Mr. Somerville

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A U.H.F. Television Link for Outside Broadcasts

by K. C. QUINTON, B.Sc.(Eng.), A.M.I.E.E.
(Formerly of Designs Department, BBC Engineering Division)

BRITISH BROADCASTING CORPORATION

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FOREWORD

THIS is one of a series of Engineering Monographs published by the British Broadcasting Corporation. About six are produced every year, each dealing with a technical subject within the field of television and sound broadcasting. Each Monograph describes work that has been done by the Engineering Division of the BBC and includes, where appropriate, a survey of earlier work on the same subject. From time to time the series may include selected reprints of articles by BBC authors that have appeared in technical journals. Papers dealing with general engineering developments in broadcasting may also be included occasionally.

This series should be of interest and value to engineers engaged in the fields of broadcasting and of telecommunications generally.

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SUMMARY

This monograph deals with the design and development of transportable radio equipment for transmitting television pictures from Outside Broadcast locations to fixed points for connection into the national network. A brief historical introduction to radio linkage in the BBC is given and the need for Ultra High Frequency equipment is shown, with particular reference to moving-camera applications and to propagation over water. The relative merits of amplitude and frequency modulation are explored, in theory and practice.

The various ways of producing a transmitter and receiver to meet the electrical and mechanical requirements are then outlined and discussed, and block diagrams of the final designs are described. A more detailed description of the frequency modulator, u.h.f. stages, and lightweight power units is included. The first year's operational experience shows the success achieved by, and limitations of, the system, and the conclusions drawn indicate that programme planning staff have been given more freedom than would have been possible with s.h.f. link equipment alone.

1. Introduction

In the early days of the BBC Television Service, when studio facilities and techniques were still somewhat experimental, outside broadcasts (O.B.s) were soon recognized as being excellent programme material, especially when national events occurred in or near London. Two problems confronted the planners: the weather hazard in view of the high value of the light intensity required for the early high-velocity camera tubes, and the difficulty of relaying the picture signals to the broadcasting station at Alexandra Palace in the North London suburbs. The latter was partially solved by the provision of a special balanced cable running east–west in the centre of London and out to the station. This was soon to be extensible for short distances by the addition of telephone pairs.[1,2] For other locations two mobile 1-kW vision transmitters were commissioned operating on a frequency near 60 Mc/s, reception being initially on the Alexandra Palace mast and later at a separate site on the special cable route. This site is still in use. These transmitters were housed in 12-ton vehicles and were used in conjunction with three other vehicles of similar size—an extensible fire-fighting ladder for raising the aerial, a power generation van, and the mobile camera control room (see Fig. 1).

After the war, plans were laid to build more television broadcasting stations throughout Britain; this had a twofold effect—to increase the range of outside broadcasts and to remove the availability of Band I v.h.f. channels for link work. The logical development was the construction of a Band III v.h.f. transmitter, together with a diesel-driven power generator, housed in a 14-ton vehicle carrying a 120-ft extensible ladder for elevating the aerial.

By this time communication engineers, who had developed advanced techniques in the Super High Frequency spectrum during the war, were producing links for picture transmission; some for O.B. applications. The BBC took all available prototypes from the British manufacturers and, resulting from those early tests, every O.B. crew now has its 'micro-wave' link equipment. Indeed, such systems have become well established throughout the world, in most countries to the exclusion of links on lower frequencies. The great advantages are the simplicity of the transmitting terminal and the absence of man-made interference at the receiver. This latter point cannot be too highly stressed, since receiving sites are generally in urban areas or close to roads, and an engineer prefers to remove all elements of doubt concerning what will happen during the programme time.

The advent of the micro-wave transmission link introduced two new concepts—frequency modulation applied to television transmission and a 'starting link'. The former arose because frequency modulation of s.h.f. valves is simply achieved and bandwidth was plentiful, and the latter was a demand created by a system which required the receiver to be optically within range of the transmitter. Micro-wave is a hilltop-to-hilltop system and short range links were required to connect the camera control vehicle to the nearest vantage point. As this path may not be optical, compact v.h.f. units were developed.

Enterprising engineers and producers soon exploited these for O.B.s where the picture source is mobile—firstly in river boats, then in sea-going vessels, and later in aircraft and 'roving eye' vehicles. The success of these O.B.s was largely due to specially designed BBC receivers with extended a.g.c. range. Micro-wave systems require accurate alignment of somewhat bulky aerials and thus are not suitable.

This v.h.f. venture was to be short-lived, partly because man-made interference restricted the range but primarily because the frequencies used were now put to the purpose for which they were allocated, namely television broadcasting. The 14-ton v.h.f. transmitter was similarly affected.

2. U.H.F. Link—Requirements

The production staff had had their appetites for truly mobile O.B.s whetted and the loss of v.h.f. links created a considerable demand for replacements. In addition, links of fair range were required as it had been found that micro-wave equipment rigged on a temporary basis without diversity reception was not reliable for transmission across water. (Often it is necessary to transmit the signal across broad estuaries in order to reach the television network.) Since Britain is unlikely to use all the u.h.f. spectrum allocated to television broadcasting for many years, and the range of continental stations is unlikely to be sufficient to cause serious interference, experiments were started in Band IV and were later transferred to Band V.

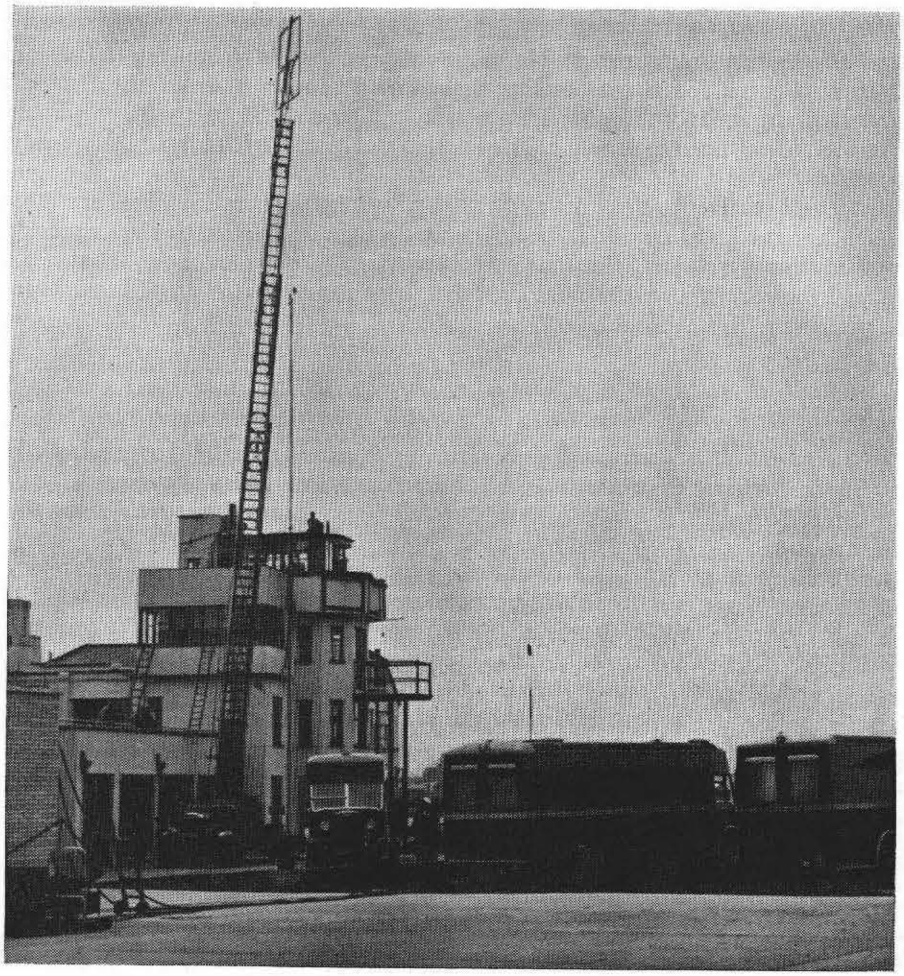


Fig. 1 — Television O.B. Fleet assembled at Heston Aerodrome for the return of Mr Neville Chamberlain from Germany, September 1938. Left to right: *aerial, transmitter van, mobile control room, and power van*

It was decided, as no commercial equipment in this band was available, to develop a link capable of an optical range of ten miles or more, using portable broad-beam aerials; the transmission standards being such that negligible degradation of signal quality should occur. Further, if any existing equipment could be modified for u.h.f. operation it would save the BBC design effort to use it. This latter point had some bearing on the balance to be held when assessing the relative merits of amplitude and frequency modulation, since good v.h.f. and s.h.f. receivers (a.m. and f.m. respectively) were in use and these could be converted to u.h.f. service; only the v.h.f. transmitters, however, could be converted, thus giving a bias towards using a.m.

Before any real design work could be undertaken it was necessary to decide, both from theory and field trials, whether amplitude or frequency modulation would best suit the BBC's practical requirements. Points considered included:

(*a*) Transmitter power for a given signal : noise ratio at receiver, assuming r.f. channel bandwidth to be limited by existing receiving equipment.

(*b*) Nature of the noise spectrum—subjective effects on picture.

(*c*) Man-made interference at u.h.f. and its suppression in the receivers.

(*d*) Aerial bandwidths and the effects of imperfect matching.

(*e*) The subjective effects of multipath propagation.

(*f*) Complexity of receiver a.g.c. arrangements, also rapidity of operation for mobile transmissions.

(*g*) Possibility of channel bandwidth conservation in the f.m. case if the d.c. component of the vision signal is preserved in the modulator.

(*h*) Equipment size and weight, ease of alignment and maintenance.

Items (*a*), (*b*), (*f*), and (*g*) could be considered theoretically, although items (*c*), (*d*), and (*e*) would require some experimental evidence, whilst (*h*) could be estimated reasonably accurately, although, if f.m. were chosen, original work would be needed to decide several details.

