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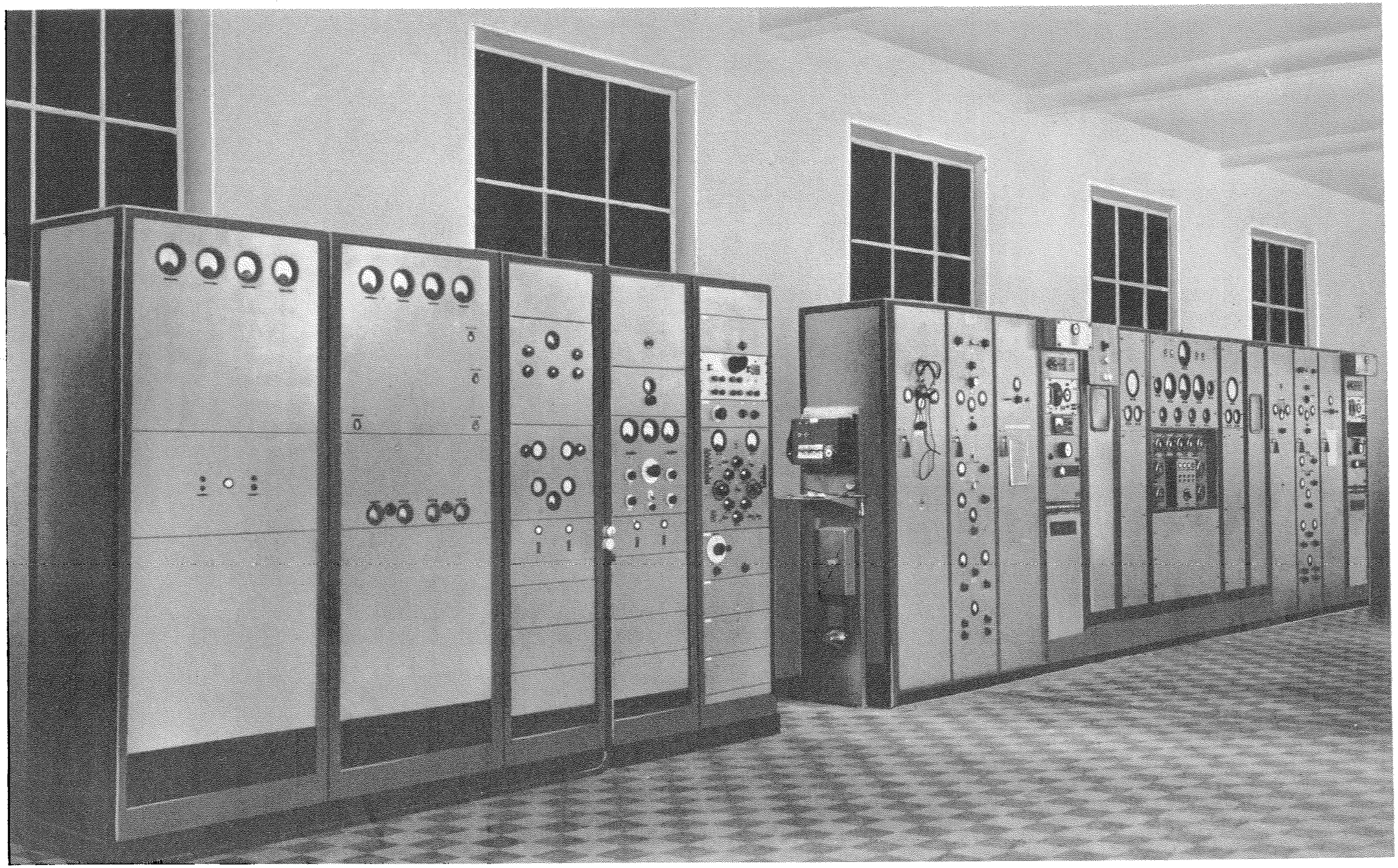

The single-sideband high-frequency transmitter in the illustration provides two telephone channels for the New York-Paris link and is installed at Pontoise, France. At the left is a 1-kilowatt driver and at the right is the 60-kilowatt output stage. The construction of this equipment by Laboratoire Central de Télécommunications is a logical result of its many years of work in this field.

Microwave Radio Relay Systems*

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VARIOUS technical problems involved in the design of microwave radio relay links are surveyed. Propagation characteristics, types of modulation, signal-to-noise conditions, and system engineering aspects are considered. The great value and the possible limitations of such links are pointed out.

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The final goal of telecommunications often has been defined as being the ability of communicating with anyone, anywhere, any time. Ten years ago, this was still a dream, now it seems that it might come true. The scientific foundations for fulfilling our goal exist already. However, it will certainly be a long time before such a global communication network can be completed, and certainly social and economic difficulties will be at least as important as the technical factors.

The main progress that has made this dream possible is the advance accomplished recently in the extension of the radio-frequency range actually available to the engineer. The existing telecommunication network is essentially composed of wires and cables, extended by a relatively small number of fixed and mobile radio links. The fixed radio links were, until recently, almost all below 30 megacycles per second. In spite of the small density of this radio network, the ether below 30 megacycles is terribly crowded and there is practically no space available for additional services. The shortage of frequencies explains the constant efforts of all research laboratories to extend the range of practicably workable frequencies toward higher and higher values.

The laboratories of the I.T.&T. System recognized the importance of this question a long time ago, and in fact by 1932, an experimental microwave link was tested across the English Channel. But these experiments were isolated and far in advance of the general state of the art; so much so, that in 1938 the frequency range that we really knew how to handle did not extend above 500 megacycles. The accelerated developments during the war have changed this picture, and now the practical limit of usable frequencies has been extended up to at least 30,000 megacycles.

In the last ten years, it has not been possible to explore completely this vast range of frequencies. Much remains to be done and practically all telecommunication laboratories are busily developing new tools and various applications of microwaves. Aerial navigation and mobile links for communication with planes, cars, ships, and railroads are some of them. Microwaves are also invading a domain that wires and cables have previously filled. Many projects have been described for using microwave links with repeaters for long-range communication, television, telegraphy, and multichannel telephony. The purpose of this paper is to present a short general survey of the technical aspects of this last problem.

1. General

Microwave radio relay systems consist of a series of transmitters and receivers spaced 30 to 60 miles apart in direct visibility. On flat ground, towers are used to extend the horizon. The signal is retransmitted at each relay or repeater station, generally at a different frequency from the one at which it has been received. Relay systems of this sort have been proposed for television transmission or multichannel telephony. Essentially, it is hoped that relay radio systems not requiring physical connections between repeaters will be more economical than wire or cable connections and that the relatively greater facilities offered by radio for wide-frequency-band operation will open up new types of services. Most proposals

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now concern carrier frequencies between 1000 and 10,000 megacycles. There are two reasons for choosing such high frequencies.

A. Higher frequencies have certain technical advantages.

B. Lower frequencies are indispensable for existing services.

It should, indeed, be clear that mobile services cannot, generally, make use of highly concentrated radiations. For equal directivity at the transmitter and receiver and for equal transmitted power, the received power is proportional to the square of the wavelength. In other words, for the same transmitted power, the power received for a comparable angular coverage would be one hundred times more at 100 megacycles than at 1000 megacycles. This is why mobile services rightly request priority for lower frequencies.

For fixed services, the situation is technically reversed, and because maximum directivity not only can be used but is even desirable, the useful power actually increases with frequency. Factors which must be considered are the propagation characteristics of waves between 1000 and 10,000 megacycles, various types of modulation, signal-to-noise ratio, and the over-all system aspects of microwave relay links.

2. *Propagation*

For fixed installations, the propagation characteristics can be expressed in a most useful manner by the attenuation between the transmitting point and the receiving point. If P_t designates the transmitted power and P_r the received power, the attenuation A is:

$$A=\frac{P_t}{P_r}=A_0\, A_1\, A_2\, A_3, \qquad (1)$$

where

A_0 = free-space factor,
A_1 = topographical factor,
A_2 = atmospheric factor, and
A_3 = absorption factor.

In (1), the attenuation has been expressed as a product of various factors. For convenience, these factors may be expressed in decibels, the total attenuation then being their sum.

2.1 Free-Space Factor

The free-space factor A_0 represents the attenuation that would exist in free space at a given distance between transmitter and receiver. It is a factor which can be calculated closely by the principles of geometrical optics. Essentially,

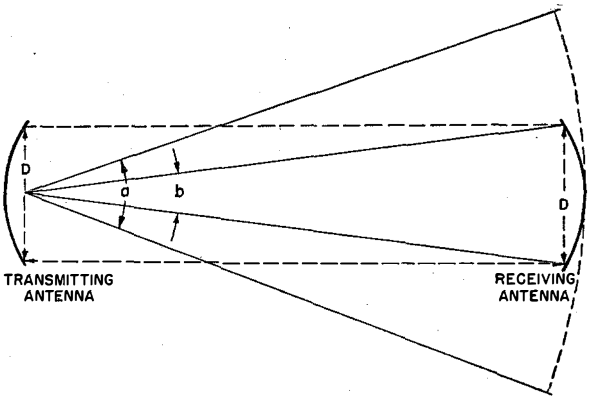

Fig. 1—Free-space attenuation is a function of the beam characteristics of the antennas. The angle in which the radiation is concentrated when using dipole radiators and parabolic reflectors is $a=1.7\,(\lambda/D)$. The angle in which the receiving antenna is viewed from the transmitting point is $b = D/L$, where L is the distance between transmitting and receiving antennas.

it represents the loss resulting from the fact that the beam is not concentrated in an infinitely narrow angle. It is clear from Fig. 1, that A_0 is given by (2).

$$A_0=\left(\frac{a}{b}\right)^2. \qquad (2)$$

For sake of simplicity, axial symmetry is assumed. The angle a is the equivalent beam width, i.e., the width the beam would have if all the energy were radiated uniformly into that angle. It differs only slightly from the angle usually considered between the directions of half-power points. For a given type of antenna, the value of a can be obtained from diffraction theory of electromagnetic waves. If the antenna aperture is D, it can be shown that a is proportional to the ratio λ/D.

The exact numerical coefficient depends on the type of radiator, type of illumination, shape of reflectors, etc. For parabolic reflectors and dipole radiators, the angle a is given by

$$a=1.7\,\frac{\lambda}{D}\ \text{radians}, \qquad (3)$$

The angle b designates simply the angle under which the receiving antenna is viewed from the transmitting point and is essentially given by

$$b = \frac{D}{L} \text{ radians.} \qquad (4)$$

Transposing (3) and (4) into (2) yields

$$A_0 = 3\,\frac{\lambda^2 L^2}{D^4}. \qquad (5)$$

This simple derivation of the free-space coefficient A_0 applies, of course, only when D is much larger than λ and when a is larger than b; and also assumes no fringing effects. It is interesting to note that $a = b$, which would mean no attenuation in free space, corresponding to conditions which can actually be met.

In most practical cases for distances of the order of 30 miles, A_0 will result in a power ratio of the order of 10^6 to 10^8 or of 60 to 80 decibels. The importance of using short wavelengths, i.e., small values of a, appears clearly from (2) or (5). It is also obvious from (5) that the most important single factor is the diameter D of the antennas used because it affects both angles a and b in the same proportion.

It is not possible to reduce the equivalent beam width a indefinitely. Two lower limits have to be considered: (1) The fluctuation of the position of the beam as a result of atmospheric conditions. This limit is probably below half a degree or 1/100 radian; and (2) the fluctuation of the position of the beam because of the limited mechanical rigidity of the antenna support. It seems likely that values of 0.03 to 0.06 radian would represent in most cases a good compromise between the costs of additional radio power and the additional costs of extremely rigid supporting structures.

2.2 Topographical Factor

Actually, the transmitter and receiver are not in free space. The presence of the earth changes considerably the simple propagation conditions of free space. When the transmitter is directly visible from the receiver over a smooth spherical earth, the coefficient A_1 can be calculated and many papers have been published dealing with this problem. A_1 in such conditions depends on the height of the transmitters and receivers above ground. A well-known interference pattern results from the reflection from the ground.

It is also well known that when the atmosphere is supposed to be "standard," the bending of the waves resulting from the variation of the index of refraction with altitude can be taken into account by using an effective radius for the earth's surface equal to 4/3 of the true radius. The theory of the factor A_1 is important especially at lower frequencies of the order of 30 to 300 megacycles. At these frequencies, it might be difficult to find a position of the transmitter and receiver that would make A_1 close to unity and, therefore, it is important to know what value it might take. For higher frequencies and narrow beam angles, it is not safe to assume that the earth is smooth; as soon as the link is not over flat ground, most of the formulas do not apply, and also the simple application of wave theories is often misleading.

As a compensation for these theoretical difficulties, the practical conditions are such for this frequency range that A_1 is generally close to unity if the height of the transmitting and receiving antennas are properly chosen and, therefore, the exact knowledge of A_1 is not too important. However, in special surroundings, such as a narrow valley or street, the factor A_1 could, of course, be quite different from unity.

Furthermore, from the point of view of the communication engineer, what is more important than the absolute value is the variation with time of the coefficient A_1. These changes are caused by variations of reflection coefficient of the ground. On land, variations are small because they result only from variations of conductivity at the reflection points caused by changes of humidity of the ground or presence of leaves or snow, etc. Such variations usually do not exceed 6 decibels. The variations might be larger if the reflecting region is over sea. It might move with the tides, but even so, the variations of A_1 would hardly be larger than 6 to 12 decibels, because the minima of the interference pattern resulting from reflection from the ground are seldom less than 12 decibels below the free-space conditions.

2.3 Atmospheric Factor

All that has been said before concerns standard atmospheric conditions. A standard atmosphere is defined as an atmosphere in which the refraction index varies steadily with altitude at a given rate. When the atmosphere is not standard, the propagation conditions might be greatly changed and the factor A_2 can reach very large values. Important theoretical and experimental investigations of variations of propagation with changes of climatic conditions in the lower atmosphere have been made recently. It has been found that variations of the coefficient A_2 by as much as 30 to 40 decibels are possible depending on a great variety of factors. Usually in these studies, the refractive state of the atmosphere is most conveniently described by means of a curve showing the relation between the so-called excess modified index of refraction M and the height h. M is given by

$$M = \left[n(h) + \frac{h}{r\text{-}1} \right] \cdot 10^6, \tag{6}$$

where $n(h)$ is the actual index of refraction at height h above the ground, and r is the radius of the earth.

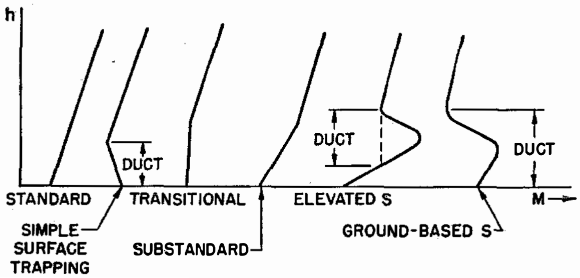

Fig. 2—Variations of refractive index of the atmosphere *M* with height *h*. The regions marked "duct" are capable of propagating waves over very long distances with little attenuation.

Fig. 2, taken from a report by I. Katz of the Radiation Laboratory of Massachusetts Institute of Technology, shows various possible aspects of the M curves. Various types of M curves correspond to various meteorological conditions. Only when the M curve is standard, or when it has a different slope but remains uniform, can the simple ray theory be applied to determine the value of the coefficient A_2. A slope variation of the M curve is equivalent to a bending of the whole interference pattern which determines the previous coefficient A_1.

When the M curve has a knee, the conditions become much more complicated and an actual duct is formed in the atmosphere, usually between the ground and the altitude at which the M curve changes its slope. These altitudes may vary from a few hundred to a few thousand feet. The waves can be trapped in the duct and be propagated for very long distances, but they might also never reach the desired receiving point if that point is not located in the right position with respect to the duct. Complete trapping is rather infrequent and, therefore, complete fading at the receiving point is seldom encountered but, as stated previously, variations up to 40 decibels have been observed at many frequencies. It is not obvious which frequencies are to be preferred from this point of view. It is true that, generally speaking, for a given duct position no trapping will occur at frequencies lower than a certain value but, the height of the duct being variable, this minimum frequency is also variable.

The relation between the types of M curves and meteorologic data are complex, but it seems that some very broad statements can be made. Irregularities in the M curve generally correspond to temperature inversions. But not all inversions will yield ducts. Often these conditions are realized when warm dry air blows out over a cool body of water. Similar effects can be obtained at night in summer over land. Generally speaking, when the air is strongly agitated or in windy weather, standard propagation conditions will prevail over land. In summer, and especially over sea, vagaries of propagation are more likely.

2.4 Absorption Factor

The coefficient A_3 characterizes additional losses caused by true absorption in the atmosphere. For the factors previously considered, A_0, A_1, A_2, it is assumed that no absorption takes place in the atmosphere. This assumption is justified up to frequencies as high as 6000 megacycles. Fog, rain, or snow affect the propagation of frequencies at 3000 megacycles, but the losses encountered most of the time are negligible and do not represent more than 0.05 decibel per mile on the average. At wavelengths as short as 1 centimeter (30,000 megacycles), on the contrary, absorptions of 35 decibels per mile can be observed for heavy rainfalls. Most of the absorption effects result from the presence of water which

TABLE I

A Multiplexing	B Modulation of Each Channel	C Modulation of Radio-Frequency Carrier
a. Frequency Selection	a. Amplitude Modulation Single Sideband	a. Amplitude Modulation
b. Time Division	b. Frequency Modulation	b. Frequency or Phase Modulation
	c. Pulse-Amplitude Modulation	c. Amplitude Keying
	d. Pulse-Time Modulation	d. Frequency Keying
	e. Pulse-Code Modulation	e. Modulation *a* or *b* by a Subcarrier Itself Modulated by Methods *a* or *b*

has a strong absorption region at wavelengths around 1.25 centimeters (24,000 megacycles).

It is interesting to note that the factor A_3 represents a type of attenuation which varies exponentially with distance and which is, therefore, similar to what is encountered normally for propagation on wires or cables. As soon as factors of this type become important, they overshadow all others because they increase so rapidly with distance.

The practical conclusion concerning the various aspects of propagation conditions which have been outlined is that, in communication links, provisions for fading should be made taking into account variations of received power of the order of 30 to 40 decibels. It is possible that, in many cases, these variations could be considerably reduced by the use of two receivers at different heights. This method of space diversity has been tested only recently and it is difficult to estimate how successful it will be. Also, in spite of the abundance of information already available, it is still difficult to state how often fading conditions will be present for a given link and, therefore, what the probability of failure of the link might be. A 30-decibel margin in power is quite feasible and, therefore, the actual probability of failure could be relatively small, especially in cases where space diversity provides an additional protection. Some extreme cases of fading will probably be encountered where neither additional power nor space diversity can help.

3. *Modulation*

We are mainly concerned with multiplex telephony or telegraphy. The method of modulation best suited to the problem would be one which would require minimum transmitted power for a certain amount of noise present, minimum bandwidth, and would minimize difficulties due to the accumulation of distortions of each repeater. It is, of course, difficult to find a single figure of merit that would take into account all these various factors. Efforts have been made recently to arrive at a classification of various modulation methods by using the Hartley law relating the amount of intelligence transmitted, bandwidth used, and time required to transmit the intelligence, but even such efforts do not take into account the type of tubes available or the relative difficulty of avoiding distortions which might favor one type of modulation with respect to another. A list of the most promising methods will be given together with some information concerning the types that have been actually used.

Essentially three different operations have to be performed for the transmission of multiplex telephony:

A. Multiplexing of the various channels.

B. Transmission of the intelligence in each individual channel.

C. Modulation of the radio-frequency carrier with the complex signal formed by *A* and *B* above.

Each of the three operations described can be performed in various manners and a large number of systems can be obtained by combining the methods for each operation in various ways. Table I, which is far from complete and is limited to the most interesting types, will give an idea of the variety of systems possible.

In ordinary radio practice where the ether is crowded, one of the most important factors is economy of bandwidth. The same view certainly will apply to microwave operation but because of the unavoidable instability of the carriers used, the economical bandwidth is generally much larger than at lower frequencies. Even with the greatest of care, it is unlikely that the frequencies of the transmitter and receiver in a radio relay system could be adjusted and maintained stable within better than 0.01 percent. This means that at 5000 megacycles the bandwidth necessary to take care of instabilities alone would be at least 1 megacycle. In other words, the microwave equipments are inherently relatively wide band and, therefore, it seems reasonable to use modulation schemes which require bandwidths larger than strictly necessary for transmitting the intelligence but which make good use of these extended bandwidths by reducing distortion difficulties or by improving the signal-to-noise ratio.

Both frequency modulation and pulse-time modulation have similar advantages from these points of view. Although the choice between these two systems has been discussed at length, it seems obvious from Table I that the true problem is not what type of modulation of the radio frequency is to be used but rather to determine the most desirable multiplexing method. There are only two multiplexing systems: frequency selection where all channels are transmitted simultaneously and are seperated by frequency filters; or time division where the channels are transmitted successively.

Frequency selection is widely used for carrier transmission on wires and the same system should receive first consideration for radio. The main difficulty is that frequency selection requires extremely linear repeaters. To reduce cross talk below 60 decibels, the total over-all harmonic content between terminals has to be less than 0.1 percent. If 20 repeaters are to be put in tandem, each repeater should contribute less than 0.05 percent to the harmonic content over the signal frequency spectrum! It is not too difficult to meet such severe specification for wire communication with negative-feedback amplifiers. But until a similar tool is developed for radio repeaters, they will necessarily involve modulation and demodulation processes that introduce nonlinearities even if the radio carrier is frequency modulated.

One way out, which has been applied in the equipment developed for Western Union by Radio Corporation of America,[15] is to use a subcarrier. This system is a combination of the types *Aa*, *Ba*, *Ceb* of Table I.

For a limited number of repeaters, frequency or phase modulation is possible. It might be feasible to increase the number of repeaters by using a large amount of negative feedback. An experimental 12-channel equipment[19] of that type has been developed by Laboratoire Central de Télécommunications, for the French administration. It is now in operation between Paris and Montmorency.

Another possibility is to perform the multiplexing operation by time division and use pulses. For modulation of each channel, either pulse-amplitude or pulse-time modulation or the more complex telegraphic methods, such as pulse-code modulation, could be used. For modulation of the radio carrier, the choice remains between amplitude or frequency modulation. In any case, linearity requirements are much less severe. For time modulation, the linearity of the repeater is of no consequence at all for cross talk. A system using time-division multiplex for 24 channels has been developed by Federal Telecommunication Laboratories. It is a combination of the types *Ab*, *Bd*, *Cc*, of Table I. The main characteristics of the system are reproduced in the appendix. An experimental link with two repeaters is now in operation between New York and Trenton.

The total frequency band necessary might appear somewhat large but it should be noted that the system based on frequency selection with a subcarrier finally leads to quite similar frequency bands. Both systems take advantage of bandwidth to overcome the inherent difficulties of the design of linear repeaters.

Important improvements can be expected soon for both frequency-selection and time-division methods. It is difficult to say now which one is preferable and it seems most likely that both will find useful fields of application.

4. *Signal-to-Noise Ratio*

In all communication problems, the major question is finally: How large must the input power be to override all noise present and to achieve the output signal-to-noise ratio required by the type of service desired?

[15] Numbered references will be found on page 140.

At microwaves, barring interferences, the only appreciable sources of noise are thermal agitation in the real part of the input impedance, the input tubes, and in the incoming radiation itself.

These three sources of noise are essentially of the same nature and can, therefore, all be combined in an equivalent noise power generator at the receiver input of internal power N_0P_0 in series with the received power P_r, i.e., with an internal impedance equal to the antenna impedance. N_0 is the receiver "noise factor."

$$P_0 = 1.6 \cdot 10^{-20} B \text{ watts}$$

where B is the effective noise bandwidth of the receiver before limiter or demodulator, and P_0 is the minimum possible noise power. The numerical coefficient is actually $4KT$ where K is Boltzmann's constant and the absolute temperature T is arbitrarily taken to be $T=293$ degrees (20 degrees centigrade).

The required power P_r can be expressed in terms of P_0 by what could be called a "system noise factor N" given by

$$\frac{P_r}{P_0} = N = \frac{N_0\,N_1\,N_2}{N_3}. \tag{7}$$

Equation (7) determines the power P_r if the various factors N_0, N_1, N_2, N_3, and the bandwidth B are known.

At microwave frequencies, the noise factor N_0 for good receivers is generally between the following limits: $10 < N_0 < 50$.

N_1 is the output signal-to-noise ratio. N_1 might vary from 20 decibels for teleprinters to 60 decibels for high-class music. For telephony, 40 to 50 decibels are generally considered adequate for good commercial quality.

N_2 is a factor which takes into account the presence of a certain number of receivers in tandem. Normally, the noise of each receiver will be added to the total and therefore N_2 is simply equal to the number of relays in series. N_2, resulting from accumulation of noise in repeaters, may equal zero decibels for all practical cases having any number of repeaters if pulse-code modulation were used.

N_3 is the improvement factor resulting from the type of modulation, bandwidth, type of limiters and demodulator, etc.

For frequency and pulse-time modulations, N_3 is proportional to the square of the ratio of the transmission bandwidth to the bandwidth covered by the signal at least so long as the ratio P_r/N_0P_0 is larger than 6 to 12 decibels to let the limiters operate correctly. The choice of the factor N_3 will determine the bandwidth and P_r or, inversely, the choice of the bandwidth will determine N_3 and P_r.

These calculations are straightforward for simplex systems. For multiplex systems, they become more involved because the signal-to-noise ratio per channel alone is determined, also because often the bandwidth is determined not only by the desired improvement factor but also by the amount of cross talk that can be tolerated. In all cases, it seems theoretically advantageous to use effectively as wide a bandwidth as possible without reaching a value where selective fading and amplification difficulties cause trouble. From this point of view, time-division methods with amplitude keying are attractive. Indeed, in this case, the power to be considered for operating the limiters should be the peak power. For a given number of channels, the peak power can be made proportional to the bandwidth keeping the average power constant. In other words, for frequency modulation, the average power necessary increases with bandwidth for a given input-to-noise ratio, but in pulse-amplitude keying, the average power necessary increases much more slowly. As a first approximation, it is constant; when the probability of noise peaks overriding the limiter level is taken into account, the average power should increase as the logarithm of bandwidth.

It is not intended to reproduce the calculations leading to possible optimum values of the various factors N, but only to indicate practical limits. A typical example follows:

$N_0 =$ 15 decibels (average noise factor)
$N_1 =$ 45 decibels (telephony)
$N_2 =$ 10 decibels (10 repeaters)
$N_3 = -20$ decibels (improvement factor)

$N =$ 50 decibels and $B = 8 \cdot 10^6$ cycles
$P_r = 1.6 \cdot 10^{20} \times 8 \cdot 10^6 \times 10^5 = 13 \cdot 10^{-9}$ watt.

The necessary power to operate the receiver is of the order of several millimicrowatts. Knowing the power required at the receiver, the transmitted power will be determined by (1).

$A_0 = 60$ decibels (free-space attenuation)
$A_1\,A_2\,A_3 = 30$ decibels (allowance for fading)

$A = 90$ decibels
$P_t = 10^9 \times P_r = 13$ watts.

The transmitter power necessary to operate the link is of the order of several milliwatts if no allowance is made for fading and of the order of several watts with such an allowance.

The figures above are, of course, only representative and each case has to be calculated specially.

5. System Engineering

In the previous paragraphs, consideration has been given to the most important theoretical aspects of microwave relay links. Of practical importance are many other aspects, such as: type of tubes available, cost of towers, type of power supply available, cost of ground installations, roads, houses, and integration of the radio link into the existing telephone network.

Progress during the war in microwave tubes indicates that practically all types of tubes necessary for such links can be designed and some will soon be commercially available.

The magnetron has proved to be the most efficient microwave generator so far but it cannot be modulated easily. Probably, it will be possible to design frequency-modulated magnetrons and it is already possible to key magnetrons on and off as required for pulse-time modulation.

Velocity-modulated tubes of the reflex type are easily frequency modulated but have poor efficiency and, so far, are available at low-power levels only. The main tool lacking is a broad-band amplifier. Very promising results have been obtained during 1946 with models of traveling-wave amplifiers and of a broad-band velocity-modulated tube. As has been pointed out, many problems of radio relaying would disappear if it were possible to amplify at each relay without changing frequency.

The towers necessary for obtaining the desired antenna height represent a considerable part of the investment for radio relay links. The height and rigidity of the tower are probably the most important elements in determining the technical characteristics of the link.

It is quite obvious that from a maintenance point of view it is preferable to house all the equipment at ground level and install the antennas only at the top of the tower. But such a solution raises the difficult problem of transmission between the transmitters and receivers and the antennas. Transmission lines, either coaxial or wave guides, introduce additional losses and are susceptible to failure under unfavorable climatic conditions. One very attractive solution, possible only at the higher frequencies, is to install the antennas also at ground level and to use a mirror at the top of the tower.

An entirely different school of thought is that expensive towers are justified as a permanent investment. Even if the equipments should be modified or replaced by future developments, the towers could still be used.

Actual cost estimates for the 24-channel system outlined in the appendix, Section 7.2, show that a 100-foot steel tower designed to house all the equipment on top costs 20 percent more than the repeater equipment. This does not include any allowances for purchase of grounds or for eventual road construction.

For economic reasons, radio relay links in many cases should operate with unattended repeaters. It seems likely that the repeater equipment proper could be designed to operate without attention for several months but it is not yet clear how to design an independent power generator for such a long life. When a source of power is not available in the immediate vicinity of the relay station, it will be necessary to set up an independent power supply.

Power generators of 500 to 2000 watts, guaranteed for reliable continuous operation for several thousand hours, do not seem readily available. Radio relays, therefore, are often in the paradoxical position that, though they have eliminated physical connections between relay stations for carrying signals, it is necessary to resort to such connections for carrying power for operation of the equipment.

The integration of a radio relay link into an existing communications network is not essentially different from similar problems for carrier transmission links, but radio engineers often are not aware of the considerable amount of system planning required to set up or to expand the wire and cable networks.

Requirements for ringing, signaling, and dropping channels might react on the design of the radio link itself or at least on the terminals. Links designed to operate with frequency-division multiplex are generally connected to existing carrier terminals and the system planning is done by wire-transmission engineers.

Links designed to operate with time-division multiplex are generally connected to the switchboard itself and include the multiplexing terminals. A more intimate coordination between radio and telephone planning is, therefore, necessary. Time division here offers attractive possibilities such as direct-current signaling and quite simple methods for dropping channels.

6. *Conclusion*

An attempt has been made to give a general view of the various problems involved in the engineering of radio links with repeaters. As for most similar problems, there is no single answer and the final design is essentially a matter of compromises between conflicting requirements. Further experiments are required before the optimum compromises will be known.

Radio relay links definitely seem promising both on technical and economic grounds, but there is not enough operating experience available to indicate how reliable these new communication systems will be when compared to wire or cable links. The economic balance between radio and wire transmission will, indeed, depend essentially on the degree of reliability desired.

It seems unlikely that radio relay systems could be quite as reliable as buried cables but they might well in the near future be able to compete with open-wire links and they will, also, facilitate the introduction of new, broadband services.

7. *Appendixes*

7.1 PARIS-MONTMORENCY MICROWAVE LINK (EXPERIMENTAL EQUIPMENT)

A. General System Characteristics

Multiplexing: Frequency Selection, 12 Channels
Channel Modulation: Single-Sideband Amplitude Modulation
Carrier Modulation: Frequency Modulation with Negative Feedback
Number of Repeaters: None
Distance Between Terminals: 24 Kilometers (15 Miles)

B. Main Technical Characteristics

Frequencies: 3333 Megacycles One Way, 3000 Megacycles the Other Way
Transmitter Power: 30 Watts with Velocity-Modulated Output Amplifier Tube
Antenna Aperture: 0.5 Square Meter (Horn-Type Antenna)
Antenna Gain: 22 Decibels Referred to Half-Wave Dipole
Radiation Beam Width: 6 to 7 Degrees in Both Horizontal and Vertical Planes
Radiation Polarization: Horizontal at 3333 Megacycles, Vertical at 3000 Megacycles
Input Signal Bandwidth: 12 to 60 Kilocycles
Carrier-Frequency Deviation: ± 360 Kilocycles
Nonlinear Distortion at the Transmitter: -65 Decibels
Over-All Output Signal-to-Noise Ratio for Each Channel: 55 Decibels
Over-All Output Signal-to-Cross-Talk Ratio for Each Channel: 65 Decibels.

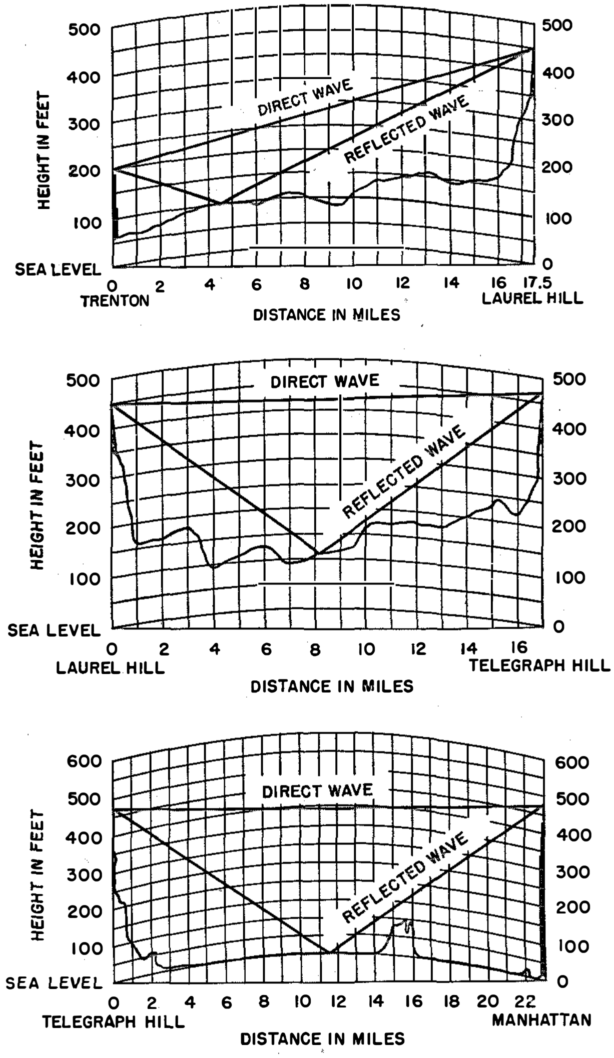

Fig. 3—Topographic paths of the three links in the circuit between the lower tip of Manhattan in New York City and Trenton, New Jersey.

7.2 New York-Trenton Microwave Link (Experimental Equipment)

A. General System Characteristics

Multiplexing: Time Division, 24 Channels
Channel Modulation: Time Modulation
Carrier Modulation: Amplitude Keying
Number of Repeaters: 2
Altitudes and Distances Between Stations: See Fig. 3
General Map of the Links: See Fig. 4

B. Main Technical Characteristics

Frequencies: 1375 to 1425 Megacycles
Transmitted Power: 2 Watts Average, 20 Watts Peak
Antennas: Paraboloid 10-Foot Diameter with Horizontal Dipole Radiator
Radiation Beam Width: 5 Degrees Vertically, 7 Degrees Horizontally
Receiver Bandwith: 8 Megacycles
Signal Bandwidth: 2.4 Megacycles at Video Frequencies
Signal-to-Noise Improvement Factor: 20 Decibels
Receiver Noise Factor: 15 Decibels
Over-All Frequency Response per Channel: Constant within ±2 Decibels from 200 to 3400 Cycles
Over-All Distortion in Each Channel: 2 Percent Harmonic Content for ±1-Microsecond Time Modulation
Over-All Signal-to-Noise Ratio in Each Channel: 45 Decibels ±1-Microsecond Time Modulation
Over-All Cross-Talk-to-Noise Ratio in Each Channel: 55 Decibels for ±1-Microsecond Time Modulation.

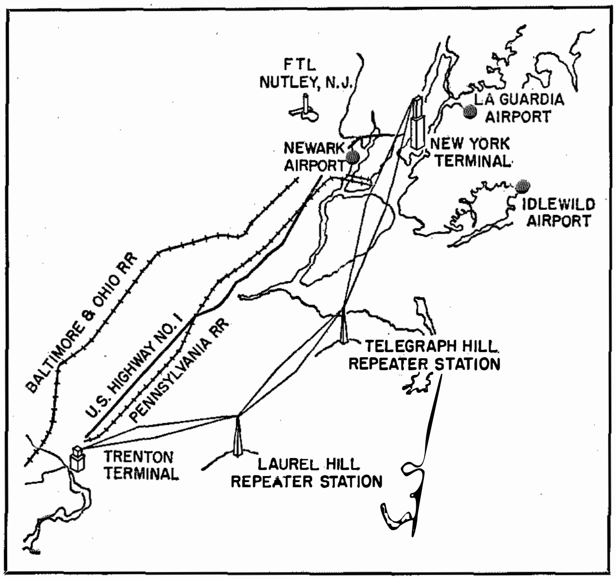

Fig. 4—Map showing locations of the four stations comprising the New York City-to-Trenton circuit.

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Pulse-Time-Modulated Multiplex Radio Relay System—Radio-Frequency Equipment

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TERMINAL EQUIPMENT for a radio relay system[1] has already been described. This paper covers the additional apparatus consisting of radio-frequency equipment, antenna and transmission-line systems, towers, power sources, and auxiliaries such as monitoring devices. Also included are test results on an experimental relay system incorporating the apparatus described.

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1. Radio Relay Considerations

1.1 Frequency of Operation

The choice of operating frequency is of primary consideration for radio relay links irrespective of transmission and modulation methods. From a theoretical viewpoint, any radio frequency consistent with bandwidth requirements may be utilized satisfactorily; from the practical point of view, the range of frequencies that can actually be utilized is limited.

Except for restricted applications in nonpopulated areas, the frequencies below 100 megacycles per second are unavailable because of the congestion of other services. For frequencies between 100 and 1000 megacycles, large transmitter powers must be used for a reasonable signal-to-noise ratio because of the limited size of practical antennas and the attendant small antenna gain. This limits the application to short links where considerable amounts of power are available, and makes impracticable the use of many repeaters over long distances where the provision of primary power sources is difficult.

Ignoring for the moment the intermediate microwave region, the application of frequencies above 7000 or 8000 megacycles to radio links is again limited. For these frequencies, reasonably sized antennas give large gains and make the transmitter power requirements small. Unfortunately, economical design limits the rigidity of a given tower used to meet the line-of-sight requirements. This in turn sets a lower limit to the beam angle utilized and, therefore, to the gain achievable. Unless automatic follow-up mechanisms are used with the antennas, practical beam widths are limited to approximately 1 or 2 degrees (3-decibel points) for reasonable tower rigidity. Otherwise, undue signal fluctuation may result from tower sway.

There are additional reasons for limiting the frequency to the values given. As frequency is increased, absorption and diffraction effects become more important. Power generation and reception difficulties, although of a temporary nature so far as future development is concerned, increase with frequency. Then, too, frequency stability, transmission lines, components, and other allied system items introduce difficulties.

This brief examination of the range of frequencies suitable for relay operation has been rather general but, if the items indicated are studied in detail, it will be found that the range from approximately 1000 to 7000 megacycles should offer the most likely prospects for such application, at least for the present time and with current techniques.

1.2 Repeater

A second problem of major magnitude for long radio relays is the lack of a true repeater-amplifier for the frequencies that can be used. For long relays and especially for multiplex operation, severe requirements are put on the linearity of the repeaters to prevent undue distortion and cross talk. The invention of negative feedback for low-frequency narrow-band

[1] D. D. Grieg and A. M. Levine, "Pulse-Time-Modulated Multiplex Radio Relay System—Terminal Equipment," *Electrical Communication*, v. 23, pp. 159–178; June, 1946.

amplifiers has solved the repeater problem for that service and for cable application. A similar solution has not been successfully applied to the higher frequencies and hence other means of amplification must be used.

Lacking a direct amplifier for wide-band high-frequency work, indirect amplification is utilized. Thus, the high frequency as received is transposed to an intermediate frequency. All amplification takes place at this intermediate frequency, and the amplified signal is used to remodulate a high-frequency carrier.

Unfortunately, the mechanics of this transposition inherently introduce distortion which rules out amplitude modulation for any reasonable number of repeaters. Even for the constant-carrier type of frequency modulation where amplitude nonlinearities are of minor importance, phase nonlinearities introduced by intermediate-frequency amplification must be carefully controlled.

1.3 Frequency Stability

An important item in a radio relay is the stability of the component transmitters and receivers included in the system. This stability is required not only for the conservation of frequency spectrum but is important because minimizing bandwidth also reduces the total noise entering the system. If a direct amplifier could be utilized, the over-all frequency stability of the system would be determined by the terminal transmitters and receivers. Suitable precautions, even though necessitating relatively complex equipment, could then be taken at these single points. Where indirect amplification involving change of frequency is utilized, the frequency spectrum required for the over-all link is increased by the summation of the percentage instability of the various receivers and transmitters comprising the link. Special precautions must, therefore, be taken to maintain frequency stability.

1.4 Transmission Lines

A problem of considerable importance particularly at the repeater points is the method of feeding the antennas. The radio-frequency equipment may, of course, be placed close to the antennas on top of the towers with only a short transmission line connecting the units. This, however, requires a tower structure of considerable strength and complexity, capable of safely supporting all this equipment. Alternatively, the radio-frequency equipment can be located at the base of the tower and the antenna connected through a transmission line equal in length to the tower height.

At the lower frequencies, a solid-dielectric transmission line can be used with some loss of power. With higher frequencies, however, the loss in the solid-dielectric line becomes prohibitive, and either a gas-filled line or wave guide must be used. With these two latter types, considerable difficulties are encountered in, among other things, maintaining airtight seals, providing for expansion, and preventing vapor condensation.

A partial solution to the problem is to divide the equipment so that the video-frequency apparatus is at the base of the tower and only the radio-frequency equipment required for transmission is installed at the tower top. The connection between the two units is then made by video-frequency cable.

This method is open to serious criticism from the maintenance point of view as it is necessary to mount the tower to service or adjust the radio-frequency equipment. A possible solution, which has been partially investigated, is the use of radio-frequency mirrors on the top of the tower with the radio equipment located at the base. A directive antenna concentrates the beam on the mirror which is arranged at the proper angle to obtain effective transmission. This method increases the transmission path by a negligible amount equal to the height of the tower, but effectively eliminates the transmission line.

1.5 Power for Repeaters

An additional problem is that of a primary power supply for unattended repeaters. If commercial electric power is available at the repeater site, no undue problems are encountered other than that of forestalling interruption of service. If, however, such a repeater is located remotely from available power sources, which in general would be the case where the system runs through undeveloped territory or takes advantage of isolated high points of ground, a serious problem is faced. Unlike cable operation where the power can be supplied over the same medium as used for connecting the repeaters, local power must be provided. This dictates the use of a local fuel dump if natural sources such as wind or water power are not available, together with the necessary electricity-generating equipment. If the repeater is relatively inaccessible, the power source must be capable of supplying power for considerable periods of time without attendance. This in turn necessitates efficient and reliable means for generating electric power and also indicates the desirability of minimizing power consumption.

1.6 Two-Way Operation

In most cases of relay operation, particularly for telephone service, the link must be capable of two-way performance. This type of operation can, of course, be achieved by installing repeater equipment for each direction of transmission at the common repeater sites. If continuous-wave transmission is used, an alternation of frequencies is necessary to prevent feedback between transmitter and receiver. This puts a severe requirement on the selectivity and image characteristics of the repeaters, particularly if the total frequency band is to be minimized.

It is theoretically possible to use only two frequencies by proper alternation in each direction. In practical installations, however, the topography may be such that repeater hopping or by-passing of the immediately following repeater may take place. This may be avoided by additional frequency transpositions. In addition, two-frequency operation calls for a high discrimination ratio between the directional antennas at the common repeater site and this also may be impossible because of local topography. If the attempt is made to combine the four antennas required for normal two-way operation into two antennas, one for each direction of transmitting and receiving, an extremely difficult design problem is raised unless a plurality of frequencies are used with highly selective repeaters.

1.7 Reliability and Maintenance

A most important item is the reliability and maintenance requirements at the repeater. For a long link containing many repeater elements, the performance of the poorest repeater determines the over-all operation of the entire link so far as reliability is concerned. When it is considered that a single repeater may contain as many as twenty vacuum tubes, a long link would have the equivalent of many hundreds or thousands of tubes in series. Failure of any one of these tubes may render the link inoperative unless suitable precautions are taken.

Reasoning similarly, it is evident that the over-all stability of the repeaters must be largely independent of weather conditions, primary-power fluctuations, tube aging, and similar factors. Where the repeater equipment is accessible, the degree of adjustment and servicing allowable may involve daily or weekly checking consistent with the economies of operating the relay link. If the repeater is located remotely, the requirements of maintenance are much more severe and it may be necessary that the equipment operate for several months completely unattended in all respects.

To meet the severe requirements of reliability, it is necessary to operate most of the equipment at low rating and to provide duplicate apparatus with automatic switch-over mechanisms. A remote telemetering arrangement should be provided to indicate at the terminals of the link the operating condition of the various equipments.

1.8 Applicability of Time-Division Multiplex

The use of time-division multiplex together with pulse modulation, such as pulse-time modulation,[2] solves many of the radio-frequency transmission problems previously mentioned.

An inherent characteristic of this system of modulation is that only one increment of the signal is transmitted at any one instant of time and that incremental signal is characterized by the relative timing of the transmitted pulse. This on-off type of operation, unlike straight

[2] E. M. Deloraine and E. Labin, "Pulse Time Modulation," *Electrical Communication*, v. 22, n. 2, pp. 91–98; 1944.

amplitude or frequency modulation, may utilize a considerable number of methods of radio-frequency generation and hence the type of modulation need not be considered in the choice of operating frequency.

A most important aspect is that no matter what distortion is produced in the amplifying means, only a minimum of cross talk or distortion of the modulating signal can take place if a sufficient bandwidth is provided to prevent carry-over from one pulse to another. Hence the repeater problem is considerably simplified and reduced to the design of a repeater amplifier of the proper noise characteristics, gain, bandwidth, and efficiency.

Additional characteristics of pulse transmission include the possibility of transmission and reception on a common radio frequency similar to radar operation with a consequent reduction in bandwidth as well as a simplification in equipment requirements. Indirectly, a gain in over-all frequency stability may be achieved also as fewer frequency changes are necessary. A further characteristic of importance is the ease of drop-channel operation at branching repeaters which allows any number of channels to be dropped and new channels to be inserted without necessitating the handling of large groups of channels. Additional advantages include signal-noise improvement possibilities of the subcarrier modulation which can be further enhanced by the signal-noise improvement achieved by the over-all radio-frequency transmission method. Further, constant-level transmission allows the output signal level to be substantially independent of propagation vagaries.

2. *Radio-Frequency Equipment*

2.1 General

The design of a radio link with a specific set of operating characteristics requires a knowledge of several transmission factors. These factors include over-all signal-to-noise ratio, repeater gain and power, number of repeaters, antenna size and beam angle, propagation variations such as fading, and height of supporting structures necessary to yield the requisite propagation characteristics.

The largest proportion of noise in the link originates at the receiver input. For each receiver, the theoretical thermal agitation noise[3,4,5] (Johnson noise) at the antenna must be multiplied by the noise factor of the receiver. This factor takes into account the increase in the receiver noise resulting from such component parts as the mixer, local oscillator, and first intermediate-frequency stage. Assuming linear addition of noise power, the over-all link noise is the total receiver noise multiplied by the number of link hops.

The signal power received at the terminals of the link is determined by the output signal-to-noise ratio desired. For an amplitude-modulated system, the required received power is simply the total link noise multiplied by the desired signal-to-noise ratio. For systems where the signal-to-noise improvement over amplitude modulation is obtained by a specific type of transmission, this latter power is divided by the improvement factor. For the time-modulated relay to be described, the improvement factor is of the order of 16 decibels and thus the required power is reduced by this amount. Knowing the transmission attenuation factor, which is determined by the spacing between repeaters and the antenna gain, the repeater gain and power can be computed.

The repeater spacing, which is an important consideration, is determined by economic factors as well as technical requirements. The greater the number of repeaters, the less gain required of each repeater and the lower the antenna height may be. However, an increase in the number of repeaters increases the amount of apparatus required and the cost. A study of the various

[3] D. O. North, "Absolute Sensitivity of Radio Receivers," *R.C.A. Review*, v. 6, January, 1942.

[4] E. W. Herold and L. Malter, "Some Aspects of Radio Reception at Ultra-High Frequencies," *Proceedings of the I.R.E.*

Part I—"The Antenna and the Receiver Input Circuits," v. 31, pp. 423–438; August, 1943.

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Part III—"The Signal-to-Noise Ratio of Radio Receivers," v. 31, pp. 501–509; September, 1943.

Part IV—"General Superheterodyne Considerations at Ultra-High Frequencies," v. 31, pp. 567–574; October, 1943.

[5] H. T. Friis, "Noise Figures of Radio Receivers," *Proceedings of the I.R.E.*, v. 32, pp. 419–422; July, 1944.

factors involved has indicated[6] that a proper balance is reached for spacings of the order of 20 to 30 miles unless special topographical conditions prevail.

As directional transmission is desired, the type of antenna utilized concentrates the transmitted energy in a narrow beam, and hence the required repeater power is reduced by the factor of antenna gain at both the receiving and transmitting points. As has been indicated previously, the beam angle is limited by mechanical considerations of tower rigidity for the higher frequencies. For the particular frequencies used in the present relay, the limit of beam angle is not reached, but a mechanical limitation is imposed by the size of reflector dish that can be accommodated on top of the tower.

The prevalence of fades and other propagation anomalies must be provided for in the determination of the transmitter power. These variations, in general, will affect only the final signal-to-noise ratio in the link for pulse-time modulation rather than the level of the signal transmitted. Where a large number of repeaters are used, extending over a large geographical area, it can be assumed that the fading conditions do not affect all repeaters simultaneously and hence the fading factor need not correspond to the sum of the individual factors.

[6] C. W. Hansell, "Radio-Relay-Systems Development by Radio Corporation of America," *Proceedings of the I.R.E.*, v. 33, pp. 156–168; March, 1945.

Where the higher frequencies are used, the height of the antenna is determined not only by the condition of line of sight, but must include an additional height so that the summation of the free-space wave and the main reflected wave yields a wave at least equal in magnitude to that of free-space propagation. Normally, advantage is taken of topography to provide line-of-sight conditions and the tower need only be tall enough to clear local obstructions such as trees.

The radio-frequency equipment has been designed to operate in an experimental pulse-time-modulated multiplex radio link having the overall characteristics specified in reference 1. As this equipment was designed for experimental purposes only, it was not necessary to include all of the factors that would be obligatory in a commercial installation. However, provisions were made for testing facilities to duplicate conditions representative of commercial operation. This link equipment comprises terminal radio-frequency apparatus as well as a repeater. The terminal equipment transposes the outgoing time-modulated pulse series to radio frequencies, and in addition translates the incoming radio-frequency pulses back to pulse frequencies for application to the multiplex terminal. The repeaters, of course, compensate for the attenuation along the radio path.

Fig. 1 illustrates the disposition of this equipment in a radio relay system. The link incorporates a transmitter and receiver at each radio-

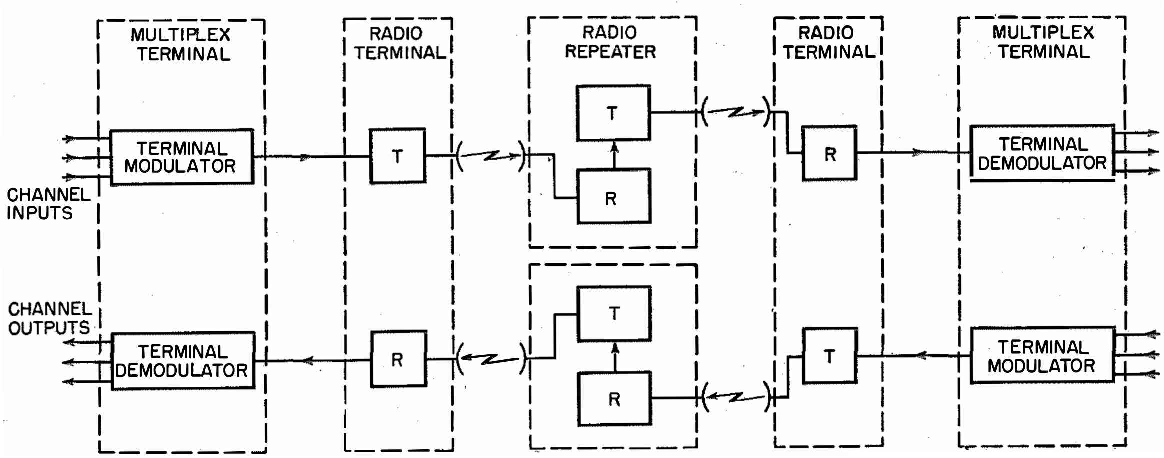


Fig. 1—Disposition of equipment in a radio relay system. *R* = receiver and *T* = transmitter. Only one repeater is shown; additional repeaters may be included.

frequency terminal and two receivers and transmitters, one for each direction, at the repeater stations. Except for minor differences in impedance termination at the receiver output and transmitter modulator input, the electrical and physical requirements for the radio-frequency terminals and repeaters are the same, and essentially identical equipment can be used for both applications. The description can therefore be limited to a receiver and transmitter which can be combined in the required manner to serve as either terminal or repeater equipment.

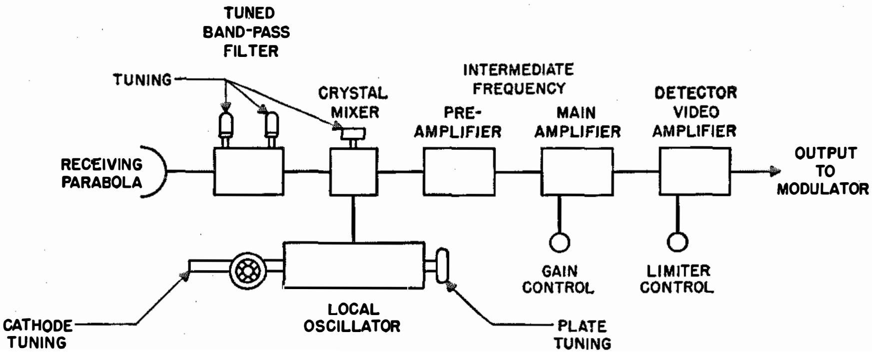


Fig. 2—The receiver consists of the components indicated in this block diagram.

2.2 Receiver

Fig. 2 shows the over-all receiver arrangement while Fig. 3 details the input end of the receiving circuit. The band-pass filter utilized to reduce interchannel interference consists of two micrometer-tuned coaxial cavities over-coupled to produce an 8-megacycle bandwidth having an attenuation of 50 decibels at the image frequency, 60 megacycles from resonance. The crystal mixer is a single tuned cavity connected to the output of the filter. The filter output, local oscillator, and crystal detector are coupled to the cavity by current loops along the cavity wall. The loops are adjusted for proper coupling and loading to produce the required bandwidth. An additional 22-decibel image-frequency attenuation is achieved by the tuned mixer, giving an over-all receiver image-rejection ratio of 72 decibels. Fig. 3 shows the crystal detector coupled to the first intermediate-frequency stage through a series tuned circuit made up of a tuned inductance and the grid-circuit capacitance to ground. This first stage is followed by two double-tuned stages. Each tuned circuit is shunted by resistance to provide the proper bandwidth. The resultant pass band, flat-topped and steep-skirted, is 8 megacycles wide at the 3-decibel points. The output stage is a triode cathode-follower which is connected by a 70-ohm cable to the intermediate-video-frequency chassis. The local oscillator is similar to the transmitter oscillator and will be described under that heading. Table I contains the technical details and specifications for the receiver. Front-panel metering jacks are provided for measuring

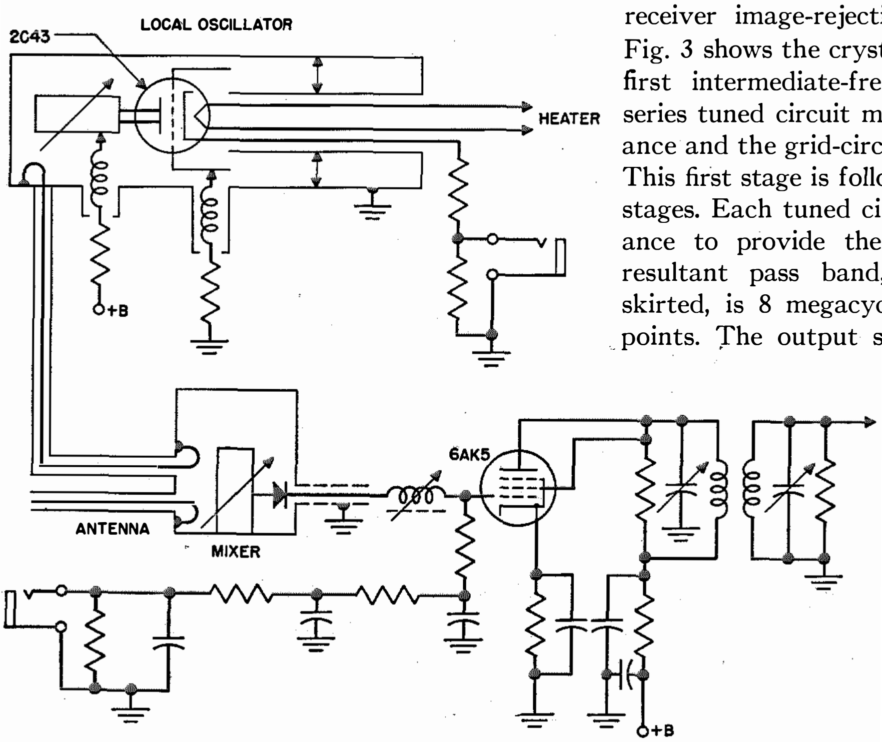


Fig. 3—Input end of the receiver showing local oscillator, input tuning, mixer, and first stage of intermediate-frequency preamplifier.

TABLE I

Characteristics of Transmitter and Receiver

Radio-Frequency Terminal-Repeater	
Repeater (1 way)	
Transmitter	1
Receiver	1
Radio-Frequency Terminal	
Transmitter	1
Receiver	1
Transmitter-Receiver	
Size in inches	72×19×17
Weight in pounds	280
Power consumption in watts	280
Transmitter	
Oscillator	
Tuning range in megacycles	1225 to 1325
Power output in watts, average	2.0
Bandwidth of pulse envelope in megacycles	5.6
Frequency stability in megacycles from −20 to +40 degrees centigrade	±0.5
Duty cycle	1:13
Oscillator tube	2C43
Oscillator circuit	Reflex coaxial cavity
Output impedance in ohms	50
Modulation	Grid pulsed
Pulse-time-modulation noise	Negligible
Cross talk	Negligible
Efficiency in percent	12 to 15
Modulator	
Circuit	Wide-band amplifier
Bandwidth in kilocycles	0.5 to 2800
Pulses per second	200,000
Pulse shape	Trapezoidal
Pulse width in microseconds	0.5
Pulse build-up time in microseconds	0.15
Pulse decay time in microseconds	0.15
Input impedance in ohms, adjustable	70 to 1000
Input level in peak positive volts	5
Output impedance in ohms	70
Output level in volts	60
Noise contributed to channel pulses	Negligible
Cross talk contributed to channel pulses	Negligible
Tubes	
Clipper (1)	6AC7
Driver (1)	6AG7
Cathode follower (2)	807
Receiver	
Input Section	
Frequency range in megacycles	1225 to 1325
Bandwidth in megacycles at 3-decibel points	8
Noise factor in decibels, approximate	14
Image rejection with input filter in decibels	72
Gain in decibels	20
Input impedance in ohms	50
Output impedance in ohms	70
Tubes	
Crystal mixer (1)	1N23B
1st radio-frequency amplifier (1)	6AK5
2nd radio-frequency amplifier (1)	6AG5
Output cathode-follower (1)	6J4
Local oscillator (1)	2C43
Intermediate- and Video-Frequency Amplifiers and Detector	
Input impedance in ohms	70
Bandwidth in megacycles at 1-decibel points	8

TABLE I—(*Continued*)

Noise factor in decibels	Less than 2
Gain in decibels	60 to 80
Minimum signal level in microvolts	200
Output volts, positive	5
Output impedance in ohms	70
Noise contributed to input signal	Negligible
Cross talk contributed to channel pulses	Negligible
Tubes	
Intermediate-frequency amplifier (4)	6AG5
Video-frequency detector (1)	6AG5
Video-frequency amplifier (1)	6AG5
Cathode-follower output (2)	6J4

the crystal-mixer current and oscillator grid and cathode currents.

The intermediate-frequency amplifier contains four amplifying stages, detector, pulse-frequency amplifier, and cathode-follower output stage. A study of the comparative gains of different interstage coupling networks for a wide-band intermediate-frequency amplifier resulted in the choice of triple-tuned circuits. Using 6AG5 tubes, a gain of 20 decibels per stage is realized for a bandwidth of 8 megacycles between 1-decibel peaks. Fig. 4 shows the over-all selectivity curve of the receiver including the selectivity of the intermediate-frequency amplifier and preamplifier.

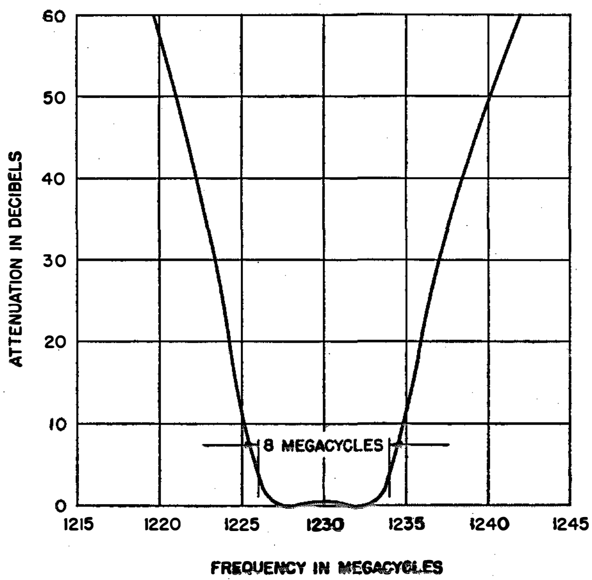


Fig. 4—Over-all selectivity curve of the receiver. A bandwidth of 8 megacycles is obtained at points corresponding to an attenuation of less than 3 decibels. This characteristic results from the combined selectivities of the preamplifier and the main intermediate-frequency amplifier, each of which has an 8-megacycle bandwidth at approximately 1-decibel attenuation points.

The detector and pulse amplifier are operated as limiters to remove noise from the top and bottom of the pulses and to make the output voltage essentially independent of variations in the received signal.

Two controls are provided in the intermediate-frequency unit, a gain control in the first stage and a bias control in the detector. In operation, these controls are set for optimum signal-to-noise ratio over a normal range of received signal-strength variations.

2.3 Transmitter

Fig. 5 illustrates the transmitter, consisting of a modulator and radio-frequency oscillator. The transmitter utilized in the repeater differs from the terminal transmitter in that a delay line is interposed between the modulator and radio-frequency oscillator to transmit the pulse at a later time than it is received. This, of course, reduces the possibility of "ringing" between the transmitter and receiver and permits their frequencies to be closer together.

The modulator accommodates the proper frequency band as determined by the allowable carry-over between pulses. With the present design, all circuits are capable of amplifying up to 3.5 megacycles although the frequency spectrum of the transmitted pulses is of the order of 2.8 megacycles. The low-frequency design was considerably simplified by the absence of appreciable components below the pulse base repetition rate. The low-frequency cutoff is of the order of 500 cycles. The various amplifier stages clip both the top and bottom of the pulse, and the output pulse voltage is thus independent of variations of input level to the modulator.

Figs. 6 and 7 illustrate the oscillator design. This unit comprises a tuned coaxial grid-pulsed oscillator with a "grid-bell" type of re-entrant cavity utilizing the 2C43 lighthouse tube. The cathode line is tuned to either ¼ or ¾ wavelength by a piston. The plate is an open-ended ½-wavelength line adjusted by a screw-feed arrangement. The cathode resistor and its bypass capacitor provide a cut-off bias between

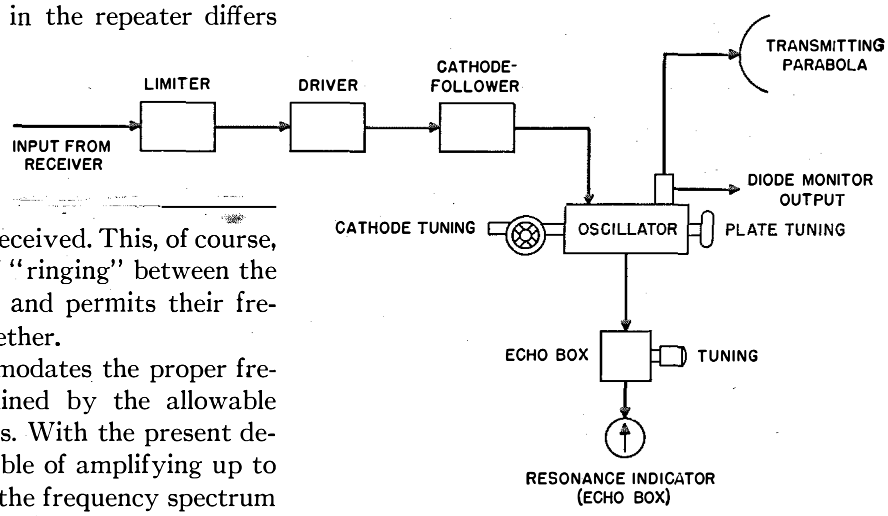


Fig. 5—Block diagram of transmitter. The modulation is applied to the oscillator through the cathode-follower. The tunable cavity resonator (echo box) and resonance indicator are used to monitor the output radio frequency.

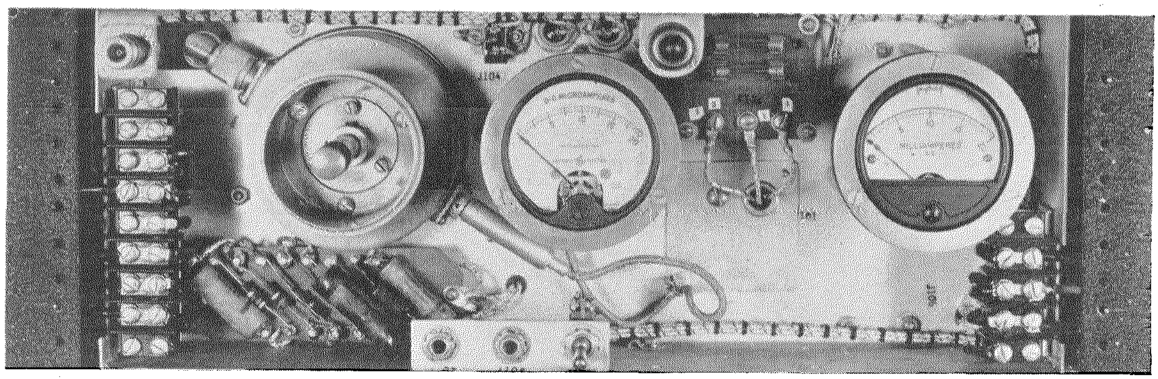


Fig. 6—Front view of transmitter. The echo box and its resonance-indicating meter are on the left end of the unit.

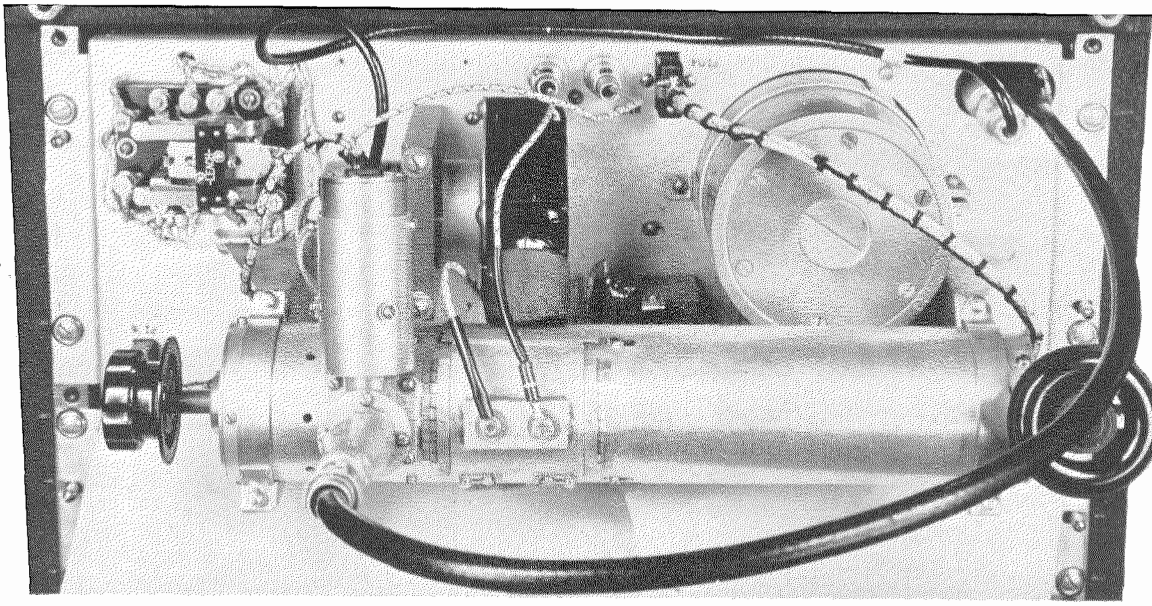


Fig. 7—Rear view of transmitter. The tuned coaxial oscillating circuit is at the bottom. The screw-feed adjustment at the left is for plate-circuit tuning. The cathode tuning control is at the right.

