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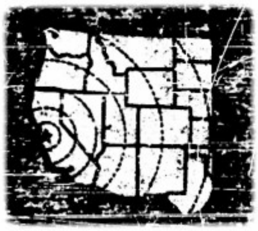
FINAL REPORT

SRI Project 882

ENGINEERING SURVEY OF U. S. NAVAL RADIO STATION (T) LUALUALEI, OAHU, T. H.

Contract No. N220s - 80776A
Req'n No. 311 - 53 - 7528/228

December 1953



STANFORD RESEARCH INSTITUTE

STANFORD, CALIFORNIA

DECEMBER 1953

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ABSTRACT

This report describes the findings of an engineering survey of the U. S. Naval Radio Station (T), Lualualei, Oahu, T. H. The investigation revealed only a few points where immediate changes seem indicated. The conclusions summarized at the end of the report therefore may be regarded for the most part as a guide to long-range planning of installations and operations. The reasons underlying the recommendations are fully explained in the body of the report.

Criteria for the evaluation of the existing installation and procedures were obtained from a discussion of long-distance propagation given at the beginning of the report. Circuit outage on the point-to-point circuits has been examined and much of it can be explained by the variations in the sky-wave transmission path with the time of day and the seasons of the year. Ways and means are suggested which may lead to considerable improvements in circuit reliability.

Several new designs for broadcast antennas are presented; most of these have broadband characteristics. The use of the suggested antennas would therefore not only provide better omnidirectional radiation, but would also add greatly to the flexibility of station operation.

The power gain of the existing rhombic antennas has been computed. On the basis of these data it is recommended that these antennas be used over more restricted ranges in frequency than is presently the practice. Designs for new rhombic antennas have been obtained, and a site plan is included showing suggested locations for these antennas.

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The writers gratefully acknowledge the help they received from the District Communications Office and the Electronics Office at Pearl Harbor, and from the personnel of the U. S. Naval Radio Station at Lualualei.

Thanks are also due to Mrs. L. G. Clarke who performed all the computations required for this report.

ENGINEERING SURVEY OF
U. S. NAVAL RADIO STATION (T)
LUALUALEI, OAHU, T. H.

CHAPTER 1

INTRODUCTION

The U. S. Naval Radio Station (T) at Lualualei, Oahu, T. H., is one of the largest military communication stations in existence today. Like many other long-distance communication stations, it grew from an early installation of modest capacity to its present size, where over fifty transmitters ranging in power output from 0.5 to 500 kw, may be on the air at any one time. The ultimate extent of this installation could not be known at the time of the original planning. What appears as best engineering practice, in view of the present size of the station, could therefore not be anticipated at the start. This survey had the purpose of determining ways and means for improving the overall efficiency of the installation. Possible improvements to existing equipments were examined, as well as plans for long term changes in equipment and operational practices, wherever these might be found desirable.

The transmitting station at Lualualei is remarkably sound from an engineering point-of-view, taking into account the rapid growth to which it was subjected. As a consequence, the changes proposed in this report should in most cases be considered as goals-desirable in the long run-but not urgently required for immediate improvement in the operation of the station. It was found in the course of the survey, however, that in some instances better service could be achieved by minor modifications of existing equipment or by using this equipment differently from the way it is used at present. In these cases, early adoption of the proposals should prove advantageous.

The investigation was carried out along two broad lines. The first of these was an examination of the relation between radio propagation factors and the installations and operations of the transmitting station. This study provides a basis for judging the performance of existing facilities. It is also a guide to the design of new installations, as well as a guide to changes in existing installations and operating procedures. A considerable share of the outages reported for the point-to-point circuits can be traced directly to propagation factors, and means are suggested whereby greater reliability of the circuits can be achieved.

The second part of the investigation consisted of an examination of the layout of the transmitting station, of the arrangement of transmitters within the buildings, of the ground systems, switches, and feeders, and of the antenna systems. Changes in the assignment of circuits to the two main transmitter buildings are suggested, which would lead to more effective use of the available transmitters and of the land area in the vicinity of the buildings. Proposed alterations of one of the ground systems should lead to a reduction of coupling between transmitters operating in proximity to each other. The use of Marconi antennas also leads to undesirable interaction between circuits. It is therefore recommended that this type of antenna be entirely eliminated except for use at low and medium frequencies. The output of the transmitters using Marconi antennas would then be fed into coaxial cables which deliver power to antennas suitable for use with such feeder systems. The designs for several such antennas are presented. Some of these must be used at a single frequency while others are suitable for use over a considerable range of frequencies without retuning of the antenna-matching system. A new type of broadcast antenna design is suggested for use with the 600-ohm parallel-wire transmission lines. This antenna provides good omnidirectional coverage, and it can be used over a frequency range of 1.5 to 1.

The limitations of rhombic antennas for the point-to-point circuits are discussed. It is suggested that, wherever practical, existing rhombics be used over a more restricted range in frequency than is the present practice. Finally, new rhombic antennas have been designed which should give adequate coverage at all frequencies between 4 and 24 Mc, and for all required distance ranges of transmission. A site plan has been prepared, incorporating the suggested rhombic design. Even if not adopted in this form, the plan provides a guide to the most desirable location of antennas for the point-to-point circuits, while at the same time leaving more room for the installation of broadcast antennas than is now available.

Details of designs for the proposed new rhombic antennas are given in Appendix D. Appendix B gives a description of scatter-sounding equipment that provides a means for determining, instantaneously, the best frequency to be used for h-f transmissions over a given path. The power gain in useful directions of the existing rhombic antennas is shown in Appendix C.

