass.

MAY 11-13, 1966: **12th Nat'l ISA Symp.**, ISA, Shamrock Hilton Hotel, Houston, Texas. **Prog. Info.:** G. I. Doering, Tech. Prog. Chairman, Industrial Nucleonics Corp., 650 Ackerman Rd., Columbus, Ohio.

MAY 16-18, 1966: **NAECON (Nat'l Aerospace Elec. Conf.)**, IEEE, G-AES, AIAA, Dayton Sect., Dayton, Ohio. **Prog. Info.:** IEEE Dayton Office, 1414 E. 3rd St., Dayton 3, Ohio.

MAY 16-18, 1966: **1966 Internat'l Symp. on Microwave Theory & Techniques**, IEEE, G-MTT, Palo Alto, Calif. **Prog. Info.:** Rudolf E. Henning, c/o Sperry Microwave Co., P.O. Box 1828, Clearwater, Fla.

P R O F E S S I O N A L   M E E T I N G S

DATES *and* DEADLINES

Be sure deadlines are met—consult your Technical Publications Administrator or your Editorial Representative for the lead time necessary to obtain RCA approvals (and government approvals, if applicable). Remember, abstracts and manuscripts must be so approved BEFORE sending them to the meeting committee.

MAY 16-19, 1966: **4th Nat'l ISA Symp. on Biomedical Sciences Instrumentation**, ISA, Disneyland Hotel, Anaheim, Calif. **Prog. Info.:** Dr. Thomas B. Weber, Prog. Co-Chairman, Beckman Instruments, Inc., 2500 Harbor Blvd., Fullerton, Calif.

Calls for Papers

APR. 20-22, 1966: **1966 Intl. Nonlinear Magnetics Conf. (INTERMAG)**, IEEE, G-Mag VDE; Stuttgart, Germany. **Deadline:** Manuscripts, **4/1/66.** TO: Dr. E. W. Pugh, IBM Corp., 1000 Westchester Ave., White Plains, N.Y.

APR. 26-28, 1966: **Spring Joint Computer Conf.**, IEEE, AFIPS, ACM; Boston Civic Ctr., Boston, Mass. **For Deadline Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

MAY 2-4, 1966: **1966 AIAA Communications Satellite Systems Conf.**, AIAA, IEEE; Wash., D.C. **Deadline:** Manuscripts, **3/21/66.** TO: N. Feldman, Electronics Dept., The Rand Corp., 1700 Main St., Santa Monica, Calif.

JUNE 1-4, 1966: **Acoustical Society of America Mtg.**; Boston, Mass. **Deadline:** Abstracts, **3/2/66.** TO: L. Batchelder, Raytheon Co., 20 Seyon St., Waltham, Mass.

JUNE 6-8, 1966: **Design & Construction of Large Steerable Aerials for Satellite Communications, Radio Astronomy & Radar Mtg.**, IEEE, IEE, et al.; IEE, Savoy Pl., London, England. **For Deadline Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

JUNE 13-17, 1966: **Soc. for Applied Spectroscopy Mtg.**; Chicago, Ill. **Deadline:** Abstracts **3/1/66.** TO: J. E. Burroughs, Borg-Warner Corp., Roy C. Ingersoll Res. Ctr., Wolf and Algonquin Rds., Des Plaines, Ill.

JUNE 15-17, 1966: **1966 IEEE Intl. Communications Conf.**, IEEE, G-ComTech, et al.; Sheraton Hotel, Phila., Pa. **Deadline:** Abstracts **3/1/66.** For Info.: IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

JUNE 20-22, 1966: **San Diego Symp. for Biomedical Engineering**, IEEE, U.S. Naval Hosp.; San Diego, Calif. **For Deadline Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

JUNE 21-23, 1966: **Conf. on Precision Electromagnetic Measurements**, IEEE, G-IM NBS; NBS Standards Lab., Boulder, Colo. **For Deadline Info.:** Dr. Kiyo Tomiyasu, Genl. Electric Co., Schenectady, N.Y.

JULY 4-8, 1966: **Rarefied Gas Dynamics Mtg.**, Amer. Phys. Soc.; Oxford, England. **Deadline:** Abstracts, **March 1966.** TO: C. L. Brundin, Dept. of Eng. Science, Univ. of Oxford, Parks Rd., Oxford, England.

AUG. 23-26, 1966: **WESCON (Western Electronic Show & Convention)**, IEEE, WEMA; Sports Arena, Los Angeles. **Deadline:** Abstracts, approx. **5/1/66.** FOR INFO.: IEEE LA. Office, 3600 Wilshire Blvd., Los Angeles, Calif.

AUG. 29-31, 1966: **2nd Intl. Congress on Instrum. in Aerospace Simulation Facilities**, IEEE, G-AED; Stanford Univ., Stanford, Calif. **For Deadline Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

AUG. 30-SEP. 1, 1966: **21st Nat'l Conf., Assoc. for Computing Machinery**, IEEE, ACM, Ambassador Hotel, Los Angeles, California. **Deadline:** Rough Manuscripts, **Mar. 15, 1966.** TO: B. R. Parker, Tech. Prog. Chairman, 21st Nat'l Conf., P.O. Box 4233, Panorama City, Calif.

SEPT. 5-9, 1966: **Intl. Organization for Pure and Applied Biophysics Mtg.**, Amer. Phys. Soc.; Vienna, Austria. **Deadline:** Abstracts, **5/15/66.** TO: E. Weidenahus, Viennese Medical Academy, Alserstr 4, Vienna 9, Austria.

SEPT. 8-13, 1966: **Physics of Semiconductors Mtg.**, Physical Soc. of Japan; Tokyo, Japan. **For Deadline Info.:** G. M. Hatoyama, PSJ, Hongo, P.O. Box 28, Tokyo, Japan.

SEPT. 12-14, 1966: **Eastern Conv. on Aerospace & Electronic Systems**, IEEE, G-AED; Wash. Hilton Hotel, Wash., D.C. **For Deadline Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

SEPT. 21-23, 1966: **Physics of Semiconducting Compounds**, Inst. of Physics and Physical Soc.; Univ. of Wales. **For Deadline Info.:** R. H. Jones, Dept. of Physics, Univ. College of Swansea, Singleton Park, Swansea, England.

SEPT. 26-27, 1966: **14th Jt. Engrg. Management Conf.**, IEEE, G-EM et al., Statler-Hilton Hotel, Washington, D.C. **For Deadline Info.:** Homer Sarashon, IBM Corp., Armonk, N.Y.

OCT. 3-5, 1966: **Natl. Electronics Conf.**, IEEE, et al.; McCormick Place, Chicago, Ill. **Deadline:** Abstracts, approx. **5/1/66.** FOR INFO.: Natl. Elec. Conf., 228 N. LaSalle St., Chicago 1, Illinois.

OCT. 5-7, 1966: **Allerton Conf. on Circuit & System Theory**, IEEE, G-CT, Univ. of Ill., Conf. Center Univ. of Illinois, Monticello, Ill. **For Deadline Info.:** Prof. W. R. Perkins, Dept. of EE, Univ. of Ill., Urbana, Ill.

OCT. 13-14, 1966: **4th Canadian Symp. on Communications**, IEEE, Region 7, Queen Elizabeth Hotel, Montreal, Canada. **For Deadline Info.:** Prof. G. W. Farnell, McGill Univ., 805 Sherbrooke St., W., Montreal, Canada.