2.1 *Theoretical Merits of F.M. and A.M.*

(*a*) For amplitude modulation double sideband is preferred to vestigial operation, since the accuracy required in receiver tuning is lower and overall distortion is likely to be less in practice. For frequency modulation the deviation is bound to be limited by available channel width, but as no decision had, at the time of development, been made in respect of permanent O.B. allocations, thoughts turned to existing s.h.f. receivers which could be adapted and a decision was made to estimate on a basis of 6-Mc/s peak-to-peak deviation. S.h.f. experience showed that a channel bandwidth of 12–14 Mc/s would give adequate performance with this deviation, since, at the high-frequency end of the video spectrum, some non-linear distortion can be tolerated and in a practical picture full h.f. modulation is seldom achieved. This channel bandwidth is quoted on the basis of d.c. modulation and a deviation of 6 Mc/s from sync. bottom to peak white (see point (*g*)).

For a 100 per cent amplitude modulated wave entering a double sideband receiver we have the expression for signal:noise ratio at the video output (assuming a linear detector):

$$\frac{\text{Peak-to-Peak Signal (voltage ratio)}}{\text{r.m.s. Noise}}=\sqrt{\frac{\sqrt{2}P_c}{2KTBF}}$$

where P_c=received signal power corresponding to peak white, watts

K=Boltzmann's constant$=1\cdot374\times10^{-23}$ joule/°K

T=absolute temperature, °K

B=video bandwidth, cycles/sec.

F=receiver noise factor, power ratio

The received power is multiplied by $\sqrt{2}$ to allow for linear detection.[3] The corresponding expression for frequency modulation is[4]

$$\frac{\text{Peak-to-Peak Signal (voltage ratio)}}{\text{r.m.s. Noise}}=\sqrt{3\left(\frac{\Delta f}{B}\right)^2\cdot\frac{P_c}{KTBF}}$$

where P_c=received signal power

Δf=total deviation, otherwise as above

In both cases the signal:noise ratio at the input to the demodulator is assumed to be $\gg 1$. For a given input power, if the modulation standards described earlier in this paragraph are used, f.m. gives an improvement of 12·3 dB over a.m. for a 3-Mc/s video passband. It is reasonable at u.h.f. to assume that the noise factors of both receivers would be similar.

(*b*) The nature of the noise output merits some attention. In the a.m. case the spectrum is 'flat', i.e. noise power/unit bandwidth is constant, whereas in the f.m. case the noise is 'triangular', i.e. noise power/unit bandwidth rises 6 dB/octave. Subjectively on a picture display this latter 'noise' is more easily tolerated by the eye, giving the f.m. system a further advantage of about 7–8 dB without pre-emphasis.[5]

(*f*) The automatic gain control of an a.m. video receiver is simple if the modulation is negative, i.e. peak power at sync. bottom, whereas with positive modulation the synchronizing pulses have to be separated and measured. In Britain positive modulation is preferred as a linear performance is more easily achieved, both in transmitter and receiver, for the picture information, also noise and interference cannot extend beyond sync. bottom—a distinct advantage for link operation. A black-level clamp, necessary for sync. measurement, is likely to be erratic in operation in the presence of severe noise and interference, also it fails when the transmitter modulation is removed.

Whether positive or negative modulation is used, a.g.c. information is derived from the synchronizing pulses. These contain information at field frequency, thus, to avoid video distortion in the receiver, the a.g.c. circuit needs to integrate several fields, resulting in a long time constant. Experience of mobile O.B.s has shown this to be a considerable disadvantage, since the a.g.c. is inoperative during rapid signal fluctuations.

There is no corresponding limit on a.g.c. time constant in an f.m. receiver, indeed if the a.g.c. can be made fast enough the function of limiting is obtained. This latter, however, is not common practice, since with the loop-gain necessary the stability problems associated with feedback amplifiers are acute. A.g.c. is desirable in a multi-stage f.m. receiver, since limiting should occur as close to the demodulator stage as possible. This condition arises because the bandwidth between limiter and discriminator must be very large to ensure good 'capture' of the wanted signal in the discriminator.

(*g*) If the frequency, in an f.m. system, is fixed at sync. bottom and at peak white, then the maximum deviation is the difference of these frequencies. If, however, the d.c. component is not applied to the modulator, then the maximum possible deviation is 1·68 times this figure (assuming British video standards) due to the asymmetric nature of the waveform. In this case the channel bandwidth is increased but the signal: noise ratio is unaffected. Use of this latter extravagant technique has only one advantage—if automatic frequency control is used in the receiver then this control is simpler and need not be gated during the sync. period. For u.h.f. links, a.f.c. can be avoided by careful local oscillator design.

3. Early U.H.F. Experiments

The first practical field tests designed to answer the outstanding points listed in the previous paragraph were conducted in April and May 1954. In April static tests were made, whilst in May the transmitter was mounted in a launch on the Thames, passing up and down the course used for the University Boat Race.

The transmitter operated at 511 Mc/s and was amplitude modulated in a positive sense, peak-white power being 30 watts. A 4X150A output tetrode was used as the final stage and was grid modulated. The receiving equipment was in three parts—a broad band frequency changer giving a flat output from 30 to 50 Mc/s, the post frequency changer sections of an a.m. link receiver or, alternatively, the equivalent sections of an f.m. link receiver. The frequency changer included a low-noise pre-i.f. amplifier, therefore the noise factor was fixed for all tests at a low value.

(*c*) A short link was set up in the central London area and initially a comparison was made between 190 and 511 Mc/s using amplitude modulation to assess the relative levels of man-made interference.

The aerials were horizontally polarized and had similar gains and feeder losses. This test showed that similar signal : interference ratios were obtained when the u.h.f. receiver input was 8–10 dB less than the v.h.f. receiver input. This indicated that the field strength of interference (mostly from motor-car ignition systems) is roughly similar in Band III and Band IV.

By adjusting the u.h.f. transmitter for plain carrier radiation and using the f.m. receiver, the improvement (using the standards stated) in interference suppression was about 20 dB for large incoming signals, dropping to about 8 dB when the thermal noise became marginal judged by transmission standards. This test was made by setting the video gain of the f.m. receiver such that if the carrier had been deviated $\pm$ 3 Mc/s an output of standard level would have been obtained.

(*d*) A few measurements showed that aerials of the Yagi or corner reflector types, with gains up to 10 dB referred to a dipole, could easily be matched to a 50-ohm feeder. The impedance mismatch and change of polar diagram over a band $\pm$10 Mc/s were found to be very small, and, since for mobile applications braided feeders 50 ft or more long have enough loss to mask these small changes, no ghosting effects were expected or observed. No troubles have since been experienced due to lack of aerial bandwidth.

The tests on the Thames allowed further comparisons of 190 Mc/s and 511 Mc/s. Firstly recordings were made of received signal levels, and these showed that for optical and near-optical path conditions the received field strengths were similar for similar effective radiated powers, but that the attenuation caused by large buildings in the path was greater for the higher frequency. For example, a large furniture depository caused a 16-dB loss at 190 Mc/s and 23 dB at 511 Mc/s. Signal level fluctuations due to reflections and propagation through metal bridges were of greater amplitude and were more rapid for the higher frequency. These effects caused a corresponding deterioration of the video signal.

It was further proved that transmitting aerial gains could not exceed 10–12 dB since the boat would often roll $\pm15°$ or more due to passing craft.

Measurements made on the f.m. receiver, but without transmitter modulation, showed a considerably greater noise-free range and complete absence of the video output flutter caused by the inevitably slow a.g.c. operation of the a.m. receiver. The noise output was observed by modulating the receiver output with a suppression and synchronizing waveform and viewing on a picture monitor.

To sum up, the early tests showed that Band IV is not necessarily limited to optical paths—some obstructions can be tolerated—but attention must be focused on obtaining adequate power and minimum feeder losses since aerial gains for mobile work must be restricted. In view of the more stable receiver output and improvement in noise and interference suppression, it was decided to construct an f.m. link equipment.

The comparison of multipath propagation effects on f.m. and a.m. was yet to be made, but reference to an article on this subject[6] indicated that subjectively f.m. might give rather less disturbing results.

4. General Descriptions of Transmitter and Receiver Operating at 610–660 Mc/s

The experiments were transferred to the lower end of Band V where four channels, each 12·5 Mc/s wide, had been provisionally allocated to O.B. links. It is now proposed to describe the f.m. u.h.f. equipment which has been developed and put into service.

4.1 *Transmitter*

Broadly speaking, three possible methods of constructing a transmitter appeared worthy of consideration—a modulator of low frequency and low deviation followed by frequency and power multiplication, or a modulator of required final deviation followed by a frequency mixer and power amplification, or a modulator at s.h.f. followed by a mixer and power amplification. It is obvious that some compromise between the first two possibilities is also possible. The first technique was considered the least attractive, since frequency multiplying stages seldom give much power gain, and the final frequency stability was likely to be poor. The second suggestion has the disadvantage that the unwanted products of mixing would require suppression in tunable filters, and if transmitters and receivers are likely to be used in close proximity (for instance when links are used in tandem) the suppression problems may become insuperable if the frequency from the modulator is low. A transmitter of this type can easily be converted to a non-demodulating repeater, but for BBC O.B. applications this is not important and, in certain cases, might be undesirable. For the third suggestion two similar klystron oscillators were considered, their operating frequencies spaced the required output frequency apart, one or both being frequency modulated. The outputs would then be mixed and amplified. The main objections to undertaking this development were its costliness and the number of coaxially tuned amplifier stages which would be required.