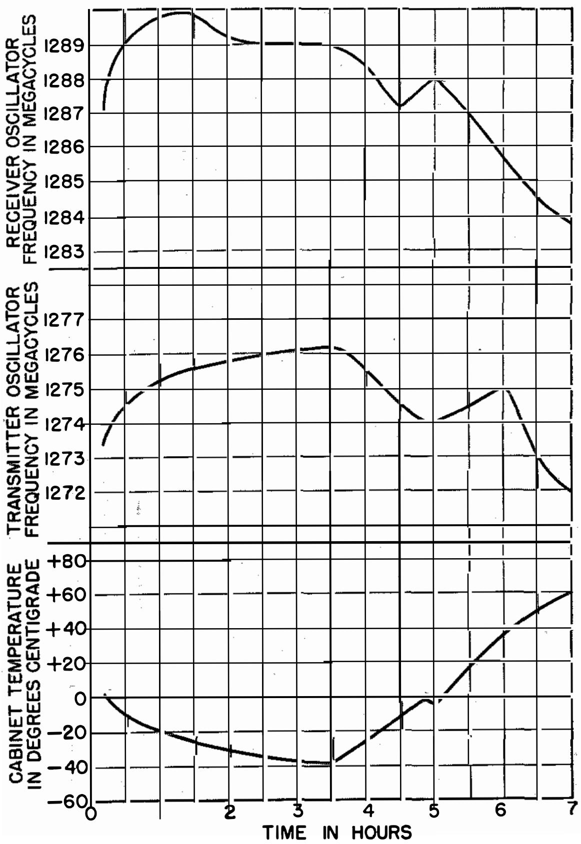


Fig. 8—Frequency variation of transmitting and receiving oscillators during 7 hours in which the temperature was changed from 0 to −38 to +60 degrees centigrade.

pulses. In addition, a grid resistor supplies the dynamic bias during oscillation.

A tunable echo box is loosely coupled to the oscillator cavity, and a crystal detector, also coupled to this cavity, indicates resonance. A linear diode monitor is coupled to the output line to provide an indication of the transmitted radio-frequency envelope. Temperature compensation of the oscillator is achieved by mechanical design, proper ventilation, and the avoidance of mechanical discontinuities in the resonant cavities. Fig. 8 shows the frequency drift of a unit for a temperature excursion from −38 to +60 degrees centigrade. The transmitter spectrum measured during pulse modulation is indicated in Fig. 9.

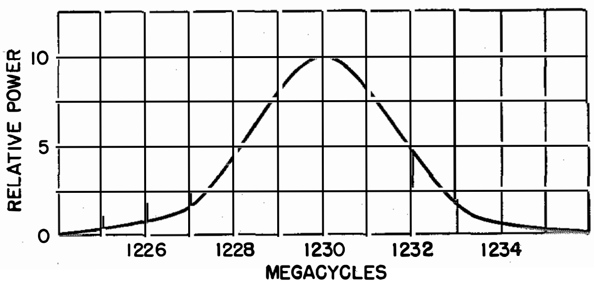
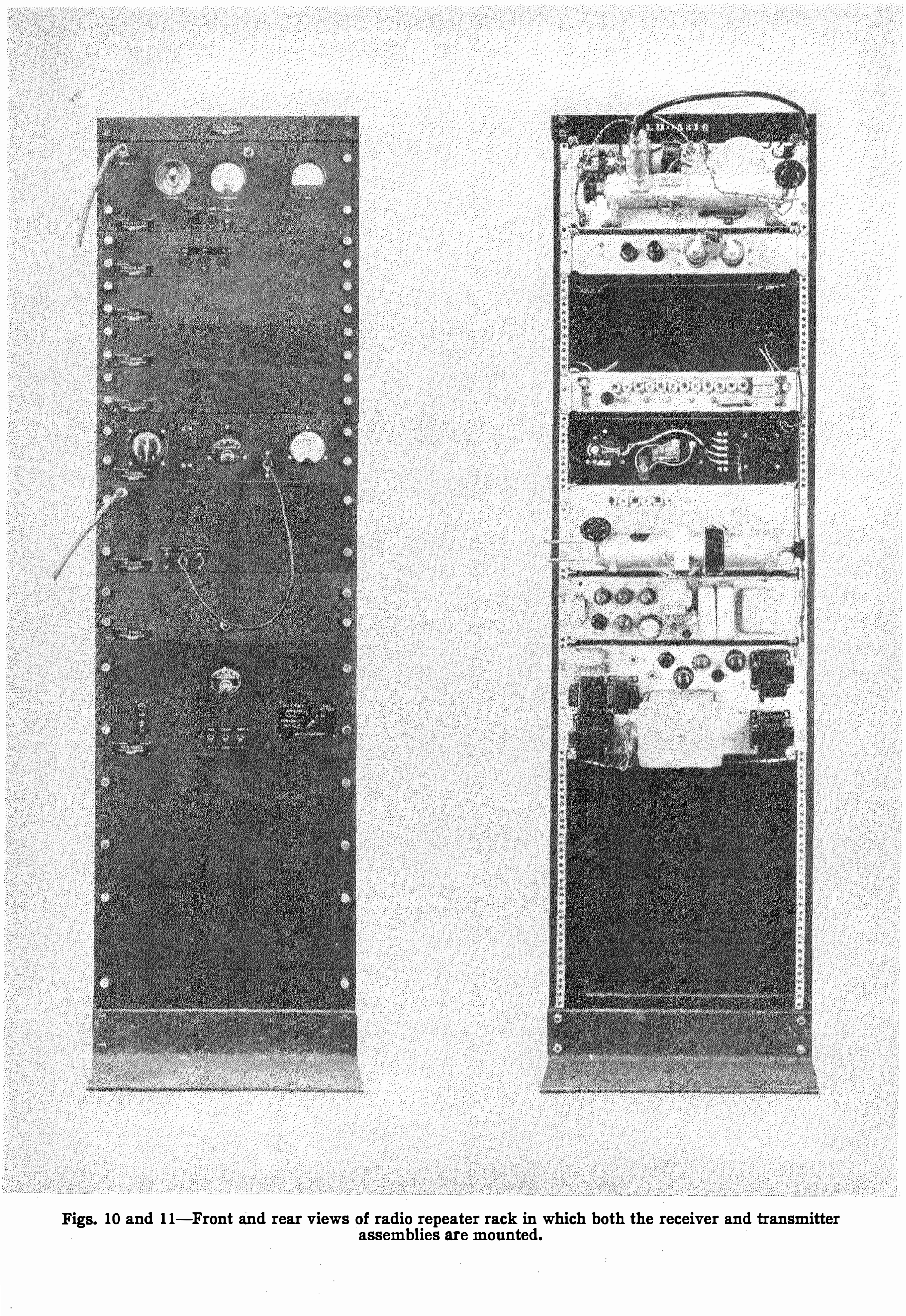


Fig. 9—Frequency spectrum of transmitter during pulse modulation.



Figs. 10 and 11—Front and rear views of radio repeater rack in which both the receiver and transmitter assemblies are mounted.

Table I indicates a few of the technical characteristics of the circuit. The identical type of oscillator, but without the echo box and monitor assembly, is used as the local oscillator in the receiver. Figs. 10 and 11 illustrate both the transmitter and receiver assemblies including power supplies and monitoring facilities mounted in a standard relay rack for repeater and terminal installation.

3. *Relay Plant*

3.1 General

Associated with the repeater elements of the relay are the important allied apparatus and structures which compose the "plant" of such a system. These items include:

A. Primary power source.
B. Antenna for radiating the radio-frequency energy and its associated transmission lines.
C. Towers for supporting the antenna at the required height.
D. Housing to protect repeater and other equipments from climatic conditions.
E. Miscellaneous mechanical and electrical items such as switch-over equipment, repeater monitors, etc.

The items enumerated, of course, are not necessarily limited to a single system of relay transmission such as pulse-time multiplex, but apply equally to all other types.

3.2 Power Supplies

A most important function of the auxiliary equipment at either a terminal or a repeater station is that of furnishing power to the radio-frequency units. This is further complicated by the varying conditions of operation.

The radio-frequency terminal station would normally be at a location where commercial electric power is available. In such a case, the principle problem is to forestall interruption of service resulting from failure of the commercial source. Several schemes may be used and choice depends on the degree of protection required. Where an interruption of a few minutes can be tolerated, an automatic engine-generator, electrically started on failure of the line power, may be used. Such a machine could carry the load only after a warm-up period of approximately one minute and would then be able to maintain service for an indefinite period, determined by the quantity of fuel available and the operating condition of the equipment.

If no interruption can be tolerated, it would be desirable to operate from a storage battery with a line-operated charger maintaining full charge. For further reliability this would be backed up by a gas-engine-generator automatically operated if the line power fails.

If there is primary electric power available at the repeater station, similar considerations apply. However, the power-supply problem is likely to be more severe at such a station for the site will probably be remote from normal sources of power. A significant characteristic of a repeater site is its elevation above the surroundings and this makes wind power entirely feasible. Fig. 12 indicates the practicability of wind-power sources in the United States. At a wind-powered station, the equipment can operate from a storage battery

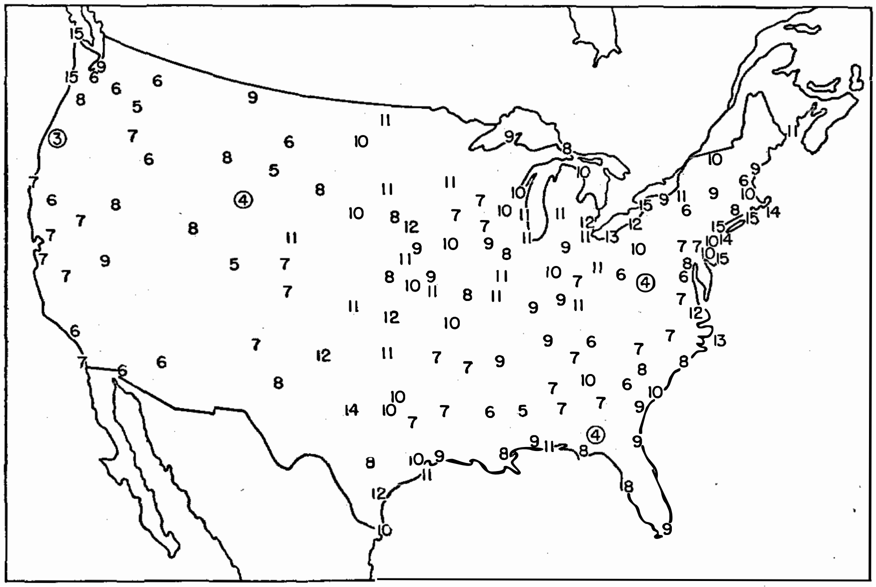


Fig. 12—Yearly average wind velocity in miles per hour for the United States of America. It is evident that adequate wind velocities are available, particularly on the high ground that would be chosen as relay sites, to make this an attractive source of power. The few circled values are considered to be inadequate.

of rather large capacity which is maintained charged by a wind-driven generator under both current and voltage regulation. To carry over periods of calm, an automatic gas-engine-generator is arranged to operate at any time the battery drops in charge.

To obtain complete reliability, a duplicate power source at each repeater station can be considered; for example, an independent power plant for each direction of operation. In the event of failure of one plant, the whole station load may be carried by the remaining unit. An experimental installation similar to that described has been set up and is illustrated in Fig. 13.

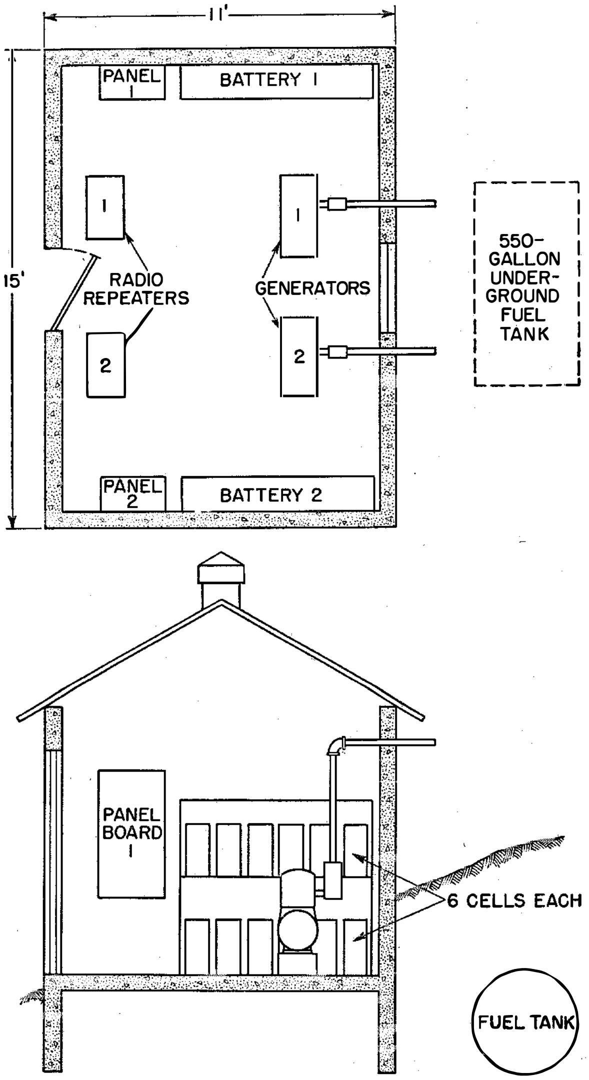


Fig. 13—Power plant for unattended repeater station.

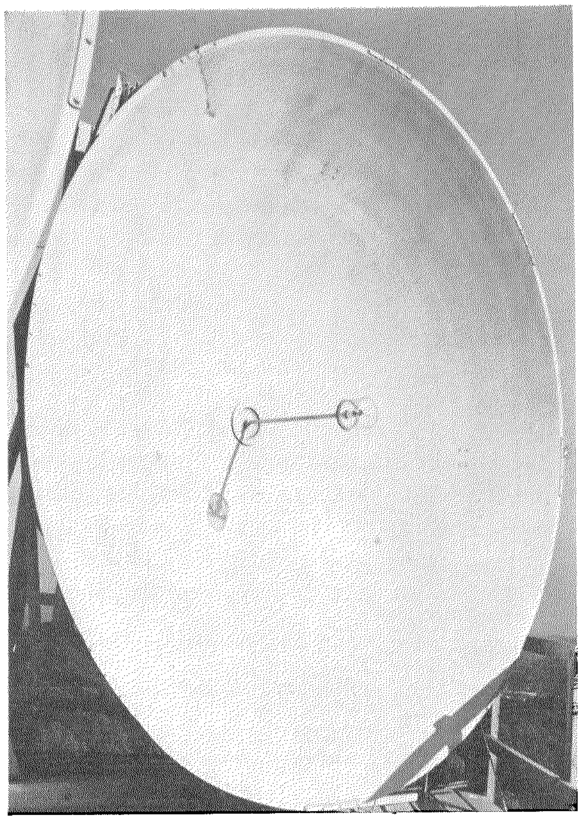


Fig. 14—Typical dipole and parabolic reflector for use in the 1000- to 3000-megacycle region. The enclosure around the dipole protects it from rain, snow, and sleet.

The equipment includes an automatic clock control which operates the engine at regular intervals daily to maintain the engine in running condition. Such an installation is capable of unattended operation over a period of many weeks, or even months, as it is necessary to service the batteries at intervals of only three to four months. The engine generally requires attention only after 200 or more hours of actual running time. Of course, criticism can be directed at the relative complexity of the installation. Unfortunately, reliable operation can be expected only through the use of several power sources, each backing up the other. Attempts are being made to simplify the problem by utilizing a heat engine or turbine. Also, the use of an atomic energy source is not ruled out for future application.

3.3 Antennas

To obtain satisfactory range with reasonable power, a directional antenna is used. For fre-

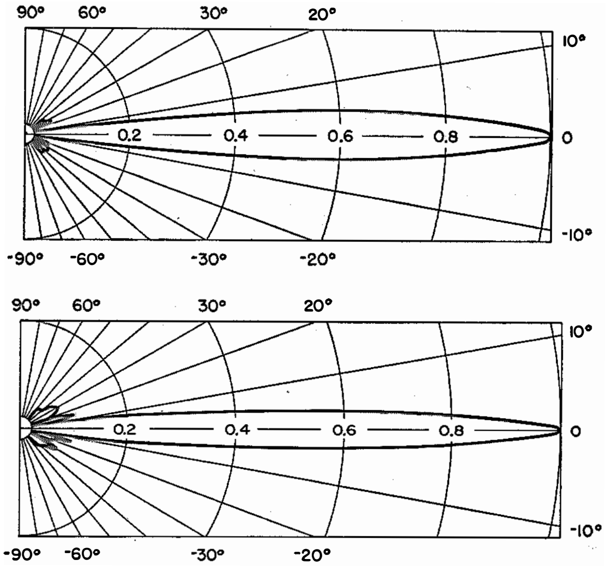


Fig. 15—Horizontal and vertical directivities of a 1400-megacycle (21.4-centimeter) dipole in a 10-foot parabolic reflector. Relative voltage output is plotted against angle of radiation. At the top, the directivity is measured with the dipole horizontal, while below it is vertical. Half power (3 decibels down) is equivalent to 0.7 relative voltage.

quencies between 1000 and 3000 megacycles, this generally consists of an enclosed dipole radiator with a parabolic reflector. At the higher frequencies, a similar reflector is used with a wave guide. Of course, other types of antennas and reflector systems may be used.

The reflector may be of perforated sheet or expanded metal. The expanded metal allows somewhat less wind loading under nonicing conditions and slightly less weight. A typical antenna is illustrated in Figs. 14 and 15. This antenna has been designed for an operating frequency of 1200 to 1400 megacycles with a gain of approximately 29 decibels over a half-wave dipole. For a two-way repeater station, four antennas are generally required unless special systems are used to combine the receiving and transmitting functions. In an actual installation, each antenna mount is generally adjustable over a considerable angular range, both horizontally and vertically, to allow accurate positioning.

3.4 Towers

For a working range of 30 miles between stations, a compromise tower height which can be utilized for most applications is of the order of 100 feet. This assumes that reasonable advantage is taken of topographical conditions. Under special conditions, this height may vary considerably. At sites having adequate elevation, the main requirement is that sufficient clearance be maintained with respect to immediate local obstructions such as trees and buildings.

The tower must be strong enough to withstand any possible combination of wind and ice loading which might occur in the area. If this condition is met, the structure will usually be sufficiently rigid to maintain antenna position with necessary constancy as well as providing support for additional equipment such as wind generators.

Relay towers may be constructed of steel, wood, or concrete. The steel structure is suitable for use most anywhere and is immune to severe fire, such as may occur in a forested area. The design and manufacture of a tower of this material can be controlled rather closely giving a product of known strength. Also, it is readily adaptable to quantity production, and maintenance requires little more than periodic painting and inspection. The chief disadvantage is the cost of transportation from factory to site.

Fig. 16—100-foot wooden tower at Telegraph Hill, New Jersey.

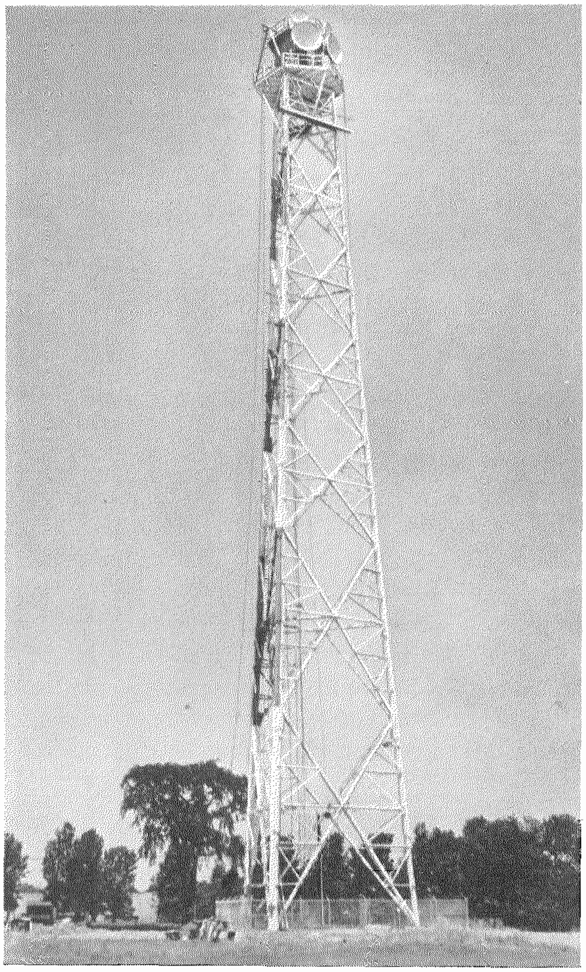


Fig. 17—200-foot wooden tower at Nutley, New Jersey.

Wood has some advantage in locations where it is a natural product. However, use of local material introduces an unknown factor of quality. Wood, of course, is also highly susceptible to damage by fire and lightning. It must be protected from insect and fungus attack, but does not require as frequent painting as steel.

It is also feasible to build a tower of concrete using local materials. This presupposes complete construction on the site, and hence limits the degree of quality control obtainable. Nevertheless, by proper safety factors, an entirely dependable structure can be built which is immune to fire, insect, and fungus. Figs. 16, 17, and 18 show representative towers that have been utilized in radio relays.

3.5 Transmission Lines

As mentioned previously, the method of supplying radio-frequency energy to the antenna depends to a large extent not only on the carrier frequency, but also on the location of the repeater apparatus with respect to the antenna. To simplify servicing, it is preferable that the complete repeater equipment be located at the base of the tower with the antenna at the top and some suitable connecting means such as a transmission line between them. In the experimental relay link described, the radio-frequency equipment was located at the top of the tower and a transmission line about 25 feet long was used. This short length, of course, greatly simplified the transmission-line problem and allowed the use of solid-dielectric coaxial cable.

For remote location of the radio-frequency equipment, rigid gas-filled lines are needed. An electrically operated compressor and dehydrator would be required to maintain proper pressure and keep the line dry. A more satisfactory solution is the use of a mirror arrangement on top of the tower with the antenna and radio-fre-

Fig. 18—100-foot steel tower at Laurel Hill, New Jersey.

quency equipment located at the base. Such an arrangement, however, is limited to the higher frequencies where a narrow beam can be projected with a reasonably sized antenna and mirror.

3.6 Miscellaneous Items

Items which comprise part of the relay plant but need be mentioned only briefly are the various housings to shelter and protect the radio-frequency equipments, antennas, and power units. In addition, there are the various control items such as relay units for switch-over of both radio-frequency and power-supply equipments and which also incorporate the necessary signaling apparatus to indicate at a remote monitoring location the condition of the equipment in the link. The characteristics of these items, of course, depend on the specific type of link as well as on the various operating features required.

4. Over-All Link Operation

4.1 General

To verify the performance of a radio link utilizing time-division multiplex with pulse-time modulation, experimental links incorporating the types of equipment previously described have been installed. Two such links have been set up; one having two repeaters with the terminals at a common location, arranged in a triangle, and a second representative of operation between two remote terminal points. As the closed-loop triangular link permits a simplified testing procedure, the majority of the measurements referred to have been performed on this link.

As indicated in Fig. 19, the terminals of the triangular link are at Broad Street, New York City, with one repeater at Telegraph Hill, New Jersey, and the second at Nutley, New Jersey. This arrangement includes an overwater link of 23 miles from New York to Telegraph Hill, an overland 30-mile path from Telegraph Hill to Nutley through a heavy industrialized area, and a comparatively short path of 10.6 miles to the southern tip of Manhattan island where the radio waves pass through gaps among the taller skyscrapers. The figure also shows the profiles of each path and the tower heights.

The repeater installations utilize the wooden towers illustrated in Figs. 16 and 17. Two 8-foot-diameter parabolas at each tower are connected by coaxial cable to the repeater equipment in adjacent shacks. Each station was operated from the local power main. The parabolas used at the Broad Street terminal were similar to those at the repeater points and the respective terminal radio-frequency transmitting and receiving equipment was located adjacently and connected by short runs of solid-dielectric coaxial cable. Telephone and pulse-time-modulated multiplex facilities were arranged at the common Broad Street terminal to provide two-way operation by assigning

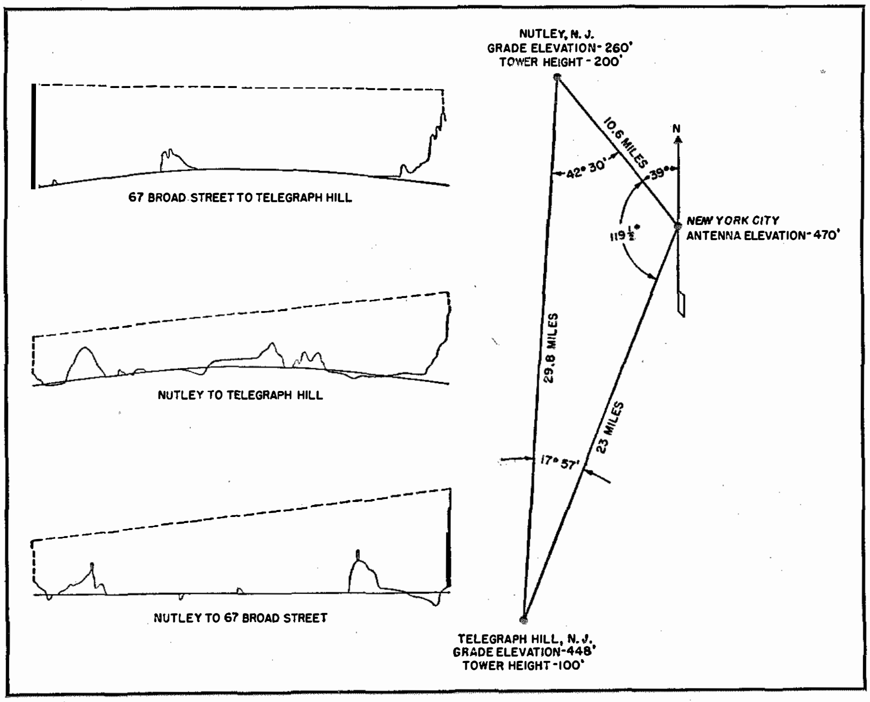


Fig. 19—Triangular relay system on which much experimental data were obtained. The terminal is at the southerly tip of Manhattan Island in New York City. Two repeaters are located at Nutley and Telegraph Hill, both in New Jersey. Overland and overwater links are thus included.

one half of the available channels for each of the calling and answering paths. In this manner, radio-frequency transmission was maintained in one direction while at the same time allowing simulation of two-way telephone operation. Two radio frequencies were employed; 1225 megacycles at the Broad Street transmitter, 1280 megacycles at the Telegraph Hill transmitter, and 1225 megacycles at the Nutley transmitter. They provided more than adequate frequency separation for the transmitter and receiver at each location.

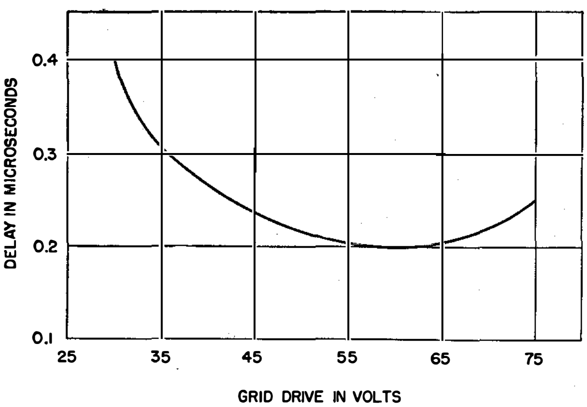


Fig. 20—Variation in starting time of the pulses as a function of the grid driving voltage on the oscillator. The pulse width was maintained constant.

4.2 Siting

Although the three antennas were nominally within line of sight of each other, conditions were such that alignment could not be achieved visually. By sighting prominent New York City skyscrapers from the Broad Street and Nutley locations, the true azimuth angles were determined and permitted approximate aiming of the antennas. Final readjustment was made after radio contact was established.

4.3 Signal to Noise

For the average power of 2.0 watts supplied by the radio-frequency equipment and for the signal-to-noise improvement ratio of 16 decibels provided by the pulse-time modulation method, the theoretical signal-to-noise ratio for the link was of the order of 53 decibels. Initial measurements indicated results to be short of the calculated value. It was found that inaccuracy in starting the transmitter oscillators reduced the signal-to-noise ratio unduly. The resistance noise in the oscillator was responsible for the variation in starting time. Several methods were found to minimize this noise.

One method utilized the trailing edge of the received pulse to start the transmitter as the noise on this edge is less than that on the leading edge. A second method involved the injection of radio-frequency power into the oscillator during pulses to provide a "catalyzation" effect or, alternatively, a similar effect was obtained by maintaining a small constant plate voltage between pulses. Fig. 20 illustrates the variation in starting time as a function of the oscillator operating conditions. The simplest method, and the one utilized in the link equipment, involved increasing the oscillator excitation by adjustment of the grid and cathode coupling. Under this condition, the transmitter noise was reduced to more than 65 decibels below the signal and thereby introducing a negligible amount of noise into the link. With this reduction in transmitter noise, it was found possible to approach closely the theoretical signal-to-noise ratio for average propagation conditions.

4.4 Multipath Reflection

The effect of multipath reflection on the various methods of transmission is similar. With frequency modulation, for example, distortion is experienced and may give rise to cross-talk effects if multichannel signals are transmitted. A similar effect can be obtained with pulse transmission where time-division multiplex is utilized. If the secondary wave is delayed from the primary wave by a time equal to the timing between adjacent channels, the information corresponding to the two channels arrives simultaneously and cross talk results. This effect is, of course, reduced considerably by the directivity of the transmitting and receiving antennas and also if the antenna locations are suitably chosen.

Although some difficulty with this effect was anticipated, the cross talk experienced in the link was found to be negligible even under conditions where antenna locations were unfavorable and where large reflecting objects such as buildings and hills were located adjacent to the

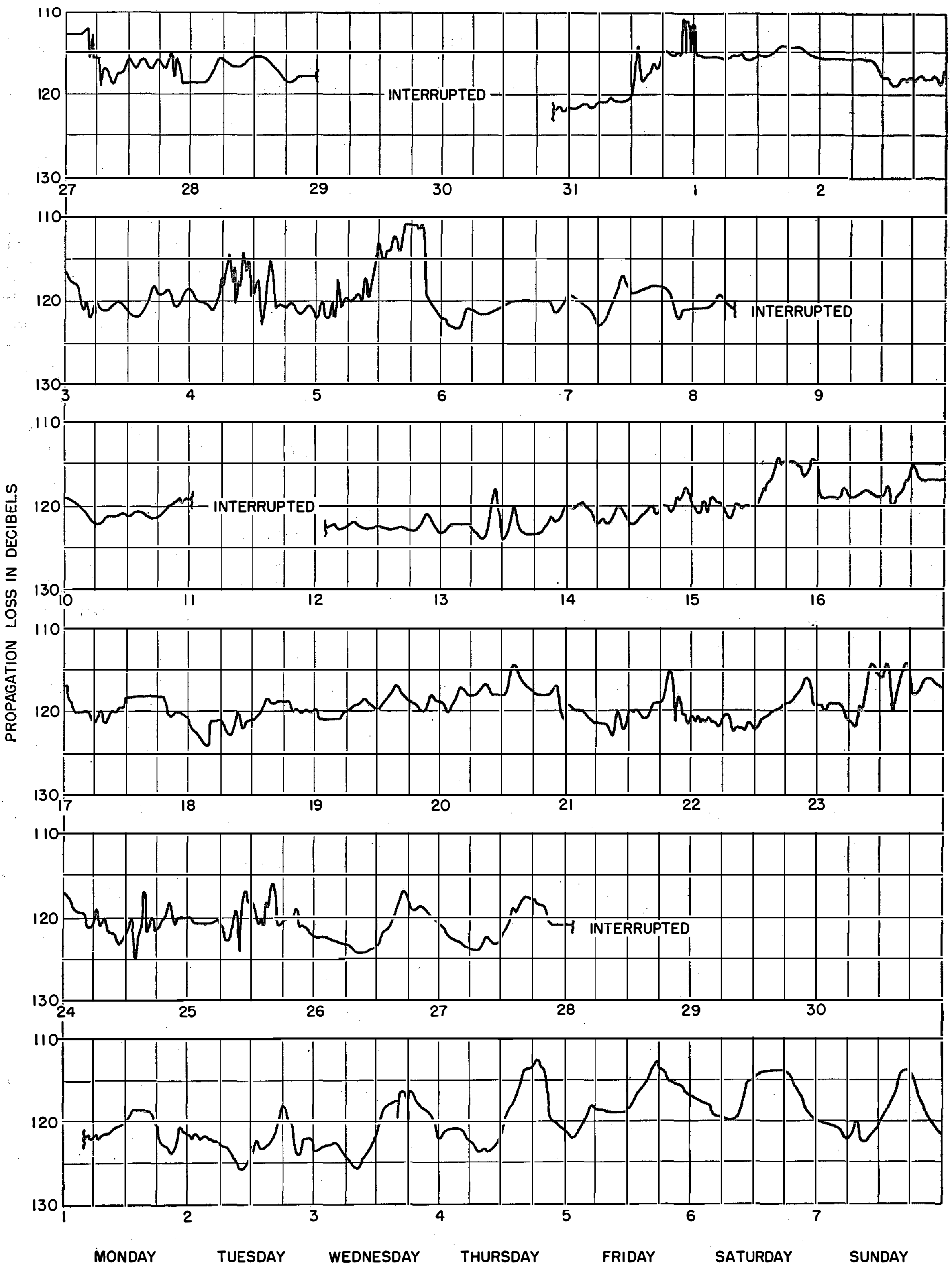


Fig. 21—Signal variations over the Nutley—Broad Street path during representative periods of a 42-day test starting on Monday, May 27 and terminating on Sunday, July 7, 1946. Propagation loss is the relation between the transmitted and received powers.

repeater sites. The absence of cross talk can be ascribed to the directivity of the antennas and the interference-reducing properties of the transmission method. In this latter case, the use of

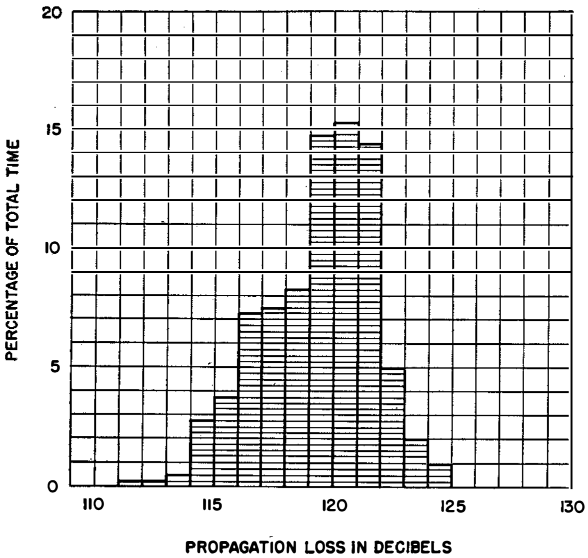


Fig. 22—Statistical presentation of the data given in Fig. 21.

limiters and similar circuits, together with the noise-improvement ratio of the system, minimized the effects of the resulting carry-over between pulses.

4.5 Propagation Variations

To check propagation variations, continuous 24-hour-a-day records were made at the receiver outputs along the link. Fig. 21 illustrates the observed signal variations over the Nutley–Broad Street path for representative periods during a 42-day interval. The statistical distribution of attenuation for the data given is plotted in Fig. 22. These charts show a variation of ±6 decibels from the theoretical attenuation of 119 decibels for this path.

It should be noted that the path is essentially an all-land route. Tests on the overwater link, Telegraph Hill to New York, have shown more severe fades of the order of 20 decibels. These fades were particularly noticeable during hot damp summer days when no wind was present. This would tend to indicate a change in the relative phase between the free-space and the reflected vectors resulting from a change of velocity of the reflected wave through the water-laden air near the water surface. For the normal fades, no dropouts were experienced although momentary loss of signal was observed during severe fading conditions. Although diversity reception was not utilized, it would be expected that a minimization of the rapid-fading dropouts would be obtained by this means. Negligible effects were observed from snow, ice, and rain, as well as seasonal variations except for the conditions previously indicated.

4.6 General Observations

Although the equipment was not specifically designed for continuous operation, it was possible to obtain essentially unattended operation at the repeater points after initial adjustments were accomplished. It was thus possible to operate the radio relay in a manner similar to that of a normal wire line. Interruption of service caused by propagation anomalies was rather a rare occurrence and reliable telephone service on an experimental basis was possible.

The equipment described is in operation and additional over-all tests are being conducted at present. To determine the full applicability of such relays to commercial practice, a large amount of testing will be required. It is safe to anticipate, however, that a time-division-multiplex relay similar to the type described will offer attractive possibilities as a commercial multichannel radio relay system.

5. *Acknowledgment*

Acknowledgment is made to Mr. E. Labin, Mr. H. G. Miller, and various engineers and technicians of Federal Telecommunication Laboratories who contributed to the development and design of the equipment described.

Paris-Montmorency 3000-Megacycle Frequency-Modulation Radio Link*

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INAUGURATION by the Minister of Posts, Telegraphs, and Telephones of a centimeter-wave link between Paris and Montmorency occurred on April 19, 1946. This is the first time that a multiplex radio link has been inserted in the telephone network of the Paris region. The new service permits simultaneous transmission of twelve conversations in each direction, with a quality of transmission comparing favorably with the best type of telephone cables.

The quality demanded of international telephone circuits corresponds to a ratio of signal to intelligible cross talk of at least 65 decibels in each audio-frequency channel. This is the main technical difficulty encountered in inserting a multiplex radio section in a high-quality telephone line. The cross talk originates with nonlinearity in the modulation stages at the transmitting end, and in the demodulation stages at the receiving end. Special circuits were designed to achieve the desired magnitude of signal-to-cross-talk ratio.

There are many advantages in certain cases in substituting a radio link for a section of telephone cable. The obvious instance is where considerable difficulties are encountered in installing and maintaining submarine telephone cables. It is natural that such insular countries as Great Britain and Japan were the first to apply very high radio frequencies to multichannel telephone communication, to bridge bodies of water 10 to 80 kilometers wide. As a forerunner, the communication established in 1933 between the airports of Lympne, England, and Saint Inglevert, France,[1] is worthy of mention. A wavelength of 17 centimeters (1800 megacycles per second) was used, and the radiation was focussed in a sharp beam by parabolic reflectors; one telephone or teleprinter circuit was operated across the English Channel until the beginning of the second world war.

A commercial link was put in operation in 1937 between Scotland and Ireland, with 9 telephone channels on a wavelength of 4 meters (75 megacycles). The distance is 65 kilometers with line-of-sight transmission. This is an amplitude-modulation system, and the signal-to-noise ratio is approximately 45 decibels in each channel. Since that time, other links have been installed utilizing amplitude modulation; the cross-talk performance has been improved by using inverse feedback.

Centimeter waves are inherently suitable for multiplex radio systems, as had been foreseen when the Lympne–Saint Inglevert link was designed, and still earlier in the preliminary Calais-Dover[2] experiments of 1930. A high concentration of radiated energy in a desired direction is readily achieved with microwaves, the antennas for which are of relatively small dimensions. Also, wider frequency bands are easily obtained and handled.

This latter fact makes the use of frequency modulation attractive. The radio transmitter may be frequency modulated with the signal from a standard carrier cable system utilizing frequency-division multiplexing. Frequency modulation brings a number of well-known advantages, such as an improvement of signal-to-noise ratio proportional (in root-mean-square value) to the modulation index; independence from nonlinearity of vacuum-tube characteristics; and stability over a wide range of received signal strength through the use of amplitude-limiting devices.

* Originally published in French as "Le Câble Hertzien," *L'Onde Electrique*, v. 26, pp. 331–334; August-September, 1946.

[1] A. G. Clavier and L. C. Gallant, "Anglo-French Micro-Ray Link Between Lympne and St. Inglevert," *Electrical Communication*, v. 12, pp. 222–228; January, 1934.

[2] "Micro-ray Radio," *Electrical Communication*, v. 10, pp. 20–21; July, 1931.

To achieve the required cross-talk level, however, it has been found necessary to add carefully designed feedback circuits both at the transmitter and receiver. Inverse feedback is already well known in carrier-cable amplifiers and in some amplitude-modulation radio circuits. When applied to frequency-modulation equipment, it takes a particular aspect, inasmuch as it results in a compression of frequency deviation in the intermediate-frequency circuits of the receiver.

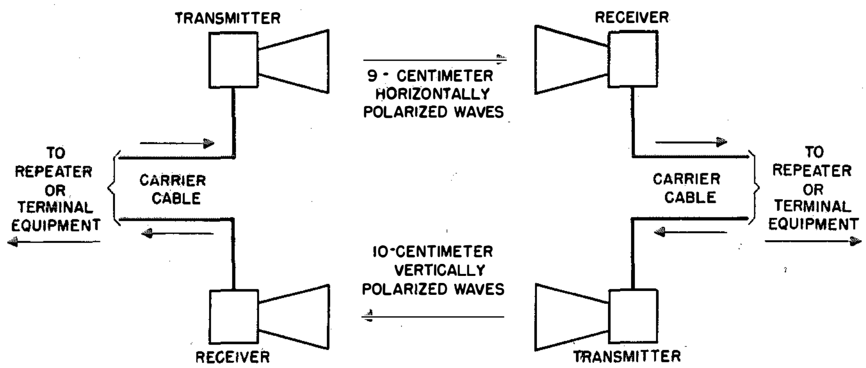

Fig. 1—General arrangement of the Paris-Montmorency radio link.

The improvement attained through inverse feedback is known to be limited by the degree of fidelity achieved in the feedback loop. In frequency modulation, the feedback loop includes a local oscillator, the frequency of which must vary in a very linear way with the applied voltage. This constitutes the limiting "linear reference" of the system. Fortunately, the positive-grid oscillator used in the Calais-Dover experiments has a very linear characteristic over a frequency range of some 50 megacycles. Used for a frequency deviation of only ±0.5 megacycle, it is sufficiently distortion-free to permit the severe international cross-talk standard to be achieved.

The design of the Paris-Montmorency equipment was preceded by experiments carried on during the last months of 1941 near Toulon, on the Mediterranean coast. The purpose of these experiments was to test the properties of horn-type directional aerials and to study the propagation of 3000-megacycle waves. The transmitter was located north of Toulon at an altitude of 700 meters. A receiver on a ship made it possible to test the propagation of high-frequency signals to the horizon and beyond. A number of experiments revealed that beyond the horizon, two modes of propagation were encountered; the normal one with a fast quasi-exponential decrease of field strength and, under certain atmospheric conditions (mostly hot and calm weather), an anomalous one in which the field strength passed through several minimum and maximum values out to a distance of more than 80 kilometers beyond the horizon of the transmitter.

Frequency-modulated waves were used and the limiter held the audio-frequency signal constant over a wide variation of high-frequency field strength.

Consideration was then given to the design of a radio equipment to be inserted as a section of a long-distance telephone line; this led to the Paris—Montmorency installation.

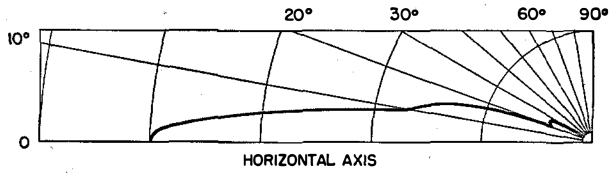

Fig. 2—Polar diagram of vertically polarized radiation from the horn in the vertical plane. The beam angle is about 11 degrees at points 3 decibels below maximum relative voltage.

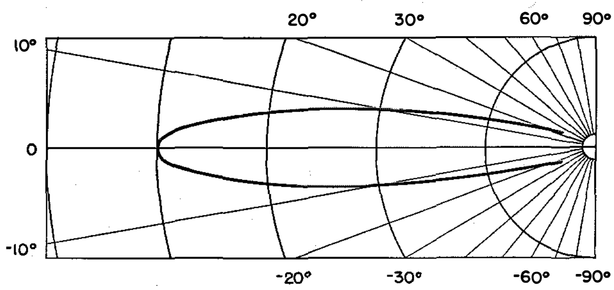

Fig. 3—Vertically polarized radiation from the horn in the horizontal plane. The beam angle is 14 degrees at the 3-decibel points of relative voltage.

1. General Characteristics

The signal to be transmitted comes from the carrier terminal equipment and consists of 12 audio-frequency channels transposed in frequency within a band ranging from 12 to 60 kilocycles. A 4-kilocycle band is allocated to each channel.

The general arrangement of the system is shown in Fig. 1. It can be said to be of the "4-wire" type, a separate carrier frequency being used for each direction of transmission. The Paris-Montmorency direction operates on 3333 megacycles (9 centimeters), and the opposite direction utilizes a 3000-megacycle wave (10 centimeters). As an added precaution, the two planes of polarization are at right angles; horizontal from Paris to Montmorency, and vertical for the return direction.

The composite signal from the 12-channel telephone cable is applied directly to modulate the transmitter. Conversely, at the receiving end, the signal from the radio receiver is introduced directly into the cable.

The directional radiators are of the horn type. Because of the rather high transmitter output (30 watts), the aperture area need only be 0.5 square meter for satisfactory reception. This results in a gain of about 22 decibels for the 3000-megacycle wave, as compared with a half-wave antenna in free space. The gain is somewhat larger for the 9-centimeter wave. The horn is preferred to a parabolic reflector because of its sturdiness and the ease with which it can be constructed. The problem of coupling the transmitter output to the radiator is also simpler and more efficient, as the transmission line is at the rear of the horn, instead of being in front as in the case of a reflector.

Figs. 2 and 3 show the shape of the radiation patterns as experimentally determined. Different flare angles have been adopted for the two sides of the horn; for instance 25 degrees in the vertical plane, and 30 degrees in the horizontal plane, for vertical polarization. As the diagrams show, lateral lobes have thus been avoided. The sharpness of the beam is such that the 3-decibel attenuation points occur at ±6 degrees in the vertical, and ±7 degrees in the horizontal planes.

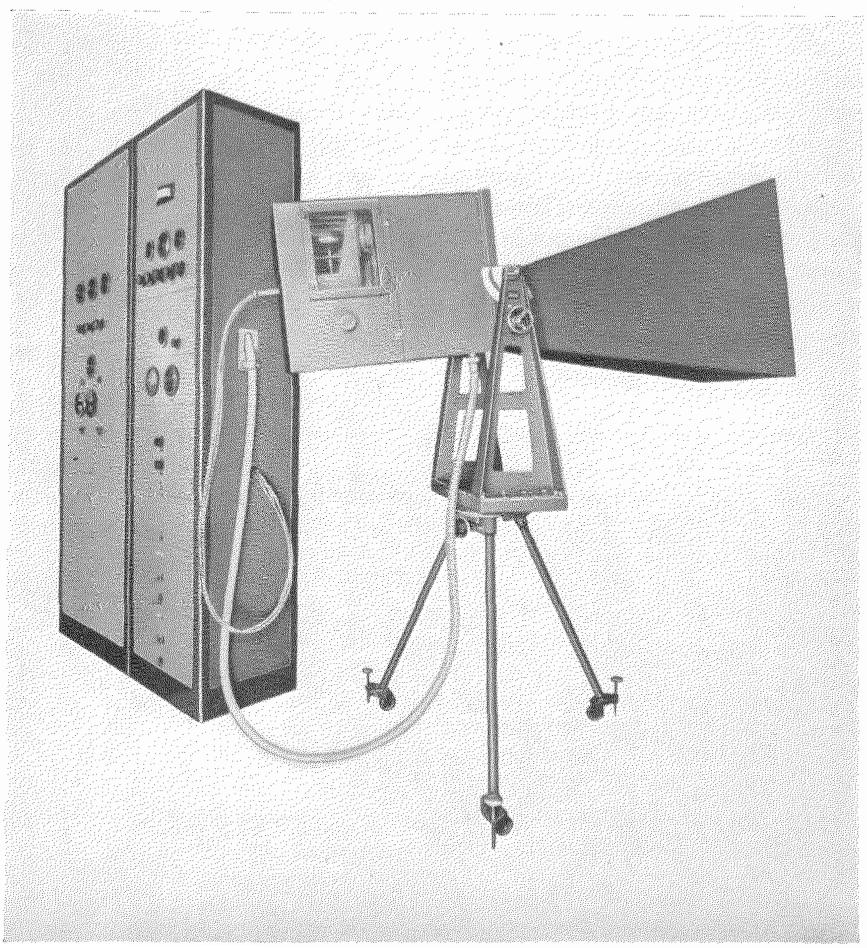

Fig. 4—Transmitting equipment. The microwave transmitting tube and radiating horn are mounted on the tripod for convenience in aiming.

The small end of the straight-sided horn terminates in a rectangular wave guide which is coupled to the transmission line to the transmitter or receiver. The waves in the guide are of the $H_{0,1}$ type, either vertically or horizontally polarized as required. Each horn is mounted on a tripod fitted with graduated sectors for the exact adjustment of elevation and azimuth of the beam axis.

2. *Transmitting Equipment*

Fig. 4 shows a general view of the transmitting equipment. A velocity-modulated oscillator delivers about 30 watts to the transmission line. This tube, developed in 1941, is placed in a housing mounted on one side of the smaller end of the horn, as shown in Fig. 5. The output of the oscillator is transmitted to the horn through a coaxial line. An impedance-matching arrangement is provided and may be seen in Figs. 5 and 6.

Frequency modulation of the oscillator is obtained by variation of the voltage applied between cathode and cavities of the tube. It is particularly important to maintain this 5000-volt supply constant, as fluctuations are an obvious source of noise. Therefore, a fraction of the ouput voltage is compared to the fixed voltage of a dry battery, and the difference is applied to the input of a direct-current amplifier. The output circuit of the amplifer is in series with the power supply circuit and thus stabilizes the output voltage. The residual ripple is less than 1 part in $3 \cdot 10^4$ of the applied voltage. The stabilization ratio, defined as the ratio of the percentage variation of the mains voltage to the corresponding percentage variation of the regulated voltage, is approximately 1000. With this arrangement, the frequency

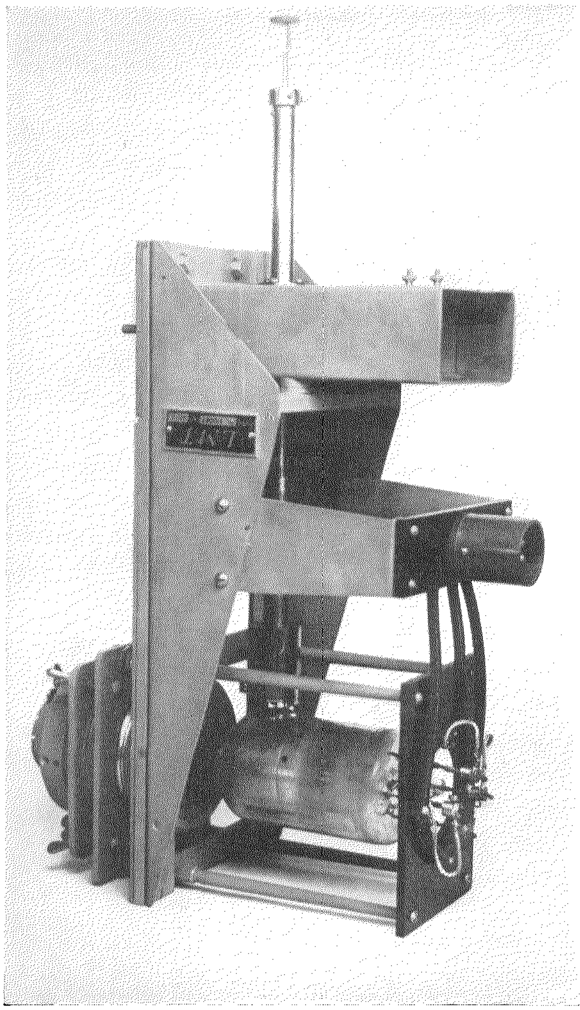

Fig. 6—Oscillator and transmission lines to the horn with their adjustment stubs.

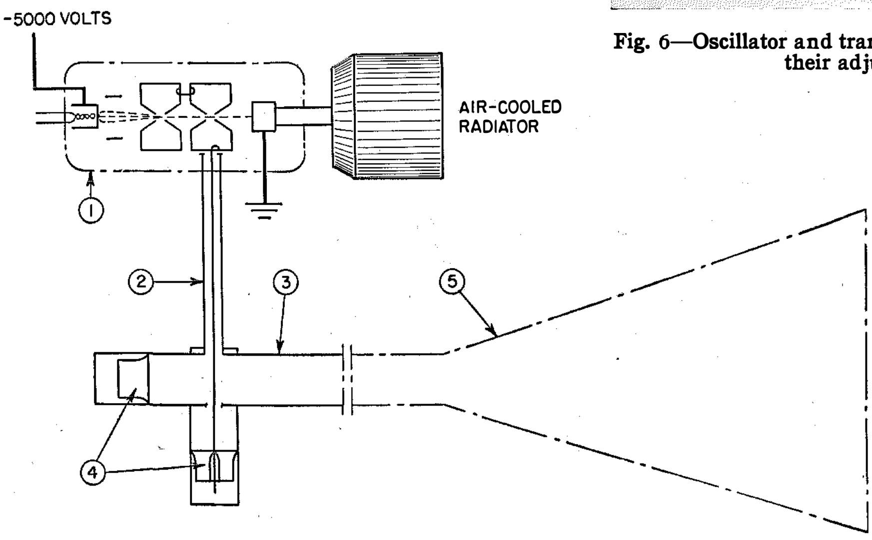

Fig. 5—Arrangement of oscillator and radiator. 1 is the velocity-modulated oscillator, 2 is the transmission line which connects the oscillator to the rear section of the horn, 3 is a section of wave guide to which the horn is coupled, 4 are the tuning stubs, and 5 is the horn radiator.

stability of the transmitter is of the order of 1 part in 10^5.

The maximum frequency of the signal being 60 kilocycles, a modulation index of 6 has been adopted, leading to an improvement of approximately 20 decibels in signal-to-noise ratio compared with amplitude modulation. The maximum frequency deviation is thus ±360 kilocycles, and the voltage-frequency characteristic of the tube is sufficiently linear for a range of ±500 kilocycles.

The modulating signal is received at the input level normally applied to a repeater for a carrier cable. A modulation amplifier must be inserted, and distortion is kept very low by use of inverse feedback. The signal-to-distortion ratio of the transmitter was found to be of the order of 50 decibels. This is not sufficient, and to obtain the specified 65-decibel ratio, frequency-modulation feedback circuits were developed.

2.1 Measurement of Distortion

It may be of interest to describe briefly the method and instrument used to measure over-all and component distortions, so as to determine the improvement actually contributed by the frequency-deviation-compression arrangements.

The block diagram of the measuring apparatus is shown in Fig. 7. Two sine-wave voltages of frequencies f_1 and f_2, which are in the modulating range of 12 to 60 kilocycles, are produced by a signal generator having the very low distortion level of −75 decibels. These signals are applied with equal amplitudes to the input of the equipment to be checked. At the output of the equipment, there will then appear, in addition to the two input signals, parasitic terms originating in the equipment as a result of nonlinearity.

The nonlinear distortion can be evaluated by comparing the amplitudes of the fundamental frequencies with the level of the so-called 2nd-degree terms, such as $2f_1$, $2f_2$, f_1-f_2, etc., and of the 3rd-degree terms, such as, $3f_1$, $3f_2$, $2f_1-f_2$, etc. This is achieved by a special measuring receiver tuned to a fixed frequency of 20 kilocycles, and provided with means of measuring 10 microvolts accurately. Accurate measurements of distortion terms of the order of −65 decibels are thus possible. The adjustment of separate elements and of the entire installation made in this manner have been confirmed by standard measurements in the low-frequency output channels.

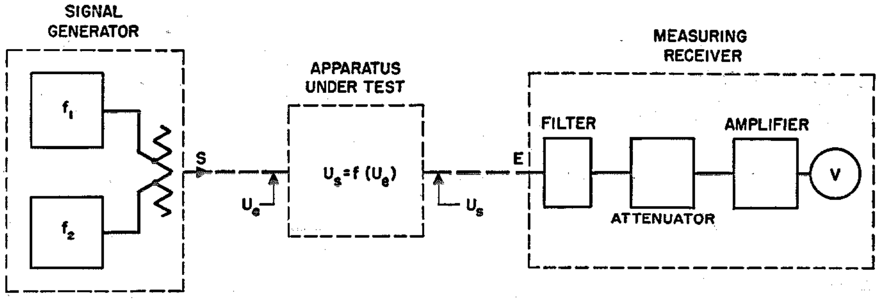

Fig. 7—Schematic arrangement of equipment for measuring cross talk using two input signals.

2.2 Frequency-Modulation Feedback Circuits

Just as in the case of amplitude modulation, the distortion of a direct path of amplification can be reduced by the addition of an inverse path. This corrects the defects of the direct path provided that distortion does not occur in the return path. To achieve the desired result, the return path itself had to be fitted with an inverse-feedback loop, and thus the total arrangement includes both a local and an over-all feedback loop, as shown in Fig. 8.

Frequency-modulation feedback circuits can, of course, operate only if the loop circuits are sufficiently stable. The general principles are the same as those given in the fundamental works of Black, Nyquist, and Bode dealing with amplitude-modulation feedback circuits. The stability of the amplifier is similarly evaluated by means of the "Nyquist criterion." The modulus of the amplification factor around the entire loop must fall below 1 at frequencies for which the phase shift reaches 0 or 2π, the phase shift being substantially equal to π in the useful band where inverse feedback is utilized. To obtain a stable inverse-feedback amplifier, it is necessary to control the gain characteristic around the complete loop from the highest useful frequency to

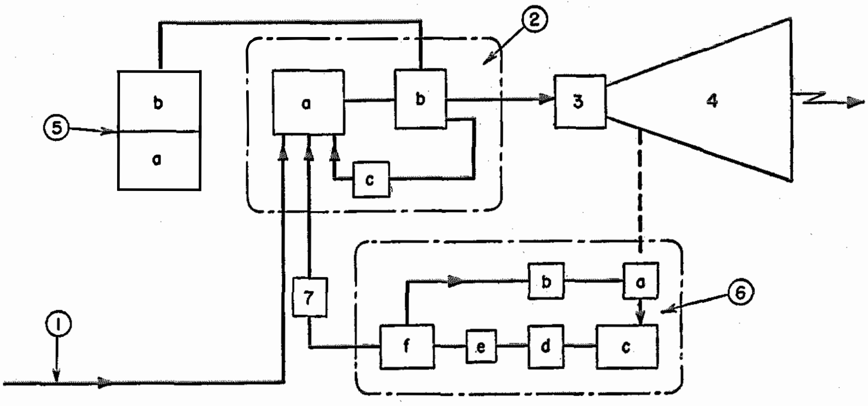

Fig. 8—Schematic arrangement of the feedback circuits in the transmitter. 1, carrier cable; 2, *a* and *b* are modulation amplifiers and *c* is a phase corrector; 3, transmitting tube; 4, radiating horn; 5, stabilized high-voltage supply; 6, auxiliary feedback receiver consisting of *a* mixer, *b* positive-grid local oscillator, *c* 9±1-megacycle intermediate-frequency amplifier, *d* limiter-discriminator, *e* phase corrector, and *f* direct-current amplifier; and 7, phase corrector for the over-all feedback loop.

the asymptotic part of the curve, which is determined at the higher frequencies by the unavoidable parasitic capacitances in the tube and circuits employed. There is thus an optimum cutoff characteristic which should be followed as closely as is practicable up to a frequency which increases with the inverse-feedback ratio and with the number of amplification stages within the loop. Consequently, amplifiers must be designed with a band width considerably larger than the useful band, and passive phase-correcting networks generally have to be added.

The best way to determine the safety margins that separate the actual characteristic from the conditions that would cause oscillation is to develop the Nyquist diagram; the gain around the open loop is plotted as a complex vector in a system of polar coordinates. This, however, means measuring not only the absolute value of gain, but also the phase shift around the entire loop, which requires the use of a phase meter capable of operating at relatively high frequencies. It has been found more convenient to avoid direct measurement of phase shift and operate as follows, provided the looped amplifier has already proved to be stable.

In Fig. 9, let a gain-measuring apparatus be inserted in the inverse-feedback loop as shown, and let $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ be the complex values of amplification for the forward path, the return path, and the over-all amplifier, respectively. Those three complex values are related by

$$\boldsymbol{C}=\frac{\boldsymbol{A}}{1-\boldsymbol{AB}};$$

that is to say,

$$\boldsymbol{AB}-\frac{\boldsymbol{A}}{\boldsymbol{C}}=1.$$

In the latter expression, $\boldsymbol{AB}$ represents the complex gain around the open loop, and $\boldsymbol{A}/\boldsymbol{C}$ represents the ratio of the gain of the amplifier before and after the introduction of inverse feedback. Let the moduli of $\boldsymbol{AB}$ and $\boldsymbol{A}/\boldsymbol{C}$ be measured; it is then possible to trace the triangle representing the above equation and to deduce the value of the vector $\boldsymbol{AB}$. The Nyquist diagram can thus be plotted as in Fig. 9, and the degree of stability of the amplifier can be evaluated. This determination is accurate only if $\boldsymbol{AB}$ is approximately 1, the region in which a precise knowledge of the diagram is important.

To obtain an improvement in signal-to-noise ratio of 20 decibels over amplitude modulation for a frequency band of 60 kilocycles with a large number of stages of amplification, the shape of the gain characteristic had to be investigated up to 1 megacycle. The intermediate-frequency amplifier of the auxiliary frequency-modulation receiver has a bandwidth of 2 megacycles; the modulation amplifier has constant gain up to 1 megacycle. Suitably connected phase-correcting circuits are introduced to obtain optimum cutoff characteristics.

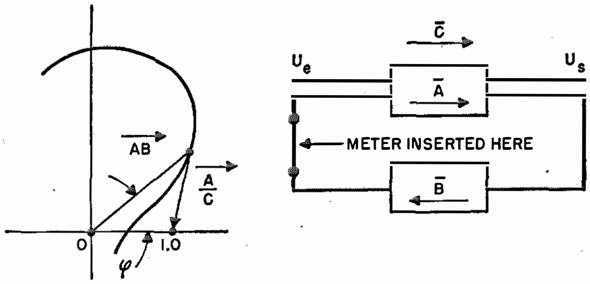

Fig. 9—Simplified method of obtaining data for plotting Nyquist diagrams. Only measurements of gain are required.

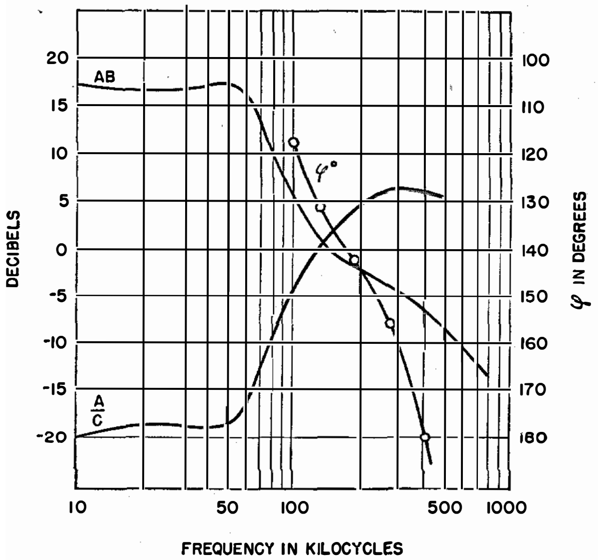

Fig. 10—Curves for determining the general frequency-compression characteristics of the transmitter.

As already mentioned and shown in Fig. 8, there are two main feedback loops in the transmitter, not counting the additional amplitude-modulation-feedback loop in the modulation amplifier. One is a so-called "local loop" which affects the auxiliary frequency-modulation receiver only; the second one is the over-all loop, which concerns the whole of the transmitter from radio-frequency output back to the low-frequency input at the modulation amplifier.

The auxiliary receiver is a superheterodyne, with a local oscillator of the positive-grid type having a very linear relation between frequency deviation and anode voltage. The mixer is a special diode with short electron transit time between cathode and anode. The frequency converter is followed by an intermediate-frequency amplifier, limiter, and frequency discriminator. The modulating signal is thus locally reproduced and applied to the anode of the receiver local oscillator in a direction suitable to cause a compression of the frequency deviation at the receiver output. As a result, there is a considerable decrease in the distortion which usually attends demodulation. In addition, the local-feedback loop being arranged to transmit the direct-current component, the center value of the local-oscillator frequency follows any drift of the transmitter, and the intermediate-frequency signal remains within the pass band of the receiver.

The auxiliary receiver described has a high degree of fidelity and can be incorporated as the return path in the general frequency-deviation-compression circuit of the transmitter. The output of this receiver is applied to the input of the modulation amplifier in phase-opposition to the main signal, so that inverse feedback is obtained. This is effected through a phase-correcting circuit which adjusts the gain around the open loop to approximately 17 decibels in the 12- to 60-kilocycle band, and produces a cutoff characteristic above 60 kilocycles such that the stability of the whole circuit is assured with a sufficient margin of safety. The curves shown in Figs. 10 and 11 illustrate the results actually obtained.

The improvement in quality of transmission resulting from frequency-modulation feedback has been confirmed by means of the cross-modulation meter described previously. Accordingly, the signal-to-distortion ratio, which is of the order of 50 decibels without frequency compression, has been found to exceed 65 decibels for full modulation of the transmitter when the feedback arrangement is utilized.

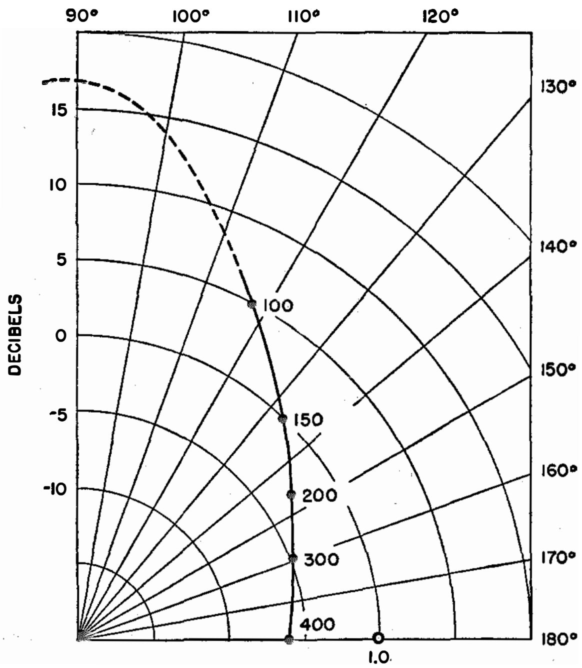

Fig. 11—Nyquist diagram of the frequency-modulation feedback circuit of the transmitter.

Fig. 12—9-centimeter receiver of the Paris-Montmorency radio link.

positive-grid local oscillator. The intermediate-frequency signal is amplified at 15 megacycles, and then converted to 9 megacycles. The total intermediate - frequency gain is 120 decibels over a 1-megacycle band. A limiter-discriminator detects the frequency-modulation signal and the low-frequency output is sent to the carrier cable terminals.

Fig. 13 is the block diagram of the receiver. Note that it is provided with a feedback loop for frequency-deviation compression. To achieve this, the output signal from the discriminator is applied to the anode of the positive-grid local oscillator in such a direction as to reduce the frequency deviation in the receiver intermediate-frequency circuits. This loop includes a phase corrector; stability is adjusted and checked by the method already described for the transmitting equipment.

3. Receiving Equipment

At the receiving end shown in Fig. 12, the high-frequency signal is picked up by a horn identical to that of the transmitter. From the rear wave-guide portion of the horn, the signal is sent through a coaxial cable to the mixer. Use is made of a short-transit-time diode, and a

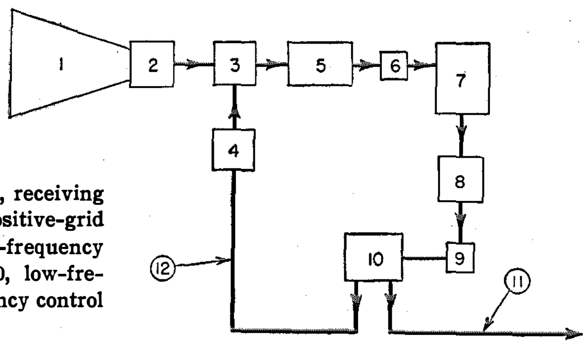

Fig. 13—Schematic arrangement of the receiver. 1 and 2, receiving horn and matching circuits; 3, balanced diode mixer; 4, positive-grid local oscillator; 5, 6, and 7, 15- and 9-megacycle intermediate-frequency amplifiers; 8, limiter-discriminator; 9, phase corrector; 10, low-frequency amplifier; 11, carrier cable; and 12, automatic-frequency control and feedback loop.