OCT. 19-21, 1966: **13th Nuclear Science Symp.**, IEEE, G-NS, Statler Hilton, Boston, Mass. **For Deadline Info.:** IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

OCT. 20-22, 1966: **Electron Devices Meeting**, IEEE, G-ED, Sheraton Park Hotel, Washington, D.C. **Deadline:** Abstracts approx. **8/1/66.** FOR INFO.: IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

OCT. 26-28, 1966: **East Coast Conf. on Aerospace & Navig. Elec. (ECCANE)**, IEEE, G-AES, Balt. Sect., Baltimore, Md. **Deadline:** Abstracts, approx. **6/4/66.** FOR INFO.: IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

NOV. 2-4, 1966: **N.E. Research & Eng. Mtg. (NEREM)**, IEEE, Region 1, Boston, Mass. **Deadline:** Abstracts approx. **6/7/66.** FOR INFO.: IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

NOV. 8-10, 1966: **Fall Joint Computer Conf.**, IEEE, AFIPS, (IEEE-ACM), Brooks Hall, Civic Center, San Francisco, Calif. **For Deadline Info.:** AFIPS Headquarters, 211 E. 43rd St., N.Y., N.Y.

NOV. 14-16, 1966: **19th Ann. Conf. on Eng. in Medicine & Biology**, ISA, IEEE; Sheraton-Palace Hotel, San Francisco, Calif. **Deadline:** Abstracts, **7/15/66.** TO: Dr. Victor Bolie, Genl. Chairman, Autonetics, 3370 Miraloma Ave., Anaheim, Calif.

NOV. 15-18, 1966: **12th Conf. on Magnet. & Mag. Materials**, IEEE G-MAG et al., Sheraton Park Hotel, Wash., D.C. **Deadline:** Abstracts, approx. **8/19/66.** FOR INFO.: IEEE Headquarters, Box A, Lenox Hill Station, N.Y., N.Y.

Engineering NEWS *and* HIGHLIGHTS

RCA PLANS RECORD $195 MILLION CAPITAL OUTLAYS IN 1966

RCA plans to double capital outlays in 1966 over those of 1965 to a record $195 million to meet the growing demand for its products, particularly in the areas of color TV, computers, and electronic components. This program is expected to add approximately 15,000 new jobs to the RCA work force, according to **Dr. Elmer W. Engstrom,** Chairman of the RCA Executive Committee, and **Robert W. Sarnoff,** President. Major new projects that will get underway in 1966 include:

Memphis, Tenn.—Construction of a $20 million complex for the assembly of color and black-and-white TV receivers. This facility will cover more than 1-million square feet and will supplement production at the Bloomington, Ind. plant.

Indianapolis, Ind. Area—Construction of a $13.7 million plant in Wayne Twp. for the manufacture of RCA Victor radios, Victrola phonographs, and tape recorders. The 625,000-square-foot plant will permit conversion of the Indianapolis plant exclusively to the manufacture of television components; the conversion will cost $9.6 million.

Lewiston, Me.—A $4.1 million outlay to acquire and equip a 116,000-square-foot plant for the manufacture of semiconductor devices; pilot production to start in June.

Palm Beach Gardens, Fla.—A $3 million expansion of production capacity of the computer plant to handle the growing backlog for Spectra 70 electronic data processors.

Other Funds—Additional funds are earmarked for: expansion and modernization of RCA's world-wide communications network; modernization and further colorization of the NBC broadcasting facilities; and expansion of facilities to produce semiconductor devices and integrated circuits.

SUN-POWERED LASER BEAM TRANSMITS TV SIGNALS

A sun-powered laser device built by DEP's Applied Research organization in Camden, N.J. for NASA's Manned Spacecraft Center is considered a first step toward a 50-million mile communications link between the earth and a spacecraft in the vicinity of Mars. This device demonstrates, in a laboratory experiment, the feasibility of using sunlight to power a laser in a communications system by transmitting a TV picture over the narrow beam of light. **William J. Hannan,** RCA project engineer for the program, said the experiment was the first known wideband communications via a sun-pumped laser.

The sun-pumped laser system consists of a 31-inch parabolic mirror, laser, modulator and associated electronics, optical elements, and optical receiver. These components are mounted on an equitorial mount which automatically tracks the sun, keeping its rays reflected from the mirror onto the laser.

The water-cooled laser, a double-doped yttrium aluminum garnet, is optically pumped by sunlight collected from the mirror. It is modulated by a gallium arsenide electro-optic crystal modulator which rotates the plane of polarization of the laser beam in proportion to the modulating signal.

HELICOPTER OBSTACLE WARNING SYSTEM

Laboratory and field measurements on a sensor to be used in a laser-equipped helicopter obstacle warning system are being made by the RCA Aerospace Systems Division, Burlington, Mass. The system will enable military helicopters to fly lower and faster, day and night, with greater safety by warning the pilot of obstacles (often not easily seen) in his path. The system incorporates lasers with realizable high repetition rates and sophisticated beam shaping and image tube techniques. The tubes used in the study are supplied by the ECD plant in Lancaster, Pa. Measurements being made by ASD will result in final recommendations and proposals for the implementation of an operational system consisting of a laser illuminator plus an imaging light sensor.—*D. Dobson*

BURLINGTON ENGINEERS HONORED

Recipients of Technical Excellence Awards at the Aerospace Systems Division, Burlington, Mass., have been announced for the last quarter of 1965. They are: **Frank C. Hassett, Richard B. Elder,** and **James J. Knoll.**

AUDIO AWARD TO DR. OLSON

The Audio Engineering Society Award has been presented to **Dr. Harry F. Olson,** Director of the Acoustical and Electromechanical Research Laboratory, RCA Laboratories, Princeton, N.J. Dr. Olson was honored for his contributions to the advancement of the Society. A Past President and Governor of the Society, Dr. Olson has served on several of its committees since the organization was founded in 1948. He is presently Editor of the Journal of the Audio Engineering Society.—*C. W. Sall*

RCA CITED FOR NEW PRODUCTS

RCA has been cited by *Industrial Research* magazine for producing three of the 100 most significant products introduced in 1965. The RCA products cited include: 1) high voltage silicon *npn* power transistor that enables transistorized radio receivers and other equipment to operate directly from 117-volt power supplies without transformers—developed by ECD Commercial Receiving Tube and Semiconductor Division, Somerville, N.J.; 2) lightweight, low-power digital tape recorder than can operate unattended for more than a year—developed by Astro-Electronics Division, Princeton, N.J. for Orbiting Geophysical Observatory; and 3) a rectangular, 90-degree color TV tube—developed by ECD Television Picture Tube Division, Lancaster, Pa.

RCA PUBLISHES NEW FREQUENCY ALLOCATION BOOKLET

A new edition of *Frequency Allocations* has been published by the RCA Frequency Bureau. The new booklet, revised to December 1, 1965, gives both the International and the FCC frequency allocations for the entire radio spectrum, including those recently assigned to space communication. Convenient lists of TV, AM, and FM channels and frequencies are featured in the new edition. Copies of the booklet can be obtained, at $2.00 each, from RCA Frequency Bureau offices at 60 Broad St., N.Y., N.Y.; 425 13th St., NW, Washington, D.C.; or Building 2-4, Camden, N.J.

RCA SALES TOP $2 BILLION FOR FIRST TIME IN HISTORY

RCA sales in 1965 surpassed $2 billion for the first time in the company's history, **Chairman David Sarnoff** announced in a year-end statement. Profits after taxes, he said, will be approximately $100 million, also a new record. It is the fourth consecutive year in which RCA sales and earnings have risen to new peaks. General Sarnoff noted that RCA's prospects for the future "have never been more promising." Subject to final audit, sales for 1965 will be more than 11 percent greater than for the previous year, and profits will be more than 21 percent higher. In describing RCA's progress during 1965, General Sarnoff noted the following:

Home Instruments—Highest sales and profits in RCA's history. Color TV receiver unit sales increased by 70 percent over 1964. Total color and monochrome TV sales exceeded 2 million units.

