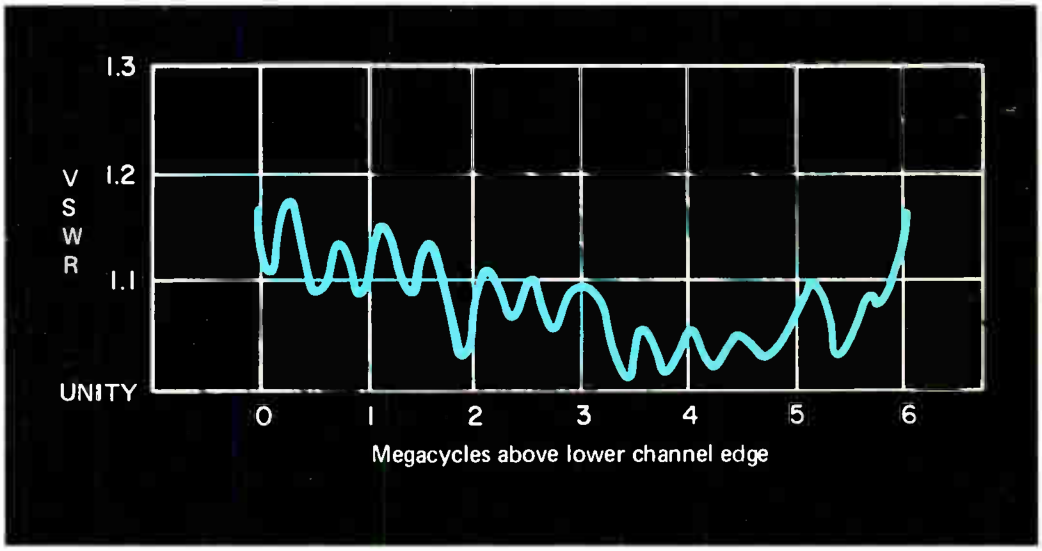
RCA

TV Antenna Performance Evaluation

Using RF Pulse Techniques



TV ANTENNA PERFORMANCE EVALUATION
WITH RF PULSE TECHNIQUES

by Dr. M. S. Siukola

The TV antenna system must introduce a minimum of picture quality deterioration. One of the most critical performance characteristics of an antenna is its ability to transmit a "ghost-free" picture. In the past, system VSWR methods were relied upon to evaluate this performance. With time, however, it became evident that new criteria were required for certain systems. The search led first to visual studies, then to the RF pulse techniques that have gained wide acceptance here and abroad in the past several years. But only recently has the RF pulse measuring method been developed to the present stage where it very closely simulates actual TV system operation. Pulse techniques now correctly measure the most complex TV antenna systems.

This paper discusses the principles of these techniques, their advantages, their limitations, and the instrumentation necessary today to measure antenna system performance.

VSWR No Longer A Criterion

In early TV systems with their short transmission lines and broadband antennas, the familiar antenna VSWR of 1.1 to 1 really signified good performance because it meant low reflection magnitudes. The specification was simple and manufacturers established internal goals of better and better VSWR's for the antennas themselves, at least in the picture carrier area. After the "freeze", taller towers were employed and of course longer transmission lines. Despite the excellence of the lines, significantly more and more of the 1.1 VSWR tolerance was absorbed

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by "accumulative effects". Manufacturers spent great effort and money to reduce these effects without seemingly gaining any advantage in system performance. Clearly, VSWR system specifications which had worked so well for so long were not now reflecting true performance requirements. Obviously, they were not right for the new conditions.

Of primary concern was the deterioration of picture quality. This led one to question what kind of deterioration can take place, and then what type of performance must be measured.

TV Test Concepts

The TV signal in its simplest form is a train of video pulses modulating the picture carrier. Not all of these pulses are of concern in antenna system performance measurements; only those with widths (at the 6 dB level) of from 0.25 μs to almost one line duration (i.e., less than 63 μs) may be affected by the antenna system (Fig. 1). In terms of TV bandwidth, this means that the "zero-magnitude" sideband area is at about 4 MHz for the narrowest pulses (Fig. 2), and at about 33 kHz for the 30 μs pulses. Figure 3 illustrates the sideband content for a 1 μs pulse. In each case the signal is restricted by the transmitter and receiver responses, which in the idealized forms are depicted in Figure 4. For color transmission, the color bandwidth is limited to about +0.6 to -1.6 MHz, requiring pulse widths equal to or greater than about 0.75 μs. In practice, the receiver color band is often limited to symmetrical width about the color subcarrier for reasons of economy. The color sideband content is superimposed over the luminance sidebands at the high end of the video portion (Fig. 5). It is obvious from the distribution of sidebands that the frequency range at and above the picture carrier is of most importance, since the highest magnitudes concentrate there. In most cases, the sidebands up to 1 MHz are of prime concern. Color signal concentrated about the 3.58 MHz color subcarrier has to be considered separately.

With TV antenna systems the most restricting effect upon picture quality tends to be radiation of the "far-end" reflections, i.e., reflections set up by the antenna and upper transmission line components, re-reflected from the transmitting equipment and then radiated (Fig. 6). The principal reason is that antennas are theoretically quite complicated multiport networks which must radiate to all the various directions with proper magnitudes and at the same time maintain good video transfer and input characteristics. This complexity almost invariably necessitates some compromise in design, but if done judiciously results in very minute reflections that are invisible to viewers. For practical systems a series of transmission line components, generally called an "elbow complex", is needed to connect the antenna to the vertical transmission line. This complex also may produce a slight reflection. Reflections from the antenna and the complex do not generally show up as separate identities but combine as one due to the short time delay between them and the limited resolution of the TV system.

Compared to far-end effects other factors such as accumulative reflections from transmission line components are generally of second order importance. Present day transmission line designs are so good that practically only the elbow complexes are of concern. In complex installations, such as multiple antenna systems, accumulative effect can occur unless proper precautions are taken (Fig. 7).

The possibility of imperfect antenna system impedance presenting a varying load to the transmitter and thus causing video distortion in the final stage (Fig. 8) must also be considered. But, again, this is generally a second order effect compared with far-end reflections.

Early RCA Studies

In response to the need for meaningful specifications and a reliable test method for all TV antennas, RCA initiated three programs:

1. The far-end reflection visibility study of 1957 and 1958.
2. Development of RF pulse test equipment based on the results of the above study.
3. Extensive computer programming during 1961 and 1962 to analyze far-end reflection response versus frequency in terms of pulse response.

Visibility of Reflections

In the visibility studies, both black-and-white and color pictures were observed and rated on lab TV receivers. Changes in both the magnitude and shape of the reflection response within the TV channel (Fig. 9) were obtained by terminating the end of a long transmission line with a variable load. These subjective tests were made under laboratory conditions and viewed by technically oriented personnel. Tests showed that the best single common denominator was the "reflection voltage percentage" and not the customary input VSWR. Results also indicated that the threshold of visibility, as viewed on a correctly adjusted TV monitor, is about 1 percent (Fig. 10). Reflection values of about 2 percent, although visible to a critical eye in the laboratory, are not visible under viewing conditions at home. Systems having values of greater than 3 percent may be considered marginal. The value of direct measurement of the pulse performance was obvious.

Reflected Pulse Response

The computer program was developed as a tool for gaining further knowledge of the relationship that exists between far-end reflection coefficients versus frequency and the corresponding pulse response (Fig. 11). It has also been used subsequently as an antenna development aid, since

reliable RF pulse measurements at manufacturing plants are exceedingly difficult to obtain due to the length of low-loss delay line (not less than 400 feet) required for evaluation. Another difficulty is presented by the transition from delay line to the antenna input. This has to be essentially perfect to avoid excessive errors in measured values, which by themselves are at the threshold area of the measuring capabilities.

The relationship between the reflection coefficient and the pulse response is unique. The conversion is quite elaborate and without present day computers, it would be impractical to achieve. In the program which was developed, operation of the TV system is mathematically duplicated (Fig. 12).

The train of video pulses, which can have arbitrary lengths and rise times, modulate an RF carrier. Depth of modulation, base carrier magnitude and repetition rate can be varied at will. The composite signal can have hundreds of sidebands depending upon the parameters chosen. The signal is then passed through several black boxes.

Sideband amplitudes are reduced linearly from unity at 0.75 MHz above picture carrier, down to one-half at picture carrier, and to zero at -0.75 MHz, as would occur in the idealized transmitter and receiver. Sidebands 4.2 MHz above the picture carrier are also cut off linearly. Since the far-end reflection effect is being studied, the sidebands are further modified by the reflection coefficient amplitude and phase of the far-end at each frequency. And finally the signal is detected, giving the pulse magnitude as well as the shape versus time.

In actual broadcast operation, the reflection from the far-end is "re-reflected" from the transmitting equipment, and propagates along with the main signal up the transmission line to the antenna where it is radiated to the receivers. While the reflection and the main signal are propagated at the same time, the phase relationship between the two signals is determined by the

reflection co-efficients at the far-end and at the transmitter, and by the electrical distance between these two points. In the receiver, the re-reflected and radiated sideband signals are detected against a carrier which is the composite of the re-reflected carrier and the carrier of the main signal. Thus the total carrier phase and magnitude, as well as the final detected signal, depend upon individual installation details and cannot be predetermined. The best and worst case conditions for a given far-end impedance can be readily computed and studied. To facilitate a thorough analysis, insertion of a dummy carrier with any desired amplitude and phase is provided for. Figure 13 shows, as an example, the reflection pulse magnitudes and shapes when 0.25 μs $\sin^2$ signal is reflected by two far-end combined impedances.

The many free variables, such as pulse length, pulse shape, and carrier phase, combined with many output forms including peak-to-peak, peak-to-average readings and automatic optimization by shifting devices, made the program a powerful tool. A sample calculation for a 2 μs pulse is illustrated in Fig. 14.

Antenna Performance Criteria

Analysis of the RCA visibility studies, in conjunction with work performed by others, resulted in new specification forms for TV antenna systems. The RF pulse, as well as the "K-Factor" criteria (extensively used abroad), apply directly to the type of operation utilized by TV systems and are based on the following conclusions:

(1) With reflection delays of from 2 to 4 μs, which are common with present systems, the threshold of visibility of monochrome ghosts under simulated control room conditions, of optimum illumination and average monitor contrast is of the order of 1.0 percent.

(2) Good TV antennas exhibit far-end reflection in order of magnitude ranging from 2 to 2-1/2 percent. A practical specification is a value of 3 percent.

(3) Radiated ghosts, due to far-end reflections, appear to become first visible on pulses about 1 μs long (Fig. 3). Reflections of shorter pulses look like narrow ringing, and those of longer pulses overlap with the main picture and are not readily visible.

(4) For the same visibility of the color ghost and black-and-white ghost, the color sidebands about the 3.58 MHz subcarrier can tolerate about 2.5 to 3 times higher reflection magnitudes than the low frequency black-and-white sidebands around the picture carrier.

(5) Proper location of the far-end impedance curve on the impedance chart is much more important than the size of the curve and the maximum value of VSWR (Fig. 13). This, of course, is due to various energy levels at different parts of the band. This characteristic has popularized "impedance-shifting" devices, such as the RCA Variable Transformer, by which the lower reflection performance on the right is obtained from the original far-end impedance on the left.

(6) With the aid of the computer, a "performance-evaluating-pulse-response" can be calculated for each antenna, so as to facilitate the development of the best performance capabilities into each design. Of course, advantage can be taken also of the fact that the same performance can be obtained by various shapes of the impedance curve. Figure 15 shows for instance two far-end impedance characteristics which provide approximately the same reflection performance, VSWR of 1.07 constant across the band and the V-shaped curve. The shape resulting in optimum performance depends upon the specific antenna design and is best determined by the manufacturer.

Antenna Performance Test Methods

To measure the most critical performance characteristics of present day TV antenna systems, far-end and accumulative reflection voltage percentages, three test methods are used: RF sweep, double sideband RF pulse, and vestigial sideband RF pulse techniques. If, due to the complexity of the system, measurement of other effects is deemed desirable such as input impedance behaviour which may effect the transmitter response, techniques such as RF sweep and slotted line techniques are employed. All are suitable for field operations. Manufacturers in development work have to use techniques which give both amplitude and phase of the reflection coefficient, the slotted line being the most commonly used. The impedance function is then translated into pulse functions by computer techniques to evaluate the antennas.

Sweep Method

This technique is the simplest. It requires a minimum of equipment, and has been used for many years to evaluate VHF total system VSWR (Figs. 16 and 17). The far-end reflection magnitude can be extracted easily from the display (Fig. 18). Simply ignore the "slow" variations of the trace and determine the magnitude of the far-end from the "fast" ripple peak-to-peak variation. Thus, by using the far-end VSWR information with the background obtained by computer translation techniques, the sweep method provides a good, updated way to evaluate performance. At UHF where small low-loss delay lines are not available, the main transmission line can be employed. With some equipment, a calibration by shorting or opening the far-end may be needed. With others, no calibration is required.

Double Sideband RF Pulse Method

The double sideband RF pulse measurement is next in order of sophistication. In this method, a video-pulse modulated RF carrier with 0.25 to 2 μs pulse widths is transmitted toward the antenna (Fig. 19). The signal contains both upper and lower sidebands. Reflected signals are often detected by simple diodes.

Since the TV system is band-limited, the incident pulse is followed by a trail of minor ripples as shown in Figure 20. Since the concern is with relatively low far-end reflections of up to only 3 percent, the reflection is difficult to detect and measure. An increase in reading accuracy can be accomplished by employing an isolating device such as a reflectometer to separate the reflected from incident signals.

Application of the reflectometer is similar to that used in the vestigial sideband equipment (Fig. 21). By setting the reflectometer in the "incident" and "reflected" positions, the two signals can be observed independently (Fig. 20). A further increase in accuracy is obtained by adding a calibrated means to adjust the gain over a range of 30 or 40 dB. Good scope amplifiers, or calibrated attenuators may be used.

Since no isolating means exists in actual TV operating, at least the 12.5 percent white level signal is always present. Thus the reflected sidebands in actual operation always have a carrier to be detected against. During measurements the reflectometer, when set for sampling of the reflection, may eliminate carrier completely. This may take place in two ways. The far-end may provide a perfect match for the transmission line at the picture frequency and thus cause no reflection of carrier. The other possibility is that due to a finite front-to-back ratio of the reflectometer some incident signal carrier may "leak through" to the detector and cancel the carrier reflected from the far end. In either case, the detected pulse will be distorted. To assure correct reading, care should be exercised to provide adequate carrier, for instance, by slightly reorienting the reflectometer or reinserting a carrier. However, the likelihood of having either no carrier reflection from the far-end, or the cancellation of carrier by "leak-through", is quite small.

The double sideband RF pulse technique features simplicity, and although it sacrifices a certain amount of accuracy when measuring the performance of antenna systems built for vestigial sideband transmission, the method is widely used abroad where almost all TV antennas are of the multi-dipole panel type. These antennas are relatively broadbanded and have a low input VSWR, even at the channel below (Fig. 22, Antenna "A"). Therefore, the error occurring due to the lower sidebands is small and results are likely to be conservatively higher than the actual values.

In this country, more emphasis is placed upon factors such as wind loads, which lead to smaller designs with generally narrower bandwidths. RCA Pylon and Traveling Wave antennas, for instance, are very narrow physically and bandwidths are good for single channel operation. However, not far outside the channel, the reflection coefficient increases, and the lower sidebands reflected by the reflection coefficient below the desired channel make the double sideband measurements unrealistic. Antenna "B" illustrated in Figure 22, for instance, would provide about the same performance as antenna "A", but would result in an erroneoulsy high reading with the double sideband RF pulse technique. This method could be employed successfully with Zig-Zag or Superturnstile antennas.

Double sideband RF pulse methods are frequently used in locating problems in transmission line systems. For this, a 6 dB pulse width of 20 ns is often chosen, the sidebands then extending to about ± 50 MHz. The distance resolution is quite high, in the order of 5 to 10 feet, as compared to about 100 feet with the 0.25 μs pulse, as illustrated by the relative sharpness of the traces in Figure 23. Again, the broad frequency spread has to be kept in mind to avoid erroneous conclusions.

Vestigial Sideband RF Pulse Method

To facilitate performance measurements on all kinds of TV antennas, RCA developed the vestigial sideband RF pulse technique which more closely simulates TV operation than any other method. The VHF test setup diagram is shown in Figure 24.

In this test method, an RF carrier is also modulated by video pulses, the width and repetition rate of which are adjustable. The repetition rate does not, as long as it is below about 0.5 MHz, affect the results and thus is not at all critical. A rate of about 15 kHz is generally used. This RF

pulse train is fed toward the antenna and the returning signal is observed after detection by a precision receiver. In the modulation process, a signal with both sidebands is produced. Of course, in normal TV transmission, the transmitted signal is limited to vestigial sideband form and at the receiver it is further restricted (Fig. 4). Since the equipment has linear characteristics, the order of operations can be changed, with the receiver performing all the band-limiting, and a simple, square-pulse modulated signal can be employed as the transmitted signal.