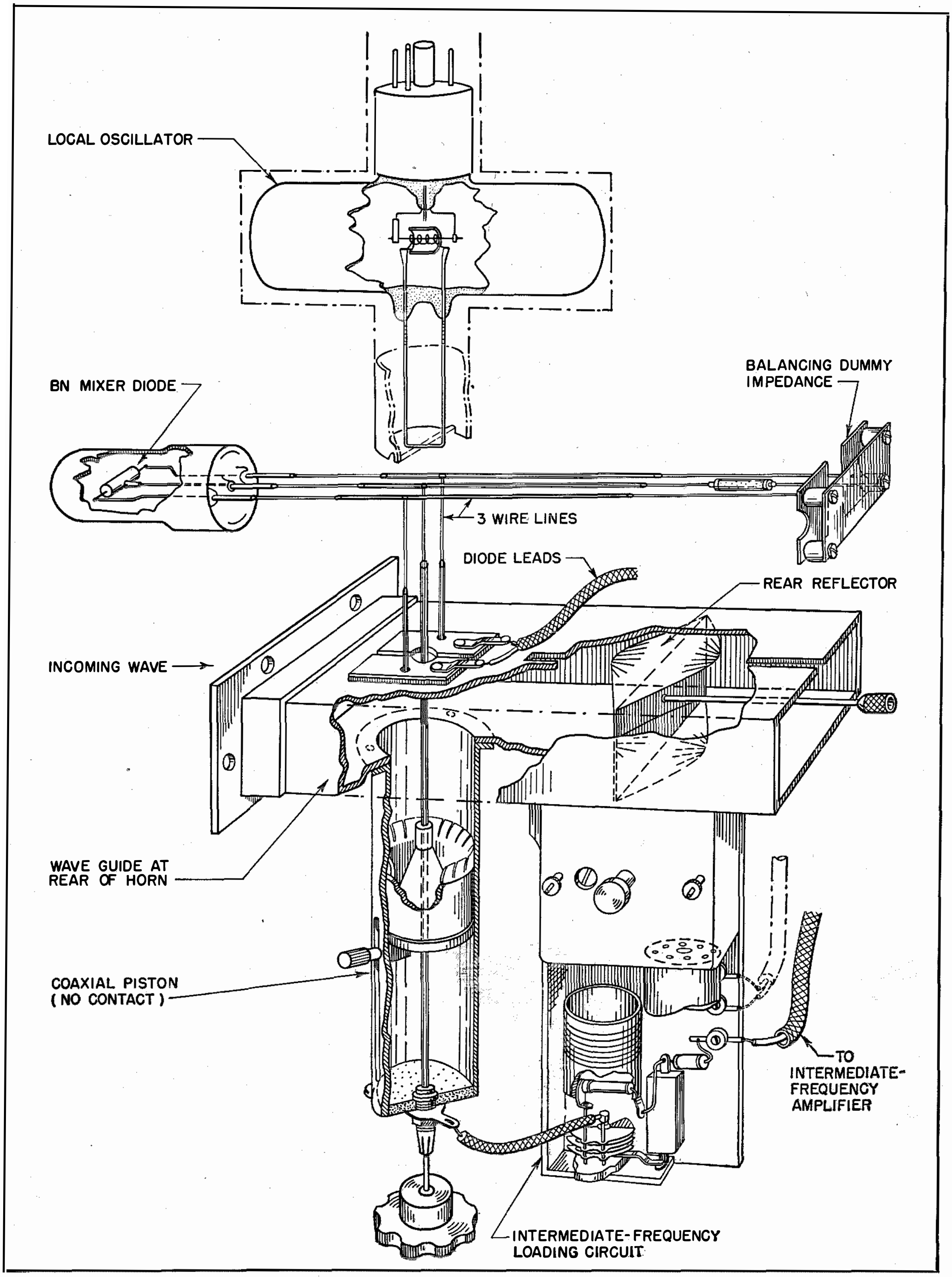

Fig. 14—Balanced mixer used in receiver. This entire equipment is mounted in the box at the rear of the horn as shown in Fig. 12.

The frequency deviation of the positive-grid oscillator with variation of voltage must be very linear in the range of frequency deviations utilized, as this is the limiting factor in freedom from cross talk. It has been found that when such an oscillator is coupled directly to the receiver horn, reflections back into the horn from exterior obstacles cause irregularities in the operation of the tube. It is, therefore, necessary to do away with any possible radiation from the local oscillator. To achieve this, the tube is mounted in a shielded housing and the mixer circuit is of the balanced type, balance being obtained through the use of a dummy impedance duplicating that of the mixer diode as shown in Fig. 14. It has thus been possible to decrease the radiation of the local oscillator by approximately 30 decibels, and under these conditions the linearity of the tube characteristic remains practically unimpaired.

It has been shown above that the intermediate-frequency amplifiers should be carefully adjusted to have bandwidths of one megacycle for the receiver, and two megacycles for the transmitter auxiliary receiver. Furthermore, the discriminators must have operating bandwidths at least as large as the bandwidths of the associated intermediate-frequency amplifiers, and their demodulation characteristics must be as linear as possible. Adjustment of all of these circuits is difficult and lengthy if each point has to be plotted; the process is greatly simplified by projecting the whole response curve on an oscilloscope during adjustment. To do this, a signal generator must be obtained which can produce a frequency-modulated signal having constant amplitude over a range of several megacycles. One convenient way of doing this is to use the beat frequency between two positive-grid oscillators, one being stabilized by a high-Q cavity, and the other being modulated with a low-frequency generator by variation of its anode voltage. Fig. 15 shows oscillograms obtained by this method from the auxiliary receiver of the transmitting equipment.

4. Conclusion

The entire equipment of the Montmorency terminal is shown in Fig. 16. The installation has been in traffic operation since January, 1946, and has given very satisfactory results. This is a first step in the insertion of radio links in high-quality multiplex telephone networks. The number of channels will, of course, have to be increased considerably to compete with cables. The transmission range will also have to be extended; the Paris-Montmorency link is only 15 miles long, while the same equipment could be used for twice that distance provided the terminal stations were located in sight of each other. Further extension may be provided by the installation of relay stations. There is no doubt that the recent advances in centimeter-wave technique will soon be applied to covering longer distances and supplying a greater number of simultaneous channels. The installation inaugurated at Paris will nevertheless remain a pioneering step in that direction.

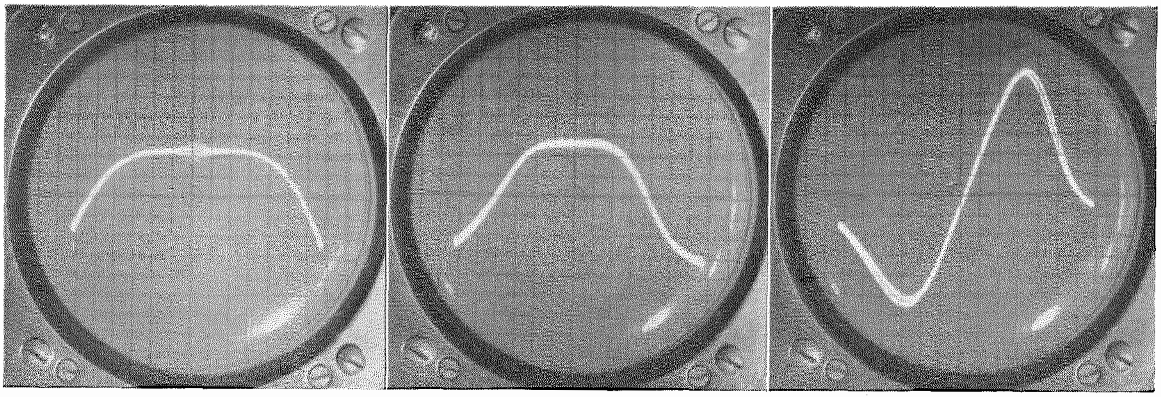

Fig. 15—Three oscillograms obtained from the auxiliary receiver of the transmitting equipment. The first two curves are the response-frequency characteristics of the intermediate-frequency amplifiers. The bandwidths are 2 megacycles. The discriminator response-frequency characteristic is displayed in the oscillogram at the right.

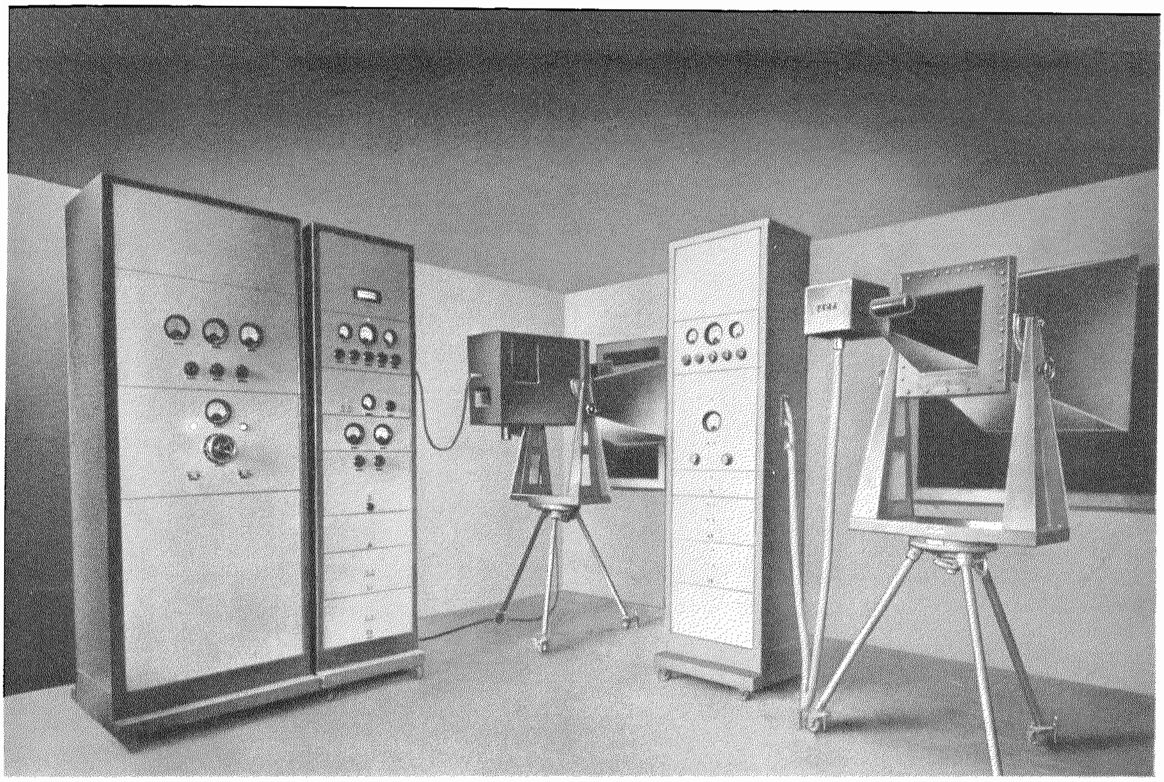

Fig. 16—Montmorency terminal. The 9-centimeter receiving horn is at the right, and the 10-centimeter radiating unit is in the center. The multiplexing equipment and power supplies are contained in the three cabinets.

5. Acknowledgment

The successful conclusion of this project was made possible by the cooperation of the French governmental technical services and the research laboratories of private industry. It may be interesting to note that this work was conducted in France during the most difficult period of enemy occupation. Started in 1941, it was actively helped by the French Communications Coordination Committee, of which Admiral Bourrague was President, and to which the late Colonel Labat gave his valuable cooperation. It was subsequently sponsored by the Administration of Posts, Telegraphs, and Telephones, under Mr. Lange, Director, and Mr. Marzin, Assistant Inspector General and Director of the Research Center.

A group of engineers and technicians of Laboratoire Central de Télécommunications contributed to the success of the project. The authors of the paper express their thanks to all their colleagues, and particularly to Mr. Altovsky.

Mobile Frequency-Modulation 30–44-Megacycle Equipment

By R. B. HOFFMAN and E. W. MARKOW

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RECENT YEARS have witnessed increasing interest in radio communication to moving vehicles, particularly in the emergency services for police and fire protection. Its convenience for dispatching taxicabs, public-utility repair crews, and similar services has not been overlooked. A description is given of transmitting and receiving equipment for mobile, main, and remote stations. Operation is in the 30- to 44-megacycle band using frequency modulation. When Selecto Call is employed, up to four mobile stations or groups of stations may be called individually, without disturbing unwanted mobile stations.

• • •

A line of equipment has been designed to provide single-frequency two-way radio communication between a land[1] station and any number of mobile stations.

The equipment operates in the band from 30 to 44 megacycles per second, assigned by the Federal Communications Commission for mobile communication services, and uses frequency modulation.

The complete system consists of equipment for mobile and for both central and remote land stations. It is characterized by simplicity of operation, small size of mobile equipment, improved receiver squelch circuit, low power drain for mobile equipment during stand-by, plug-in arrangement of units for ease of replacement and servicing, and a self-contained selective calling system. This selective calling feature, or "Selecto Call," permits the land station to call any of four mobile stations or groups of stations without alerting other mobile units in the system.

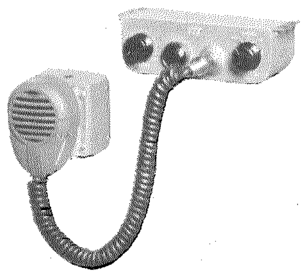
In some instances, incorporation of Selecto Call may avoid duplication of land-station equipments. For example, a small community may combine its mobile communication with fire, police, and ambulance services by using a single headquarters station and equipping cars of the separate departments with different Selecto Call decoders. In this way, cars of any single department could be alerted without disturbing any other cars.

Mobile receivers are available without the Selecto Call decoder unit which is plugged in if required. Similarly, the land-station equipment need not include the special signaling devices for Selecto Call if this feature is not needed.

1. *Mobile Equipment*

The standard mobile equipment, shown in Fig. 1, consists of a 25- to 50-watt transmitter, receiver, control box, loudspeaker, microphone,

[1] A "land" station is a radiotelephone installation in a fixed location. The older term of "fixed" station commonly denotes one in point-to-point service.



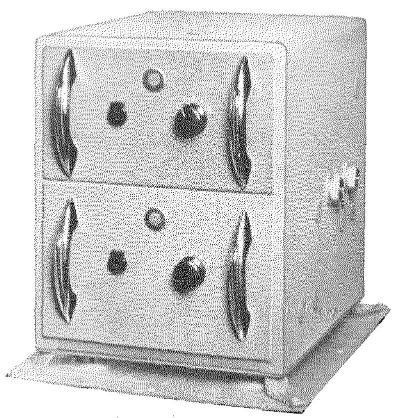


Fig. 1—The mobile receiver and transmitter are mounted in the cabinet and may be placed in any convenient space in the automobile. The microphone and control box are usually mounted on the instrument board.

microphone hook, and whip antenna. Both the receiver and transmitter are on separate plug-in chassis, which are inserted in either a vertical or horizontal housing. The control box is normally mounted on the instrument panel of the automobile.

The transmitter and receiver units predominantly employ miniature tubes. Crystal-controlled oscillators keep both receiver and transmitter on frequency. The over-all response-frequency characteristic of the system is shown in Fig. 2. The equipment can be tuned to operate at any radio frequency between 30 and 44 megacycles. Power is obtained from the 6-volt automobile storage battery. The current drain during stand-by periods is 7.12 amperes; while transmitting, the current increases to 33.2 and 50.5 amperes for the 25- and 50-watt transmitters, respectively.

Operation of the mobile equipment requires only lifting the microphone off the hook, depressing the microphone switch, and speaking. The receiver volume is adjusted from the control box to suit conditions of ambient acoustical noise which varies with speed and traffic conditions, among other things. The receiver may be operated in any one of three conditions designated as carrier, monitor, and Selecto Call.

In the "carrier" position, the receiver audio-frequency channel is silenced by a squelch circuit which maintains control until an on-frequency carrier is received. This completely removes all annoying electrical noises, which would normally be present in the absence of a carrier. The receiver is completely operative only when there is a transmission on the frequency to which it is tuned. The squelch circuit is of high sensitivity, turning on the audio-frequency system with signals producing only 6 decibels of noise quieting. Such signals are too weak to be understood with ease, therefore, no readable signal will be undetected when the receiver is in "carrier" position.

In the "monitor" position, the squelch circuit is inoperative and the audio-frequency channel is not silenced. The operator hears the annoying hissing and rushing noise characteristic of all high-gain receivers in the absence of a quieting signal. This position is useful for the reception of very weak and fading signals and to check the operation of the receiver.

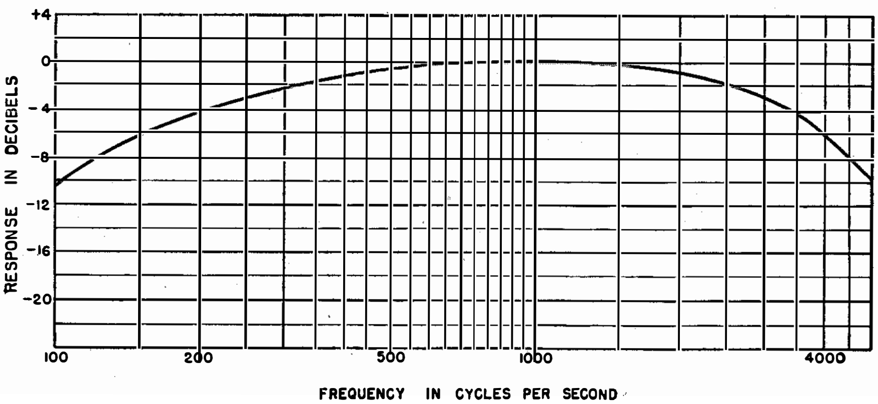


Fig. 2—Response-frequency characteristic of the mobile equipment. Reference level is the response at 1000 cycles.

In the "Selecto Call" position, a frequency-selective decoding circuit renders the receiver audio-frequency system operative only in response to a predetermined calling signal. When the microphone is lifted from its hanger, the receiver is switched to the "carrier" position. It is unnecessary thereafter for the land station to repeat the Selecto Call.

2. Transmitter

The mobile transmitter, a block diagram of which is shown in Fig. 3, consists essentially of a crystal-controlled master oscillator, a phase-shift variable-transconductance modulator, and four frequency-multiplying amplifiers which drive the output stage. The final amplifier consists of either one type 5516 tube or two in parallel to provide, respectively, 25 or 50 watts of radio-frequency power to the antenna.

The oscillator is of the conventional crystal-controlled type employing a 6AK5. Frequency shift is less than ±0.01 percent over a temperature range from −30 to +70 degrees centigrade (−22 to +158 degrees Fahrenheit). After modulation, the signal is applied to a series of frequency multipliers which operate as saturated class-C amplifiers. The output of the power amplifier stage, also operating class C, is coupled to the antenna through a tuned π network. The transmitter may be operated at any frequency between 30 and 44 megacycles by inserting a crystal of the proper frequency and adjusting the tuned circuits.

The variable-transconductance phase-shift modulator is shown in Fig. 4. A 6AK5 is connected as a triode. A very high resistance at R_k produces a large grid bias with a consequent low tube transconductance. The master-oscillator voltage E_g applies two voltages to the tuned plate circuit Z_p of the modulator: one through C_{gp} the grid-to-plate capacitance, and the other E_{pg_m} through the tube conductance. Thus the voltage developed across the tuned plate circuit Z_p consists of two components, nearly opposite in phase with respect to each other. With no modulating signal E_a these two components are equal in magnitude, and the resultant E_{po} is shown in Fig. 5. When an audio-frequency signal E_a is applied from the microphone to the grid, the instantaneous value of tube transconductance and of E_{pg_m} varies in accordance with the instantaneous magnitude of the audio-frequency voltage as shown by two arrow heads on the vector diagram. Thus as the audio-frequency voltage increases and decreases through its cycle, the component across the tuned circuit Z_p resulting from tube conductance changes in magnitude. However, the component caused by the grid-to-plate capacitance E_{pc} remains constant, and the resultant radio-frequency voltage across the tuned plate circuit shifts in phase through the angle α. Thus, instantaneous changes in the magnitude of the audio-frequency signal cause

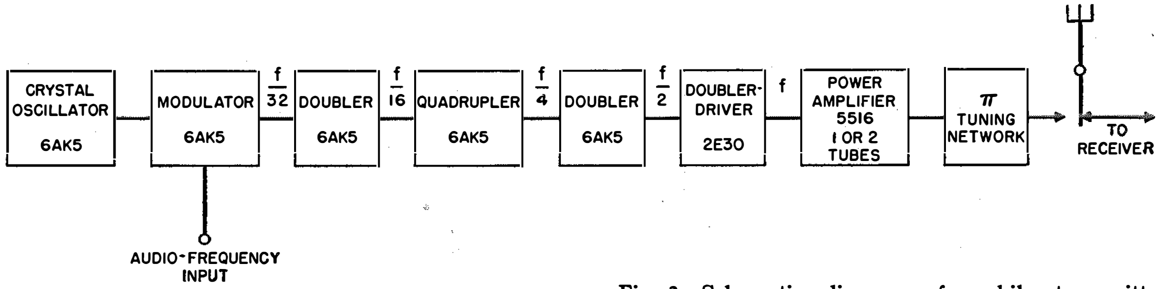


Fig. 3—Schematic diagram of mobile transmitter. Only one power-amplifier tube is used for the 25-watt rating and two for 50 watts. Closing the microphone switch operates the antenna change-over relay and another relay in the primary circuit of the transmitter dynamotor.

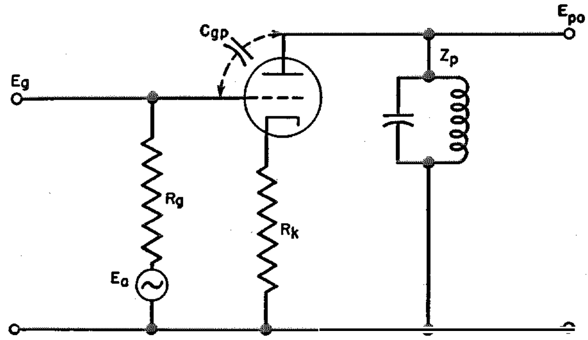


Fig. 4—Variable-transconductance phase-shift modulator.

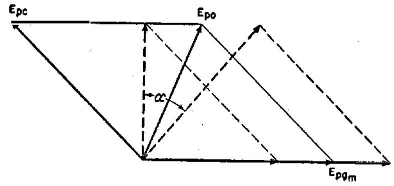


Fig. 5—Vector analysis of the operation of the circuit of Fig. 4. E_{pc} and E_{pg_m} are the voltages on Z_p as a result of E_g being applied through C_{gp} and through the conductance of the tube, respectively. A voltage E_a applied to the tube grid, changes the magnitude of E_{pg_m} without affecting E_{pc}, producing a phase variation α in the resultant output radio-frequency voltage E_{po}.

corresponding excursions of the phase angle and produce phase deviations of the radio-frequency voltage from the phase obtained in the absence of modulation. The frequency of the modulating signal expresses itself as the rate with which the phase of the resultant radio-frequency voltage changes. The highest audio-frequency modulating signal used is about 3500 cycles. The maximum equivalent frequency deviation does not exceed 15 kilocycles and complies with the regulations of the Federal Communications Commission. Any amplitude modulation introduced is eliminated by the chain of saturated radio-frequency amplifier stages.

Plate and screen potentials are obtained from a built-in dynamotor operated from the car battery. For land installations, the dynamotor is replaced by a power pack operated from the 117-volt 50/60 cycle supply lines.

3. Receiver

A block diagram of the receiver is shown in Fig. 6. The units connected by solid lines comprise a conventional double-conversion superheterodyne. The components connected by broken lines comprise the Selecto Call mechanism. When the switch $S2$ is in the "On" position, and switch $S1$ is in the "Carrier" position, the receiver is operative without being under the control of the Selecto Call mechanism.

The Selecto Call actuating signal is a single low-frequency wave between 150 and 442 cycles, which modulates a 7000-cycle subcarrier. This combined signal modulates the transmitter carrier. The discriminator in the receiver reproduces this calling signal, which passes through the 7000-cycle filter when switch $S2$ is in position "Off." It then passes through the audio-frequency and Selecto Call amplifiers to the decoder. In the process, the 7000-cycle subcarrier is discarded and, if the lower-frequency modulation is of the proper frequency, the decoder operates. The decoder is essentially a single-pole single-throw switch, which is normally in the open position. When the decoder is actuated, the switch is closed and the audio-frequency system becomes operative.

If switch $S2$ is thrown to the "On" position, the audio-frequency channel will continue operative as long as the radio-frequency carrier is being received. If the carrier is removed, the audio-frequency system is disabled and the

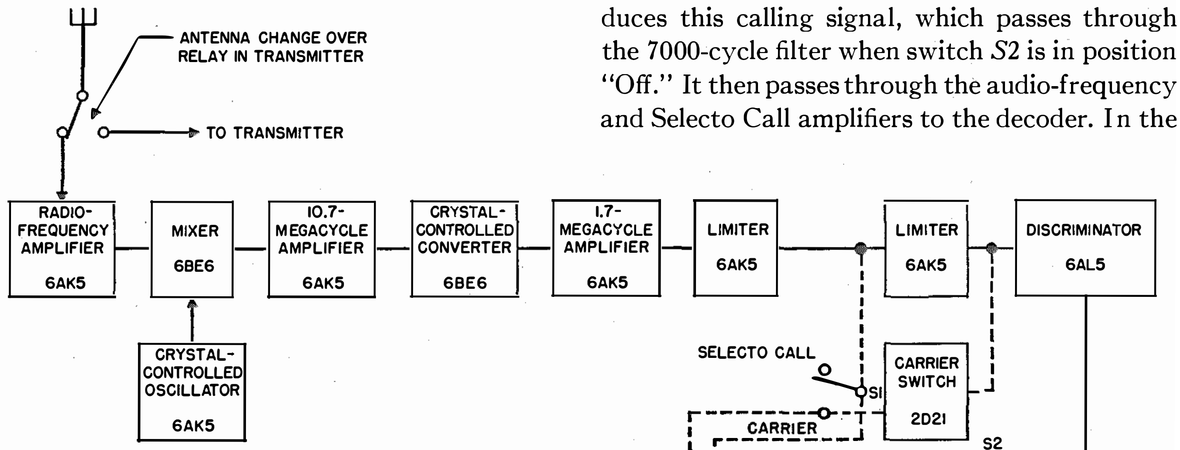
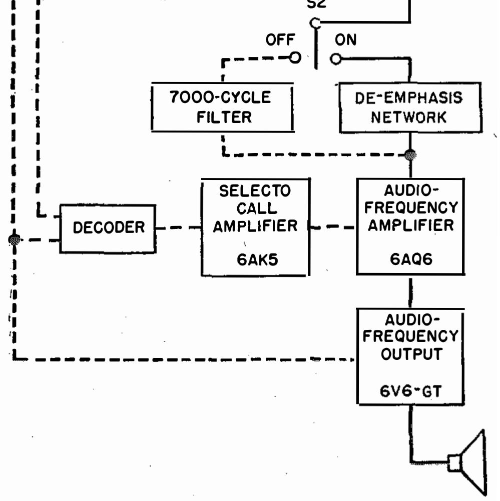



Fig. 6—Schematic arrangement of the receiver. The units connected by solid lines comprise a conventional double-conversion superheterodyne circuit. The broken lines connect the Selecto Call and squelch circuits.

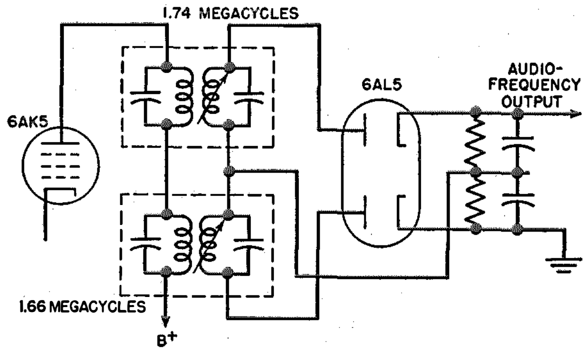


Fig. 7—Discriminator circuit. The capacitor in the primary of the lower transformer tuned to 1.66 megacycles is adjusted to produce zero direct-current output for an input signal of 1.7 megacycles.

decoding signal will be required to open the channel again. A carrier alone, or a carrier with any modulation other than that for which the decoder was designed, will not operate the receiver.

Switch *S*2 is shifted from the "Off" to the "On" position by lifting the microphone from its hook.

Decoders are available for four frequencies which may be assigned to individual or groups of receivers to meet the requirements of various installations.

Modulation of the transmitter carrier with frequencies between 150 and 442 cycles results in very small deviations of frequency with the phase modulator employed. The use of a subcarrier of 7000 cycles, which is modulated in turn by the low-frequency decoding signal, avoids this difficulty and, by giving a full 15-kilocycle deviation, provides a maximum signal to the receiver. Only the frequencies between 150 and 442 cycles reach the decoder coil, the 7000-cycle frequency being attenuated in a low-pass filter in the Selecto Call amplifier.

3.1 Squelch Circuit

The squelch circuit employs a type 2D21 thyratron, which conducts current in the stand-by condition. A relay in its plate circuit is operated and disconnects the voltage supply to the screen of the 6V6-GT audio-frequency output tube, rendering the audio-frequency channel inoperative.

The grid of the thyratron receives voltages from two sources. A negative voltage is taken from the bias resistor in the grid circuit of the second limiter tube. The second voltage is obtained through a high-pass filter from the plate of the second limiter tube. Under stand-by conditions, the limiter is noise-saturated and the positive peaks from the plate circuit exceed the steady negative voltage derived from the grid circuit. The positive noise pulses dominate and are strong enough to fire the thyratron. Resistance and capacitance in the grid circuit of the thyratron produce relatively long operating periods. At the end of each operation, another noise pulse triggers the thyratron and sufficient plate current is maintained to hold the relay in the operated position.

If a signal is received at the frequency to which the receiver is tuned, there will be no change in the limiter grid voltage. However, the positive peaks of noise voltage are reduced and cannot maintain the thyratron in operation. The plate relay then opens and voltage is applied to the screen of the audio-frequency output tube, placing the output channel in operation.

If an adjacent-channel signal of sufficient strength is present, the early radio- and intermediate-frequency stages tend to saturate and reduce the noise signal on the limiter grids. With sufficient input signal, the limiter grid bias will drop to zero, in the absence of noise pulses from the early stages, as will the discriminator output voltage in the absence of noise. The discriminator output voltage also is applied to the grid of the thyratron through suitable isolating filters and the thyratron bias becoming zero, the tube remains fired. This effect protects the receiver against adjacent-channel input signals of all signal levels.

3.2 Crystal Oscillator

The first local oscillator uses a crystal which oscillates directly at the third harmonic of its fundamental frequency. No energy is present at the fundamental frequency. Higher output and greater frequency stability are obtained than from the conventional mode of operation.

3.3 DISCRIMINATOR

The discriminator circuit, shown in Fig. 7, is a double-tuned dual-transformer type. The transformers are tuned to peaks 80 kilocycles apart (1.7 megacycles ±40 kilocycles), and the outputs are phased so that the linear portion of the pass-band curve between the transformer peaks can be utilized as a frequency-modulation discriminator. Adjusting the primary inductance of the lower-frequency transformer will vary the amplitude of the signal in the secondary winding and permit center-frequency zero adjustment.

The over-all sensitivity is such that a 0.5-microvolt radio-frequency signal will produce 20 decibels of thermal-noise quieting, when measured in accordance with the procedure recommended by the Radio Manufacturers Association.

The audio-frequency system utilizes a 6V6-GT output tube driven by a 6AQ6 amplifier. A maximum output of 1.5 watts is obtained, and about 1 watt with not more than 10-percent harmonic distortion.

The over-all battery drain for the receiver in mobile service is about 6 amperes, stand-by, and 7 amperes in full operation. A power supply, employing an OZ4A gas rectifier tube is used for 6-volt operation. This is replaced by a conventional full-wave rectifier using a 5Y3-GT tube when in land-station service.

4. Land-Station Console

The land-station console, shown in Fig. 8, is a complete self-contained equipment which will fit on top of a standard office desk. It is designed specifically for operation with the mobile radio equipment already described, and contains the special Selecto Call oscillator-modulator circuits. The equipment includes a 50-watt transmitter, power supply, speech amplifier, and receiver. A second receiver may be included for monitoring. All units are of the plug-in type. The sloping front panel minimizes glare on the meter and clock windows. Chrome-plated trim and a baked gray wrinkle finish make for attractive appearance.

Fig. 8—Land-station console containing 50-watt transmitter, power supply, speech amplifier, receiver, and monitoring receiver.

The transmitter and receiver are interchangeable with the corresponding units of the mobile equipment, except that power supplies are changed to permit operation from 117-volt 50/60-cycle mains. The receiver is not equipped with the Selecto Call decoders and will, therefore, respond to all mobile transmissions. Fig. 9 is a rear view, which discloses how these standard units are mounted in the console.

When calling a mobile receiver that is using Selecto Call, the land-station operator must first select, by depressing a push button, the decoder frequency to which the mobile receiver will respond. To call several groups of cars, the station operator may depress the desired push buttons in any order.

Operation of a lever switch automatically transmits the Selecto Call signal for about one second. The transmitter remains on as long as this switch is operated. A panel light indicates the completion of the calling signal and that the equipment is ready for the attention tone or speech. Depressing the attention-tone lever, transmits an 800-cycle note.

Gripping the microphone handle permits voice modulation if neither lever switch is depressed. The microphone switch also turns on the transmitter and permits immediate speech and rapid back-and-forth communication with the mobile unit. If the lever switches are depressed simultaneously and the operator starts to speak or transmit attention tone before the completion of the calling signal, the calling signal will take precedence over the other signals. Likewise, attention tone takes precedence over speech.

4.1 Transmitter Power Supply

The transmitter power supply operates from the 117-volt alternating-current mains and supplies heater, relay, and plate power to the transmitter. The 6-volt relay power is obtained from a bridge-type selenium rectifier and filter. Plate power is obtained from a conventional full-wave rectifier circuit using a 5R4-GY vacuum tube. Heater power is taken from the secondary winding of the filament transformer.

4.2 Speech Amplifier

The speech amplifier includes oscillators for four Selecto Call signals, an 800-cycle attention tone, and a 7000-cycle subcarrier. It also contains a modulator, a two-stage preamplifier, and a modulation level limiter. The Selecto Call oscillators generate the low-frequency signal to which the receiver decoders are responsive. The 7000-cycle oscillator provides the carrier for the low-frequency signal; their combination occurs in the modulator stage. The timing of the Selecto tone transmission is controlled by a large capacitor in series with a relay; the relay opens and breaks the Selecto oscillator circuits after an interval of about one second.

4.3 Preamplifier

The preamplifier provides gain for the crystal microphone and consists of one stage of audio-frequency amplification, one limiter stage, and one power output stage, employing 6SL7-GT, 6AL5, and 6V6-GT tubes, respectively. A conventional resistance-coupled circuit is used.

The function of the limiter is to provide constant amplifier output to keep the transmitter frequency deviations within the required limits of ±15 kilocycles. The circuit is arranged so that one-half of the 6AL5 limits the positive peaks of modulating voltage and the other half controls the negative peaks. The limiter is capable of maintaining output variations to with-

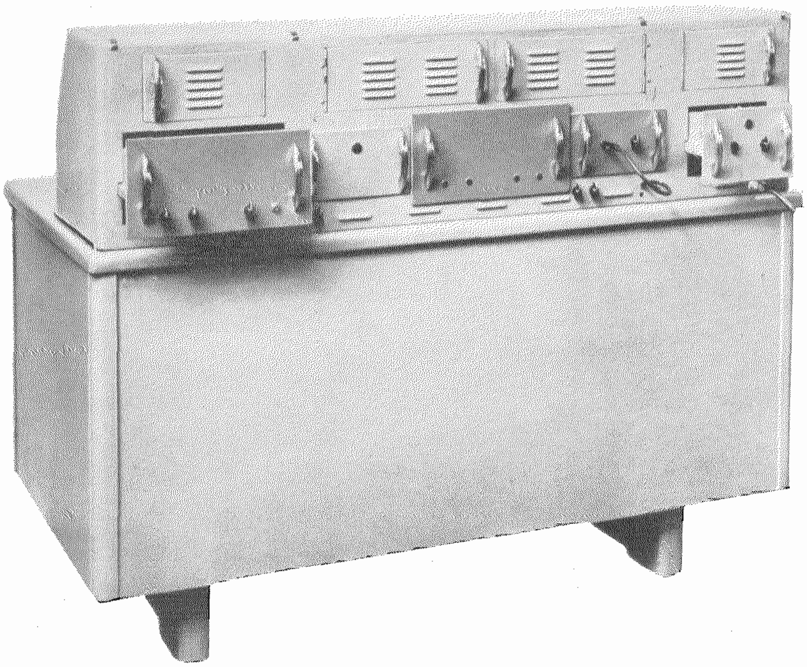


Fig. 9—Rear view of land-station console showing how the component units are mounted.

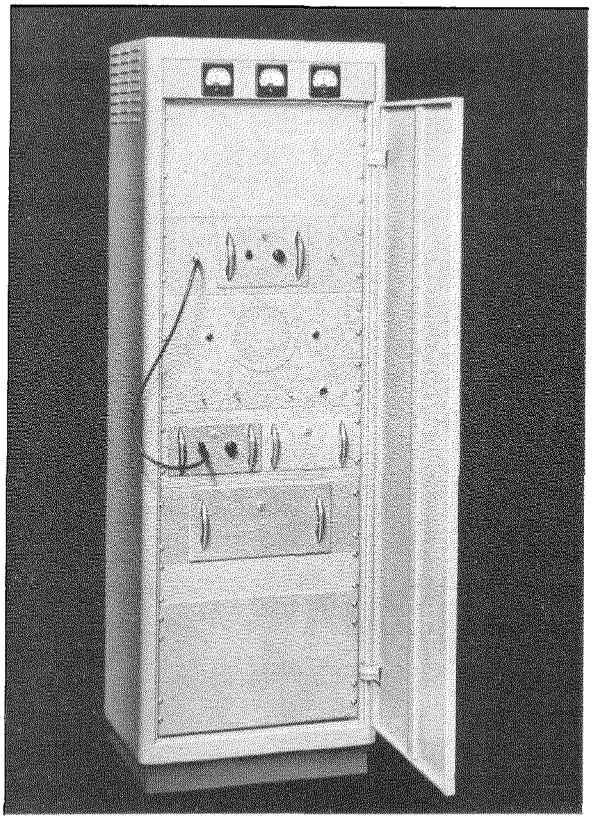


Fig. 10—Remotely controlled land-station 250-watt transmitter and receiver, front door open.

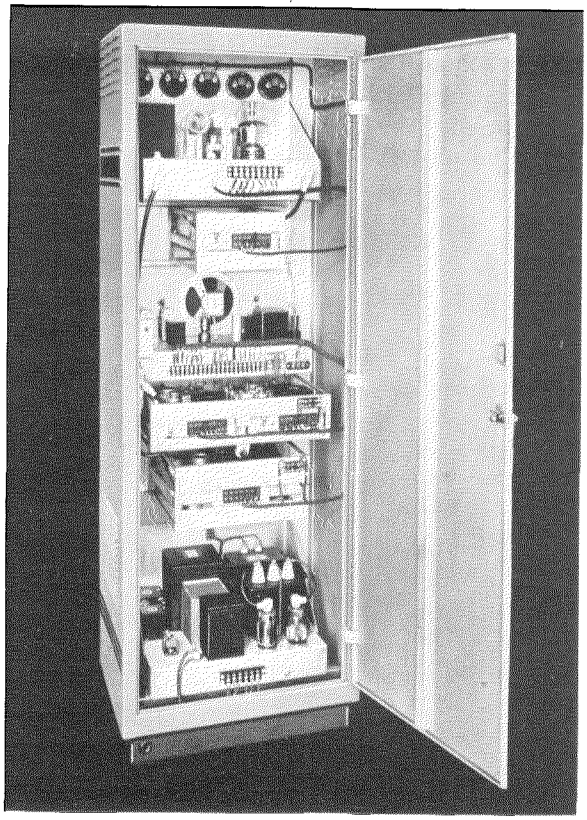


Fig. 12—Rear view of 250-watt remotely controlled equipment, with door open.

in 10 decibels for a 40-decibel variation of input signal. This provides constant output for all normal microphone uses. The level at which limiting begins, as well as the output of the amplifier, may be adjusted by potentiometers at the rear of the console.

4.4 Selecto Call Oscillators

Each Selecto Call oscillator is a two-tube Wien bridge. One section of a 6SL7-GT and of a 6SN7-GT, both dual triodes, is used for each oscillator. Components have been chosen to provide optimum frequency and amplitude stability. The subcarrier and attention tone are also generated by similar Wien bridge oscillators.

4.5 Modulator

The modulator stage consists of a dual-triode 6SN7-GT connected as a conventional Heising amplitude modulator. The modulator is very

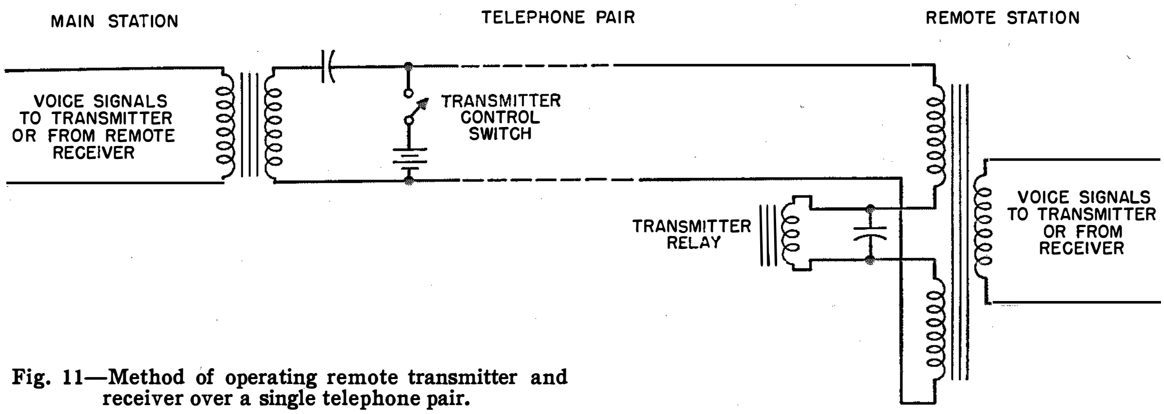


Fig. 11—Method of operating remote transmitter and receiver over a single telephone pair.

simple and produces practically 100-percent modulation of the 7000-cycle subcarrier by the low-frequency Selecto signal. A tank circuit resonant at 7000 cycles is shunted across the output to pass the subcarriers but not the low-frequency signals.

5. Remote-Station Equipment

It is not always possible for a single land station of reasonable power to cover completely the area which must be protected by an emergency service. Consequently, remotely located transmitters and receivers are necessary in some installations where the area to be covered is extensive or where highly industrialized regions cause abnormal attenuation of radio waves and high noise levels, both radio and acoustic.

The equipment, shown in Fig. 10, includes a 50-watt transmitter, one or two receivers, a line-terminating unit, and a transmitter power supply. The transmitter and receiver units are the same as those used in mobile service. This apparatus may be remotely controlled over a telephone line. It operates from a 117-volt, 50/60-cycle source.

The control console is similar in appearance and manner of operation to the main-station console. It provides all the controls and facilities required for operating the remote transmitting and receiving station from a location as far as 20 miles from the main station, and includes a speech amplifier and remote-control unit.

The speech amplifier is identical to the unit in the main-station console; the audio-frequency output is connected to a 600-ohm telephone line. The signals received over the telephone line from the remote receiver pass through the amplifier. The Selecto Call, attention tone, and other circuits operate as previously described.

The remote-control relay unit includes power-level controls for the telephone line, microphone and loudspeaker, and control relays, as well as matching networks necessary to permit remote operation of the transmitter and receiver units. Both audio-frequency and control signals are transmitted over a single line as shown in Fig. 11.

The transmitter-receiver cabinet is arranged to permit receivers tuned to different frequencies to be used over the same telephone line so one operator may monitor several stations. The circuit is arranged so that in the event of simultaneous reception through both receivers, the guard or monitor receiver is automatically silenced.

6. Higher-Power Transmitter

A remotely controlled land station of higher power is shown in Fig. 12. It employs a 250-watt power amplifier and a higher-voltage plate supply. The 25-watt transmitter functions as an exciter for the power amplifier, which employs a 4-250 vacuum tube in a single-ended stage. Tuning is accomplished from the front panel. A current overload relay removes plate voltage to avoid damage to tubes and components in the event of any failure. A blower, thermostatically controlled, provides positive ventilation. The cabinets for both remote stations have individually locked doors, the rear door being electrically interlocked to avoid danger from high voltages.

7. 152—162-Megacycle Equipment

In addition to the 30–44-megacycle equipment described above, there has been developed similar apparatus for operation in the 152–162-megacycle band. The equipments differ only in circuit details; over-all sizes, methods of operations, and available equipments are identical.

The 30–44-megacycle equipments have their major application in rural services where large relatively noise-free areas are to be covered. The 152–162-megacycle equipments, although not providing quite as great a distance range, are more suitable for congested urban areas where ambient noise may be high. Measurements have shown that static and man-made radio noise is much less at the higher frequencies as compared with 30–44 megacycles, so that coverage will probably be better using 152–162 megacycles in such noisy areas because of the improved signal-to-noise ratio.

Medium-Power Triode for 600 Megacycles*

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THE air-cooled triode, L600E, was developed to produce a peak pulse power of 25 kilowatts at 600 megacycles for radar operation. The water-cooled 6C22 was then developed to provide higher efficiency in continuous-wave operation at that frequency. The construction and characteristics of these tubes are described. In an experimental crystal-controlled transmitter, the 6C22 has delivered 500 watts at 600 megacycles.

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The large peak power required by pulse radar systems demands vacuum tubes capable of delivering high peak emission currents at high voltages. The tubes are usually employed as oscillators and the modulation, in the form of the pulses, is applied to the anode. The pulse is, thus, the envelope of several radio-frequency cycles. The radio frequency is determined by the oscillator circuit constants.

The high instantaneous voltages that exist during operation make it desirable to avoid spacing insulators between tube electrodes and to lengthen the external glass paths as much as possible. At the same time, rigidity of the electrode structure must be attained.

Interchangeability of tubes in any equipment is necessary and applies not only to the electrical characteristics, but to the physical mounting of the tube in the circuit as well.

In addition, the tubes must maintain their original characteristics and the available thermionic emission must not decay appreciably over long periods of operation. Satisfactory life requirements have been met in pulse radar tubes employing either thoriated-tungsten filaments or indirectly heated oxide-coated unipotential cathodes.

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1. L600E

As radar development proceeded, it was evident that higher frequencies and powers had much to offer in increasing accuracy and range. Consequently, the development of a tube capable of delivering peak pulse powers of 25 kilowatts at 600 megacycles was undertaken in the latter part of 1941. After several designs had been made and tested, a developmental tube known as the L600E proved most promising. Technical information on this tube is given in Table I.

TABLE I

CHARACTERISTICS OF L600E

Filament	Thoriated Tungsten
Filament volts	6
Filament amperes	13.5
Amplification factor	20
Mutual conductance (ma/volt, $I_b=2a$, $E_c=-100v$)	10
Maximum anode volts (pulse)	25,000
Maximum anode dissipation (kilowatts)	0.3
Capacitance ($\mu\mu f$) C_{gp}	4
C_{gf}	5
C_{pf}	0.25

The L600E consists of a bifilar thoriated-tungsten-filament emitter with its electrical center brought out to a pin terminal, a squirrel-cage-type grid, and a re-entrant copper anode with a bayonet ring at its lower end to provide a simple means for securing and positioning the tube in the socket.

With anode modulation in a concentric-line-type oscillator circuit, 25 kilowatts of peak power output could be produced at 600 megacycles by a single tube. In one application using grid modulation, 7200 anode volts, and 1.62 pulses per second, each of 200 microseconds duration, 7.3 kilowatts of peak power were developed at 600 megacycles and 33 percent efficiency.

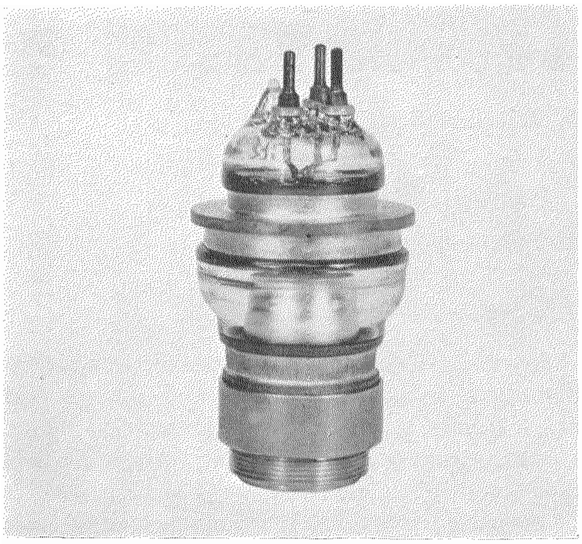


Fig. 1—6C22.

In high-frequency tubes, transit-time effects must be seriously considered. By decreasing interelectrode clearances, the deleterious effects of the long time of electron travel compared with the period of the applied potentials are reduced. Transit-time effects are also decreased when high anode voltages are employed. Thus, a tube that may operate at a given high frequency with good efficiency under pulse conditions where high voltages are employed, may exhibit very low efficiency in continuous-wave operation at the same frequency because lower anode voltages must be employed.

One result of transit-time effects is that not all electrons emitted by the filament or cathode when the grid is positive reach the anode. Many emitted electrons return to the cathode space-charge region. This causes a decrease in anode current and power output. To increase the anode current, the filament or cathode must supply a larger quantity of electrons to compensate for those electrons which do not reach the anode. It is obvious that the emission capabilities of the filament or cathode must be much greater in high-frequency applications than in low-frequency applications. The emission required may be several times as great as in low-frequency applications where transit-time effects are negligible.

2. *6C22*

While the L600E performed well as a pulse tube, it was unsatisfactory for continuous-wave operation. Employed as a continuous-wave oscillator in a concentric-line grid-separation circuit with 1000 anode volts, the efficiency at 600 megacycles was only 10 percent, although at 300 megacycles the efficiency was 40 percent. Consequently, a design formerly known as the L600N, now designated as the 6C22, was developed.

2.1 Construction

With the exception of the filament terminals and screw-type water jacket on the anode, the 6C22 is similar in outward appearance to the L600E. It is shown with the jacket in Fig. 1 and a sectional view appears in Fig. 2.

Internally, it differs dimensionally from the L600E. The filament-wire diameter is 25 percent greater and the number of turns has been increased by approximately 35 percent. The grid-filament and grid-anode clearances were reduced by approximately 60 percent.

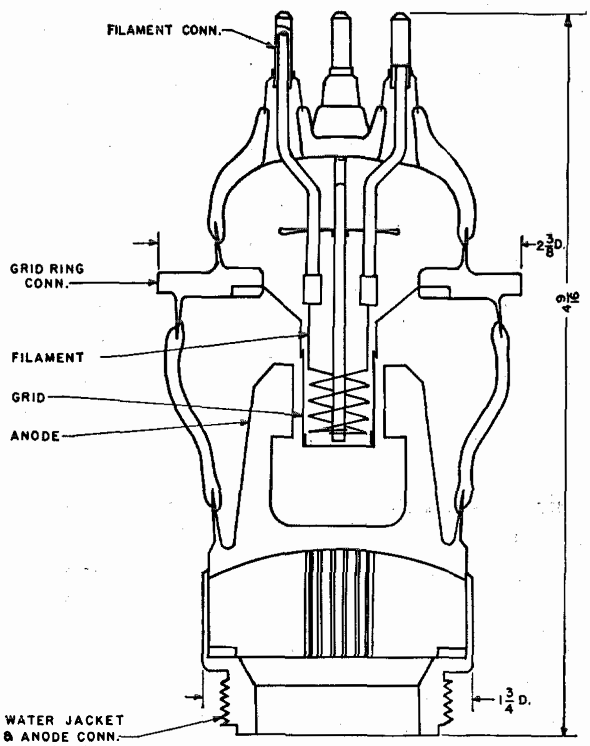


Fig. 2—Cross-sectional view of 6C22.

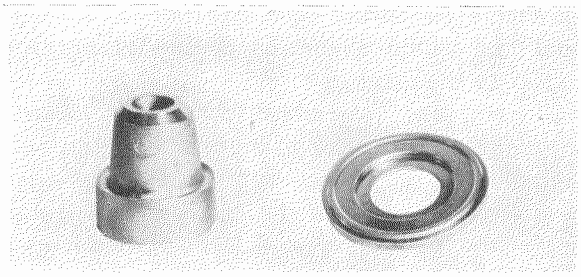


Fig. 3—Re-entrant anode and grid ring of 6C22.

The result of this reduction in clearances and increased filament surface area was a much higher perveance and a lower amplification factor. The additional surface area increased the available thermionic emission.

2.2 Filament

The helical bifilar thoriated-tungsten filament is made of 0.025-inch-diameter wire and has an active emissive surface area of 3 square centimeters. The filament ends and center lead are terminated in monel-kovar cup assemblies sealed to a molded glass flare. This construction has the advantage of great mechanical strength and resistance to impact at the seals.

A shadowgraph comparator with a magnification of 10 times is used to inspect the filament for alignment of the turns to minimize unequal grid heating.

2.3 Grid

The grid is of the squirrel-cage type, consisting of 32 wires, 0.008 inch in diameter, spot welded to and supported by a low-inductance cone. After completion, the grid is cold stretched on the welding mandrel and then hot stretched in vacuum on a special fixture to relieve all stresses and equalize the tension in the cage wires. In addition, this procedure assures equal heating and expansion of the grid in operation. The grid is inspected on the shadowgraph comparator for wire straightness.

2.4 Grid Ring and Anode

The grid ring and the anode are made of oxygen-free high-conductivity copper and lend themselves to fabrication by coining because of their unusual shape. The ring is coined from a washer $2\frac{1}{4}$ inches in outside diameter, 1 inch in inside diameter, and $\frac{3}{16}$ inch thick. Under 250 tons pressure it assumes the shape shown in Fig. 3. The stubs are then trimmed so that they are $\frac{1}{16}$ inch square, and the feather edges are formed from these stubs. The re-entrant anode is coined from $1\frac{5}{16}$-inch-diameter bar stock 2 inches long under 300 tons pressure to the shape shown in Fig. 3 and is then slotted on the water-jacket end. The feather edge is formed in the same manner as that of the grid ring in a conventional machine lathe especially adapted for the purpose. The feather edges are carefully inspected for dimensions and flaws, after which the parts are cleaned and then glassed.

2.5 Assembly Procedure

The present bifilar filament is mounted on the tungsten leads of the molded flare, as shown in Fig. 4, and carburized. This assembly has the prebeaded grid ring sealed to it. Special fixtures

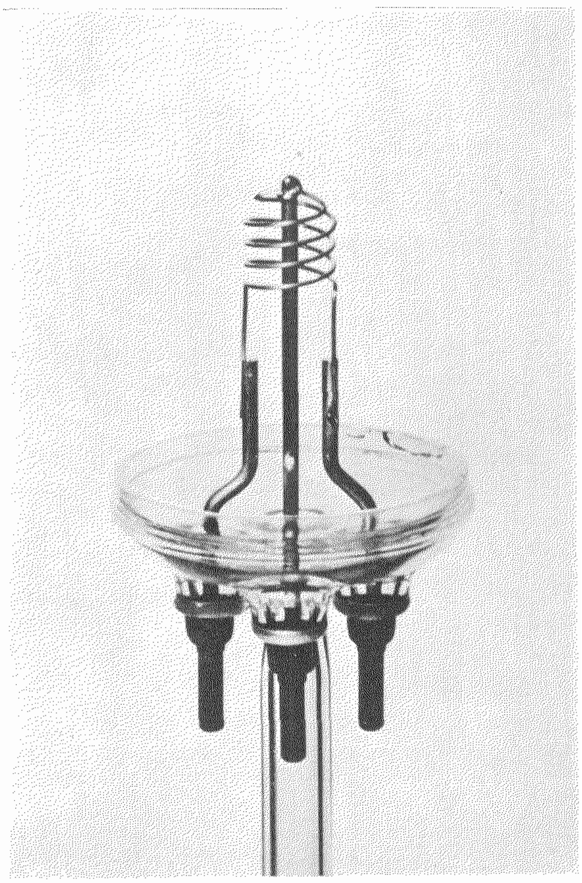


Fig. 4—Filament mounted on molded glass flare.

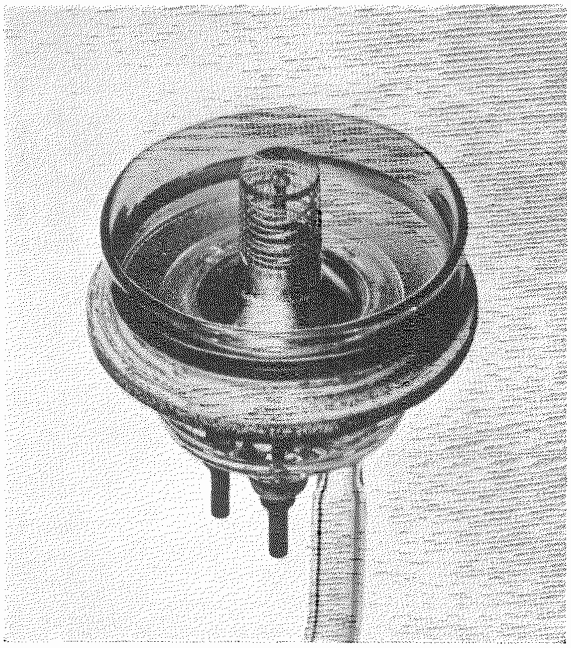


Fig. 5—Grid and filament assembly. The grid connecting ring and cone support may be clearly seen.

are employed during this operation to assure axial and radial alignment of this ring with respect to the filament.

The grid is next assembled to its ring by means of a copper clamp ring and four flat-head screws. Before these screws are tightened, the grid is carefully aligned with the filament by again employing the shadowgraph. The resultant assembly is shown in Fig. 5.

The anode, with glass of proper length and shape already sealed to its feather edge, is now joined to the glass skirt on the grid connecting ring after careful alignment with respect to each other. This operation is shown in Fig. 6.

During all sealing operations, an atmosphere of nitrogen gas is employed to prevent oxidation of the tube parts.

2.6 Characteristics

As a result of the care used in making and assembling the electrodes, the electrical char-

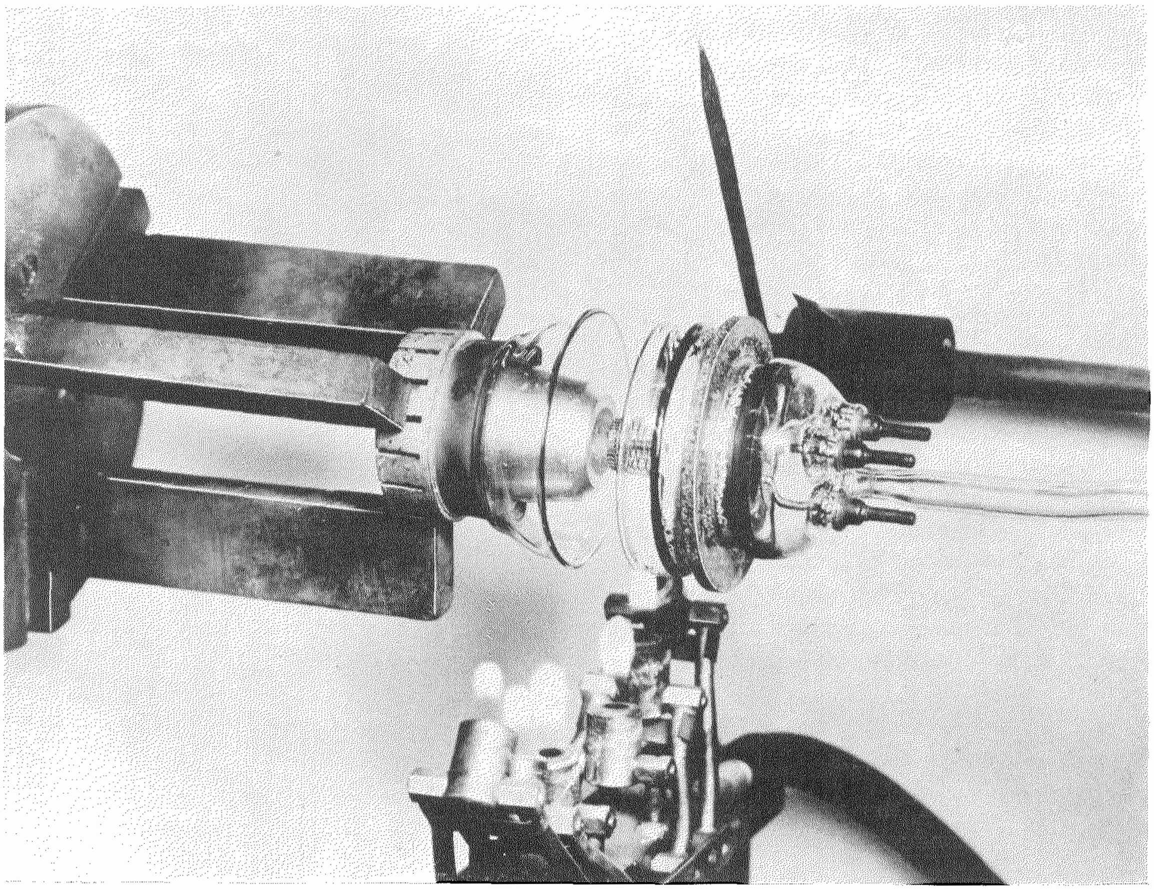


Fig. 6—The glass-mounted anode, held by the jaws of the lathe chuck, and the filament-grid assembly are joined at the two glass surfaces.

TABLE II
CHARACTERISTICS OF 6C22

Filament	Thoriated Tungsten
Filament volts	6.5
Filament amperes	18
Amplification factor	9
Mutual conductance (ma/volt, $I_b = 3a$, $E_c = -100v$)	13
Maximum anode volts	3000
Maximum anode dissipation (kilowatts)	2
Maximum grid dissipation (watts)	25
Capacitance ($\mu\mu$f) C_{fp}	6
C_{gf}	7
C_{pf}	0.4

acteristics are very uniform. They are given in Table II.

Constant-current curves are shown in Fig. 7. A typical curve of grid watts and primary grid current is shown in Fig. 8. A curve of current division between anode and grid for the same applied voltage on both electrodes is shown in Fig. 9. The average ratio of anode-to-grid current is 2.5 to 1.

A flow of water of 0.5 to 1 gallon per minute is necessary and sufficient to cool the tube in operation.

3. *Tests and Results*

Typical operating conditions for oscillator and amplifier are shown in Table III.

Most of the recent studies of this tube have been made at 600 megacycles with continuous-wave operation. At this frequency, it has been studied as an oscillator and as a neutralized amplifier in a grid-separation circuit. It has also been operated successfully as a doubler from 240

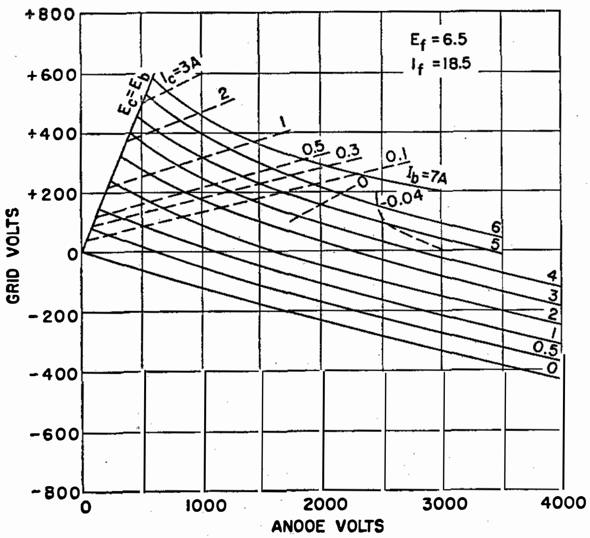


Fig. 7—Constant-current curves of the 6C22.

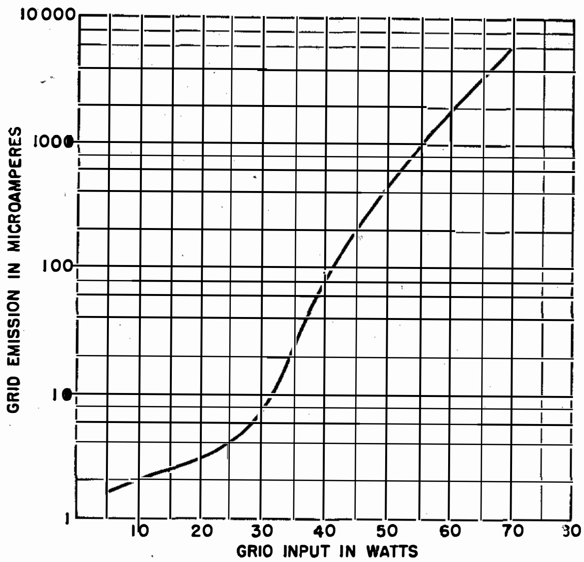


Fig. 8—Primary grid current plotted against grid input power.

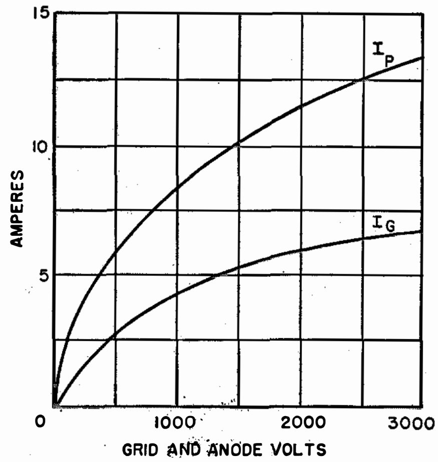
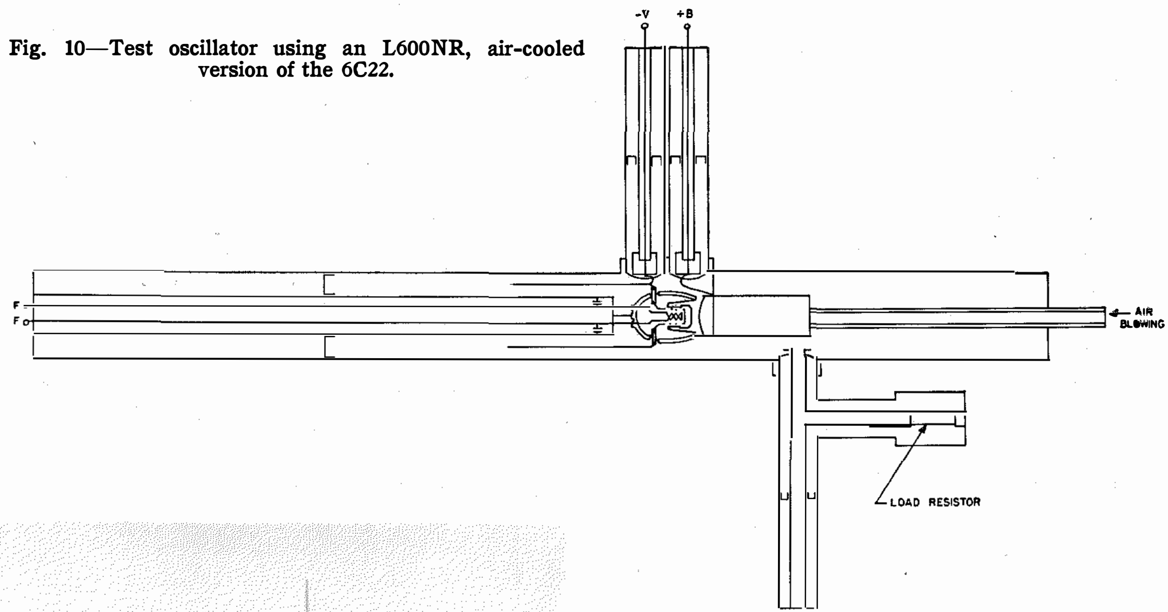


Fig. 9—Current division between anode and grid with the same voltage applied to both electrodes.

TABLE III
TYPICAL EXPERIMENTAL OPERATION OF 6C22

	Oscillator	Neutralized Inverted Amplifier
Frequency (megacycles)	600	600
Anode direct volts	1200	1600
Anode direct current (amperes)	0.6	0.65
Anode power input (watts)	—	1040
Grid direct current (amperes)	0.050	—
Power output (watts)	250	500
Driving power (watts)	—	190
Power gain	—	2.6
Anode dissipation (watts)	470	—
Efficiency (percent)	35	—

Fig. 10—Test oscillator using an L600NR, air-cooled version of the 6C22.