NBC—Record sales of nearly $500 million were approximately 12 percent higher than 1964.

Computers—Total bookings were about 68 percent higher than 1964. A major factor was the success of the Spectra 70 series.

Broadcast Equipment—Color was primarily responsible for a 50 percent increase in sales over 1964.

RCA Communications, Inc.—Sales were approximately 13 percent greater than the previous record set in 1964. Profits increased by more than 21 percent over the previous year.

RCA Victor Records—New all-time peak in sales for the second successive year.

TEST POINT COMPUTER PROGRAM

Engineers at the RCA Aerospace Systems Division, Burlington, Mass. are developing a Test Point Algorithm Computer Program that aids in the selection of test point locations in an electronic circuit and automatically generates a fault isolation procedure for that circuit. The program simulates faults one at a time and specifies the corresponding impedance or voltages between appropriate circuit test points which are indicative of the faults. As a part of the program, ASD has developed a practical technique for reducing the number of tests for stage-to-stage gain measurements. The work is being done for the Air Force's Research Technology Division, Patterson AFB, Ohio, which has termed the work a "definite advancement in the state of the art of automatic testing utilizing a computer." Additional information about the Test Point Algorithm Computer Program can be obtained from **O. T. Carver** at Burlington, Mass. phone 2768.—*D. Dobson*

LICENSED ENGINEERS

J. L. Cammarato, DEP-MSR, Moorestown, PE-14394, N.J.

P. F. Gibson, ASD, Burlington, PE-008210, Pa.

STAFF ANNOUNCEMENTS

Broadcast and Communications Products Division, Camden, N.J.: The organization of the Engineering Department, reporting to **W. C. Morrison,** Chief Engineer, is announced as follows: **H. N. Kozanowski,** Mgr., TV Advanced Development; **A. H. Lind,** Mgr., Studio Equipment Eng.; **A. C. Luther,** Mgr., Tape Equipment, Projector, and Scientific Instruments Eng.; **H. S. Wilson,** Mgr., Microwave Eng.; and **J. E. Young,** Mgr., Eng. Administration and Service.

Communications Products Operations, Meadow Lands, Pa.: The announced organization, reporting to **A. F. Inglis,** Division Vice President, includes: **N. C. Colby,** Mgr., Communications Products Eng., and **T. M. Gluyas,** Mgr., Broadcast Transmitter Eng.

ECD Industrial Tube and Semiconductor Division, Somerville, N.J.: The organization of Industrial Semiconductor Engineering, reporting to **J. Hilibrand,** Mgr., Engineering, is announced as follows: **D. R. Carley,** Mgr., Industrial RF Transistor Design; **K. E. Loofbourrow,** Resident Engineer, Mountaintop; **C. R. Turner,** Mgr., Transistor Applications; **N. C. Turner,** Mgr., Industrial Power Transistor Design and Model Ship; **H. Weisberg,** Mgr., Industrial Rectifier Design and Applications; and **D. Winans,** Administrator, Eng. Administration.

ECD TV Picture Tube Div., TV Picture Tube Manufacturing Dept., Lancaster, Pa.: The organization of Equipment Development Engineering reporting to **A. W. Comins,** Mgr., Equipment Developing Eng., is announced as follows: **D. S. Garman,** Mgr., Electrical Drafting and Design; **E. E. Hoffman,** Mgr., Electrical Design; **A. L. Lucarelli,** Mgr., Mechanical Design, **W. J. Maddox,** Mgr., Electrical Design, **J. F. Segro,** Mgr., Electrical Drafting and Design; and **M. VanRenssen,** Mgr., Mechanical Design.

Graphic Systems Div., Princeton, N.J.: **M. P. Barnett** is appointed Mgr., Advanced Planning, reporting to **N. I. Korman,** Chief Engineer, Graphic Systems Div.

Industrial and Automation Products Dept., Plymouth, Mich.: The announced organization, reporting to **N. R. Amberg,** Mgr., Industrial and Automation Products Dept., includes: **C. A. DellaBella,** Mgr., RCA Automation Program, and **R. G. Walz,** Mgr., Automatic Equipment Eng.

Electronic Data Processing, Camden, N.J.: **H. Kleinberg** is appointed Mgr., Engineering, Palm Beach, Fla., reporting to **A. D. Beard,** Chief Engineer, Engineering, Camden.

Corporate Staff, Camden, N.J.: **J. J. Brant,** Staff Vice President, Personnel Administration, announced the following staff organization: **F. C. Dohan,** Medical Director; **P. C. Farbro,** Mgr., Professional Personnel Programs, **D. Kirchhoffer,** Mgr., Wage and Salary Administration; **H. Krieger, Jr.,** Mgr., Personnel Planning and Controls; **J. Siegal,** Mgr., Labor Relations; **W. E. Swartz,** Mgr., Personnel Benefits and Services.

J. T. Bolden, Jr. is appointed Administrator Training Design and Application, reporting to **R. F. Maddocks,** Mgr., Training and Professional Program Development. **D. J. Raffensperger** is appointed Administrator, College Relations Programs, reporting to **D. M. Cook,** Mgr., College Relations.

. . . PROMOTIONS . . .

to Engineering Leader & Manager

As reported by your Personnel Activity during the past two months. Location and new supervisor appear in parentheses.

DEP Missile & Surface Radar Division

W. F. Tester: from Class "A" Eng. to *Ldr., Engrg. Sys. Projects,* (W. L. Hendry, Mgr., Moorestown)

R. B. Lund: from Class "A" Eng. to *Ldr., D.&D. Engrs.* (W. L. Hendry, Mgr., Moorestown)

E. B. Darrell: from Class "A" Eng. to *Ldr., Field Support,* (W. L. Hendry, Mgr., Moorestown)

G. S. Black: from Class "A" Eng. to *Ldr., D.&D. Engrs.,* (J. F. Herbert, Ldr., Moorestown)

D. Owen: from Class "A" Eng. to *Ldr., D.&D. Engrs.,* (E. S. Lewis, Moorestown)

C. A. Spurling: from Ldr., D.&D. Engrs. to *Mgr., Adv. Design Eng.,* (J. P. Schwartz, Moorestown)

D. Flechtner: from Class "AA" Eng. to *Ldr. Engrg. Sys. Projects,* (M. Korsen, Moorestown)

M. Weiss: from Class "AA" Eng. to *Ldr., D.&D. Engrs.,* (I. D. Kruger, Moorestown)

DEP Defense Engineering

G. Katz: from "A" Engr. to *Ldr. Des. & Development,* (C. H. Kreck, Mgr. Material Standards, Camden)

R. D. Smith: from "A" Engr. to *Ldr. Des. & Development,* (J. G. Smith, Mgr., Machine Organization Research, Camden)

F. Huber: from Engrg. Scient. to *Engrg. Ldr.,* (Dr. W. Y. Pan, Mgr. Thin Films & Special Circuits, Camden)

H. Borkan: from Engrg. Scient. to *Engrg. Ldr.,* (E. E. Moore, Mgr. Def. Microelectronics, Camden)

DEP Communications Systems Division

P. E. Hauser: from "A" Eng. to *Ldr. Design & Development,* (F. D. Fell, Camden)

C. R. Thompson: from "B" Eng. to *Ldr. Design & Development,* (J. D. Rittenhouse, Camden)

DEP Aerospace Systems Division

S. Patrakis: from Sr. Project Member to *Ldr., T.S.,* (B. Joyce, Burlington)

DEP Astro-Electronics Division

E. Dusio: from T35001 Eng. to *T35050 Ldr. Eng.,* (M. V. Sullivan, Princeton)

G. Frippel: from T35001 Eng. to *T35050 Ldr. Eng.,* (M. V. Sullivan, Princeton)

F. Luteran: from T35000 Senior Eng. to *T35050 Ldr. Eng.,* (M. Shepetin, Princeton)

S. Ravner: from T35001 Eng. to *T35050 Ldr. Eng.,* (M. V. Sullivan, Princeton)

M. Shepetin: from T35050 Ldr. Eng. to *D95971 Mgr., Subsystem Qualification & Test,* (A. A. Garman, Princeton)

Electronic Components and Devices

W. J. Maddox: from Eng., Equipment Development to *Mgr. Mechanical Design,* (Mgr., Equipment Development Engineering, Lanc.)