In TV operation, the reflected signal is re-reflected from the transmitter and superimposed on top of the main signal, appearing as a radiated ghost if the magnitude is high enough. As with double sideband techniques the measurement of this spurious signal without isolating it is difficult because not only is it close to the threshold of visibility, but it is mixed with the ripple following the incident signal pulse. So, separation is necessary.

Separation is performed by using a reflectometer to sample either the incident or the reflected signal. By separating the signals for independent observation, different magnifications can be used to increase reading accuracy.

As described before, the phase relationship between the main signal and the re-reflected signal (and thus the visibility) is affected by transmission line length. Thus, the final result may not be known at the time of measurement, especially if the plant installation is not complete. By measuring the downward-coming signals independently, the most conservative value is obtained. The actual re-reflected signal visibility can be no greater than the measured value because the reflection coefficient of the transmitting equipment is less than unity, and the phase relationship between the main signal and the re-reflected signal may be such (as in quadrature, for instance) as to reduce the visibility of the reflection.

To guard against loss of carrier, due to the use of the reflectometer as previously mentioned, a check with a slight re-orientation of reflectometer should again be made. A line stretcher or other form of phasor can be used to adjust the phase of the combined carrier. Since RF is being handled, matched conditions must prevail wherever high VSWR might otherwise result in errors.

The measured difference between the incident and reflected voltages can range from about 30 to 50 dB, which for RF is quite large and would rely too heavily on equipment linearity. Therefore, in the measurement of the incident and reflected signals, levels at all active components are maintained. Measuring accuracy is obtained by a calibrated passive attenuator in addition to the ability of the reflectometer to sample the incident and the reflected signals in the same proportions. RF amplifiers were employed to maintain adequate noise-free levels, and the step attenuator provided a reliable reading of the difference between the incident and reflected signal levels.

Operation of VSB RF Pulse Equipment

In early VHF setups, the first step was to tune the RF amplifiers (30 to 40 dB gain) for the channel. The setup was then terminated with a load. The correct operating angle for maximum front-to-back ratio of the reflectometer is determined by alternately checking and minimizing its output by rotating the reflectometer and adjusting the small loading capacitors. By successive approximations (generally two) a condition is reached when the two essentially-zero-output angles are the same in both reflectometer locations. At these angles the minimum of signal is extracted from the incident signal. One of these orientations is arbitrarily used as "reflected position". The "incident position" is achieved by turning the reflectometer 180 degrees, at which the minimum of reflected signal is sampled. It is to be noted that in either position the sampling of the desired signal is not at a maximum. Throughout the process a predetermined penetration

is maintained. With the base of the reflectometer body approximately flush with the inner surface of the coaxial line, maximum output with minimum disturbance to matching conditions is obtained.

Next, with the setup connected to the antenna system, the reflectometer in incident position and the attenuator set to about 35 dB insertion loss, levels and modulating pulse width are set to produce a pulse about 4 cm high with a minimum of trailing ripples as observed on the oscilloscope ("incident" in Fig. 25). The pulse width at the pulse generator turns out to be approximately 0.2 μs. After the reflectometer is set to the reflected position, attenuation is reduced until either the reflected or the "apparent incident" signal, (as defined below) whichever is larger, reached the 4 cm level of the incident pulse.

At the place where the incident pulse was on the scope, there is now the apparent incident. This comprises some "leak-through" from the incident signal superimposed with near-in reflections from cones, line stretchers, etc. This apparent incident pulse can be readily reduced below reflected pulse level by readjusting the capacitors in the directional coupler assembly without affecting the line and the far-end reflections. Line stretchers are used to maximize the reflected pulse magnitude for the "worst-case" reading.

Adequate carrier for detection purposes is assured, if the "zero level" indicated by the trace preceding the apparent incident and also trailing after the "far-end reflection", is separate from the absolute zero RF level given by the "chopper line". In Figure 25, the separation is about 5 mm.

With maximizing performed by phasing, the maximum of trace level at reflected position set by the attenuator, and with adequate carrier present, the difference is read between the incident

and reflected pulse levels and the change made in the attenuator setting. By converting the readings to percentage, the maximum possible radiated ghost level is obtained.

Later equipment is more sophisticated but the principles of operation have not changed. Diagrammed in Figure 21 is a setup for testing on UHF channels, and Figure 26 shows the UHF test equipment. The reflectometer housing is pictured in Figure 27.

Modulation is now accomplished by a diode switch. Carrier reinsertion is by a compact pickup-phasor combination (eliminating the line stretcher) and is fed through the reflectometer without disturbing matched conditions. Much smaller attenuators with an accuracy of 0.25 dB are used, and sensitive demodulators are employed eliminating the bothersome RF amplifiers.

Accumulative Effects

As previously mentioned, certain antenna systems such as candelabras (Fig. 7) employ many components 50 or more feet apart which are likely to result in small reflections. Transmission of short pulses, say 0.25 μs, may result in reflections that are so small, and being separated by a time interval, they will not be visible as ghosts (Fig. 28). When longer pulses of 1 to 2 μs duration come along they may (or may not, depending upon phase) add up to a large enough magnitude to make the combination visible (bottom trace on Fig. 28). To guard against overlooking such a possibility, the RF pulse tests should in those applications be performed in addition to the 1/4 μs measurement, and with long enough pulse duration (1 or 2 μs) to assure that the combined effect is measured. During such measurement, it seems advisable to maximize and read the mean level of the reflected pulse rather than the peak.

Measuring Color Signals

Since the color portion of the signal appears to be one-third as sensitive to ghost effects as the luminance portion, this measurement in well designed antennas is hardly necessary. Nevertheless, the RF pulse technique lends itself to that evaluation simply by first centering the test carrier at color subcarrier frequency, then by employing a pulse width of about 1.5 μs and properly band-limiting the receiver response (Figs. 4 and 5).

Conclusions

Since most TV antenna installations employ present-day, highly developed hardware, the performance characteristic demanding most attention is the far-end reflection.

The vestigial sideband RF pulse measuring techniques best simulate the actual operation of the TV system, and this direct relationship between the simulative technique and the actual condition gives the most positive evaluation of an antenna system's performance capabilities. Accuracy of the vestigial sideband RF pulse method relies only upon reflectometer precision and attenuator calibration. So, even though the equipment is complex the measurement is quite foolproof. The results obtained indicate the worst case, avoiding any unpleasant surprises. Impedance shifting by field adjustments, such as optimizing with variable transformers (See Figs. 12 and 25) is also facilitated by the technique.

In many antenna installations, these are the only performance measurements required. With complex systems, however, care should be exercised to avoid large variations in the loading impedance of the transmitter. In practice input VSWR values of 1.15 to 1.25 do not appear to result in noticeable detrimental effects when primarily produced by reflections close to the transmitter.

In addition to performance, reliability and correct assembly must of course be assured, possibly with other measurements.

The author, in presenting these developments in vestigial sideband RF pulse techniques, has attempted to describe in more detail than previously available, both the theoretical background and instrumentation used in RF pulse techniques. The hope is that more insight will be gained, facilitating a more effective view of these techniques in providing industry with better and more economical antenna systems through meaningful specifications.

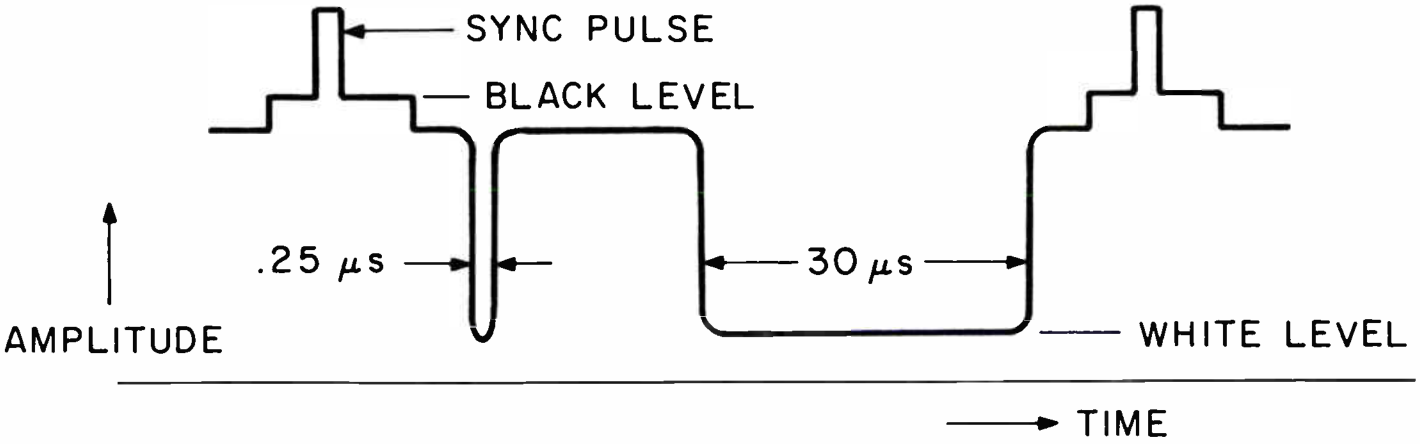

Figure 1. TV Signal Envelope

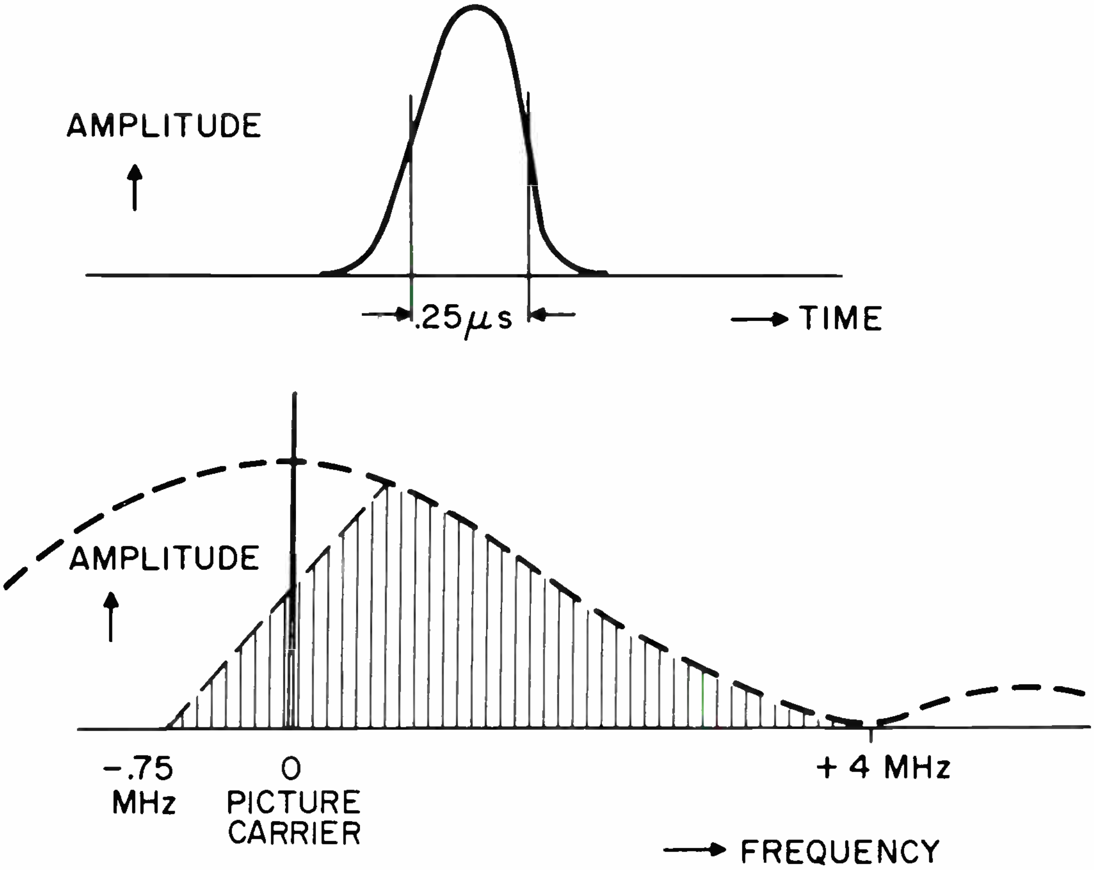

Figure 2. Approximate TV Signal Sideband Content (.25 μs Pulse)

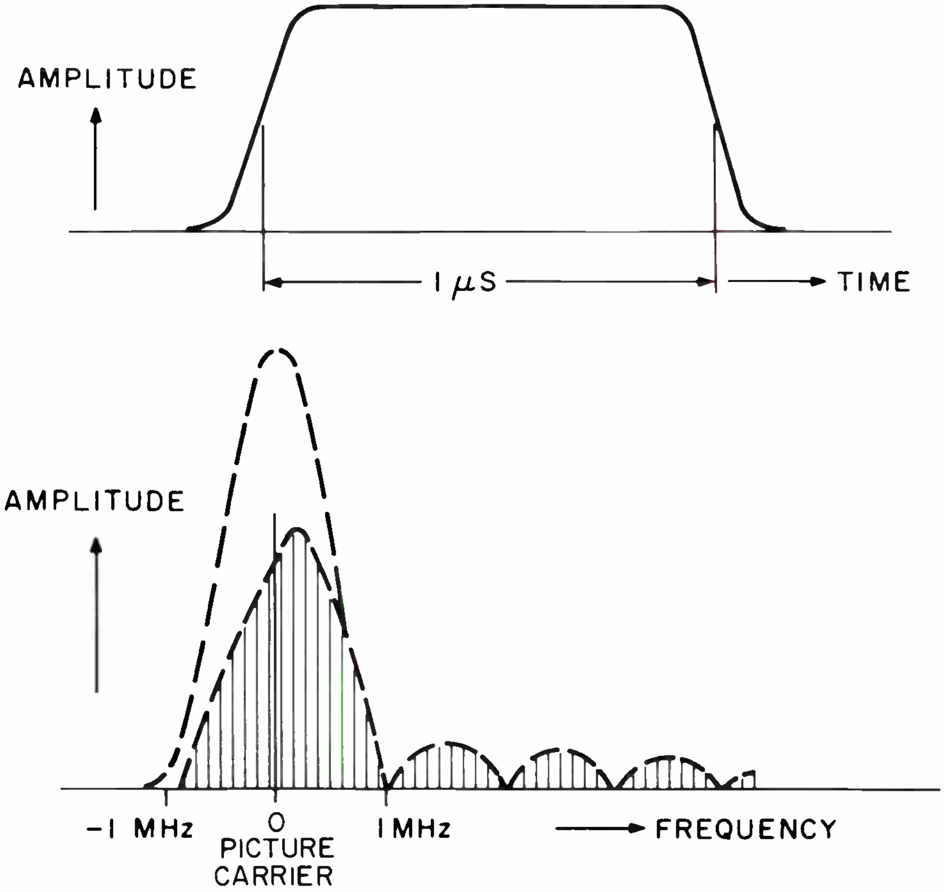

Figure 3. Approximate TV Signal Sideband Content (1 μs Pulse)