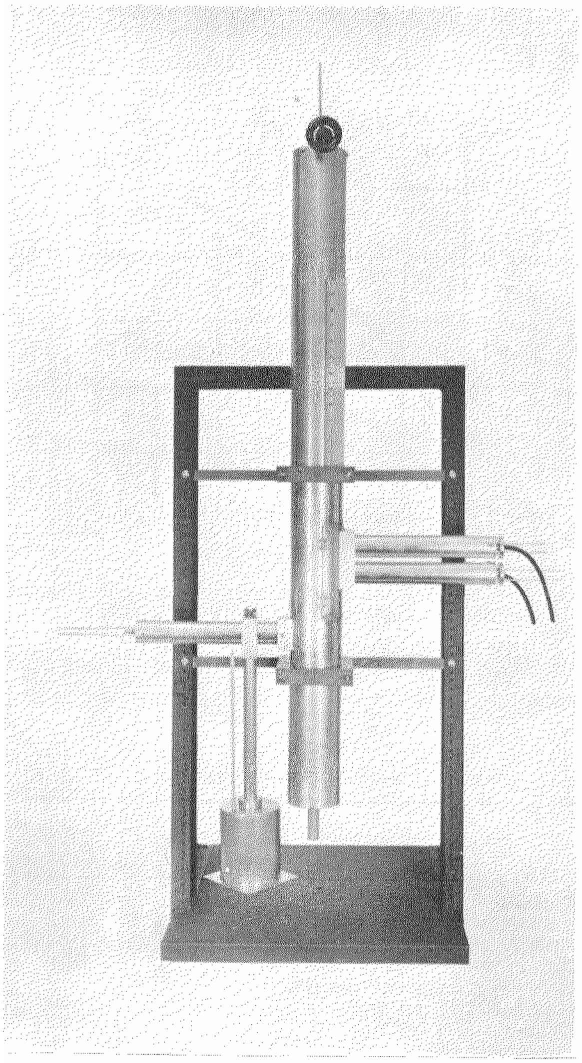


Fig. 11—Experimental setup of test oscillator with calorimeter load.

to 480 megacycles and as a tripler from 200 to 600 megacycles. The performance data under these conditions are given in Table IV.

In all cases, the circuits used are of the coaxial type to assure uniform current distribution and thereby reduce losses to a minimum. This is

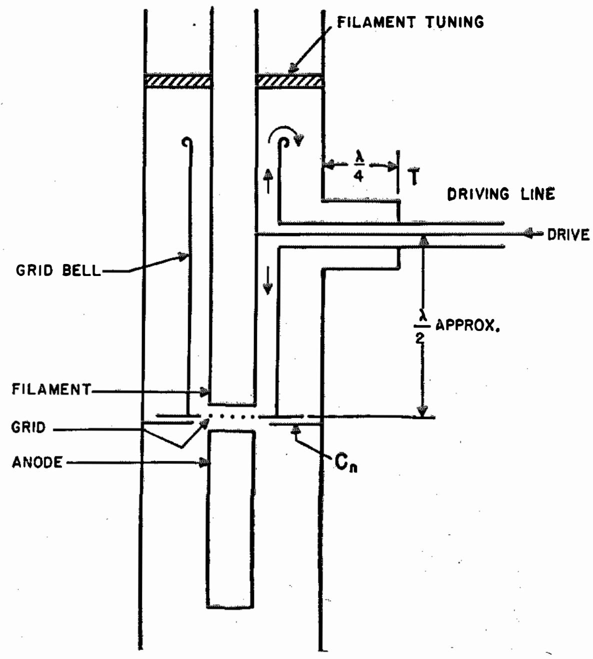


Fig. 12—Neutralization arrangement.

desirable in any case, but is particularly necessary to protect the grid seal from over-heating caused by high current concentration.

A diagrammatic view of a test oscillator using an air-cooled developmental version of the 6C22 known as the L600NR is shown in Fig. 10. A view of the experimental set-up with calorimeter load is shown in Fig. 11. Anode voltage and grid bias voltage are brought in through quarter-wave chokes. The cathode circuit is piston tuned, while the anode is adjusted for "half-wave-length" open-line operation. Radio-frequency output is coupled to the load by means of a capacitive pickup and matching section.

A hollow brass cylinder, connected at one end to the grid ring, open at the other end, and commonly termed a "grid bell," is adjustable in length, and serves to determine the amount and phase of feedback from output to input circuits.

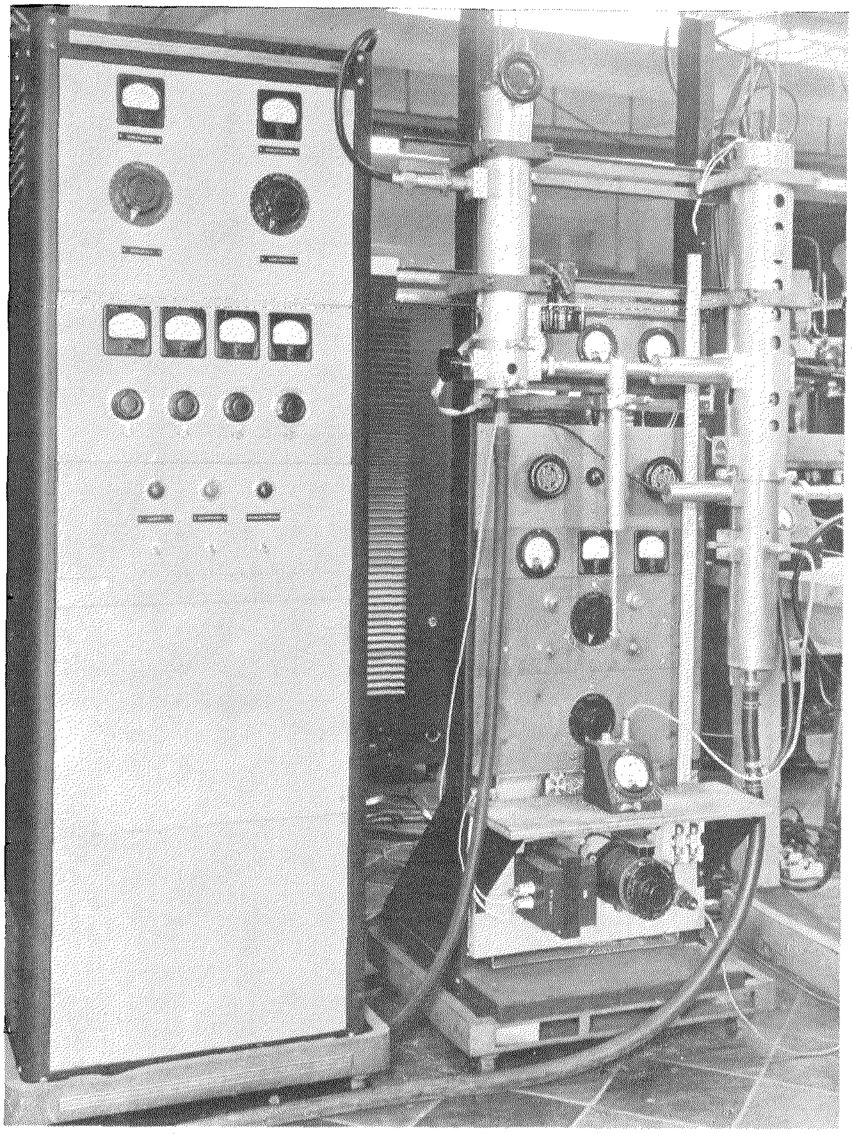


Fig. 13—Laboratory model of crystal-controlled transmitter delivering 500 watts at 600 megacycles. The exciter operates a 6C22 tripler at the left which drives the final 6C22 amplifier at the right.

Cooling air is brought to the anode through a dielectric pipe which extends into the inner region of the anode-line cylinder. In the case of the 6C22, which is liquid cooled, two dielectric pipes of small diameter are used.

TABLE IV

TYPICAL OPERATING CONDITIONS FOR 6C22

	Frequency Doubler	Frequency Doubler	Frequency Tripler
Input frequency (megacycles)	240	240	200
Output frequency (megacycles)	480	480	600
Anode direct volts	1500	1700	1100
Anode direct current (amperes)	0.540	0.640	0.275
Anode power input (watts)	810	1080	—
Grid direct volts	−430	−430	−400
Grid direct current (amperes)	0.025	0.025	0.020
Power output (watts)	285	360	100
Driving power (watts)	—	—	150
Efficiency (percent)	35	33	33

When operated as a neutralized grounded-grid amplifier, results are obtained as given in Table III. Neutralization may be considered to have a twofold purpose. The first purpose is to reduce regeneration to prevent oscillation or to eliminate feedback through the tube entirely. The second purpose is to reduce interaction between the amplifier output circuit and its driving circuit to a minimum.

At lower frequencies these conditions can be satisfied simultaneously by the adjustment of a single parameter because the output terminals of the driver and the input terminals to the active elements of the grid-cathode structure can be considered electrically identical. At ultra-high frequencies, where the impedance in the tube leads prevents access to the active tube electrodes, this simplification is no longer valid. Consequently, in general, two separate adjustments are required.

When these requirements, together with the desirability of coaxial-type structures, are taken into consideration, neutralization arrangements such as the example shown diagrammatically in Fig. 12 result. Here C_n is a comparatively large capacitance which permits a small amount of additional coupling between the input and output structures. Simultaneously, the length of the grid bell is adjusted so that the resulting feedback voltage is zero as determined by a null reading in a detector inserted in the driving line. In this manner, the two requirements for neutralization are satisfied.

The amplifier can deliver approximately 500 watts at 600 megacycles when driven either from a doubler or a tripler, or from another amplifier using the same type of tube. Fig. 13 shows a laboratory crystal-controlled transmitter delivering 500 watts at 600 megacycles. The cabinet on the left is an exciter with the following tube complement:

807 crystal oscillator and tripler (to 12.5 megacycles)
807 doubler (25 megacycles)
807 doubler (50 megacycles)
HK54 doubler (100 megacycles)
6C22 doubler (200 megacycles)

This exciter drives the 6C22 tripler shown on the rack at the left to deliver driving power to the 6C22 final amplifier (on rack at right) at 600 megacycles.

A neutralized water-cooled amplifier using a 6C22 has been grid-modulated satisfactorily in a television transmitter with video-frequency components up to 10 megacycles at a carrier frequency of approximately 500 megacycles. The synchronizing peak power output was 1 kilowatt.

Satisfactory life tests have been conducted on the 6C22 as a continuous-wave oscillator at 535 megacycles with 725 watts input, 35 percent efficiency, for 500 hours.

Vibration tests in both the horizontal and vertical mounting positions show no failures up to 11 g, with 120 watts of filament and 20 watts of grid power applied during the test.

4. *Acknowledgment*

Acknowledgment is made of the contributions to this development by P. G. Chevigny, who originated the design of the tubes, and to G. Lehmann for theoretical analysis of the tubes and circuits.

Standard Telephones and Cables Issues Second Edition of Reference Data for Radio Engineers

In 1942, Standard Telephones and Cables, Ltd., London, produced a small handbook, "Reference Data for Radio Engineers," catering primarily for the needs of British engineers. In 1943, Federal Telephone and Radio Corporation produced a companion volume under the same title, but primarily intended to meet American requirements. Both books were so well received that second, and considerably enlarged, editions were published in both countries in 1946.

The compilers of these two volumes, working independently, but within the common framework of the I.T.&T. System, have of course been able to take advantage of each other's work, and while each volume has an individuality in style and arrangement corresponding to its country of origin, both volumes also bear the System stamp in respect of the breadth and technical treatment of the fields with which they deal.

Triodes for 3- and 10-Kilowatt Frequency-Modulated Transmitters

By P. I. CORBELL, JR. and H. R. JACOBUS

Federal Telephone and Radio Corporation, Newark, New Jersey

TRANSMITTING TRIODES, 7C26 and 7C27, designed for low and medium power in the new frequency-modulation broadcasting band are described. They permit from 1 to 10 kilowatts of output power to be generated with a minimum number of triode amplifier stages. Mechanical and electrical design features are discussed.

• • •

Assignment of the frequency band from 88 to 108 megacycles per second by the Federal Communications Commission to frequency-modulation broadcasting resulted in a need for a completely new line of power transmitting tubes. The 7C26 and the 7C27 were designed for the output stages of 3- and 10-kilowatt transmitters, respectively.

The smaller tube, type 7C26, will give a power output of 1.5 kilowatts and is designed for use in a grounded-filament circuit, as neutralization at low power is not difficult. It is of conventional design with the concomitant advantages of low cost and ease of production.

At the next higher power level, neutralization becomes more difficult because of the higher voltages and capacitances encountered. Therefore, the design of the 7C27 was based on its use in grounded-grid circuits, which do not require neutralization. A pair of 7C27's will easily deliver

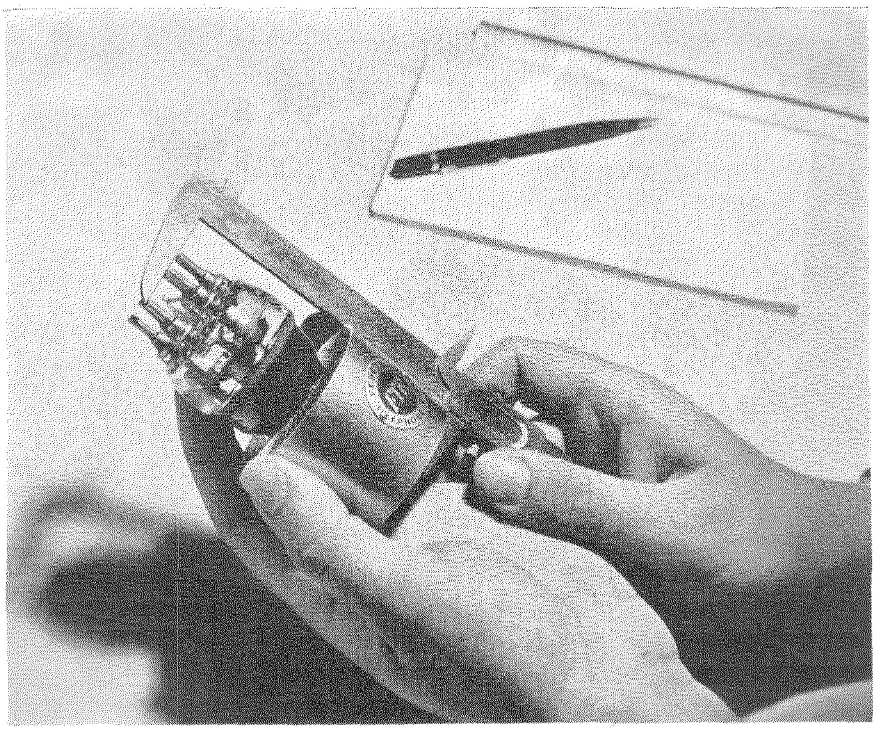


Fig. 1—7C26, air-cooled triode capable of giving 1.5 kilowatts of power at 150 megacycles. The overall length is 4⅜ inches, and the diameter is approximately 2½ inches.

10 kilowatts of output power when driven by a pair of 7C26's.

The operating frequencies impose certain design limitations and introduce problems not encountered in low-frequency work. At these frequencies, tuned circuits are resonant lines because the required small values of inductance and capacitance are impractical in lumped-constant form. The tube interelectrode capacitances that shunt these lines are an appreciable portion of the total circuit capacitances. Similarly, the inductance of the tube electrodes and leads contributes substantially to the total circuit inductance. It is evident that those distributed impedances affect over-all circuit performance and must be minimized to attain satisfactory operation.

The physical length of the two tubes has been reduced to the minimum, consistent with such other design considerations as voltage stress on the glass and heat dissipation. The grid-support structures are cylindrical or cone shaped, have low inductance, and provide good shielding between filament and anode.

Kovar-to-glass seals have been utilized wherever possible because they provide a strong mechanical structure at low production cost.

Forced-air-cooling has been provided by using an adequate and convenient radiator consisting of radial copper fins silver soldered between two copper shells.

At 100 megacycles, electron transit time must be considered. The time taken by an electron to traverse the grid-filament space may approach the period of one radio-frequency cycle if the grid-filament spacing is large. This effects a phase shift in the output current and voltage, and reduces efficiency. Some electrons, accelerated late in the cycle, may be returned to the filament with a resulting loss of radio-frequency output power. It has been found experimentally that tube operating efficiency will not be adversely affected by a total transit time of the order of one-tenth the period of the applied signal.

Close electrode spacings serve to aggravate the grid-emission problem, and it is desirable to choose the maximum spacing dictated by the transit-time limitation. Even with the maximum allowable spacing, primary grid emission was a very serious problem, and exhaustive tests had

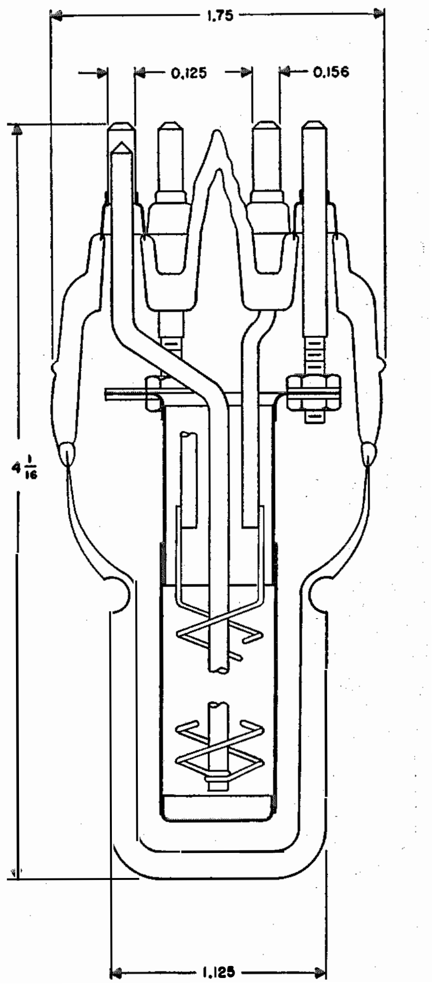


Fig. 2—Plan drawing of the 7C26. There are six base pins, three of which are connected by short leads to the grid structure. The other three are for the thoriated-tungsten filament and its center tap. The radiator is not shown.

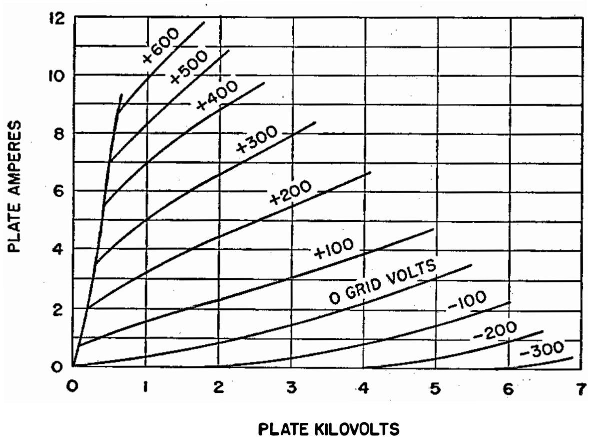


Fig. 3—Average plate characteristics of the 7C26.

to be made on various grid materials. After selecting a satisfactory material, it was necessary to develop suitable methods of processing with particular emphasis on minimizing grid contamination during exhaust. The resulting grid structures are practicable to build and possess electrical characteristics that represent a good compromise between extremely high perveance and negligible emission. In addition, these grids have been made extremely rigid so that uniformity of characteristics may be maintained.

Both tubes have thoriated-tungsten filaments which operate at a lower temperature and require less heating power than pure tungsten for a given thermionic emission. The general characteristics of the tubes are given in Table I, and Table II shows maximum ratings and typical operating conditions.

TABLE I

General Characteristics of 7C26 and 7C27

General Characteristics	7C26	7C27
Electrical		
Filament	Thoriated Tungsten	Thoriated Tungsten
Volts	9.0	16.0
Amperes	28.0	28.5
Amplification Factor	19	30
Direct Interelectrode Capacitances (micromicrofarads)		
Grid-Plate	10.0	14.0
Grid-Filament	11.0	14.0
Plate-Filament	1.0	0.4
Mechanical		
Type of Cooling	Forced Air	Forced Air
Minimum Flow (cubic feet per minute)	75	175
Maximum Over-All Dimensions (inches)		
Length	4.375	8.031
Diameter	2.55	3.532
Mounting Position	Vertical, Anode Down	Vertical, Anode Down
Direction of Air Flow	Up	Up

TABLE II

Maximum Ratings and Typical Operation of 7C26 and 7C27

Class-C Radio-Frequency Power Amplifier and Oscillator without Amplitude Modulation

Characteristic	Typical Operation		Maximum Rating	
	7C26	7C27*	7C26	7C27
Plate, direct volts	3000	4000	3000	4000
Plate Current (amperes)	0.75	1.5	1.0	2.0
Grid, direct volts	−800	−600	−800	−1000
Grid Current (amperes)	0.100	0.200	0.125	0.200
Plate Input (watts)	2250	6000	3000	8000
Plate Dissipation (watts)	680	2350	1000	3000
Power Output (watts)	1570	5150	—	—
Maximum Frequency (megacycles)	108	108	150	110

* In push-pull grounded-grid amplifier with 3-kilowatt driver. All values for one tube.

1. Type 7C26

Type 7C26, shown in Fig. 1, is of conventional construction. Its short structure reduces inductance to a value where grid-ring construction is unwarranted in view of accompanying increased production costs. Instead, three leads are brought from the grid cone to terminal pins at the top of the envelope, permitting symmetry in external connections. This multiple connection, shown in Fig. 2, is essentially a low-inductance arrangement, and permits a balanced distribution of radio-frequency currents to the grid structure. The leads are threaded and connection to the grid cone is by means of nut-and-washer assemblies. This method allows accurate grid-to-filament alignment without demanding subassemblies of unusually close tolerances.

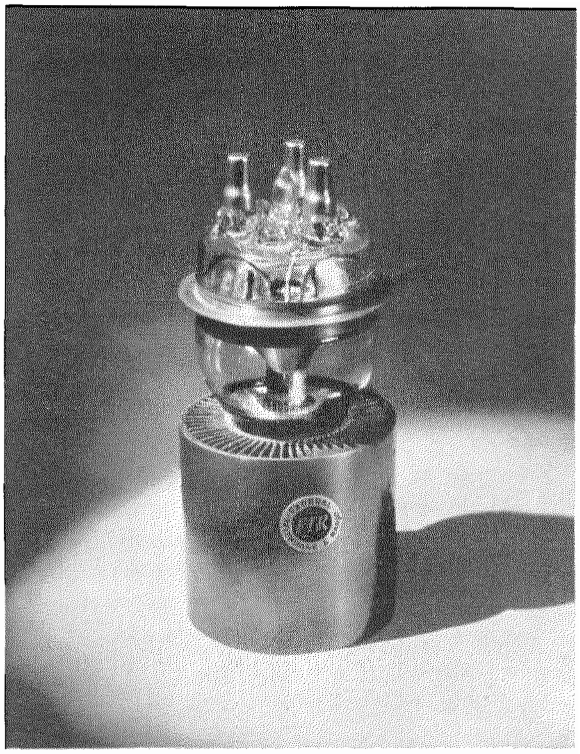


Fig. 4—7C27 air-cooled triode capable of giving 5 kilowatts of power at 110 megacycles.

The filament is a double helix with a center-tap supporting member; external connections are symmetrically located with respect to the grid terminals as may be seen in Fig. 2.

The location of these terminals at the top of the tube envelope permits use of a molded glass dish with filament and grid leads fixed in position by kovar sealing cups.

The anode is grooved, as may be noted in Fig. 2. The reduced wall thickness of this section

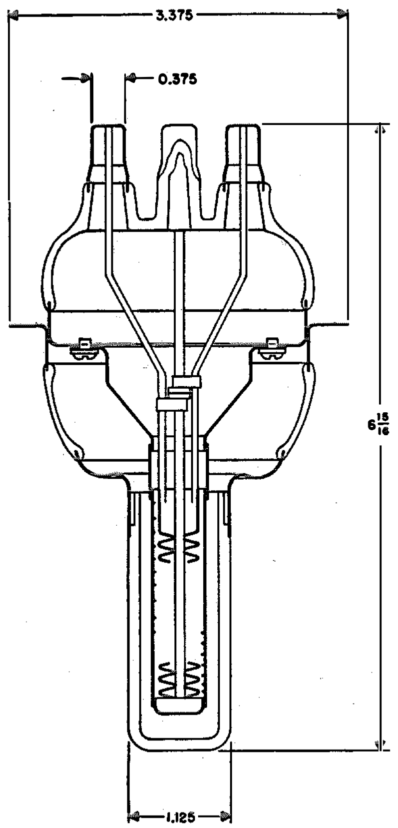


Fig. 5—Plan drawing of the 7C27. The radiator is not shown.

offers resistance to heat flow toward the anode seal area. The main anode body below the groove may be operated during exhaust at a uniformly high temperature while the seal area, subjected to an air blast, remains cool. This permits very thorough anode degassing. An air flow of 75 cubic feet per minute through the radiator allows operation at full ratings. The plate characteristics are shown in Fig. 3.

These tubes have been operated in a push-pull

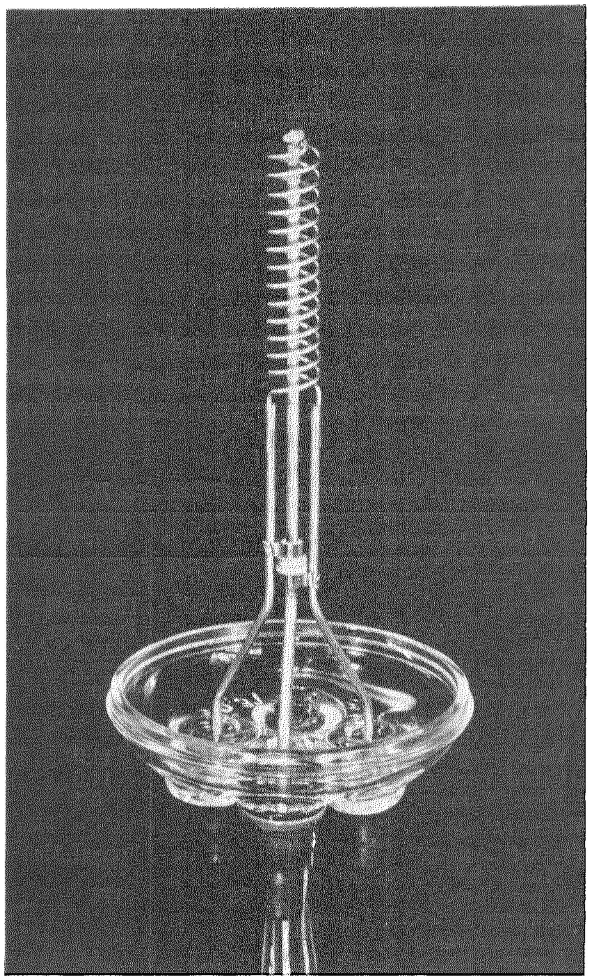


Fig. 6—Filament assembly of the 7C27. The filament leads are strapped to the heavy center-tap rod for rigidity. Small ceramic insulators are used under the straps.

oscillator circuit at 280 megacycles at approximately half ratings and have oscillated at 340 megacycles with lower outputs. At these frequencies, however, the transit-time effects, in addition to decreasing the power output, may seriously affect filament life because of electron back-bombardment.

2. *Type 7C27*

Type 7C27, a photograph of which is reproduced in Fig. 4, will provide 5 kilowatts of output power at 110 megacycles. As the tube design includes a grid ring and a conical grid support, good filament-plate shielding is obtained, and the tube is very satisfactory in grounded-grid circuits. As may be seen in the general assembly

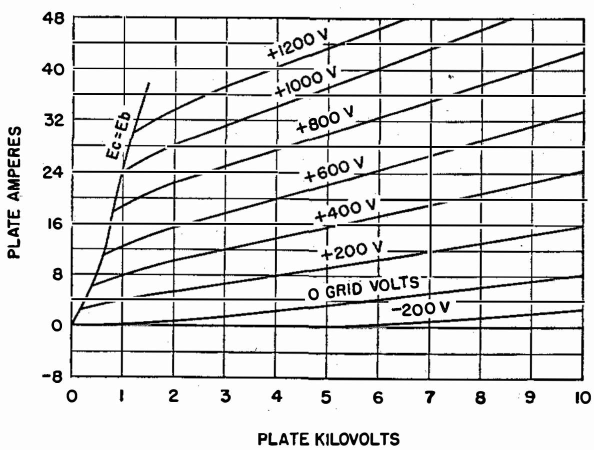


Fig. 7—Average plate characteristics of the 7C27.

drawing, Fig. 5, the tube has a slightly reentrant anode. This serves two purposes. It increases the length of the glass bulb between grid and anode without increasing the over-all tube length, and it eliminates sharp glass contours between these electrodes by providing a large diameter for the anode sealing edge. All glass-to-metal seals are of the kovar rounded-edge type. The grid support consists of a copper cone fused directly to a molybdenum band, using a special radio-frequency brazing technique. This combination of materials aids in simplifying the problem of degassing the grid structure and minimizes radio-frequency losses.

The filament-supporting structure, Fig. 6, is short and simple. Rigidity is improved by mechanically strapping the two leads to the center support rod below the spiral filament. A small ceramic spacer insulates the straps. The center tap provides a connection to the external circuits.

The plate characteristic curves are shown in Fig. 7.

3. Acknowledgment

Acknowledgment is herewith given to the Federal Telecommunication Laboratories for the initial electrical design. Appreciation is extended to Messrs. A. K. Wing, Jr.; W. Happe, Jr.; H. W. Baker; and J. Budig for assistance and suggestions during the development of these tubes.

Insertion Loss and Effective Phase Shift in Composite Filters at Cut-Off Frequencies

By VITOLD BELEVITCH

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THE USUAL METHODS of estimating the insertion loss of a nondissipative filter as a sum of several terms (reflection and interaction losses) fail at the theoretical cut-off frequencies because the reflection losses are infinite, whereas the interaction loss is negatively infinite. By direct calculation, however, very simple formulas for the total loss are obtained, at least in the most practical case of filters having equal or inverse image impedances at both ends. These formulas are also of practical value for dissipative filters, although the usual method could then be applied, because the supplementary dissipative loss is generally small compared to the loss in a nondissipative filter.

All the preceding considerations hold good for the calculation of effective phase shift at cut-off frequencies.

In the first part of this paper, formulas and notations are listed. In the second part, proofs are developed for the main cases.

• • •

1. Low-Pass-Filter Formulas

Let us first consider the case of a low-pass filter having equal image impedances and working between equal ohmic resistances at both ends. The image impedances may be of the constant-k or m-derived type, either mid-series or mid-shunt. The following usual notations are employed:

f_c = cut-off frequency.

$f_1, f_2, \ldots$ = frequencies of infinite image attenuation.

$m_1, m_2, \ldots$ = corresponding parameters of Zobel, defined by

$$m_i = \frac{(f_i^2 - f_c^2)^{\frac{1}{2}}}{f_i}. \qquad (1)$$

$m_t = m$ corresponding to the terminal m-derived image impedances; $m_t = 1$ if image impedances are of the constant-k type.

μ = ratio of the image impedances at zero frequency to the terminating resistances, if the image impedances are of the mid-series type; inverse ratio, if the image-impedances are of the mid-shunt type.

A_c = insertion loss in decibels at cut-off frequency.

B_c = effective phase shift in radians at cut-off frequency.

We then have the formulas

$$A_c = 10 \log_{10} \left[1 + \frac{m_t^4}{\mu^2} \left(\frac{1}{m_1} + \frac{1}{m_2} + \ldots \right)^2 \right], \qquad (2)$$

$$B_c = n\pi - \tan^{-1} \frac{m_t^2}{\mu} \left(\frac{1}{m_1} + \frac{1}{m_2} + \ldots \right), \qquad (3)$$

where n is the total number of entire sections of which the filter is composed; the principal value of $\tan^{-1}$ between 0 and $\pi/2$ must be considered.

These formulas are easily applied to symmetrical low-pass filters having no coincident frequencies of infinite attenuation. The number of terms in the sum appearing in (2) and (3) is then equal to the total number of *entire sections* composing the filter. If there is any multiple frequency of infinite attenuation, it must be considered with its order: for instance, if a filter be composed of two entire sections with $m = 0.5$, and one entire section with $m = 1$, the sum $1/m_1 + 1/m_2 + 1/m_3$ is $2/0.5 + 1/1 = 5$.

In lattice filters, frequencies of infinite attenuation may be imaginary or may occur in conjugate complex pairs. It will be seen from the subsequent proof that (2) and (3) still hold in those cases.

Consider now filters having inverse image impedances at both ends. More precisely, if the terminating resistances and the image-impedances are denoted by R_1, R_2, Z_1, Z_2, the condition

$$Z_1Z_2=R_1R_2 \quad (4)$$

will be assumed, thus producing the equality of the reflection losses at both ends. As in the symmetrical case, both Z_1 and Z_2 are supposed to be either of the constant-k or of the m-derived type. Formulas (2) and (3) are still valid, but it must be observed that the filter now necessarily contains a half section of the constant-k type. This must appear as a term 1/2 in the sum $1/m_1+1/m_2+\ldots.$ and must also be taken into account in the value of n.

By frequency transformation, (2) and (3) are easily extended to high-pass filters and to band-pass filters having a symmetrical characteristic on a logarithmic frequency scale.

2. *Band-Pass Formulas*

For band-pass filters having different attenuation characteristics on either side of the transmitted band, new formulas must be developed, as the insertion loss and effective phase shift will be different at either cut-off frequency. Consider only the case of a symmetrical filter having a constant-k impedance at both ends and working between pure equal resistances.

The following notations apply:

f_{-c}, f_c = cut-off frequencies ($f_{-c}<f_c$).

$f_1, f_2, \ldots.$ = frequencies of infinite attenuation.

$m_1, m_2, \ldots.$ = corresponding parameters defined by[1]

$$m_i=\left(\frac{f_{-c}}{f_c}\times\frac{f_i^2-f_c^2}{f_i^2-f_{-c}^2}\right)^{\frac{1}{2}}. \quad (5)$$

$$\rho=(f_c/f_{-c})^{\frac{1}{2}}+(f_{-c}/f_c)^{\frac{1}{2}}. \quad (6)$$

μ = ratio of the image impedances at the frequency $(f_{-c}f_c)^{\frac{1}{2}}$ to the terminating resistances, if the image impedances are of the mid-series type; inverse ratio if they are of the mid-shunt type.

A_{-c}, A_c = insertion loss at frequencies f_{-c}, f_c.

B_{-c}, B_c = effective phase shift at frequencies f_{-c}, f_c.

The formulas are:

$$A_{-c}=10\log_{10}\left[1+\frac{1}{\mu^2\rho^2}(m_1+m_2+\ldots.)^2\right], \quad (7)$$

$$A_c=10\log_{10}\left[1+\frac{1}{\mu^2\rho^2}\left(\frac{1}{m_1}+\frac{1}{m_2}+\ldots.\right)^2\right], \quad (8)$$

$$B_{-c}=B'_{-c}+\tan^{-1}\frac{1}{\mu\rho}(m_1+m_2+\ldots.), \quad (9)$$

$$B_c=B'_{-c}-\tan^{-1}\frac{1}{\mu\rho}\left(\frac{1}{m_1}+\frac{1}{m_2}+\ldots.\right), \quad (10)$$

where B'_{-c} and B'_c are the image phase constants at the cut-off frequencies.

3. *Derivation of Formulas*

It is known that a symmetrical filter, having an image transfer constant θ and image impedances W, is equivalent to a lattice structure composed of impedances

$$Z_1=W\operatorname{cotanh}\theta/2, \qquad Z_2=W\tanh\theta/2. \quad (11)$$

The insertion loss of a lattice network between resistances R is given by the formula

$$A=20\log_{10}\left|\frac{(Z_1+R)(Z_2+R)}{(Z_2-Z_1)R}\right|. \quad (12)$$

As both Z_1 and Z_2 are purely reactive, the absolute value can be calculated. Using the notation

$$q=\operatorname{cotanh}\theta/2, \qquad w=W/R, \quad (13)$$

the insertion loss becomes

$$A=10\log_{10}\left[1+\left(\frac{jq}{w}\frac{1-w^2}{1-q^2}\right)^2\right], \quad (14)$$

a j factor having been artificially added to the terms enclosed in brackets to make jq/w a real quantity.

The transfer constant θ of a symmetrical low-pass filter may be considered to be the sum $\theta_1+\theta_2+\ldots.$ of the transfer constants of partial filters, each having a single attenuation peak. By (13),

$$e^\theta=\frac{q+1}{q-1},$$

[1] This is not the usual definition of m introduced by Zobel, but differs from it by a constant factor so chosen as to give inverse m for attenuation poles symmetrically located with respect to the midband frequency.

and we may write

$$e^{\theta}=e^{\theta_1}e^{\theta_2}\ldots, \text{ or } \frac{q+1}{q-1}=\frac{q_1+1}{q_1-1}\times\frac{q_2+1}{q_2-1}\times\ldots \quad (15)$$

Each partial q function is obtained by multiplying the q_0 function of a constant-k section by the m parameter corresponding to the attenuation peak, i.e., by the formula

$$q_1=m_i q_0=m_i\frac{\Omega}{(\Omega^2-1)^{\frac{1}{2}}}, \quad (16)$$

where Ω stands for the ratio f/f_c. Solving (15), we have

$$q=\frac{M_n q_0^n+M_{n-2}q_0^{n-2}+\ldots}{M_{n-1}q_0^{n-1}+M_{n-3}q_0^{n-3}+\ldots}, \quad (17)$$

where the M's are the fundamental symmetrical functions of the m_i: $M_0=1$; $M_1=m_1+m_2+\ldots$; $M_2=m_1m_2+m_1m_3+m_2m_3+\ldots$; $M_n=m_1m_2\ldots m_n$.

As the insertion losses of inverse networks are equal, the m-derived image impedance may be assumed to be of the mid-series type.

$$w=\frac{W}{R}=\mu\frac{(1-\Omega^2)^{\frac{1}{2}}}{1-(1-m_i^2)\Omega^2}. \quad (18)$$

At the cut-off frequency, $\Omega=1$, all quantities become zero or infinite because of the factor $(1-\Omega^2)^{\frac{1}{2}}$. The principal value of q is

$$M_n/M_{n-1}(\Omega^2-1)^{-\frac{1}{2}},$$

and that of w is $j\mu m_t^{-2}(\Omega^2-1)^{\frac{1}{2}}$.

$$\frac{M_{n-1}}{M_n}=\frac{1}{m_1}+\frac{1}{m_2}+\ldots \quad (19)$$

By replacing q and w in (14) by these values, (2) is obtained.

The effective phase shift of a lattice structure is given by the formula

$$B=\arg\frac{(R+Z_1)(R+Z_2)}{R(Z_2-Z_1)}, \quad (20)$$

which may be transformed into

$$\tan B=\frac{1+w^2}{jw}\times\frac{q}{1+q^2}=\frac{1+w^2}{2w}\tan B', \quad (21)$$

where B' stands for the imaginary part of θ, i.e., the image phase constant. Formula (3) is then easily derived but it contains implicitly an arbitrary term $k\pi$. The exact value can only be determined by a continuous frequency variation starting from the zero frequency, where both B and B' are known to be zero. As B' is monotonically increasing and the factor involving w in (21) is always larger than 1, the following inequalities hold in the transmitted band:

$$\left.\begin{array}{ll} B'+\frac{\pi}{2}>B>B', & \text{if } k\pi<B'<(k+\frac{1}{2})\pi, \\ B'>B>B'-\frac{\pi}{2}, & \text{if } (k-\frac{1}{2})\pi<B'<k\pi, \end{array}\right\} \quad (22)$$

k standing for any integer. The determination of B_c given in (3) is deduced from the preceding inequalities taking into account the known value $n\pi$ of B' at cut off.

A similar derivation is possible in the case of filters having inverse image impedances, if (4) is satisfied. It may be shown that (14) still holds if q is replaced by

$$q'=\text{cotanh}\left(\frac{\theta}{2}\pm i\frac{\pi}{4}\right). \quad (23)$$

For band-pass filters, similar results are obtained by using the decomposition (15) with the partial functions

$$q_i=m_i\left(\frac{f_c}{f_{-c}}\times\frac{f^2-f_{-c}^2}{f^2-f_c^2}\right)^{\frac{1}{2}}, \quad (24)$$

where m_i is given by (5). The mid-series constant-k image impedance is

$$w=\frac{\mu[(f^2-f_{-c}^2)(f_c^2-f^2)]^{\frac{1}{2}}}{f(f_c-f_{-c})}. \quad (25)$$

To overcome the indetermination arising in the phase expressions, they have been written as differences from the image phase constants.

The general validity of the formulas, even for filters with complex m's, proceeds from the decomposition formula (15), which was first proved by H. W. Bode[2] for band-pass filters and generalized by W. Cauer[3] who introduced the notations q and q' used in this paper.

[2] H. W. Bode, "A General Theory of Electric Wave Filters," *Journal of Mathematics and Physics,* v. XIII, pp. 275–362; November, 1934.

[3] W. Cauer, "Theorie der linearen Wechselstromschaltungen," Akademische Verlagsgesellschaft Becker & Erler, Leipzig, 1941; p. 244.

Portable Direct-Reading Traffic Recorder

By AUGUST F. JONES

Federal Telephone and Radio Corporation, Newark, New Jersey

ESTIMATES of the amount of equipment required for a telephone central office are based on the average number of calls and their duration for the busiest hour in the day. The portable direct-reading traffic recorder described in this paper will indicate the average occupancy of each of four groups of 50 traffic paths from which the traffic in 100- or 120-second calls is directly evident.

1. *General Concept of Telephone Traffic*

The amount of switching equipment required in a telephone exchange depends not only on the number of subscribers' lines served but also on the amount of traffic passing through the exchange in a given time. The traffic varies during the day and from day to day, but estimates of the amount of equipment needed are usually based on the "busy-hour traffic," that is, the average load during the busiest hour of a normal day. The number of calls that can be handled by a group of circuit paths during the busy hour is affected by the length of time each call occupies a path, or the "holding time." Thus traffic intensity involves both "calling rate" and "holding time."

Traffic is usually measured by an equivalent number of calls of a fixed holding time, two popular standards being the 100-second call and the 120-second call. The maximum capacity of a group of 10 paths during one hour is 360 100-second calls, or 36 100-second calls for each path. This assumes, however, that calls arrive at precisely timed intervals, and there is no time during which any path is idle. This is a false assumption, as indicated by the prediction of the formulas of probability that a group of 10 paths can handle 149 100-second calls occurring at random intervals during an hour (with a loss probability of 0.01).

2. *Measurement of Telephone Traffic*

As the number of paths to be provided, and hence the cost of the exchange equipment, depend on the "busy-hour traffic," it is of first importance to be able to measure traffic accurately and conveniently. A common method of measuring the number of calls is by use of "message registers," or meters, one connected to each path in such a way as to be operated each time the path is seized. The total number of calls during the busy hour is obtained by totaling the meter readings, and the average holding time is estimated by making observations with a stop watch, or by other means.

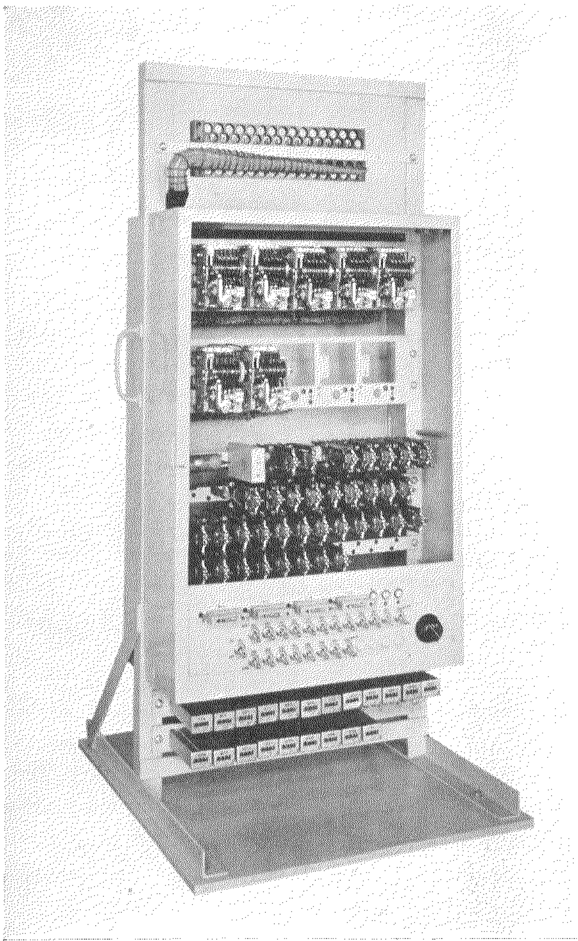
The equipment to be described in this article is designed to avoid any calculation or estimation of holding time and to give a direct reading of the traffic carried by a group or groups of circuit paths in 100-second (or 120-second) calls. It is based on the fact that the total traffic carried by a group of circuit paths during the busy hour is directly related to the average of the number of paths in use at any instant, or more specifically that the average occupancy of a group of paths, multiplied by 36, will give the number of equivalent 100-second calls carried by that group during the hour to which the average applies. For example, if during the busy hour an average of 5 of a group of 10 circuit paths is simultaneously engaged, the equivalent traffic carried by that group during the busy hour is $5 \times 36 = 180$ 100-second calls.

3. *Performance of the Traffic Recorder*

The traffic recorder illustrated can measure the average occupancy of several groups of circuit paths, and give a direct reading in 100-second calls of the traffic handled by each group. Instead of making periodic checks during the busy hour of the number of paths of a group simultaneously occupied, it accomplishes the same result by going through rapidly repeated cycles of testing each path of a group for occupancy, one at a time, adding the total number of occupancies shown by these tests, and dividing by the number of test cycles performed to obtain the average occupancy of the group. This average occupancy is multiplied by 36 to give the traffic in 100-second calls. The machine accomplishes this computation by making exactly 360 test cycles. Each time a path is found busy, a message register assigned to the group of paths under observation is operated, and its complete reading shows the total number of occupancies encountered. Division of this number by 360 and multiplication by 36 are indicated by neglecting the last digit of the message register reading.

The recorder can measure directly the traffic on groups of as many as 50 paths. The tests for occupancy are made through five ratchet-driven selector switches connected in cascade. The message register is connected through the brush of the first switch successively to each of 10 contacts in the arc of the switch, then through the 11th contact to the brush of the 2nd switch, which steps successively over 10 contacts in its arc and then stops on its 11th contact to extend the connection to the brush of the 3rd switch, etc. The stepping is accomplished by means of periodic impulses generated in the recorder. The effect of the five 11-point switches operating in cascade is that of one large switch with an arc of 50 contacts, each contact connected to a separate circuit path. The five separate switches, however, give flexibility and permit traffic measurements of five separate groups of 10 paths each by the use of a separate message register connected to the brush of each switch.

Each of the above-mentioned switches has, besides control levels, 4 levels or rows of terminals to which can be connected circuit paths on which traffic is to be measured. Each level has its own brush and associated message register. Thus, in addition to the group of 50 paths observed as described above, 3 additional groups of 50, or 15 groups of 10, or any intermediate combination, can be observed. Traffic on a group of more than 50 paths can be observed by dividing the group into subgroups of 50 paths or less and adding together the readings of the



subgroups. The number of paths in the groups being observed need not be in multiples of 10. If some of the arc contacts of the selector switches are not connected to circuit paths, tests in these positions will of course never cause an operation of the message register, and the traffic recorded will be that on the paths connected through terminals of the recorder to the selector arcs.

The impulse generator is calibrated to give an impulse every 200 milliseconds, and therefore effect a complete cycle of 50 steps every 10 seconds, or the series of 360 cycles in 1 hour. The impulse frequency does not affect the accuracy of the traffic-recorder readings, however, because these are based on average occupancy during the observation period. The only effect of changing the impulse frequency is to change the length of time over which the results of the 360 test cycles are averaged.

4. *Construction*

The illustration shows a front view of the portable traffic recorder. It is 38 inches high, weighs about 75 pounds, and is equipped with handles for convenience of transportation. At the top is the terminal strip to which connections are made from the paths to be observed. The capacity of the recorder is 200 paths, in groups not exceeding 50 each. The required connections of the message registers within the recorder are also made on this terminal strip. The 20 message registers provide for the maximum number of groups that can be observed at one time, i.e., one for each of the four brushes of each switch.

The 5 selector switches used for the occupancy tests are shown at the top of the equipment just under the terminal strip. Below these are two additional selector switches arranged to count the cycles and to stop the test after 360 cycles of 50 steps each. By changing a strap, the test can be stopped after 300 cycles and the readings will then be in 120-second calls. The 21st message register is used to record the number of cycles completed.

A relay and a toggle switch are associated with each message register. The relay controls the operating circuit of the message register, and the switch connects positive or negative potential to the winding of the relay, depending on which potential appears on the particular circuit path being observed to indicate a busy condition, or occupancy.

The impulsing circuit consists of relays, capacitors, and a variable resistor. The time constant of the circuit, and hence the frequency of impulsing, can be adjusted by the variable resistor, the knob of which is shown to the right of the toggle switches.

Operation of the starting switch causes all selector switches to return to normal position if not already there, and starts the impulsing circuit. The switches step automatically until the required number of cycles has been completed, after which the recorder shuts itself off.

5. *Acknowledgment*

This instrument was originally conceived by Mr. C. F. J. Boehlen, then a member of the Federal Telephone and Radio Corporation engineering staff. The recorder was designed and built under his direction and is now in regular use in an important telephone operating company in the U.S.A.

Comité Consultatif International Téléphonique

By P. E. ERIKSON
Standard Telephones and Cables Ltd., London, England

THE Comité Consultatif International Téléphonique resumed its activities by holding a plenary meeting in London on October 29 and 30, 1945, at which 24 countries were represented. It was preceded by a meeting of technical and operating experts from various telephone administrations and private operating companies.

One of the most important problems concerned the restoration of international telephone service. The general consensus was that it should be done as quickly as possible so as to speed the solution of the problem of feeding the European population and aid in the reconstruction of destroyed property and equipment.

The plenary meeting unanimously recommended that: (A) a certain number of circuits, indispensable for the resumption of European service, should be established at once; (B) the use of radio circuits for overland traffic should be confined to cases where it is manifestly impossible to use wires; and (C) the latent, but heavy, demand for future facilities should be met by establishing a general program of international circuits designed to insure a rapid service of good quality.

The last-mentioned objective, it was pointed out, should be attained by the most modern methods developed for transmission and switching techniques. A special commission was appointed to study this problem.

The commission, known as the Mixed Commission on the European Toll Switching Plan, is composed of operating and technical experts from the various European telephone administrations. It held four meetings and submitted its report to the plenary meeting in Montreux, Switzerland, on October 26 to 30, 1946. The approved plan is to use high-speed multichannel carrier telephone circuits which, as far as possible, are to be carried in cables and laid so as to form a traffic ring around Germany. From the ring there will be traffic spurs radiating outward and inward to toll switching centers not located on the ring. Manual switching is visualized at the start, but rapid operating methods will be applied, one feature of which will be the use of a single toll ticket made out in the country where the call originates. It is also contemplated that it will be possible to route traffic over the ring in both directions in the event of a breakdown in any part of the ring.

The Mixed Commission prepared extensive intercountry circuit tables compiled from data supplied by the various administrations as their best estimates of the traffic to be handled in 1952, three years after the ring is expected to be put in service. On the basis of these data, there will be a considerable number of circuits in the ring. For example, it is estimated that, in 1952, there will be 300 circuits passing through Belgium and France.

The eight regular commissions of Rapporteurs and their subcommissions have resumed the study of questions which were pending since 1939, and have undertaken consideration of new questions that have arisen in connection with the European toll switching plan. It may, therefore, be said that the Comité Consultatif Internation Téléphonique is now operating on a pre-war basis with the same organization as before.

Investigation of Errors in Spaced-Collector Direction-Finder Systems

By T. H. CLARK

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PRINCIPAL sources of errors in design and installation of direction-finder equipment using spaced vertical collector systems are considered. Errors attributable to the site are enumerated. The calculable errors arising from the design of one directional pair are investigated mathematically for particular arrays. General conclusions are applicable as specific design principles.

The errors from combining two orthogonally placed directional pairs are investigated generally and quantitatively as are errors resulting from the use of long cables connecting the antennas to the goniometer. Errors stemming from mechanical misalignment are investigated.

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The purpose of these studies is to determine the principal sources of error in design and installation of direction-finding equipment using spaced vertical collector systems.

The collector system for direction finders of this type usually consists of five vertical antennas placed at the corners and the center of a square. The antennas at diagonally opposed corners are connected so that their outputs are opposed. This results in a figure-of-eight reception diagram for this pair. Such a pair of antennas shown in Fig. 1 will be called a *directional pair.* Each directional pair is a receiving system in itself; however, its directional properties are not useful for direction finding unless a second directional pair is similarly placed on the other diagonal of the same square. The two directional pairs are to be considered as two separate receiving systems. The fifth antenna at the center of the square is a third independent receiving system, having omnidirectional characteristics, and is used for the determination of sense. When it is combined with either or both of the directional pairs, a cardioid diagram of reception plotted against direction will result.

In the examples to be cited below, a direction finder designed for the nominal frequency range of 1.5 to 30 megacycles per second is used. The complete direction finder consists of four arrays, each designed for maximum sensitivity and lowest errors in its particular frequency range. This design proved to be very conservative, and an actual frequency coverage much greater than that originally specified was secured. In Table I, the nominal and the extended frequency ranges for each array are shown.

The sources of errors may be divided conveniently into several groups:

A. Site
B. One directional pair
C. Combination of two directional pairs
D. Goniometer.

These will be investigated mathematically as well as practically, and general conclusions will be drawn as applicable.

1. Site Errors

The errors of the site may be classified as the results of three general effects:

A. Nonhomogeneous ground conductivity
B. Reflections from nearby conductors
C. Absorption obstacles in the path of the waves.

The above sources of errors have been investigated to a certain extent by various writers,

TABLE I

DIRECTION-FINDER SYSTEM USING 4 ARRAYS

Array	Frequency Range in Megacycles	
	Nominal	Extended
1	1.5– 3.3	1.25– 5
2	3.3– 7.5	2.5 –10
3	7.5–15	5 –20
4	15 –30	10 –40

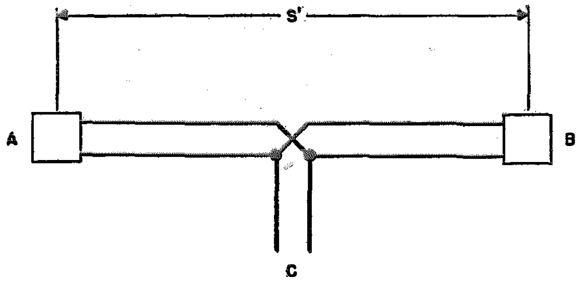


Fig. 1—A two-element array or directional pair equally applicable, from the standpoint of field pattern, to the transmitting or receiving cases.

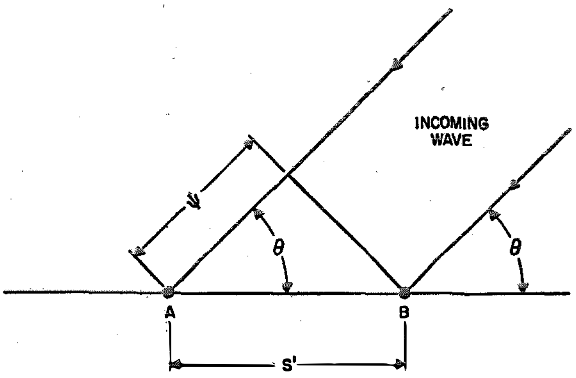


Fig. 2—Factors involved in calculating the receiving pattern of the two-element array (Fig. 1). θ = angle of reception to plane of array. S' = spacing angle = 360 S/λ, where S = actual spacing. $\psi = S' \cos\theta$.

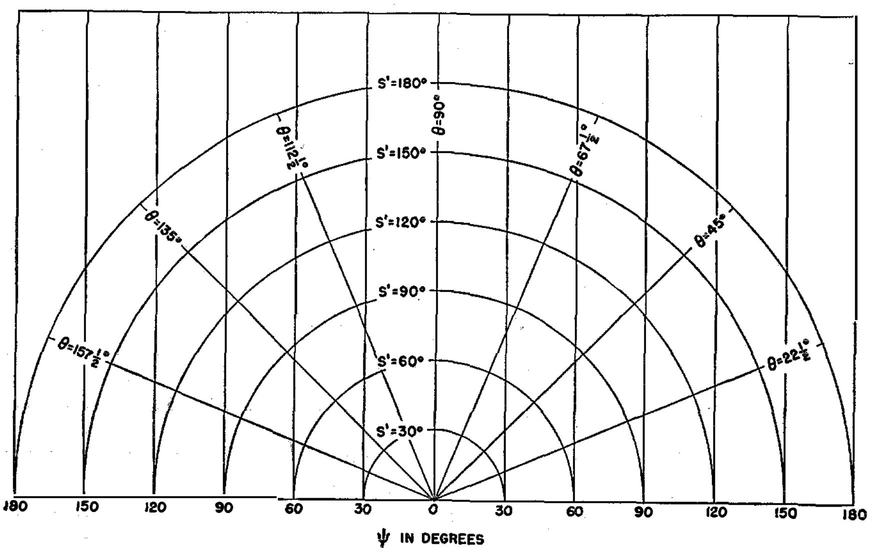


Fig. 3—Graph showing the relationship of ψ, S', and θ.

as well as by the direction-finder group in these Laboratories.[1] Further investigation is very desirable since many of the problems are not yet clearly understood. The investigation of site errors is a complete study in itself, and will not be considered further in this paper as it is largely beyond the control of the equipment designer.

2. *One Directional Pair*

The errors which can be postulated in the design and construction of one directional pair will be investigated by a method which has been used previously to determine the field-strength diagrams of two-element transmitting arrays.[2]

Only those errors which result when the wave is arriving in the horizontal plane, i.e., when the vertical angle is zero, will be considered. The errors resulting from vertical angles of incidence other than zero are complicated by the horizontal-vertical reception ratio of the pair, and lead into another aspect of the subject which deserves special detailed treatment. For this study, therefore, consideration will be given only to the horizontally propagated field which the designer and installation crew can create for test purposes with a local source of emission such as a target transmitter placed on the ground at a distance of several wavelengths from the directional pair or array.

2.1 Directivity of Two-Element Array

The relative field strength at a given angle θ (Fig. 2) from the plane of such a two-element *transmitting* array is given by:

$$E_\theta = 1 + k \times (\cos\alpha + j\sin\alpha). \quad (1)$$

In other words, the relative field strength at

[1] H. Busignies, "Evaluation of Night Errors in Aircraft Direction Finding, 150–1500 Kilocycles," *Electrical Communication*, v. 23, pp. 42–62; March, 1946.

[2] E. A. Laporte, "Directional Antenna Design," *Electronics*, v. 9, pp. 22–25, 48; April, 1936.

any angle θ is equal to 1 plus a constant k at an angle α. This formula serves equally well for reception if the symbols are properly redefined.

Let k equal the ratio of the effective heights of the two elements. (To be discussed in more detail later.)

Let angle α be determined by the combination of the relative phases of the outputs from the two receiving elements at the point of cross connection; defined mathematically as

$$\alpha = \psi + \phi,$$

where ϕ is equal to the relative electrical phase from the two elements, A and B, at the terminal point C of the connecting transmission line (Fig. 1) when a wave arrives simultaneously on the two elements, i.e., when $\theta = 90$ degrees.

Angle ψ is determined by the angle of arrival of the incoming wave, and is equal to $S' \cos\theta$, where θ, as stated above, is the angle of arrival of the incoming wave, and S' is the phase difference in electrical degrees between the voltages induced in the two elements for a wave arriving in the plane of the elements.

Distance S' in electrical degrees is equal to $360\ S/\lambda$. Here, S is the element spacing, and λ is the wavelength, both measured in the same units.

In the determination of the response pattern (or for the solution of (1) above) for a two-element antenna array, one may make use of short-cut graphical methods to determine the angle and resultant response E_θ.

2.1.1 *Determination of ψ and α*

In Fig. 3 we have plotted about a central point a number of circles having radii equal to S' in degrees. From this same center are laid off a number of radii whose angles, with respect to the horizontal axis, correspond to θ the angle of arrival of the waves. To determine ψ for any electrical separation S' and any angle of arrival θ, it is only necessary to determine the intersection of the circle corresponding to S' with the radius θ. The horizontal component of this point of intersection is equal to ψ in degrees. This will be evident from the mathematical treatment above. It is now necessary only to add the phase angle ϕ to the previously determined ψ to obtain α.

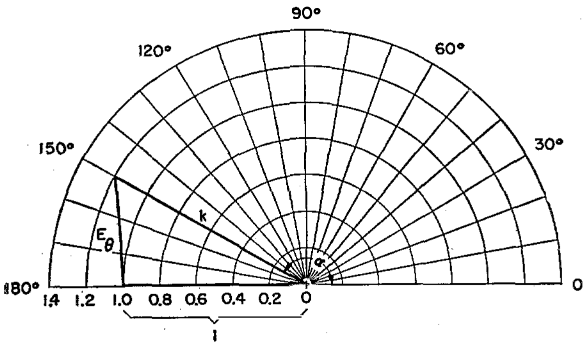


Fig. 4—Graphical solution of E_θ, where α and k are known.

2.1.2 *Determination of E_θ*

The magnitude of E_θ can be determined graphically by the means shown in Fig. 4. On polar-coordinate paper, a distance of one unit at an angle of 180 degrees has been laid off from the center. This represents the unit 1 in (1).

Now, lay off from the center the distance k at the angle α. The length of the line joining the two terminal points is E_θ.

The cases of most interest in direction finding occur when ϕ is very close to 180 degrees, and when k is equal to 1. A plot of E_θ for $k=1$ as a function of α in degrees is shown in Fig. 5. In

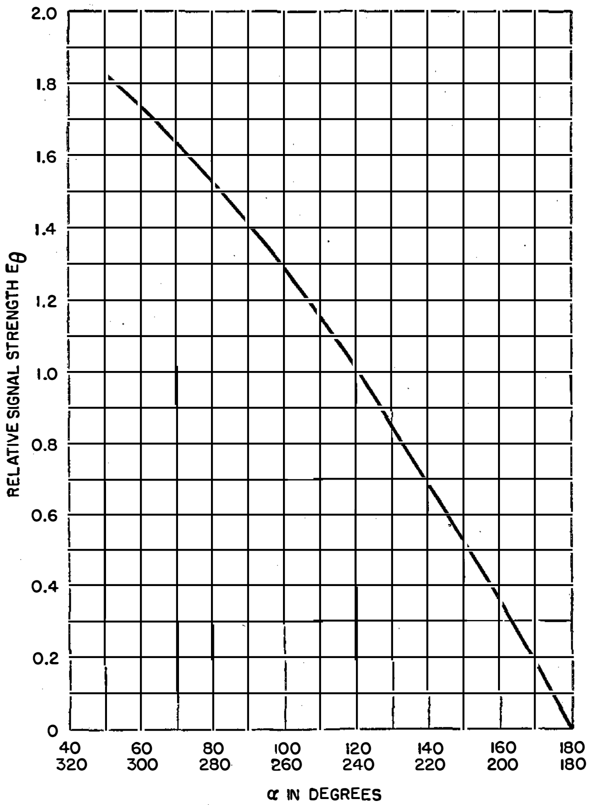


Fig. 5—Variation of E_θ with α for $k=1$.

Fig. 6 are plotted several field patterns which will be obtained for the conditions shown. Note that when ϕ differs by only a few degrees from 180 degrees, the nulls are quite visibly displaced. This case will be treated further below.

2.2 Vector Representation

In Fig. 7, vector addition has been performed at the crossover point. This point is represented by C in Fig. 1. The following discussion refers only to one directional pair.

Referring to Fig. 1, let the output from antennas A and B be E_1 and E_2, respectively. When a wave arrives in the null direction, E_1 and E_2 are in phase and, being connected in opposition, the resultant E_R is zero, if E_1 is equal to E_2 (i.e., $k=1$). This is shown vectorially in Fig. 7A.

In Fig. 7B we have shown the resultant E_R for an angle of wave arrival θ which causes E_1 to lead E_2. Note that E_R is at right angles to the positions occupied by E_1 and E_2 in Fig. 7A. This condition is obtained when k is equal to 1 and θ is neither 90 nor 270 degrees.

At 7C is shown a condition similar to that at 7B with the exception that E_1 does not equal E_2. The resultant E_R is no longer at right angles to the previous positions of E_1 and E_2 as shown in 7A.

At 7D is shown the resultant of the same conditions as 7C, except that the transmitter is now located at a position where $\theta = 90$ degrees. As E_1 is larger than E_2, E_R is now in the direction of E_1, and therefore its phase has changed by 90 degrees from the phase shown in 7B. Note that even though the transmitter is in the desired null direction, there is still a resultant voltage. This is the common condition of blurred nulls.

In 7E, we have shown the condition resulting from equal E_1 and E_2 voltages, but when ϕ does

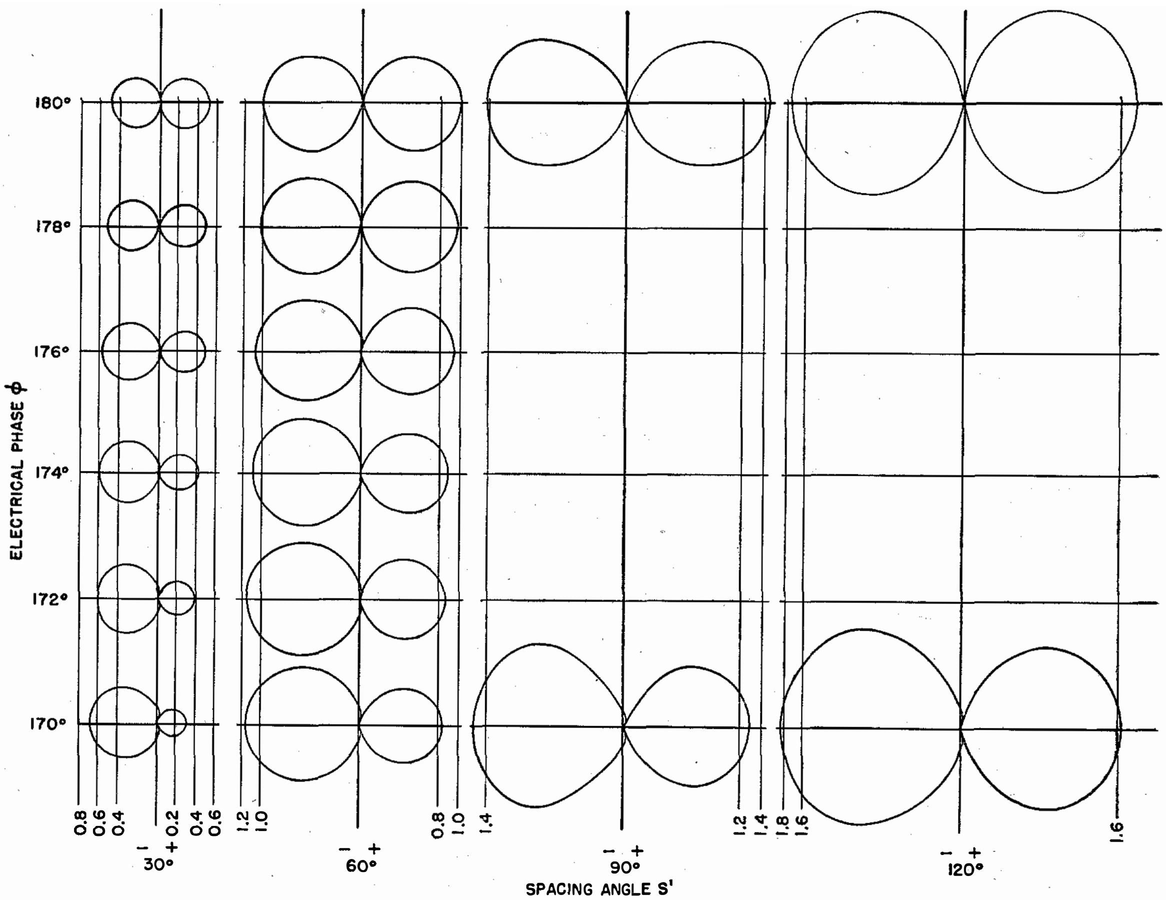


Fig. 6—Variation of field pattern with ϕ and with S'. Note the relatively large dissymmetry occurring when ϕ differs even slightly from 180 degrees.