M. VanRenssen: from Eng., Equipment Development to *Mgr. Mechanical Design,* (Mgr., Equipment Development Engineering, Lanc.)

W. A. Sonntag: from Senior Eng., Product Development to *Engrg., Ldr., Product Development,* (Mgr., Application & Reliability Laboratory, Lanc.)

A. C. Limm: from Production Eng. to *Ldr., Production Engrg., Silicon High Frequency,* (A. E. Mohr, Mfg. Mgr., Silicon High Frequency, Mountaintop)

H. W. Menzel: from Production Eng. to *Ldr., Production Engrg. Silicon Power,* (R. E. O'Brien, Mfg. Mgr., Silicon Power, Mountaintop)

H. Weisberg: from Engrg. Ldr. to *Mgr., Rectifier & SCR Engrg.,* (J. Hilibrand, Mgr., Industrial Semiconductor Engrg., Mountaintop)

J. W. Ritcey: from Mgr., Plant Manufacturing Operations to *Mgr., Integrated Circuit Engineering,* (R. L. Klem, Mgr. Integrated Circuits Operations Dept., Somerville)

RCA Service Company

T. J. Reed: from Assoc. Engineer BMEWS to *Ldr., Engineers—BMEWS,* (R. L. Johnson, Cherry Hill)

S. S. Landau: from Sr. Field Support Eng. to *Ldr., Field Support Eng.* (W. G. Kolter, Cherry Hill)

C. Bulleman: from Assoc. Engineer to *Ldr., Field Support Engineers* (G. N. Berube, Cape Radar-Missile Test Proj., Cocoa, Florida)

J. B. Galpin: from Engineer to *Ldr., Engineers* (G. B. Cope, Data Translation & Optics Engineering-Missile Test Proj., Cocoa, Florida)

D. L. Partlow: from Ship Instrumentation Engr. to *Mgr., Navigation Data Handling* (L. F. Dodson, Signature Data Acquisition-Missile Test Project, Cocoa, Florida)

DEGREES GRANTED

M. J. Campanella, DEP-MSR	Ph.D., EE, University of Pennsylvania
H. R. Gutsmuth, DEP-CSD	MSEE, University of Pennsylvania
R. Pschunder, DEP-MSR	Dr., Tech. Sciences, ME, Technical University of Vienna
W. R. Sheridan, DEP-CSD	MSEE, University of Pennsylvania
S. M. Sherman, DEP-MSR	Ph.D., EE, University of Pennsylvania
S. M. Tucker, DEP-CSD	MSEE, University of Pennsylvania

BECKHART NAMED ASQC FELLOW

Gordon H. Beckhart has been named a Fellow of the American Society for Quality Control. Mr. Beckhart is Administrator, Program Product Assurance, Missile and Surface Radar Division, Moorestown, N.J. He is Chairman of the Reliability Training Conference co-sponsored by ASQC and the IEEE.

DR. ZWORYKIN ELECTED TO ENGINEERING ACADEMY

Dr. V. K. Zworykin, Honorary Vice President of RCA, was recently elected to membership by the National Academy of Engineering. He was one of 27 new members honored for outstanding contributions to engineering theory and practice or for the pioneering of new and developing fields of technology. The National Academy of Engineering, which now has a total membership of 70, was established in December 1964 with 25 founding members. **Dr. E. W. Engstrom,** President of RCA, is one of the original members, and **Dr. George H. Brown,** RCA Executive Vice President, Research and Engineering, was one of the first 19 members to be elected.

NEW RCA RECEIVING TUBE MANUAL RC-24 PUBLISHED

The new *RCA Receiving Tube Manual, RC-24,* is available (suggested price, $1.25) from authorized RCA tube distributors or from Commercial Engineering, Electronic Components and Devices, Harrison, N.J. The most complete and authoritative reference in its field, the new edition provides up-to-date information on the complete RCA line of receiving tubes for home-entertainment applications, picture tubes for black-and-white TV receivers, and voltage-regulator and voltage-reference tubes.

DR. H. H. BEVERAGE NAMED TO URSI

Dr. Harold H. Beverage, retired Vice President, Research & Development, RCA Communications, and Chief Technical Advisor, Communications, RCA Laboratories, has been appointed an honorary member of the U. S. National Committee for the International Scientific Radio Union. The membership of the Union, also known by its French title "Union Radio Scientific Internationale," or URSI, consists of scientists and engineers from all parts of the world engaged principally in radio propagation research.

RCA-RANDOM HOUSE MERGER ANNOUNCED

David Sarnoff, Chairman of the Board of RCA and **Bennett Cerf,** Chairman of the Board of Random House, Inc., have announced an agreement in principle for the acquisition of Random House by RCA. Incorporated in 1925, Random House, Inc. is engaged in a broad range of publishing activities, including textbooks, reference books, trade books, and juvenile books.

The agreement is subject to approval by the Boards of Directors of the two companies and by the shareholders of Random House. If the agreement is approved, the publishing company will become a wholly owned subsidiary of RCA, and Mr. Cerf will be proposed as a member of the RCA Board of Directors.

ENGINEERING COURSES AND LECTURES STARTED BY CSL

The Technical Education Committee of the Communications Systems Laboratory (CSL), Communications System Division started in January two graduate-level courses and a graduate-level lecture series for engineering personnel. The 4-month program, is being given at CSL, 75 Varick St., New York City. Approximately 70 engineers have registered. **Dr. Wen Y. Pan** formulated a 7-session lecture series on Integrated Electronic Technology with lectures being given by engineers from RCA Defense Microelectronics, Somerville, N.J. **Richard Gardner** is presenting a course in "Mathematical Tools for Modulation Theory," and **Dr. Halina Montvila** is giving a course entitled "An Introduction to Digital Computer Programming."

NEW HOME INSTRUMENTS BUILDING SLATED FOR APRIL OCCUPANCY

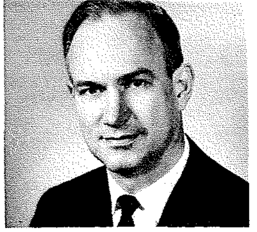
Construction on a new RCA Home Instruments Division engineering building is proceeding on schedule. The three-story structure will have an area of approximately 60,000 square feet and will be located adjacent to the existing engineering facilities at 600 South Sherman, Indianapolis. Occupancy is scheduled for about April 1966. —*K. A. Chittick*

COMPUTER CHARACTERISTICS PUBLISHED

Field Support Services of RCA Service Company's Government Services announced the publication of a characteristics chart covering 22 RCA digital computers. Information is provided on: processor speed; internal storage capacity and cycle time; word size; storage capacity for disc, magnetic card file, and drum storage; access times and data transfer rates for the various methods of storage; magnetic tape transfer rates; read and punch speeds for cards and paper tape; printer speeds; communications circuits; and standard instructions. The chart also gives typical monthly rentals and first delivery dates for RCA computers. Copies of the chart may be obtained on request from **Jack E. DeLong,** Field Support Services, Building 206-2, Cherry Hill, N.J.