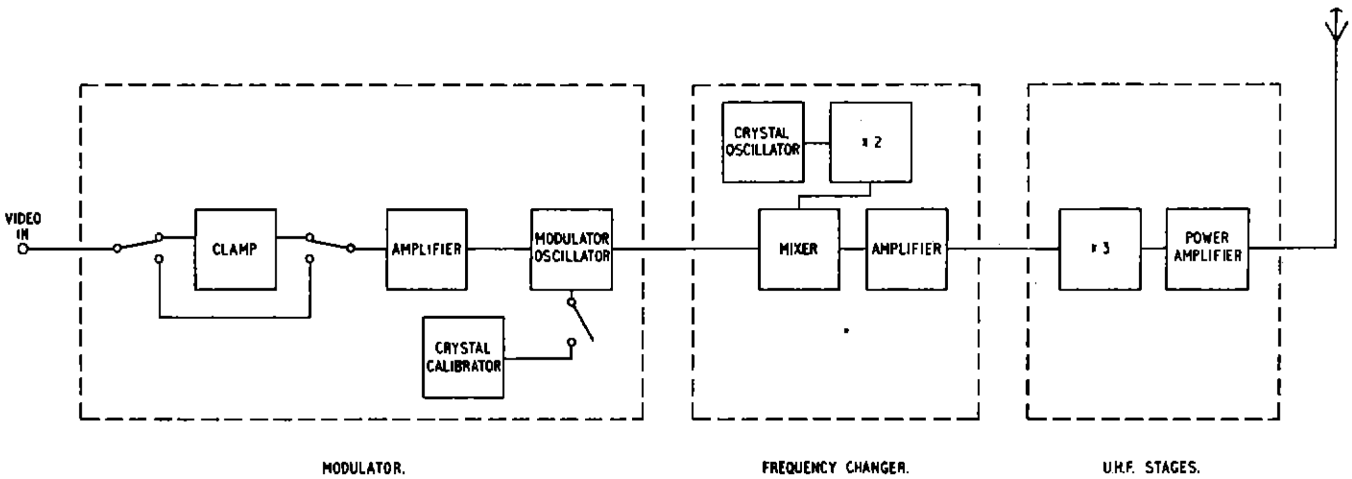


Fig. 2 — Block diagram of transmitter

Whether the required frequency stability would be achieved without a.f.c. was also a matter of some conjecture.

Thoughts then turned to some compromise between the first two suggestions, and since a wide-band frequency modulator had recently been designed to provide vision O.B. injections into the repeater stations on the Manchester–Scotland trunk network, this modulator was taken as the basis of the transmitter. It was capable of deviation up to 6 Mc/s at a mean frequency of 60 Mc/s. Direct multiplication to Band V was not possible due to inadequate stability and the lack of tuning facilities. The operation of a modulator within a fixed frequency spectrum has the advantage that the output at sync. bottom and peak white may be crystal checked, thus establishing both frequency and deviation with some accuracy. The operational channel would be fixed by mixing the output with a crystal-controlled drive frequency.

The final transmitter block diagram is shown in Fig. 2.

The output from the modulator which is described in Section 5 is mixed with a frequency of about 150 Mc/s, derived by multiplying by two the output frequency from an overtone crystal, and then selecting the upper sideband. Mixing takes place in a small double triode at a level of about 100 mW. Some experiments were conducted with a power triode mixer operating with 2-W inputs, but difficulties were encountered with spurious outputs due to high order products. High-level mixing would have reduced the number of wide band stages to be retuned when changing from one channel to another.

The deviation in the modulator, and at the mixer output, is 2 Mc/s. The upper sideband of the latter is amplified to a level of 4 watts in three stages—one miniature pentode and two grounded-grid triodes, type CV2214.

The output unit, comprising tripler and final amplifier, uses planar triodes type 2C39A delivering 17 W at about 630 Mc/s, deviation being 6 Mc/s. The overall radio-frequency bandwidth of the transmitter referred to the aerial terminal is greater than 12 Mc/s to the 3-dB points.

From the previous arguments perhaps a more attractive technique would have been to frequency double in the penultimate stage, thus obtaining greater power efficiency in this stage as well as improving output stability. This course was not adopted since valves of high figure of merit were not available for 300 Mc/s operation, and the idea of using planar valves with lumped circuit elements was not attractive.

This latter point brings in a further design consideration—the requirement to keep weight to a minimum. This restricted the number of valves requiring coaxial cavities and, in the output stages, use has been made wherever possible of aluminium alloys. Some of these having a low silicon content are readily silver plated. Brass is, however, inevitable in some details requiring precision tubes or fine threads.

For portability the transmitter is in three cases, each housing a unit and power supply. The first two cases complete weigh less than 50 lb each, whilst the last weighs 90 lb, but here the power unit can be quickly released if required, thus permitting it to be handled by one man. The second case carries a general cooling fan, whilst the final case contains blower, air ducting and filtering. The transmitter input from the supply mains is approximately 650 VA.

The power unit for the final stages is conventional, using selenium rectifiers and thermal h.t. delay with bias interlock. The planar valves are protected by series chokes in accordance with the maker's recommendation. The other two power units use electronic stabilization and smoothing and are described in Section 7.

4.2 *Receiver*

Although a comparatively small part of the receiving terminal was designed by the BBC, it may be useful, for completeness, to discuss briefly the design requirements. The r.f. channel bandwidth has already been given, and it is a function of the receiver to accept the full bandwidth and discriminate against interference on other frequencies. A

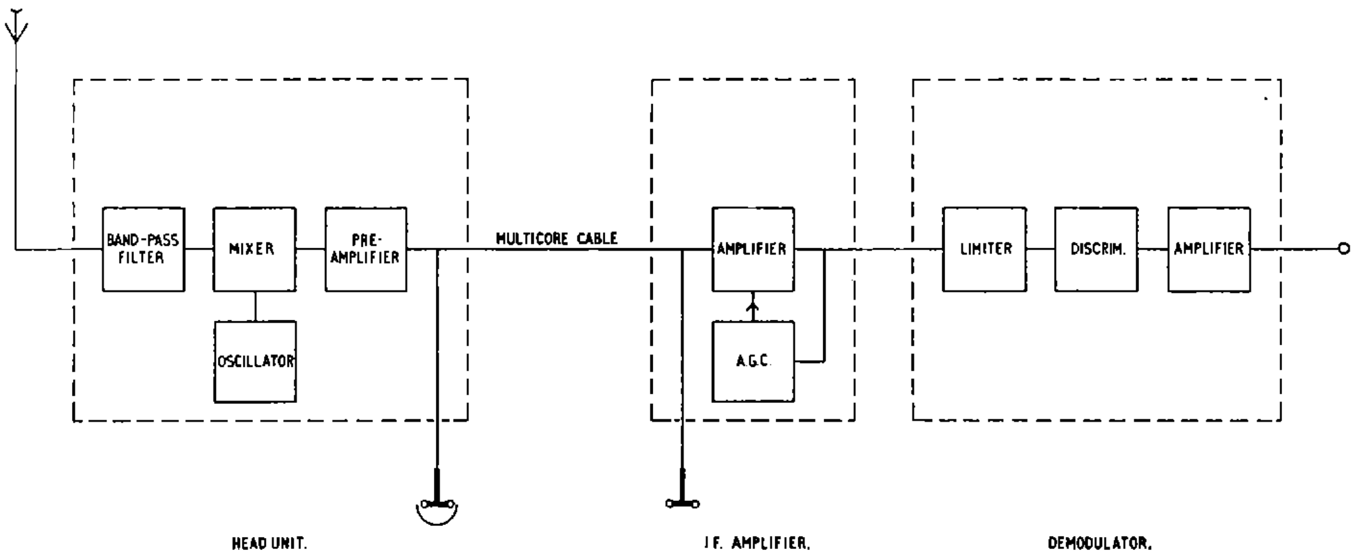


Fig. 3 — *Block diagram of receiver*

band-pass input circuit is therefore required and, if no r.f. gain stage is used, this performs a triple role—selectivity against u.h.f. interference, reduction of local oscillator radiation, and a stop against i.f. break-through. This last requirement seldom occurs in s.h.f. receivers since wave-guide horns are usually very effective high-pass filters.

The equipment described incorporates no r.f. gain stage, since the extra bulk was not considered justified in a mobile equipment, particularly as it was known that at many sites the receiver would deliver more man-made interference than thermal noise. Receiving aerial feeders with losses up to 2 dB were envisaged, otherwise this last argument might be invalidated.

Passing to sensitivity, it is important to have sufficient gain to saturate the limiters until the output signal : noise ratio approaches unity. Line-by-line clamps in television broadcast apparatus will function when this ratio is very low by visual standards, thus the efforts to maintain the signal level during rapid fades is justified.

A noise factor of 14 dB has been achieved, using a silicon crystal mixer and well-designed pre-i.f. amplifier. The input s.w.r. is better than 1·1 : 1, making the design and measurement of the bandpass filter simple.

The choice of intermediate frequency for O.B. receivers is one of compromise. For a good noise factor it must be low, providing the local oscillator contributes negligible noise in the r.f. pass band. On the other hand the limiters should not be followed by circuits an octave wide and practical discriminators improve in sensitivity as the frequency is raised. Image channel rejection will likewise improve. However, the overriding factor is i.f. interference and, where receivers are likely to be used at broadcasting sites, one is forced to choose either a frequency above 100 Mc/s or have alternative units on lower frequencies, to be selected according to site. In this receiver the latter arrangement was used, the i.f. being 30 or 60 Mc/s. Amplifier and discriminator stages are mounted on strip chassis for easy replacement.

This arrangement calls for a continuously variable local oscillator with sufficient tuning range to allow either i.f. to be used on any allocated channel. Experience with links in tandem has shown that the local oscillator should also be capable of operating above or below the input frequency. A typical case arises when the channel spacing is 30 Mc/s and the i.f. is 60 Mc/s. The local transmitter can give rise to a spurious i.f. of 30 or 90 Mc/s according to the position of receiver local oscillator. In the former case, if the signal is sufficiently strong, frequency doubling can occur in the i.f. amplifiers and cause interference.

A disc-seal valve mounted in a coaxial cavity will give sufficient mechanical stability in the local oscillator for mobile use, but precautions are also necessary to ensure good frequency stability with change of temperature, since a receiver head unit must be compact and may therefore run quite hot. In the oscillator described in Section 6 use has been made of the low coefficient of expansion of a carbon compound to reduce frequency drift. Power supply variations should not affect the oscillator frequency and it is a simple matter to ensure that drift due to changing mains supplies is small and that modulation due to h.t. and l.t. ripple causes a deviation of less than 6 kc/s (—60 dB on signal).

Further receiver requirements are automatic gain control, limiters, discriminator, and video stages to deliver a standard waveform. It is useful to indicate carrier level (particularly when aligning aerials) and intermediate frequency. If the local oscillator frequency may be above or below that of the r.f. signal, then in an f.m. video system an inverting switch must follow the discriminator.