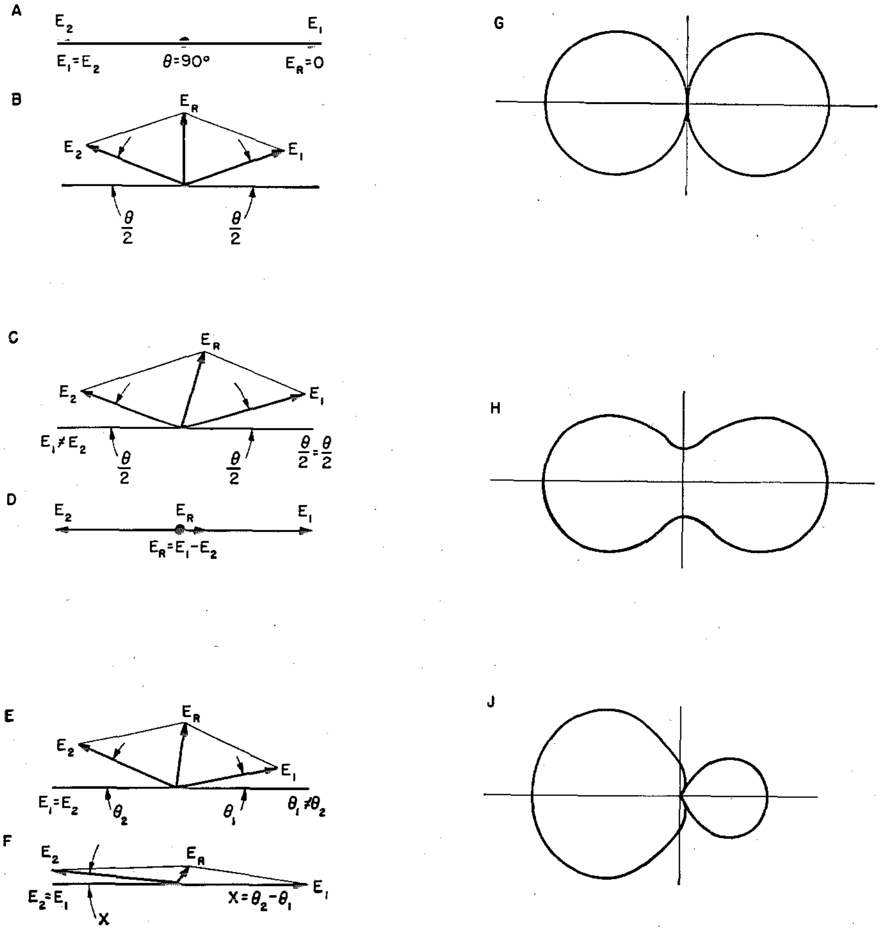


Fig. 7—Field pattern and vector diagrams illustrating various effects of the voltage and phase relationships in a directional pair array. *A*, *B*, *G*—correct figure-of-eight pattern. *C*, *D*, *H*—Pattern showing effect of amplitude inequality which results in blurred nulls. *E*, *F*, *I*—phase unbalance, causing shifted null in pattern.

not equal 180 degrees. In this case the two angles, which were shown in 7*B* and 7*C* by $\theta/2$, are not equal and have, therefore, been designated as θ_1 and θ_2. The resultant E_R is no longer at right angles to the position of E_1 and E_2 as shown in 7*A*, although its length is not greatly modified.

In Fig. 7*F*, the same condition as 7*E* has been shown except that the transmitter is at right angles to the array, i.e., at the null point. Note that E_R does not equal zero, and that it is not at right angles to the phases of E_1 and E_2.

A study of the entire Fig. 7 enables an experimental determination of whether amplitude or phase unbalance exists in a directional pair. First, if a transmitter located at right angles to the array produces a zero resultant voltage, it is certain that there is no amplitude or phase unbalance in the array. This is the condition shown at 7*A* and also at 7*B*. If there is a resultant voltage, either phase or amplitude unbalance is present.

It is quite difficult to measure the phase of the resultant voltage as shown in 7*C* and 7*D*. The equipment designer, however, can include provisions for comparing the amplitudes from the two antennas of one pair. It is also possible to move the transmitter about the null position, and if no position is found for which a good null can be secured, we may assume that there is amplitude unbalance. If it is possible to find a position where the null is good, but not at right angles to the array, it is well to investigate the null on the opposite side of the array. If these nulls are both displaced in the same direction, it is certain that there is phase unbalance in the array, i.e., that ϕ does not equal 180 degrees.

The amount of phase unbalance can be determined by reference to the development above, which shows that a shift in phase of n degrees (where n is small) results in a shift of the nulls by an equal number of degrees. If n is more than a few degrees, the amount of null shift is greatly dependent on S'. This case is hardly worth consideration because n should always be zero. If it is more than a few degrees, the resultant array will be so inaccurate as to be useless.

An example of this might be an antenna array in which poor nulls were observed at right angles to one pair. First, obtain the best amplitude balance possible. In current designs, the control unit is equipped with voltage dividers for varying the gain of the coupling units on the separate antennas; it is possible by this means to obtain amplitude balance. The target transmitter is, therefore, set up at right angles to the array and the quality of the null is measured. Then, by adjusting the voltage dividers of the two coupling units, an attempt is made to better the quality of the null. This operation balances amplitude only. After the best null has been obtained, the target transmitter is moved slightly to one side of its former position (say, toward antenna B), and the null is rechecked. If results are worse, a position in the opposite direction, toward antenna A, should be tried. The best position might, for instance, be found at 87 degrees, i.e., 3 degrees from its correct position.

The transmitter is then taken to the 270 degrees position, i.e., on the opposite side of the array. If it is found that the null, as previously, is moved toward the zero point by the same amount (3 degrees, or to 273 degrees, instead of 270 degrees), it is certain that the transmission lines connecting the pair do not cause the same phase shift. The amount of phase difference in the above example is approximately 3 degrees. In actual practice, the phase difference can be made 1 degree or less.

The polar diagrams that will be obtained for the conditions shown in Figs. 7*A* and 7*B* are shown in 7*G*. This is the perfect figure-of-eight pattern. At 7*H*, is illustrated the polar diagram which results from an inequality of amplitude. This is the condition of blurred nulls, and is illustrated vectorially at 7*C* and 7*D*. At 7*J*, is shown the polar diagram that would be obtained for the unbalance of phase illustrated vectorially at 7*E* and 7*F*. This is the shifted-null pattern.

These conditions show in a general way the results which are to be obtained from a directional pair such as is used in the spaced vertical-monopole array, as used for direction finding. (Compare with Fig. 6.)

2.3 General Conclusions

From the studies above, the following general conclusions may be drawn:

Unless k is equal to 1, E_θ can never be 0. An inequality of effective heights of antennas therefore results in blurred minima or rounded nulls.

The pattern is always symmetrical about a line formed by the intersection of the plane of the antennas with the horizontal plane.

The minima of reception occur at $\theta=\phi-90$ degrees and $\theta=90-\phi$ degrees. (A change in position of the terminal transmission line by n degrees results in a shift of the minima of n degrees, if n is small. In a current model of direction finder, the antennas of one pair are connected by an air-insulated transmission line. The characteristics of this line are such that the velocity of propagation is substantially equal to the speed of light. It may be said with considerable accuracy that the phase shift along the cable is 0.1 inch per degree per meter of wavelength. Thus, 0.1 inch is 1 degree at 1 meter, 1 inch is 1 degree at 10 meters, 10 inches are 1 degree at 100 meters, etc.)

The minimum occurs when k equals 1 and $\alpha=180$ degrees. The equation for θ under these conditions is

$$\theta=\cos^{-1}\frac{180-\phi}{S'}.$$

The two lobes of the figure-of-eight pattern are symmetrical about the minima only when ϕ is equal to 180 degrees; i.e., when the minima occur at 90 and 270 degrees.

3. Combination of Two Directional Pairs

Two identical directional pairs are combined at right angles to form the antenna array. The outputs from the two pairs connect separately to the orthogonal stator windings of a goniometer. It is quite evident that one stator will receive a signal proportional to the sine of θ (the angle of arrival), while the other stator receives a signal proportional to the cosine of θ. The addition of these two signal amplitudes in space quadrature creates a resultant field in the goniometer which is proportional in strength to the received signal, and which is at an angle θ. Aside from the errors of each directional pair, which were investigated in paragraph 2 above, only two sources of error resulting from distortion of the field patterns of the directional pairs are evident in the combining goniometer. The treatment following assumes that $k=1$ and $\phi=180$ degrees (paragraph 3).

3.1 Quadrantal Error

When one stator receives a stronger maximum signal from its directional pair than the other, the error is zero in the plane of either directional pair. The greatest error occurs at the 45-degree points. Therefore such errors are investigated

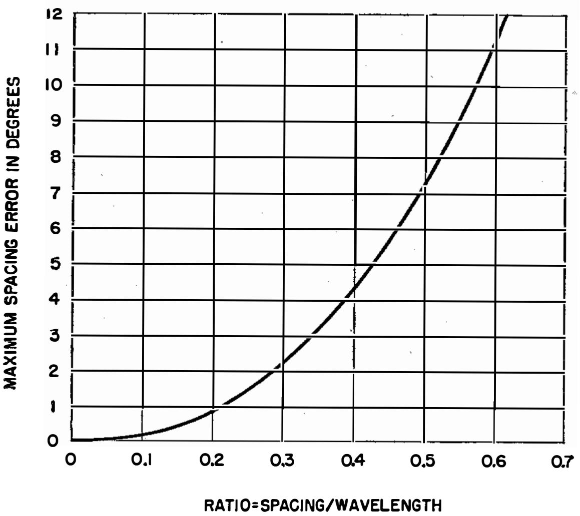


Fig. 8—Error incurred as the spacing S between elements becomes an appreciable portion of a wavelength.

experimentally by determining the error for all frequencies at the 45-degree points of the array. This is the common *quadrantal* error.

3.2 Octantal Error

A second error occurs when the spacing S is an appreciable fraction of a wavelength. This error might have been treated under paragraph 2 as an error of the directional pair, but it is included here because its experimental determination becomes very simple when the array is studied as a whole. This error is greatest on the 22.5-degree points. It is the common spacing or *octantal* error, and has been completely and rigorously covered by various authors. Note that this error is zero at the 45-degree points, and that the value of the error is sinusoidal between its maximum (22.5-degree) and its minimum (45-degree) points.

In Fig. 8 the maximum spacing error in degrees has been plotted against the ratio of spacing to wavelength when this ratio lies between 0 and 0.6. This permits a determination of the maximum spacing error to be expected in a particular equipment at the frequencies for which the equipment was designed. These results for four arrays, covering the frequency range of 1.5 to 30 megacycles, are plotted in Fig. 9, where for each band the maximum spacing error to be expected is plotted against frequency. The maximum errors are given in Table II.

3.3 Random-Pattern Distortion

In Fig. 10A, are shown the resultant vectors, A and B, which result from a signal being received at an angle θ to an array of two orthogonal pairs of spaced collectors. The diagram for each of the pairs is considered to be a perfect "figure-

TABLE II

Spacing Error for Four Arrays Between 1.5 and 30 Mc.

Range	Error in Degrees			
	Band 1	Band 2	Band 3	Band 4
Nominal	1	1.3	2.1	3.5
Extended	2.8	2.8	4	7

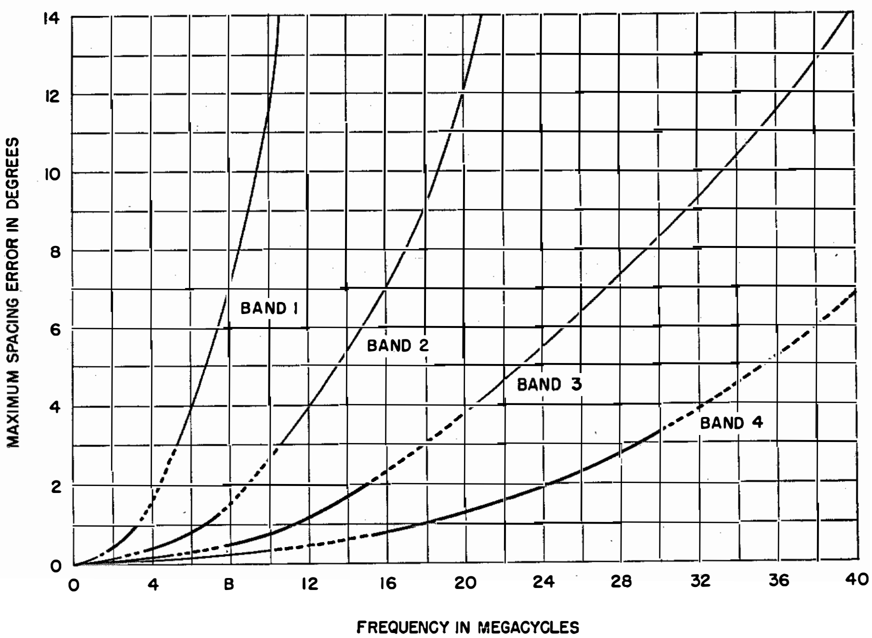


Fig. 9—Maximum spacing error in arrays covering 1.5 to 30 megacycles in four bands. The heavy solid line indicates the nominal range for each band, the dotted line indicates the extended range, and the light solid line shows errors which occur outside the range of each band.

of-eight." Therefore these two vectors, combined in the orthogonal stator windings of the goniometer, will produce a resultant at an angle θ without error.

At 10B, the same signal is shown being received at the same angle on a collector system which does not give perfect figure-of-eight reception and, therefore, the result is vectors A' and B' whose relationship to the correct vectors A and B is given by:

$$A' = XA$$
$$B' = YB.$$

In 10C is shown the resultant of the vectors A' and B' as obtained in the goniometer. This resultant is at an angle β to the correct resultant. β is therefore the correction that must be applied to the indicated bearing.

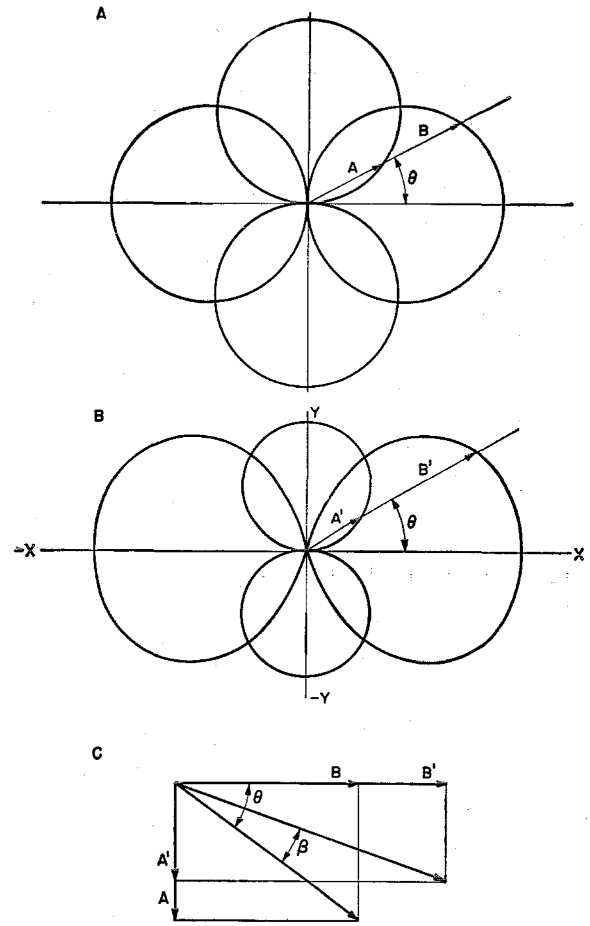


Fig. 10—A perfect set of figure-of-eight patterns are shown in *A*. In *B* the patterns are not symmetrical. The vectors in *C* illustrate the correction β which must be applied to the indicated bearing to obtain the correct bearing.

The equation for β is:

$$\beta = \tan^{-1}\left(\frac{XA}{YB}\right) - \theta. \qquad (2)$$

In Figs. 11A and B are plotted values of β for various ratios of Y/X and θ in increments from 10 to 80 degrees. Note that this is a perfectly general analysis of this error. The results may be applied graphically to any system of collectors, provided their field pattern is known. By this graphic method, it is possible to postulate the error for any field configuration of either pair.

3.4 Phase Errors

Phase errors occur in a system of two pairs when the signals do not arrive at the goniometer in the same phase relationship as the voltages which have been induced by the incoming wave in the corresponding array elements.

This condition will always occur when the velocities of propagation or the lengths of the cables between the two directional pairs of the array and the corresponding goniometer stators are not equal.

This results in a maximum error at the 45-degree points, and in blurred minima for signals in this direction. The error in the planes of the array pairs is zero and good minima are observed here; the maximum error is at the 45-degree points, and blurred minima or rounded nulls are observed simultaneously with the error.

In a properly designed and installed direction finder, this error is never observed, and the study will not be carried further in this paper.

4. Goniometer

An indicator system used in conjunction with the goniometer may consist simply of a pointer and dial arrangement attached to the shaft of the goniometer for finding an aural null or, more elaborately, of a continuously rotating goniometer together with a cathode-ray indicating device. The screen of the cathode-ray tube usually has an azimuth scale associated with it. The instantaneous position of the goniometer must then correspond exactly with the instantaneous angular deflection of the cathode-ray-tube beam. The indicator usually contains in order: the goniometer, a motor drive, and a device for controling the circular deflection of the cathode-ray-tube beam. The shafts of these three units

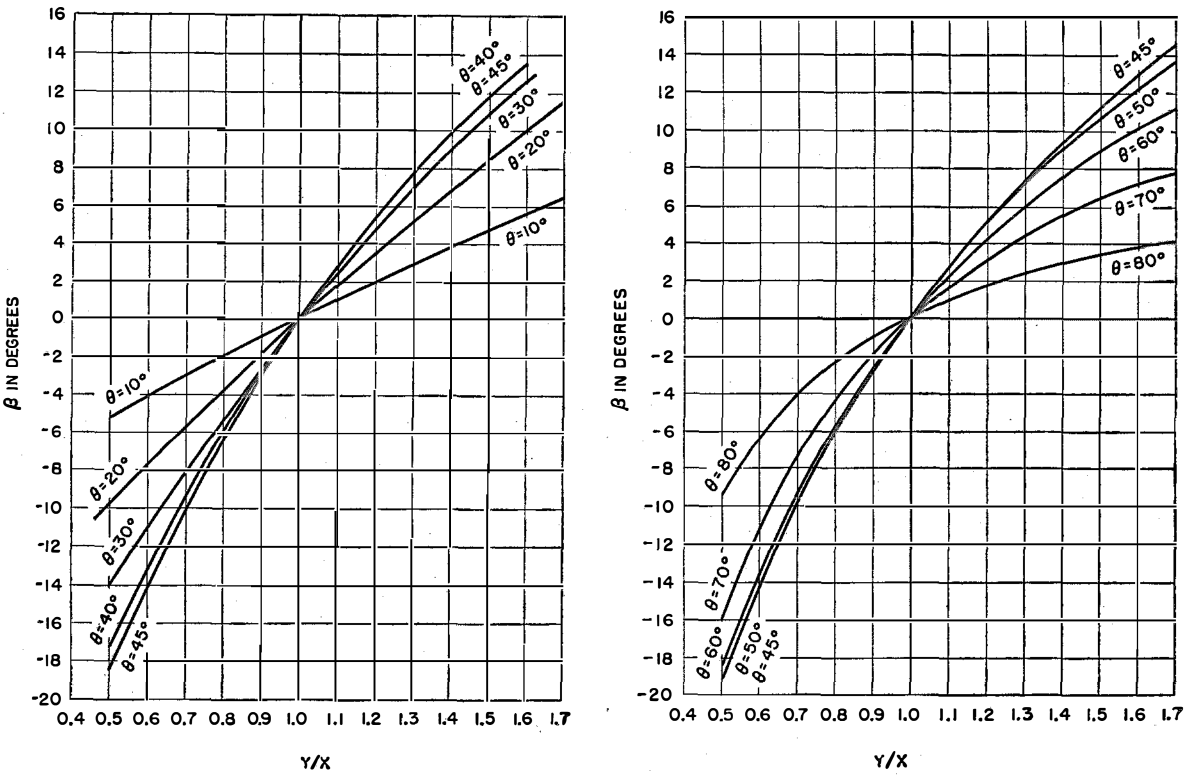


Fig. 11—Correction term β as a function of the angle of reception θ for different ratios of relative amplitude between reception from X and Y figure-of-eight patterns (Fig. 10*B*). At the left, for angles up to 45 degrees, the error increases, after which it again decreases as at the right.

must lie on the same straight line. Mechanical considerations and provision for maintenance usually require that the units be separable. Since it is almost impossible to keep the shafts aligned, some flexibility is provided. Initial alignment and realignment after demounting for maintenance are important considerations in maintaining the over-all accuracy of the system.

Goniometers are usually carefully designed for very small errors in the operating range. Many production goniometers have been thoroughly tested by several independent methods, and the maximum error recorded has always been less than 2 degrees.

TABLE III

ERRORS RESULTING FROM MISALIGNMENT IN GONIOMETER

Misalignment a in Inches	Pattern Bend (2α)	
	Front-Coupling Error in Minutes	Rear-Coupling Error in Minutes
0.001	4	10
0.005	21	56
0.010	42	110

The over-all equipment, however, may give errors larger than this if the goniometer is not carefully aligned both mechanically and electrically with the indicating means. The indicator used for illustration has been previously described.[3]

There are two universal joints in the indicator which might cause a bending of the pattern. The joints are between the motor and the goniometer, and between the motor and the indicator shaft. Misalignment at either of these points will cause errors. The coupling between the motor and the indicator has a fixed arm length of 1.625 inches. That between the motor and the goniometer has a fixed arm length of 0.625 inch.

If the misalignment in inches is a, and the fixed arm length is d, then the total pattern bend 2α will be given by

$$\alpha = \tan^{-1} \frac{a \sin \theta}{d - a \cos \theta}. \tag{3}$$

The maximum value of (3) to be expected in the indicator described is shown in Table III.

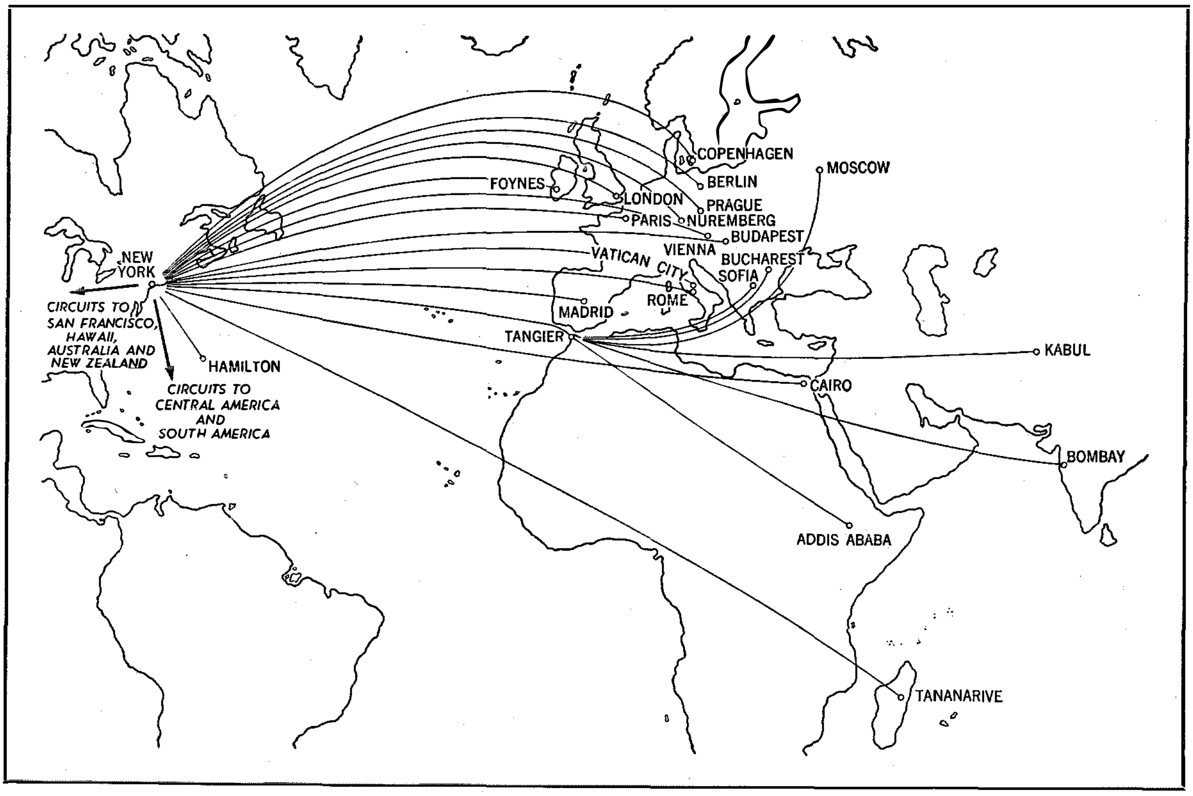
[3] Giltner Twist, "Army Radio D-F Networks," *Electronics*, v. 17, pp. 118–124; November, 1944.

Tangier Radio Relay Station

WITH THE ADVENT of technical improvements, which make practicable for radiotelegraph circuits the use of mechanical terminal equipment such as printing apparatus, automatic or semiautomatic operation of circuits in tandem becomes possible. By automatic is meant the direct relay of signals by regenerating them and removing distortions that occur during propagation. By semiautomatic is meant the reperforating of messages on paper tape and the use of this tape for retransmission.

Many radio transmission paths, such as the routes between New York and Moscow, and New York and Bombay, traverse areas near the magnetic poles of the earth. Such radio circuits either are subject to poor propagation conditions, or are so long as to offer only a limited number of hours of daily use, in addition to which they are very seriously affected by such solar disturbances as magnetic storms, aurora, and sunspots.

Mackay Radio and Telegraph Company overcame these difficulties in the Atlantic area first by establishing relay operations through its wartime station at Algiers, North Aftica, in 1944. In 1945, a permanent relay station was inaugurated in the International Zone of Tangier, North Africa. This station provides a through teletype service between New York and Moscow and furnishes twenty-four hour service from New York to other distant points such as Bombay, India; Kabul, Afghanistan; Sofia, Bulgaria; Bucharest, Rumania; and Addis Ababa, Ethiopia. The path between New York and Tangier is sufficiently distant from the north magnetic pole so that ionospheric disturbances affect it only to a minor extent. The paths between Tangier and points in Europe, Asia, and Africa are still more remote from the pole and, therefore, quite immune from such effects. The reliability of these relayed circuits is consequently of a high order.



Mackay Radio and Telegraph Company radiotelegraph circuits showing the new radio relay links operated from New York via Tangier to Moscow, Bombay, Kabul, Sofia, Bucharest, and Addis Ababa.

Carrier-Frequency Submarine Cable and Equipment for U.S.S.R.

By E. S. McLARN and G. H. GRAY

International Standard Electric Corporation, New York, New York

LESS than eight months after placement of the order, a submarine cable to connect two terminals 240 kilometers apart, terminal equipment, and one repeater were constructed, tested, packed, and readied for shipment to the U.S.S.R. Design and constructional details of the cable and terminal equipment are given.

• • •

During the last quarter of 1942, an inquiry was received from the Purchasing Commission of the U.S.S.R., through the U.S. Treasury Department, for an urgently needed submarine cable and all accessory equipment to provide four two-way telephone channels and four two-way telegraph channels between two points about 240 kilometers (150 miles) apart. An island 40 kilometers (25 miles) from one end of the cable was available for the installation of a repeater if this was considered necessary.

The proposed location of the cable was not given, but it was stated that the following conditions existed:

A. Maximum depth of water was 1300 feet (near center of longer section).

B. Static conditions very bad.

C. Salt content of the water less than that of the ocean.

D. Water at shore ends of both sections mixed with free oil, sulphur, and hydrogen.

E. Sea bottom generally smooth, but slightly stony near shore ends.

F. No currents strong enough to cause motion of cable.

G. Depth of water increases very gradually being less than 3 meters (10 feet) up to 200 meters (656 feet) from shore.

H. No power lines within 1 kilometer (5/8 mile) of proposed cable site.

Although the installation presented many new problems among which may be mentioned the great length, the number of channels required, and the fact that, because of war conditions, neither gutta percha nor paragutta were available, International Standard Electric Corporation agreed to assume the responsibility as prime contractor for the entire project up to and including the safe loading of the cable and equipment on board ship at a port in the U.S.A.

The U.S.S.R. was responsible for the safe delivery of the material to its destination as well as for the laying and subsequent testing of the cable, the installing and testing of the equipment, and putting the circuits in service.

Urgent military necessity required that the cable system be engineered and manufactured in the U.S.A., and arrangements were made through the Western Electric Company to have the Bell Telephone Laboratories undertake the over-all design of the system and the detailed design and manufacture of the terminal and repeater equipment. The Simplex Wire and Cable Company accepted the order to design and manufacture the cable under the general supervision of Bell Telephone Laboratories from the standpoints of performance and testing.

Although it was not a part of the original contract, International Standard Electric Corporation also undertook to furnish a considerable amount of information relating to cable-laying equipment and methods and to the testing of the cable after laying.

1. Design of Cable

A study was undertaken of possible substitutes for gutta percha and paragutta, and it was decided that deproteinized (anhydrex) rubber offered the best chance of success.

Accordingly, some 30 samples of variously constructed cables were made by Simplex Wire and Cable Company and, from tests on these samples by Bell Telephone Laboratories, the best construction was chosen. This was of the concentric type with a stranded center conductor of 10 small tinned copper wires, 0.0414 inch in diameter, laid spirally in parallel over a heavy central conductor 0.0987 inch in diameter. The total weight of the copper core was 500 pounds per nautical mile (122 kilograms per kilometer). This conductor was insulated with 1/4-inch thickness of deproteinized rubber. Over this was laid a noncorrosive rubber-filled tape which provided the base for the return conductor. This latter consisted of 48 tinned copper wires each 0.037 inch in diameter laid in parallel and applied spirally.

To protect against possible harmful effects from the crude oil in the water near the shore, about 2 kilometers of each shore end was covered by a plastic seal, 5/64 inch thick, extruded over the cable core. Two different weights of armoring were used: a light armor for the deep-sea sections and a heavier armor for the shore ends. The latter was provided both with and without the plastic seal, necessitating the manufacture of three different types of cable. The cores of all three types were identical up to the plastic seal. Layers of jute yarn and filled tape were placed throughout the cable as required. About 60 kilometers of cable, mostly of the heavily armored plastic-seal type, were provided as spare. Fig. 1 shows the layups of the three different types of cable.

The completed cable had the approximate over-all weights and outside diameters given in Table I.

Before making the approximately 500-kilometer journey from the point of manufacture to the port of loading, the cable was spliced in sections varying in length from 10 to 50 kilometers. Lengths too great for one flat-car were coiled on several cars, with a loop of cable between cars to prevent cable injury. For the 50-kilometer lengths, 5 cars were required.

By June, 1943, less than 6 months from the date the order was placed, the entire cable had been manufactured, tested, and shipped to the steamer.

At a temperature of 24 degrees centigrade (75 degrees Fahrenheit), the direct-current resistance of the central conductor averaged 1.214 ohms and that of the return conductor 0.532 ohm per kilometer.

The characteristic impedance over the range used for the telephone channels, about 3.2 kilocycles to slightly under 30 kilocycles, was fairly constant at about 54 ohms. Over the telegraph range from 300 to 3000 cycles the impedance was somewhat higher.

To determine the attenuation of a section of the cable, one end was terminated in its image impedance and a frequency of 40 kilocycles applied at the other end. The currents at the two ends were determined by thermocouples. With the 40-kilocycle frequency replaced by direct current and the cable by a calibrated resistance box, the input voltage and the resistance box were adjusted until the two thermocouples gave the same indications as before. The attenuation was then computed from the value of the box resistance and the image resistance of the cable.

The attenuation at 40 kilocycles and 52 degrees centigrade (126 degrees Fahrenheit) as measured under water in tanks at the factory varied from 1.00 to 1.04 decibels per nautical mile and averaged about 1.02 decibels per nautical mile or 0.55 decibel per kilometer. The guaranteed maximum value of attenuation was 1.13 decibels per nautical mile.

TABLE I

PHYSCIAL CHARACTERISTICS OF CABLE

Type of Cable	Weight		Outside Diameter	
	Pounds per Nautical Mile	Kilograms per Kilometer	Inches	Millimeters
Light Armor, No Oil Seal	15,200	3750	1.55	40.25
Heavy Armor, No Oil Seal	22,000	5400	1.84	46.75
Heavy Armor, Oil Seal	25,750	6310	2.01	51.05

It is interesting to note that the cable not only met the specification requirements in every respect but its over-all transmission capabilities proved to be approximately 10 percent better than were specified.

2. *Carrier Equipment—General*

As four two-way telephone and four two-way telegraph channels were required, carrier offered the only means of furnishing these circuits over one cable. It was decided that an intermediate repeater would be necessary on the island previously mentioned. In addition to the commercial channels, a telegraph order wire was provided from each terminal to the repeater station. This could be used for through telegraph communication (terminal to terminal) by connecting the direct-current extension circuits of the order wires at the repeater station. Teletypewriter equipment was installed for use on the order wire.

For convenience, the terminal at the end of the 200-kilometer section of cable is hereafter referred to as *A*, that at the end of the 40-kilometer section as *C*, and the repeater at the junction of the two as *B*.

To meet the quick delivery required, it was decided to use standard panels, or parts of panels, to as great an extent as possible, even though this did not result in quite as satisfactory an arrangement as could have been obtained from an entirely new design. One result of this decision was that the equipment made use of a larger number of different types of vacuum tubes than would ordinarily have been necessary.

The frequency arrangement selected is shown in Table II.

TABLE II

Direction of Transmission	Circuit Number	Frequency in Cycles per Second			
		Order Wire	Telegraph Channels	Telephone Channels	
				Carrier	Pass Band
B-A	—	255	—	—	—
C-A	1	—	425	5,900	3,200– 5,600
C-A	2	—	595	8,850	6,150– 8,550
C-A	3	—	765	11,800	9,100–11,500
C-A	4	—	935	14,750	12,050–14,450
C-B	—	1105	—	—	—
A-C	4	—	1615	17,700	18,000–20,400
A-C	3	—	1785	20,650	20,950–23,350
A-C	2	—	1955	23,600	23,900–26,300
A-C	1	—	2125	26,550	26,850–29,250
A-B	—	2295	—	—	—
B-C	—	2465	—	—	—
				32,450 (Group Modulator and Demodulator)	

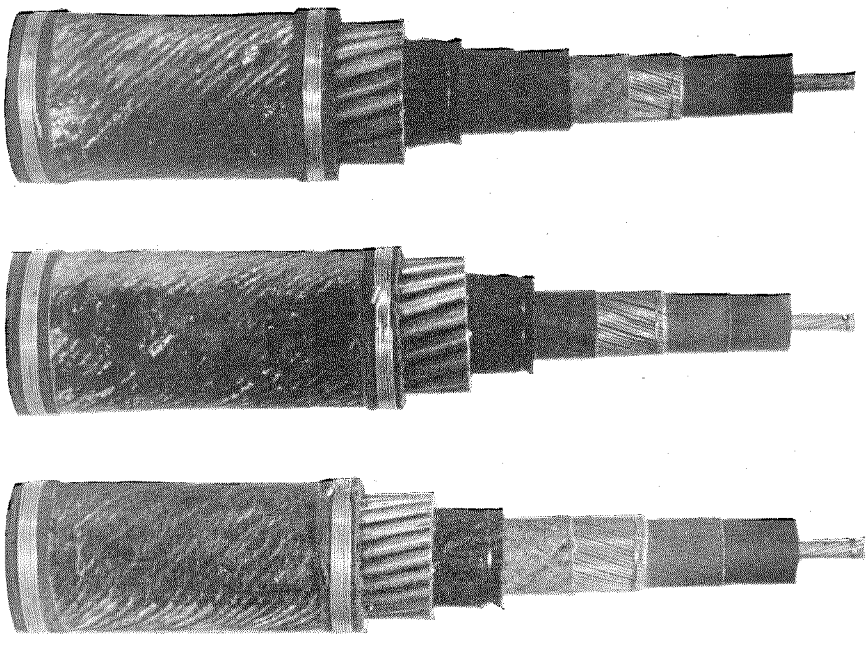


Fig. 1—Three types of cable were used and differed in the weight of armoring and in the application of an oil seal for the shallow-water sections. All have identical center conductors, 1/4-inch wall of anhydrex insulation, 0.012-inch layer of noncorrosive rubber-filled tape, coaxial conductor of 48 strands of round wire, and a 0.012-inch noncorrosive rubber-filled tape. The top cable has a 5/64-inch Plastex oil seal and another 0.012-inch rubber-filled tape. The two lower cables do not have an oil seal. All three then have a serving of 200-pound cutched jute yarn, galvanized steel armor wires, and two serves of impregnated jute yarn. The outside diameters in inches are 2.01, 1.84, and 1.545, respectively.

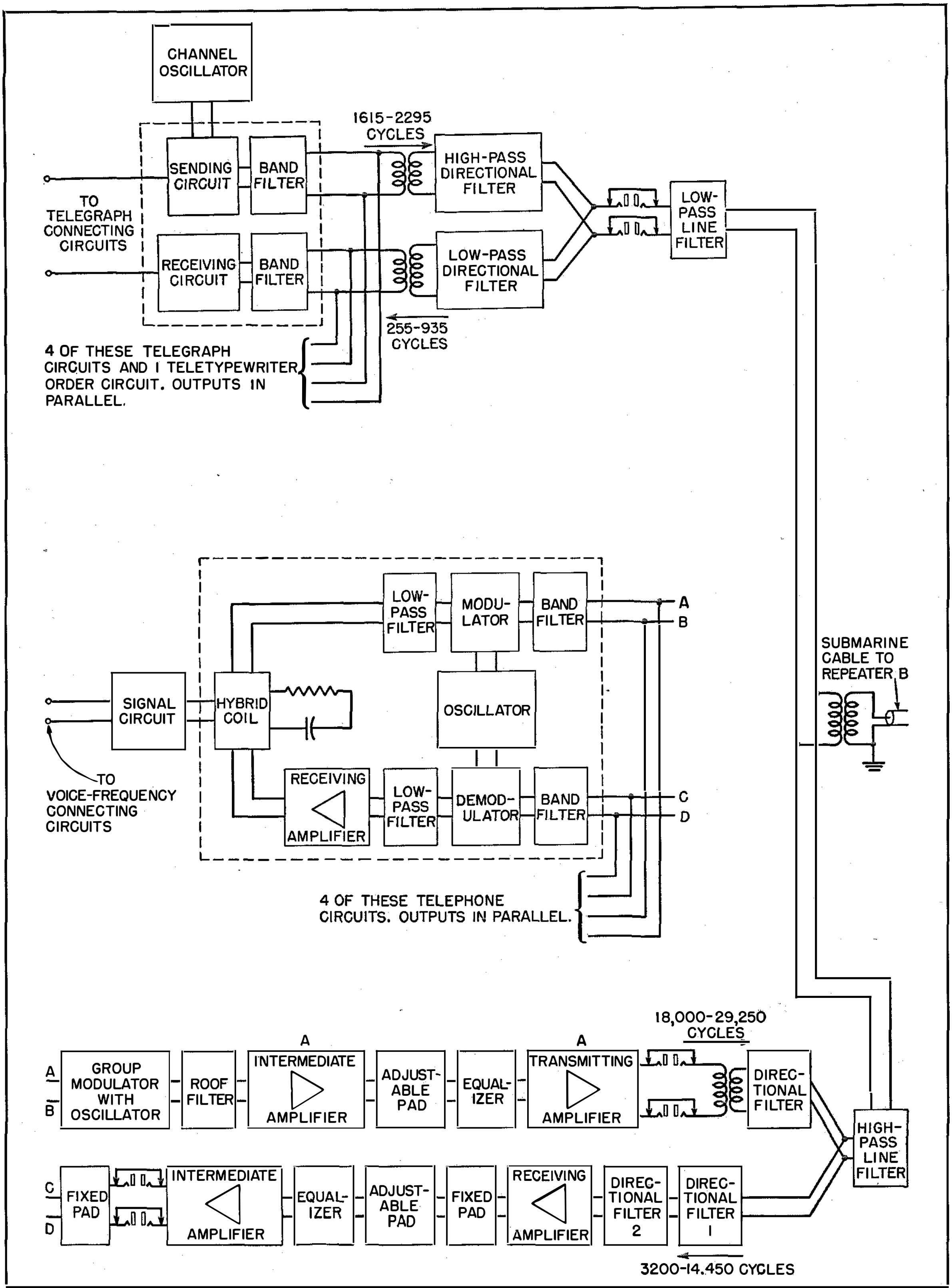


Fig. 2—Schematic arrangement of the carrier telephone and telegraph equipment; Terminal *A* equipment.

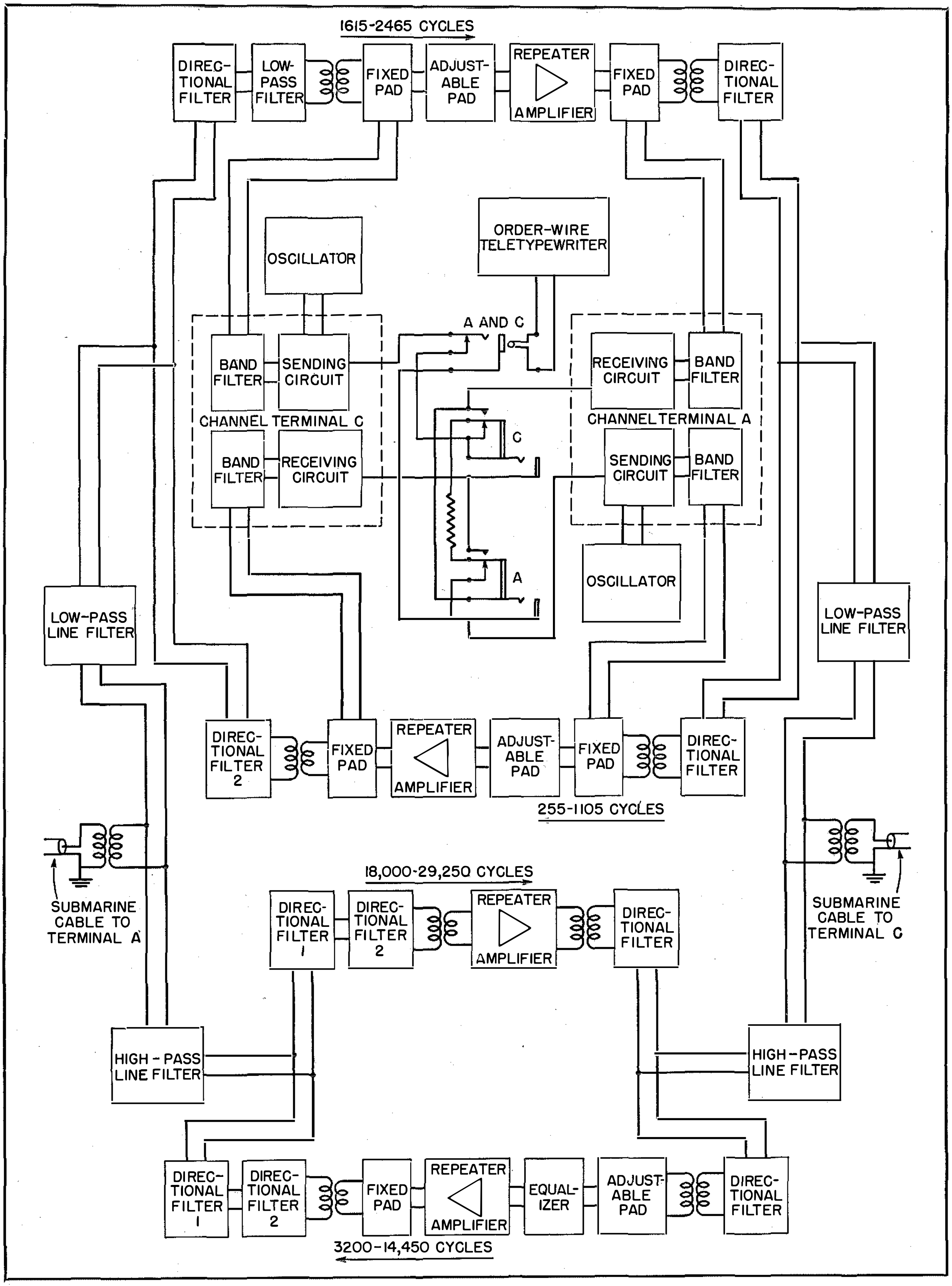


Fig. 3—Schematic arrangement of Repeater *B* equipment.

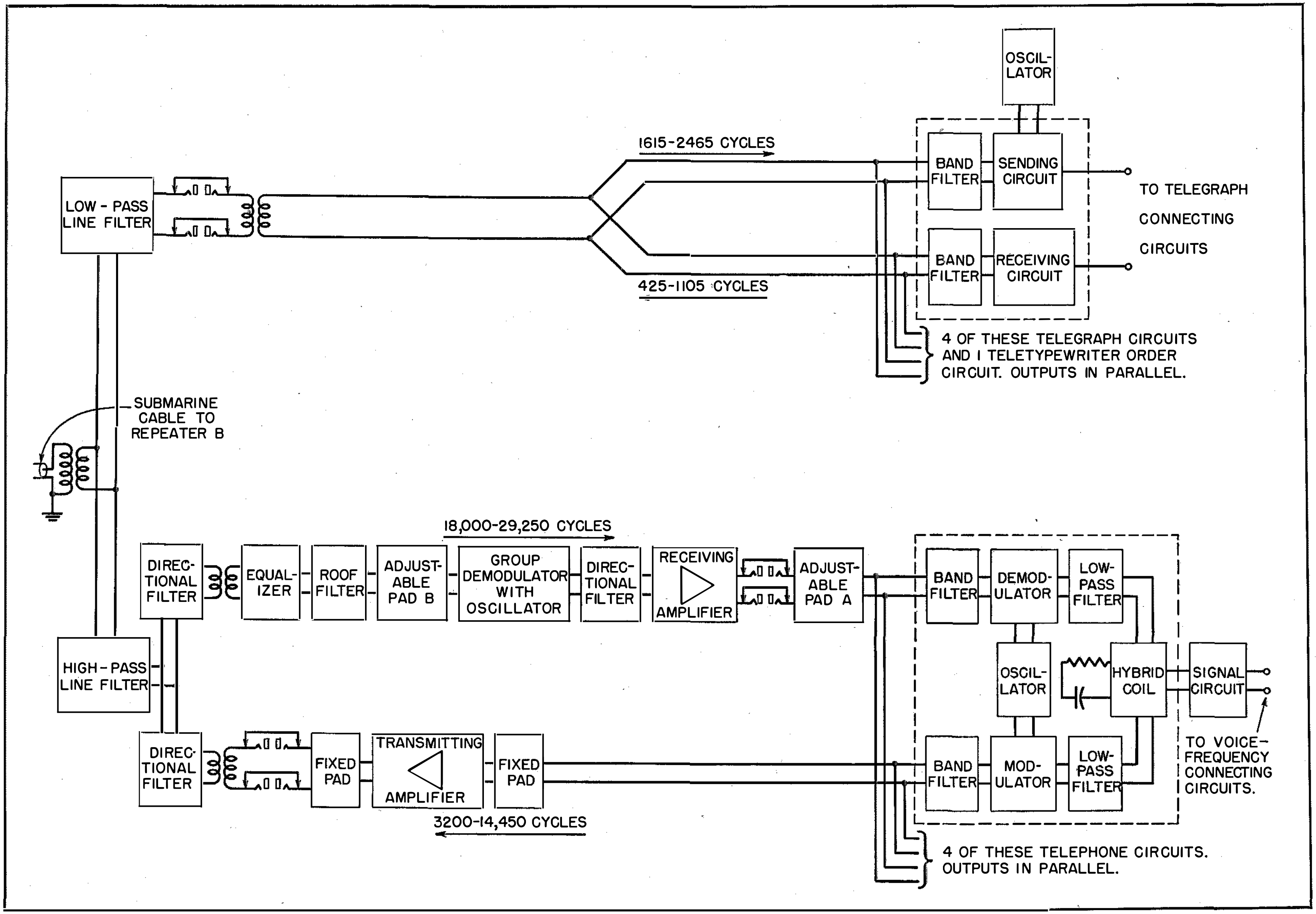


Fig. 4—Schematic arrangement of Terminal *C* equipment.

It will be noted that each telephone channel transmitted a band extending from about 300 cycles to 2700 cycles. Single-sideband transmission was used with suppressed carrier. The telegraph system transmitted the carrier and both sidebands.

Separate terminal and repeater equipment was used for the telephone and telegraph circuits, the separation being made by low-pass and high-pass line filters. A common power supply was, however, used for all equipment at each location. To obtain the proper impedance match, a 600- to 54-ohm repeating coil was installed at each end of each cable section.

Figs. 2, 3, and 4 show over-all application schematics of both terminals and the repeater station. The general arrangement is clear from these figures but the following comments are made as to details.

A. Copper-oxide modulators and demodulators were used.

B. The intermediate and transmitting amplifiers shown in the "high group" transmitting path of terminal *A* are capable of furnishing a gain of 53 decibels each.

C. The amplifier in the "high group" transmitting path at the repeater *B* is capable of a gain of 66 decibels.

D. The receiving amplifier provides a fixed gain of 50 decibels.

E. Lower gains are, of course, satisfactory for transmitting in the reverse, *C-A* direction, as the line losses are smaller.

F. 1000 cycles, interrupted at a 20-cycle rate, is used for ringing.

G. It is expected that each channel will operate at an over-all loss of about 9 decibels.

H. The sending circuit of each telegraph channel includes means for interrupting the carrier in accordance with the signals to be sent.

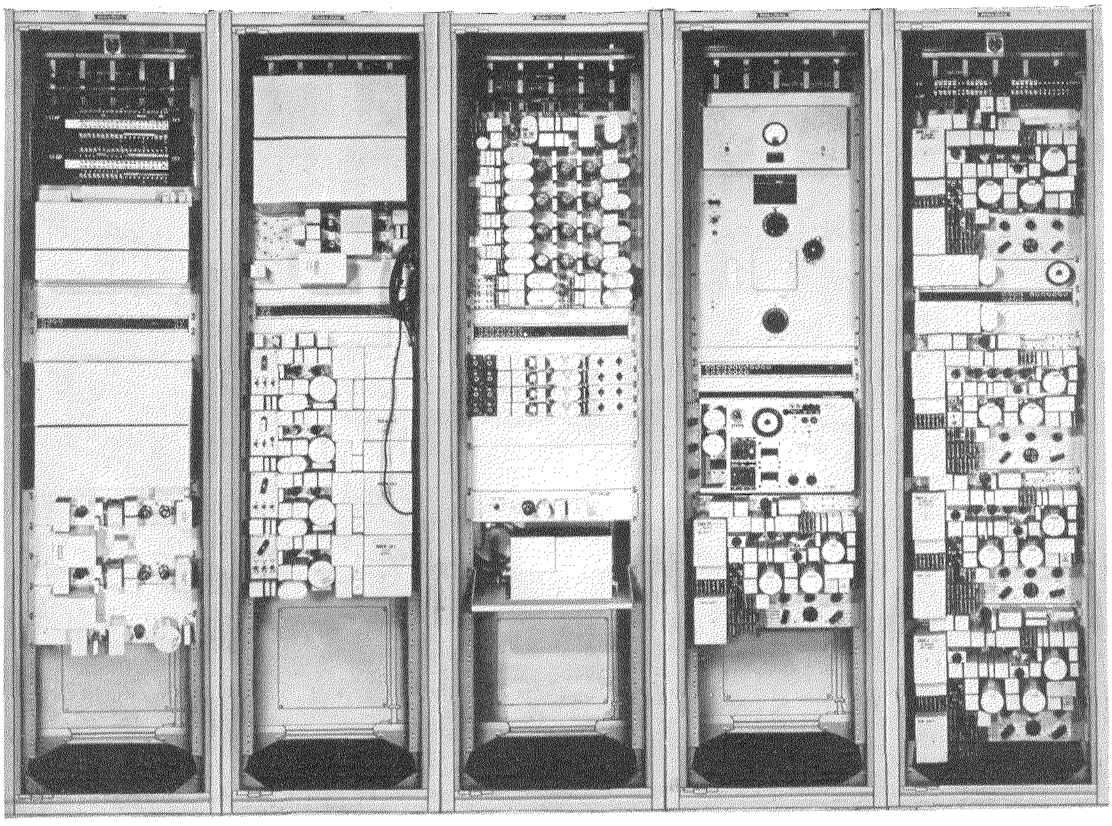


Fig. 5—Telephone and telegraph bays for terminal *A* with doors removed. From left to right are the following bays: telephone high group, telephone low group and channel, signaling, test and order wire, and telegraph.

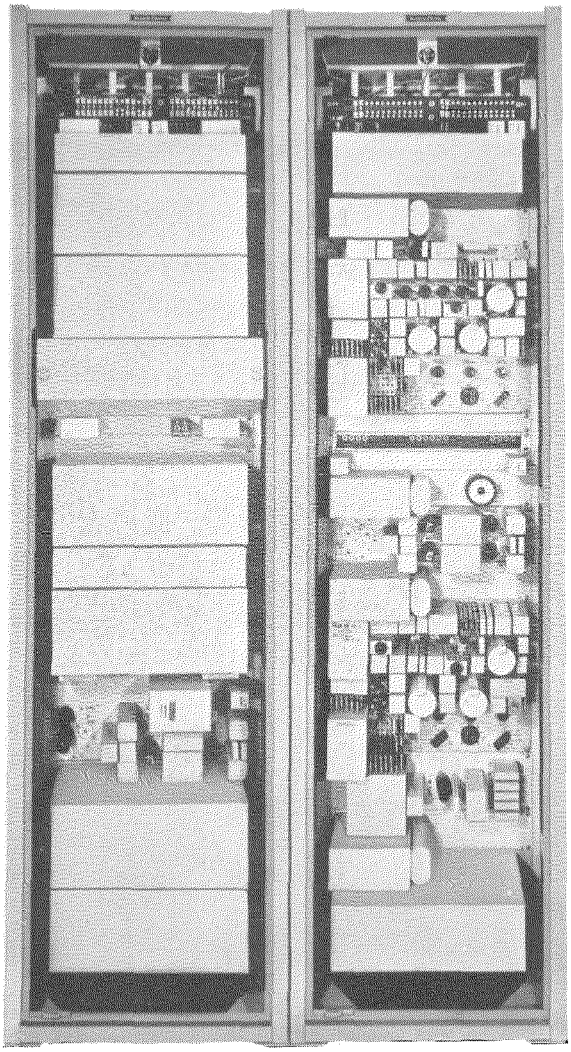


Fig. 6—Telephone (left) and telegraph bays of the repeater equipment with doors removed.

I. The telegraph terminals were designed for use with different types of direct-current extension circuits or "loops," such as:

Neutral to Positive Battery—Half and Full Duplex
Neutral to Negative Battery—Half and Full Duplex
Polar Full Duplex.

J. Teletypewriters may be connected directly to the telegraph terminal or through telegraph switchboards or repeaters.

K. The jacks at *B* were so arranged that teletypewriter communication could be carried on with both terminals simultaneously or with either terminal separately.

Fig. 5 gives a general idea of the arrangement of the equipment in the cabinets of terminal *A*, and Fig. 6 is a similar view of the repeater equipment. Terminal *C* is very much like terminal *A* but has slightly less equipment.

3. *Power Supply*

Both terminals were designed to operate normally from 110–125-volt, 50/60-cycle mains. For emergency use, a gas-engine-driven alternator was provided. At the repeater station, two gas-engine sets were furnished as there was no commercial supply. Regulated tube rectifiers, operating from the alternating-current mains, or from the alternators, were used to provide the direct voltages, the following being required at each terminal: +150, +130, −130 and −24. At the repeater point, direct voltages of +150, +65, −65 and −24 were provided.

Each regular direct-voltage supply consisted of a full-wave rectifier with an associated battery to act as a filter, take care of peak loads, and provide a short reserve in case of a power failure. Suitable alarms provided indications of high- and low-voltage conditions or of failure of any source of power.

Static ringing generators converted the input of 105–125 volts at 50 or 60 cycles to 75–100 volts at $16\frac{2}{3}$ or 20 cycles which were used for the normal 20-cycle signaling supply. On failure of the alternating-current source, transfer was automatically provided to a 24-volt battery-driven generator.

The general arrangement of the power equipment at the *A* or *C* terminal is shown by Fig. 7. The power equipment for the repeater is shown in Fig. 8.

4. *Testing Facilities*

For testing purposes, oscillators, transmission-measuring sets, current-flow test sets, voltohmmeters, relay test sets, and vacuum-tube test sets were provided.

5. *Mounting Arrangements*

The equipment was mounted in steel cabinets approximately 7 feet by $22\frac{1}{4}$ inches by 17 inches, with the exception of those for the 24-volt power equipment which were 4 inches wider.

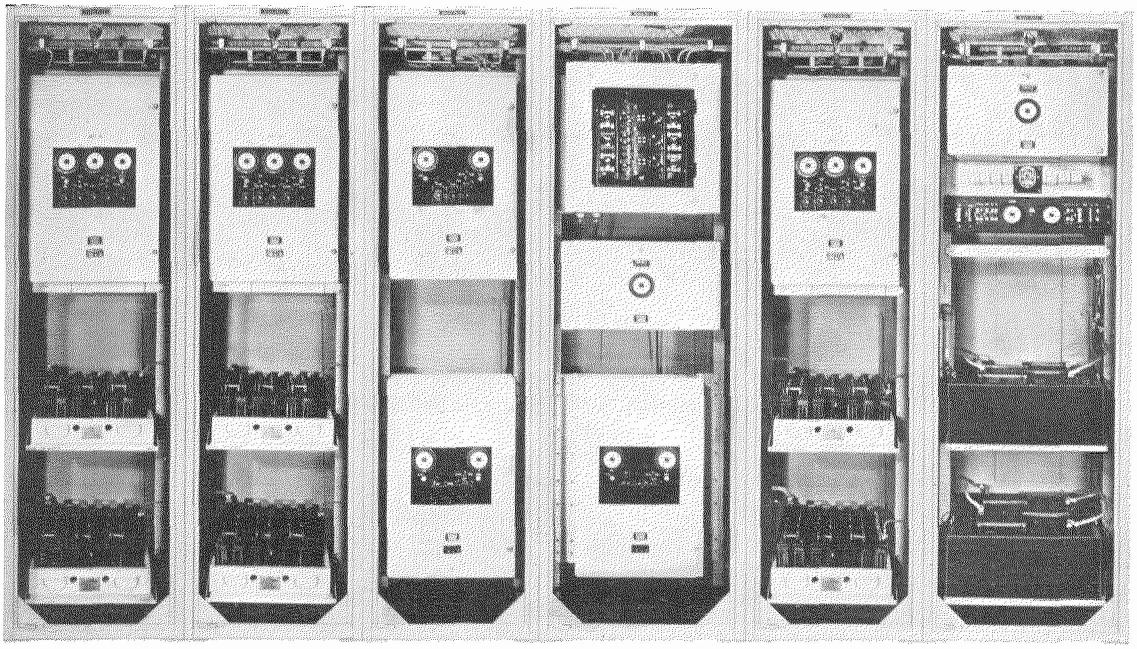


Fig. 7—Power supply equipments for the *A* or *C* terminals. From left to right are bays for +130 volts, −130 volts, +130-volt and −130-volt spare rectifiers, power service panel with cover removed and −24- and +150-volt spare rectifiers, +150 volts, and −24 volts. This is a front view with doors removed.

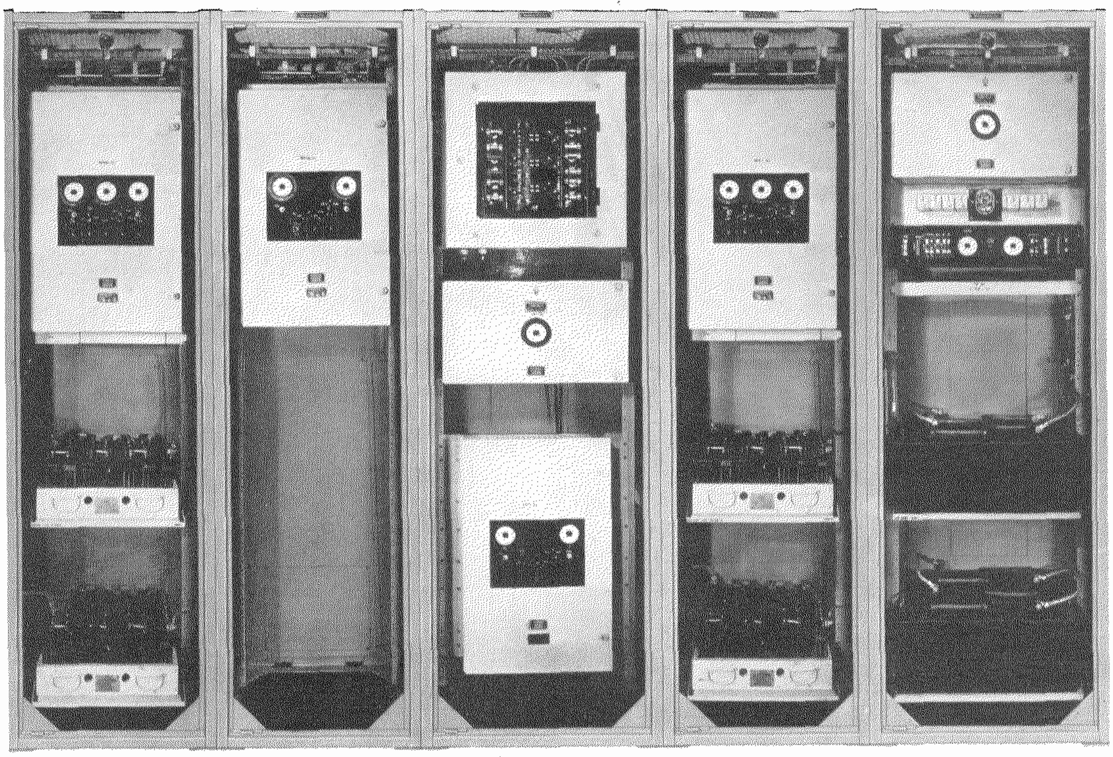


Fig. 8—Front view with doors removed of the repeater power-supply equipment. From the left are bays for ±65 volts, ±65-volt spare rectifier, power service panel with cover removed and −24-volt and +150-volt spare rectifier, +150 volts, and −24 volts.

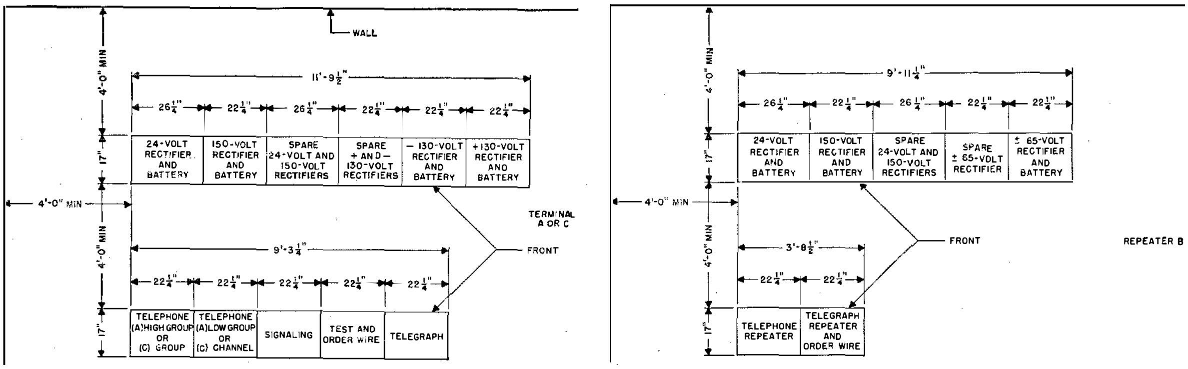


Fig. 9—Possible floor plan of the terminals and of the repeater.

All cabinets had full-length front and rear doors, each containing ventilating louvres.

A telephone handset was mounted in the telephone channel cabinet at each terminal.

Fig. 9 shows a suggested floor plan for the terminal and repeater stations and gives an idea of the amount of space required.

6. Over-All Test

On completion of the equipment, it was set up in the Bell Telephone Laboratories and artificial cables of the proper constants were connected between each terminal and the repeater equipment. A complete series of talking, telegraphing, and signaling tests was run. Careful measurements indicated that the desired transmission levels could very easily be obtained, that the necessary cross-talk and telegraph-interference limits had been met, and that all the signaling equipment functioned properly. It was even found possible to operate a 0-decibel circuit over the four telephone channels connected in tandem although under this condition the margin was very small. With a 9-decibel circuit loss and all four channels in tandem, a very satisfactory circuit was obtained.

The equipment was packed and ready for shipment about August 1, 1943, less than eight months from the date the order was placed.

Survey of Radio Navigational Aids

By ROBERT I. COLIN

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Editor's Note: The field of radio aids to air navigation has become increasingly complex, particularly as a result of war activities. Those actively engaged in specialized aspects within the field, as well as newcomers, find it difficult to obtain a broad and up-to-date view of even the major developments and proposals. A number of co-workers suggested to the author that he prepare a compact survey of the field; the reception which this timely paper met prompted its publication in Electrical Communication.

1. *Introduction*

AIRPLANE NAVIGATORS dream of a day of no sextant, no compass, no Greenwich time, no lines of position, no pressure-pattern or assorted other charts and computers, no mathematics, and no time out at the plotting board. Commerical airline operators dream of a day of no navigators.

They await the perfection of some sort of completely automatic direct-reading indicator of position, such as the latitude-longitude meter sketched in Fig. 1; or a mechanism that moves a stylus or spot of light to pinpoint the observer's position on a map; or a combination radio beam and automatic pilot that guides the airplane as unerringly along a prescribed path as the flanged wheels of a railway car. Such devices would be a great convenience, and with the rapidly increasing density, range, and speed of traffic, they become urgently desirable for aircraft use.

Many promising and glamorous radio aids for navigation have been developed or proposed for short- or medium-distance applications; radar techniques are often employed. The very long distance or transoceanic air navigational problem appears to be a knottier one. Appreciating the technical difficulties, if not sheer impossibility, such an instrument as pictured in Fig. 1 can now be called only an "artist's conception," a fantasy. But men have dreamed before, as of talking over wires, flying through the air, and using atomic energy.

With the relaxation of wartime restrictions, a number of new types of navigational aids have been disclosed, their principles no longer dissimulated by the military code names under which they masqueraded. The time is, therefore, opportune for making a general survey and classification of radio aids to navigation to see what they might contribute toward the "impossible," yet eagerly awaited, ideal system.

1.1 Dead Reckoning Versus Radio Methods

Devices like the so-called air-position indicators (API) or ground-position indicators (GPI) should be mentioned at the outset. They are in various stages of development; their indicators in fact resemble that of Fig. 1 quite closely. These are essentially dead-reckoning devices which attempt to indicate present position by computing the net direction and distance made good from some known past position of the craft. They are analogues of the "dead-reckoning tracers" sometimes used on surface ships, in which the track of the ship is mechanically plotted on a map by taking continuous account of the direction of the ship's heading as indicated by a compass, and the distance or speed of travel as indicated by the revolutions of the propeller.

The basic difficulty with such methods is that a ship or airplane is moving through a medium—the sea or the atmosphere—which is itself moving with respect to the earth. That movement of ocean current or wind drift is erratic in speed and direction, and its measurement by an observer immersed in the very medium is quite a feat. Inherently difficult problems arise in the accurate and continuous determination of true direction and distance from compass, time, acceleration, and air-speed readings, since compass variations, wind speed, wind direction, and other troublesome factors must be both determined and taken into account.

Besides, for reliability, it is fundamentally desirable that a navigational system should place no dependence on unbroken continuity of all past readings, even if all the factors were capable of being measured accurately. One should rather be able to make an independent or fresh position determination at any time instantaneously, or nearly so, "starting from scratch" so to speak. Indeed, reliability, independence, and capability of covering all traveled areas at all times are basic requirements for an ideal navigational system, for which mere convenience should be sacrificed, if necessary.

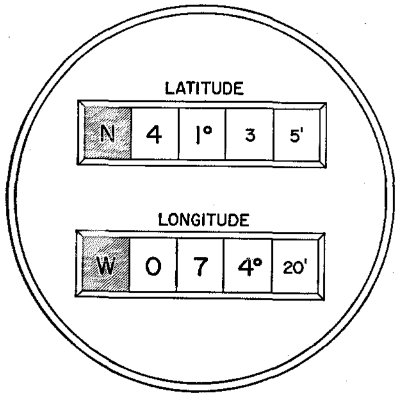


Fig. 1—An ideal indicator for navigation.

Radio waves travel great distances almost instantly; the idea of using radio for giving navigational guidance quickly and freshly occurred to people only shortly after radio proved useful for communication purposes. Many and various, even confusing, are the radio navigational schemes and their names. To evaluate them intelligently, one should have in mind a clear classification of their principles and their inherent capabilities and drawbacks; very often the differences between systems are merely in details that may be changed. Fundamental principles and characteristics are emphasized in the following description of the four basic types into which all radio navigational aids may be classified, even those whose fanciful *noms de guerre* may still only be whispered.

The classification used in this survey and the order of presentation are to a certain extent arbitrary for there are various ways of classifying radio navigational aids, such as by navigational techniques, electronic techniques, radio-frequency bands, modulation, etc. No compartmentation can be absolutely clean-cut. The simple one used, however, is quite logical and illuminating, and is a convenient framework for the survey.

I. Basic Types of Radio Navigational Systems

2. *Type A: Directional Receiving Systems*

2.1 General Principle

These are the oldest radio navigational aids and probably will always be useful to some extent. Their principle is based on the fact that certain types of antennas, loops in the simplest case, receive radio energy strongly or weakly depending on how they are oriented with respect to the incoming direction of the radio waves. Thus, by turning the antenna and observing how the received signal strength varies, the direction from which a radio ray from a distant transmitter strikes the antenna may be determined.

Many aircraft and most surface craft carry direction finders (DF) working on this principle, such as simple radio compasses, aural-null direction finders, or automatic visual direction finders. Indications may be of the aural, meter, or cathode-ray-tube type. Some of the companies that have contributed to the development of direction finders for air and marine use include Sperry, Bendix, Radio Corporation of America, Federal, British Marconi, Société Française Radio, and a number of others. The antennas are commonly loops; but may be other special arrays such as Adcocks, horns, or curved surfaces as in radar applications.