LIFE STORY OF DAVID SARNOFF TO BE PUBLISHED BY HARPER & ROW

A definitive biography of **David Sarnoff,** electronics industry pioneer and leader, will be published by Harper & Row Inc. on February 28, the day following General Sarnoff's 75th birthday. The 384-page book, entitled *David Sarnoff,* recounts the remarkable life story of the immigrant boy who rose to Chairman of the Board of RCA. The author of the book is Eugene Lyons, a noted biographer and senior editor of *Reader's Digest.* The biography treats in detail the role of Sarnoff in stimulating the growth and development of RCA, in founding NBC as the nation's first commercial radio network, and in encouraging research efforts to expand the scope and effectiveness of communications and electronics. The author recounts Sarnoff's efforts to develop and market television, which he characterizes as "the greatest fight of his career, long, bitter, costly and conducted against the overwhelming opposition of powerful elements inside and outside his own industry."



H. N. Crooks

H. Goodman

H. N. CROOKS AND H. GOODMAN ARE NEW ED REPS

The RCA ENGINEER welcomes two new editorial representatives: **Dr. H. N. Crooks** has been named Editorial Representative for the Graphic Systems Division, Princeton, N.J., and **H. Goodman** has been named an Ed Rep for Communications Systems Division Engineering, replacing **G. Lieberman.** Both will serve as members of the DEP Editorial Board.

Dr. H. N. Crooks holds BS, MS, and D.Sc. degrees in Physics from Carnegie Institute of Technology. He joined RCA in 1949 as an engineer in advanced development, where he worked on a variety of projects including magnetic memory units, cathode-ray-tube display, display storage tubes, high-voltage power supplies, color TV circuitry, and classified military communications studies. He was promoted to Manager, Optics and Recording Systems Development in 1956, and was named Manager, Signal Processing in 1957. In 1960 he transferred to the Communications Systems Division in Cambridge, Ohio, where he was Manager, Tactical Radio Engineering. In 1965 he transferred to Graphic Systems Division in Princeton, N.J., where he is currently Manager, Advanced Engineering. Dr. Crooks is a senior member of the IEEE and a senior member of the Society of Photographic Scientists and Engineers. He holds 10 U. S. patents.

H. Goodman received his BSRE in 1939 from Indiana Technical College. He was employed by Philco and Bendix Radio prior to joining the U. S. Navy Department as an electronics inspector in 1941. During World War II he served as a radar instructor and operator with the Army Air Force. After the war he returned to civil service employment. In 1948 he transferred to the U. S. Naval Air Development Center at Johnsville, Pa., where he was engaged in the evaluation and development of airborne radar and navigational aids. In 1956 he joined the Lincoln Laboratory of MIT as a staff engineer and was engaged in the SAGE program. He joined RCA in 1958 as a communications analyst in the Airborne Systems Division, Camden. There his major efforts have been devoted to Time Division Data Link applications, communications studies for Boss-WEDGE, SAINT, Dyna-Soar, Surveyor Lunar Roving Vehicle, MOL, LEM, and CONDOR. Mr. Goodman is a senior member of the IEEE.

RCA VICTOR LTD. SCHEDULES $25 MILLION TV TUBE PLANT

RCA Victor Company, Ltd. plans a $25 million plant for color TV picture tube production, the largest single expansion program in the history of the Canadian electronics industry. The new 250,000-square-foot facility, to be located in Midland, Ontario, will have an annual capacity of more than 300,000 rectangular color picture tubes upon completion in mid-1967, and will employ about 500 workers. RCA Victor initiated pilot assembly of color TV picture tubes at its Prescott, Ontario facility last year.

PACKAGING THE LEM ATCA AND DECA

This paper discusses the mechanical and thermal requirements of the attitude, translation, and descent engine controls of the Lunar Excursion Module (LEM). In the attitude and translation control assembly, high parts reliability is maintained by limiting maximum hot-spot temperatures to 160°F. Thermal control is achieved by conductive cooling from the liquid-cooled prime structural members of the LEM. The descent engine control assembly depends upon internal thermal inertia for temperature control. Both assembly designs require extremely high mechanical stability combined with excellent thermal characteristics.

S. WALDSTEIN, Ldr and P. J. SACRAMONE

Guidance & Control Engineering

Aerospace Systems Div., Burlington, Mass.

THE packaging of electronic assemblies for spacecraft is governed by weight, volume, configuration, electromagnetic interference, maintainability, reliability, and cooling medium requirements. For manned spaceflight, packaging constraints as interrelated with reliability are very severe. The most significant requirement for the attitude and translation control assembly (ATCA) is the maximum temperature limit of 160°F set for hot-spot temperatures of electrical part surfaces during operation. The real significance of this limit cannot be fully appreciated unless the cooling means and its parameters are specified.

Final manuscript received December 15, 1965.

ATCA

The ATCA (Figs. 1 and 2) in the aft equipment bay of the LEM is flange-mounted to a ladder-like structure; rungs of this structure serve both as prime structural members and as *cold rails* or heat sinks. Coolant flowing through these rails transfers heat from the electronic assemblies to the central vehicle heat exchanger. If the thermal flux density in the flange of the electronic replaceable assembly (ERA) does not exceed 2.25 watts per linear inch, the cooling system will maintain the temperature at the root of the ATCA case flange at less than 135°F. This condition permits a maximum temperature rise of 25°F from the root of the flange to the part hot spot.

Packaging Design Concept

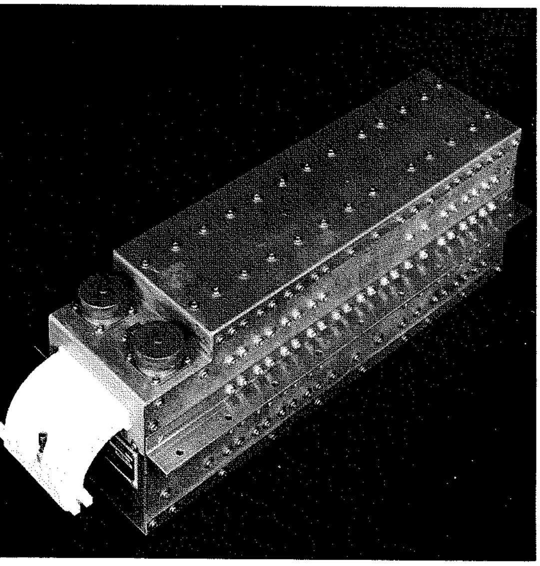
The packaging case is constructed of unified side plates with permanent front and rear plates. The heat-sink flange is an integral part of the side plates, which are one-piece machinings. Plug-in subassemblies are fastened to the side plates by screws which serve as structural members and complete the thermal path from the subassembly to the side plate. Conduction is the only means of heat transfer, with the screws serving as a part of the thermal path.

A handling fixture must be used during assembly of the ERA for support and protection. The ERA remains in the fixture at all times, except during acceptance tests, until it is installed in the vehicle.

The packaging concept of the output subassembly shown in Fig. 3 is typical for all but the wiring subassembly. The subassembly structure is a fully machined, one-piece, I-beam structure. Parts not directly mounted on the subassembly structure are *cordwood* packaged. The cordwood modules are electrically interconnected by a double-sided printed circuit board and are bonded to the subassembly structure by an adhesive which completes the thermal path.