A block diagram of the receiver is shown in Fig. 3. Aerial feeder losses are reduced to a minimum by adopting the technique of frequency conversion in a unit designed

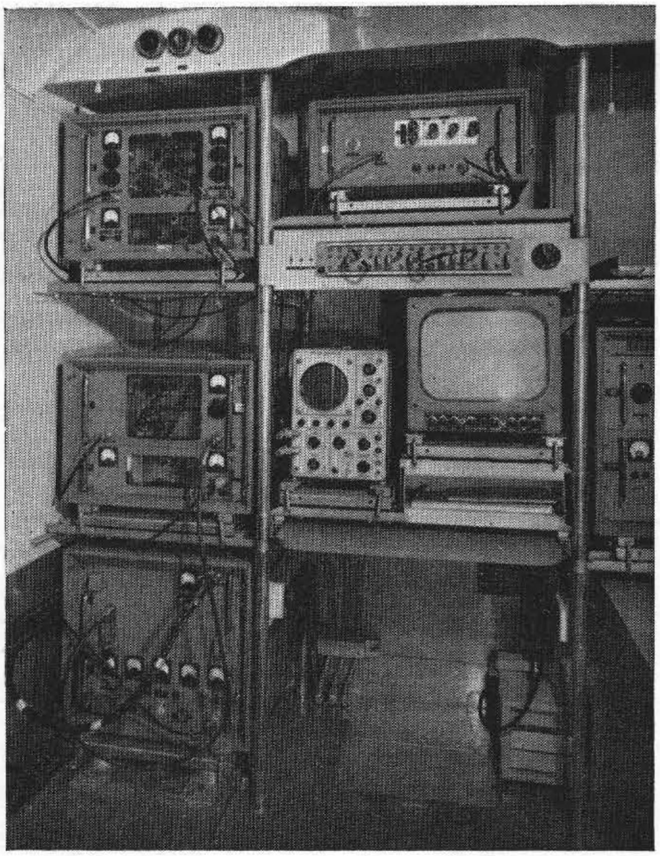


Fig. 4 — Band V transmitter in a link vehicle. Left-hand side: top, modulator; centre, frequency changer; bottom, v.h.f. stages. Centre: top, transmitter monitor unit

Fig. 5 — Band V receiver in the Roving Eye tender. Right-hand side, from top: 1st i.f. amplifier; 2nd discriminator. The cast case mounted on a scaffold tube is the head unit

for mounting close to the aerial. This unit contains band-pass filters, local oscillator, crystal mixer, pre-i.f. amplifier, power unit, and intercommunication facilities. It connects by multicore cable with the main i.f. amplifier; the two units may be several hundred feet apart before the performance is impaired. The main i.f. amplifier is connected to a unit housing limiters, discriminator, and video output stages.

The pre-i.f. amplifiers and subsequent units used are s.h.f. link items, produced by a well-known manufacturer and their design is described elsewhere.[7]

Fig. 4 shows a transmitter and Fig. 5 a receiver, mounted in a link vehicle.

5. Modulator Description

The modulator unit shown in the block diagram, Fig. 2, comprises four circuits which may be treated separately according to their functions. They are: waveform stabilizer, video amplifier, modulated oscillator, and crystal calibrator.

The first circuit is an optional refinement which may be switched in or out as required. Briefly, it is a conventional black-level clamp designed to remove l.f. distortion and hum from the incoming signal. The clamped valve has cathode resistance feedback, this resistor being shunted by a biased crystal diode so that the feedback is reduced during the sync. pulse period and the valve current is cut off. The picture/sync. ratio may then be controlled by altering the input attenuator and any incoming interference can be removed from the bottom of the sync. pulses.

The second circuit is shown in Fig. 6. It is a simple feedback amplifier designed to drive the reactance valve from a low-impedance source with a signal having the necessary d.c. content. V1 inverts the signal and V2, V3, and V4 form a triple with a cathode-to-cathode feedback network. The output terminal drives the cathode of a reactance valve; thus the resistive component of the load varies considerably. The reactive component of the load is a 200-pF condenser (Cx). The measured output impedance at terminal D with Cx connected is low, rising to (9+j19) ohms at 3 Mc/s. The diode, V18, conducts during the sync. period, restoring the d.c. component of the signal. For satisfactory restoration the video level on V4 grid is several volts and this explains the need for taking the output from a point tapped down the cathode load.

Two features of this amplifier may be of interest. Firstly, it may be thought that the feedback would remove the sync. pulse crushing caused by the diode. This is not so, since the forward gain is so far reduced during diode operation that the stabilizing effect of feedback is lost. Secondly, V2 is auto-biased to isolate the quiescent current from that of V4. The return of R2 to the feedback connection brings the time constant C2 R2 into the equations governing the l.f. stability.

The modulated oscillator shown in Fig. 7 is based upon a circuit suggested by Dennis and Felch.[8] The oscillator valve, V5, has its anode and grid connected to the ends of a two section low-pass filter which is terminated in its iterative impedance at 0·7 fc. The reactance valve, V6, anode is connected to the sending end of the filter and the grid to the mid-point. Consider V6 to be cut-off. The phase-shift through the filter will be 180° at 0·7 fc and oscillation will occur, the loop gain being unity when $g_m=\frac{1}{R_T}$. V5 is grid-leak biased and, by making $\frac{1}{R_T}$ large enough, a small amplitude of oscillation can be maintained with the valve in Class A conditions. The low-pass filter will tend to reduce harmonic distortion in the valve. The voltage at the mid-point of the filter is in quadrature with that at either end and thus V6 functions as a 'reactance' valve. However, since exact quadrature is only possible when the mutual conductance, g_m, of V6 is zero, the operation is more rigorously explained with the aid of a vector diagram, Fig. 8. In practice R_T is sufficiently low that V5 and V6 can be regarded as current generators feeding the filter input, and for small deviations the input impedance may be assumed to be R_T. I_o is the alternating oscillator current, I_m the reactance valve current, thus I_x is the total current entering the filter at X, Fig. 7. Whether I_x leads or lags I_o can be determined by putting $I_m \to 0$ whence I_m is in quadrature leading I_o. I_y lags I_x by an angle θ and I_z, which produces a voltage in phase with I_o, lags I_x by 2θ. The frequency of oscillation is that at which the phase shift across the filter is 2θ. Since $\phi=\pi-\theta$ and $\gamma=2\theta-\pi$ and $\beta=\pi-\gamma-\phi \therefore \beta=\phi$, i.e. the constructed triangle is isosceles.

Therefore the magnitude of I_x is independent of I_m, and amplitude modulation is absent.

Similarly, I_m is proportional to $\sqrt{1-\cos\gamma}$

For small angles $\cos\gamma \approx 1-\frac{\gamma^2}{2}$, i.e. γ is proportional to I_m, and if the filter has a linear phase-frequency characteristic then frequency will approximate to a linear function of the mutual conductance of V6.

Several assumptions have, of course, been made, one being that the reflection loss in the filter will remain at zero over the operative band. The phase linearity of the filter could be improved by using more sections and a higher fc, but the capacitors would then become impracticably small. M-derived sections could be tried, and the possibilities of the circuit have by no means been exhausted.

The choke, L3, reduces amplitude modulation due to the video component of V6 current being developed across R_T. L3 has a small self-capacity and self-resonates at 60 Mc/s. It does, however, degrade the modulator performance and experiments were made with band-pass filters inserted between the main filter and R_T, but without improvement on the choke.

A typical plot of reactance valve bias against frequency is shown in Fig. 9.

The application of the modulating waveform to V6 set a problem, since R1 should be a negligible load on the filter and C1 must be large to avoid a phase shift. The grid is therefore not a suitable electrode for a wide-band drive. Some experiments were conducted with a short suppressor-based valve but the mutual conductance was insufficient