A great advantage is that the system always (in principle at least, neglecting errors) indicates the direction of the radio waves regardless of the type of transmitter. Its frequency, modulation, directivity, etc., is practically of no consequence; no special transmitting stations need be erected. A craft equipped with a simple direction finder can take bearings of any radiotelegraph, radiotelephone, or radio-range station within its distance and tuning range. Unfortunately, no direction finder is a completely independent or self-sufficient navigational aid, as next explained.

2.2 Airborne Direction Finding

Fig. 2 illustrates how a direction-finder reading observed on an airplane reveals the direction of

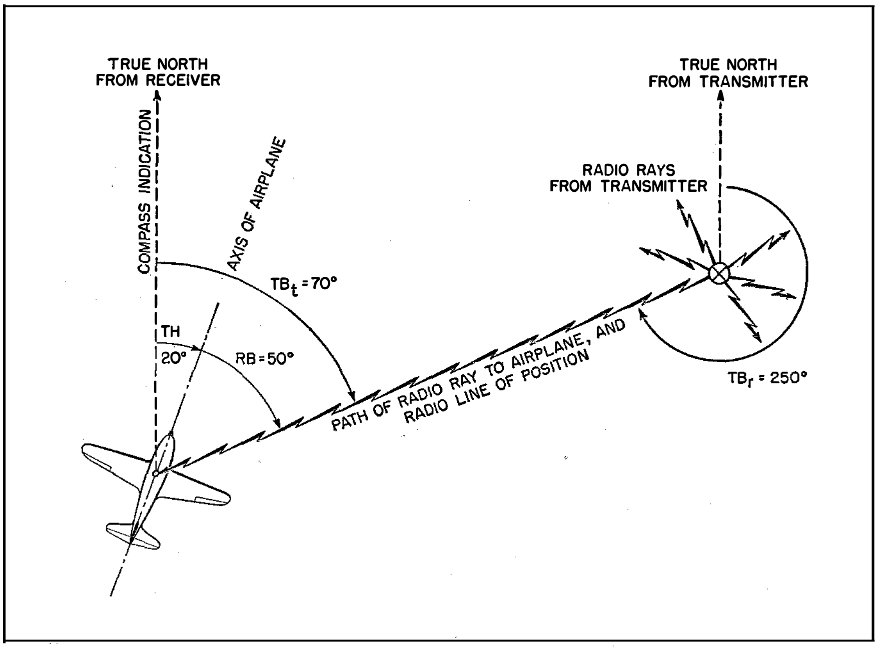


Fig. 2—Principle of airborne direction finding.

TH = true heading, determined by compass indication with corrections.
RB = relative bearing of the transmitter, obtained with the direction finder.
TB_t = true bearing of the transmitter = $TH + RB$.
TB_r = true bearing of the receiver = TB_t + 180 degrees = reciprocal of TB_t.

the incoming waves only with respect to the airplane's fore-and-aft axis, a rather vague reference except for homing purposes.

Homing makes use of the fact that the radio ray follows the most direct or shortest path between the transmitter and receiver. This path is actually the arc of a great circle on the earth; for short distances it is practically a straight line. Thus the direction finder may be said to "point toward the transmitting station." A homing flight, however, making use of this property alone for guidance, will in general not result in the airplane actually following such a direct path. Just as in the case of courses steered by reference to magnetic compass directions or bearings, cross winds alter the actual track of the airplane into something other than a direct path.[1,2]

To determine the *true bearing* of the radio ray, that is, its direction with respect to the local meridian or true north line, the navigator would have to read, in addition, a magnetic compass (and correct it for variation and deviation). This additional step is necessary to establish the observer's latitude-longitude position by direction-finding methods. Homing ability is only one item in navigation; ability to make a complete "fix" at any time is the basic navigational requirement.

Whether observations are aural, visual, celestial, or radio type, a fix is always established by measurements of distances, directions, or both, of the observer from other objects whose geographical positions are known. As a surface has length and breadth, any single observation locates one only partially on it. Knowledge of the distance from a known landmark means only that one is somewhere on a circle of that radius centered about the landmark. Knowledge of the direction from a known landmark means only that one is somewhere on a straight line, or great circle, drawn at that bearing from the landmark. A line of these or other shapes, along which an observer must be definitely located as a result of a single navigational observation, is called a line of position (LOP). For a complete location or fix, one must know the position of a landmark or two, make two observations, and draw *two* lines of position. The observer's position, or fix, is then definitely at the intersection (or at one of the intersections) of the two lines of position.

For short distances, say up to 200 miles or so where the earth's surface may be considered plane, this process is fairly straightforward using an airborne direction finder and a compass. Fig. 2 illustrates how one line of position may be drawn. Note that the direction finder and compass combination gives the direction of the transmitter as "seen" from the airplane, position unknown. A direction from an unknown point is rather vague information. To draw a line of position, the direction of the airplane from the position of the transmitter must be known. It is obvious that if a person on an airplane were to sight (by eye or by radio) along a straight line to the transmitting station, then a person at the transmitter would have to sight exactly backwards along the same straight line to see the airplane. And, as assumed in Fig. 2, if north (from which bearing angles are measured) at the receiver is parallel to north at the transmitter, then the desired line of position bearing is the exact reverse or *reciprocal* of the observed bearing. By reciprocal angle is meant the original angle plus 180 degrees.

At longer distances, however, there are complications in using airborne direction finders. The curved shape of the earth must be considered and some thought given to the precise meaning of "direction." Directions or bearings from a given point are usually specified by the angle measured, generally clockwise, from the meridian or true north line at that point. This is because north (or south), as determined roughly by a compass, ultimately by celestial observations, is the only natural reference direction available independently everywhere on the earth. Unfortunately, as Fig. 3 attempts to show, true north is not a constant reference direction always parallel to meridians or north lines at other places on the earth. Geographical north is a horizontal direction line on the earth's surface, and these lines converge toward the poles of the earth. Especially at high latitudes, the north line of an observer distant in longitude from a transmitter, is not parallel to the north line at the transmitter. The convergence, or amount of deviation from parallelism of the two meridians,

[1] "Practical Air Navigation," CAA Bulletin 24, 1945 Edition; p. 229.
[2] Stewart and Pierce, "Marine and Air Navigation," Ginn and Company, New York (1944); p. 237.

could be calculated and allowed for—provided one knew the precise location of both places. But in a navigational problem, by definition, the observer is ignorant of his own position; that is just what he wishes to find out.

The direction-finding observer is thus in this peculiar position: He has measured the arriving direction, with respect to his own compass north, of the radio ray that reached him after traveling from the transmitter along a direct path, but that knowledge alone does not tell him the departing direction, relative to the transmitter's compass north, at which that same radio ray left the transmitter. The transmitter emits radio rays in all possible directions at once; to plot a line of position, the observer must be able to identify that one of them which reached him at the observed direction-finding angle.

One partial way out is open to the navigator if he knows his position approximately, as by dead reckoning. Then by visual estimation or calculation or by reference to special tables compiled for just that purpose, he can find out the convergence between the two meridians in question. The departing direction of the ray at the transmitter is then equal to the reciprocal of the direction-finder bearing of the same ray on arriving at the airplane, plus now the appropriate meridian convergence correction. This ray could then be plotted as a great circle bearing on a suitable map.

Apart, however, from the fact that plotting a great circle on a map is not always easy, there is an additional complication. The *great-circle path of the radio ray from transmitter to receiver* is not itself the *radio line of position* corresponding to the airborne direction-finder observation. Fig. 3 illustrates how a number of radio rays may leave a transmitter at different bearings, each one traveling along a different great-circle path, and yet arrive at a number of different points at the identical incoming or direction-finding angle. The curved, non-great-circular line drawn so as to join these points smoothly is the line of position that is characteristic of a direction-finding bearing measured on an airplane. To draw it accurately is a complicated process, involving also knowledge of the geometric properties of the particular map projection being used.[2,3]

At short or medium distances, where airborne direction finding is chiefly used, the various complications may be neglected partially or completely without serious error. Since this survey is concerned with navigation at all distances, at least the existence of the complications must be mentioned. If full understanding is still lacking, that fact may illustrate the point that navigation by direction-finding methods is only deceptively simple, at least at long distances. In any discussion of long-range navigational aids, one cannot escape the three-dimensional problems caused

[3] P. 233 of reference 1.

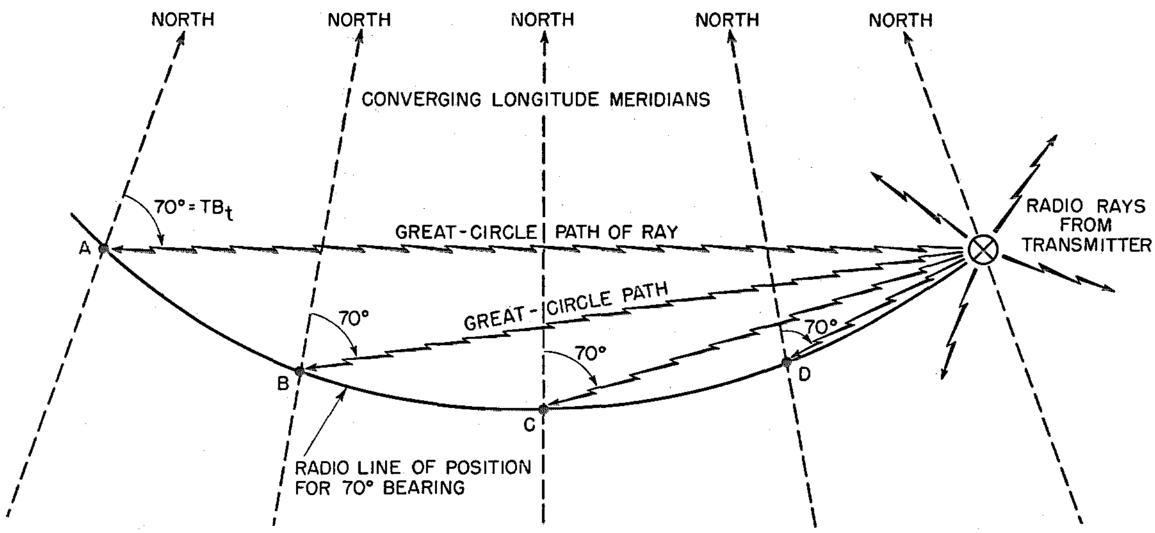


Fig. 3—Direction-finding complications at long distances. $TB_r = TB_t + 180$ degrees + meridian convergence correction.

by the sphericity of the earth. One may hope that four-dimensional space ships and navigational methods are never invented.

2.3 Ground Direction Finding

The situation is improved in some respects if the airplane transmits to two suitably located ground receiving stations. In this case, the true direction of the airplane, as "seen" from each of two known positions, is measured directly. That direction, laid out from the meridian at each ground station, is the radio line of position of the airplane. It is a great-circle arc and may be drawn as a straight line on a suitable map, viz.: on any projection for short distances, on a Lambert projection up to moderately long distances, and on a Gnomonic projection in the general case. The fix, as created by the intersection of two great-circle lines of position, might also be determined without graphical plotting by spherical trigonometry or by special devices.

Ground direction finding is frequently used for locating surface ships by reference to coastal receiving stations; it is sometimes, especially in emergencies, used for locating airplanes. For military purposes of spotting enemy ships, submarines, or airplanes, this method is fine since it requires no cooperation from the craft other than the emission of any type of radio signal. The "Huff-Duff," or high-frequency automatic direction finder, developed by Federal, is an example of this application, bearings being readable even on the shortest "squirts" of radio energy to which transmission was purposely limited to confound conventional, slow-reading direction-finding devices. But this is for special military purposes; it is applicable to ground observation of air traffic, a function important in itself but not, strictly speaking, a navigational aid. For intentional navigational use by the craft itself, ground direction finding and related methods (such as ground-based radar) suffer from certain fundamental drawbacks.

First, the distance range is more limited than in airborne direction finding because an airplane cannot carry a very powerful transmitter. Second, the airplane must first get in radio contact with a ground station to request its help; this and another suitably located ground station must take bearings on the airplane simultaneously, compare notes, plot the fix, and then radio the answer back to the airplane, which by this time may have moved. This procedure not only takes time, which is more serious with aircraft than with ships, but it also forces the navigator of the craft to depend on second and third parties, located at other places and less vitally concerned than is the navigator. This sort of thing is fundamentally objectionable in any navigational aid. Also, another return radio link is involved. Finally, ground direction finding is extremely "saturable"; that is, only one airplane at a time can use the ground stations' facilities. In summary, direction finding of the airborne or ground type is not a self-sufficient or independent navigational aid; it requires either compass indications or relaying of information from the ground.

2.4 Direction Finding Versus Range or Track Systems

Although suitably supplemented direction finding is ultimately capable of giving a fix, that ability is not the only item in navigation, or the one wanted most of the time. Especially on long overseas flights, the pilot is concerned not so much with where he may be exactly, as with the constant problem of how to steer so as to reach his destination most directly. Steering by only a compass or radio direction finder leads to troublesome off-course wanderings caused by variable wind effects, which mount up on long flights.

The pilot would like a radio navigational aid which gives him continuous track guidance or a sort of invisible radio beam to follow. He would like a *single* instrument to tell him continuously if he is on the prescribed flight path, and if not, whether he should steer left or right to return to that flight path. Such an instrument could also be arranged to guide the airplane along the flight path automatically, in conjunction with an automatic pilot. The essential thing is that each radio indication, entirely by itself, should correspond to a fixed line of position on the earth. Such systems, in contrast to directional receiving systems, are commonly referred to as radio range systems.

There may be some confusion in the use of this term, for one common meaning of range is *distance*, as in gunnery and radar. It is true that some radio navigational systems are of the pure distance type, giving circular lines of position, but, in most radio ranges, the term is used by way of analogy with the marine range principle, by which a pilot can guide his ship along the fixed straight-line path established by the visual alignment of two distant landmarks. In fact, in such radio ranges, the line of position is in effect delineated by two or more landmarks—antennas in this case—suitably aligned, the "sighting" being done by one of a variety of radio means.

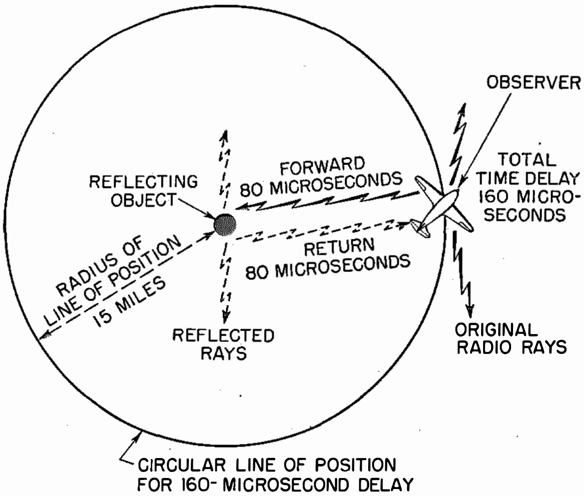


Fig. 4—Absolute-distance principle used in Shoran system.

Perhaps the most familiar and widespread example of a radio range or track guidance system is the four-course aural-type A–N installations operated all over the U.S.A. by the Civil Aeronautics Administration. A variety of other radio range schemes exist and give differently shaped lines of position. An ideal range sytem should not be limited to a specific number of beams,[4] but rather give omnidirectional service; that is, the pilot should have track guidance available completely around a ground station. Then at all points he could use intersecting beams or lines of position from two stations to get a fix whenever desired. Furthermore, the shape of the beams should be such as to offer convenient and direct flight paths between air terminals.

[4] In radio range systems, the term "beam" is perhaps misleading but it is common; it really stands for the expression "observable radio line of position."

The three remaining basic types of radio navigational systems are each capable of giving range-type service or track guidance; each has a characteristic shape of line of position. Questions of omnidirectional service and other features of convenience depend on specific system details.

3. Type B: Absolute-Distance Systems

3.1 General Principle

The principle is that the distance between an airplane and a remote point is determined by measuring the time it takes a radio wave to make a round trip between the two points, one of them being at a known position on the earth.

3.2 Pulse Method (Shoran, Oboe)

In Fig. 4, an airplane emits a brief pulse of radio energy in all directions. Some of this radiation hits the known object and causes many reflected rays to be emitted in all directions from that point. One of these reflected rays travels back to the airplane, where it is received. This all takes a very short, but measurable, time. If the reflected pulse arrives back, say, 160 microseconds after the original pulse went out, the one-way passage must have taken 80 microseconds. Since radio waves travel at very nearly 186,000 miles per second, or 0.186 mile per microsecond, by simple arithmetic the distance between the airplane and the reflecting object must be close to 15 miles.

From this single observation only distance, not direction, is revealed. Therefore the airplane must be on a line of position which is a circle 15 miles in radius centered about the plotted position of the reflecting object. The procedure for drawing a circular line of position on a map would depend on the projection used; special charts could be drawn up in advance showing numerous lines of position corresponding to various time observations. By flying so as to keep a steady time-delay indication, the pilot could accurately fly along any desired circular flight path. This radio beam is a distance type of range, analogous to piloting by means of an optical (parallax method) or acoustic (echo method) range or distance finder on board a surface ship. To get a fix, the navigator would observe the time delay from a second reflecting object and note where the two circular lines of position intersect.

Shoran, developed by the Radio Corporation of America, and various types of distance-measuring equipments (DME) work essentially on the principles just described.

Alternatively, the primary transmissions and the time measurement could take place at a ground station, the airplane itself, or a responder-beacon on it, serving as the reflecting object. This is the principle of the British Oboe system. There enters the problem of relaying the distance or fix information, determined on the ground, back to the airplane via another radio link. Lines of position are still circles centered on the ground station. Service radius is still limited by the requirement of reflections (or aided responses) from the airplane. It might also be noted that circular flight paths are not especially useful, except for "orbiting" or "holding" maneuvers around airports, preparatory to landing. These methods, however, have proved very useful for military and other applications demanding great accuracy in pin-pointing a fix as there are very accurate timing methods available.

3.3 Timing Principles

Measurement of the microscopic time intervals involved is done by special electronic means, generally in conjunction with a cathode-ray tube whose screen performs the function of the dial of a watch. An electric current is caused to make an electron beam behave like the sweep-second hand of a watch. The position of the electronic hand or beam can be made visible on the cathode-ray-tube screen. The hand starts moving from zero each time the basic pulse ("main bang") goes out, and sweeps along the time graduations at a uniform rate. Some time during this sweep, the echo pulse arrives and illuminates the hand at that instant by causing a "pip" of light; the position of this pip against the scale of uniform time graduations indicates the time interval, as when using a watch. In some cases, the electronic watch hand sweeps around in a circle continuously like an *ordinary* watch hand (circular time-base sweep); in most cases the electronic hand moves laterally or radially outward in a straight line, and at the end must be very quickly reset to zero as when one rapidly double-clicks a *stop* watch to start the process over again (linear sawtooth time-base sweep). In each case, the hand must travel at a uniform speed, and care must be taken to have it start from zero each time the main pulse goes out. The electronic hand moves too rapidly to allow one to follow its motion directly, therefore it is kept dark and its momentary position is made visible only when pulses occur. Each single pip or visible pulse is too brief to notice, as in the case of a single frame of a moving-picture film; and as in moving pictures, repetition, together with persistence of vision, solves this problem. Two ways of indicating such time intervals are shown in Fig. 5.

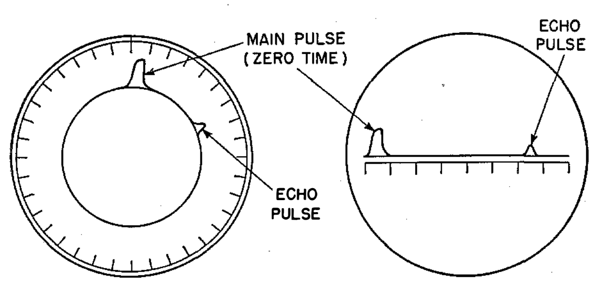


Fig. 5—Principles of two common ways of displaying on a cathode-ray tube the time interval between pulses. Graduations may indicate time in microseconds or the corresponding distance in miles.

In some cases, controls are provided to move the echo pip into apparent coincidence with the main pulse pip, and the time is given by the position of the control. In certain applications, such as radio altimeters and distance indicators, the electronic circuits may be arranged to produce a direct-reading mechanical meter-type indication, generally not so accurate. In all cases, the ultimate or theoretical limit of accuracy with which the exact time of occurrence of a pulse can be determined depends on how short the pulse can be made. As the minimum length of a pulse is inherently limited by the bandwidth of the radio channel, increases in ultimate timing accuracy for radio distance measurements require wide channels which are practically available only in the higher-frequency region of the radio spectrum.

3.4 Responder-Beacons (IFF)

There must be some provision for distinguishing those echoes that are produced by the desired reflecting object at the known location from the mass of echoes that are produced by reflecting objects located at various other points in the path of the primary radiation. Where airplane interrogators are used, the problem may be solved by installing responder-beacons at the desired ground locations. These beacons consist of a receiver-transmitter combination and are also called transponders and racons. Military code names, often of a fanciful character, have been applied to them. Reception of each interrogation signal or pulse automatically triggers the transmitter into radiating an answering signal. This answering signal (active response or artificial echo) is stronger than a passive or natural echo, so that the range of service is increased. For positive identification of the different responder-beacons, the answering signals may be coded distinctively or may occur on different radio channels.

In systems where the primary transmitter or challenger is located on the ground, responder-beacons on the airplane are valuable for increasing the range, as natural echoes from airplanes are quite weak, and for identification purposes. Identification-of-friend-or-foe (IFF) systems, used in wartime to identify airplanes spotted as pips on radar displays, worked on these principles; friendly airplanes were provided with responders which coded their answering pulses in a prearranged manner.

A single responder-beacon may provide automatic answering service for a number of different interrogators at the same time, but there is a limit. One factor determining the saturability of the system is the power capability of the transmitter portion of the responder; if the energy per response pulse (which affects the range) is not to fall off, the total number of pulses per second that the transmitter may radiate is limited by its rated (average) power output. A second factor holds true also for systems using natural echoes; there is a limit to the number of different sets of interrogation or response signals that can exist on a given radio channel without likelihood of interference, even though each set may be composed of brief and widely separated pulses.

3.5 Phase and Frequency-Modulation Methods

Absolute distance may be determined in other ways than by using brief pulses; but in all cases transmitted and reflected energy must be used and the observation is fundamentally, if not directly, a measurement of *time.*

The transmitter may emit continuous-wave radio energy. In this case, the difference between the instantaneous phase of the departing wave and the phase of the wave arriving back after reflection is measured. This phase difference depends on the total number of wavelengths and fractions thereof included in the total round-trip distance; this in turn depends on the total distance and the known wavelength or frequency of the radio signals. In all cases of wave motion, the instantaneous phase changes uniformly by 360 degrees per wavelength as one travels along the path of the wave. The phase at any one point also varies with time, according to the radio-frequency rate; but at all times the *difference* in phase between any two points is constant, depending only on the distance between the points in terms of wavelength. Thus measurement of phase differences may be a convenient and sensitive way of determining distance. This principle is used in one form of the Raydist system.

A related method is to vary the radio frequency of the outgoing radio waves, usually at a saw-tooth rate, and to compare the instantaneous difference in frequency between outgoing waves and reflected incoming waves. This difference depends on the time of travel of the waves and is measured by some type of differential frequency meter. This principle is used in some forms of radio altimeters or terrain-clearance indicators (TCI).

3.6 Radar Principle (PPI Display)

Radar is a combination of types but is logically mentioned at this point because one part of it is always an absolute-distance system, generally of the pulse type. In radar, defined as a system for "radio direction and ranging," a complete fix is obtainable by *simultaneous* determination of a circular line of position from the absolute-distance system and a radial straight line of position from the directional system, both based on the *same* landmark.

The principle is illustrated in Fig. 6. The bearing or directional line of position is obtained by the use of directional antennas for receiving or for transmitting. Actually, most radar systems use the same antenna for both emitting the original radio waves and receiving the reflected waves. Brief pulses are transmitted along a sharply defined narrow beam[5] instead of in all directions. The direction of this beam is gradually changed by physical rotation of the antenna, which is therefore said to scan in all directions. The echos are displayed pictorially as spots of light on a cathode-ray-tube screen. Radial distance of the spot of light corresponds to the time delay or actual distance of the reflecting object. The direction at which the spot appears corresponds to the actual bearing of the antenna at the instant of echo reception. All distances and directions are with respect to the position of the antenna installation, which corresponds to the center of the display. This type of display is a polar-coordinate plot and is referred to as a plan-position indicator (PPI).

If the radar set is on the airplane, bearings are relative to the axis of the airplane and require a compass correction for absolute or true orientation. On a ground radar installation, the true bearing of the airplane from the landmark is indicated directly. This is satisfactory for ground observation or traffic-control purposes, but if the ground radar is to constitute a navigational aid, both the distance and the directional information must be relayed back to the airplane via another radio link.

Radar antennas, directional and capable of rotation, add considerable weight and drag to airplanes. In any case, they require the use of rather high-frequency radio waves to avoid extreme size. This, in turn, limits the service range approximately to line-of-sight or horizon distances, even for ground radar. Thus, while absolute distance and radar systems are spectacularly useful for military purposes and appear promising for ground control of air traffic, as navigational aids they seem to be restricted to short- and medium-distance applications.

For military applications, normal (primary or unassisted) radar is particularly effective because no cooperation from the airplane is necessary. For civil purposes, the performance of ground radar, in respect to clarity of presentation and range of service, can be improved by installing responder-beacons in aircraft. The artificial responses are stronger than natural echoes and, if they are on a different radio channel, the radar receiver can reject all natural echoes and ground clutter to produce a clear display. The response, being artificially produced on the airplane, can be coded to convey information such as the altitude of the airplane and its identification. Thus, beacon (secondary or assisted) radar will doubtless find extensive use in civil air-traffic-control systems.

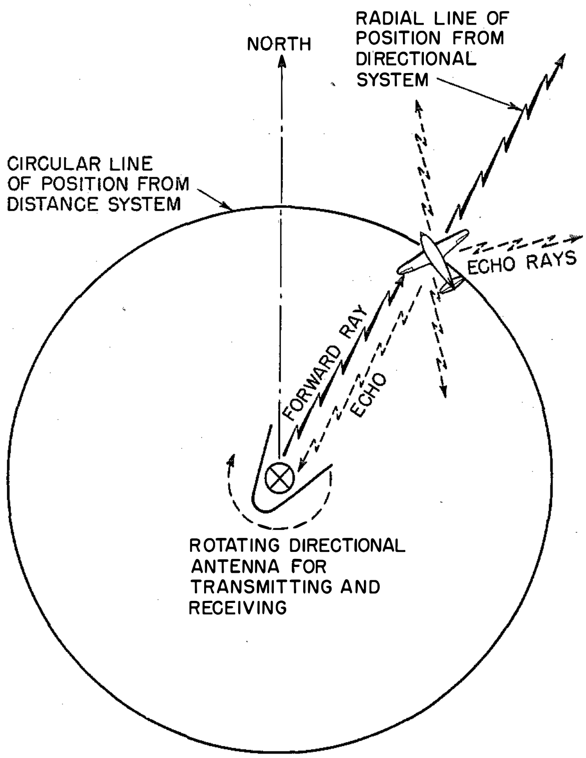


Fig. 6—Radar principle using plan-position type of indication.

4. *Type C: Differential-Distance Systems*

4.1 General Principle

In this type of system the *difference* in distance between an airplane and two different ground stations is determined, but again making use of the known speed of travel of radio waves.

[5] In this case, the word "beam" for radio line of position is used with justification.

4.2 Pulse Method (Loran, Gee)

Fig. 7 illustrates the essential principle. Two ground transmitters, *A* and *B*, each emit brief pulses of radio energy at exactly the same time. To reach an airplane located at *X*, the signals travel along different paths. If the lengths of the two paths are different, one pulse is received later than that from the other ground station. This time difference or delay is a measure of the difference in path length, or *BX* minus *AX*.

In Fig. 7, the 300-microsecond delay observed at the airplane reveals only that distance *BX* minus *AX*, or distance *BY* minus *AY*, and so on, equals about 55 miles. Many different points may correspond to that same time or distance difference. The exact line of position depends on the time difference and on the location of the two transmitters, but in any case is one of a family of hyperbolas (by the geometric definition of such curves) on a plane surface. The line of position of no time difference, or of equal path length, to express it more generally, is clearly the perpendicular bisector of the line joining the two ground stations.

This is the essential principle of Loran, developed by the Radiation Laboratories at Massachusetts Institute of Technology; Gee, developed in Britain; and a number of related systems, all sometimes referred to as hyperbolic systems. Organizations that have built or are building Loran equipment in the U.S.A. include R.C.A., General Electric, Sperry, Federal, and others. One great advantage of differential- over absolute-distance systems is that there is no need for a return signal from the airplane. This increases the practical service range. Moreover, the system is not saturable for any number of airplanes can use the signals simultaneously. The observations are made directly on the airplane.

Other basic characteristics include the following: Simple nondirectional antennas are used. Stations *A* and *B* must be separated by a considerable distance, up to several hundred miles, or the time differences become too small to measure accurately. Station *B* must constantly receive signals from station *A* for control purposes for the times of emission of signals from both stations must be accurately synchronized. To cover a given area with one family of lines of position, two suitably related ground stations are required and an airplane must be within reception distance of both stations.

A fix is established by observing the time delay with respect to another pair of ground stations within range and noting the intersection of the two hyperbolic lines of position. The two *pairs* of stations may have one station in common. Special charts are required to facilitate the interpretation of time delays into lines of position on a map. These charts have ordinary latitude and longitude lines plus the hyperbolic lines corresponding to various time delays from a number of pairs of stations in the area, with allowance for the curvature of the earth and the properties of the map projection all figured in advance.

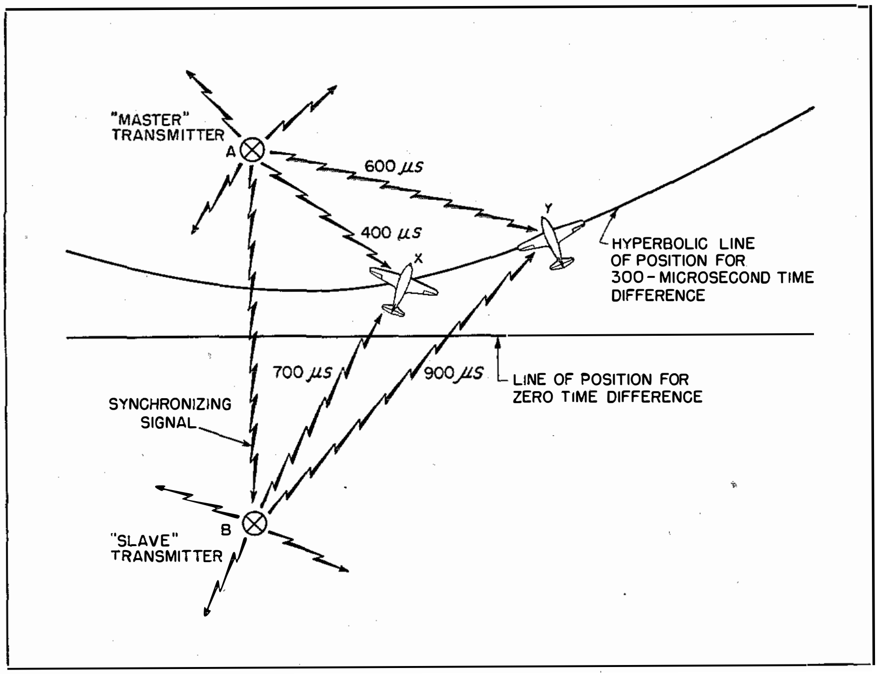


Fig. 7—Differential-distance principle utilized in Loran system. The transmission times in microseconds are given for each of the four radio paths shown.

Although Loran requires no rotating or directional antennas and is thus not restricted to very-high-frequency line-of-sight applications, the fact that brief pulses are used places some restrictions on the operating wavelength and bandwidth. The wavelengths at which Loran is usually operated allow service up to about 700 miles by day and about 1400 miles by night, but, unfortunately, the transmissions are subject to the ionospheric disturbances that plague all high-frequency radio signals.

By flying so as to keep a constant time delay, the pilot can guide his airplane accurately along any line of position as a track. Hyperbolic lines, however, are not generally suitable as direct flight paths. The central or zero-delay line of position is an exception, being a straight line or great-circle path. But for this line to pass through a given air terminal requires siting ground stations at two additional locations. This may not always be practicable in remote regions or at islands in midocean; and, in any case, none of the other lines of position "lead home." Indication of time delay is not automatic but requires skillful and time-consuming observations and manipulations of cathode-ray-tube devices. This, however, is an engineering detail which may no doubt be improved; it has certain advantages in fact in that it provides a visual indication of the quality of the signals for monitoring purposes.

With all these drawbacks, differential-distance systems have been put to extensive use for short and medium-long ranges, especially in military applications, because of their great accuracy and reliability up to a certain variable limiting range. Whether reliable world-wide coverage can be obtained, either by improving the dependable distance range or by finding sufficient pairs of suitable land sites, is a question that has not yet been answered.

4.3 Phase Method (Decca, Raydist)

Differential-distance systems, like absolute-distance systems, may employ continuous waves instead of pulses, with phase comparison instead of direct time-delay measurements. This is the principle of one form of Raydist, an accurate system suitable for surveying, and of the Decca system developed in Britain by the company of that name. In the latter, master and slave stations emit pure continuous-wave radiations accurately synchronized in radio-frequency phase. At any distant point, the difference in phase between the two waves received on an airplane depends on the difference between the number of wavelengths, and fractions thereof, in each path. The lines of position are still hyperbolas and the system has most of the other basic characteristics of Loran, except of course that there are no inherent limitations on the operating frequency or bandwidth. Other practical complications do arise. These involve the question of ambiguities and the special relations between the radio channels of a pair of stations.

Differential-distance systems of either the pulse or the phase type may alternatively work on the principle of having two separate ground stations receive signals from the airplane. Lines of position are still hyperbolas. A link is now required for comparing the time or phase of reception at the two ground stations; an additional radio link is needed to relay the information back to the airplane. Range is limited by the necessity for an airborne transmitter; and, like ground direction finding, the system is saturable. While perhaps useful for some special military applications, as in Micro-H, this method is clearly unsuitable for a long-range self-sufficient navigational aid.

5. *Type D: Directional Transmitting Systems*

5.1 General Principle

Here the fundamental principle is that the transmitting antenna system has directional characteristics; that is, the radio signals transmitted in various directions from the station are different in some measurable respect.

If the transmitter is located at a ground station, the radio lines of position are fixed straight lines or great circles radiating from that point. If airborne, type-D transmitters are generally limited to radar applications where antennas may be small; range of service is then short so that meridian convergence is negligible. The lines of position, however, are relative to the fore-and-aft axis of the airplanes as in airborne direction finding (see Fig. 2); but just such relative indications are useful in locating nearby obstacles for anticollision service.

Antennas are given directional properties by making them large compared to the wavelength or by using arrays of antennas suitably spaced and phased. The principle is the same as in any wave-interference phenomenon, as occurs also in optics and acoustics, in which the waves from the individual sources annul or reinforce each other depending on how they combine in phase along different directions.

Radar antennas are a special case in which, because of the high frequencies used, the antenna "dish" or array can be very large compared to a wavelength and yet be small or moderate in physical size. Such antennas can produce practically one single sharp beam, and the radio line of position is simply the direction in which the antenna is pointing. Being small, the antenna can be physically moved around so as to point in any desired direction. Service range, however, is limited to radio line-of-sight.

At lower frequencies, directional effects are obtained by the use of two or more antennas separated from a quarter to several wavelengths. Actual size is large and practically precludes physical rotation. Sharp beams are not produced by such systems. At these frequencies, common examples of directional radiation patterns or graphs, which indicate the relative signal strength in various directions, are shapes like the figure-of-eight and the cardioid.

This variation of signal *strength* cannot, by itself, be used immediately to indicate direction. This is because the actual signal strength existing at a given point depends also on transmitted power, distance, and propagation conditions, which factors cannot be expected to remain constant. They must be made to cancel out in some manner so that only the effect of the directional properties of the transmitting antennas on the signals remains. A radiation pattern, in fact, indicates only the relative strength of signals in different directions if all other factors are assumed to be constant. Fortunately these other factors are constant at a given point for short time intervals at least.

Therefore in these systems, the transmitter always emits at least two types of signals, corresponding to two different directional patterns, so that regardless of the actual strengths of the two signals at a given time and distance, their *relation* to each other is constant and depends only on the bearing of the observer. Both signals may vary for one reason or another—even receivers vary in sensitivity—but all these variations affect both signals in the same proportion provided the two types of signals are emitted simultaneously or in very rapid alternation.

At the frequencies in question, it is impracticable to produce different directional patterns by physical movement of the antennas. Instead, they are produced by electrical means; that is, by switching to different pairs of antennas or by changing the electrical excitation (current strength, phasing, or both) of a given set of antennas. Thus, with physical movement limited to small electrical control devices, the lobes of the directional patterns from a fixed antenna installation may be rotated, shifted, reversed, or interchanged, and so on, and at a fast rate. As a result, along each direction two or more signals of different strength, or other measurable characteristics, are repeatedly provided, which the observer compares and from which comparison the true radio line of position is determined.

The two or more types of signals, corresponding to different directional patterns, must be distinguishable at the receiver so as to permit comparisons to be made. For this purpose, the radio waves corresponding to each directional pattern are given some characteristic modulation or other identifying feature, such as tone modulations, dot-and-dash code patterns, or certain sequences or durations of emission. The method of separating and comparing these signals and of indicating their relation depends on specific system details. The comparisons are not always directly in terms of relative signal strength, but may be in terms of other characteristics such as modulation patterns (phase, code sequence) which, however, depend on the directional strength patterns. Also, usable signal relations may exist only along a limited number of directions as in single landing beams and two- or four-course ranges, or at all bearings as in the omnidirectional ranges (ODR).

5.2 Limited-Coverage Ranges (A-N Range, Landing Beam)

The four-course A-N ranges, though considered old-fashioned, are the most extensive radio navigational aids at present in the U.S.A., and may be considered as a sort of prototype of type-D systems. The indications are aural and the airplane needs no special equipment other than a communications radiotelephone receiver and headset; but there are disadvantages in that the indications in such methods are either inexact or time-consuming.

In the A-N range, two pairs of antennas are used, each located at opposite corners of a square. Spaced from a quarter to a half wavelength apart, they are excited so as to produce two figure-of-eight patterns at right angles. A dot-dash *A* code character is emitted on one pattern and a dash-dot *N* character on the other pattern. The two figure-of-eight patterns intersect along four bearings or beams where, for equal power in each radiation, both signals are equally strong. Actually a continuous tone is detected since the dot-dash alternations are suitably interleaved; this is the aural "on-course" indication of the radio line of position. Along other directions either the *A* or the *N* code stands out, and indicates on which side of the beam the airplane may be. No means is provided to make exact quantitative comparisons of strength. Thus, only four useful fixed beams result as will be seen from Fig. 8. Navigation along other routes is not provided for;

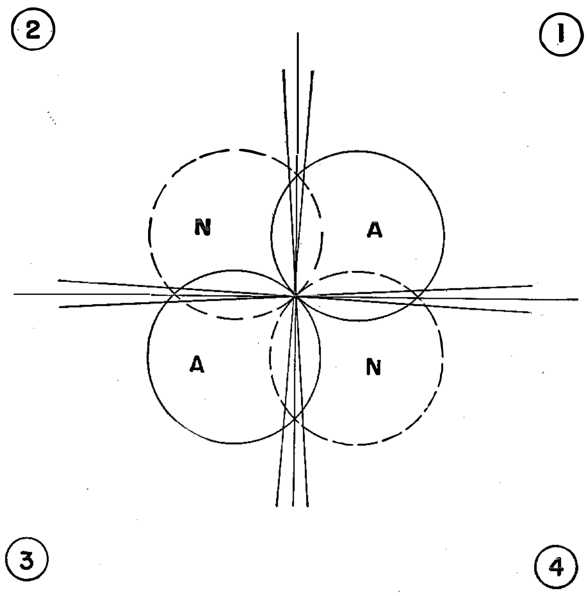


Fig. 8—Principle of the A-N radio range system showing the two figure-of-eight patterns alternately radiated and the four equisignal sectors or beams.

fixes by means of intersecting beams from other stations are only occasionally possible. The four beams sound alike, so if the pilot is completely lost, considerable ingenuity and time are required to judge which of the four beams he is on—if at all possible.

The equisignal intersecting-lobe or lobe-switching principle is a fundamental one, and is often applied. Landing systems and other two- or four-course range systems use it, even though the indication of equality or balance may be presented visually on a meter. In landing systems a single, but very accurate, beam is all that is desired. For this purpose, larger arrays, in terms of wavelength, are used to produce sharp lobes, only one pair of which are used. The alternating radiations have different audio-frequency modulations which can be separated by filters in the receiver and applied to a zero-center meter to pull the needle in opposing directions. The principle is even used in some radar receiving antennas to increase the directional sharpness, for radar beams have some width; two intersecting lobe patterns, at a slight angle to each other, are produced electrically from one antenna, which is accurately lined up by using some sensitive balance indicator.

5.3 Intermediate-Coverage Ranges (Consol, Sonne)

Greater coverage of a given area with useful beams or radio lines of position can be provided if directions, in general, are quantitatively indicated in terms of the measurable ratio of strength between the alternating signals. Operation is not restricted then to equisignal directions. Coverage is still not complete, because some portions of the lobes are not useful; at the nulls or minima, signals are too weak to be heard; at the maxima, the variation of strength with direction is too gradual to permit accurate determinations. If, however, the available lobes from a given set of antennas are rotated or shifted enough so as to cover all sectors at one time or another with useful portions of lobes, continuous coverage is possible. Complete omnidirectional service is still not possible by any schemes using one pair of antennas; the two angular sectors along the line joining the antennas turn out to be "dead zones" in this respect.

The principles just described are used in the British Consol system developed from the German Sonne system. Equipment for an American form of the system has been built by Federal. This system is also aural, requiring only a radiotelephone receiver and headset; great accuracy is possible because the lobes are narrow; and continuous coverage of wide, but not unlimited, areas is provided. The readings, however, take considerable time, special reference charts are required, and there are many ambiguities which depend on the number of lobes.

Two or three in-line antennas are used, spaced up to as many as six wavelengths apart, resulting in many narrow lobes. Successive, intersecting pairs of lobes are produced by rapidly alternating reversals of current. For identification purposes the complementary lobe patterns are radiated in a sequence of alternating dots and dashes. At a slower rate, and with the rapid lobe switching meanwhile continuing, the lobes are gradually swept around in bearing by means of gradual, uniform changes in phasing. The result is that an observer at a given bearing hears a peculiar pattern of dots and dashes. The apparent coding sequence that is heard depends on the observer's bearing. He counts the number of dots and the number of dashes heard during some specified time interval, consults a special calibration chart, and reads off his true bearing.

The nature of the radio emission is such that the system may operate on any radio frequency, even very low; and very narrow bandwidths may be used. The ambiguities and the lengthy aural presentation, together with the lack of complete coverage, are the chief drawbacks.

5.4 Omnidirectional Ranges (Navaglobe, CAA Omnirange)

For omnidirectional service, so that beams are available through all 360 degrees, and so that fixes by crossed beams are everywhere possible, more antennas aligned in different directions are needed. To avoid the need for an excessive number of antennas, the previously described principles of lobe sweeping or of non-equisignal measurements may be used at the same time.

For very long distances, the straight lines of position of ground-based directional transmitting systems are desirable, but no entirely suitable systems of this type have been installed. The main problem is devising a system which is propagationally (frequency, bandwidth, etc.) suitable for very long distances and which is also omnidirectional, direct-reading, and free of troublesome ambiguities.

One interesting example of a system for that application, and which serves to illustrate the general principles of directional transmitting methods, is the Navaglobe system,[6,7] now being developed. This was proposed by Federal at the national radio navigation conference in Washington in February, 1946.

Three adjacent antennas are used for the ground station installation. Three is the minimum theoretical number of antennas capable of giving omnidirectional service. The antennas are spaced triangularly, as shown in Fig. 9, about 0.4 wavelength apart. In turn, each pair of antennas is equally excited so that in effect three signals are radiated in rapid succession, over and over again. The relative strength of each signal depends on the direction of the receiver from the array; this is indicated graphically by the

[6] H. Busignies, P. R. Adams, and R. I. Colin, "Aerial Navigation and Traffic Control with Navaglobe, Navar, Navaglide, and Navascreen," *Electrical Communication,* v. 23, pp. 113–143; June, 1946.

[7] P. R. Adams and R. I. Colin, "Navaglobe Long-Range Air Navigation System." *Proceedings of the National Electronics Conference,* October 1946.

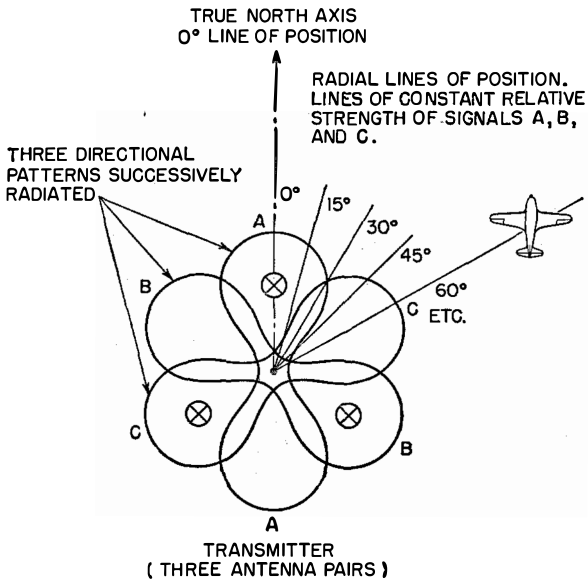


Fig. 9—Directional transmitting principle on which the Navaglobe system is based.

radiation patterns or relative signal-strength curves shown. Along each straight radial line, the *relative* strengths of the three signals received in rapid succession are constant; at greater distances all three signals are weaker, but in the same ratio. The receiving system measures this relation between signal strengths and translates it automatically into the setting of a pointer around a dial calibrated directly in degrees of azimuth or true bearing.

In common with all ground-based directional transmitting systems, and in contrast with both ground or airborne direction-finding systems, the indicated bearing is directly the bearing of the observer from the ground station, and is at the same time observed directly on the airplane. The radio line of position is that bearing laid off as a great-circle bearing from the meridian of the ground station. This is easily plotted on the Lambert projection, commonly used in government air navigational maps, as on that projection great circles may be represented by straight lines for even moderately long distances. In any case, a straight line may be drawn on the Gnomonic projection, which is also furnished by the government for air navigational purposes. For a fix, the bearing from another ground station is observed and the intersection of the two lines of position is noted. There are also devices which quickly give the latitude and longitude of a fix corresponding to two great-circle bearings from known points without need for maps or calculations. In short, ground-based type-D lines of position and fixes are as simple and straightforward as in ground-based direction-finding, yet they arise from ground transmitters and airplane observations instead of the reverse.

Furthermore, because the lines of position are great circles, they are useful direct flight paths or radio beams for traffic to follow. They all lead to or from the ground station; and if ground stations were located at or near the main terminals of long-distance air routes, the lines of position would be direct fixed homing paths.

In addition, as Navaglobe is an omnidirectional system, the pilot could select any desired radial direction as a flight path; and could use crossed lines of position for a complete fix at any place as long as he is within range of two stations. Moreover, since the Navaglobe indicator is a direct-reading pointer type, the pilot could easily "keep on the beam" by setting an index mark along the dial at any desired bearing and steering so as to keep the pointer aligned with the index. A differential left-right meter might be added to give him corrective steering directions still more conveniently, or to guide an automatic pilot.

The nature of the system is such that the operating wavelength may be of any value, even very long. This is because the emissions may be very slowly modulated continuous waves with their attendant extremely narrow bandwidths.

The Civil Aeronautics Administration has developed an omnidirectional visual radio range system, which is intended eventually to replace the four-course aural A-N ranges for medium-distance overland navigation. This new system uses higher radio frequencies than does the old aural system, partly because its modulation features appear to require it. The antenna array, incidentally, is smaller.

This omnidirectional range uses five antennas, four being spaced at the corners of a square, and one at the center. The effect of almost uniform circular rotation of lobes is obtained electrically by the rotation of small control devices or goniometers instead of by movement of the antennas. Suitable excitation of each pair of antennas at diagonally opposite corners of the square, in conjunction with the central antenna, produces a cardioid or heart-shaped directional pattern. By a scheme of modulation which fades the four cardioid patterns in and out properly at a slow audio-frequency rate, the effect is similar to that of a cardioid directional pattern rotating uniformly. The resulting signal heard at a distance is a wave which has a corresponding audio-frequency modulation imposed on it, but the phase of this modulation depends directly on the bearing of the observer. An additional audio-frequency modulation is imposed on the radiation through the central antenna, at the same rate; but this signal is nondirectional and has the same phase at all bearings. This serves as a reference signal.

The receiver on the airplane has automatic means for separating the two modulations and indicating the phase difference directly on a meter, in terms of true bearing. There are no ambiguities since the antenna produces a cardioid, or single-lobed pattern. One degree of phase difference corresponds, almost exactly, to one degree of bearing change. As there are no large moving parts in the transmitting system, the rotation rate can be fairly high and the reading time of the indicator correspondingly short.

The system has all the features of observational convenience described under Navaglobe; one basic difference is that its system of modulation is more complicated and requires, in present form, wide bandwidths and high frequencies. Thus, while it is propagationally suitable for medium distances, its suitability for very long ranges appears unsettled; development work, however, is being done on a low-frequency design of this system.

6. *Ambiguities*

6.1 General Nature

An ambiguity exists when a single navigational observation corresponds to two or more lines of position. Thus two observations may result in a fourfold or greater ambiguity of the fix. Ambiguities exist even in celestial navigation, as in the most common method (Sumner lines of position by means of zenith distances) wherein two circles of position intersect at two points. It might almost be said, in general, that all fixes are subject to an ambiguity caused by the fact that so-called straight lines of position are really great circles on the earth, and two great circles intersect at diametrically opposite points on the earth. A navigator, however, is not generally lost to the extent that he is ignorant of which hemisphere he is in.

It is possible, on the other hand, for the alternate lines of position or fixes to be so related as to cause troublesome ambiguity even to good navigators; this may be a major factor when appraising some radio navigational systems. Characteristic types of ambiguities occur in each type of system.

6.2 Directional Systems (Types A and D)

In these systems, ambiguities depend on how many lobes there are in the directional patterns. The Navaglobe pattern, for example (Fig. 9), has two diametrically opposite lobes per antenna and there is an ambiguity in indicated *bearing* of exactly 180 degrees. Simple loop-type direction-finding systems have the same ambiguity, for the same reason. In direction-finding systems, however, it is possible to "resolve" the ambiguity by the use of an additional omnidirectional or sense antenna, properly connected, which produces a single-lobed directional pattern, the familiar cardioid.

In either case, however, there is no ambiguity in *line of position*. To illustrate, a line of position of bearing 60 degrees is the exact backward prolongation of the line of position of bearing 60 degrees plus 180 degrees or 240 degrees. Both bearings result in the same straight line. Thus two bearings, each with a possible 180-degree ambiguity, can result in no more than two straight lines; and two straight lines can intersect at only one point. Therefore, there is also no ambiguity in the *fix*, except for the antipodal ambiguity caused by the fact that the lines are actually great circles.

Other systems of type D may have ambiguities in bearings by amounts other than 180 degrees, in which case there are necessarily ambiguities in lines of position and fixes. This, in general, results from radiation patterns with many lobes, close together. Such systems, on the other hand, are inherently capable of better accuracy; that is, there may be a greater, more accurately measurable difference between the radio indications corresponding to lines of position that are close together. The reason for this is that with many lobes, the lobes are narrower or sharper, the signal strength varying more rapidly for a given change in direction. Wider spacing of the individual antennas in terms of wavelengths, or increased number of antennas, causes this situation. In any case, it is the number of lobes that are physically indistinguishable from each other by the means provided in the system, which determines the number of ambiguities.

In the A-N type aural range, for example, there are four lobes, created by the two intersecting figure-of-eight patterns. The pilot can only distinguish, directly, the fact that he is on one of four possible equisignal intersections or radio beams. If he is completely lost and wishes to determine just which one he is on, rather involved mental (and aerial) gymnastics are required,[8] and are then not foolproof.

[8] Page 207 of reference 2.

The Consol system uses wider spacing of antennas, up to six wavelengths, so that there are many narrow lobes. Accuracy is greater, but the line of position corresponding to a given observation is ambiguous to a manifold degree, for it may occupy similar positions along some of the other lobes.

The Civil Aeronautics Administration omnidirectional range is unambiguous because the antenna pattern is essentially a broad but single-lobed cardioid figure, as in direction-finding systems using a loop plus a sense antenna.

In directional transmitting systems of the radar type, great accuracy can be obtained without ambiguity by using antennas very large compared to the operating wavelength, so that a single very narrow lobe is produced. The range is limited to radio line-of-sight distances; and since only one lobe is produced, its movement to cover all areas must result from physical rotation of the antenna. In practice, this physical rotation cannot be very fast; not nearly so fast as with the purely electrical scanning described under longer-wave type-D omnidirectional systems. Also, increased radar-beam sharpness brings in other complications, involving practical limitations on pulse-repetition rate, transmitter power, and scanning rate.

If a set of observations corresponds to several possible fixes, the ambiguity may be resolved if, by some alternative means, one can determine his position with sufficient accuracy to judge that all but one of the fix locations is out of the question. The alternative means may be dead reckoning, rough celestial observations, or alternative radio aids. Or one might have avoided the ambiguity by having made observations continuously from some known point, and having kept track of them so as to be sure that one has not "slipped a whole cog" (lobe) en route. But if any such procedures are absolutely necessary, the navigational aid, whatever its other advantages may be, cannot be called an independent or self-sufficient system, one that requires no previous knowledge of position.

6.3 Pulse-Distance Systems (Types B and C)

In pulse-type absolute-distance or differential-distance systems, there is also a connection between the limiting accuracy of the system and the existence of ambiguities. The accuracy with which the time interval between two events can be measured depends on the speed of the time sweep. Though the time intervals are microscopic and the measurements are performed electronically on a cathode-ray tube, the principle is entirely analogous to using a sweep second hand of a stop watch.

A fast time sweep "stretches out the time," and is analogous to measuring the time between two swings of a pendulum by means of a watch hand that turns at a rate of 10 times per second. A slow time sweep "compresses the time" and is analogous to measuring the same time interval with a watch hand that creeps around the dial at a rate of once per hour. In the latter case, only a very rough measurement could be made of a brief time interval.

In pulsed radio systems, the basic pulses occur repeatedly at some fixed pulse-recurrence frequency (PRF); the time sweep or electronic stop-watch hand is reset to zero and started moving each time the basic pulse occurs. But one basic pulse must not follow the previous one until a sufficient interval has elapsed to allow the delayed or echo pulse to arrive. If this safety precaution is not followed, the delayed or echo pulse might not arrive until after the "second or third time around" of the watch hand; one could not be sure which. Thus the indicated time interval would be ambiguous to the extent of some integral number of whole time sweeps, or pulse-recurrence-frequency intervals. The situation is quite analogous to timing an interval with a stop watch that has a sweep second hand but no hand for recording whole minutes.

To avoid such possible ambiguities, the pulse-recurrence-frequency and, accordingly, the time sweep speed, must be decreased to an amount depending on the longest delays or distances expected to occur in the radio distance-measuring system. But slowing the time sweep decreases the accuracy of time measurement as previously explained.

6.4 Phase-Distance Systems (Types B and C)

In absolute-distance or differential-distance systems using phase comparison of continuous waves, the same general connection between accuracy and ambiguity holds true. At an operating frequency of 100 kilocycles per second a wavelength is about 10,000 feet; a phase difference of as much as 10 degrees, for example, corresponds to only 280 feet. At 1000 megacycles, a wavelength is about 12 inches; 10 degrees of phase difference correspond to a mere 1/3 inch. As either round trips or differential trips are actually concerned, the difference in a line of position corresponding to 10 degrees phase difference may be half that just quoted. Thus, by choosing a suitable radio frequency, the phase method of measuring distances (as in Decca, Raydist, and related methods) can, in principle, be made very accurate. In the Raydist system, a phase type of absolute or hyperbolic system using heterodyne methods for increased precision of measurement, an accuracy of 1 inch to the mile is claimed.

The trouble, however, is that phase characteristics repeat themselves in cycles of 360 degrees per wavelength. A phase difference of 10 degrees is indistinguishable from one of 10 plus 360 or 370 degrees; and so on. Thus, the phase-measuring device or distance indicator shows phase differences from zero to 360 degrees only without revealing the total number of whole cycles or wavelengths involved. It is like having a very accurate vernier or micrometer scale without a main or coarse scale; or like trying to measure a long distance with a tape that is graduated in sixteenths of an inch but has no whole inch or foot figures printed on it.

One way out of this manifold ambiguity problem is to use a recording or cumulative type of phase meter, the instantaneous indication of which at any time is actually the algebraic sum of all phase changes occurring since a particular setting was made at the start of the trip, or at some other known point. This method is especially feasible if the navigational system is of such a type that the indications are given by a direct-reading mechanical meter. The Decca, a phase type of differential-distance system, uses this idea.

This scheme, however, has the fundamental drawback, for any navigational aid, of dependence on unbroken continuity and unfailing accuracy of all past readings. There must be no interruptions caused by propagation disturbances, such as static or severe fading; by temporary malfunctioning of transmitting or receiving equipment, such as blown fuses; or by human errors such as pulling a wrong switch.

Furthermore, one could not risk tuning out a station or pair of stations temporarily to get a fix by tuning to another station for an intersecting line of position. The airplane would have to carry two or more receivers and indicators for reading two lines of position continuously and concurrently for fix purposes. Navigation on a long trip could not be by piecemeal guidance from a succession of different stations of limited range along the route, as this would also require interruptions. A given ground station, or pair of stations, would have to be sufficiently powerful to serve an airplane at all points during its flight.

Or, as described in connection with ambiguities in other systems, the difficulties might be resolved by dead reckoning or other alternative means of location having requisite precision. One might use direction-finder bearings on the system stations or on any radio stations within range, for a fix sufficiently accurate for resolving the ambiguities. Direction finding may perhaps always be useful as an adjunct to other types of radio navigational aids, for rough checks, ambiguity resolution, emergencies, or other auxiliary purposes; but no navigational method which absolutely requires direction finding or other schemes to resolve ambiguities can be called an independent or a self-sufficient system. A navigational aid should be capable of giving a fix at any time "from scratch" no matter how lost the navigator may be, how careless he may have been at a past time, or what temporary interruptions may have occurred in the past.

II. Air Navigational Applications

7. *General Navigational Requirements*

7.1 Types of Information

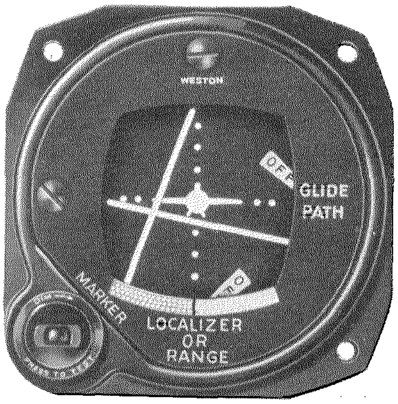
Navigation means to conduct a ship or airplane to its destination via a desired route. For the fullest and most convenient solution of the problems occurring in navigation, the navigator should have available:

A. Knowledge of his absolute position, in terms of latitude and longitude, bearing and distance, or any other intersection of lines of position. Aural, visual, celestial, and radio means are at hand.

B. Knowledge of altitude above the earth. As flight is three dimensional, this item is necessary for a really complete fix. Barometric and radio means are available. A surface ship would like to know the depth of the water below it, for which purpose sonic devices, the acoustic analogues of radio altimeters, are available.

C. Knowledge of his position relative to a prescribed flight path or intended track. One can use any line of position, whether established by visual, celestial, or radio observations, as a flight path, but directly indicated radio flight paths are most convenient.

D. Knowledge of the true heading of the airplane. A compass is necessary for this, radio means being at present insufficient, except possibly in a round-about manner, using a certain disposition of direction-finding beacons. A direction-finding transmitter at the north pole is one theoretical solution.



Photograph courtesy of Weston Electrical Instrument Corporation.

Modern type of cross-pointer meter or deviation indicator. Vertical and horizontal pointers, respectively, give left-right and up-down directions to the pilot for following a localizer (or radio range) and glide path. The small flags marked "Off" are hidden from view in normal operation; their appearance is a warning of lack of signals or other malfunctioning of the system. The marker-beacon lamp is located at the lower left corner of the instrument.

E. Knowledge of time. A fixed time reference is provided by a watch which may be corrected periodically by radio time signals which are related to Greenwich time.

F. Knowledge of speed. True ground speed may be determined if (*A*) and (*E*) are always available, but no single instantaneously reading instrument is available for this purpose. Certain approaches, however, are possible, as by using rate meters on a radio distance indicator, or by using the Doppler effect.

G. Knowledge of the presence and location of other moving (i.e. non-charted) objects nearby. Radar is the indicated radio aid for this anticollision service. Knowledge of weather conditions ahead might be construed as falling within this requirement. Weather conditions may be reported verbally by radio from ground stations; or anticollision type radar might even be used to give direct warning of certain types of weather conditions immediately ahead.

It is seen that radio, or electrical devices in general, are capable of providing the chief items of navigational information, at least in principle. At present, however, not all such devices have been developed to the requisite degree of accuracy, reliability, range, convenience, or practicability.

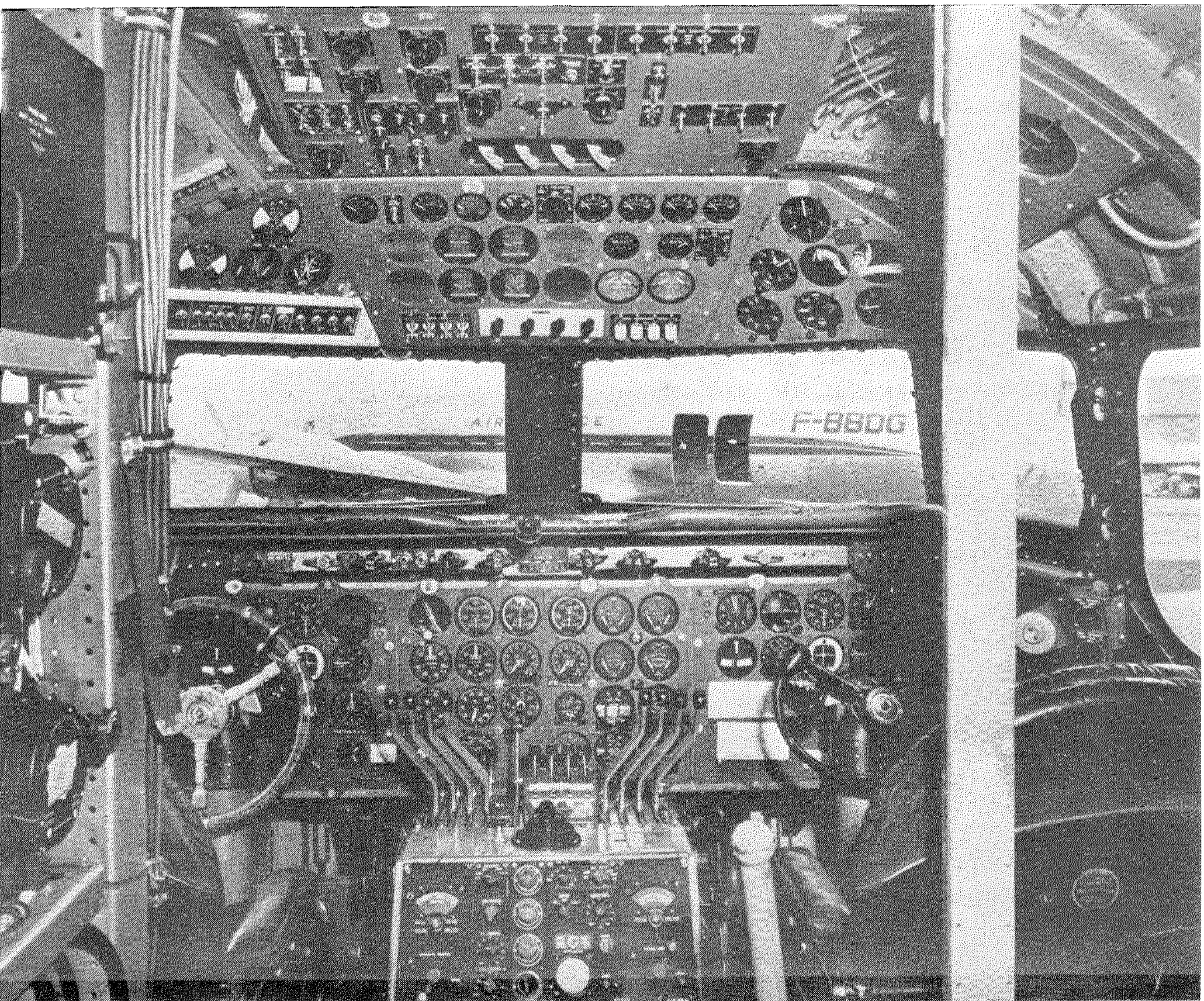
7.2 Reliability

Reliability, in a radio navigational system, has two aspects. First, since transmission over distances is concerned, there is the matter of propagational reliability. The signals *must come in* at all times and over all specified service areas with sufficient strength to override interference and noise. Propagational reliability is a problem around which the general features of a system must be designed at the outset. It involves matters such as distance coverage, frequency, bandwidth, polarization, static, transmitter power, receiver sensitivity, interference, and ionospheric effects, and is an especially important problem in the long-range navigational case.

The second aspect of reliability is the conventional one that enters whenever life and limb have to depend on electrical or mechanical devices. In the case of airplanes, even more so than in the case of sea or land carriers, which can stop and wait things out if they are totally lost, extremely high standards of reliability are required. Meeting these standards is especially difficult because of the size, weight, power, and drag limitations for airborne equipment.

In addition to the insistence on reliability for any airplane equipments, another safety feature has come to be universally demanded for airborne navigational devices. That is the provision for automatic indication of failure. It is recognized that no device can be 100-percent reliable forever; tubes may blow or wires may break in the face of the most rigid manufacturing and preflight tests. As a result of such a failure in a navigational device, a navigator may be totally lost. But bad as that may be, one thing that is definitely worse is if the navigator does not know it and trusts the equipment, flying on blindly in his happy ignorance. If, at least, he is apprised of the fact that the device is out of order, he may be able to repair the defective part, radio for help, or use other means of navigation.

In this connection, there are two points of interest. The first is that those navigational systems that give visible indications on a cathode-ray tube have a certain advantage. They may be more bulky, more tiring to read for long times, and require time-consuming manipulations before a reading is made; but on the other hand they allow visual monitoring of the actual *quality* of the incoming signals. This tells a great deal about the propagation aspect of reliability and something about the electromechanical functioning, but it is not a cure-all.



Pilot's compartment of a Douglas DC-6 airliner. An important group of instruments supplies navigational information and includes altimeters, compasses, and radio range and landing indicators. Standardization of appearance and placement of the newer radio navigational indicators for safest and most effective use is an important subject being studied by various coordinating committees.

The second point is that emergencies will always occur and preparations must be made for them. Thus, it is highly advisable for airplanes to have alternative navigational aids, even if less accurate or convenient. A sextant can always be carried, of course; a direction-finding receiver or attachment, as an alternative radio aid, appears to be highly advantageous also. In some systems—as in most directional transmitting (type-D) systems—a direction-finding attachment could be provided to work off the same receiver and the same ground stations, with no extra ground station equipment and insignificant extra airplane equipment. In any case, in emergencies a direction finder can be used with a communications receiver to take bearings on any stations within range, such as broadcasting, radiotelegraph, or surface-ship installations.

Reliability is not to be confused with accuracy. The closeness with which a navigator can pinpoint his location on the earth is one thing. It may be within ten feet or within ten miles depending on the system. High reliability means that whatever the limits of error are, they are known in advance and will not be exceeded. What limits of error might be desirable, or sufficient, depend on circumstances.

7.3 Accuracy

One might first demand 100-percent accuracy for a radio navigational aid; but this might be obtained only at the expense of a number of other factors of importance. Fortunately, something less than 100-percent accuracy may be all that is absolutely necessary, so that in practice some sort of compromise between the various factors is sought.

A fundamental law is that the total amount of information that can be transmitted by a radio system per unit time depends on the total amount of radio channel space or bandwidth used. This is a law of far-reaching implications in communications work, instances of it being familiar to all radio engineers. It is of equal fundamental importance in radio navigational aids, although in this case the amount of information required per unit of time is much less.

Total information per unit of time is a product compounded of such terms as amount of information given out in each direction, area of service, accuracy of information, freedom from ambiguities, quickness of indication, and convenience of presentation. Engineers can improve one or another of these factors by good design, but there comes a limit, depending on the bandwidth, beyond which an improvement in one factor is at the expense of deterioration of another. And the supply of available bandwidth is limited since it must be shared by many users without mutual interference.

The physical relation between two of these factors, accuracy and ambiguity, has already been described. Some proposals suggest getting around this complication by providing, in essence, two systems side by side: one a coarse system, good enough for quick work and for resolving ambiguities; the other a very accurate or fine system. Similarly, some proposals for improving the coverage of an essentially non-omnidirectional system entail construction of two installations, suitably oriented to fill in each others' gaps.