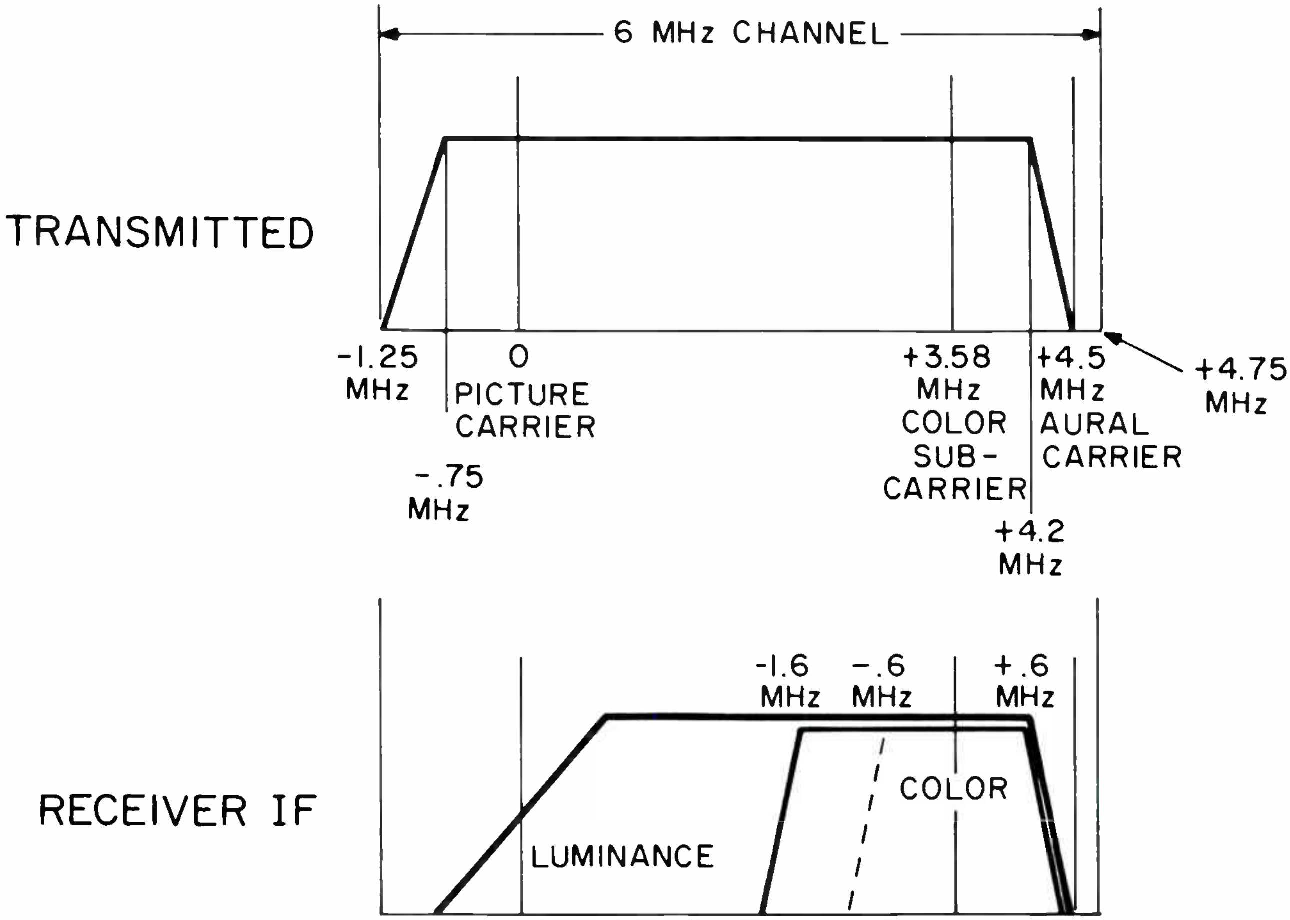

Figure 4. Idealized Transmission Characteristics

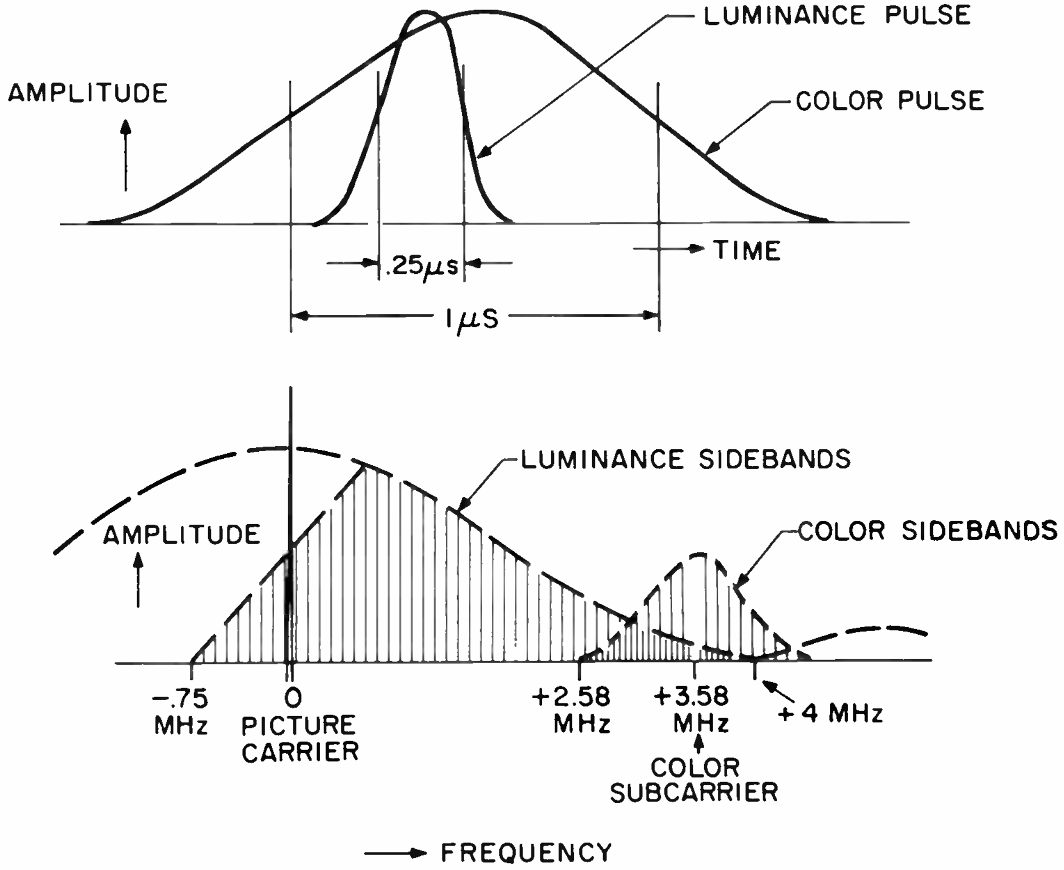

Figure 5. Approximate TV Signal Sideband Content (.25 μs Luminance Pulse and 1 μs Color Pulse)

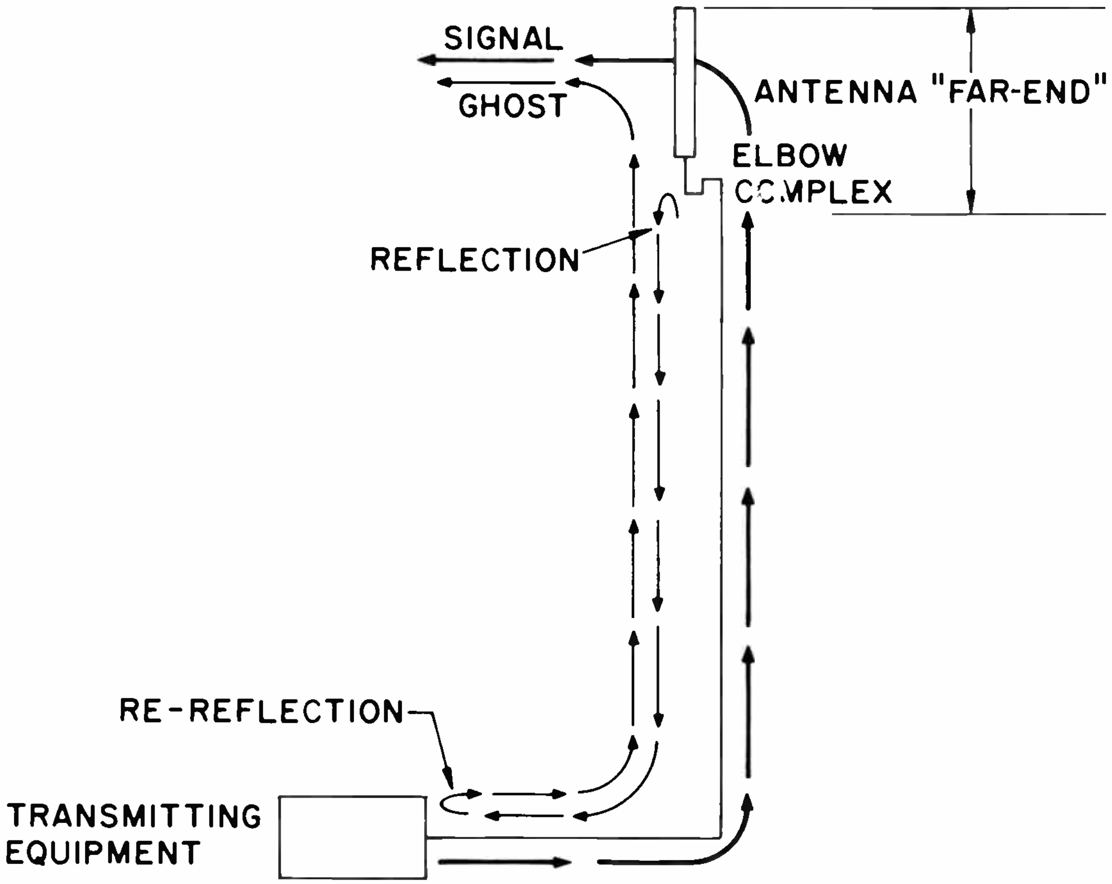

Figure 6. Far-End Reflection

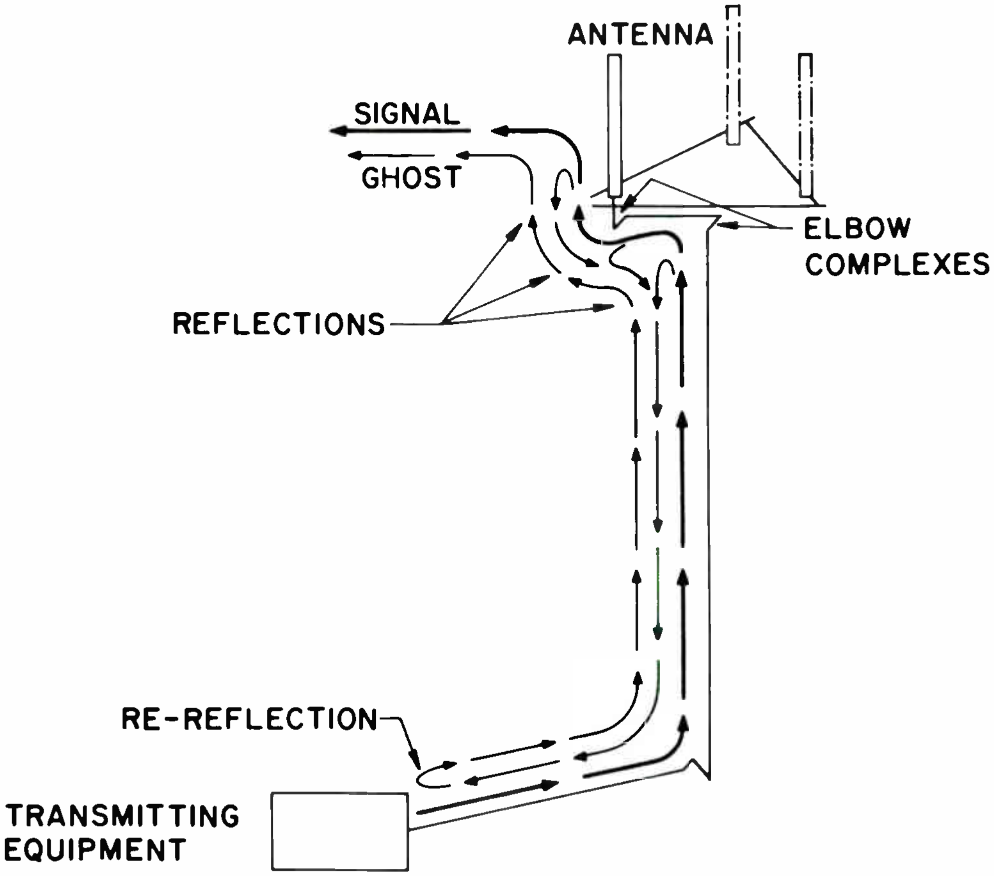

Figure 7. Accumulated Reflections

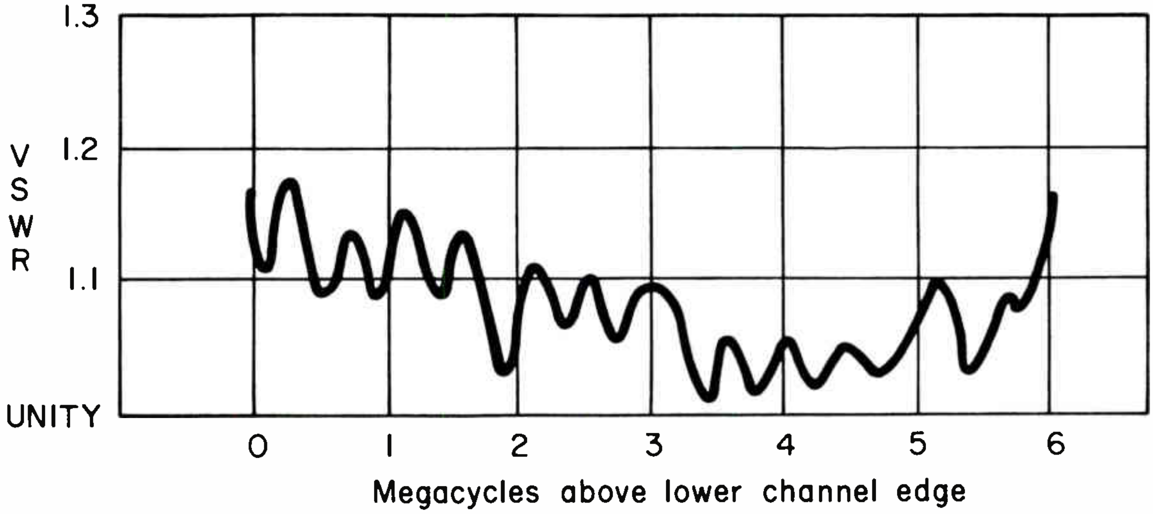

Figure 8. VSWR versus Frequency for Typical TV Antenna System
(Total Transmission Line Length 1100 Feet)