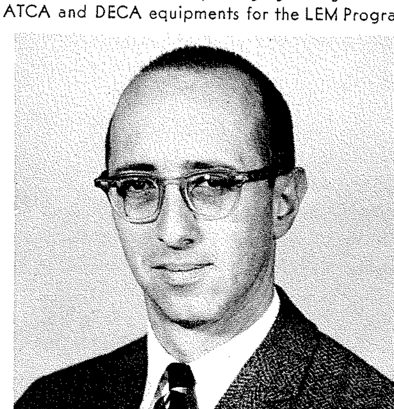
The subassemblies are electrically connected to the wiring subassembly by split-pin wire-wrap connections. The

Fig. 1—ATCA moment-of-inertia and center-of-gravity test model.



PHILIP J. SACRAMONE received his BS degree in Mechanical Engineering from Northeastern University in 1955. His initial work was with Electronics Corporation of America, where he designed electronic equipment packaging. From 1957 to 1959 he worked at the Raytheon Company in the electromechanical design and environmental testing of shipboard radar equipment. He then spent two years at the Avco-Everett Research Laboratory, performing studies on satellite power supplies for optimum energy-to-weight ratio for various mission times. Upon joining RCA-Burlington in 1961, he was assigned to transient and steady-state thermal analysis of satellites using both passive and active cooling systems. This work involved the specification of proper solar absorptivity, infrared emissivity, and fluid flow on subsystems to obtain proper thermal balance in space. He is now engaged in the thermal design of the ATCA and DECA equipments for the LEM Program.

SAMUEL WALDSTEIN received his BS degree in Mechanical Engineering from the Massachusetts Institute of Technology in 1947 and his MS degree in Mechanical Engineering from Northeastern University in 1956. Early experience consisted of the design and development of environmental test equipment for Sylvania Electric Products and the electro-mechanical development of electric switches for the U.S. Army Chemical Corps. Since joining RCA in 1955, he has been designing and developing instrumentation and mechanisms for airborne and space applications. Areas of endeavor included test instruments, infrared instruments, and guidance and control instruments. In the latter area he was responsible for the design and development of three- and four-gimbal platforms for fire control, inertial navigation, missile guidance, and space vehicle guidance systems. As Leader, Technical Staff, Guidance and Control Engineering, he is responsible for the packaging design of the ATCA and DECA equipments for the LEM Program.



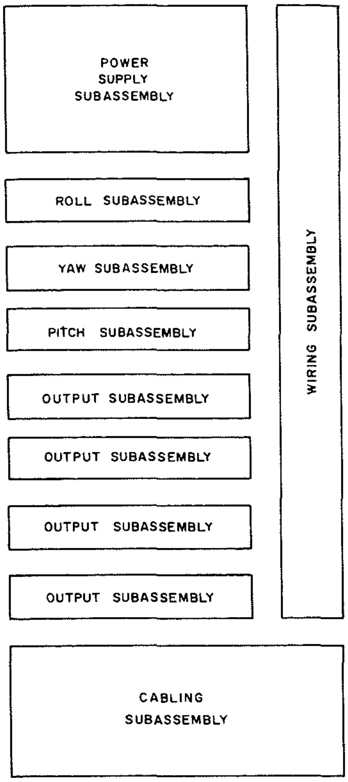


Fig. 2—ATCA internal configuration.

wiring subassembly, a welded wire matrix, interconnects all subassemblies and interfaces with the input/output and test connectors. The test connector and elapsed-time indicator are mounted at the top of the box; the input/output connector is wired to a flat cable.

Thermal Analysis

Preliminary analysis indicated that the design of the output subassemblies, power supply subassembly, and side walls would be thermally constrained; structural wall thicknesses would be determined by thermal impedance requirements rather than by structural requirements. Using the ratio K/P (thermal conductivity/density) as a figure of merit, an analysis of materials quickly led to a choice of aluminum for the structural material. (Beryllium has approximately the same value of K/P.) Since the ATCA thermal design is based on steady-state operation, specific heat is inconsequential.

The thermal impedance path from the root of the flange to the hot spot of the part is shown in Fig. 4. An extensive test program determined the thermal interface drop (impedance) across the bolted joint. Operation in a vacuum precludes predictable thermal flow at the interface of the subassembly and side plate anywhere but in the immediate vicinity of the bolted joint. The interface drop for the No. 8 bolts being used is 2.25°F/watt/bolt (with material, configuration, and tolerances considered).

To determine the temperature drops at points within the subassembly structure, a computer program of the finite difference technique was used. This program permits the solution of 1400 simultaneous differential equations. Since the program considers the effect of the bolted-joint impedances, its output is a grid showing the temperature rise from the reference (root of the flange) to grid points on the structure (Fig. 5).

The thermal conduction path of the cordwood design for resistors, diodes, and transistors is shown in Fig. 6. (The following analysis is based on unidirectional flow of the heat flux from the part.) Heat flow in the resistor is down along the body, through the lead, and into the copper-clad area at the base of the printed circuit board. Thermal flux is distributed across the copper-clad area and then flows through the potting compound to the heat sink. A transistor thermal path through the potting compound interface and into the copper-clad surface on top of the printed circuit board facilitates heat dissipation, thus reducing thermal impedance through the board and the potting compound. Since diode heat dissipation is predominantly at the collector end, this end is mounted nearest the heat sink.

Results of tests performed on several types of resistors to determine thermal impedances are shown in Table I, where T_1 is the temperature at the end of the resistor near the heat sink, and T_2 is the temperature at the opposite end of the resistor.

The operational amplifier and the comparators are typical of the ATCA cordwood design. Analysis of these circuits demonstrated that the ΔT between the hot spot of a part and the web heat sink may be maintained at approximately 5°F. For a resistor, the hot spot

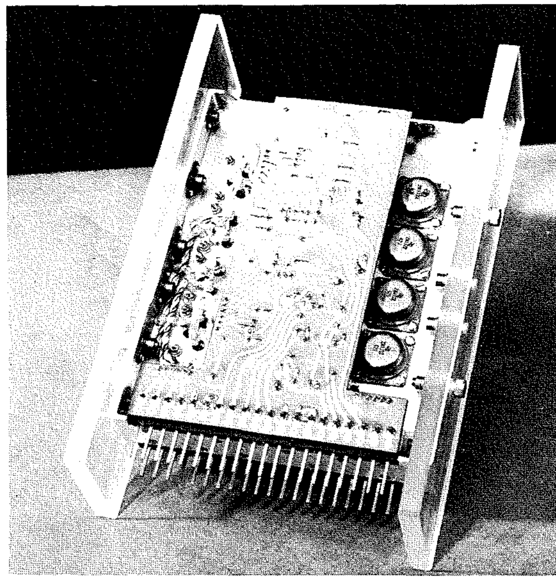


Fig. 3—ATCA output assembly.

ΔT gradient from the web heat sink is computed from:

$$\Delta T_C = Q_C R_C + \Delta T_{pc} + \Delta T_L$$

where R_C is the experimental value of resistor impedance from lead to lead, ΔT_{pc} is the thermal drop across the potting compound, Q_C is the part dissipation, and ΔT_L is the drop along the lead. The thermal drop across the potting compound is conservatively calculated from the relationship:

$$\Delta T_{pc} = \frac{l_{pc}}{K_{pc} A_c} \times Q_c$$

Fig. 4—Thermal flow path.