Such solutions involve increase in the total bandwidth used, of course, but may be valid solutions since the accuracy-ambiguity relation is one of the most troublesome among the factors mentioned. But for a practical single system, using a bandwidth dictated by other considerations (propagational, legal, etc.), one must decide which of the two properties is more important, razor-sharp accuracy or complete lack of ambiguities; or else make a reasonable compromise. For certain special military applications, which like atomic bombs one hopes may never be used, pin-point accuracy may be essential. Everyday civil air navigation is something else.

The type of mental gymnastics required to unravel complex ambiguities might intrigue a professor of logic, a cross-word-puzzle expert, or other "armchair navigator." The crew of a big airliner completely lost at sea, with time and fuel fast running out, might favor a navigational device that tells them directly and positively that they are *somewhere* within a circle 10 miles around Bermuda, rather than a device that tells them they are *exactly* 12.863 miles due east of Bermuda, but possibly also 104.394 miles due south of Halifax or 0.875 mile due west of the Empire State Building.

The distance that an airplane may be off course without serious danger or inconvenience, the time allowable for making readings and playing around with ambiguities, and the likelihood that the airplane may at all cross zones of ambiguity, depend on the exact purpose of the radio navigational aid.

In landing systems, for example, the need for precision is greatest; being "off" by 100 feet, even less, might well be fatal. Also time is short so that indications must be very quick and direct. A complete fix dare not be given by methods requiring successive tuning to different stations and reading different instruments; all the necessary information must be given concurrently. On the other hand, omnidirectional or wide coverage is not necessary; is not even desired. The pilot is supposed to keep on one unidirectional beam, once he gets started on it; thus he runs little risk of being so far off as to "slip a cog" or end up on a wrong line of position even if ambiguous lines were around somewhere.

To get him safely started on the correct beam while far out, other navigational aids that are less accurate but give wider coverage and less ambiguity are depended on, after which the airplane keeps strictly on the one landing beam. In short, in landing systems the highest precision is necessary; but is feasible because the airplane's route is such as to avoid situations where ambiguities are significant.

In cross-country medium-distance nagivation, on the other hand, provision should be made for omnidirectional lines of position and fixes. As the pilot cannot fly a whole trip by sticking to one beam, and may have to tune to different stations for a fix, ambiguities do have to be considered. By the time the pilot has tuned back to the original station, after getting an intersecting line of position from a second station, he may have "slipped a cog" or moved across one or more zones of ambiguity, such as lobes, wavelengths, pulse-recurrence intervals, etc., without knowing it. Therefore, ambiguous zones should at least be a certain distance apart, depending on the speed of flight and on the reading time of the navigational aid. In short, in overland ranges, ambiguities should be totally absent or at least fairly wide apart, which is feasible as the need for precision is not extreme. The navigational facilities need only enough accuracy to guide airplanes into airport areas and to landing beams far out from the airport where they are wide, and to segregate traffic safely into lanes perhaps 500 or 1000 feet apart. For this application, there are possibilities of using radar-type systems which give the requisite accuracy and yet are omnidirectional, free of ambiguities, and sufficiently quick-reading.

In very-long-distance transoceanic service, traffic is less dense and there is more room and time available, so that ambiguities or slower reading times could be tolerated to increase accuracy. In this connection, it is to be noted that the total bandwidth limitation for the long-distance case is more stringent than for the short or medium cases because of propagational requirements; very great accuracy could not be obtained without excessive deterioration of other desirable factors. Great accuracy, fortunately, is least necessary in the long-distance navigation case. All that is necessary is the ability to follow a definite flight path at midsea with a precision of, say, 10 to 20 miles; and the ability to make a fix within about the same distance to initiate a "square search" for disabled craft in emergencies. In directional-type systems, this precision amounts to an angular precision of approximately one-half to one degree, at a maximum range of 1500 miles. For the same angular precision, the lateral distance accuracy increases proportionately as the ground station is approached; thus the beam, even though it may be fairly wide far out, brings the airplane using it for track guidance close in to the ground station, like a funnel. In any long-range navigational aid, relatively poor accuracy is permissible at midsea, where most of the time exact knowledge of position is merely of academic interest; closer in, however, the precision should at least permit a reasonably close landfall or permit the airplane to strike somewhere within the service area of a more accurate medium-range radio navigational facility, extending say 100 miles offshore, which can guide it to a specific airport or radio landing beam.

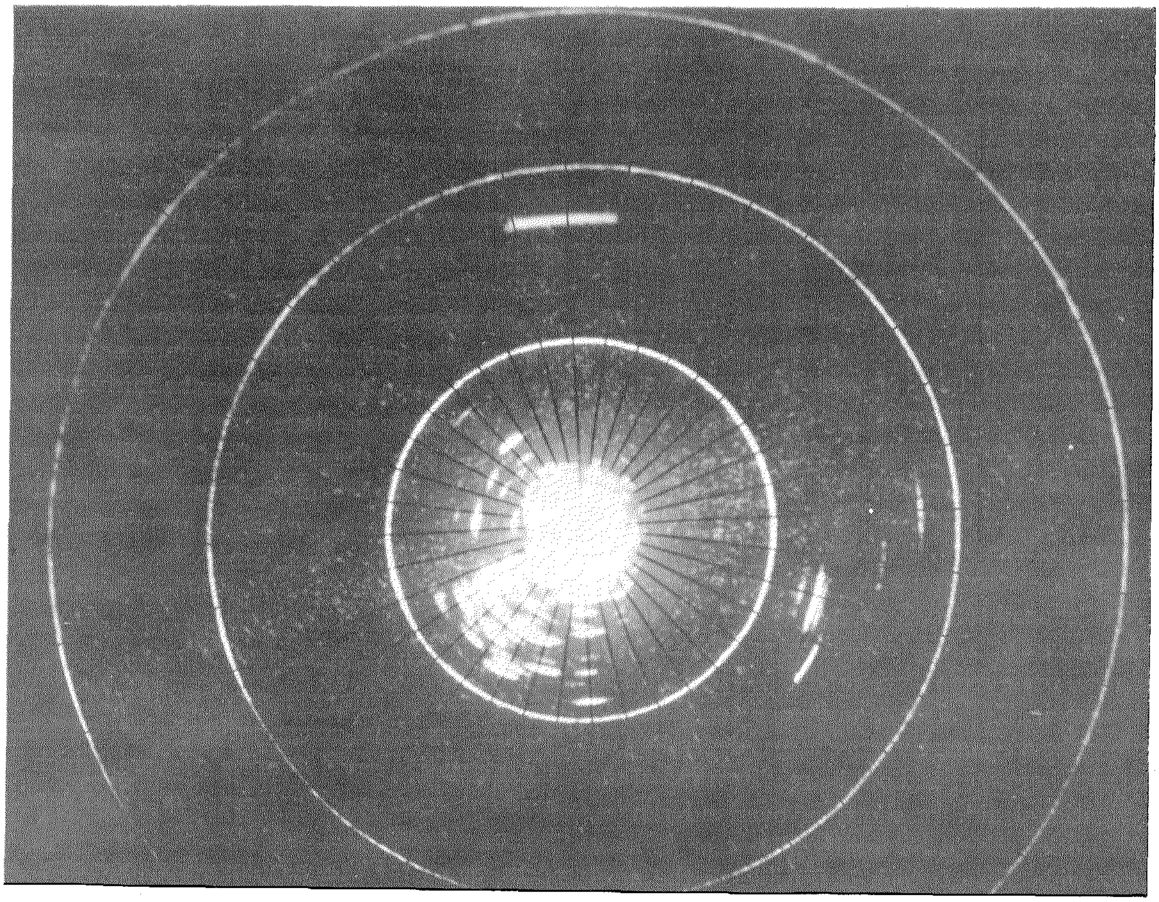
In short, for the very-long-distance case, the total bandwidth limitation is severest so that all factors must suffer; but fair amounts of ambiguity and inaccuracy can be tolerated in practice.

7.4 PRESENTATION

The way in which the navigational indications are presented is not of basic importance, compared to reliability and accuracy, but it is something that interests the navigator; or would especially interest the second pilot, radio operator, or flight engineer, in the event that navigators are dispensed with even on long-distance flights. It is more important on aircraft than on surface ships because airplanes do not have the time and space facilities for long drawn-out observations and calculations; that indeed is one of the reasons why radio navigational aids are at all favored over celestial navigation, even when visibility conditions are good.

Automatic direct indications, requiring nothing other than pushing a button to receive a desired ground station, are of course ideal. Meter or dial indications are direct; radar plan-position displays are direct and even pictorial. At present, cathode-ray screens are not quite bright enough for viewing in a daylight-illuminated cockpit; but this may be remedied in time. Cathode-ray screens are more tiring on the eyes of observers than are meters, especially when protracted observations are necessary. Cathode-ray tube indicators, especially of the radar plan-position type, are at present rather bulky pieces of equipment for a cockpit. It is conceivable that graphic automatic position plotters, simulating a plan-position display but more suitable for daylight viewing, could be provided, if desirable, with meter-type indications. For this, two lines of position would have to be indicated concurrently.

Certain types of cathode-ray indicators, such as used in pulse-timing systems, require considerable time before a reading can be made, but



View of plan-position-indicator screen showing combined normal-radar and assisted-radar displays. Range circles are at 5-mile intervals. Wide pip at top is beacon response from an airplane. Prominent pips at lower right are natural echoes from structures on the ground. Other illumination is due to ground clutter, permanent echoes, and random noise. With the natural-radar receiver off, the screen becomes completely dark except for the bright airplane beacon response.

have the advantage, already mentioned, that the quality of the signals is visually apparent at all times. Meter indicators are quickly read, but must always be provided with an automatic warning feature to show that the meter and everything behind it is in working order. Meters also have the advantage that the mechanical motion of the pointer can more feasibly be transmitted to operate an automatic pilot, if desired.

Aural indications have the great advantage of not requiring special indicating equipment, the airplane's regular radiotelephone receiver being used and, incidentally, providing continuous monitoring of the quality of the signals. This may be an advantage for pilots of small private airplanes; but aural indicating systems appear to be on their way out. The indications are tiring, and are either quite approximate or time consuming.

The necessity for quick, convenient, and direct indications depends on the particular purpose of the system, being, as already described, most pronounced in landing systems and least urgent, though still desirable, in long-distance navigational aids. It should be remembered, moreover, that other things being equal, the simpler the type of presentation and the simpler the skills required in making various receiver and indicator adjustments, the less likely are ordinary human errors and careless mistakes.

7.5 Independence

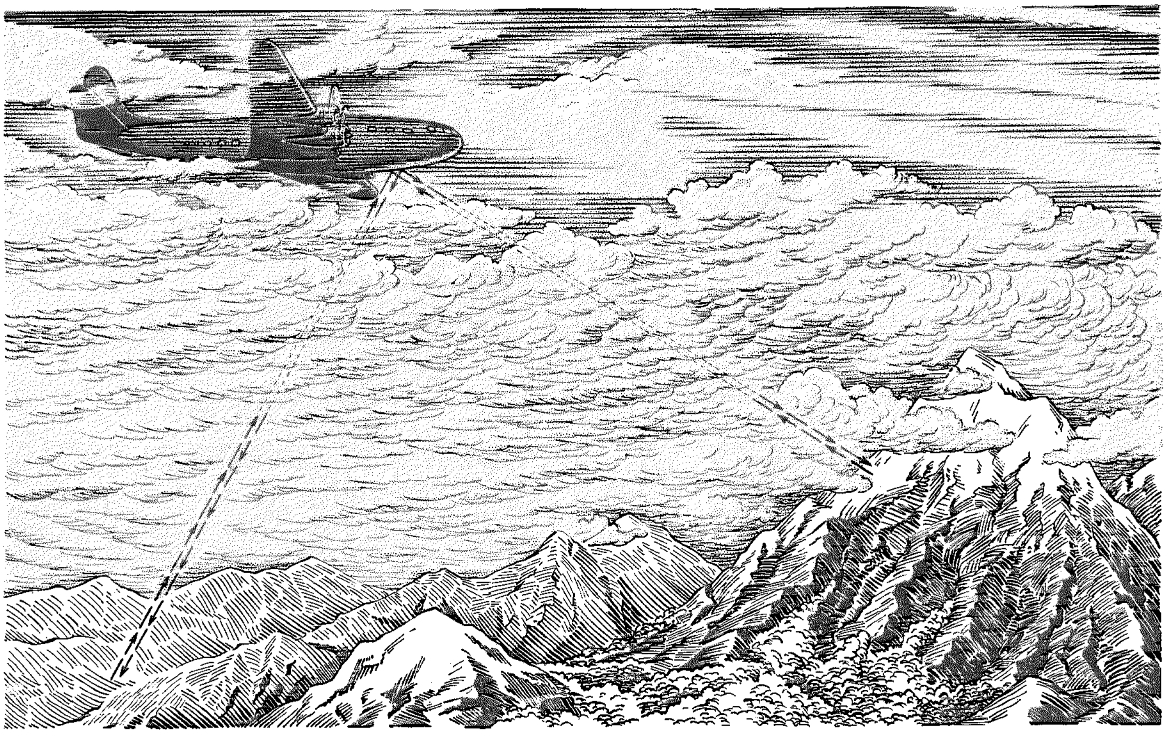
Self-sufficiency or independence has been stressed as a fundamental requirement for radio navigational aids, regardless of type of service. This means that there is no need for reading any additional instrument, like a compass, to determine a line of position or a fix; and that the indications are given directly on the airplane, instead of occurring on the ground for a second party to relay to the airplane.

Table I shows how each of the four basic types of radio navigational aids compare on this requirement. In each type, two possible designs have been separately considered: a design in which the basic or primary transmitter is

TABLE I

CHECK-LIST OF BASIC RADIO NAVIGATIONAL SYSTEMS

Basic Type of System	Bearing Systems				Distance Systems			
	Directional Receiving		Directional Transmitting		Absolute Distance		Differential Distance	
Primary Transmitter Located on	Ground	Plane	Ground	Plane	Ground	Plane	Ground	Plane
Examples	Radio Compass, Aural and Automatic Visual Direction Finders	Ground Direction Finder, Huff-Duff	CAA Ranges, Consol, Sonne, Navaglobe, Rotating Beacon	Directional Part of Airborne Radar	Oboe	DME, Shoran, Distance Part of Airborne Radar	Gee, Loran, Decca, Popi	Micro-H
Independent of Plane's Compass	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Original Observations on Plane	Yes	No	Yes	Yes	No	Yes	Yes	No
SYSTEM MAY BE SELF-SUFFICIENT	NO	NO	YES	NO	NO	YES	YES	NO
Number of Radio Links Required for Establishing One Line of Position Including Links for Speech, Synchronization, Natural Echoes, and Active Response								
Ground Station to Plane	1	1	1	1	2	1	2	1
Ground Station to Ground Station	0	0	0	0	0	0	1	1
Plane to Ground Station	0	1	0	1	1	1	0	2
Total Number of Links Required	1	2	1	2	3	2	3	4
SUITABLE FOR LONG RANGE AS NO EMISSION REQUIRED FROM PLANE	YES	NO	YES	NO	NO	NO	YES	NO
YES ON BOTH COUNTS			√				√	



Radio altimeter measures absolute height of the airplane by timing echo signals reflected from the terrain below.

airborne, and another in which that transmitter is on the ground.

From the first half of Table I, it is seen that systems of only the following types are fundamentally capable of being independent: ground-based directional transmitting, ground-based differential distance, and airplane-based absolute distance.

It appears, incidentally, that an airborne radar installation cannot be a completely independent navigational aid. The absolute-distance part is self-sufficient, but the directional-transmitting part gives relative direction, requiring a compass. A ground radar, considered as a navigational aid, is also incomplete. The directional part may or may not be, but the distance indications have to be relayed back to the airplane.

Even among the three preferred types of systems, different specific types of radio aids appear necessary for short-, medium-, and long-range navigation because of the different characteristics of various types of radio emissions and because of the different kinds of practical problems concerned. For the short-range applications such as landing systems, the chief problem is the extreme precision of guidance required. The medium-distance applications for overland navigation and traffic control present a great problem in the multiplicity of indications that must be provided and the large number of airplanes that must be cared for simultaneously. In the long-range case, traffic density is negligible and great accuracy is not a primary requirement, the chief problem being that of providing reliable signals at the large distances involved.

A brief outline of some of these special problems and a discussion of some present and future solutions follows, all based on the principles outlined under the four basic types of radio navigational aids.

8. Short-Range Applications

8.1 Radio Altimeters (TCI)

Radio methods that are used for measuring absolute distance (type-B systems, Section 3) are applicable to making a determination of the vertical height or altitude of an airplane. As they indicate the height above the terrain immediately below the airplane, not above sea level, and without regard to barometric weather fluctuations, radio altimeters are also called *absolute* altimeters or terrain-clearance indicators (TCI).

The ground immediately below the airplane reflects radio energy emitted from the airplane. Any of the forms of type B may be used: pulse timing, continuous-wave phase comparison, or saw-tooth frequency modulation. Two special problems have to be taken into account. First, short distances have to be measured with a sensitivity at least equal to a barometric altimeter, 10 feet or so. Any one of the three radio methods described results in ambiguities which limit the maximum altitude range of the system. Often, two range settings are provided, a low-altitude high-sensitivity range using high pulse-recurrence frequencies and fast time sweeps, and a high-altitude lower-sensitivity range using a low pulse-recurrence rate and slower time sweeps.

Secondly, one must be sure that the echoes used for measurement are those returned from ground points directly underneath. Fixed beacon responders obviously may not be used in radio altimetry, nor are they necessary for adequate signal strength for the distances are short and the natural reflecting surface is large. To ensure that the echoes come from straight below, the transmitting antenna must have a certain amount of downward directivity. Although no scanning or motion of the antenna is needed, this directivity requirement does increase the size and drag over that of a plain antenna. The indicator can be a cathode-ray tube or meter.

If the transmitter were fixed on the ground, an airborne responder might be used; the distance indicated would not be the vertical terrain clearance, but the slant range. Also, the information would have to be relayed back to the airplane. Any conventional ground radar, in fact, measures the slant range of the airplane. The vertical height may be computed from this by trigonometrical formulas or devices if the angle of elevation of the airplane is known. This is done, in some military applications such as height finders, by using a sharply directive antenna that can scan up and down and noting the vertical angle at which the echoes appear.

It should be noted that regardless of the state of perfection of radio altimeters, they may supplement conventional barometric altimeters but not supplant them. A radio altimeter, or terrain-clearance indicator, gives indications with respect to the terrain below and is thus useful for avoiding collisions with large fixed objects such as mountain tops. Its indications are not suitable for establishing a system of assigned altitude layers for safe segregation of traffic. An airplane in perfectly level flight over rough country would have constantly changing terrain-clearance indications, which would differ from even those of nearby airplanes flying at the same actual level. For traffic regulation and avoidance of collisions between airplanes, altitude indications should be with respect to a datum level that is the same for all airplanes near each other. "Pressure altitude" indications, as given by a barometer-type instrument, meet this requirement because the reference datum is sea-level pressure; this is actually variable with weather conditions but the variations are common to all airplanes in the same general region.

In this connection, there is a quite recent air-navigation principle known as "pressure-pattern" flying, which makes use of information gathered simultaneously from radio and barometric altimeters. Comparison of absolute and pressure altitudes enables the wind factor to be determined, which in turn increases the accuracy of dead-reckoning procedures. An extension of this method theoretically allows airplanes to fly the shortest *air* course between two distant places, the point being that, because of wind effects, the direct great-circle route is not necessarily the route of minimum flying time and fuel consumption.

8.2 Landing-System Requirements

Instrument approach or "blind landing" systems require basically one fixed straight-line track; thus ground-based directional transmitting systems (type D, Section 5) are in order. The antenna array, on or near the runway, must be small; the range need not be long, 10 to 20 miles or so; but the line of position must be exceptionally precise. For all these reasons, landing systems use very high radio frequencies.

What have been heretofore referred to as *lines* of position are actually parts of *surfaces* of position. Ordinary antennas radiate energy

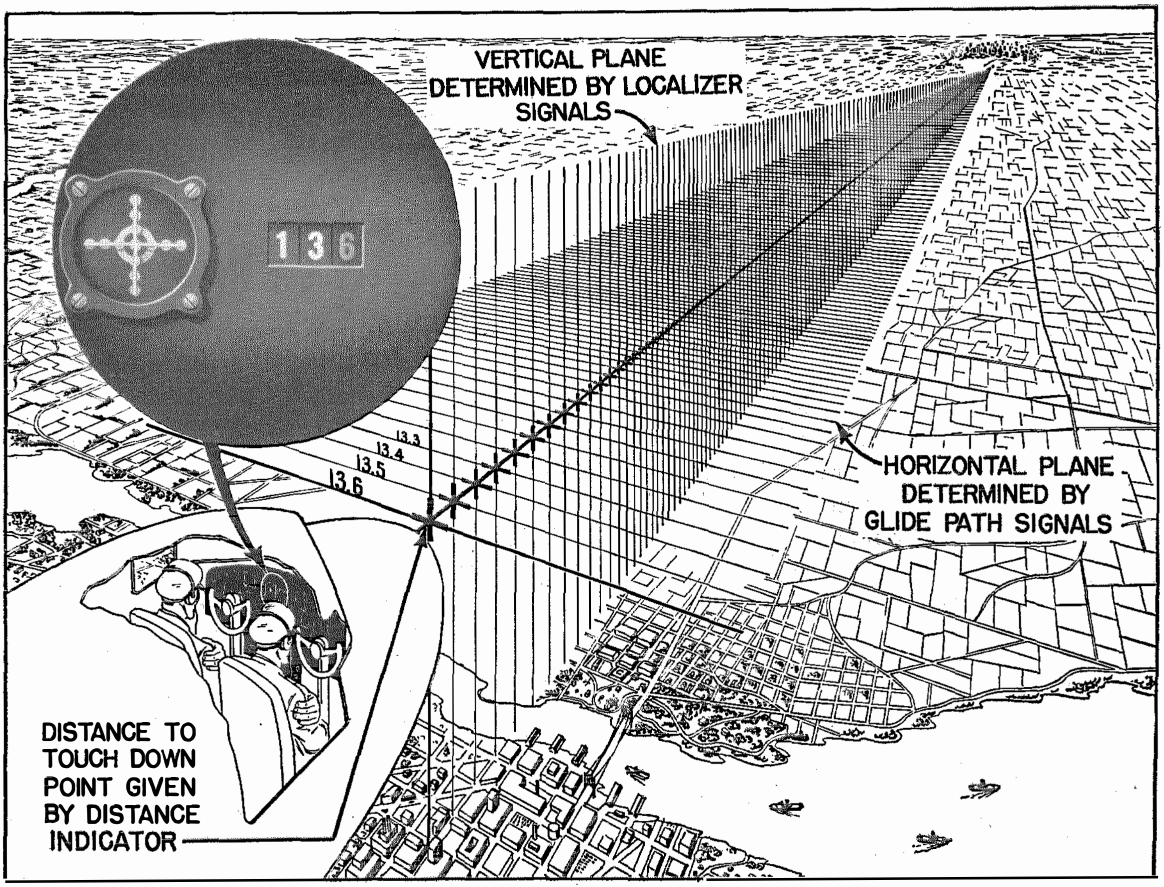


Fig. 10—Instrument landing system principle used in Navaglide.

in all directions, vertically as well as horizontally. Thus, for example, in an absolute-distance system a given echo-time measurement means that the observer is somewhere on a spherical *surface*, of corresponding radius, centered on the ground station like a giant dome. The intersection of this spherical surface with the earth's surface gives the conventional *line* of position. For most navigational purposes, however, one is concerned with only that *line* on the earth's surface; this is because the altitude of an airplane is negligibly small in comparison with its horizontal distance from the ground radio stations. In directional transmitting applications considered up to now (except in the angle-of-elevation application) the surfaces of position are vertical plane surfaces, whose intersections with the earth's surface produce the conventional straight radial lines or great circles of position.

In landing systems, a true line and not a surface of position must be furnished, for now the altitude of the airplane and the proper gradual change of it are of vital concern. This true line of position should be a straight one rising at a certain small gliding angle from the desired touch-down point on the runway, and should be aligned with the runway.

8.3 Instrument Landing Systems (ILS)

Examples of instrument landing systems are the glide-path localizer such as the so-called Civil Aeronautics Administration Indianapolis and Army SCS-51 systems,[9,10] types in the development of which Federal played an active part; and other equipments developed by Sperry, Bendix, Massachusetts Institute of Technology, and other organizations. Two intersecting sur-

[9] H. H. Buttner and A. G. Kandoian, "Development of Aircraft Instrument Landing Systems," *Electrical Communication*, v. 22, n. 3, pp. 179–192; 1945.

[10] S. Pickles, "Army Air Forces Portable Instrument Landing System," *Electrical Communication*, v. 22, n. 4, pp. 262–294; 1944.

faces of position are created by two directional transmitting arrays, horns, or dishes, properly oriented. Generally the switched-lobe equisignal principle, as described under type-D radio ranges (Section 5), is used for extreme precision of each surface of position. Each lobe transmission has a characteristic tone modulation, thus enabling a receiver to separate the two and compare their strengths.

As seen in Fig. 10, the localizer transmissions result in a vertical plane surface of position aligned with the runway. The glide-path transmissions result in a plane surface of position slightly inclined up from the horizontal. The intersection of the two plane surfaces creates now a *true line* of position, which constitutes the landing flight path or beam. On the airplane, both vertical and horizontal deviations of that airplane from this line of position are indicated automatically and visually by the cross-pointer or left-right and up-down meter. There are two pointers, one for the equisignal glide path, the other for the equisignal localizer path. If the pilot is off the beam laterally or vertically, the corresponding signals are out of balance and the pointer for that direction moves off center. In doing so, it indicates the direction in which to steer to get back on the beam.

For safest and smoothest landings, especially if completely automatic landings are contemplated, a complete three-dimensional fix should be given at all times and must include position along the beam. In the Navaglide system being developed by Federal out of its earlier landing systems, a direct-reading indicator giving the distance to the touchdown point is included on the airplane. This is of the pulsed absolute-distance (type-B, Section 3) principle, the responder-beacon being situated at or near the touchdown point.

It is conceivable that distance along the landing beam could be indicated by a precise directional transmitting station (type D, Section 5) off to one side of the runway; but in view of landing speeds of airplanes, the indications would have to be direct, quick, and simultaneous with the beam indications. Conceivably, also, the information could be provided by sensitive barometric or radio altimeters. An airborne direction-finding indicator (type A, Section 2.2) might also be used in conjunction with one or more transmitters located to one side of the localizer course, and in fact this system of compass locators has been used as a supplement to or substitute for marker beacons along landing beams.

8.4 Ground-Controlled Approach (GCA)

In this so-called talk-down system, both the distance of the airplane and its deviations from the prescribed landing path are determined by essentially ground-radar means of high precision. This type of landing system was developed by the Radiation Laboratories at Massachusetts Institute of Technology. Equipments were manufactured for wartime service by Gilfillan, Federal,[11] and Bendix. The system is now being adopted for civil use. Extended surfaces of position are not created, but only small angular sectors of the surfaces as shown in Fig. 10. Two antennas, very sharply directive in directions at right angles to each other, are used. These are relatively small radar antennas or parabolic dishes, and are scanned through a small search or exploring angle, one left and right, the other up and down, from the landing path. One of these two type-D (Section 5) directional transmitters (both using pulses) is also used as a type-B (Section 3) absolute-distance system. If the airplane is on or not too far off the beam, the directional antennas, during their scanning or searching, will detect it and also measure its distance. The position of the airplane relative to the prescribed path is displayed pictorially on a cathode-ray screen. These observations, however, are made on the ground. The information concerning the airplane's deviations from the beam, its distance, and corrective steering instructions, must be relayed to the pilot over another radio link, usually by radiotelephony. Such procedure may be advantageous, especially in emergencies, as it is possible to guide to a landing an airplane which has no special equipment other than a radiotelephone receiver. Also, the ground-controlled-approach system allows the ground observers to see any other airplane that is near the landing path at the time.

[11] J. S. Engel, "Landing Aircraft with Ground Radar," *Electrical Communication,* v. 24, pp. 72–81; March, 1947.

Since the sectors of search about the beam are small, and the airplane has no detecting mechanism, it is very unlikely that the airplane could, coming in from a distance, get started into the beam by itself. Accordingly, a conventional omnidirectional search radar of the plan-position-indicator type is used to spot the airplane far out and guide the pilot into the beam; after which the more precise radar takes over. The search radar information must also be relayed to the pilot.

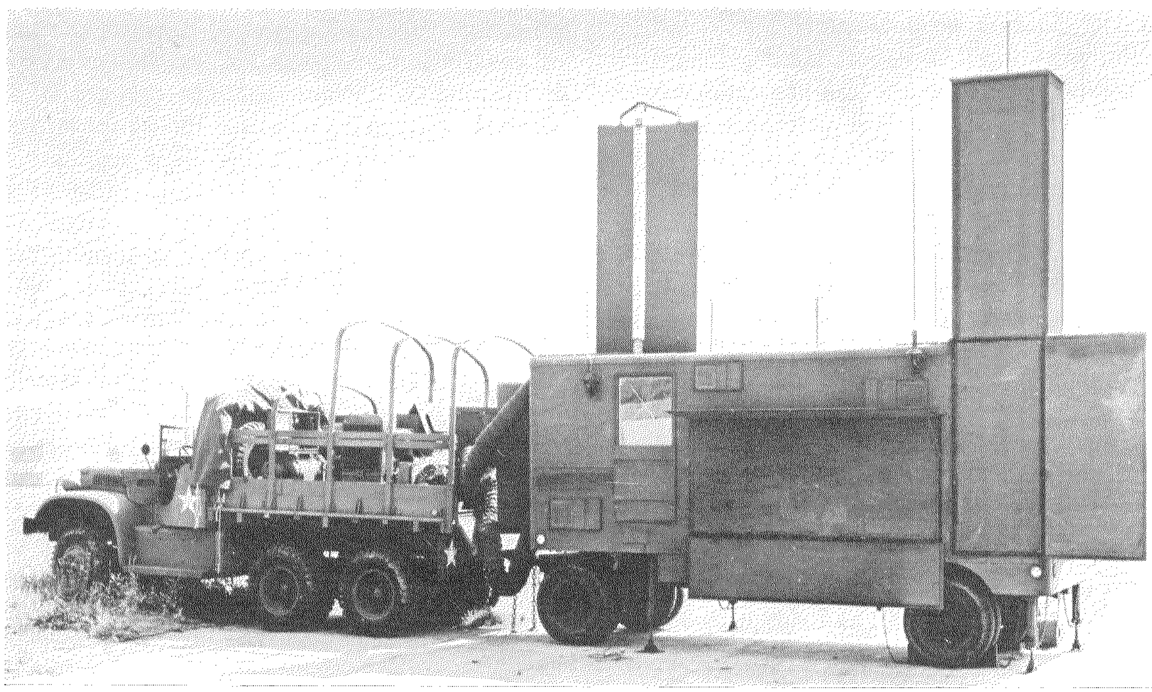
In instrument landing systems, the surfaces of position are quite broad and the airplane has direct indicators. Thus, even if he should enter the airport area quite far away from the landing beam, the pilot may be able to locate the beam by himself. Or, knowing in advance the bearing of the beam, he could guide himself into it by using other medium-range navigational facilities. At least, the pilot will known immediately and directly when he comes somewhere near the beam by observing his own cross-pointer.

The relaying of information for a ground-controlled approach might possibly be done by other nonverbal methods, but the system still requires an additional radio link and intermediary personnel to make the observations on the ground, just as in ground-based direction finding. Thus the ground-controlled-approach system is not an independent or self-sufficient navigational aid.

8.5 Radio Mileposts (Marker Beacons)

Because of unavoidable errors in observational methods and in electrical and mechanical devices, no navigational indications are 100-percent accurate. Knowledge of position is thus always inexact to some extent, even when systems and devices are well engineered. A surface of position thus is actually a thin shell or wedge; a line of position on the earth is actually a narrow strip of position; a fix is not a mathematical point but a small area or solid *volume of position*, its size corresponding to the amount of uncertainty.

Aside from all this, it is possible intentionally to devise a directional-transmitter installation so that it produces a fairly extended and definite volume of position. This principle is used in so-called marker beacons (fan, Z, cone of silence). The aural or visual indication is of the simple on-or-off type, and the pilot knows only that the



Wartime model of a mobile ground-controlled-approach (GCA) installation. Power and air-conditioning equipment is in truck at left; radar and communication antennas are seen on the roof and side of the trailer unit. The trailer contains all equipment and indicators required to enable the operators to "talk down" an airplane.

airplane is inside or outside of a specified region.

The marked space may be shaped like an inverted cone with its vertex resting on the ground station, or like a thick fan standing on end as in the fan type. It is effectively limited horizontally by the directional properties of the antenna array (type D, Section 5), but being limited in height by transmitter power and receiver sensitivity, it is indefinitely high and intercepts airplanes at any likely altitude.

These radio markers may be coded for identification to inform the pilot of the zones through which he is passing, the system being similar to that of mileposts or buoys for surface traffic. In air navigation, the markers have been used to provide rough indications of important points along radio ranges such as the entrance to airport control areas, intersections with other ranges, or for local warning purposes. They are thus a sort of radio curtain, used for much the same purpose as the curtain of wires (telltale) before the entrances to railroad tunnels or low bridges. A series of two or three marker beacons is also used to give knowledge of position along landing beams of the instrument landing type. Marker beacons for all these purposes are essentially makeshift devices, are on their way out, and will no doubt disappear completely when omnidirectional radio ranges are installed for cross-country use so that a radio fix is possible at any point, and when landing systems include automatic distance indicators.

Marker transmitters may perhaps be retained for ground observation and control of air traffic. Automatic responders in the airplane might be tripped when passing through the marker region and report to the ground coded information revealing identity, altitude, direction, and time of the transit. This would be analogous to the block signal in railroad traffic organization, where the trains trip switches along the tracks and cause indicating lights to flash in the dispatcher's office.

9. *Medium-Range Applications*

9.1 General Requirements

For overland traffic service, ranges of about 100 miles or so are sufficient since chains of stations may be installed to cover larger areas or distances. Convenient direct beams between important air terminals are desirable, as is omnidirectional coverage, so that navigators can use radio aids for both track guidance and fixes at any location. At present, the most extensively used radio aids in the U.S.A. are the Civil Aeronautics Administration's aural A-N four-course ranges, but these will be supplanted by improved types which are visual, omnidirectional, or both. There is some use of airborne direction finding, and this will probably continue; even ground direction finding is used somewhat. For the ranges required, medium radio frequencies may be used, but the trend seems to be toward higher frequencies where antennas may be smaller, power less, static less troublesome, and accuracy greater.

This trend is heightened by the exhaustion of available channel space in the medium- and high-frequency bands. The still-higher frequencies offer more room for expansion, and the line-of-sight propagation limit permits frequency assignments to be repeated at fairly close geographic intervals without danger of interference. Hence the current intensive developments in the 960–1215-megacycle band, allocated in the U.S.A. for many future air-navigational and traffic-control aids, largely of the pulse type (wide band). Further raising of the frequency, except for specialized aids, appears questionable, for at appreciably higher frequencies there arise considerable problems in respect to tuning, frequency stability, transmitter power, and atmospheric absorption.

Ambiguities are undesirable because the coverage should be omnidirectional, flights may be short, and traffic quite dense. While there is no need for the extreme precision that is required in landing beam systems, high frequencies may be used for aircraft navigation for the altitude at which airplanes fly extends the line-of-sight considerably beyond the sea-level-horizon distance. It is extended to about 150 miles for an airplane at 5000 feet. Thus radar or allied systems, with their very small antennas, pulse transmissions, and other advantages, may be put to good use.

9.2 Distance Indicators (DME)

Distance indicators are absolute-distance (type-B, Section 3) devices, similar in principle with radio altimeters, and may likewise use pulse, continuous-wave, or frequency-modulated transmission. The range is greater than for radio altimeters, extending out to possibly 100 miles, or as far as the power or line-of-sight propagation allows. The accuracy need not be so great and, consequently, ambiguities are not prevalent. The indicated distance is again the slant range; but the horizontal distance is generally so great, compared to the height of the airplane above the earth, that the two are practically equal.

Unless the airborne distance indicator is part of a complete radar plan-position indicator, a ground responder-beacon is necessary. Distance indicators which are not part of a radar are generally of the meter type, and therefore require stronger pulses than do cathode-ray indicators. They give no directional information. The location of the reflecting landmark may be definitely established by using responder-beacons which either code the aided echoes, or respond on a definite radio-frequency channel, or both. The use of a special transmission frequency for the responder-beacon permits echoes from other reflecting bodies to be disregarded by the airplane receiving apparatus as in assisted radar. Responder-beacons are obviously saturable if a number of airplanes make simultaneous use of their facilities. This number can be increased by giving each airplane's interrogation signal a distinctive pulse-recurrence rate. The receiver must then include not only a time-measuring device but also an automatic "tracking" mechanism (strobe) for recognizing the desired echoes from those put out by the ground beacon in response to challenges from other airplanes.

Distance measuring equipments (DME) are very desirable operationally, as distance to destination may be read directly without the need for plotting a fix by crossed lines of position and then scaling off the distance on a map. The service is limited to moderate distances by the requirement for airborne transmitters; the practical limitation is actually to radio line-of-sight distances because the short pulses required for accurate time measurements necessitate the use of very high radio frequencies.

The various national and international policy-making bodies in aeronautics such as the Civil Aeronautics Administration, Provisional International Civil Aviation Organization, and Army Air Forces have recognized the urgent need for automatic meter-type distance indicators to make possible a complete distance and bearing (Rθ)

Simple meter type of presentation for an Rθ radio navigational system. Distance in miles and tenths is shown by the number-wheel type of indicator; bearing or azimuth is shown in degrees by the pointer. As distance and bearing are indicated simultaneously from the same radio landmark, complete information for a position fix is constantly presented in direct terms.

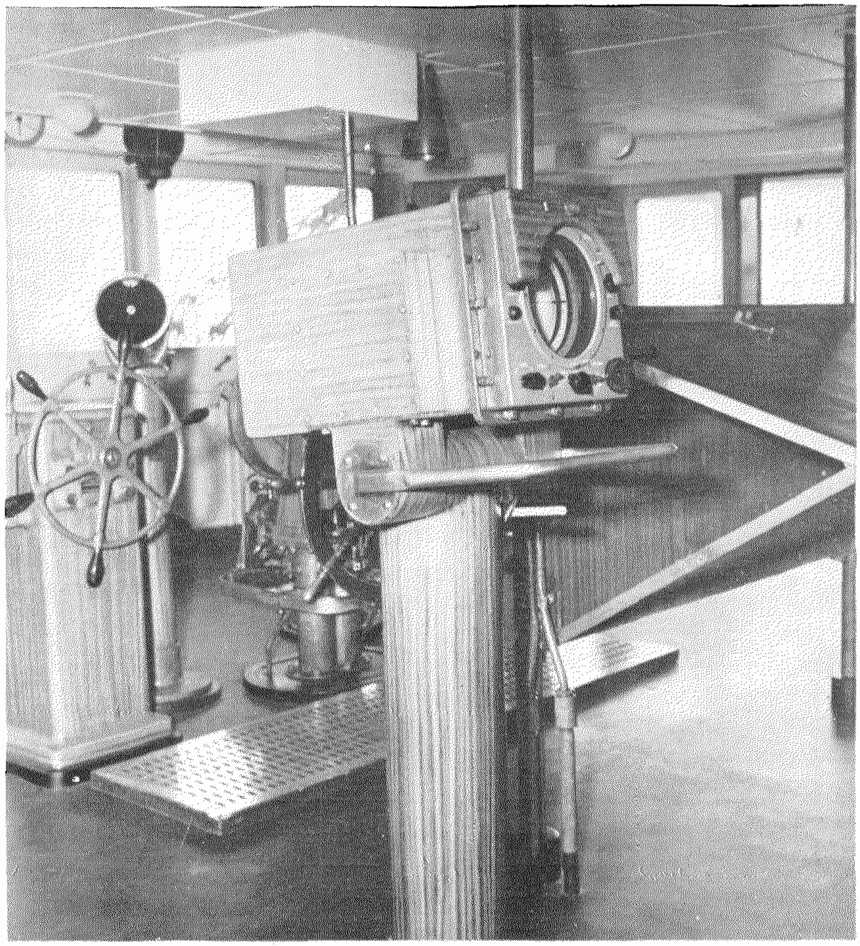
navigational system in conjunction with existing or proposed directional-type aids. Development of distance-measuring equipment operating in the 960–1215-megacycle band is in intensive current progress by Federal, Hazeltine, and other organizations. Equipments were demonstrated at the October, 1946, session of the Provisional International Civil Aviation Organization at Indianapolis, and are scheduled for extensive flight testing preparatory to commercial and military installation. The associated directional system which, with the distance-measuring equipment, will provide a complete polar-coordinate or Rθ navigational system along airways, cross country, and around airports, is to be the new Civil Aeronautics Administration omnidirectional range system operating in the 112–118-megacycle band.

9.3 Radar for Navigation and Anticollision

Radar essentially gives a pictorial display in the form of spots of light on a screen and reveals the location of distant objects with respect to the position of the radar station. This information could be used in reverse to ascertain the location of the radar station itself, if the true positions of the distant objects appearing on the radar display were known.

The first use is well fitted for military purposes, spotting objects which the enemy may prefer to conceal. With responder-beacons on airplanes to increase the range or clarity of service, the use of radar for civil aviation as part of the problem of ground observation and control of air traffic is very promising. The return pulses from the airplane could even be coded to reveal, always or on demand, the altitude, identity, or similar information regarding the airplane. Use would be made of the principle of identification-of-friend-or-foe (IFF) systems of Section 3.4. For this purpose, radar is a direct and independent system; the basic transmitters are on the ground, indications are in convenient pictorial form, and various elaborations and refinements are possible. The use of radar for a number of observational and automatic reporting functions may ease the load on pilots and on radiotelephone channels for routine reports, and possibly, by remote indicating systems, the control tower may avoid use of radiotelephone channels for routine orders to airplanes.

The second or reverse use is as a navigational aid. A ground station obviously needs no such aid; but a ship or airplane might use radar to locate itself by reference to known landmarks, such as coded responder-beacons, harbor buoys, coastlines, bridges, or other natural features appearing on the display. Navigation then might be very skillful, even in close quarters. Several important considerations, however, enter the picture. If the radar is ground based, observational information must be relayed back to the airplane; therefore the system is not an independent one. If the radar is airborne, a compass may still be necessary because all airborne radar bearings are relative to the axis of the craft. (If *two* or more known landmarks could be depended on always to appear on the plan-position indicator, true directions could be determined.) Finally, a radar installation requires heavy bulky rotating directional antennas; thus mobile radar, though quite practical for surface ships, appears for the present to be impractical for most civil aircraft.



Photograph courtesy of Raytheon Manufacturing Company.

Mariners Pathfinder shipborne radar installation, an all-weather aid in marine navigation. Marine radar is being increasingly used. Sets are generally of the short-range type, showing nearby objects with great accuracy, so that other ships, buoys, and obstructions may be located.

This is unfortunate because radar as a navigational aid can do one thing that no other system can do. It can show the presence and location of other moving objects for anticollision warning service. Knowledge of one's own position alone, no matter how exact, is inadequate for this purpose; the need for anticollision service is becoming more and more urgent with increasing density of air traffic. The fact that the airborne plan-position display shows the position of other objects relative to the axis of the airplane is just what is wanted. Limited airborne radar for anticollision use only and not providing a complete navigational service is less impracticable. Low transmitter power will do as the range need only be several miles or so, very sharply directional antennas are not required, and only a small sector ahead of the airplane must be scanned; thus space, weight and drag requirements are less burdensome.

The physical movement of an antenna to cover all desired directions is an advantageous feature of radar and allied systems. By making the antenna very sharply directional, the transmitted power is concentrated instead of being spread out, thus increasing the effective radiated power and range of service. The rotational rate of the antenna, however, must be slow enough to permit a sufficient number of pulses to hit each reflecting object. The pulse rate might be increased to insure this, but at the expense of increased transmitter power.

9.4 Rotating-Beacon Principle (Orfordness Range)

The uniformly rotating unidirectional ray feature which is characteristic of plan-position-indicator radar can be applied in other ways, even at comparatively low frequencies. In one design already described, the Civil Aeronautics Administration omnidirectional range (Section 5.4), which is a medium-distance method and may possibly be applicable also for long distances, the uniform rotation is produced electrically rather than by physical means. Before these methods were invented, the use of actual physically rotating antennas of large size, operating at medium frequencies, was tried.

An example of this type of directional transmitting system is the British installation at Orfordness. A fairly large directional antenna radiates a rather broad beam. The whole antenna is bodily rotated at a fairly slow rate, say once per minute. Each time the radiation is to the north, a distinctive reference or marker signal is emitted. With an ordinary stop watch, the observer measures the time elapsed between reception of the north signal and of the rotating beam. Knowing the rotational rate, this time interval is a measure of the angle through which the moving beam has turned from the north until it momentarily points at the observer, and gives the observer's true bearing from the ground station. The stop watch could be calibrated directly in degrees of azimuth.

A fully automatic indicator could also be devised. Other interesting forms may suggest themselves. The rotating directional transmitter might have a modulation changing uniformly with time so that its instantaneous value corresponds to the instantaneous bearing. Different audio-frequency tones might be used for this purpose. The direction of the antenna might even be recited by phone modulation every five degrees or so, each observer hearing only his bearing. Systems of this sort were used during the war as rough homing aids for airplanes. This method is very simple in principle but, at medium frequencies, antenna systems are either insufficiently directional to be accurate or much too bulky for physical rotation. Thus this system has not been extensively used.

9.5 Navar Principle

That same principle, however, is promising for use at higher frequencies, where antennas may be sharper in directional characteristics, smaller, and capable of faster rotation so as to give quicker indications. Furthermore, the principle opens up an interesting attack on the problem of integrating the ground traffic-control problem with the navigational problem, for medium-distance overland traffic.

One would start with a conventional ground radar station of the plan-position-indicator type for ground observation of air traffic. This type of radar always has a physically rotating, sharply unidirectional antenna as its basic element. To extend this into an omnidirectional and unambiguous rotating-beacon type of radio range, practically all that is needed is the additional emission of a distinctive omnidirectional north signal, each time the radar beam passes through north.

This is the principle of the omnidirectional range or azimuth-meter service which is one part of the Navar system being built by Federal. The timing is done automatically and true bearings or azimuths are indicated visually and directly on the airplane by the pointer of a 360-degree-type meter.

The other basic navigational part of the Navar system is a direct-reading distance indicator on the airplane. This uses pulses sent out by the airplane, as described under distance indicators (Section 9.2). The responder-beacon is at the ground station; its transmitter, in fact, may be the same one that produces periodic omnidirectional north signals in the direction-indicator system. A large number of airplanes may use this simultaneously without interference by use of the random-pulse-recurrence principle, also described in Section 9.2.

The Navar system resembles radar but is not identical with it; Navar and radar may work together. In radar, both the distance and directional transmissions and indications are on the ground. In Navar, the directional transmissions occur at the ground but their indications are produced in the airplane; the distance transmissions, which require no bulky directional or rotating antennas, take place from the airplane and the indications occur directly in the airplane. Moreover, a large part of the equipment, both on the ground and in the airplane, may be used in common for the bearing, distance, ground plan-position indicator, and possibly other functions.

Like radar, Navar gives a complete fix by means of a bearing line of position and a distance line of position, both on the same landmark and both indicated directly and concurrently. Furthermore, both indicators may be small easily read meters instead of bulky and not-too-bright cathode-ray tubes. In fact, for the medium-distance overland navigational problem, the presentation is practically the same as the ideal instrument shown in Fig. 1, except that indications are in terms of bearing and distance rather than latitude and longitude. This is even preferable for land orientation, where latitude and longitude are not particularly meaningful at first glance. Where air terminals are the important reference points, bearing and distance from them are most pertinent. The Provisional International Civil Aviation Organization has recommended that overland air navigation be standardized according to a distance and bearing system of reference. This implies a combination of some form of airborne distance-measuring equipment and omnidirectional azimuthal service.

For track guidance, any straight-line radial path leading to or from the ground station could be flown with facility by keeping on a line of position of fixed bearing; any circular flight path, such as an orbiting or holding maneuver, which is common near airports in preparation for landing procedures, could be easily flown by keeping on a line of position of fixed distance. A left-right meter or an automatic pilot could be used for guidance of the airplane along such paths, or even along any desired offset straight-line path, if a computing device which worked off both bearing and distance indications simultaneously were provided. Development of such computers is in progress by Minneapolis-Honeywell, Collins, and other organizations. Fig. 11, shows useful types of flight paths possible with a distance-bearing system.

9.6 Automatic Position Plotting (APP)

It is conceivable that the Navar type bearing and distance indicators could be provided with a mechanical polar-coordinate tracer to indicate the position of the airplane graphically and continuously on a map centered about the region of the ground station.

Any radio navigational system that indicates two intersecting lines of position concurrently gives a continuous indication of fix. The two lines of position might be radial as in any type-D system (Section 5), or as determined by combining direction finding (type A, Section 2) and compass indications, or they might be two circular lines of position from an absolute-distance (type-B, Section 3) system, or even two hyperbolic lines from a differential-distance (type-C, Section 4) system. In all such cases, it is conceivable that the two simultaneous indications could operate an automatic position plotter. This has been proposed by Bendix for the direction-finder and compass case.

The bearing-distance combination, however, has a number of advantages over any other combination of lines of position. First, the bearing-distance indications are from a single landmark and may occur from use of one radio-frequency channel, thus requiring only one tuning operation. Bearing and distance from a single place, even as numerical quantities, give a clearer mental picture of a location than do two bearings, two circles, or two hyperbolas, from two landmarks. Finally, the airplane needs to be within range of only one station, rather than two widely separated, specially related stations at the same time.

The automatic position plotter would be mechanically much simpler with the polar coordinates of bearing and distance than with two bearings, circles, or hyperbolas, especially as in the latter cases the distance and direction between the two landmarks would not be any fixed amount. A manual adjustment would have to be provided for introducing these factors into the apparatus, depending on the relative location of the available pair of ground stations. Also, the two ground stations might not always appear on one sectional map. Finally, with crossed straight lines, circles, or hyperbolas, fix errors are liable to be greatly magnified under certain circumstances, as when the two lines of position are not close to being perpendicular; whereas distance and bearing lines of position from one landmark are always at right angles, the best angle of intersection for high accuracy.

9.7 Relayed Radar (Teleran, Navascope)

Radar, together with the advantage of giving simultaneous bearing and distance lines of position from one landmark, can give pictorial plan-position displays and is uniquely suited for anticollision service. Airborne radar, however, has the installation drawbacks already noted. The idea has therefore been proposed to use a ground radar station to collect such information as distance and bearing of airplanes and terrain features for display in conventional form for ground observation and control of air traffic. All this information might then be relayed to the airplane by radio for navigational purposes. The airplane would require a relatively small radio installation without bulky directional and rotating antennas and would require no powerful transmitter.

This scheme would seem to allow one powerful ground radar station to serve a large group of airplanes with navigational and anticollision information cheaply. The information preferably should not be relayed to the airplanes verbally; the airplanes should be provided with either a picture or a duplicate of the original ground plan-position display.

The picture method has been proposed by the Radio Corporation of America as the essence of its Teleran system for air-traffic control and

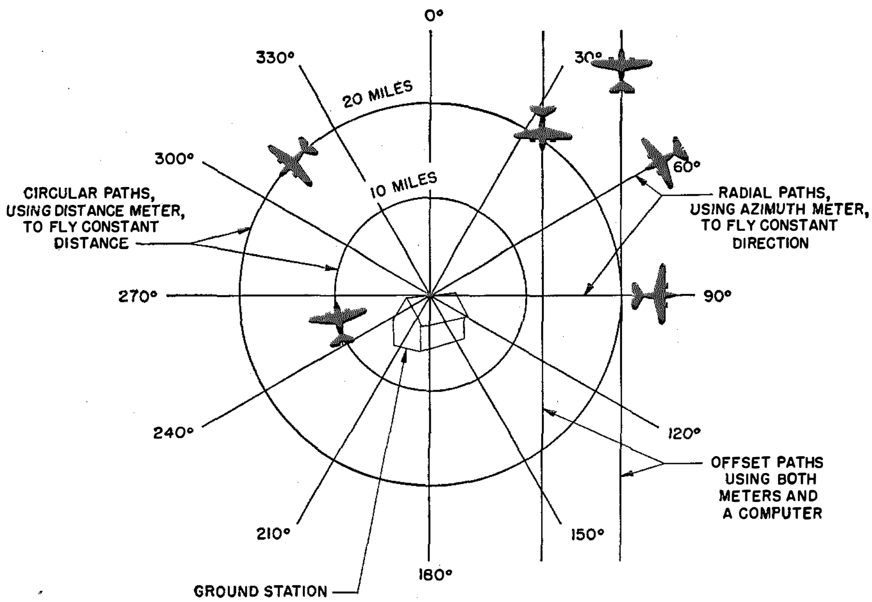
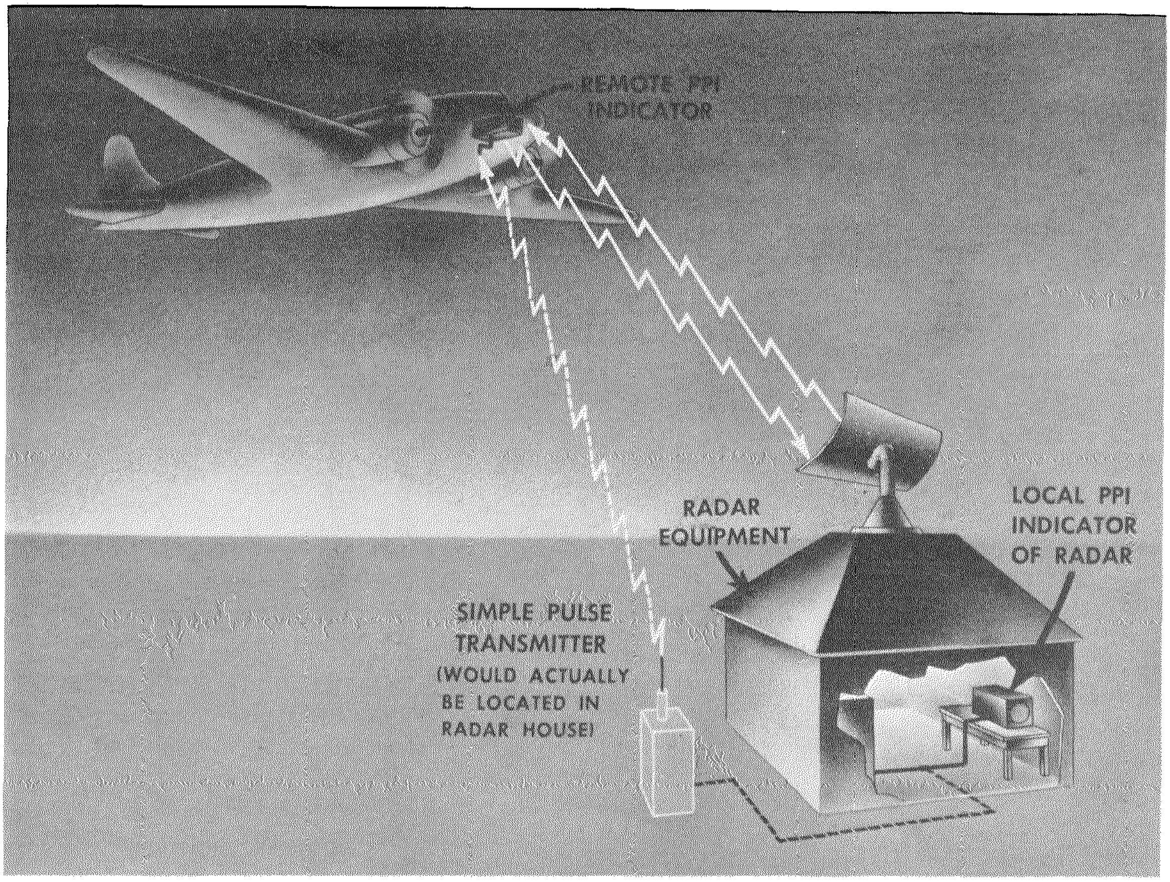


Fig. 11—Useful types of flight paths possible in an Rθ or distance-bearing radio navigational system. Tracks may be accurately followed by reference to a distance-azimuth meter like that shown in a previous illustration.



Principle of remote radar as used for the Navascope, or airborne duplicate of the ground radar plan-position display.

navigation. Principles of ordinary television practice are to be used. The ground radar display is produced in the usual manner; the plan-position indicator is scanned by a television camera and broadcast by an omnidirectional television transmitter. The picture is displayed on an airborne television receiving set. This scheme offers a number of interesting possibilities; for example, additional information, map indications, traffic orders, etc., could be written on the plan-position indicator or held in front of the television camera, and would instantly appear on the airplane television receivers.

The duplicate or remote radar method has been proposed by Federal as one part of its Navar system for traffic control and air navigation. Again a conventional ground radar station produces a plan-position display in the usual manner. Airplanes are given a duplicate of this display in much the same manner that an additional display would be produced in an adjoining room, except that radio instead of wire links are used. The incoming echo pulses are used not only to create the light spots on the ground plan-position indicator, but are broadcast in original form but on another radio channel in all directions. Other control pulses for synchronizing the time sweep and the bearing sweep are likewise broadcast, all in proper time relationship, so that the airplanes use essentially the same pulses to create a plan-position display as does the ground station and in the same manner. Certain extra information could also be put in at the ground station by special electronic means. Also, the pilot can vary the content and manner of presentation, such as scale, heading, or offset, to suit his purposes.

This type of relayed radar, which has been used for certain wartime applications involving the repeating of radar displays between surface ships and airplanes, is proposed as part of the integrated Navar system to give a pictorial display on the airplane in addition to the primary meter-type indications of distance and bearing. In this connection the remote radar or Navascope display would use, to a certain extent, the same ground and airborne equipment installed for the airborne distance and bearing indicators as well as for the ground radar display.

While relayed radar, whether televised or remoted, appears to obviate the need for a complete airborne radar, on closer analysis three fundamental defects appear.

In the first place, the system is a "second hand" one as indications originally assembled on the ground are relayed to the ultimate user over an extra radio link, whereas independence has been stressed as a desirable feature for any navigational aid.

Secondly, the original radar display uses assisted techniques; cooperating equipment, such as responders, are required on all airplanes, and only those so equipped will appear on the display. However, until airborne radar is made more practical, relayed radar may be a useful compromise solution to the anticollision problem.

Thirdly, the information given by relayed radar alone is necessarily incomplete; the system is not a self-sufficient navigational aid.

The ground station collects only directional and distance information regarding the airplanes. Airplanes are not identified; they are just so many spots of light on a cathode-ray screen, indistinguishable from each other. When the ground display is transmitted to the airplane, the center of the picture is the ground station and the spots of light still look alike. The result is that the observer on a particular airplane, looking at the radar picture, does not know which of the many spots of light corresponds to his airplane. The only way he could identify his own light spot is by knowing his own bearing and distance, the information he is trying to obtain. Attempting to resolve this vicious circle is like trying to lift oneself by one's own bootstraps.

The fact that the ground radar antenna acts as a rotating beacon, irradiating an airplane once during each rotation, could be used to determine bearing. This principle is used to actuate the direct-reading azimuth indicator which is one of the basic parts of the Navar system. Other airplanes, however, might be at the same bearing at the same time.

Additional schemes may be used to aid in judging which spot of light corresponds to a given airplane. If, however, an independent source of distance information were also continuously available, then the question would be answered completely. If desired, the bearing and distance information could be combined automatically to mark in some distinctive manner the light spot corresponding to the observer's airplane. This principle is incorporated in the remote radar part of the Navar system, for independent airborne distance and bearing indicators are already provided as primary navigational devices.

For complete identification and really effective anticollision warning service, the relayed radar display should give altitude information also. The observer, for anticollision purposes, does not need to know the actual altitude of his or other airplanes; he need only know which other airplanes are near his own airplane. He does not even need to see on the display those airplanes which are at considerably different altitudes. By the following principles, in either televised or remoted radar, this might be accomplished at least effectively enough for the purpose.

The ground radar display originally shows all airplanes regardless of altitude; but each airborne relayed display is devised so as to be altitude selective. To accomplish this, the aided echoes from the responder-beacon in the airplane are coded in accordance with a barometric altimeter mechanism. The coding thus corresponds to the instantaneous altitude of the airplane. This feature permits each airplane to include in its radar or television display only those spots of light indicating airplanes whose return pulses have the particular altitude coding corresponding to any altitude layer selected by the pilot.

Furthermore, in remoted radar there is the possibility of an automatically adjusted altitude presentation, that is, the barometric coder can control the relayed radar indications so as to show only airplanes at the same altitude region as the observer's airplane and this display level will follow the airplane as it changes in altitude.

Only *true mobile* radar, however, may be a first-hand, pictorial navigational aid and anticollision indicator. For anticollision service, it is unique and is the ultimate device. For practical reasons, mobile radar is only suitable at present for surface ships and possibly for very large aircraft. If anticollision service or a pictorial radar display is nevertheless wanted on airplanes, it might well turn out that some sort of relayed radar is the practical solution, especially for small or moderate-sized airplanes where weight, power, drag, and expense must be held down. For fundamental reasons, however, an independent self-sufficient navigational system, one with unambiguous observations made directly on the airplane, is still desirable as a primary navigational aid, with or without relayed radar as an adjunct.

10. Long-Range Applications

10.1 General Requirements

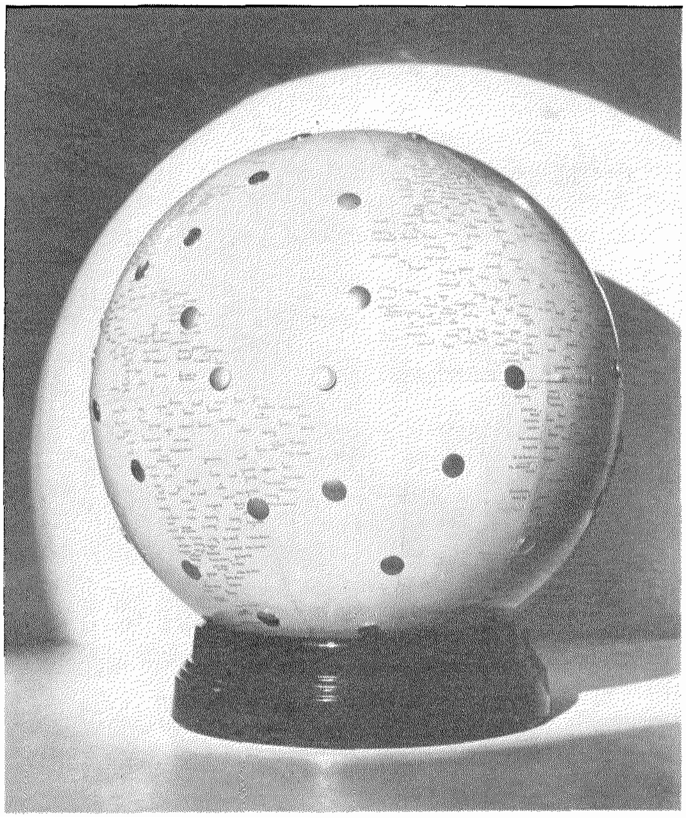
Navigational aids for transoceanic routes or routes passing over large desolate areas like the polar regions present special problems. Relayed radar, for example, is out of the question, for this facility requires chains of ground stations of limited line-of-sight range. If anticollision service should be desired, pure airborne radar is a necessity. As regards the main navigational items, great accuracy is not too important. Reliability of service over great distances is the big problem; in midocean there are no emergency landing fields. Midocean landings, even for seaplanes, are not too safe; and the trend seems to be toward land-type planes for transoceanic traffic. Good track guidance is desirable since on a long trip much time and fuel may be wasted by erratic wanderings off the direct course.

10.2 Distance Requirements

The first question that occurs when discussing radio navigational systems that are to be ultimately capable of covering all oceans, polar areas, etc., is just what distance range is required for the ground stations. It may be assumed that to establish a fix by crossed lines of position, an airplane must be within range of at least two ground stations whose lines of position cross at a usable angle; and that ground stations are to be at actual land points, coastal or island, and not on moored ships or man-made islands. A recent study[12] indicates that if a reliable range of about 1500 miles is postulated, sufficient land sites are available. With this range, 4 to 6 stations could service the important North Atlantic area, and some 60 stations could cover all oceanic and polar areas. For differential-distance type systems (Section 4), where for each family of lines of position two widely separated suitably related sites must be found, the situation is more complex, especially at midsea where islands may be few.

At 1500 miles, any radio navigational aid that requires transmissions of any sort, including echoes or responses, from an airplane appears to

[12] P. R. Adams and R. I. Colin, "Frequency, Power, and Modulation for Long-Range Radio Navigation System," *Electrical Communication*, v. 23, pp. 144–158; June, 1946.



Base map copyright by Rand McNally & Co., Chicago, Ill., R.L. 4728.

Globe view showing possible locations of ground transmitters of 1500-mile range, for providing radio navigational service at all points in the North and South Atlantic oceans.

be out of the question, because an airplane cannot carry an adequate transmitter and antenna installation. The various basic types of radio systems are analyzed with respect to this requirement in the lower half of Table I. It is seen that only airborne direction finding, ground directional transmission, and ground differential-distance types may meet this condition. But among these, only the last two also meet the requirement of self-sufficiency or independence as analyzed in the first half of Table I.

This does not mean that *all* directional transmitting (type-D, Section 5) and differential-distance (type-C, Section 4) systems necessarily meet all the requirements; this depends on specific system details. It does mean that in looking for a radio navigational system that meets the two basic requirements for long-range use, no other types of systems need be considered. The question of which of the two types, or which specific system of either type, is the best or the most promising, can only be answered after thorough technical study of such details as accuracy, reliability, frequency and bandwidth requirements, availability of suitable sites, ambiguities, shape of lines of position, convenience of indications, degree of omnidirectional service, weight and complexity of equipment, and so on; and ultimately, only by actual test. Some general comparisons of the two favored basic types are next given.

10.3 Differential Distance Versus Directional Transmitting

In a sense, these two types of systems favored for long range are different only in degree. In both cases, sets of two or more antennas are used and the emissions from the individual antennas must be accurately related. In both, the lines of position are necessarily hyperbolas because they result from a differential effect between two or more antennas. The hyperbolas, however, degenerate into sensibly straight lines at distances from the array that are greater than about 5 to 10 times the spacing between individual antennas; this condition holds true for all practical purposes in type-D systems. The line of demarcation between the two types of systems appears in several other ways. One may say that in directional transmitting systems the antennas are from a fraction of a wavelength to several wavelengths, say a few feet up to a mile, apart; while in differential-distance systems the antennas may be hundreds of wavelengths, up to hundreds of miles, apart. The latter condition has it advantages; as in trigonometric surveying and plotting, a long control base line results in more accurate indications, other things being equal. Also, errors caused by nonuniformity in the terrain in the immediate vicinity of the antennas become less serious.

In differential-distance systems, the signals from individual antennas are received independently and then compared in phase or in time. In directional transmitting systems, the signals from the individual antennas merge, so to speak, and only the net effect is observable; this net signal is compared with other net-effect signals produced by the same or nearby antennas.

In differential-distance systems, the antennas are so far apart that a radio link and very careful procedures must be used for synchronizing the two distant transmitters. The signals from the two antennas travel to the distant observer by quite different paths over the earth. In directional transmitting systems, the antennas are so close that a short wire link may be used for synchronizing the signals; generally, the identical transmitter is used for all antennas. On the other hand, the antennas in differential-distance systems may be of the simplest, nondirectional type, whereas in the directional transmitting systems the layout, polarization, modulation, balancing, and current relations of the individual antennas of the array must be carefully attended to, so that the correct directional patterns are always produced and are correctly modulated. All the signals, however, travel to the observer over a single propagation path.

The site-location problem is more stringent in type-C (Section 4) systems because two sites, suitably related, must be found to produce one set of lines of position. In certain regions, this might require raising the distance requirement, thus increasing the construction and power cost. Two sites mean two bases, seivices of supply, and groups of operating personnel. As Fig. 7 and the check list (Table I) shows, three distinct radio signal links per airplane are required for one line-of-position observation; this means fundamentally greater chance of breakdown.

All types of systems are subject to certain basic sources of error, which limit the accuracy of even the best-designed and engineered system. For very-long-range systems, radio propagation occurs via sky waves, that is, by waves which are reflected down to the receiving station by the various ionospheric layers. This always affects radio communication and navigational services. In directional systems, inherent errors may arise because of certain changes in the polarization of the reflected waves, and because of distortions of the wave front caused by certain terrain features. In any distance systems, inherent errors may arise because of deviations of the path of the radio signals from the most direct path, caused by irregularities in the ionspheric layers; in differential-distance systems, moreover, there are two distinct paths to the receiver, and each path may be affected differently. In all systems, errors may arise because of interference between signals arriving via the ground path and via the sky path or paths from the same transmitter. They may vary in time of arrival, phase, polarization, etc. Systems using very short pulses and cathode-ray tubes have an advantage in that the ground-wave pulse, arriving first, may be visually distinguishable from the pulses arriving over longer paths.

The comparative seriousness of the various inherent errors in the two types of systems, and the limiting magnitude of them in each system, have not yet been determined well enough to judge which type of system is preferable in this count, or to predict the limits of accuracy one may expect in long-range radio navigation in general.