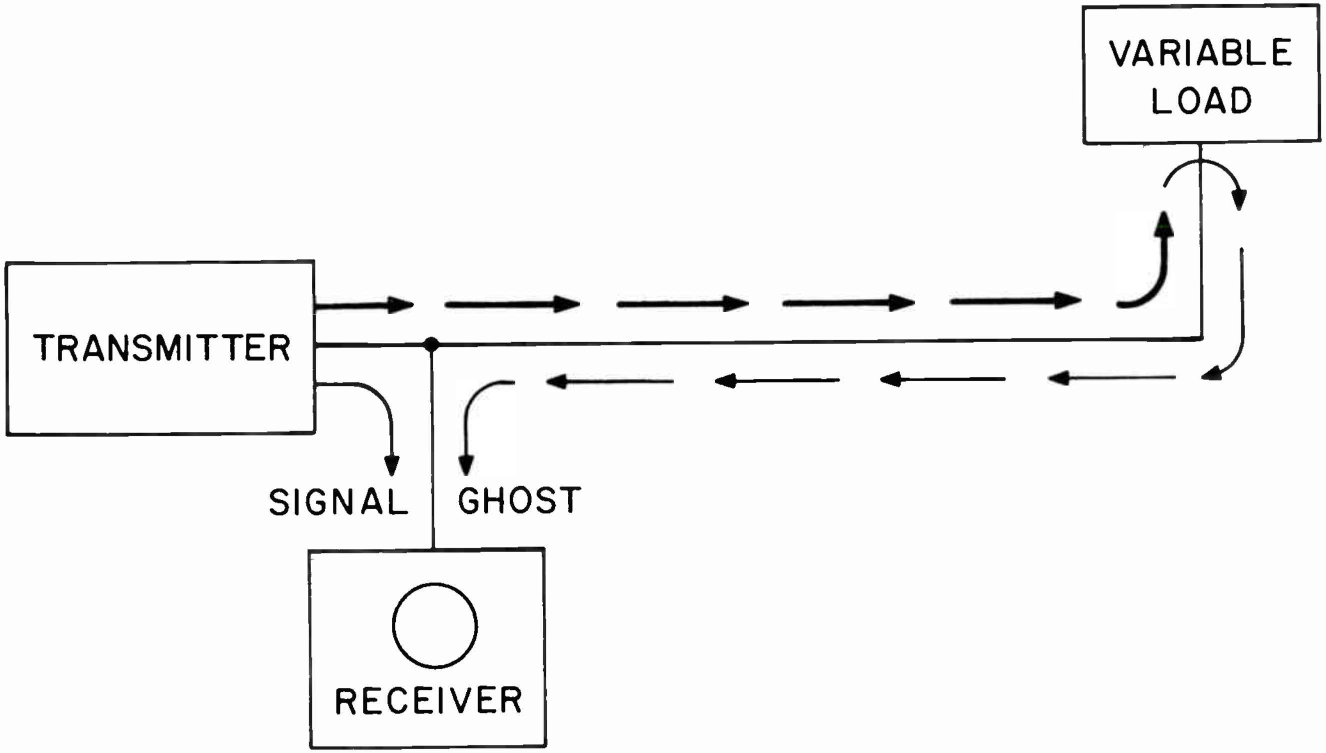

Figure 9. Visibility Test Setup

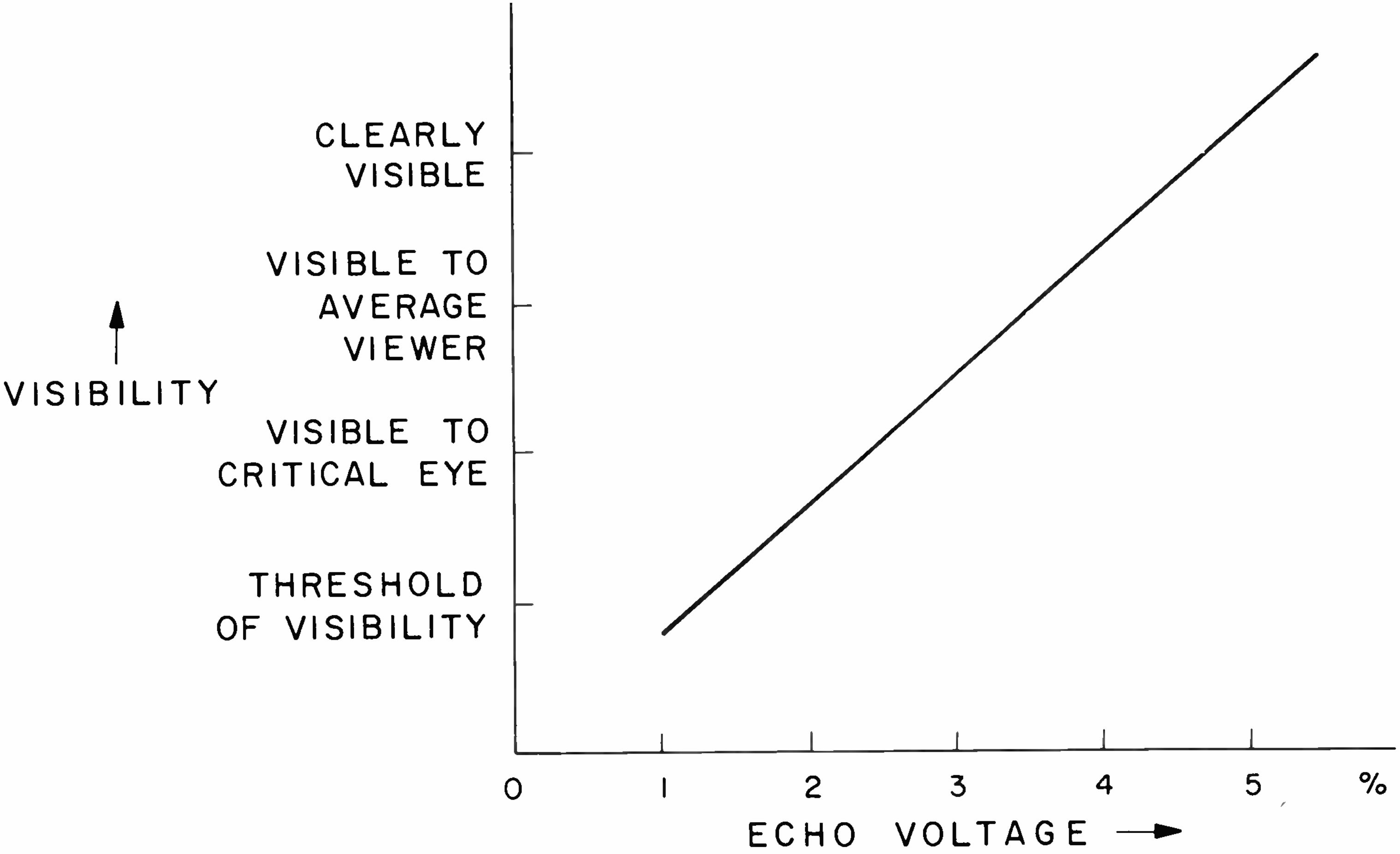

Figure 10. Visibility of Ghost versus Echo Voltage

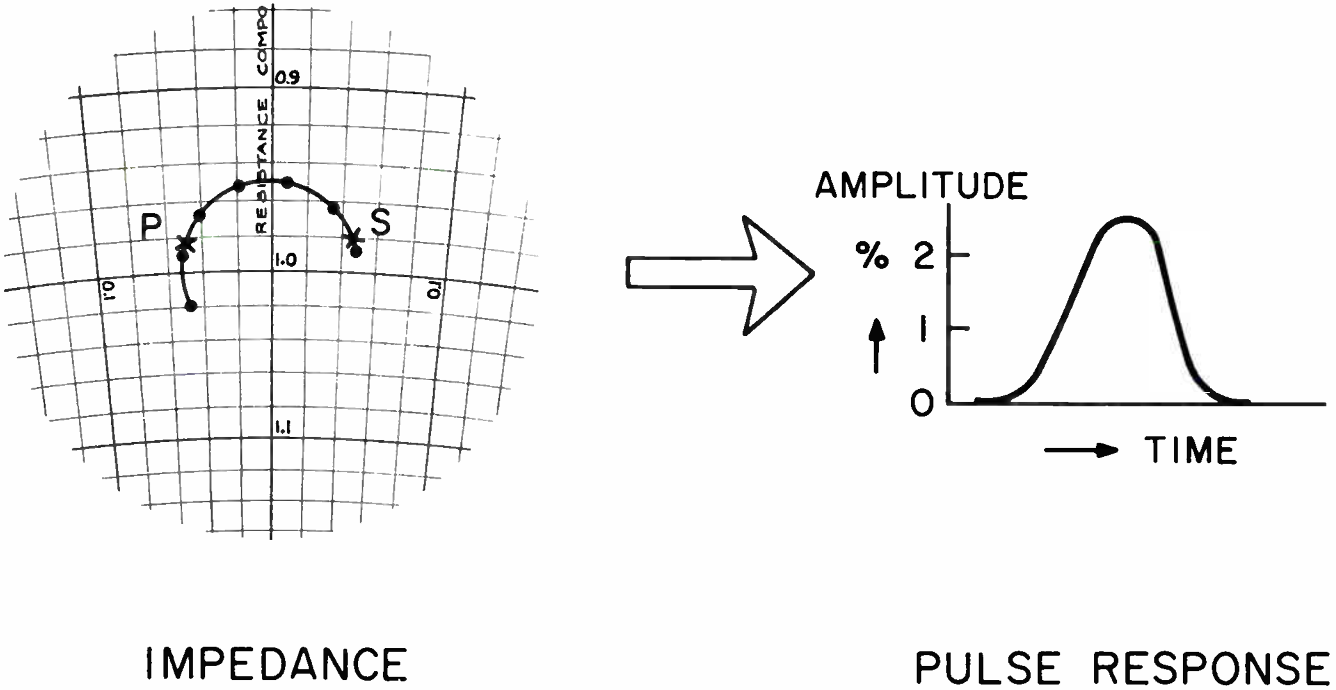

Figure 11. Computer Translation from Far-End Impedance
to Reflection Pulse Response