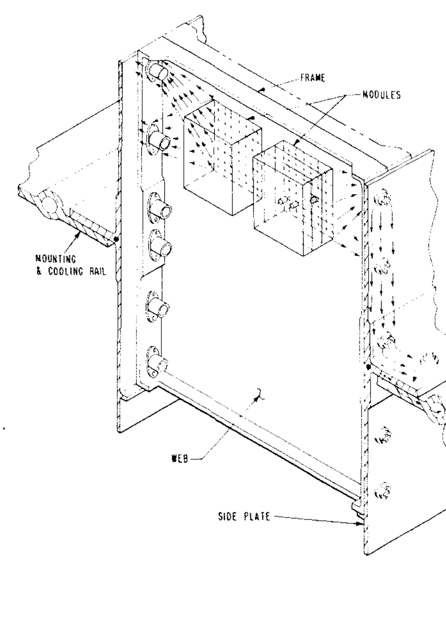


TABLE I—Thermal Impedances of Several Types of Resistors

Resistor Type	T_1	T_2	ΔT	Power (watts)	Resistance (°F/watt)	Chamber Pressure (mm Hg)
MMC (IRC)	103°	147°	44°	0.200	220	4×10^{-5}
CCM (IRC)	108°	158°	50°	0.290	173	4×10^{-5}
XLT (IRC)	137°	170°	33°	0.103	321	4×10^{-5}
NA-55 (Corning)	91°	172°	81°	0.120	675	4×10^{-5}

$i \backslash j$	3	4	5	6	7	8	9	10
2	14.56	15.34	15.63	15.47	14.99	14.25	13.32	12.24
3	15.26	16.24	16.63	16.16	15.55	14.67	13.58	12.27
4	15.95	17.22	17.2	16.71	16.12	15.26	14.06	12.34
5	16.25	17.70	17.65	17.13	16.65	15.92	14.75	13.23
6	15.25	16.71	17.20	17.14	16.91	16.41	15.46	13.97
7	14.38	15.84	16.81	17.16	17.2	16.95	16.23	14.74
8	13.3	15.04	16.13	16.81	17.19	17.45	17.89	16.08
9	13.14	14.57	15.66	16.5	17.13	17.85	18.2	16.96
10	13.12	14.35	15.36	16.2	16.84	17.37	17.26	16.28
11	13.26	14.27	15.17	15.94	16.57	17.23	16.84	16.34
12	13.38	14.23	15.03	15.72	16.27	16.63	16.46	16.0

0°F — FLANGE ROOT — 0°F

Q=8.99 WATTS MAX Δ TEMP = 18.2°F AT NODE 9.9
K=2.54 WATTS-IN / IN²-°F #8 / 2 = SCREW SIZE / NO. REQUIRED
t=0.080 INCH (WEB THICKNESS)

A. BOLT LOCATION "A"

$i \backslash j$	3	4	5	6	7	8	9	10
2	11.0	11.5	11.6	11.4	10.9	10.3	9.5	8.7
3	11.1	12.0	12.4	11.9	11.3	10.5	9.4	8.2
4	11.0	13.0	12.7	12.3	11.8	10.9	9.5	7.6
5	10.3	12.6	13.0	12.7	12.2	11.4	9.9	7.6
6	9.3	11.6	12.5	12.7	12.5	11.9	10.6	8.3
7	8.5	10.8	12.2	12.7	12.8	12.5	11.4	9.7
8	8.5	10.4	11.7	12.5	13.0	13.2	13.5	11.5
9	9.1	10.4	11.6	12.4	13.11	13.9	14.3	13.2
10	9.6	10.6	11.5	12.3	13.0	13.7	13.7	13.2
11	10.0	10.7	11.5	12.2	12.9	13.7	13.5	13.4
12	10.2	10.8	11.5	12.1	12.7	13.2	13.3	13.3

0°F — FLANGE ROOT — 0°F

Q=8.99 WATTS MAX Δ TEMP = 14.3°F AT NODE 9.9
K=2.54 WATT-IN / IN²-°F #8 / 2 = SCREW SIZE / NO. REQUIRED
t=0.080 INCH (WEB THICKNESS)

B. BOLT LOCATION "B"

Fig. 5—Output subassembly temperature variation grid.

where l_{pc} is the conductive path length through the potting compound, K_{pc} is the thermal conductivity of the potting compound, A_c is the copper-clad area directly under the resistor, and Q_C is the part dissipation.

Since two-dimensional spreading is effectively taking place during the longitudinal flow, the actual thermal drop across the potting compound is less than calculated.

The hot-spot temperature of the part is computed from the equation:

$$T_C = Q_C R_C + \Delta T_L + \Delta T_{pc} + T_o + \Delta T_{ij}$$

where ΔT_L is the drop across lead ≈ 0 (for a resistor directly in contact with the printed circuit board); T_o is the reference heat-sink temperature (flange root, Fig. 4); ΔT_{ij} is the thermal gradient from flange root to node i, j (Fig. 5); and part temperature gradient from web heat-sink to part hot spot is:

$$\Delta T_C = T_C - (T_o + T_{ij}) = Q_C R_C + \Delta T_{pc} = \Delta T_1 + \Delta T_{pc}$$

since $\Delta T_L \approx 0$.

For a typical resistor with a dissipation of 3.48 milliwatts:

$$\Delta T_1 = Q_c R_c = 240°\text{F/watt} \times 3.48 \times 10^{-3} = 0.835°\text{F}$$

$$\Delta T_{pc} = 2.70° \text{ for copper-clad dia. of } 0.070 \text{ inch}$$

Therefore,

$$\Delta T_C = 2.70 + 0.84 = 3.54°\text{F}.$$

For a part location at $i = 3$, $j = 6$ in Fig. 5B and a root flange temperature $T_o = 135°$F, the part temperature is:

$$T_C = T_{ij} + T_o + \Delta T_C = 150.44°\text{F}$$

For noncordwood, high-heat dissipators (SCR's, relays, and transformers), the thermal impedance to the heat sink can easily be maintained at 5°F/watt; the total ΔT will be as shown in Table II.

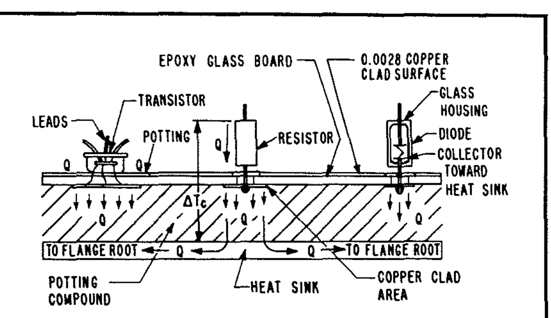


Fig. 6—Thermal conduction path of cordwood design.

TABLE II—Thermal Impedance of High Dissipators

Component	R_C	Q_C	$\Delta T = Q_C R_C$
SCR's	5°F/watt	1.25 watt	6.25°F
Relay	5°F/watt	0.50 watt	2.50°F
Transformer	5°F/watt	1.00 watt	5.00°F

From Table II it can be seen that noncordwood parts may be easily maintained at temperatures less than 160°F. Thus, for a maximum node temperature at $i = 9$ and $j = 9$, and in the region of the SCR's:

$$T_P = \Delta T_{ij} + Q_C R_C + T_o$$

$$T_P = 14.3 + 6.25 + 135 = 155.55°\text{F}$$

where T_o is the root flange temperature (135°F), and ΔT_{ij} is the thermal gradient in structure; at $\Delta T_{9\,9} = 14.3°$F.

To keep weight to a minimum and because of small cordwood height, modules are not encapsulated; instead, a two-phase conformal coating is used. The first phase is a thin polyamide epoxy; the second is a pure polyurethane coating. Total maximum film thickness of 0.010 inch provides moisture protection and damping. Glass diodes and resistors are precoated with the polyurethane prior to application of the polyamide epoxy to preclude breakage during temperature excursions. Outgassing rates, toxic products of outgassing, moisture absorption, and electrical properties were important considerations in the choice of organic materials.