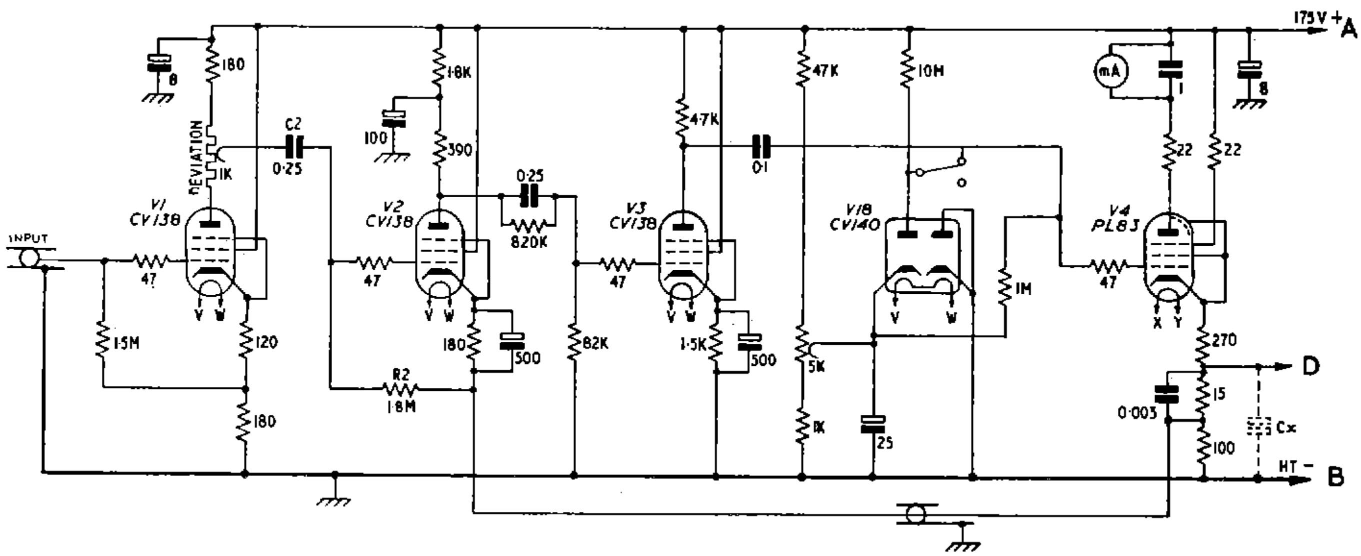


Fig. 6 — Circuit of video amplifier

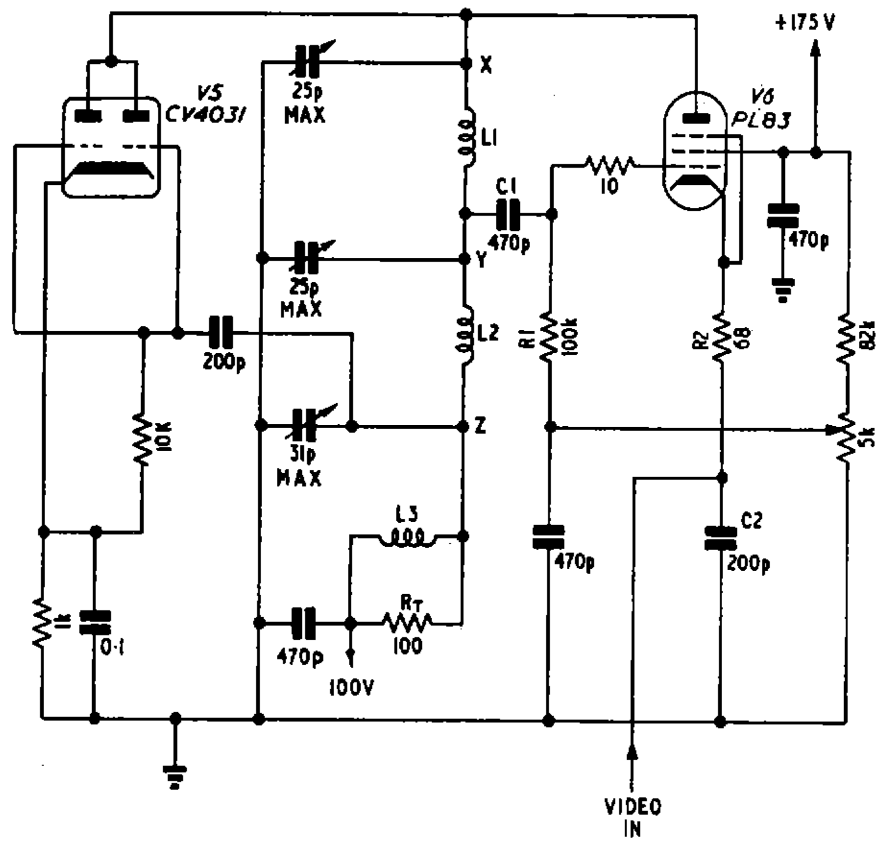


Fig. 7 — Circuit of oscillator and reactance modulator

to give the required deviation (6 Mc/s linear in the original design). Increase of the filter impedance would have been a solution, but at the expense of stability. The cathode was eventually chosen, as shown, and C2 is a disc condenser having a low reactance at 60 Mc/s. R2 improves the linearity of the $g_m - V_g$ characteristic of V6.

The modulated output is taken from the point Y (this being the largest capacity in the filter) via a buffer valve. Crystal controlled outputs of 59, 60, and 61 Mc/s can be added at this stage for calibration purposes. These give rise to zero beats at various levels in the demodulated video waveform.

The heater supplies of V4 (Fig. 6) and V6 (Fig. 7) were stabilized to reduce frequency drift due to supply voltage variations.

Since this development another wide-band modulator has been described and readers may be interested.[9]

6. U.H.F. Stages

The penultimate and final stages in the transmitter use planar triodes type 2C39A. These were selected for their high gain-bandwidth product and reliability. A cross-section of the final stage is shown in Fig. 10. A common grid circuit is employed, the cathode being tuned by a co-axial line in the $\frac{3\lambda}{4}$ mode whilst the anode-grid tank circuit is in the $\frac{\lambda}{4}$ mode. The input is matched to the valve by tapping the line, but the output is extracted by capacity probe near the grid. The anode is effectively earthy and the circuits are arranged to give easy valve access. Connections to the anode and grid of the valve are made by helical 'bracelet' type contacts similar to those used in the output circuit tuning bridge. Contacts on the cathode circuit use dimpled spring fingers. All the metal parts are electroplated with silver which is protected from corrosion by a thin deposit of rhodium. The rhodium is 0·000 015 in. thick except for contact surfaces, where it is thickened to spread the load on the soft undercoat, otherwise surface cracking would result. The resistivity of rhodium is higher than that of silver, but it gives a stable contact unaffected by atmospheric exposure. At 600 Mc/s the 'skin depth' is 0·000 087 in. in silver and 0·000 15 in. in a rhodium conductor, thus the silver undercoat will raise the unloaded circuit Qs.

The required half-power bandwidth of the output stage is 16 Mc/s. The input circuit is somewhat wider than this, being damped by the cathode impedance. The mean cathode impedance is dependent upon the angle of current flow in the valve, thus the bandwidth will fall as the drive is increased. The output circuit requires the load to be overcoupled to achieve the design bandwidth, despite an

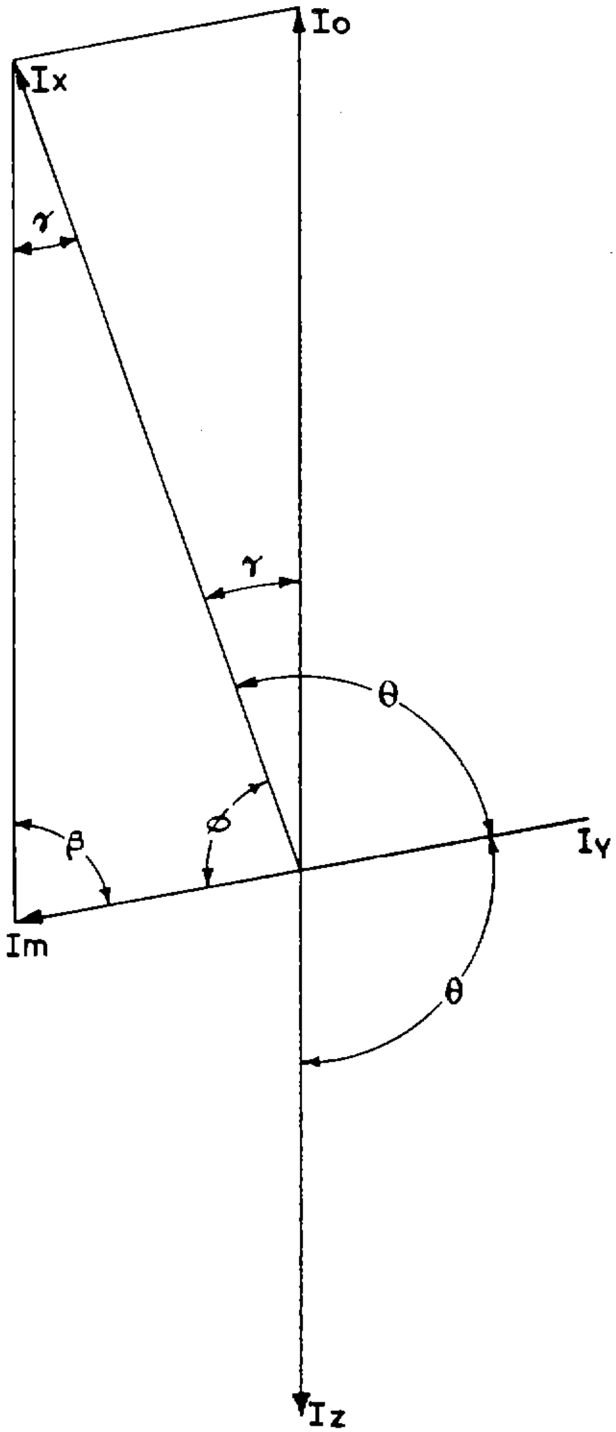


Fig. 8 — Vector diagram for Fig. 7

effort to avoid this. The lumped equivalent of the output circuit is shown in Fig. 11. C1 L1 is the coaxial cavity less than $\frac{\lambda}{4}$ long, C2 is the lumped capacity within the valve plus that due to end effects, and C3 is the coupling (probe) element and R1 the aerial feeder load. R_a is the dynamic valve output impedance, assumed to be resistive.

For a large bandwidth C1 requires to be as small as possible. The expression for C1 is given by Swift[10] as $C1=\frac{1}{2\omega Z_o}\left[\frac{\beta l-\sin\beta l\cos\beta l}{\sin^2\beta l}\right]$ where Z_o is the characteristic impedance of the grid-anode line and βl its electrical length. C1 can be made small by making Z_o large, which in turn causes βl to be small. It was not practicable to make Z_o more than 100 ohms. The replacement of C3 and R1 by an equivalent parallel arrangement C4 and R2 is valid over a small frequency range, R2 being the load resistance, Fig. 11a. C4 must be small for maximum bandwidth. In the practical case $\frac{R2}{R1}\approx 80$ and C4 approximates to C3 thence $R1R2\approx\left(\frac{1}{\omega C4}\right)^2$. Solving for $R1=50$ ohms, C4 is approxi-