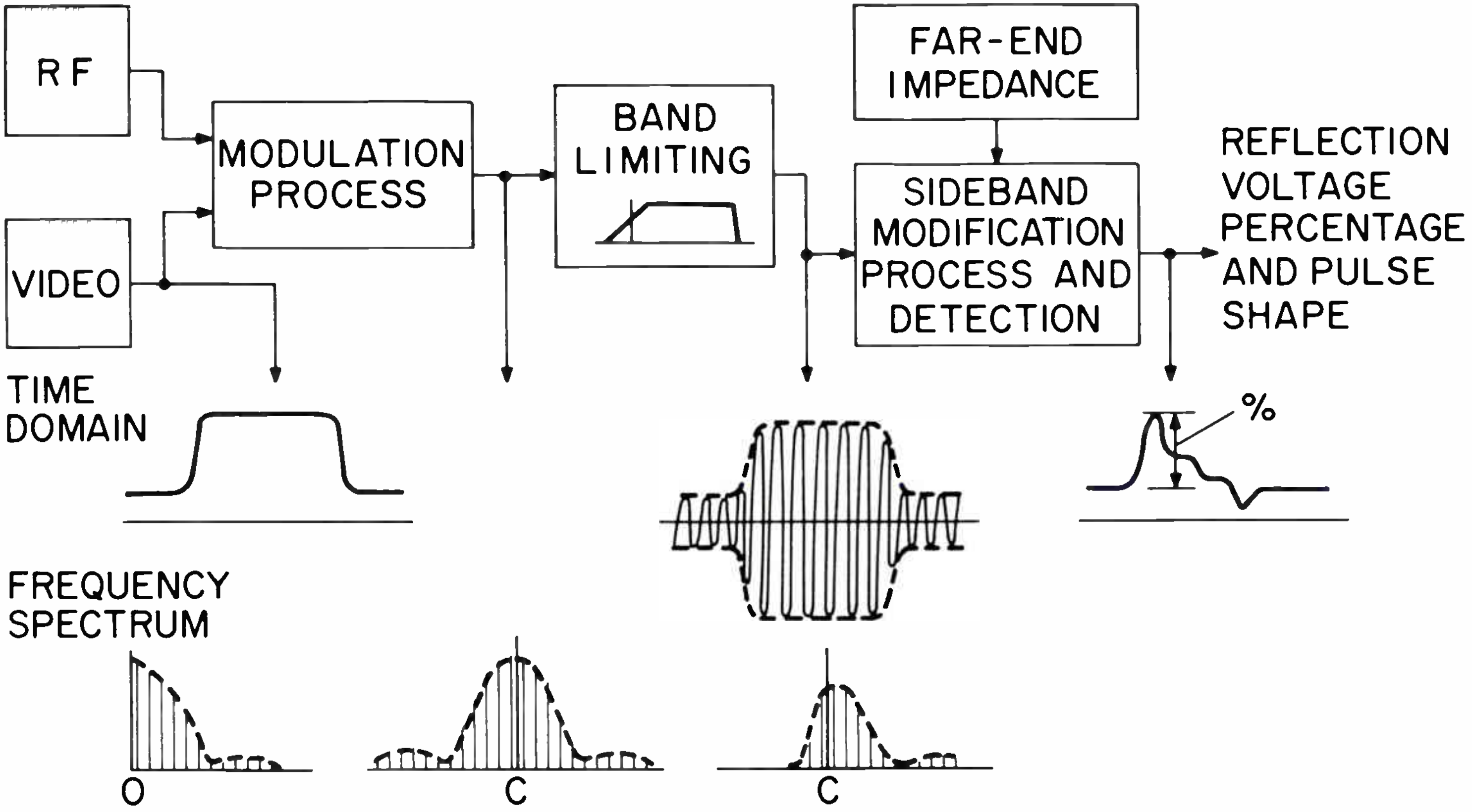

Figure 12. Computer Processing

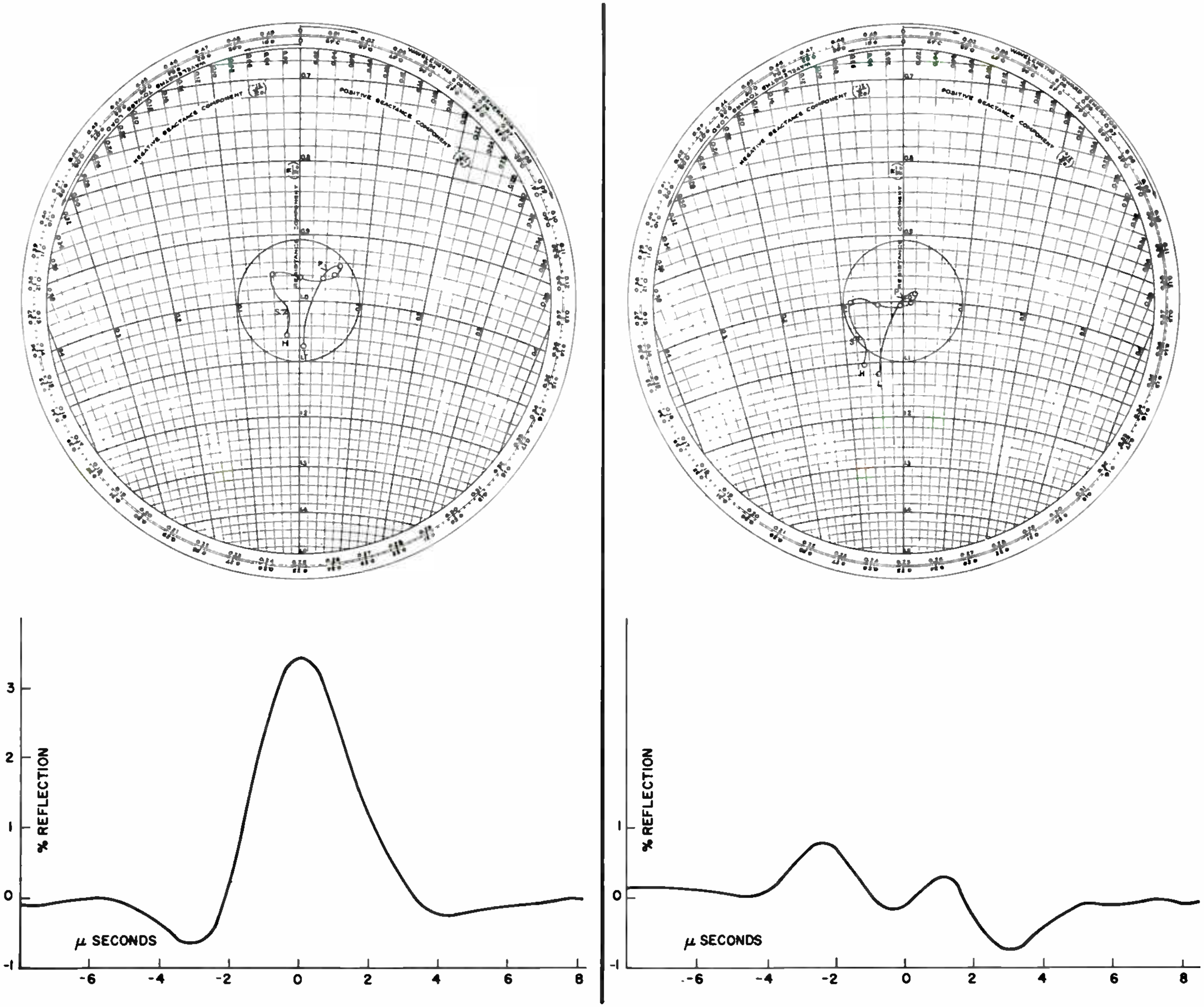

Figure 13. Reflection Pulse Magnitudes and Shapes

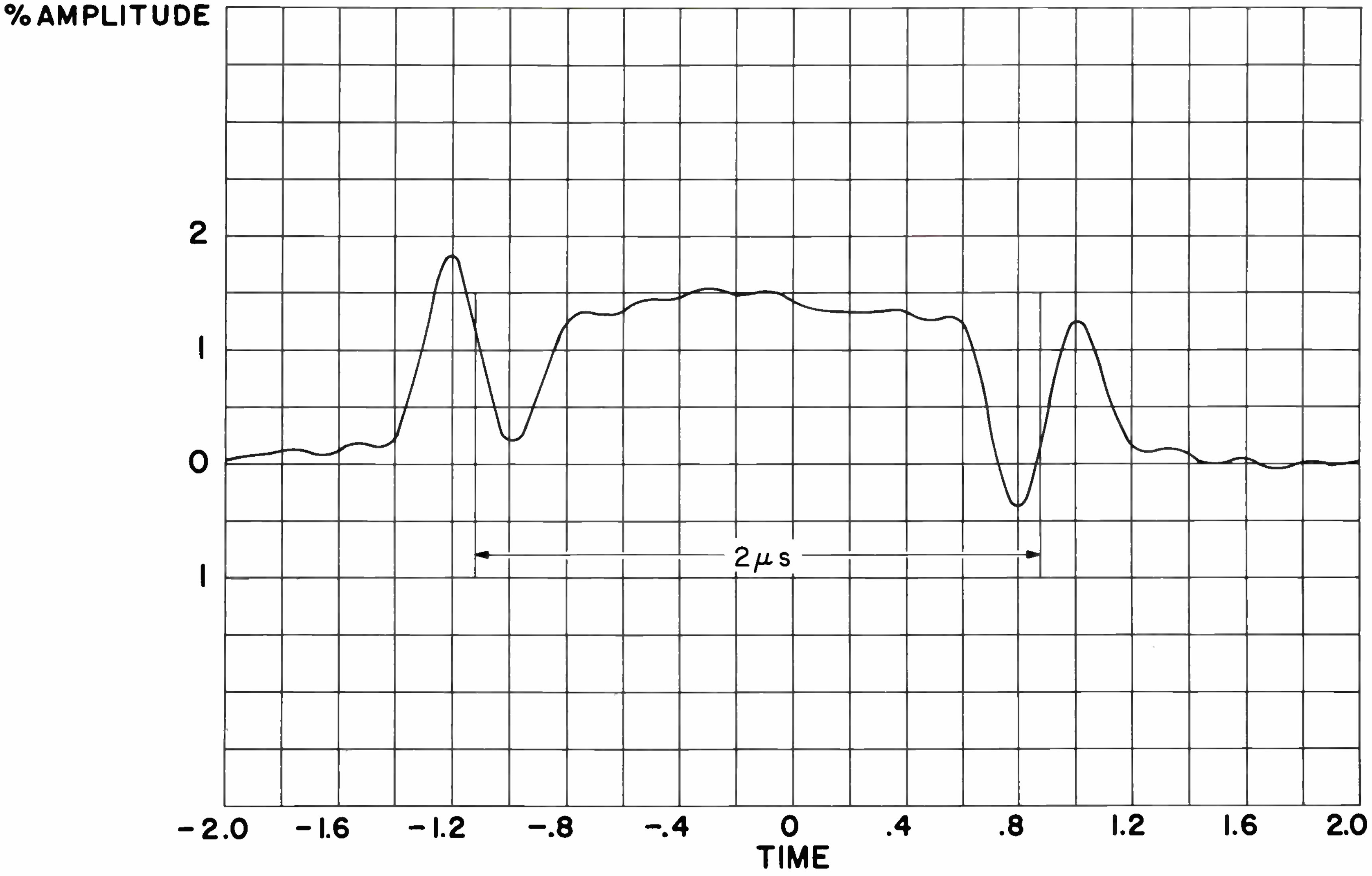

Figure 14. Calculated Far-End Reflection Pulse

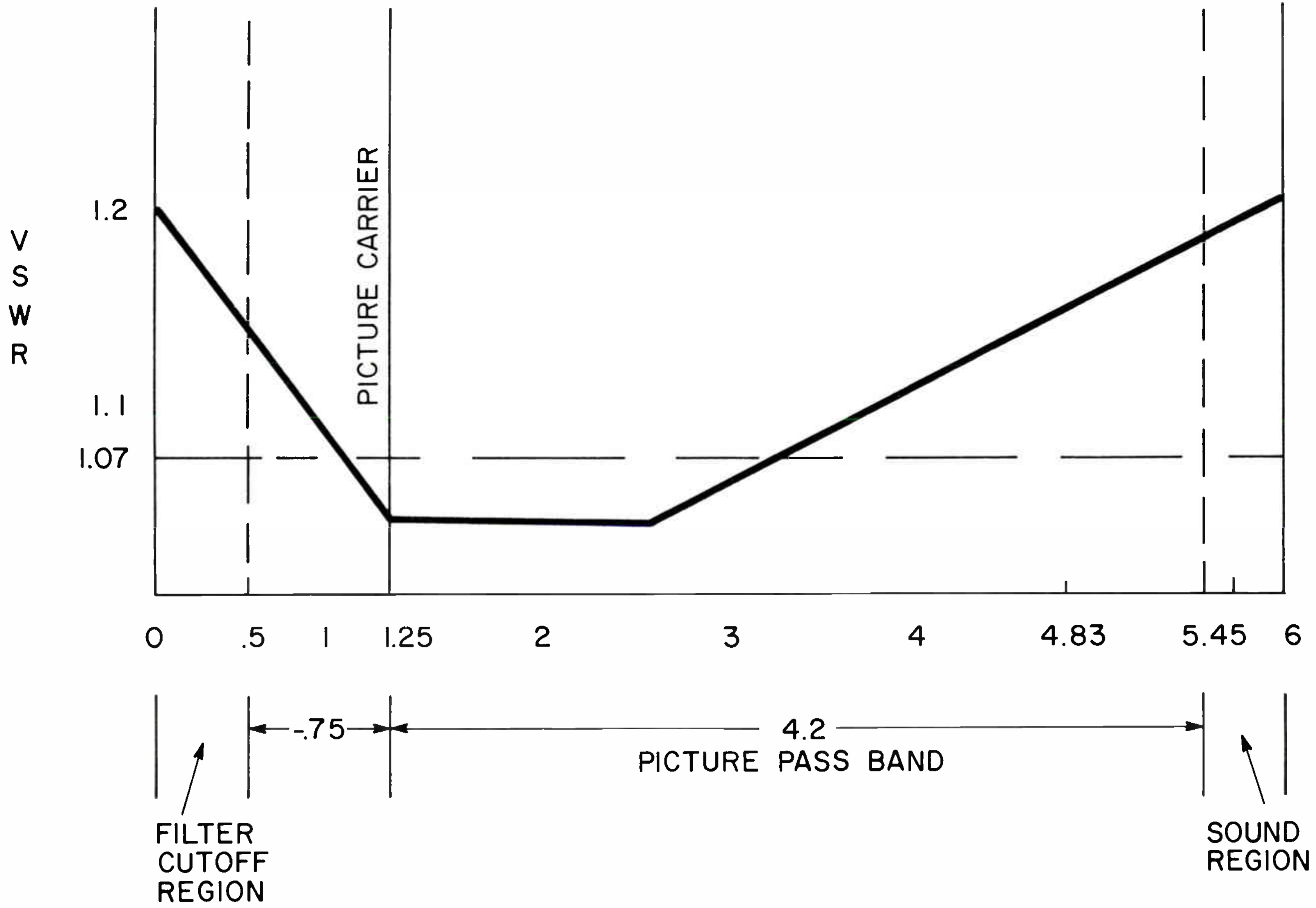

Figure 15. Two Different Far-End Impedance Curves Result in Approximately Equal Reflection Performance

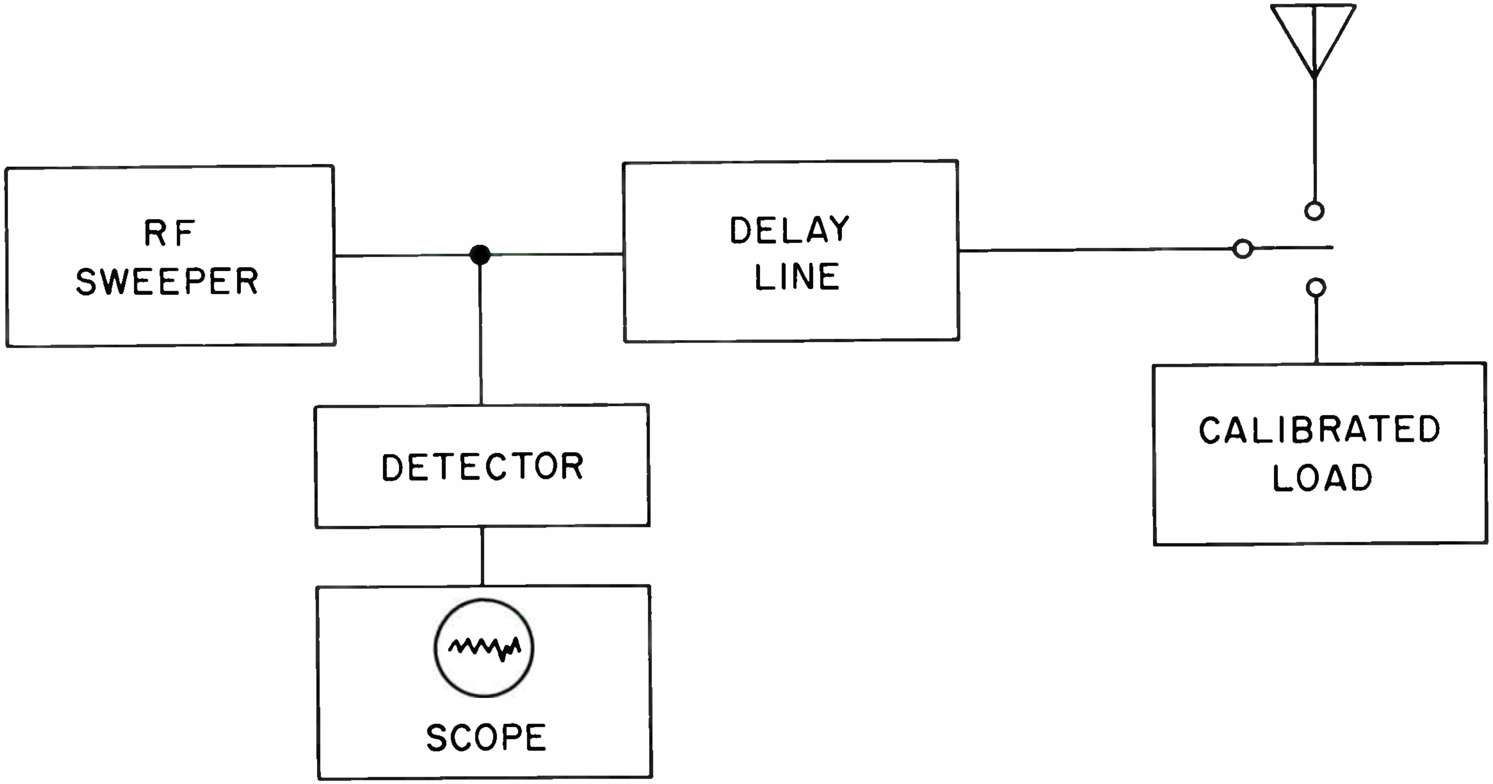

Figure 16. RF Sweep Equipment Setup

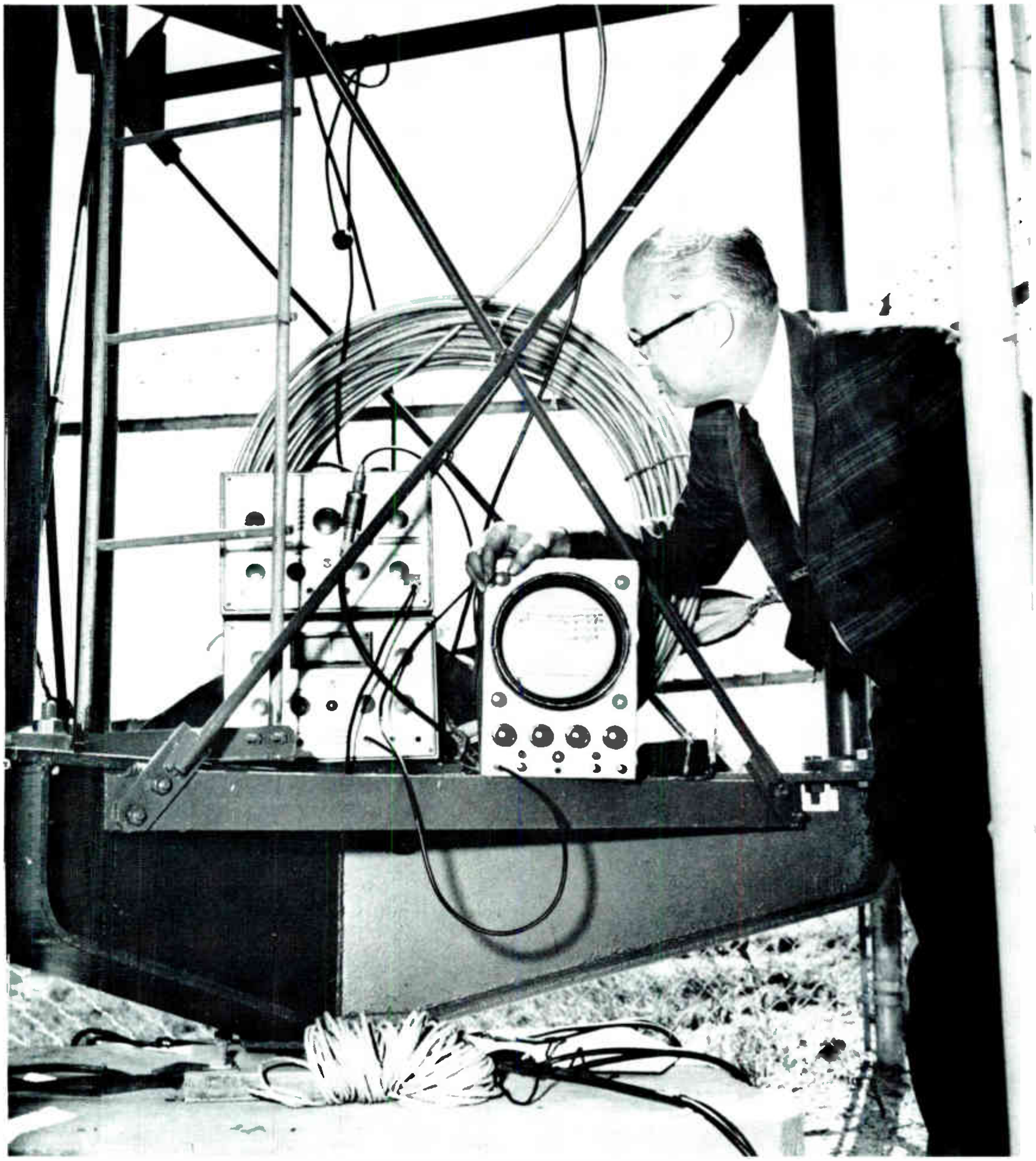

Figure 17. RF Sweep Equipment

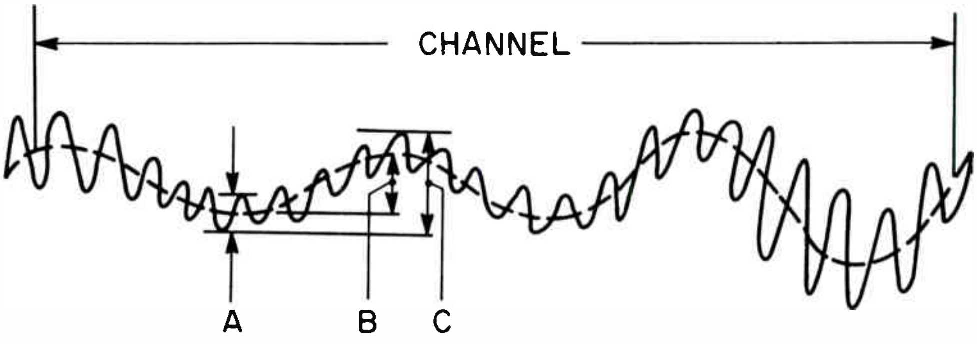

Figure 18. Analysis of RF Sweep Trace.
A = Far-End Reflection;
B = Input End Reflection; and
C = Total Input Value