The cordwood modules are designed for nominal spacing of 0.310 inch between the boards. For mechanical reasons, parts selection is based on two major criteria: thermal impedance and body length. In several cases, a *thermal jumper* (copper wire) from the top of the part to the bottom board of the cordwood provides a parallel thermal path to the heat sink. The 0.310-inch dimension precluded mounting transistors back-to-back. The 26 analog and 36 digital integrated circuits in the ATCA are mounted to the outer sides of the printed circuit boards in the conventional planar manner. They are electrically interconnected to solder-plated printed-circuit boards by a programmed-energy soldering technique.

The wiring subassembly is an encapsulated welded wire matrix. However,

TABLE III—Overall Efficiency of ATCA Packaging

Unit	No. of Parts	Volume (in³)	Parts Weight (lb)	Total Weight (lb)	Parts Wt. / Total Wt. (%)	No. Parts (per in³)	Density (lb/in³)
Functional Circuit	2570	445	3.89	18.84	20.7	5.8	—
Power Supply	490	215	3.40	6.20	54.5	2.3	—
ATCA	3060	660	7.29	25.04	29.1	4.6	0.04

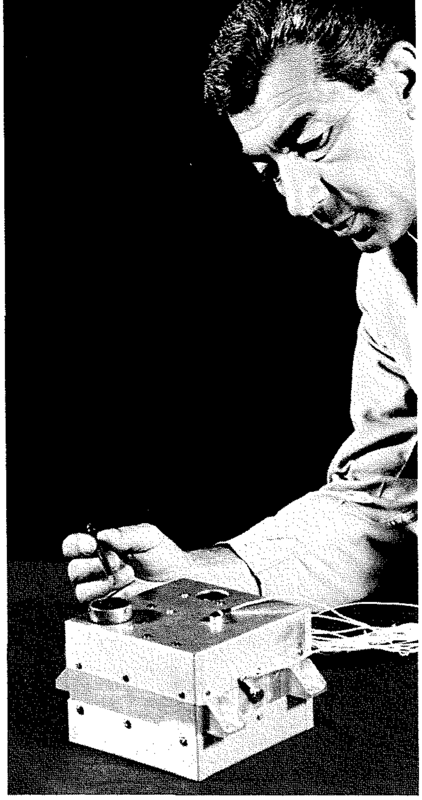


Fig. 7—DECA mechanical model.

there are 16 twisted pairs of conventional wires embedded in the assembly to carry the solenoid driver outputs.

Some figures of interest for the ATCA are listed in Table III.

DECA

The descent engine control assembly (DECA) in the descent stage of the LEM vehicle is not cooled, but it is temperature controlled by available thermal inertia. The 160°F maximum limit for surface hot spots of electrical parts applies; however, since the initial condition is 120°F, a 40°F rise is tolerable.

Packaging Design Concept

The mechanical model of the DECA is shown in Fig. 7. Approximately 95% of the electrical parts are cordwood mounted. The remainder are individually mounted and hand-wired. The packaging techniques are generally similar to ATCA with three exceptions. First, allowable cross-sectional area and configuration is efficiently utilized by mounting transistors back to back with a resultant nominal distance between module printed circuit boards of 0.570 inch. This arrangement is based on the parts complement. Second, the internal interconnections (cordwood units, integrated circuit packages) consist primarily of point-to-point wiring. Location, orientation, functional breakout and input/output pin locations minimize the number of interconnections and enhance the appearance by minimizing cross-over wiring. Third, the DECA contains an integrator circuit using 40 flat-pack integrated circuits. To minimize the area and volume required to package the thrust integrator logic, multilayer techniques are used where these flat-packs are functionally interconnected.

The flat-pack integrated circuits can be packaged in two layers of 20 units each, with overall dimensions of 2.56 inches by 2.18 inches by 0.50 inch. These dimensions include parts, multilayered interconnections (pillar layers included), insulating layers, and terminal areas for inputs and outputs to the circuit. The total volume is approximately 2.80 cubic inches, requiring a surface area of 4.58 square inches.

Integrated circuits are impulse-soldered to etched circuitry. Interconnections are made by alternating communication layers and pillar layers in a multilayer buildup, employing the minimum number of layers. Communication layers interconnect the pins of the various integrated circuits. Pillar layers conduct various voltages, grounds, and signals through the layers and insulate one communication layer from another.

Physically, the multilayer boards are *pre-preg* (pre-impregnated glass glossy epoxy) material; all layers unite structurally when laminated under controlled temperature and pressure. The pillars penetrating through the various layers are interconnected by natural epitaxial crystal growth occurring at the copper interface of adjacent layers.

The two multilayer packages are combined using a low-peel-strength adhesive which permits access to the lower board for removal of the integrated circuits. The flat-packs on the upper board are readily accessible.

Thermal Analysis

It was thought initially that the specific heat of the assembly structure would be of prime importance for thermal control. Materials such as beryllium and Lockalloy were investigated, but detailed analysis indicated that the ratio

$$\left\{\frac{\text{Mass} \times \text{specific heat of structure}}{\text{Mass} \times \text{specific heat of parts}}\right\}$$

was low enough to make this characteristic insignificant.

The lumped temperature rise (ΔT_D) of DECA versus specific heat for several possible structural materials, based on an equal strength criteria, is shown in Table IV where t is the thickness in inches, M_D is the structural weight (lb), C_D is the structural specific heat, $M_D C_D$ is the mass times specific heat, and K_o is the thermal conductivity,

$$\frac{(\text{BTU})\ (\text{ft})}{(\text{ft}^2)\ (^\circ\text{F})\ (\text{hr})}.$$

Hence, for 0.061-inch-thick beryllium, the mean temperature of the DECA becomes:

$$T_b = T_o + \Delta T_D = 120 + 18.40 = 138.4^\circ\text{F},$$

and the temperature for magnesium, which is the worst case, becomes:

$$T_m = 120 + 20.4 = 140.4$$

and the ΔT difference in the final temperature of the DECA between the best and poorest thermal inertia material based on C_D is 2°F.

Computer analysis of the time-temperature distribution as a function of thermal dissipation in the DECA, using parameters such as structural thickness, thermal conductivity, and part location, confirmed that the design was indeed structurally constrained. A material evaluation led to aluminum as the choice. The weight advantages of magnesium, beryllium, and Lockalloy over aluminum were very small (0.1 to 0.2 pound) and were more than offset by fabrication problems (beryllium) and electrical bonding (magnesium).

Some figures of interest for the DECA are listed in Table V.

CONCLUSION

The packaging designs of the ATCA and DECA have significant differences although the assemblies are mounted on the same vehicle. Temperature control by conductive cooling is used in the ATCA packaging, whereas available thermal inertia is utilized in the DECA. These designs demonstrate that the high reliability requirements of manned space flight can be achieved while accommodating differing environmental conditions of the mission.

TABLE IV—Effect of Specific Heat of Material on ΔT_D

Material	t	M_D	C_D	$M_D C_D$	ΔT_D	K_o	t	M_D	$M_D C_D$	ΔT_D
6061-T6	0.063	1.325	0.215	0.285	19.8	89	0.040	0.827	0.178	21.4
Magnesium	0.072	0.965	0.250	0.241	20.4	56	0.046	0.604	0.124	22.4
Lockalloy	0.058	0.850	0.390	0.331	19.4	118	0.036	0.530	0.206	21.0
Beryllium	0.061	0.900	0.43	0.387	18.40	93	0.039	0.562	0.241	20.4

TABLE V—Overall Efficiency of DECA Packaging

No. of Parts	Volume (in³)	Parts Weight (lb)	Total Weight (lb)	Parts Wt. / Total Wt. (%)	No. Parts (per in³)	Density (lb/in³)
989	160	2.40	8.48	28	6.2	0.053

Editorial Representatives