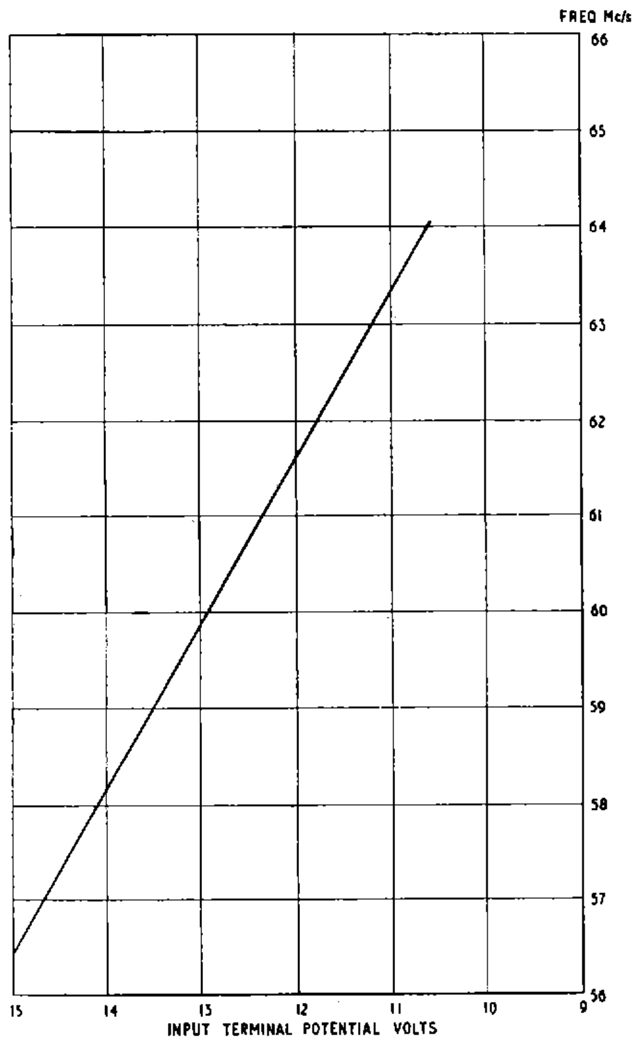


Fig. 9 — Typical reactance modulator characteristic

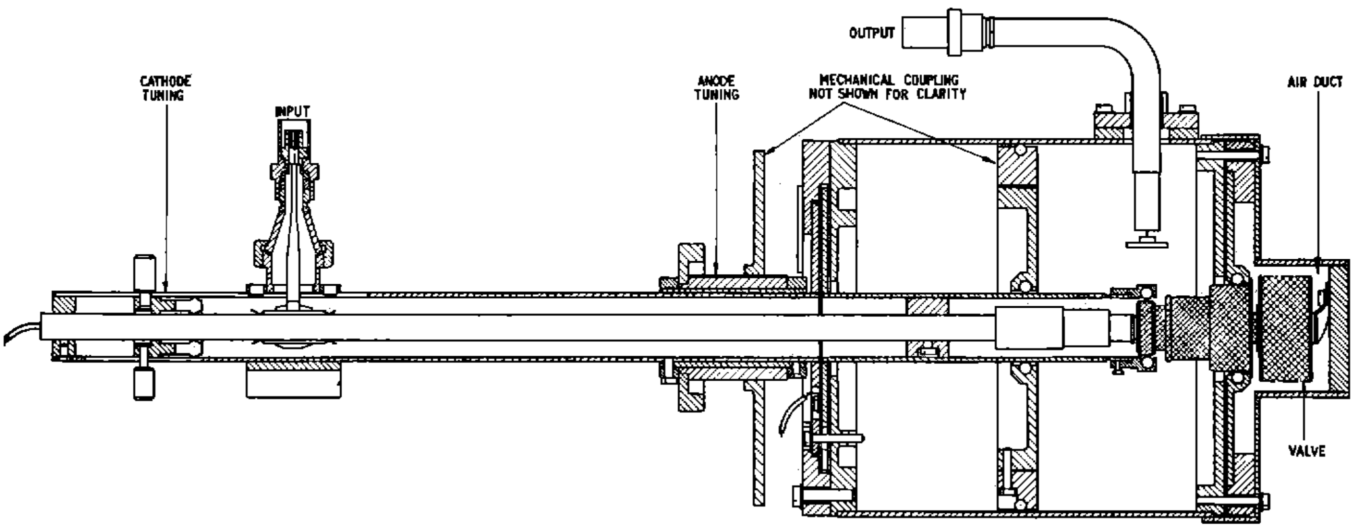


Fig. 10 — *Cross section of final stage; transmitter*

mately 0·6 pF, which is still sufficiently large to affect the bandwidth appreciably. C4 was eventually reduced by making R1 at mid-band 165 ohms. This was achieved by using a $\frac{\lambda}{4}$ transformer section of 91-ohm cable between the probe and 50-ohm feeder. Fig. 11b shows the equivalent lumped circuit near resonance where C3′ is the new coupling capacity and R2′ the transformed feeder resistance. The value of C3′ required to load the valve may approach the value desirable for transitional coupling, thus the introduction of a resonant transformer does not necessarily cause a further bandwidth reduction. The power gain of the final stage is about 7 dB, the anode efficiency with 500 volts d.c. applied is about 50 per cent.

The tripler stage is very similar in construction, the cathode line being in the $\frac{\lambda}{4}$ mode. Stage gain is unity.

As bandwidth is increased, connections between stages become increasingly important. The normal interstage arrangement comprises two tuned circuits connected by a length of cable. Coupling arrangements have been described elsewhere[11] where one cavity connects two valves, but such an arrangement is somewhat clumsy for mobile equipment.

The input impedance of a valve operating in a common grid circuit is a function of the anode load; furthermore the resonant cathode circuit will be significantly reactive at the edges of the pass-band. Any interconnecting cable will thus be mismatched towards the edges of the pass-band and this cable will become a further circuit element. The problem becomes acute when consecutive stages are mounted in cases which may be separated by up to 5 feet. It was found necessary to control the length of such cables to close tolerances, and to change short tail sections when changing from one channel to another.

The only other u.h.f. valve stage in the equipment is the receiver local oscillator. As mentioned earlier, attention was paid to thermal stability in this design, which is otherwise conventional. For good stability the anode coaxial cavity has a very low Z_o, and the mixer coupling is at all times very loose. The inner conductor is made of a standard graphited carbon furnace tube, having a very small expansion coefficient, and the outer is a cast-iron motor-car cylinder liner. This was found to be an improvement on brass from the expansion viewpoint, and preferable to mild steel, since no distortion results from cutting longitudinal slots, holes, etc. Both items are suitably electroplated. The valve heater-cathode assembly is fed via untuned chokes and coupled by a small capacity to the anode.

The mixer comprises a silicon crystal mounted in a broad-band quarter-wavelength resonator with aerial and oscillator coupled by capacity probes.

Constant 'K' band-pass filters were made by inductively coupling two quarter-wave coaxial resonators, input and output connections being made by probes. The outside resonant tubes are 1-in. square section, silver plated, and an insertion loss of 0·5 dB in a 15-Mc/s pass-band and greater than 20 dB at mid-band $\pm$40 Mc/s was achieved.

7. Lightweight Power Units

For frequency generating and video stages stabilized h.t. supplies are necessary, particularly when the power is derived from mobile sources or from poorly regulated sources subject to intermittent loads. A typical case of the latter occurs when the transmitter is operated at the top of a building and the only power available is from a lift motor room. Attention was therefore turned to producing a stabilized supply unit of minimum size and weight. Reduction of size naturally calls for minimum dissipation within the unit.

Consider the block diagram, Fig. 12. The left-hand unit accepts an a.c. supply which is subject to transient changes and delivers an output predominantly d.c. but also containing ripple and transients. A is a series element, usually a thermionic valve, and B is a controlling amplifier which samples the output from A and returns suitable information to A. The purpose of these items is to create a large dynamic impedance across A and a small static and dynamic impedance between the output terminals, YY. Considering the first requirement, the dynamic impedance R_a' of a valve subject to feedback is:[12]

For voltage feedback $R_a' = \dfrac{R_a}{1-\mu A\beta}$ ......(1)

For current feedback $R_a' = R_a - \mu A\alpha$ ....(2)

where R_a = anode impedance of valve
μ = amplification factor of valve
A = gain in unit B in Fig. 12
β = voltage feedback factor
α = current feedback factor

As R_a' is to exceed R_a, then positive voltage or negative current feedback may be considered. In the first case, μ is only approximately constant over a range of current, and A is likely to be a function of frequency, so voltage feedback will only give a large impedance over very limited conditions, and there is a danger of instability.

If a finite load is connected across YY, then measurement of the voltage fluctuations across YY will give negative current feedback in accordance with Equation (2) where $\alpha = Z_L$ (Fig. 12), i.e. $R_a' = R_a + \mu A Z_L$ and for input fluctuations δE at terminals XX the output at terminals

$$YY = \delta e = \delta E \cdot \frac{Z_L}{Z_L + R_a + \mu A Z_L}$$

$$\text{or } \delta e = \frac{\delta E}{1 + \dfrac{R_a}{Z_L} + \mu A} \quad \text{............(3)}$$

At very low frequencies Z_L is likely to be 1 000 ohms or more and the middle term in the denominator may be neglected. A small value for Z_L can only improve the performance.

If a smoothing choke is not used, then for adequate ripple suppression $\dfrac{\delta E}{\delta e} = 10^4$ approx. Achievement of such a figure is considerably eased by using a tetrode or pentode to obtain a high μ. δE may comprise supply mains 'bumps', ripple, or variations due to load current. The impedance of the rectified supply can be taken from the slope of voltage/current curve at very low frequencies, and from the reactance of the reservoir condenser at high frequencies. The part of δE resulting from load current changes is thus known.

The output impedance of the regulator is controlled in part by this latter consideration, and also by the valve A considered as an amplifier with output terminals YY. By the principle of superposition δe due to input regulation may be added to δe due to load current changes when δE is zero. With δE zero, regarding YY as the amplifier output terminals, we may again refer to Equations (1) and (2). For a low impedance, negative voltage or positive current feedback may be used. The danger of using positive feedback is the possibility of a negative impedance arising as the so-called 'constants' in Equation (2) vary with frequency and valve conditions.

Consider Equation (1), then for R_a' to be small, R_a must be small or $\mu A\beta \gg 1$. In practice the 1 in the denominator may be neglected, thus $\dfrac{R_a}{\mu}$ is the controlling feature of the series valve and there is no argument for or against triodes or multi-grid valves. From the above approximation

$$R_a' \approx \frac{1}{g_m[\text{gain in unit B (Fig. 12)}]} \quad \text{.......(4)}$$

So far the broad circuit requirements have been outlined. Many excellent analyses of regulator circuits have been published* and it is only proposed to describe the unit

* Two typical examples are: Hill, W. R. 'Voltage Regulator Operation', Proc. I.R.E., January 1945. Hogg, F. L. 'Electronic Voltage Regulators', Wireless World, November 1942, December 1953.