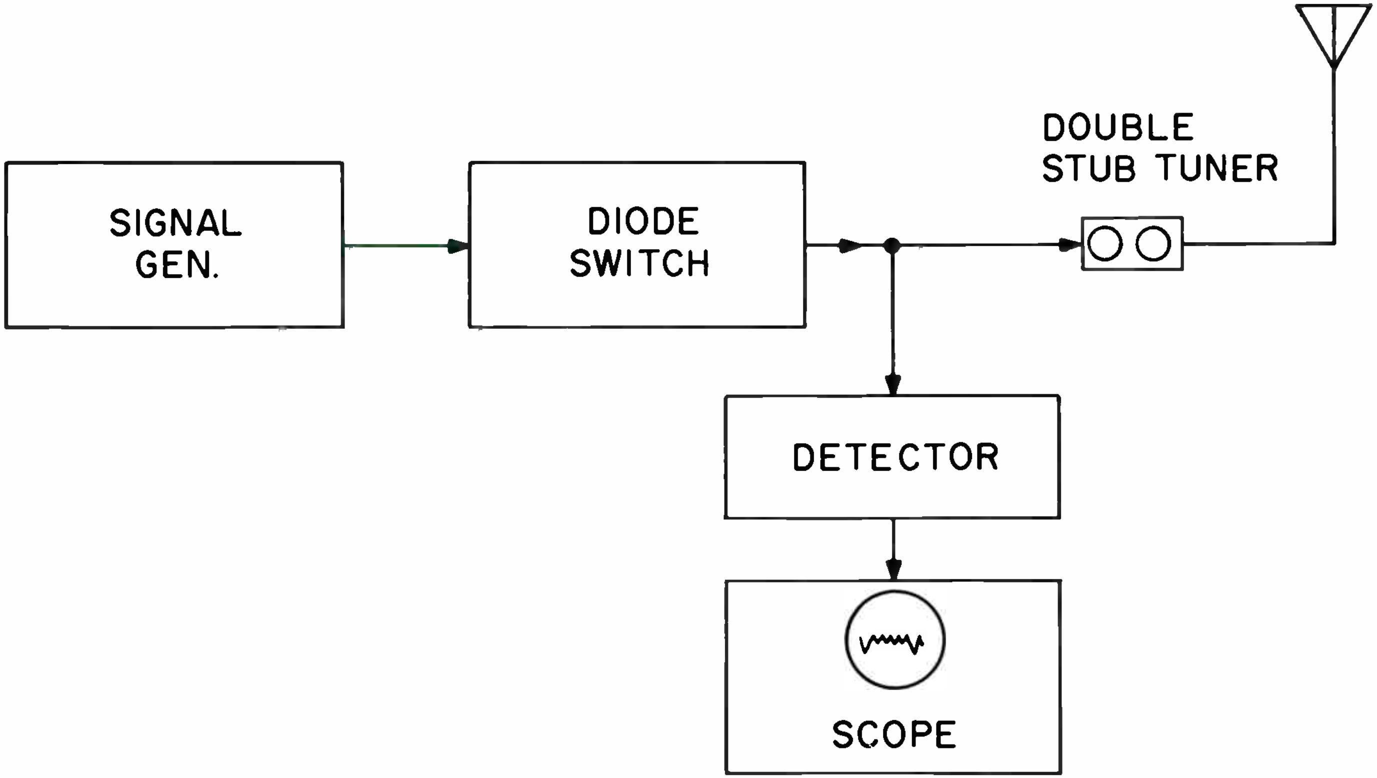

Figure 19. Double Sideband RF Pulse Setup

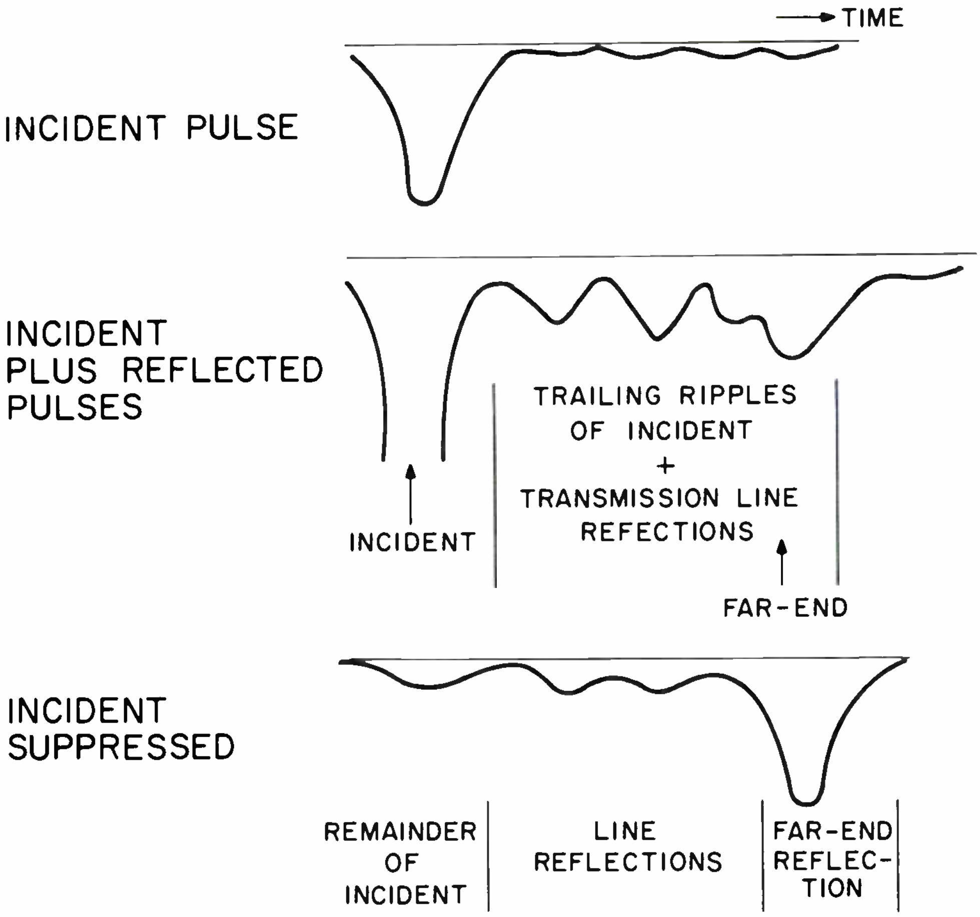

Figure 20. Separation of Signals

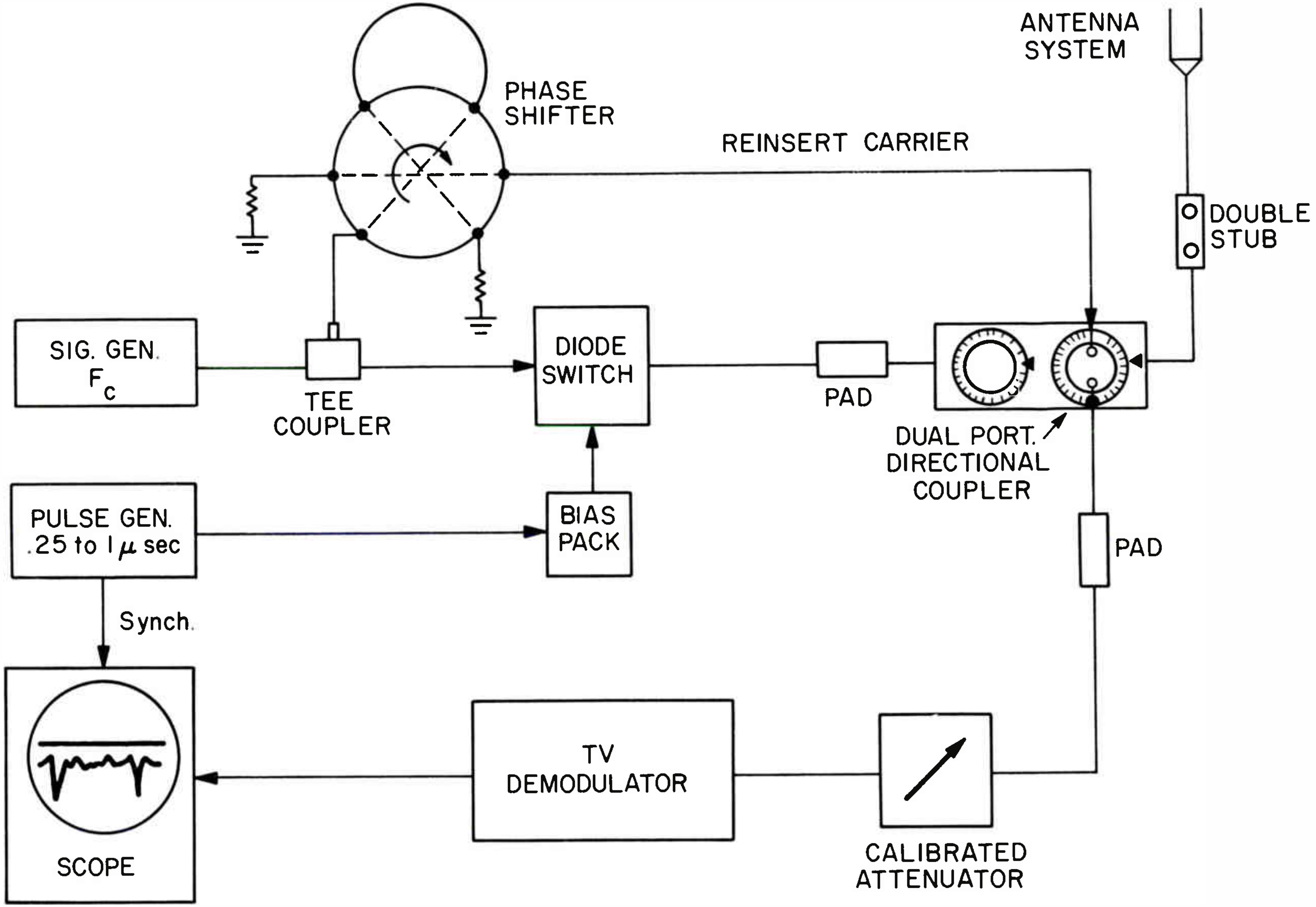

Figure 21. Setup for Testing on UHF Channels

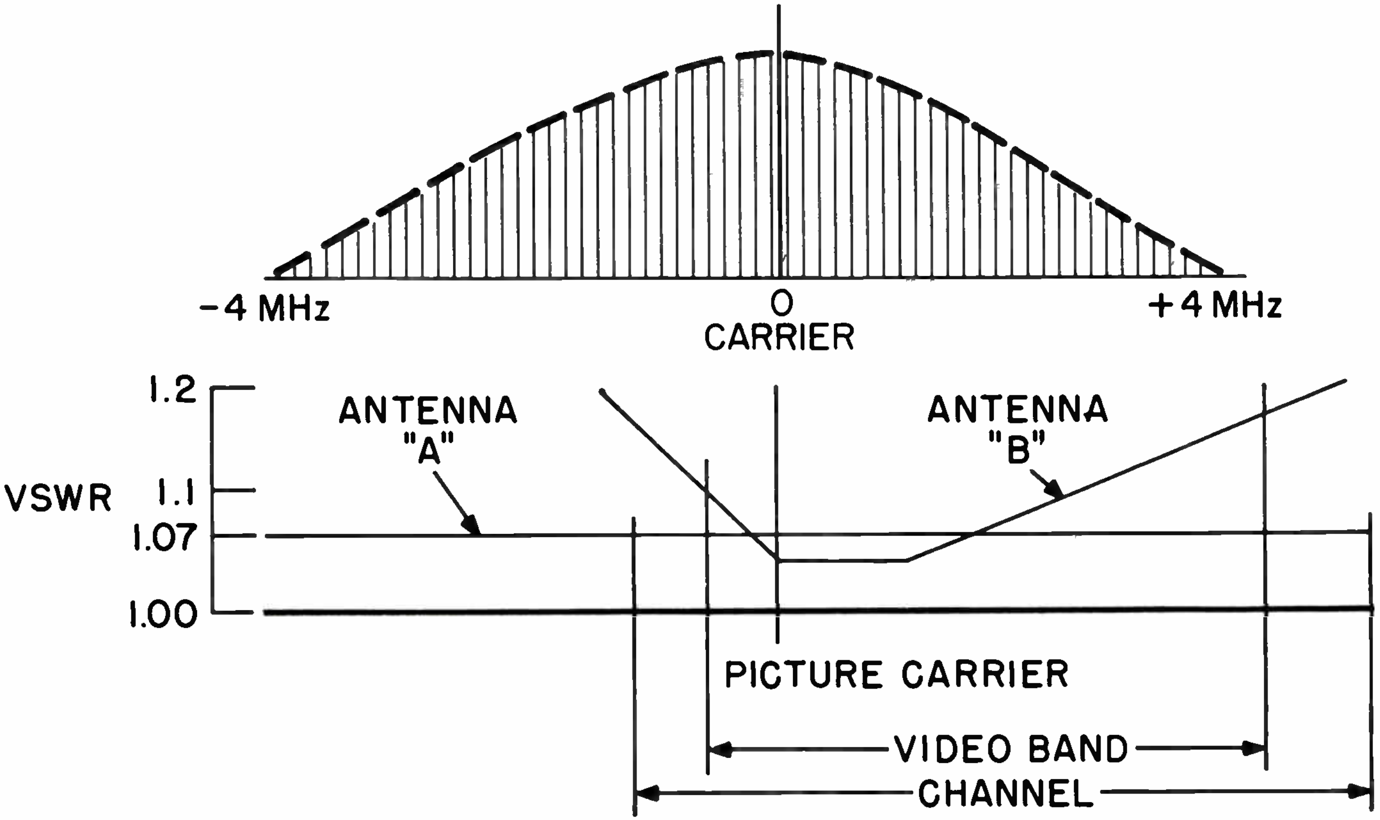

Figure 22. Antenna Measurement with Double Sideband RF Pulse

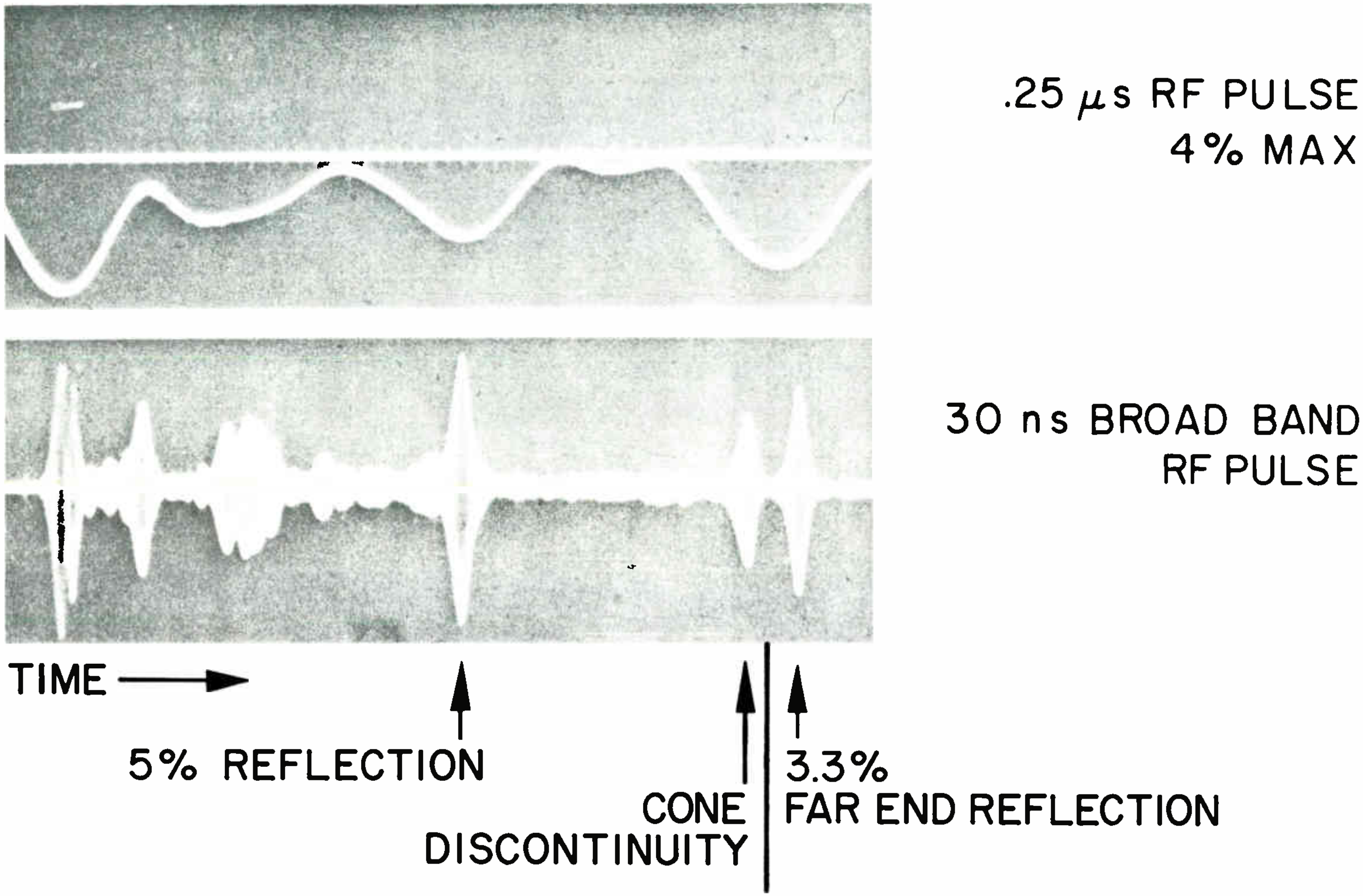

Figure 23. Pulse Comparison

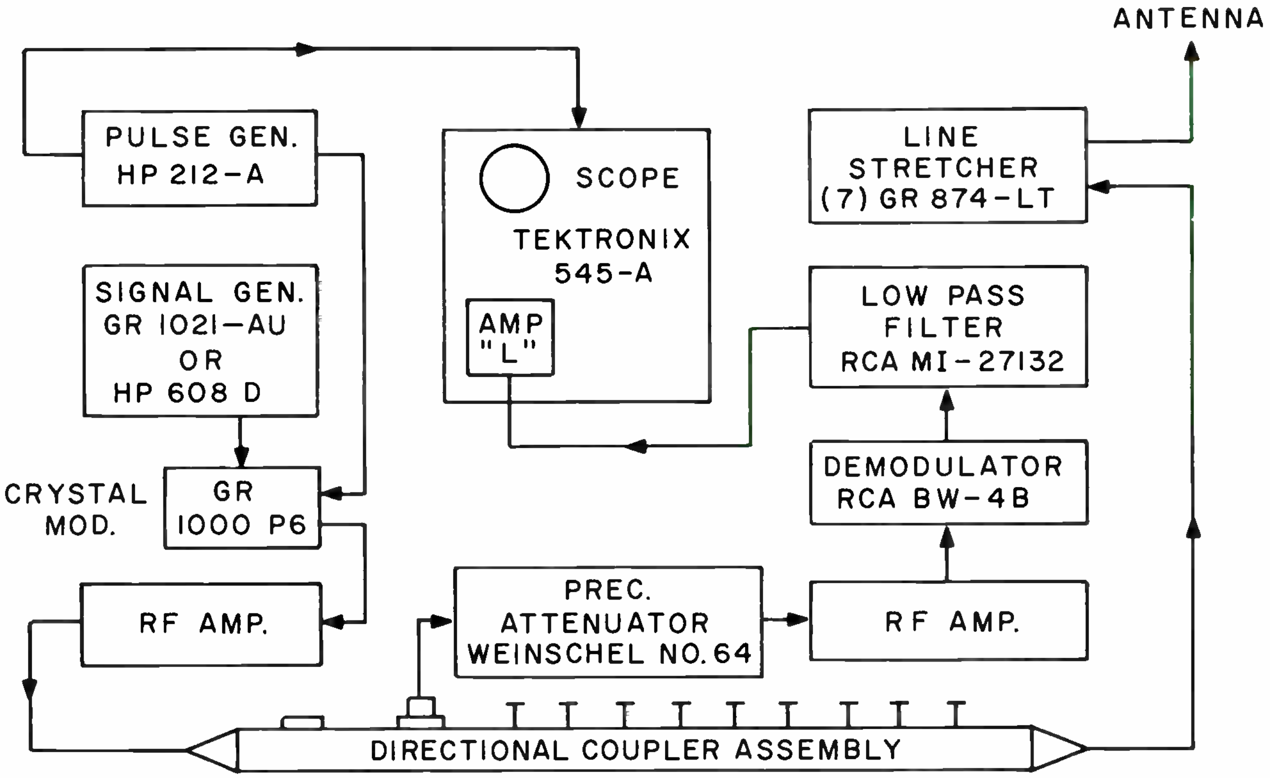

Figure 24. VHF Test Setup

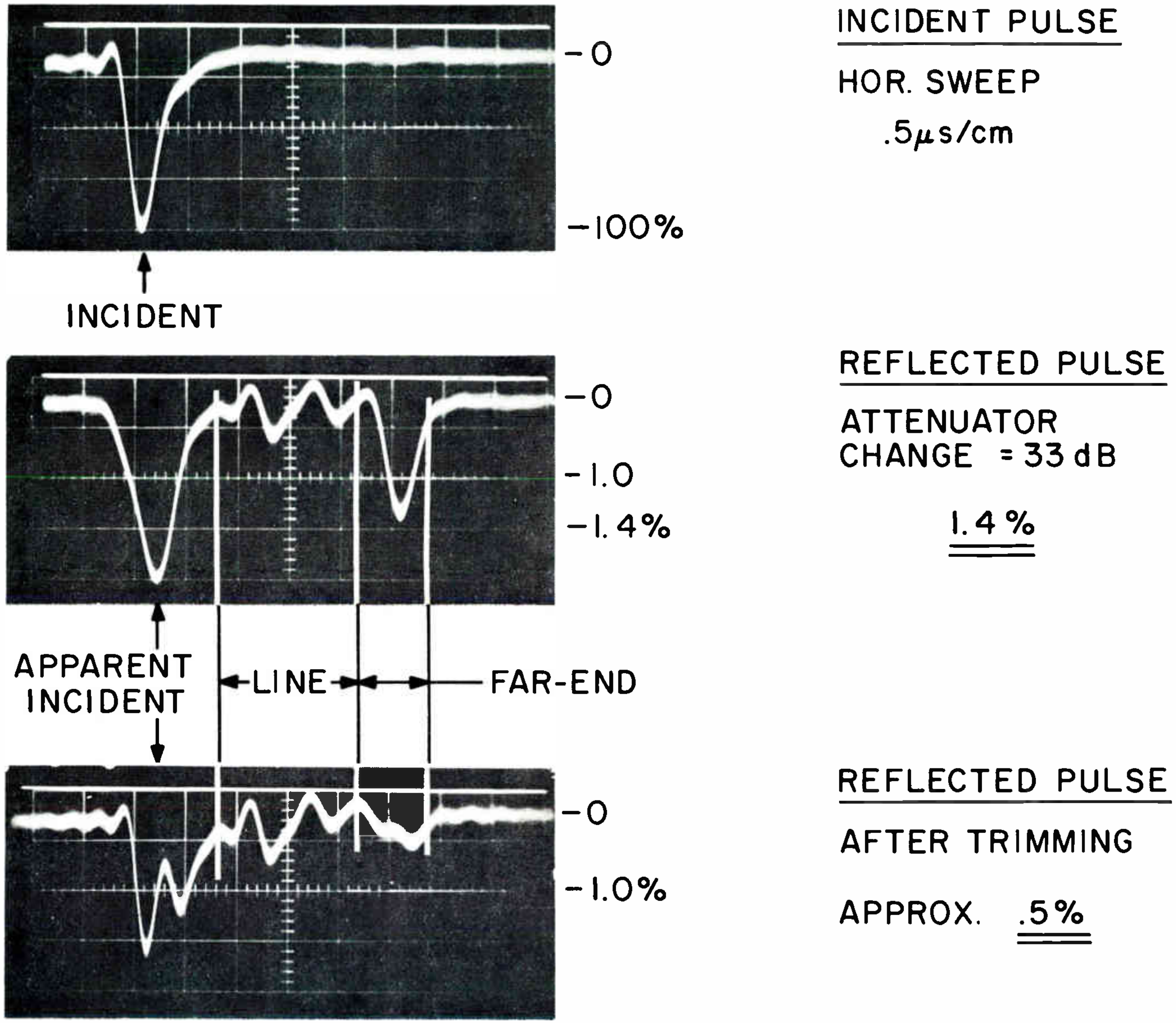

Figure 25. RF Pulse Traces (.25 µs)

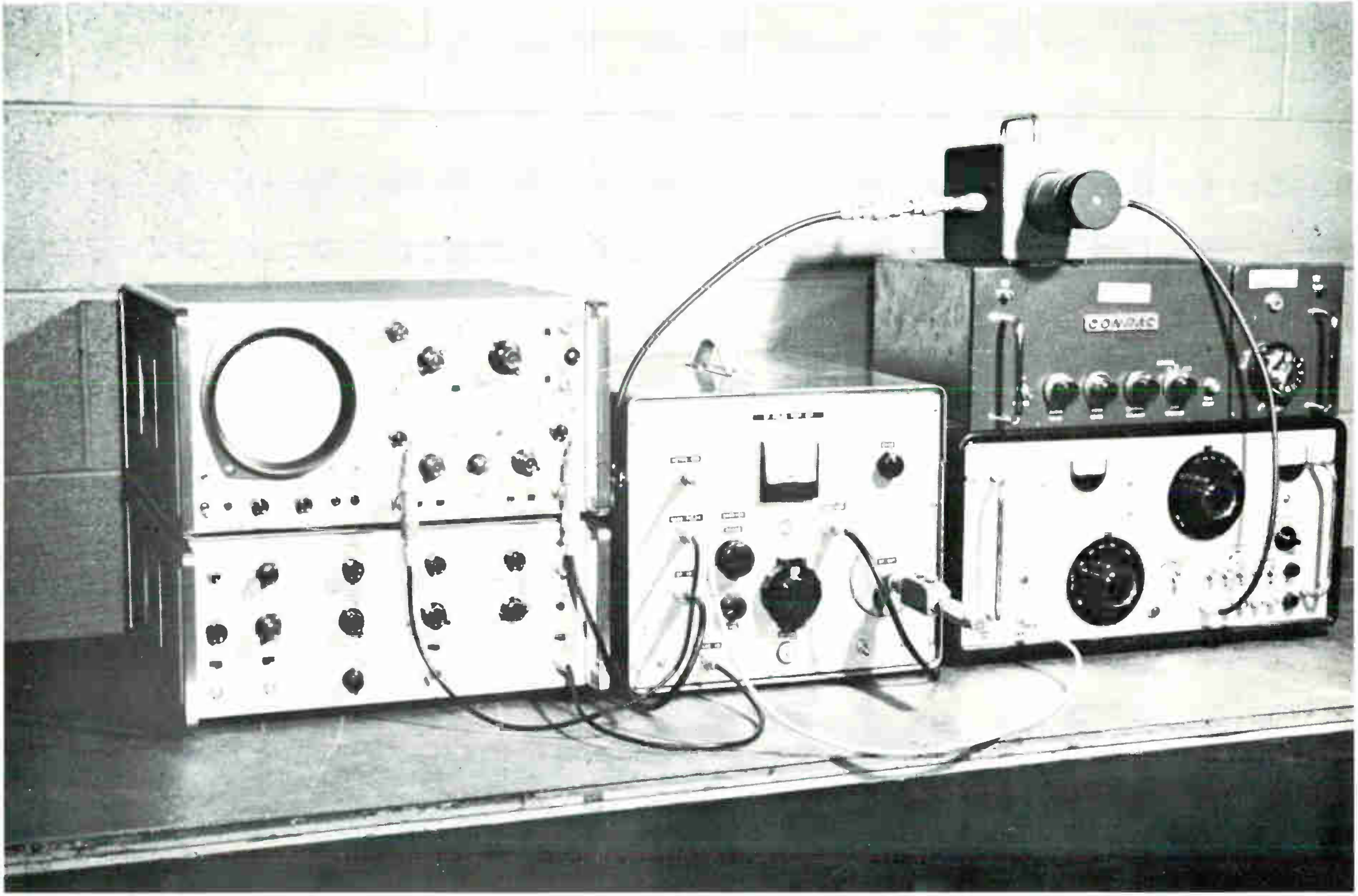

Figure 26. UHF Test Equipment

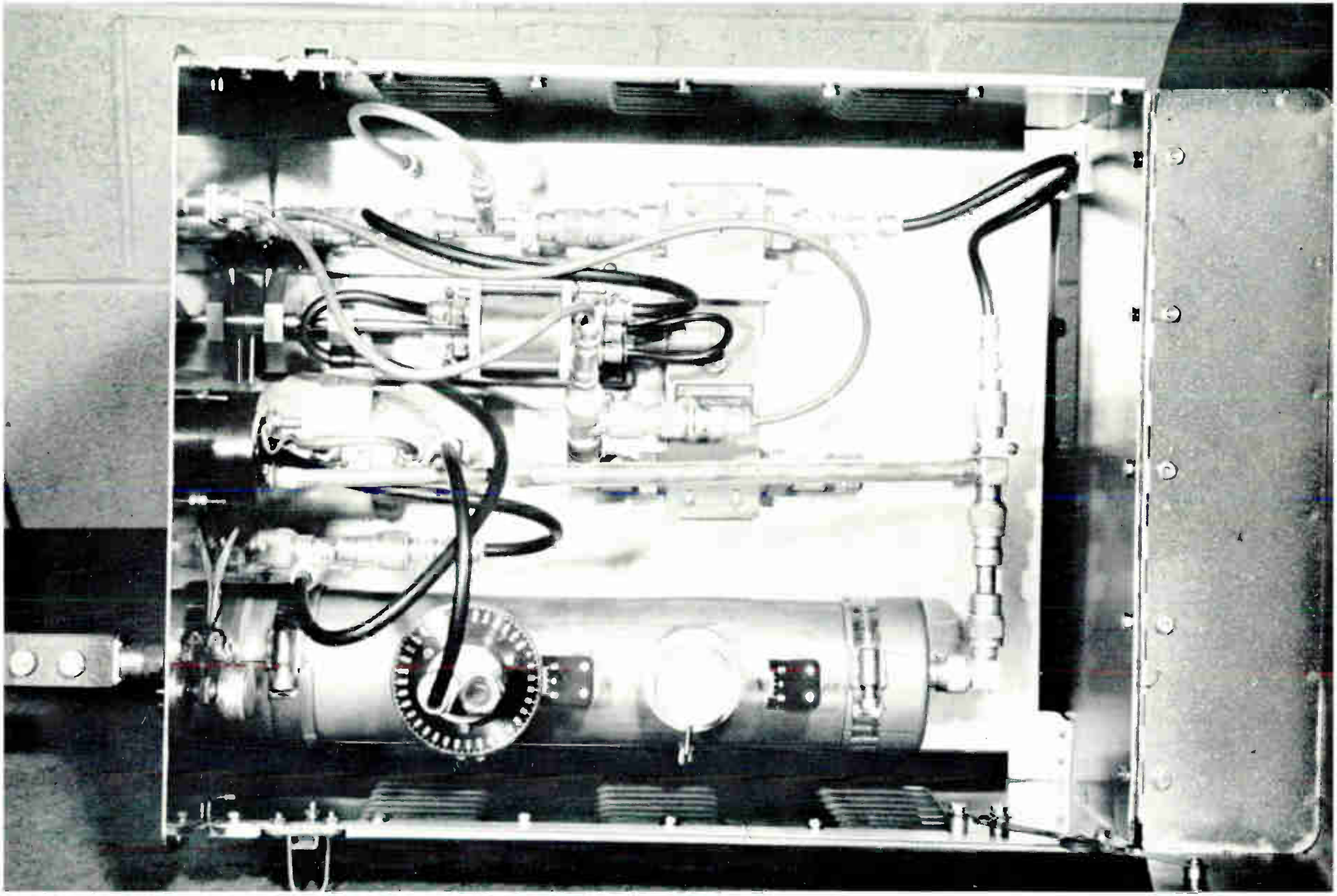

Figure 27. View Inside Reflectometer Housing

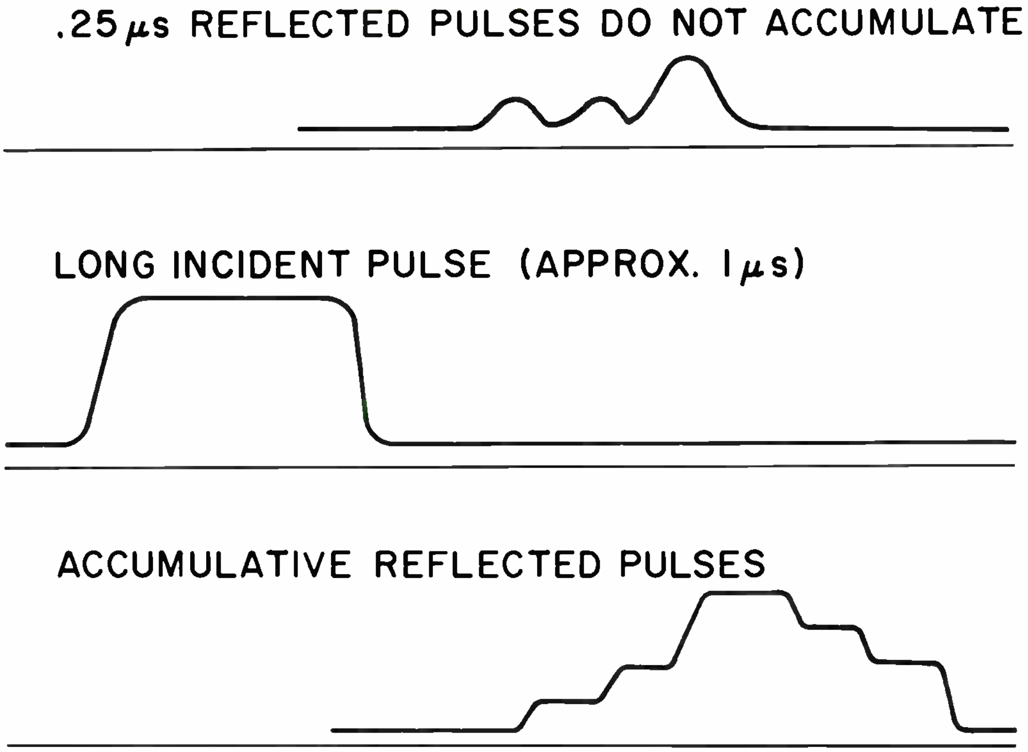

Figure 28. Accumulative Effects

Various methods of determining the gain of a proposed TV antenna

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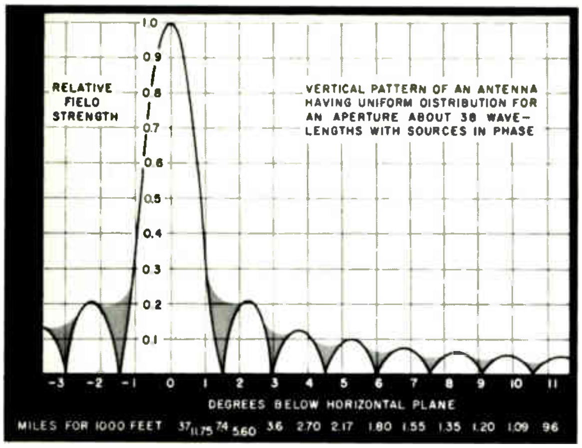

Fig. 2—Null fill increases power integral.

maximum gain, and the integral of E_ϕ represents the area of the horizontal pattern, and results in the average gain, then the horizontal gain G_H may be defined as the ratio of peak gain-to-average or RMS gain. Wherever the horizontal gain is brought out as a separate factor, the remaining factors represent the RMS gain of an antenna. Thus, in general, the RMS gain includes the various factors that affect the directional gain.

Null fill