The above sources of error are not in the transmitting or receiving apparatus but in the physical medium of propagation between the two, a medium over which engineers have little or no control. Outside of such inherent errors, which are characteristic of the basic type of system, in each specific system there may be errors caused by ambiguities, misadjustment, or mechanical malfunctioning, which errors may be reduced by good design and engineering and by careful and intelligent operation.

10.4 Propagation Problems

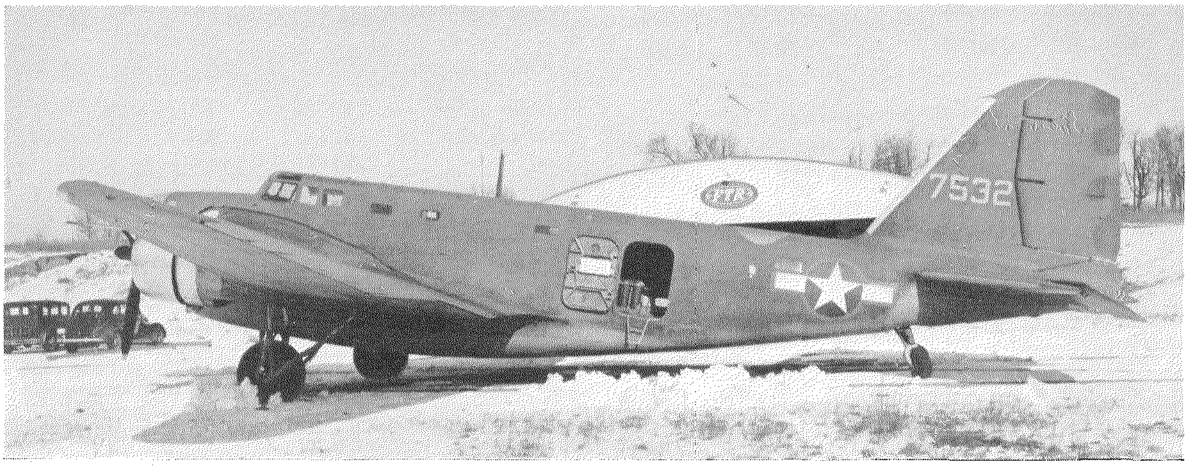
For short-distance applications, high frequencies are generally preferred because sharp directive effects are desired with small installations. For medium-range work, up to 100 miles or so, certain frequencies may be preferred for practical reasons, but almost any frequency would do. In both cases, the power requirements create no great problem. For a 1500-mile reliable range, however, the question of proper frequency for reliable transmission is a critical one as power, transmitter, and antenna costs are not inconsiderable.

The study[12] previously referred to has gone into these questions starting from first principles, and the results of the investigation prove to have some direct implications with regard to the suitability of specific systems for reliable long-range use.

For long-range propagation, only the low-frequency, very-low-frequency, and high-frequency bands may work. Medium frequencies, such as used for broadcasting, have very short ranges in the daytime and are variable at night. Very-, ultra-, and super-high frequencies are restricted to line-of-sight distances, about 250 miles for an airplane at an altitude of 20,000 feet.

High frequencies, as used in international broadcasting and communication, may travel long distances with comparatively little power and small antennas. Interruptions and disturbances, however, are very frequent and serious, the ionospheric layers being highly variable with respect to these waves. Fading is common and, at intervals that may be frequent and protracted, there are complete blackouts of reception, connected in some way with magnetic storms and sunspot activity.

Low and very low frequencies, as used since early days for very-long-distance communication, propagate quite steadily day and night, during all seasons and years, as the ionospheric layers that reflect them are less subject to upheavals. Also, one frequency serves for all distances, directions, and times of transmission, while for long-distance high-frequency communication, a transmitting station often has to choose among three or more available frequencies to fit the circumstances. Low frequencies are especially



Laboratory-equipped airplane used for gathering experimental data on performance of ground and airborne equipment during the development of a radio navigational aid (SCS-51 instrument landing system).

useful for radio communication in polar regions, where air traffic may be expected to increase in the future to take advantage of direct great-circle routes; in these regions high-frequency transmissions are subjected to such excessive ionospheric disturbances as to be practically useless, except for short distances.

Thus, from the all-important consideration of reliable and uniform propagation, low frequencies seem indicated for long-range navigational systems. Low-frequency transmitters, however, require very large antennas and considerable power. Also, the bandwidth should be extremely narrow for two reasons. First, static or noise, which may be very disturbing at low frequencies (less so in polar regions and more so near tropical areas), may be reduced in effect by use of narrow-band reception. Secondly, the low-frequency band does not have room for many or wide channels. Therefore, if a number of navigational stations are to be accommodated without interfering mutually or with other radio stations, their emissions must be so narrow in bandwidth as to use up very little channel space. The general conclusions of this study regarding the desirability of low-frequency and narrow-bandwidth operation for long-range radio navigational aids have found agreement in the recommendations and experiences of others. A great amount of experimental development work is being done on specific systems meeting these conditions.

In a subject with so many ramifications, accurate quantitative predictions cannot be made; but the aforementioned study concludes that for a 1500-mile service range, the greatest reliability may be expected with least power cost at a carrier frequency in the neighborhood of 80 to 100 kilocycles. The input power requirement, per ground station, for a receiver bandwidth of about 20 cycles, is stated as ranging from about 10 to 100 kilowatts, depending on the nearness of the station to the tropic zone. It is interesting to note that 100 kilowatts when translated into mechanical power is equal to about 140 horsepower or about one tenth the power output of a single modern airplane engine.

10.5 Specific Systems

Up to the present, no system satisfying all the basic requirements, let alone the features of convenience, of a long-range navigational system has been built. Some have been proposed or are being developed. In a number of cases, the system is merely an extension of a type used more or less successfully for medium distances. The difficulty is that mere increase of power is not always sufficient; the particular modulation, frequency, or other features being such that the systems are propagationally unsuitable for long-distance work.

The principal systems under discussion for long-distance use may, however, be mentioned and their long-range features itemized briefly. The first requirement is, of course, reliable service, which implies low-frequency narrow-band operation; then ambiguities, convenience, omnidirectional coverage, antenna complexity, etc., may be considered.

Loran and Decca are propounded as promising differential-distance systems, the hyperbolic lines of position and other general features being the same as already described under type-C (Section 4) systems. Standard Loran, which has had extensive wartime use, uses brief pulses, which require wide bandwidths and fairly high frequencies. Some promising work is being done on low-frequency forms of Loran; the inherent and practical problems (channel space, etc.) are considerable, and the final answer is not available. Decca, a recent development, uses pure continuous waves and is thus eminently suited for low frequencies and narrow bandwidths. The phase-comparison method, however, brings in the great problem of ambiguities which has been already described, and which may only be resolved by using recording meters, carrying double equipment for the receiving of two pairs of stations for a fix, and using extra high powers in the transmitters. Loran (at least in high frequencies) and Decca are capable of great accuracy, one requiring cathode-ray-tube observations and manipulations, the other requiring careful treatment of ambiguities. In Loran, although rather wide bandwidths are used, several stations can operate on the same radio-frequency channel without interference, through the principle of different pulse-repetition rates as described under distance indicators (Section 9.2). In Decca, even the two stations of one pair must operate on different channels so their signals may be distinguished at the airplane, where they are subsequently changed to identical frequencies for phase-comparison purposes. This requires essentially two receivers for observing one line of position and a special schedule of frequency allocations. Coverage is fairly wide so that many lines of position are available, though of hyperbolic shape and requiring special charts. In all cases, antennas may be the simplest nondirectional types, but accurate and reliable long-distance synchronization is required.

Among the directional transmitting systems propounded are Consol or Sonne, Civil Aeronautics Administration omnidirectional range, and Navaglobe. Consol and Navaglobe are inherently suitable for low-frequency narrow-band operation. The Civil Aeronautics Administration system, which was originally developed at high frequencies to replace the four-course A-N ranges, has special modulations that make the problem of adapting it to low-frequency narrow-band operation difficult, but some interesting work is being done on low-frequency designs of it. The Civil Aeronautics Administration and Navaglobe systems are omnidirectional and direct indicating, with little or no ambiguities. Sonne, which has been operationally used during the war, is capable of great accuracy, but the coverage is not completely omnidirectional, and alternative means, direction finding, for example, must be used to resolve ambiguities. Its aural indications require no special receiver but take considerable time. Sonne or Consol require an array of only two or three antennas; the omnidirectional Civil Aeronautics Administration and Navaglobe systems require five and three antennas, respectively. Navaglobe has not been in operational use, but an experimental model is under construction. In all type-D systems, the observations may not be as accurate as in differential-distance systems but should be precise enough for ordinary commercial purposes, and the antenna layout and excitation are critical. The lines of position are of the more convenient shape of great circles and require no special charts.

11. Conclusion

The foregoing descriptions of specific radio navigational systems were restricted to fundamental characteristics; in each system there may be hosts of other quite important considerations, intimate technical and other details, which further add to or detract from the suitability of the systems. Only tests over a period of years, especially for the long-range case, will give the final answer, insofar as any technical development can be considered final. In radio navigation, as in any other field, developments are not cheaply attained; Edison's well-known characterization of invention as being 10 percent inspiration and 90 percent perspiration still holds true. Credit for the ultimate developments in radio navigational aids, whatever form they may take, must be shared among the large number of individuals and organizations in many countries who have contributed to the advancement of the various branches of radio and electronics.

Frequency-Shift Keying in the I.T.&T. System

IMPORTANT international circuits of International Telephone and Telegraph Corporation associate companies are now employing frequency-shift keying for Morse and printer codes, and many others are scheduled for conversion to this method of operation during 1947. This method of operation makes possible utilization of printer and time-division-multiplex equipments on international circuits without increasing the power of the transmitters. On circuits where manual transcription methods are retained, frequency-shift provides the same circuit efficiency with an appreciable reduction in radiated power.

Historically, frequency-shift transmission was first employed with the old Federal-Poulsen arc transmitters. As they could not be keyed on and off, signaling was accomplished by changing frequency. This was referred to as back-wave or compensated-wave keying. However, no use was made of the back wave at the receiving point; it was considered to be a troublesome effect which at times actually interfered with reception. Proposals were advanced from time to time to forbid this method of signaling by international agreement.

The advantages of frequency-shift signaling were recognized as far back as 1923, and several satisfactory systems were demonstrated over the years. It was not until the success of wide-band frequency-modulation transmission in improving signal-to-noise ratio was demonstrated, that narrow-band frequency modulation for telegraph service was recognized as possessing great merit.

Application of this principle resulted in the development of keying involving shifting the carrier frequency alternately between two discrete frequencies, generally separated from 300 to 1000 cycles. One frequency transmits the mark elements and the other the space elements of code.

Receivers employed with this mode of operation are arranged to respond only to frequency variations in the received signals and not to amplitude variations. Inasmuch as the receiving equipment is not affected by large variations in signal amplitude caused by fading, amplitude modulation, etc., and, as noise is predominantly amplitude modulation, frequency-shift operation gives improvements in signal-to-noise ratio averaging from 6 to 12 decibels over on-off single-frequency operation.

Mackay Radio and Telegraph Company has designed special frequency-shift equipment for use on its international circuits. This embodies the principle of space-diversity reception to combat further the effects of signal fading. Profiting by experience under actual operating conditions, further improvements are being incorporated in the equipments, which include transmitter-exciter units, diversity-receiving sets, and monitoring or measuring apparatus.

Many converted radio circuits are now being operated with 5-unit printer apparatus, and time-division-multiplex equipment is being developed. In all of this work, the long experience of Mackay in radiotelegraph operation, combined with that of the associated cable companies in cable and land-wire operation, is providing a wealth of useful information.

Institute of Radio Engineers 1947 Convention

THIRTY-SIX organizations contributed 118 technical papers to the 1947 national convention of the Institute of Radio Engineers in New York, New York, on March 3rd to 6th. Included were 12 from Federal Telecommunication Laboratories, the largest number accepted from any single organization or system. Summaries of these papers follow; certain ones will be published in full in future issues of *Electrical Communication.*

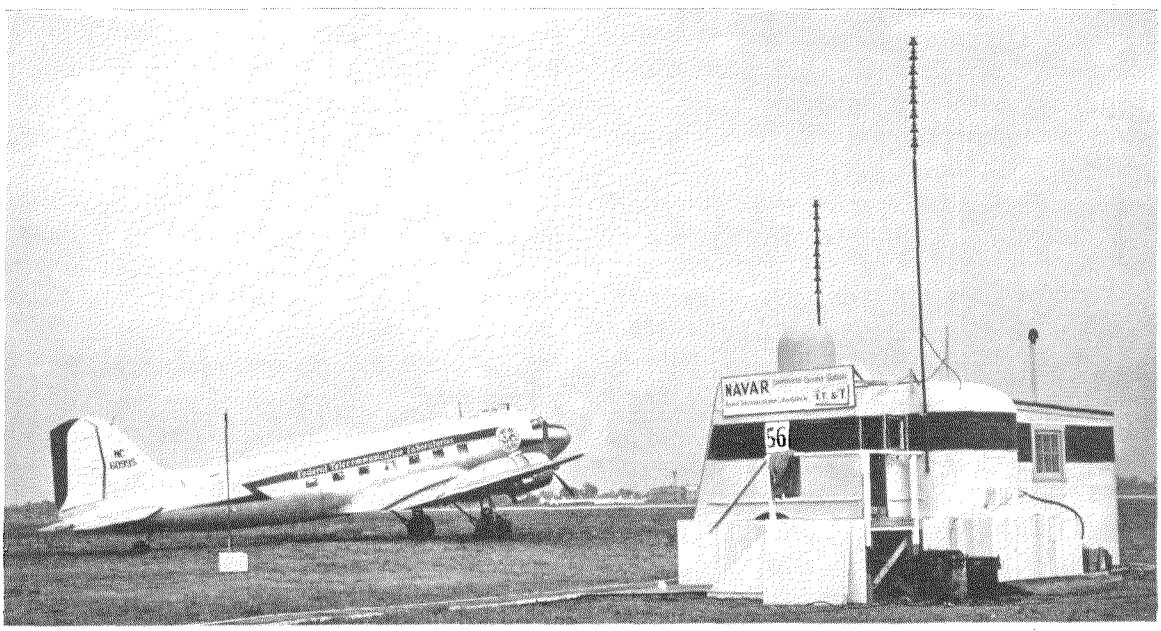
It is of interest to note the effect on this convention of wartime expansion of the telecommunication fields. The attendance was 11,895 and about 170 companies, including Federal Telephone and Radio Corporation, occupied the exhibition space at Grand Central Palace. Banquet facilities restricted attendance at that function to some 1600 members and guests.

First Tests on Navar System for Aerial Navigation and Air Traffic Control

By P. R. ADAMS, S. H. M. DODINGTON, and J. A. HERBST

Background and features of the Navar series of radio aids to air navigation and traffic control, which are being developed under U. S. Army Air Forces sponsorship, are briefly reviewed. A description is given of equipment and its performance in an experimental ground and airplane installation, assembled for preliminary tests of basic principles and the gathering of flight data on the four key facilities of the Navar system, as follows:

A. Airborne distance indicator, pulse type, with meter presentation; B. Airborne azimuth indicator, omnidirectional radio-range facility of physically rotating antenna type, with meter



Navar ground installation and the flying laboratory of Federal Telecommunication Laboratories at Indianapolis for the meeting of the Provisional International Civil Aviation Organization at which the first phase of the Navar development was demonstrated. Two stacks of discone antennas may be seen above the house.

presentation; C. Normal ground search radar, with plan-position presentation; D. Assisted radar, using an airborne responder, with presentation on the same plan-position indicator. Incidentally, signals suitable for operation of a relayed radar plan-position indicator on the airplane were provided.

In particular, features of integrated operation are described: A. Ground radar antenna utilized also as a basis of the azimuth-meter service; B. Ground distance-measuring-equipment responder useful also as an auxiliary transmitter for the azimuth service, as well as for radar relaying; C. Airborne distance-measuring-equipment transmitter performing also as part of radar responder; D. Airborne distance-measuring-equipment receiver, in conjunction with receiver part of radar responder, utilized also for azimuth service and for radar relay service. Station selectivity for azimuth service is attained in spite of common-channel operation of all ground radars. Multipurpose electromechanical type of azimuth-measuring unit is described; principle of time sharing of pulses and method of differentiation between various types of pulse signals on same channel is explained.

Performance of the experimental installation, which was also set up at Indianapolis Airport in October, 1946, for demonstrations to Provisional International Civil Aviation Organization delegates, is discussed. The second stage of development of the system, with emphasis on the earliest availability of a distance-measuring facility, is outlined and features of service-test models of equipment under construction for delivery and operation early in 1947 are described.

Relations Between Bandwidth, Speed of Indication, and Signal-to-Noise Ratio in Radio Navigation and Direction Finding

By H. BUSIGNIES and M. DISHAL

Information is transmitted and received at a very slow rate, electronically speaking, in most navigational and direction-finding systems. Accordingly, quite small bandwidths, probably of the order of only 10 to 100 cycles, are actually required. Thus simple modulation shapes to convey the desired intelligence should be used to conserve bandwidth.

In considering the relations between bandwidth and signal-to-noise ratio, narrowing of the pass band before and after final detection is compared. If large signal-to-noise ratios are always to be used, there is no choice. However, for the important case of small signal-to-noise ratio (e.g., 3 to 1), it is shown that for predetection narrowing, the signal required for a given signal-to-noise ratio is proportional to the square root of the bandwidth ratio, whereas for postdetection narrowing, the signal is proportional to the 4th root of the bandwidth ratio. Experimental confirmation of these relationships is cited.

Impulse noise cannot be limited at a "bandwidth level" equal to that required to pass the signal being received. Illustrations are given showing the excellent results which can be obtained first by impulse limiting in a wide-band portion of the receiver and then passing the signal through the narrow band. For pulse systems using wide bands, a "bucking out" system is described which cancels received impulses but does not affect the signal so long as the impulse and pulsed signal do not occur simultaneously. In this system, the outputs of two diodes are subtracted from each other. Each diode operates from pass bands of equal widths, and the carrier frequency is placed in the middle of only one of the pass bands. Similar results may be obtained by effectively using three pass bands and subtracting the output of two from the third.

A possible new method of reception is described which may allow signals to be reproduced at extremely low signal-to-impulse-noise ratios. This system utilizes the previously mentioned bucking detector scheme described above and measures the resultant impulse-noise output, which is dependent on the signal input, when carrier and impulse are simultaneously present. A graph showing the peak impulse output versus carrier input is given.

The required speeds of indication are considered for various aids to navigation, such as the aircraft radio compass, distance-measuring equipment, long-range navigational systems, Loran, and radar. Considering the rate at which information is transmitted in these systems, it is indicated that in some of the systems apparently more bandwidth is being used than should actually be required. However, it is pointed out that in some of the systems, the extra bandwidth is used to obtain greater accurracies and greater discrimination, e.g., radar.

A practical narrow-band (20-cycle pass bandwidth) navigational system is described. This is the Navaglobe and narrow-band automatic-direction-finding system.

Multiplex Microwave Radio Applied to Telephone Systems

By T. H. CLARK

The first telephone systems used a single wire and a ground return to establish a circuit for a single voice channel of communication. Improved characteristics were obtained when an additional wire was used for the return. It then was found possible to transmit two simultaneous conversations over such a circuit; one between the two wires and ground and the second between the two wires of the pair. The most commonly used long-distance circuits today consist of four wires (two pairs). Three conversations can be transmitted, two on the pairs and a third phantomed between the two pairs. The introduction of carrier techniques and, particularly, the coaxial cable further increased the number of conversations that can be carried over a single pair of conductors. All of these advances were made in the continuous effort to reduce the cost of the wire plant comprised in the telephone system. Despite all these improvements, the wire plant still is the major portion of the cost. The next logical step is the use of radio transmission.

Low-frequency radio was used for long circuits such as transatlantic telephone links at about the time of the first World War. High-frequency circuits for ship-to-shore and intercontinental communication were introduced in the 1920's. Fixed circuits at very-high frequencies came into use in the 1930's for short overwater carries where the cost of the submarine cable was excessive. About the same time, a number of experiments were carried out in ultra- and super-high frequencies for the same service.

At the present time, a number of microwave communication systems, called "microwave links," are under development. The principal purpose is still to reduce the amount of copper used to carry voice-frequency channels. Several of these systems are sufficiently advanced so that microwave links may become a reality in the 1940's as very-high-frequency links did in the 1930's.

Two principal types of systems are in advanced stages in I.T.&T. System laboratories. One system furnishes a single wide-band channel capable of transmitting by radio the frequency spectrum presented by a conventional frequency-division-multiplex carrier system. At the radio receiving terminal, the carrier spectrum is re-obtained and the signal can be applied, as carrier, to wire lines or cables or it can be handled by the receiving terminal of the carrier equipment and be reduced to the separate voice channels.

A second system is capable of taking a number of telephone conversations and applying them as voice bands to time-division-multiplexing equipment. The carrier can be modulated by conventional methods such as frequency modulation, amplitude modulation, or pulse modulation. A system of pulse-time modulation with time-division multiplex has reached a high state of development. A 24-channel system is in experimental operation between New York and Trenton, New Jersey. Two unattended repeaters are used.

Microwaves were exhaustively explored for radar and similar uses during World War II. The techniques evolved have been of considerable assistance in the further development of microwave links. The frequency spectrum above 1000 megacycles is becoming very crowded as a result of the many wartime developments.

Absolute reliability is a primary requisite for telephone systems. The anomalous propagation effects discovered in the early 1930's are being studied more carefully at the present time. Because the microwave systems are limited approximately to line-of-sight distances, repeaters must be used for transmission over long distances. Reliability of these repeaters is of utmost importance and automatic features of protection, switch-over to auxiliary equipment or power, and operation under extremes of temperature and humidity have been carefully studied. Repeaters, to be economical, must be capable of reliable unattended operation.

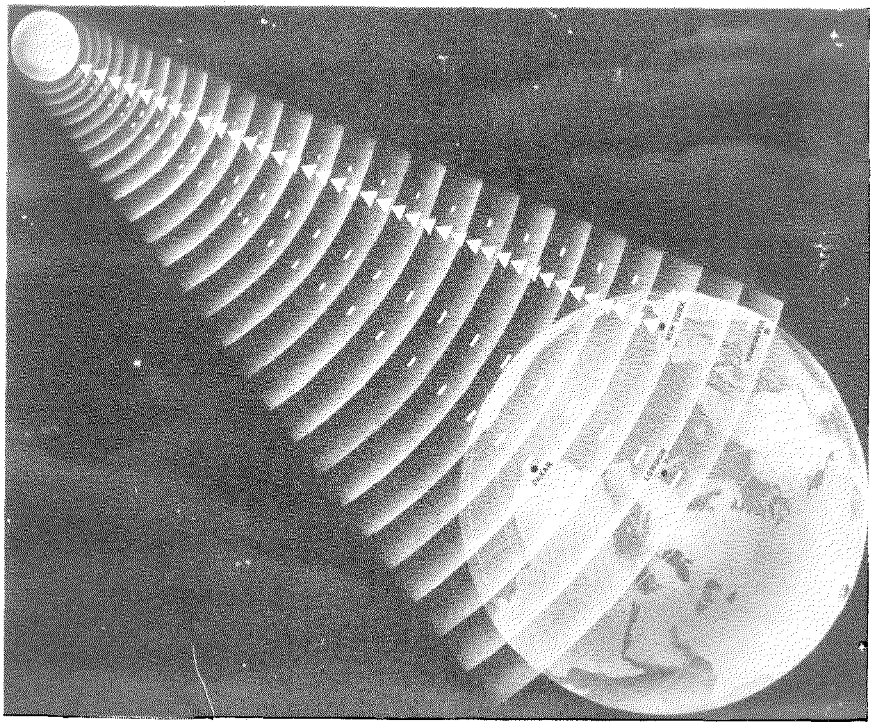
Telephone systems have attained a perfection and a complexity that is awe inspiring. The radio engineer must engineer the radio system to have the same reliability and to accept any of the complex systems of dialing, signaling, supervision, etc., which are in common use in the telephone plant.

Considerations of Moon Relay Communications

By D. D. GRIEG, S. METZGER, and R. WAER

The moon offers possibilities as a passive repeater for radio links. Such a system requires the evaluation of various phenomena, which are of no importance in conventional radio communication systems. One such phenomenon is the Doppler shift in the frequency of the received signal as a result of the relative motion of the earth and the moon. Another is possible interference by electromagnetic disturbances from the sun or other astral bodies, i.e., cosmic noise. It must also be remembered that contact can be established only while the moon is visible at both the transmitting and receiving points.

As the exact nature of the radio reflecting properties of the surface of the moon is not known, calculations have been made for two extreme cases. The first assumes the moon to be perfectly smooth, while the second assumes the moon to be a perfectly diffuse reflector. The first assumption indicates that signals of all types, including telegraph, speech, and even color television, would be reflected without distortion. On the other hand, the second assumption leads to the conclusion that the distortions are such that the transmission of telegraph or teletype signals is practicable, narrow-band speech is possible, but the transmission of television signals is doubtful.



Hemispheric broadcasting, utilizing the reflecting properties of the moon, offers interesting possibilities. Radio transmissions beamed at the moon are reflected back to earth and irradiate all points on earth facing the moon.

The conclusions from either assumption indicate that the transmitting power required for communication by telegraph, teletype, or speech, is available with existing equipment. However, the requirements for large antennas and facilities for continuously tracking the moon seem beyond the reach of a home receiver for this purpose, so that for the time being moon-reflected signals would have to be utilized by rebroadcasting.

The meager information available from the United States Signal Corps moon radar experiments indicates that the amplitude of successive echoes varies widely. An attempt has been made to explain this phenomenon by assuming the surface of the moon to be diffuse, but with a number of smooth spots, each not necessarily more than two or three miles in diameter. The echoes from smooth spots of this size have been shown to be alike and about the same as that from the whole diffuse moon. The echoes resulting from a surface of the type assumed thus could interfere with each other in such a manner as to add to one pulse and cancel a pulse sent several seconds later. Calculations indicate that two such spots located most anywhere on the moon would produce the results observed in the moon radar experiments.

Power Loads at Very- and Ultra-High Frequencies

By A. G. KANDOIAN and R. A. FELSENHELD

The design of satisfactory loads to handle and measure large amounts of power at very- and ultra-high frequencies has always been an annoying, though not necessarily a difficult, problem. There are a variety of possible solutions but each has its own particular defects. Some have poor impedance characteristics and are nonlinear, some cannot stand large voltage or heat gradients, some are very difficult to calibrate accurately, and others dissipate an appreciable portion of the power in electromagnetic radiation. Nearly all are difficult to cool if large powers are involved.

To overcome some of these defects, a study has been made of several new designs, which appear to have definite advantages over existing units.

Transmission-Line Load

The first of these is a transmission-line type of load. It is made up of a length of coaxial line using water as dielectric between the center and the outer conductor. The water is circulated to provide necessary cooling. Because of the high dielectric constant of water, approximately 80, it is not convenient to obtain a desired surge impedance in the neighborhood of 50 ohms. A surge impedance of 20 ohms, however, is easily feasible with a nominal-sized outer conductor. As a result of high dielectric constant and high propagation loss in water, an equivalent infinite line is easily obtained with a total length in air no greater than one wavelength. Transformation from 20 to 50 ohms is readily accomplished by one or more quarter-wave transformers.

In practice, such a load has been used for average powers of the order of a kilowatt and peak powers of several hundred kilowatts in the neighborhood of 500 to 1000 megacycles. It is adaptable to both lower and higher frequencies, and for higher average power.

Radiator-Type Load

Another load, which has proved useful and very convenient, is of the radiator type. The radiator or antenna is totally enclosed in a tank of water. Again, as a result of the high dielectric constant and high losses, the radiated electromagnetic energy is converted to heat in the water, which may be circulated for cooling purposes. The amount of power is easily calculated from the rate of flow and the difference in temperature between input and output water.

In practice, such a load has been used for average powers of the order of one kilowatt and peak powers of several hundred kilowatts. It is, however, not quite as satisfactory from a peak-power standpoint as the transmission type of load.

Resonant-Cavity Type of Load

A third type of load is the resonant-cavity type. It is well known that one may couple into a tuned cavity so that the input impedance will be any desired value, a particular example being a 50-ohm pure resistance. If the Q of the cavity is very high, the 50-ohm relationship will hold over a very narrow frequency range. Under these conditions, any amount of power transmitted to this load will be dissipated in the ohmic loss within the cavity. Because of the high Q of the cavity, very large circulating currents will be set up along with extremely high voltages in the current-minimum region.

When such a cavity is specifically designed as a load, however, the Q is deliberately made low. By using a quarter-wave coaxial resonant circuit and Kovar tubing for the inner conductor, Q's of the order of 30 may be obtained. The coupling consists of a direct tap into the center conductor near the current-maximum point.

Cooling is obtained by circulating water through the Kovar tubing which forms the center conductor, where the dissipation is concentrated.

A load of the resonant-cavity type has been used for testing frequency-modulated broadcast transmitters. Average powers of the order of 10 kilowatts have been handled and such a design for 50 kilowatts appears feasible.

Ultra-High-Frequency Multiplex Broadcasting System

By A. G. KANDOIAN and A. M. LEVINE

Because of the apparent need in the near future for a supplement to amplitude- and frequency-modulation broadcasting, time-division multiplexing and pulse-time modulation has been developed. This ultra-high-frequency system may be used for high-fidelity low-noise broadcasting for educational and other purposes.

Pulse-time modulation was chosen because of the many advantages it offers at ultra-high frequencies over other systems in size, simplicity of equipment, economy of power, high-quality low-noise reception, and improved stability. High transmitting efficiency is obtained with pulse-time modulation because the signal is converted to a sequence of pulses of very short time duration. The transmitter is, therefore, inoperative most of the time and a very low average power produces high peak powers when the transmitter is keyed. A further improvement is realized by the use of a high-gain omnidirectional transmitting antenna, which concentrates the power radiated vertically in a thin fan-shaped beam extending to the horizon.

At ultra-high frequencies, coverage area is limited approximately to line-of-sight distances. Maximum coverage for the service area is assured by centrally locating the transmitter at the highest elevation possible.

As all programs originate from the same transmitter, a highly directive receiving antenna is utilized which is permanently focussed on the transmitter. This feature reduces interference from near-by buildings or other fixed objects.

The receiver itself is fixed tuned to one transmission frequency, eliminating the cost of complex ganged tuning controls. Program selection may be accomplished by push-button selection of simple timing circuits. This makes the problems of oscillator drift and warm-up period unimportant.

The particular pulse-time modulation system that has been developed simultaneously transmits eight programs of 9500 cycles each over a single radio-frequency carrier of 930 megacycles.

The eight programs pass through control panels to the time-modulation mixer. Here the audio-frequencies are converted to 0.5-microsecond pulses at a base repetition rate of 24,000 per second. The various channels are then mixed and a marker added. The video-frequency output consists of a series of pulses having a bandwidth of 3 megacycles. A 70-ohm coaxial cable transmits the pulses to the modulator.

The receiving system consists of a directional antenna, a fixed-tuned radio-frequency section, and a pulse-time demodulator. The radio-frequency section includes a local oscillator, crystal mixer, and a 30-megacycle intermediate-frequency preamplifier. The pulse-time demodulator includes final intermediate-frequency amplification, video-frequency detection and tuning, and audio-frequency detection and amplification.

New home of the Institute of Radio Engineers on Fifth Avenue in New York City. Built about 1880, this replica of a portion of Chemonceaux, a famous French chateau, was one of the prominent mansions in an era of elegance. Funds for the purchase, refurbishing, and furnishing of the building were contributed by Institute members and the radio industry.

Broad-Band Very-High-Frequency Amplifiers

By A. M. LEVINE and M. G. HOLLABAUGH

The present trend in ultra-high-frequency receivers is toward use of increasingly higher intermediate frequencies. Broad-band amplifiers are being constructed for operation in the upper part of the very-high-frequency range. This is a region of transition from lumped to distributed circuit parameters, where tube damping, undesired feedback, and related effects assume important magnitudes. These effects, in fact, exercise a controlling influence in many designs.

Calculations for input damping, instability caused by feedback, and similar factors have been made. Calculated and measured values are given for various tube types and for frequencies between 30 and 300 megacycles.

Graphed values of effective input resistance were found to follow the customary frequency-squared approximation in the lower very-high-frequency region. For higher frequencies, smaller resistances were observed. For design purposes, $f^{2.5}$ lines have been found to be sufficiently accurate with three common tube types, 6AG5, 6AH6, and 6AK5.

The tube damping values were taken for amplifier stages where short cathode leads were used but without other means of input-admittance compensation. The input resistances determined under this condition were considerably smaller than those measured by a Q-meter with all electrodes except the grid at ground potential. For example, the Q-meter input resistance of a 6AK5 at 100 megacycles was in the 15,000-ohm region, whereas the resistance obtained from the same tube in the amplifier stage was in the vicinity of 5000 ohms.

It was shown that tube damping limits the minimum bandwidth obtainable, unless special precautions are taken to eliminate the effect. This minimum bandwidth may be expressed by equations or curves.

Tube damping must also be considered in connection with the choice of interstage coupling. The more complex interstage networks, i.e., those designed for greater gain and bandwidth capabilities, require higher termination or damping resistances and this may easily be in excess of the tube damping resistance present.

It is generally recognized that at high frequencies it is difficult to obtain large stable gains when the bandwidth is very small relative to the carrier frequency. Intermediate-frequency amplifiers for various frequency-modulation receivers often present this problem. It is shown that capacitive coupling caused by the grid-to-plate capacitance in amplifier tubes is sufficient to give rise to instability in amplifiers in the very-high-frequency region. A limit to the minimum bandwidth obtainable with a given gain is determined as a function of the grid-plate capacitance of the amplifier tube. Or conversely, a limit to the maximum gain obtainable with a given bandwidth exists as a function of the grid-plate capacitance. A 100-megacycle amplifier, using four stages of 6AK5's, will be unstable if the bandwidth is less than approximately 2 megacycles, assuming that the gain is not intentionally reduced or that some form of neutralization is not used.

Compensation of Phase Shift at Low Frequencies

By F. McGEE

The formerly unimportant low-frequency phase shift has recently come into the position of a first-rate problem. Terman, Hewlett, Palmer, and Pan,[1] and Sturley[2] have analyzed the resistance-capacitance amplifier and presented formulas and graphs representing low-frequency phase shifts in terms of circuit elements and tube constants. These relationships may be presented in somewhat more practical form for design purposes. A new method of phase compensation, which allows for the simultaneous correction of phase errors in cathode, screen, and coupling networks, is discussed.

The basic circuit equations

$$\left.\begin{aligned} i_p &= g_m e_g + g_s e_s \\ i_s &= G_m e_g + G_s e_s \\ e_g &= e - e_k \\ e_s &= -i_s Z_s - e_k \\ e_k &= (i_p + i_s) Z_k \end{aligned}\right\} \quad (1)$$

in which:

i_p = plate alternating current
i_s = screen alternating current
e_g = grid-to-cathode alternating voltage
e_k = cathode-to-ground alternating voltage
e = grid-to-ground alternating voltage
Z_s = screen-to-ground alternating-current impedance
Z_k = cathode-to-ground alternating-current impedance
g_m = grid-to-plate transconductance
G_m = grid-to-screen transconductance
g_s = screen-to-plate transconductance
G_s = screen-to-screen conductance (reciprocal of the dynamic screen resistance r_s)

are solved simultaneously by means of fifth-order determination yielding:

$$i_p = \frac{g_m e}{1 + G_s Z_s + G_k Z_k}, \quad (2)$$

in which for simplicity

$$G_k = g_m + g_s + G_m + G_s. \quad (3)$$

Assume for the moment that the screen impedance to ground is zero. By algebraic manipulation, the approximate formula

$$C_k = \frac{9 G_k}{\phi_k f} \quad (4)$$

where ϕ_k is the phase shift in the cathode circuit at the frequency f caused by the capacitor C_k providing the phase shift is less than 10 degrees, and G_k and R_k have normal values. Then assuming that the cathode phase shift is negligible and using similar manipulation and conditions,

$$C_s = \frac{9}{\phi_s f r_s}, \quad (5)$$

where ϕ_s is the phase shift caused by the screen by-pass capacitor C_s at the frequency f when the dynamic screen resistance is r_s. It is then shown that under the condition named, the total phase shift, when both cathode and screen contribute, is the sum of ϕ_k and ϕ_s as given by these two

[1] F. E. Terman, W. R. Hewlett, C. W. Palmer and W. Y. Pan, "Calculation and Design of Resistance-Coupled Amplifiers Using Pentode Tubes," *Transactions of the A.I.E.E.*, v. 59, p. 879; 1946.

[2] K. R. Sturley, "Low Frequency Amplification," *Electronic Engineering*, November and December, 1944; and January, February, March, April, and May, 1945.

formulas. It is observed that any phase shift resulting from the impedance in the plate circuit adds to the phase error in the current as does that caused by a coupling network. Under video-frequency conditions, the phase shift resulting from plate decoupling is derived and, by algebraic manipulation, is put in the form

$$C_p = -\frac{9}{\phi_p f R_L}, \tag{6}$$

where the phase shift ϕ_p is caused by the decoupling capacitor C_p at the frequency f, and R_L is the plate load resistor. Again ϕ_p must be less than 10 degrees and R_L must be at least equal to the decoupling resistor. The phase shift in the coupling network is derived and put in the form

$$C_c = \frac{9}{\phi_c f R_c}, \tag{7}$$

where the capacitor C_c causes the phase error ϕ_c at the frequency f. R_c is the output resistor and is assumed large with respect to the impedance in the preceding plate circuit.

It is observed that if all conditions are met simultaneously, the total phase shift ϕ_T is

$$\phi_T = \frac{9}{f}\left(\frac{G_K}{C_k} + \frac{1}{C_s r_s} + \frac{1}{C_c R_c} - \frac{1}{C_p R_L}\right). \tag{8}$$

It is, therefore, possible to obtain zero phase shift over the stage by making

$$\frac{G_k}{C_k} + \frac{1}{C_s r_s} + \frac{1}{C_c R_c} = \frac{1}{C_p R_L}. \tag{9}$$

Noise-Suppression Characteristics of Pulse Modulation

By S. MOSKOWITZ and D. D. GRIEG

The utilization of pulses for the multiplexing of communication channels has received considerable attention during the past few years. In an analogous manner to the well-known frequency or phase modulation of continuous waves, pulse-time modulation offers an improvement in signal-to-noise ratio over that obtained by the common amplitude modulation of either continuous or pulsed waves. It is shown that the improvement is proportional to the radio-frequence bandwidth used in the transmission link. In terms of the pulses, the improvement is proportional to the time-modulation displacement and inversely proportional to the build-up or decay time, whichever is the smaller.

An important measure of protection against noise interference offered by time-modulated pulses results from the high ratio of peak-to-average power used. The threshold of improvement is reached when the peak pulse amplitude is about twice the effective noise peaks. Hence, devices such as limiters may be used to considerable advantage. Experiments have been made and the results are given illustrating the outlined theory. The effectiveness of various noise-suppression devices such as limiters, differentiators, and multivibrators is demonstrated by experimental data.

The greatest degree of noise suppression is obtained when successive stages of limiting and differentiation are incorporated in the receiver. This result may be understood by considering the following manners in which noise can enter the pulse system:

A. Amplitude modulation of the pulses.
B. Width modulation of the pulses.
C. Noise occurrence between pulses.
D. Displacement in time of the leading or trailing edge of the pulses.

Noise entering by amplitude modulation of the pulses and between the pulses may be removed by proper limiting providing the input signal-to-noise ratio is greater than 6 decibels. Following this stage, a differentiator serves to extract the proper pulse edge thus removing width-modulation noise. However, as some edge-slope variation may be introduced by noise, the output of the differentiator may again contain some amplitude and width noise. Such secondary noise modulations may be further suppressed by successive stages of limiting and differentiation. The operations may also be obtained by the action of a multivibrator.

Noise entering by displacement in time of the leading or trailing edge of the pulse is of the same form as the modulating signal and is inherent in the system of modulation. However, the noise displacement may be reduced by decreasing the build-up or decay time of the pulses, i.e., increasing the bandwidth of the system.

In a similar manner, impulse noise, such as that derived from electrical machinery, automobile ignition, and interfering pulse communication systems, may be suppressed. The degree of suppression is usually greater than that obtained with random noise.

Video-Frequency Negative-Feedback Amplifiers

By M. G. HOLLABAUGH, J. A. RADO, and A. M. LEVINE

Video-frequency amplifiers having bandwidths of four or five megacycles may be readily designed using well-known methods such as shunt, series, or series-shunt peaking to achieve a uniform gain over the required frequency band. These techniques have been developed largely empirically and are adequate for relatively narrow bands and low gains. Design alignment is simple and the technique is widely known.

In color-television and pulse-modulation systems, the need for much wider bands in the range from 10 to 50 megacycles is encountered and it is necessary to exploit as fully as possible the capabilities of components to realize a practical result. Almost ten years ago, H. A. Wheeler foresaw this need.[1] His paper set down the fundamental relation that the gain-bandwidth product equals the transconductance over the geometric mean of the input and output capacitances. Filter theory was applied to the problem of interstage coupling of wide-band amplifiers and resulted in the realization of as high as 95 percent of the above criterion in practical amplifiers.

The complexity of design and manipulation of these high-performance filters, each of which may require adjustment of five or six interdependent parameters, led to the consideration of a simpler means of attaining equivalent performance, that of inverse feed-back. Wheeler proposed the use of inverse feed-back but the development and use of it was largely limited to band-pass or intermediate-frequency amplifiers and was shrouded by wartime security regulations.

Simplicity is the most important advantage to be gained in using feedback and the advantage increases with the number of amplifier stages for two reasons. First, adjustments need be made only on the terminating filter of the whole amplifier instead of on each interstage coupling filter because the interstage coupling consists of only a feedback resistor. Second, the performance of a feedback amplifier approaches more closely the theoretical criterion as the number of stages is increased. Other advantages arise out of the use of feedback, such as the reduction of distortion resulting from nonlinearity.

Analysis of the generalized feedback amplifier reveals its similarity to a transmission line or ladder network. In fact, it is a ladder network with negative-conductance shunt arms. This is the function of the amplifier transconductance which is a negative quantity. A mathematical analysis has been based on this assumption. The solution for stage gain established the fact that these amplifiers have a gain-bandwidth capability equal to that of an ideal amplifier. In actual amplifiers, the ideal has been approached very closely.

Using 6AK5 tubes, amplifiers have been constructed having video-frequency bandwidths of 13 megacycles and 20 megacycles. In these amplifiers, simple terminations were used consisting of the characteristic resistance of the network in series with a peaking inductor.

A means has been developed for correcting the low-frequency response of the amplifier resulting from the practical limitation on the size of the interstage coupling capacitor. As this requires the introduction of shunt resistance, an examination was made of the effect of shunt dissipation. It was proved that shunt resistance may be reduced to a value as low as that of the feedback resistance, at which point for equal bandwidth the gain per stage is reduced by ½ decibel. Larger values have negligible effect.

[1] H. A. Wheeler, "Wide-Band Amplifiers for Television," *Proceedings of the I.R.E.*, v. 27, pp. 429–437; July, 1939.

Ideally, it has been pointed out that the feedback path should be unidirectional in the backward direction just as G_m is unidirectional in the forward direction. Actually, if the network is properly terminated, this is unimportant as the mathematical analysis shows the backward traveling wave is negligible and decreases.

Circularly Polarized Antennas

By W. SICHAK and S. MILAZZO

A formula is derived which gives the variation in received voltage as an elliptically polarized antenna is rotated in a plane transverse to the direction of propagation of an incident elliptically polarized wave. It is shown that a circularly polarized antenna will not receive any reflected energy from a smooth metallic reflector while an elliptically polarized antenna will receive some energy, the magnitude of which depends on the ratio of the axes of the polarization ellipse. If circular polarization is used for communication, both the transmitting and receiving antennas must produce the same screw sense of polarization, otherwise no signal will be received. If the antennas are elliptically polarized, some signal will always be obtained. Some methods for obtaining circular polarization are discussed. For the case of a horizontal loop and vertical dipole, the currents in the loop and dipole must be in phase to get circular polarization. Experimental results are given to confirm the theory.

Monitoring Equipment for Frequency-Modulation Broadcasting

By M. SILVER

This paper deals with the design of monitoring equipment for frequency-modulation broadcasting and in the measurements required to prove performance.

Briefly, the equipment operates as follows: A portion of the transmitter output is mixed with a crystal standard so that the difference frequency is 150 kilocycles. This voltage is applied to a counter-type discriminator which is used both to measure the line transmitter frequency and monitor its audio-frequency output. The required linearity for this application is extremely high and in the case of this equipment it is 0.02 percent. The output of the counter discriminator is filtered and then applied to an audio-frequency amplifier for acoustic monitoring and measurement purposes. In addition, the discriminator feeds a suitable vacuum-tube voltmeter for percentage-modulation measurements and a thyratron flasher circuit for overmodulation indication.

The equipment is capable of meeting the requirements of the Federal Communications Commission and surpasses them in many aspects. The monitor is capable of measuring noise to -80 decibels and distortion of 0.2 percent. Station carrier frequency can be measured to an accuracy of ± 100 cycles under full-modulation conditions with a long-time stability of one part in 5×10^5.

Recent Telecommunication Developments

McVey Awarded Kernot Medal—Daniel McVey, Chairman of the Board and Managing Director of Standard Telephones and Cables Pty Ltd., has been awarded the Kernot Memorial Medal.

This medal was established to perpetuate the memory of William Charles Kernot, the first professor of engineering at the University of Melbourne. It is awarded

> For distinguished engineering achievement in Australia and for that achievement which is placed first in order of merit by the Assessors.

The three assessors, who are appointed by the council of the university, were unanimous in designating Mr. McVey as the recipient of the medal.

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Etchings of Heinrich Hertz—Starting in 1935, a series of etchings of men famous in the telecommunication field has been issued by Bureau de l'Union Internationale des Télécommunications, Effingerstrasse 1, Berne, Switzerland. Recently added to the series is an etching of Heinrich Hertz. Reproduced on luxury paper, each portrait measures 23 by 17 centimeters (9 by $6\frac{5}{8}$ inches) including margins. Copies of etchings of Hertz, Morse, Hughes, Bell, Marconi, Baudot, Gauss and Weber, Maxwell, Ferrié, Siemens, Popov, and Ampere may be obtained for 3 Swiss francs each, including carriage and packing. Hertz is credited with having discovered the wave character of electrical transmission through space and through wires. His work on wave propagation paved the way for the development of wireless telegraphy. Always an exacting scientist, Hertz demonstrated his principles with carefully worked out experiments. These demonstrations proved that electromagnetic waves, or Hertzian waves as they became known, could not only be transmitted through space, but could be reflected, absorbed, polarized, and made to perform in other ways similar to light waves.

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Miniature Thermal Delay Switch—Standard Telephones and Cables (London) has developed a delay switch of the thermal type which has been coded ULS631. It may be used to control the time between applying heater voltage and anode voltage in indirectly heated vacuum tubes or gas-filled rectifiers. The elements are mounted in an evacuated glass envelope having a seated height of $1\frac{3}{4}$ inches and a diameter of $\frac{3}{4}$ inch. Its ratings are as indicated in the table below.

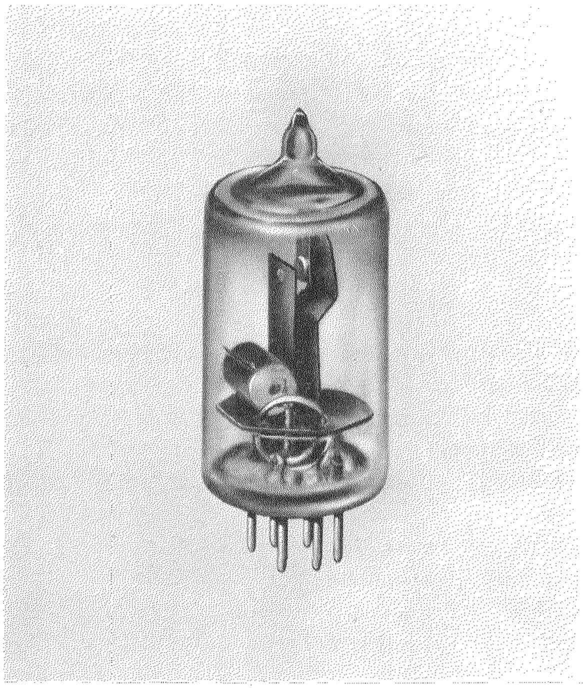

Table of Characteristics

Heater, Volts	6.3
Nominal Heater Current, Amperes	0.5
Nominal Delay at 20 Degrees Centigrade, Seconds	50–60
Ambient Temperature Range, Degrees Centigrade	−350 to +85
Maximum Open-Circuit Voltage Between Contacts, Direct Volts	220
Maximum Contact Current on Make, Amperes	1.0
Maximum Surge Current on Make, Amperes	5.0
Maximum Contact Current on Break, Milliamperes at 50 Direct Volts	100

Contributors to This Issue

TREVOR H. CLARK

TREVOR H. CLARK was born in Kansas on July 16, 1909. He received a B.S. degree in physics and mathematics from Friends University in Wichita, Kansas, in 1930, and an M.S. degree in physics from the University of Michigan in 1933. He was associated with the R.C.A. Manufacturing Corporation until 1938, when he joined the research laboratories of International Telephone and Telegraph Corporation.

Until 1940, he was engaged in research on vacuum tubes in the Paris laboratories of the I.T.&T. System. He returned to the United States in 1941, after a survey trip in Portugal and Portuguese West Africa, and assisted in the organization of the New York laboratories, which later became Federal Telecommunication Laboratories. During the war, he conducted research in direction finding, primarily for the United States Navy. In 1945, he began work with pulse-time-modulation relay systems. He has recently been appointed Manager of Technical Services of Federal Telecommunication Laboratories, Inc.

Mr. Clark is a Senior Member of the Institute of Radio Engineers, and a member of the Acoustical Society of America.

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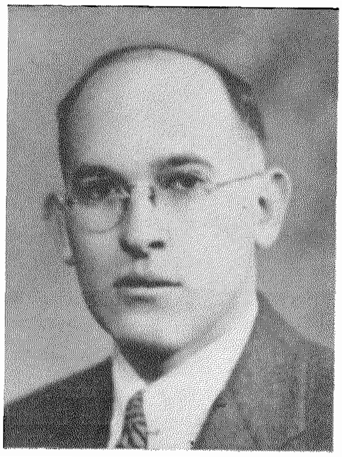
A. G. CLAVIER was born in Cambrai, France, in 1894. He received a degree in electrical engineering from Ecole Supérieure d'Electricité in 1919 and then joined the staff of engineers organized by General Ferrié at the Etablissement Central de la Radiotélégraphie Militaire. He was in charge of research on high frequencies from 1920 to 1925.

In 1929, Mr. Clavier joined Les Laboratoires Standards in Paris which later became Laboratoire Central de Télécommunications, and has been continuously engaged in research on centimeter and millimeter waves. He was in charge of the experiments which, in 1930, resulted in 17-centimeter-wave transmission across the English Channel and of the developments for the Lympne-St. Inglevert microwave radiotelephone link, which was inaugurated commercially in 1934. He was assistant director of research in 1945, when he was transferred to Federal Telecommunication Laboratories in New York, where he now holds the same position.

He has published extensively on high-frequency oscillators, wave guides, and general electromagnetic theory, and has taught field theory and applications of ultra-high frequencies at the Ecole Supérieure d'Electricité.

A. G. CLAVIER



ROBERT I. COLIN

Mr. Clavier is president of the section of the Société des Radioélectriciens dealing with hyperfrequencies. He is a Fellow of the Institute of Radio Engineers, and a Member of the Institution of Electrical Engineers.

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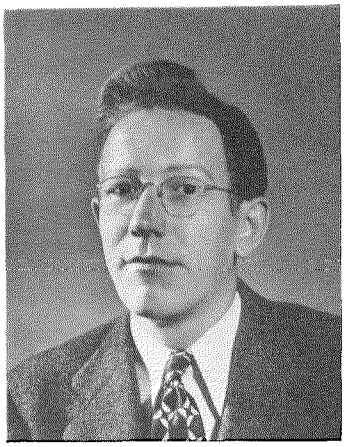
ROBERT I. COLIN was born in Brooklyn, New York, on Feb. 16, 1907. He attended Cornell University as a student in engineering and physics under two New York State scholarships. During his senior year he was on the physics staff as an undergraduate assistant. He received the A.B. degree in 1928, and was elected to the honorary scholastic society Phi Kappa Phi.

The next year, under an exchange fellowship of the Institute of International Education, he attended the University of Frankfurt A/M, Germany, majoring in physics; and visited many European countries. From 1929 to 1933, he was a graduate assistant on the physics staff of New York University, teaching and taking graduate courses. He left with an M.S. degree after doing an experimental thesis in the field of electron-optics. From 1934 to 1939, he was instructor in physics and related subjects at the Hebrew Technical Institute. From 1941 to 1944



P. I. CORBELL, JR.

he was instructor, then head, of the Aircraft Electrical Systems Branch of the Army Air Forces Technical School, first at Chanute Field, Illinois, and then at Yale University.

Mr. Colin entered the Federal Telecommunication Laboratories in September, 1944, as a technical writer, then senior engineer, where he did technical studies, wrote proposals, and shared in the development of a number of proposals in the field of radio air navigational aids, especially for long distances, including the "Navaglobe" system.

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P. I. CORBELL, JR. was born at Napa, California, in 1919. He received a B.S. degree in electrical engineering from the University of California in 1943. During his attendance there, he was employed by Pacific Gas and Electric Company, San Francisco, as an engineering assistant.

In 1943, he joined the vacuum-tube department of Federal Telephone and Radio Corporation, where he was engaged in transmitting-tube development. Since November, 1946, he has been with Litton Engineering Laboratories, Redwood City, California, working on the development of continuous-wave magnetrons.

SIDNEY FRANKEL

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SIDNEY FRANKEL was born on October 6, 1910 in New York City. Rensselaer Polytechnic Institute conferred three degrees on him: the B.A. degree in electrical engineering in 1931, and in mathematics the M.A. degree in 1934 and the Ph.D. degree in 1936. He was an instructor in mathematics from 1931 to 1933.

For a year after leaving college, Dr. Frankel served as a sound-recording engineer with the Brooklyn Vitaphone Corporation. In 1937–1938, he was an assistant engineer in the design and development of electronic flight instruments for the Eclipse Aviation Corporation.

He joined the Federal Telegraph Company staff at Newark, New Jersey, in 1938 as an engineer on the design and development of radio transmitters. In 1943, he was transferred to Federal Telephone and Radio Laboratories, now Federal Telecommunication Laboratories. At present he is engaged in the development of components for microwave systems.

He is a member of Sigma Xi and a Senior Member of the Institute of Radio Engineers.

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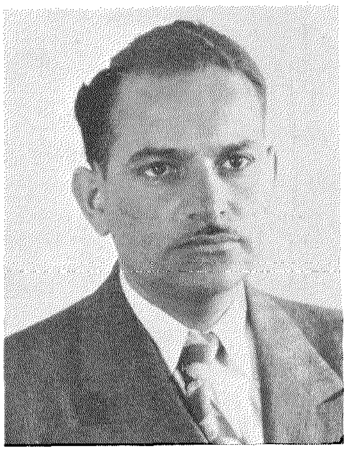

HARRIS GALLAY

HARRIS GALLAY was born in New York City on July 28, 1908. He received his B.S. degree from the College of the City of New York in 1931. From 1935 to 1943, he was associated with the U. S. Army Signal Corps, as a civilian radio engineer in the development and design of instrument landing and airborne radio compass equipment, and in aircraft radio maintenance and repair facilities.

He joined the engineering staff of Federal Telecommunication Laboratories in 1943, and is now engaged in supervising microwave communication and control-equipment projects utilizing pulse-time modulation.

Mr. Gallay holds an Associate membership in the Institute of Radio Engineers.

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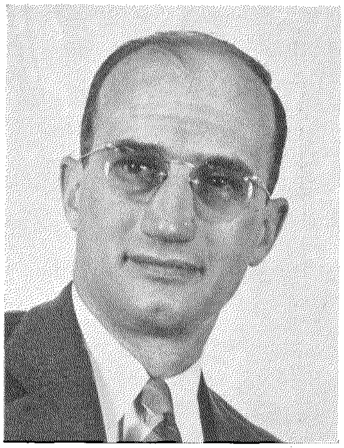
JOHN J. GLAUBER was born in New York, New York, on July 31, 1903. He received the M.E. degree from Stevens Institute of Technology in 1925.

In 1925, he obtained a position with the U.S. Tool Company in Ampere, New Jersey, on variable-capacitor design. In 1927, he joined the Arcturus Radio Tube Company, Newark, New Jersey, as laboratory assistant and was chief engineer from 1933 to 1936. He then joined the Westinghouse Lamp



JOHN J. GLAUBER

George H. Gray

Company, Bloomfield, New Jersey, as a vacuum-tube development engineer and in 1939 became development engineer for the National Union Radio Corporation, Newark, N. J. He was employed by the Clark Controller Company, Cleveland, Ohio as development engineer on special gas-filled control tubes, and by the Champion Radio Works, Danvers, Massachusetts, as quality engineer.

He joined the vacuum-tube department of Federal Telecommunication Laboratories, New York, in 1941, becoming department head in charge of the design and development of tubes. In 1947, Mr. Glauber joined the engineering staff of United Electronics Corporation of Newark, New Jersey.

Mr. Glauber is a Senior Member of the Institute of Radio Engineers.

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D. D. Grieg

George H. Gray was born in Arlington, Massachusetts, on October 8, 1885. He received an S.B. degree from Massachusetts Institute of Technology in 1909 and an E.E. degree from the University of Wisconsin in 1916.

He served as an instructor at Massachusetts Institute of Technology from 1909 to 1910. After two years with the Telluride Power Company, he spent a year with the Western Electric Company. From 1913 to 1917, he instructed in electrical engineering at the University of Wisconsin. He then went to the Northwestern Bell Telephone Company for nine years.

In 1926, Mr. Gray joined the International Telephone and Telegraph System where he served with the parent corporation and International Standard Electric Corporation except for one year (1940–1941) with the U. S. Signal Corps.

He is a Member of the American Institute of Electrical Engineers.

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D. D. Grieg was born on February 26, 1915 in London, England. He received his early schooling in England and the B.S. degree in electrical engineering from the College of the City of New York.

From 1936 to 1940, he was in charge of the television department of the Davega Radio Company. In early 1941 he taught radio communication in the Brooklyn Technical High School. Since 1941, he has been a research engineer for Federal Telecommunication Laboratories. He is now a Division Head and has charge of the Television and Communication Departments.

Mr. Grieg is a Senior Member of the Institute of Radio Engineers and a Member of the American Institute of Electrical Engineers. He has served on several technical committees including the Television Committee of the Radio Technical Planning Board and those on Television Relays and Studio-Transmitter Links of the Radio Manufacturers Association. He is the author of several technical papers and holds many patents in the field of radio.

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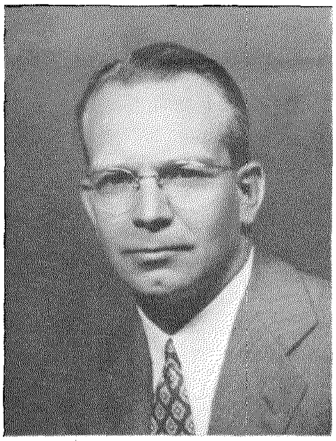

Ross B. Hoffman

Ross B. Hoffman was born in St. Louis, Missouri, on September 30, 1907. He received the B.S. degree in electrical engineering from the University of Illinois in 1929, and joined the I.T. & T. system on graduation. He spent five years in Buenos Aires on installation and operation engineering of transatlantic radiotelephone and radiotelegraph equipment for the Compañía Internacional de Radio Argentina. From 1935 to 1938, he was a development engineer in the Les Laboratoires, Le Matériel Téléphonique in Paris, France.

After returning to the United States in 1938, he was associated with International Telephone Development Corporation and Federal Telegraph Company on the development of instrument landing systems until January 1941, when he was transferred to the new Federal Telephone and Radio Laboratories in New York.

August F. Jones

Emile Labin

Late in 1943, he transferred to the Federal Telephone and Radio Corporation in Newark, and since that time has been engaged in development and product engineering in connection with aerial navigation and, more recently, on equipment for mobile communication.

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August F. Jones received a B.S. degree from Denison University in 1922 and an E.E. degree from Cornell University in 1925.

He was then employed by the International Telephone and Telegraph Corporation as a student engineer. After a year in the equipment engineering department of the Cuban Telephone Company, he was transferred to Spain to organize a commercial department in the northwest district of the Spanish National Telephone Company. In 1928, he returned to New York where he spent three years in the engineering department, after which he was transferred to the manufacturing division of the company. He was assigned to the Madrid factory in 1933, and was made chief engineer in 1939. In 1942, he returned to the U.S.A. and is at present in the telephone engineering department of Federal Telephone and Radio Corporation.

Elliott W. Markow

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Emile Labin was born on December 1, 1907 in Bucharest, Rumania. He graduated from Ecole Polytechnique in Paris in 1930.

On finishing school, he become associated with Television Baird-Natan, the Paris associate of Baird Television Ltd. of England. In 1932, he became a television research engineer for Compagnie de Compteurs. He joined the engineering staff of Le Matériel Téléphonique in 1935, where he developed the Eiffel Tower television station, then the most powerful in the world, in addition to work on transmitters, vacuum tubes, and radar.

Ernest S. McLarn

In 1940, Mr. Labin was transferred to the U.S.A. to take charge of the division which later became Federal Telecommunication Laboratories.

He is the author of numerous papers on television and radio published in both French and U.S.A. technical journals. Mr. Labin is a Senior Member of the Institute of Radio Engineers.

After the war, Mr. Labin was appointed techinal director of International Telecommunication Laboratories in charge of coordination of research and development activities of I.T.&T. System Associated Companies.

Georges Phelizon

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Elliott W. Markow was born in St. Louis, Missouri, on April 2, 1921. He obtained a B.S. degree in electrical engineering from Purdue University in 1942. Directly after graduation he joined Federal Telephone and Radio Corporation.

He worked on production and development of various types of military equipment during the war years. His present activities are in the application of mobile equipment to radiotelephone services.

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Ernest S. McLarn was born in Oakdale, Pennsylvania, on November 30, 1881. He received a B.S. degree in

Joel P. Wallenstein

electrical engineering from Pennsylvania State College in 1903.

He joined the Western Electric Company in 1903 and, in 1920, was assigned to the International Western Electric Company. He became a member of the International Telephone and Telegraph Corporation engineering department when, in 1925, it purchased the International Western Electric Company. Since that time he has continued in engineering work.

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GEORGES PHELIZON was born in Paris on October 22, 1920. He graduated in 1938 from Ecole d'Electricité et Mecanique Industrielles de Paris, and from Ecole Supérieure d'Electricité in 1941.

He joined Laboratoire Central de Télécommunications in 1942 and has worked since then on circuit design in the microwave research department.

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JOEL P. WALLENSTEIN was born on October 11, 1922, in Elizabeth, New Jersey. He received the B.S. degree in electrical engineering from the Newark College of Engineering in 1942. He then joined the Federal Telephone and Radio Corporation, Newark, New Jersey as a vacuum-tube engineer engaged in the development of high-power tubes. Since September, 1946, he has been engaged in the engineering consulting field.

Mr. Wallenstein is an Associate of the Institute of Radio Engineers and American Institute of Electrical Engineers, and a member of Tau Beta Pi.

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For a biography and photograph of V. Belevitch, see Volume 24, Number 1, page 125.

INTERNATIONAL TELEPHONE AND TELEGRAPH CORPORATION

Associate Manufacturing and Sales Companies

United States of America

International Standard Electric Corporation, New York, New York

Federal Telephone and Radio Corporation, Newark and Clifton, New Jersey

Great Britain and Dominions

Standard Telephones and Cables, Limited, London, England

Branch Offices: Birmingham, Leeds, Manchester, England; Glasgow, Scotland; Dublin, Ireland; Cairo, Egypt; Calcutta, India; Johannesburg, South Africa

Creed and Company, Limited, Croydon, England

International Marine Radio Company Limited, Liverpool, England

Kolster-Brandes Limited, Sidcup, England

Standard Telephones and Cables Pty. Limited, Sydney, Australia

Branch Offices: Melbourne, Australia; Wellington, New Zealand

Silovac Electrical Products Pty. Limited, Sydney, Australia

New Zealand Electric Totalisators Limited, Wellington, New Zealand

Federal Electric Manufacturing Company, Ltd., Montreal, Canada

South America

Compañía Standard Electric Argentina, Sociedad Anónima, Industrial y Comercial, Buenos Aires, Argentina

Standard Electrica, S.A., Rio de Janeiro, Brazil

Compañía Standard Electric, S.A.C., Santiago, Chile

Europe and Far East

Vereinigte Telefon- und Telegraphenfabriks Aktien-Gesellschaft Czeija, Nissl and Company, Vienna, Austria

Bell Telephone Manufacturing Company, Antwerp, Belgium

China Electric Company, Limited, Shanghai, China

Standard Electric Doms A Spolecnost, Prague, Czechoslovakia

Standard Electric Aktieselskab, Copenhagen, Denmark

Compagnie Générale de Constructions Téléphoniques, Paris, France

Le Matériel Téléphonique, Paris, France

Les Téléimprimeurs, Paris, France

Lignes Télégraphiques et Téléphoniques, Paris, France

Ferdinand Schuchhardt Berliner Fernsprech- und Telegraphenwerk Aktiengesellschaft, Berlin, Germany

Lorenz, C., A.G. and Subsidiaries, Berlin, Germany

Mix & Genest Aktiengesellschaft and Subsidiaries, Berlin, Germany

Süddeutsche Apparatefabrik Gesellschaft M.B.H., Nuremberg, Germany

Telephonfabrik Berliner A.G. and Subsidiaries, Berlin, Germany

Nederlandsche Standard Electric Maatschappij N.V., Hague, Holland

Dial Telefonkereskedelmi Részvény Társaság, Budapest, Hungary

Standard Villamossági Részvény Társaság, Budapest, Hungary

Telefongyár R.T., Budapest, Hungary

Fabbrica Apparecchiature per Comunicazioni Elettriche, Milan, Italy

Standard Elettrica Italiana, Milan, Italy

Societa Italiana Reti Telefoniche Interurbane, Milan, Italy

Nippon Electric Company, Limited, Tokyo, Japan

Sumitomo Electric Industries, Limited, Osaka, Japan

Standard Telefon- og Kabelfabrik A/S, Oslo, Norway

Standard Electric Company w. Polsce Sp. z.O.O., Warsaw, Poland

Standard Electrica, Lisbon, Portugal

Standard Fabrica de Telefoane si Radio S.A., Bucharest, Rumania

Compañía Radio Aerea Maritima Española, Madrid, Spain

Standard Eléctrica, S.A., Madrid, Spain

Aktiebolaget Standard Radiofabrik, Stockholm, Sweden

Standard Telephone et Radio S.A., Zurich, Switzerland

Jugoslavensko Standard Electric Company Akcionarno Drustvo, Belgrade, Yugoslavia

Teleoptik A.D., Belgrade, Yugoslavia

Telephone Operating Systems

Compañía Telefónica Argentina, Buenos Aires, Argentina

Compañía Telegráfico-Telefónica Comercial, Buenos Aires, Argentina

Compañía Telegráfico-Telefónica Del Plata, Buenos Aires, Argentina

Companhia Telefonica Paranaense S.A., Curitiba, Brazil

Companhia Telefonica Rio Grandense, Porto Alegre, Brazil

Compañía de Teléfonos de Chile, Santiago, Chile

Compañía Telefónica de Magallanes S.A., Punta Arenas, Chile

Cuban Telephone Company, Havana, Cuba

Cuban American Telephone and Telegraph Company, Havana, Cuba

Mexican Telephone and Telegraph Company, Mexico City, Mexico

Compañía Peruana de Teléfonos Limitada, Lima, Peru

Porto Rico Telephone Company, San Juan, Puerto Rico

Shanghai Telephone Company, Federal, Inc., U.S.A., Shanghai, China

Radiotelephone and Radiotelegraph Operating Companies

Compañía Internacional de Radio, Buenos Aires, Argentina

Compañía Internacional de Radio Boliviana, La Paz, Bolivia

Companhia Radio Internacional do Brasil, Rio de Janeiro, Brazil

Compañía Internacional de Radio, S.A., Santiago, Chile

Radio Corporation of Cuba, Havana, Cuba

Radio Corporation of Porto Rico, San Juan, Puerto Rico[1]

[1] Radiotelephone and Radio Broadcasting services.

Cable and Radiotelegraph Operating Companies

(Controlled by American Cable & Radio Corporation)

The Commercial Cable Company, New York, New York[2]

Mackay Radio and Telegraph Company, New York, New York[3]

All America Cables and Radio, Inc., New York, New York[4]

The Cuban All America Cables, Incorporated, Havana, Cuba[2]

Sociedad Anónima Radio Argentina, Buenos Aires, Argentina[5]

[2] Cable service. [3] International and Marine Radiotelegraph services.
[4] Cable and Radiotelegraph services. [5] Radiotelegraph service.

Laboratories

International Telecommunication Laboratories, Inc., New York, New York

Federal Telecommunication Laboratories, Inc., Nutley, New Jersey

Standard Telecommunication Laboratories Ltd., London, England

Laboratoire Central de Télécommunications, Paris, France