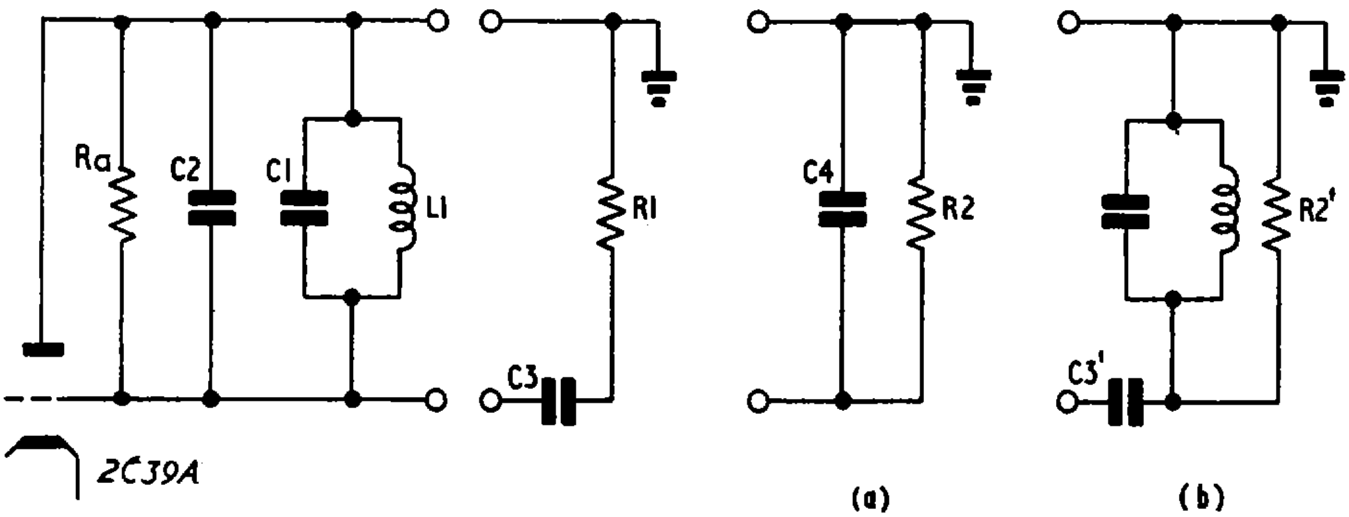


Fig. 11 — *Anode circuit of Fig.* 10 *showing derivation of load coupling in lumped form*

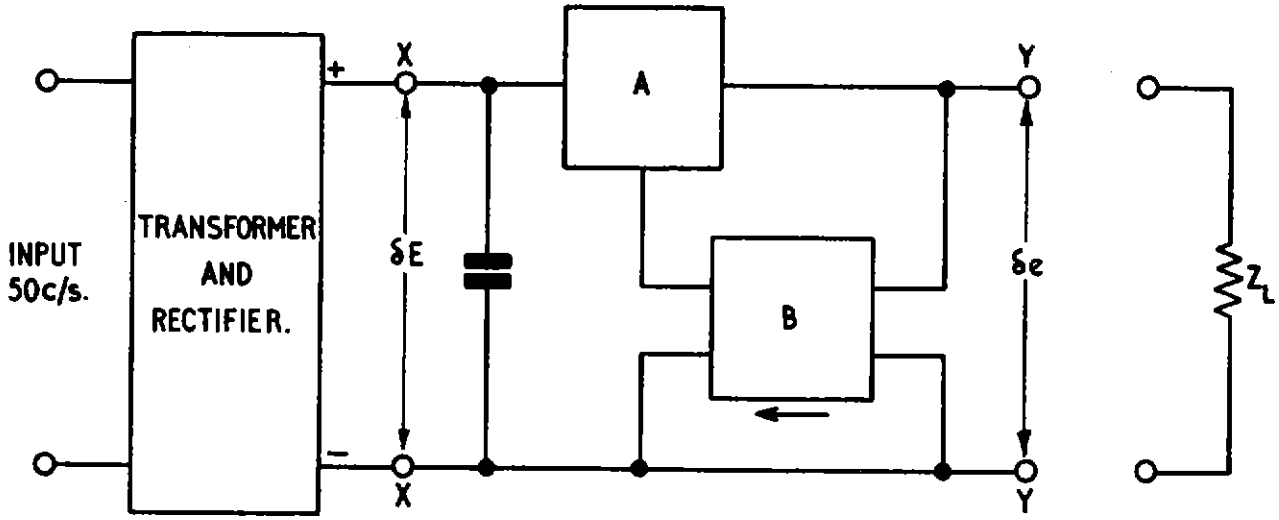


Fig. 12 — Block diagram of a stabilized power supply

designed and to point out the less orthodox features.

The circuit of one of the lightweight power units is shown in Fig. 13. The main h.t. transformer secondary winding feeds the reservoir condenser and anode of V1, the series valve, via a bridge rectifier. The ripple at full load (200 mA) is 35 V peak-to-peak at V1 anode. The shunt amplifier, comprising V2 and V3 and all components to the right-hand side of these valves, is conventional. V2 anode load, however, is returned to the auxiliary supply which also feeds V1 screen grid, full load ripple being 1 V peak-to-peak. The auxiliary supply is developed between cathode and screen of V1 and is not returned to h.t. negative; it should also be noted that the two ripple voltages have dissimilar waveforms.

Apart from the series tetrode technique, the practice of returning V2 anode to a supply containing less ripple and having better regulation is important, since V2 has to produce sufficient voltage changes across its load to compensate for applied fluctuations as well as to control V1 grid. If the load were returned to V1 anode, then the advantage of a high μ in V1 would be largely nullified.

By maintaining the screen grid of the series valve above the anode potential, the anode-cathode voltage may be reduced below the values required for this valve as a triode, increasing the efficiency. The return of the screen supply to the cathode rather than h.t. negative gives a reduction of incoming transient effects and avoids adjustment of this supply when changing the output voltage. The price is the loss of the screen current from the stabilizer output, but this is never greater than a 10 per cent loss.

The measured power supply performance is as follows:

(1) *Output* 250 *V*, 200 *mA*, *resistive load*

Output transient due to intermittent application of 10 per cent increase in mains supply (applied at crest of mains cycle)	4 mV peak
Change of output voltage for ±10 per cent supply change	±0·25 V
Output ripple	4 mV peak-to-peak

(2) *Output impedance at* 50 *c.p.s.*

Measured by applying 45 mA r.m.s. to the output terminals

At a mean current of 80 mA 0·75 ohm

At a mean current of 200 mA 0·43 ohm

(3) *D.c. output impedance*

0–200 mA Output change = 0·65 V. R = 3·25 ohms.

40–200 mA Output change = 0·4 V. R = 2·5 ohms.

(4) *Weight*

16 lb when mounted on 19 in. × 5¼ in. standard panel.

This performance is more than adequate for video and portable transmitter drive equipments. Where chokeless technique is employed the available d.c. output current is limited by the current rating of the electrolytic reservoir condenser. For large static video installations this condenser may be removed if a polyphase supply is used, and for the d.c. voltage quoted the ripple applied to the series valve anode would be similar to the present value in the case of a three-phase full-wave rectifier.

8. The Link in Service

The first production link was completed in the summer of 1956 and at the time of writing six links are in O.B. service and two are used experimentally on fixed paths. Now that crews have become familiar with the peculiarities of f.m. in Band V it is possible to assess the system.

For truly mobile applications where the path is optical or near-optical no other equipments tested by the BBC are comparable. This has been demonstrated on the University Boat Race course, from many river boat shows, sea-going vessels, and, very recently, from a helicopter (where the advance over a.m. equipment in Band III was most marked). When the 'Roving Eye' vehicle is in motion the link is only satisfactory if the receiving aerial is sufficiently well sited to be within near-optical range. Indiscriminate roving in city streets flanked by tall buildings is not possible due to reflections and obstructions. Evidently a much

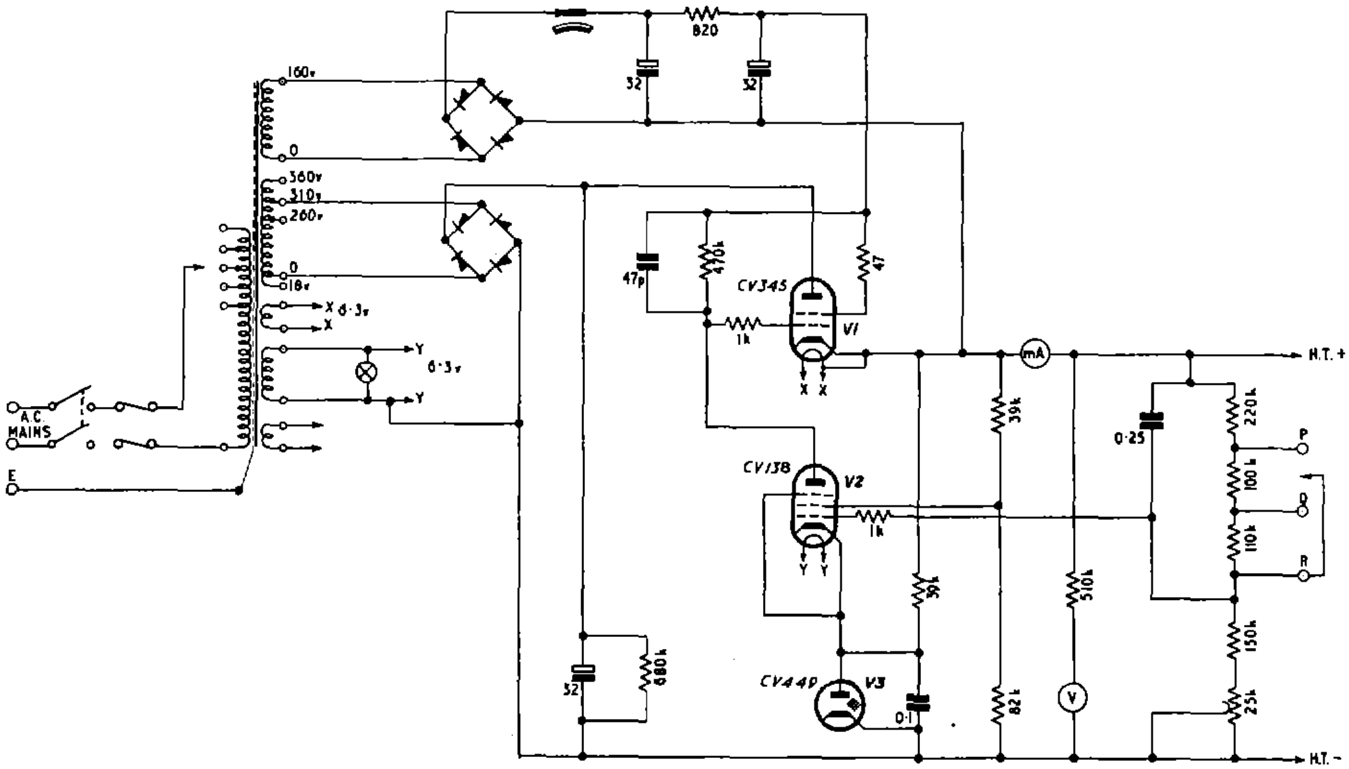


Fig. 13 — Circuit of a lightweight power unit

lower frequency system would be required for such a service.