Null fill, in general, consists of two factors: null fill by the element and null fill by the array. When the radiator is one of high gain such as a zig-zag element on a panel, there is a null-fill factor due to the natural illumination on the element. When an array of radiators has a power distribution or relative phasing so that the various nulls are filled to the desired level, a reduction of gain occurs; this may be defined as the array null-fill factor The influence of this factor upon gain is illustrated in the vertical pattern of Fig. 2. Here we see a series of complete nulls that occurs when all the radiating elements are driven with equal power and equal relative phase. To introduce pattern distribution and phasing to fill the nulls, as represented by the shaded areas, requires additional energy, of course. Thus, the array null-fill factor is generally derived when the vertical pattern of the proposed antenna is computed or synthesized. Possible values of null-fill factor ranges from 0 to 30 percent, but 20 percent is typical.

Beam tilt

Beam tilt is a factor that often influences the gain of arrays made up of high-gain radiating panels. This factor is illustrated by the two vertical patterns in Fig. 3, one being that of the radiator mounted to produce maximum radiation in the horizontal direction, and the array pattern that is tilted to an angle below the horizontal. It can be seen that, in the direction of beam tilt, or maximum radiation of the array, the relative field of the panel pattern is below its maximum field, and in this case the gain is only 96% of its maximum. This emphasizes the importance of the beam-tilt factor in determining the gain of such antennas.

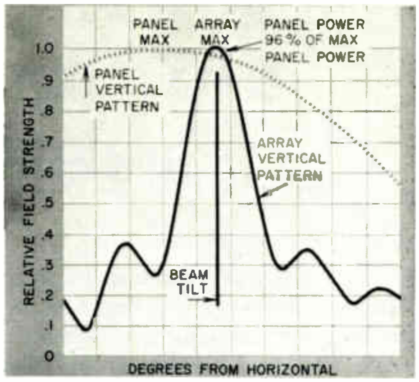

Fig. 3—Beam tilt factor illustration.