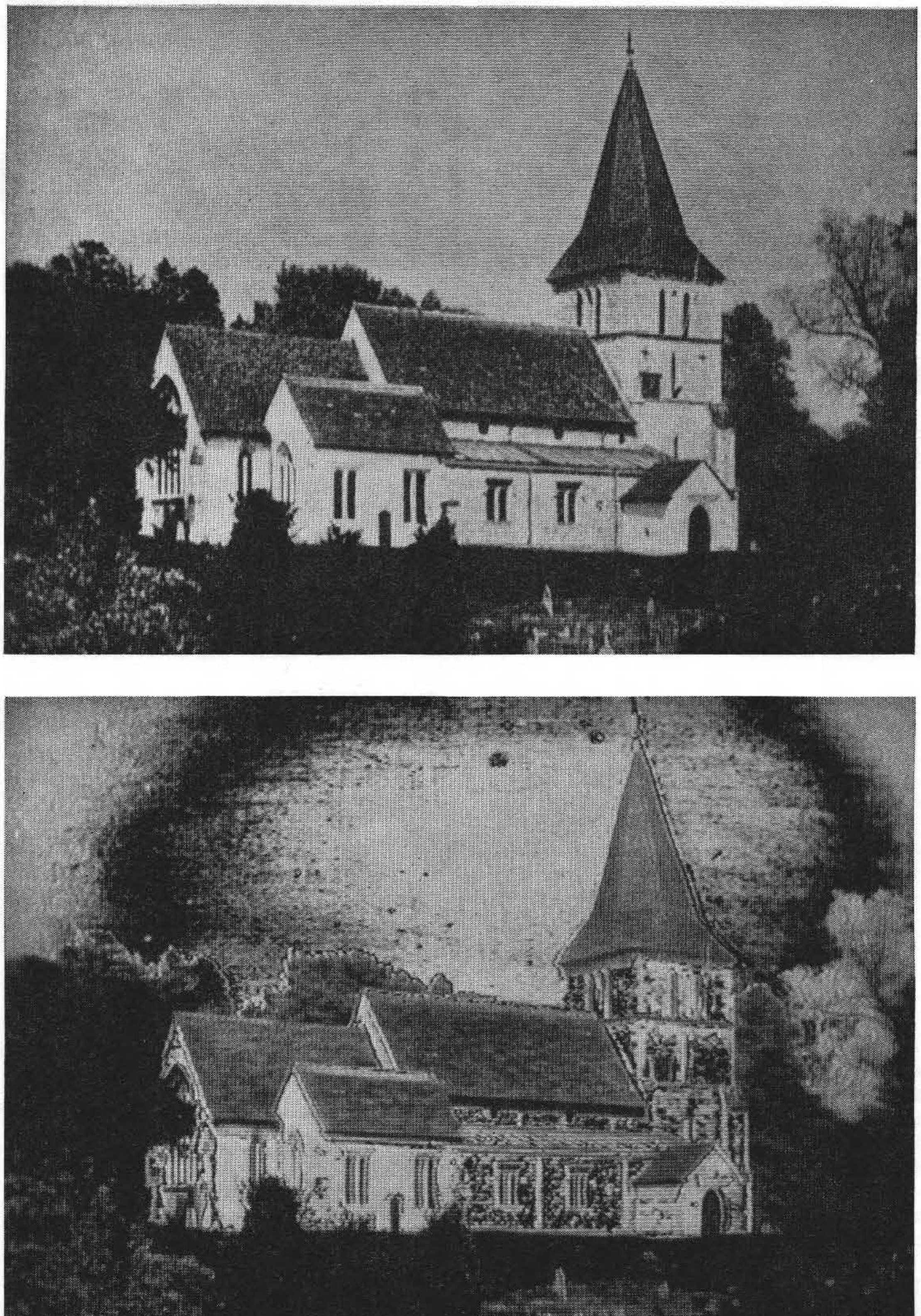
In general, by taking advantage of frequency modulation, it has been possible to obtain the same range in Band V as was achieved in Band III using a.m. on a similar transmitter power. For good optical paths, such as from air to ground, a definite improvement is apparent, acceptable pictures being obtained from an omni-directional transmitting aerial at thirty miles. Referring back to Section 2, item (*e*), it must be conceded that distortions due to indirect propagation paths limit the usefulness of this link for some purposes. For instance, the pictures of the University Boat Race in 1957, transmitted from a launch, were of high quality and were completely free from flutter. However, if careful rehearsals had not been conducted and a rigid switching schedule maintained between receiving sites, then reflections from wharves, cranes, and bridges would have ruined the signals. Distortions described in reference (6) are largely ripples following vertical edges in the picture, but in severe cases black patches have 'burst' across sky areas and trees in silhouette have been seen to sparkle as if on fire. An example is shown in Fig. 14.

Multipath distortions have always been avoidable in the few cases where they have been encountered on static links by careful positioning of aerials or use of highly directional arrays. 'Starting links' (see Section 1) and links using transmitting vehicles with extensible aerials have been successful. Experience shows that an extension to 120 ft will often increase the received signal by as much as 6 dB over that obtained from 40 ft, both in rural and urban areas. In north London, a permanent receiving site is available with a remotely steered array of 15-dB gain mounted on a 150-ft mast. The whole receiver is housed at ground level, the r.f. feeder being of the helical membrane low-loss type. A Band V transmitter operating in a vehicle with a 120-ft ladder can work into this receiver from a large area of the metropolis, giving a very flexible link available at short notice for news items, etc.

Aerials used for mobile and most Band V applications are 60° corner reflector or 6-element Yagi types, having gains over isotropic radiators of 11 dB. For the vehicle mentioned above stacked Yagi arrays may be used. In general corner reflector aerials have better front-to-back ratios than Yagis and are more easily tuned to the allocated channels, whilst the latter are more compact, even when the former are folded for transit.

Two fixed links have been installed for experimental purposes, both paths traversing areas of sea water. The first is operating between Snaefell, I.o.M., and Divis* television transmitter, a distance of sixty-seven miles, forty-three miles being over water. Height diversity reception at Divis increases the link reliability from 95 per cent to better than 99 per cent, the lower aerial being the more reliable as it is shielded by a local obstacle from sea reflections whilst the path to it has first Fresnel zone clearance. Fading on this link is neither as rapid nor as deep as was

* Divis is near Belfast, Northern Ireland.



Figs. 14 (*a*) *and* (*b*) — *Photographs taken from picture tubes at the sending and receiving terminals of a f.m. link specially arranged to show severe multipath distortion* previously experienced with 4 000-Mc/s equipment on the same path.

The second installation features in the Eurovision network between Dover and Cassel, a fifty-six-mile path including twenty-seven miles over water. This link has not been observed for more than a few winter months, so fading data are incomplete. However, it is interesting to note that the received signal has varied only a few decibels to date, the mean level being close to a free space calculated value despite lack of Fresnel clearance over the sea.

Both experimental links use 10-ft diameter paraboloid aerial reflectors. At Dover the transmitter-to-aerial feeder is some 90-metres long and a small mismatch at the aerial gave severe distortions. Whilst a ferrite isolator could have cured this problem, none was available in coaxial form for Band V. The distortions were substantially reduced by adjusting the transmitter feeder length and by following the receiver with a sharp cut-off low-pass filter. The first order effect of a delayed echo appeared to be harmonic distortion increasing with modulation frequency. Such effects have been considered in detail elsewhere.[13, 14]

Prolonged operation of transmitting apparatus on Snaefell has shown that 2C39A valves need replacing after about 2 000 hours of operation, but otherwise negligible maintenance is necessary.

9. Conclusions

There is no doubt that the decision to use frequency modulation is justified. An effort should, however, be made to reduce distortions on mobile links due to multipath propagation, and there may be some advantage in using aerials producing circular polarization. If the plane of the propagated wave can be made to rotate, then a wave which has suffered one reflection will, in some circumstances, have its direction of rotation reversed and the receiving aerial will select against this wave. Two Yagi structures mounted cruciform fashion on a common boom, and excited in quadrature, are envisaged as a practical aerial array. It may be possible to reduce multipath effects by redesigning the limiters and discriminator for broader bandwidth as suggested in Reference (6). Operation at reduced deviation into the existing receiver was found to give a small improvement.

It is now apparent that a reduction of receiver noise-factor would be useful on some occasions, but the range of the link satisfies the original requirements as it stands. Many mobile O.B.s have been made possible for the first time and it is likely that Band V links will be exploited further in this direction.

It has been established that by substituting the transmitter described in place of a Band III a.m. 300-W transmitter in the vehicle with a 120-ft extensible ladder for elevating the aerial, very little reduction in range has resulted. It is hoped to improve this very flexible arrangement still further by adding an extra stage to the transmitter to raise the Band V power to 100 watts.

Turning to the physical equipment designed, no unforeseen difficulties have arisen. For some applications, it would be desirable to reduce the bulk and weight of the transmitter, particularly when this is airborne. The obvious solution would be the adoption of velocity modulated valves, using a klystron or Heil tube as a modulated oscillator, followed by a travelling-wave tube or klystron amplifier. Unfortunately, manufacturers have little demand for such valves working at the bandwidth and power levels required and the BBC's demand hardly justifies special development. It can only be hoped that the BBC's success with Band V links will encourage other authorities to become interested and cause some new work to be undertaken along these lines.

10. Acknowledgments

The work described has been done by a small group under the supervision of Mr S. H. Padel, who has given his very expert guidance at each stage of the design. Also Messrs J. W. H. O'Clarey and O. T. Vincent have been fully engaged on the project, the former specializing in the transmitter power stages and aerial designs and the latter assisting generally, particularly with many tedious measurements.

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