Pattern variations

Vertical pattern variations in the horizontal direction from the main lobe of radiation are illustrated in Fig. 4; we see a typical vertical pattern of a panel-type radiator, measured in the maximum direction of radiation. Now, when the vertical pattern is measured in directions off the main lobe (as shown by the dashed pattern), considerable variation appears in the vertical pattern. It is a broader pattern in which energy is radiated in the elevation angle where a null normally exists, particularly in the main lobe. This condition illustrates the importance of considering radiation characteristics not only in the main lobe but in all directions.

An exception is the type of antenna which utilizes slots arranged in phase about a pole, such as the Pylon antenna. The pattern variation of the Pylon antenna is negligible. Every configuration of radiators, however, should be evaluated for this factor prior to use in a system. Other aspects of vertical pattern variation are considered later when methods of predetermining gain are discussed.

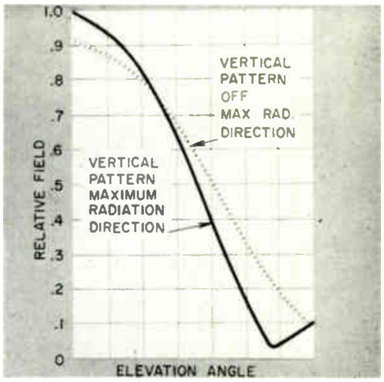

Fig. 4—Pattern variation illustrated.

Vertical polarization

Vertically-polarized energy, considered as lost in TV antennas, may be kept to within one to three percent of the total power into the antenna in good designs. The vertically-polarized energy radiated is controlled by the design of the radiating elements. This energy loss, of course, effectively reduces the gain of the antenna by the same percentages.

Feed-system losses

Feed-system losses are readily determined by calculating the losses in the transmission line and radiator. Typical values, which are a function of transmission line and radiator size, range from one to three percent.

Safety factor

Safety factor is introduced in antenna-gain calculations to compensate for manufacturing tolerances that exist in the radiating elements and feed system components. This factor is added on top of those previously determined.

Predetermining antenna gain

Antenna gain may be predetermined by any of three general approaches:

1) By complete measurements;
2) By calculations; and
3) By measurements supplemented with calculations.

In the first method, by measurement, a full-size or scale-model antenna may be fabricated and complete horizontal and vertical patterns taken to derive the gain. In the second and purely arithmetical approach, the relative field in all directions would be derived from either the complete volume integral, the maximum gain per aperture, or from the product of horizontal and RMS gains where they have been pre-

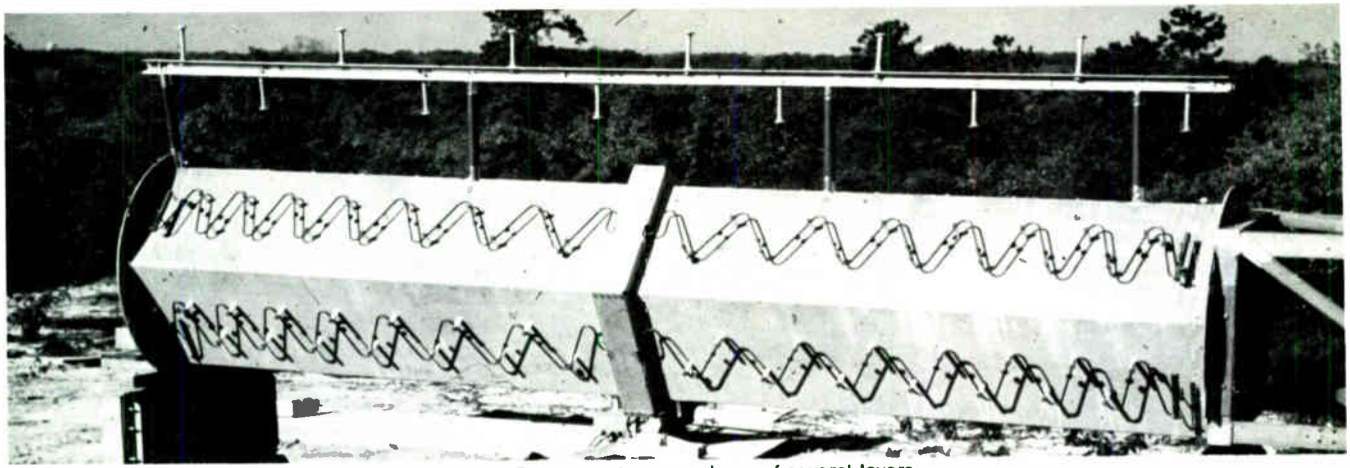

Fig. 5—Polygon antenna made up of several layers.

determined. The third method, partial measurements supplemented with calculations is the most practical approach for new custom antennas when the layer gain or panel gain is known. It is the method used in this paper to illustrate the steps in some of the methods used in predetermining antenna gain.

As expressed in Eq. 7a, the gain formula often may be reduced to a simple approximate product form.

The gain is the product of the RMS and horizontal gain, with the introduction of the safety factor. Now the RMS gain may be determined as the product of the array directivity, D_V and the various factors associated with the radiating element gain that have been previously discussed, such as element null-fill, vertical-pattern variation, vertically-polarized radiation, radiation losses, and feed-system losses. D_V is a resultant of other factors that are pertinent to the array. The 1.22 factor is the maximum gain per vertical aperture of the antenna, and A is the effective vertical aperture in wavelengths.

The peak gain in complete product form is seen in Eq. 7b with all the factors including typical values.

When the antenna is made up of several layers, such as the Polygon layer shown in Fig. 5, the gain formula is given in Eq. 8, where $G_L = 1.22$ $(A\lambda/\eta)$ (NF_E) (PV_L) (VP) (RL) and in the mutual coupling vertically small N = number of layers.

Here we gave the RMS-gain equation and the directional-gain equation, which includes the horizontal gain. The RMS layer gain, G_L, will be predetermined by a complete measurement and used as a building block in the design of the array. The gain per layer for the directional antenna would be the omnidirectional gain per layer; when the layer is redesigned for a desirable horizontal gain, the mutual coupling between adjacent panels on the layer could introduce a vertical pattern variation factor which must be considered.

An array with panels mounted close together around a small tower to achieve a desired horizontal pattern is illustrated in Fig. 6. Of course, the pattern may be either directional or omnidirectional. This is an example where there could be an infinite variety of arrangements to consider. The RMS gain as well as the directional gain of the array can be predetermined from the factors given in Eq. 9, where G_{PANEL} includes (NF_E) (VP) (RL) (PV_E) and in the mutual coupling horizontally non-zero N = number of layers.

The pattern variation factor of the array, PV_A (not as well defined as in the case of layer gain), is a function of the mutual coupling between panels, horizontally, and is generally based on experience with previous arrays with similar configurations. Since both RMS and horizontal gains of the panel are predetermined for a panel in free space, conceivably there will be pattern variations due to mutual coupling, and back lobes to be considered when it is placed in an array.

Panels mounted around a large tower as illustrated by the vee-zee array

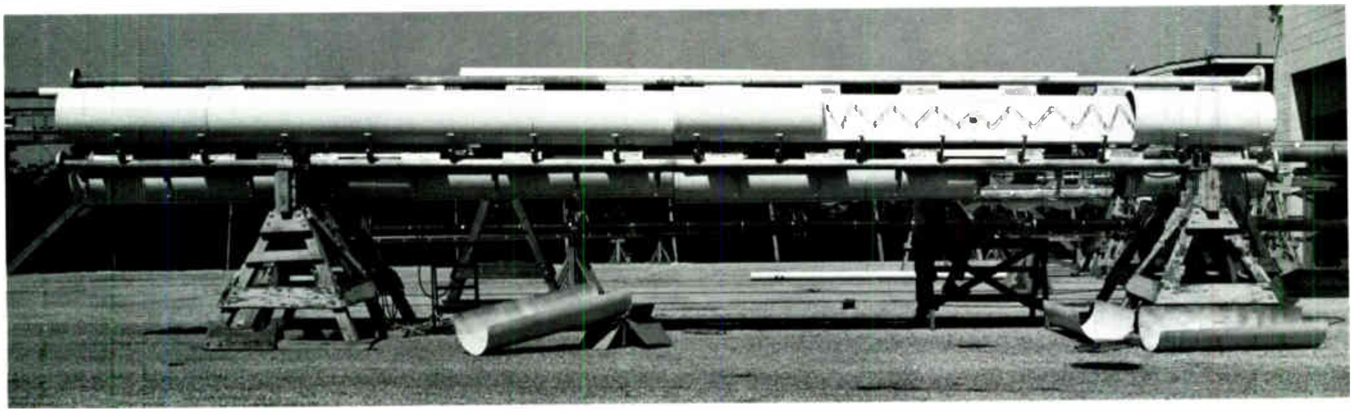

Fig. 6—Antenna designed with arrays of panels for horizontal pattern.

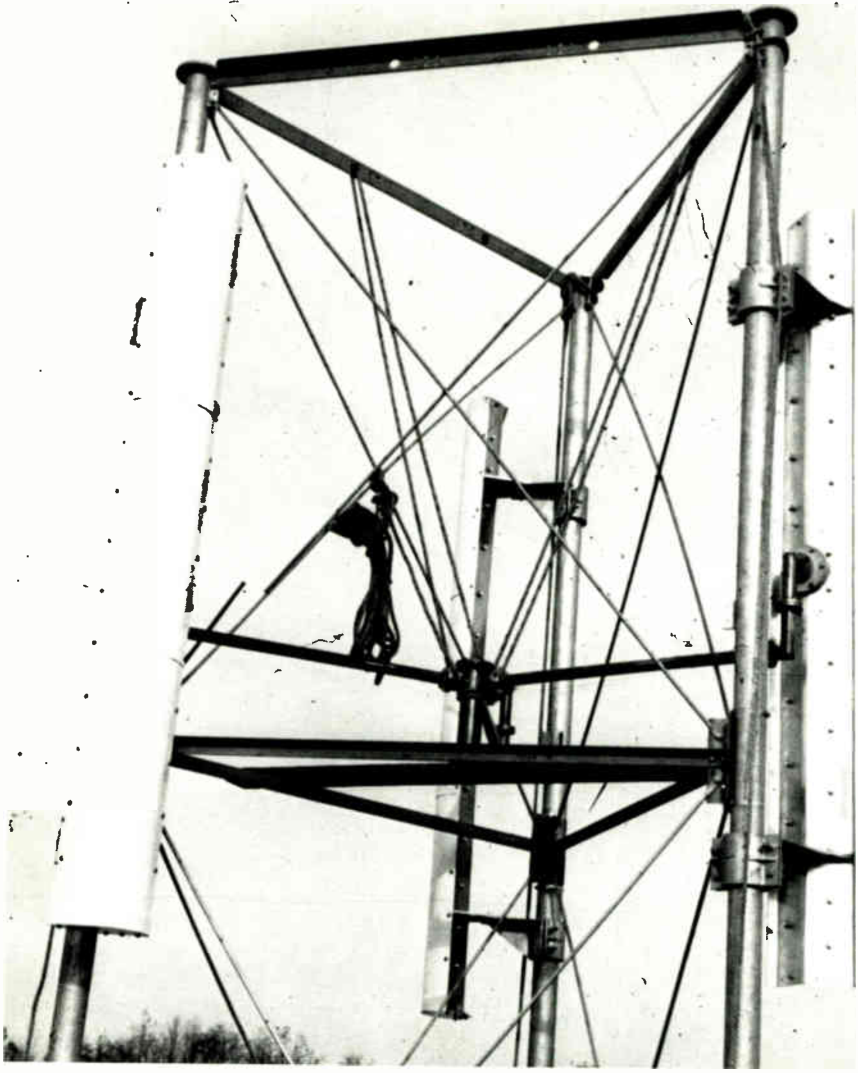

Fig. 7—Vee-Zee array with panels mounted around large tower.

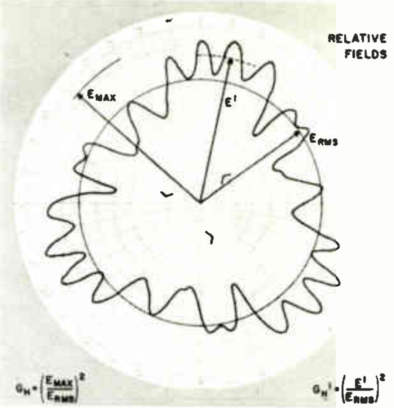

Fig. 8—Horizontal pattern of three VZ-panels around relative fields.

shown in Fig. 7 produce the typically complex horizontal pattern illustrated in Fig. 8. This pattern, achieved by a special skewed arrangement of the a panels, represents excellent horizontal coverage for the case where the panels must be mounted on such a tower. In establishing a gain formula for this array, the following is assumed: the peak directional gain of the single vee-zee panel is predetermined by measurement and since the panels are mounted far apart, mutual coupling is negligible.

Now, in observing the horizontal pattern in Fig. 8, note the relative field value of E'; this represents the maximum field produced by a single panel of the array. The serrations about E' represent the scattering effect of the tower and adjacent panels. Thus, the relative field, E', is established by the peak gain of the panel. The RMS gain is established by integration and the horizontal gain, G_H, is obtained; further, the horizontal gain G_H' is defined to represent the horizontal gain for the E′ field.

The gain formula for the vee-zee panels around the large tower is then given in Eq. 10, where $G=(G_{RMS})\ (G_H)$; G_{PANEL} includes $(NF)_E\ (VP)\ (RL)\ (PV_E)$; $(PV_A)=1$; M=number of panels in a layer; and N=number of layers.

Here it can be seen that the gain-per-layer of panels may be described as the peak-gain-per-panel divided by M, the number of panels in the layer, and G_H'. This factor represents the RMS gain-per-layer, since the peak gain in the direction of E' is the peak gain of a panel divided by the number of panels around; in this case, $M=3$. The RMS gain, of course, must include G_H', so we obtain the factor for RMS gain per layer, which may be used in a fashion similar to the previous equation where the layer gain is known. Thus, the gain formula is the number of layers, times the gain-per-layer, times the factors pertinent to the array. Where the array is being used as a directional antenna, the peak gain would be determined by the RMS gain, times the horizontal gain of the particular pattern desired.

Pattern measurements

Most custom TV transmitting antennas are measured at a test range after the design and fabrication. An acceptable test range would have facilities for rotating the antenna with the recording equipment attached to it. The test range must be equivalent to free space as far as the electromagnetic field about the measured antenna is concerned. The field that is measured must be the "far field" as previously discussed.

Gain measurement of a complete antenna system is most accurately accomplished with pattern measurements. With a practical test range of the size necessary for TV antennas, the accuracy exceeds that of other methods, such as the substitution method. Also, other vital information is obtained in the measured patterns, such as null fill and beam tilt. When the antenna gain is to be measured, all horizontally and vertically polarized radiation and all losses must be included in the measurement and computations. These components are shown in Eq. 4 and were previously discussed. Generally, when analysis or measurements have previously been made on a layer of radiators of the array, the percentage of power lost in vertical polarization can be determined. This can be easily confirmed by total array measurements of the horizontally and vertically polarized field components. The conductor and feed system losses are generally easily calculated.

An efficient TV antenna will have 90 to 95% of the antenna input power radiated as horizontally polarized energy, thus an accurate gain measurement must account for all such energy. As shown in Eq. 6, the null-fill factors, beam-tilt factor, and pattern-variations factor are related to the characteristics of the vertical pattern of the horizontally polarized field. We can thus conclude that, to evaluate these factors (NF_E, NF_A, BT and PV) correctly, the following requirements must be met in test range measurements:

1) The vertical patterns must be measured to 90° (elevation angle) above and below the horizontal plane. In this way, all power radiated (side lobes and filled nulls) will be accounted for. It should be noted that, when the main lobe is tilted below the horizontal plane, the radiation above the main lobe is not necessarily equal to the radiation below the main lobe. (Observe the array vertical pattern in Fig. 3.) The measurement of ±90° will reveal such differences. Often, measured vertical patterns are shown only where coverage is of interest, such as in Fig 2.
2) Vertical patterns must be taken in a sufficient number of horizontal directions to describe the true radiation field accurately. Pattern variations will be revealed by comparing the various patterns. Generally, eight to twelve vertical patterns measured at equally spaced azimuthal directions are adequate. With a reasonable number of patterns measured, the gain may be computed from a summation that is essentially equivalent to the integration indicated in Eq. 4, 5, and 6.

Conclusion

In describing the nature of gain and discussing the many factors that influence gain in the antenna system, extensive reference has been made to panel antennas used in TV broadcast installations. The previous discussion illustrates all the design factors that must be considered.

The gain equation in product form was expanded to include three special cases involving custom arrays, and the relationship between panels for different spacings were reviewed. Means were prescribed for determining the gain in each case, and their differences pointed out. When an antenna is designed to meet a specified null fill and beam tilt, it is necessary to consider the radiation characteristics of the antenna in all directions. Since gain, null fill, and beam tilt are generally contractual items, and gain and relative field are often considered minimums, it is very important to establish their correct values. Utilizing all of the factors discussed in this paper, the designer should be able to build an antenna which will meet the customer's specifications.