CHAPTER 2

DESCRIPTION OF TRANSMITTING STATION AND THE SATELLITE INSTALLATIONS

The Naval Radio Station (T) at Lualualei, Oahu, T. H., comprises the main transmitting facilities of the 14th Naval District. Signals from this station must reach almost all points of the Pacific area as well as Washington, D. C. More than one hundred transmitters having power outputs from 0.5 kw to 500 kw are actively available and, at any given time, over half of these may be transmitting simultaneously over the various circuits. Both directional and omnidirectional antenna systems, altogether over a hundred in number, are presently installed at Lualualei to handle frequencies ranging from 15 kc to 24 Mc. Such a large number of antenna systems, suitable for use within the frequency range mentioned, requires a considerable land area. The Lualualei transmitting station covers an area of 1750 acres of which roughly one-third is available for future expansion of the installation.

The general layout of the station is shown in Fig. 1. Building No. 2 contains the 500-kw v-l-f transmitter and its standby power generating equipment. All of the l-f, m-f, and h-f transmitters are housed in Building No. 1 (HF) and Building No. 68 (LU-4), except for a few installations intended for emergency use. The location of the various antennas, poles, and transmission lines is also shown in this figure. The land covered by the station rises gently toward the east and, except for a few isolated patches, is suitable for the construction of directive antenna systems. As a transmitting station, the Lualualei location suffers from the drawback that the area is almost completely surrounded by the Waianae Mountain Range. These mountains rise to a height of over 4000 ft and, at some points, the crest of the range is only three miles distant from the station. Some isolated peaks as high as 850 ft, only a few hundred yards away from the boundary, complete the ring of mountains around the station. Figure 2 shows the horizon profile as seen from a point at about the center of the station. The angle shown is that between the horizontal plane and the skyline, as a function of azimuthal direction about the point of

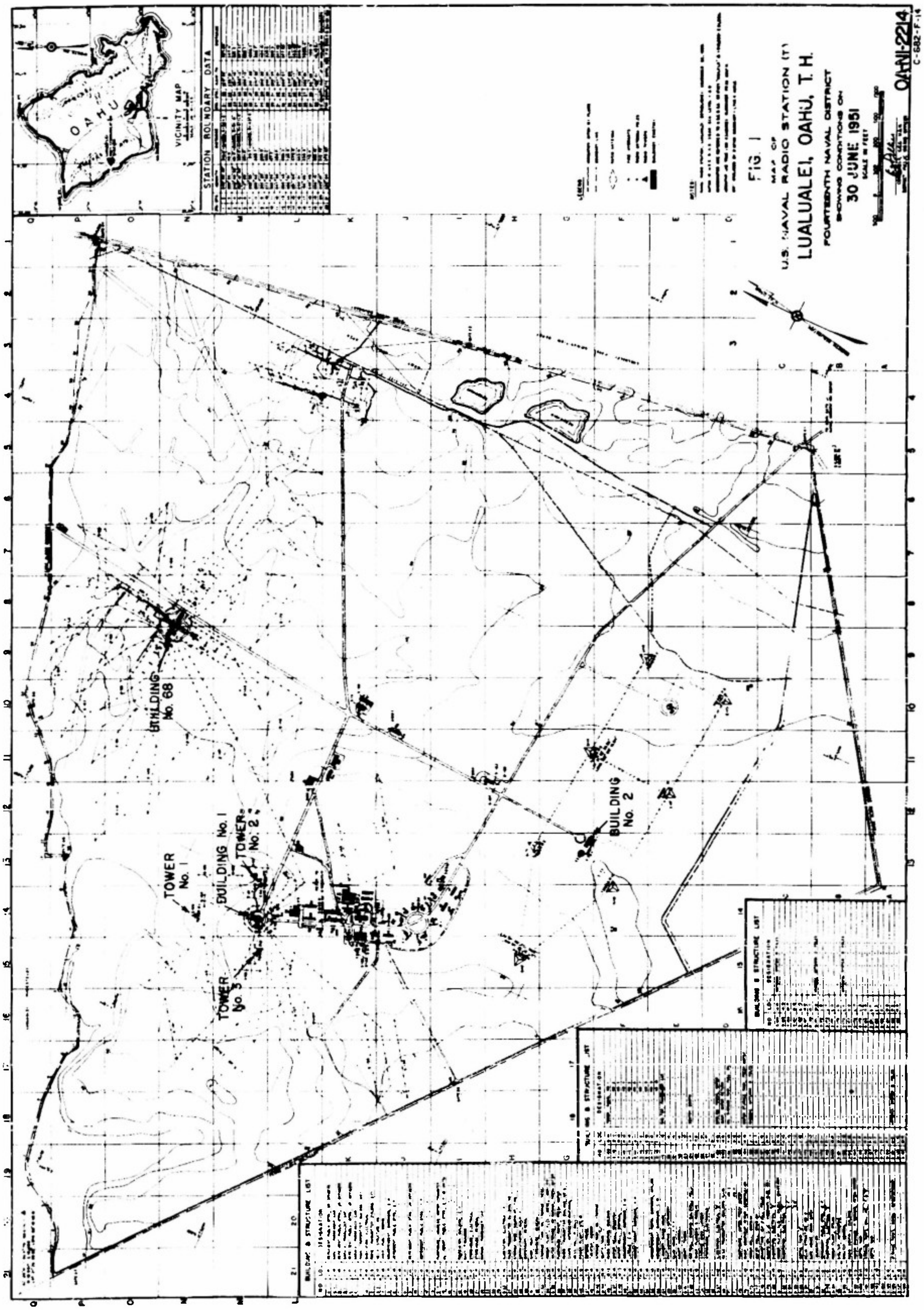

FIG. 1
MAP OF
U.S. NAVAL RADIO STATION (T)
LUALUALEI, OAHU, T.H.
FOURTEENTH NAVAL DISTRICT
SHOWING CONDITIONS ON
30 JUNE 1951

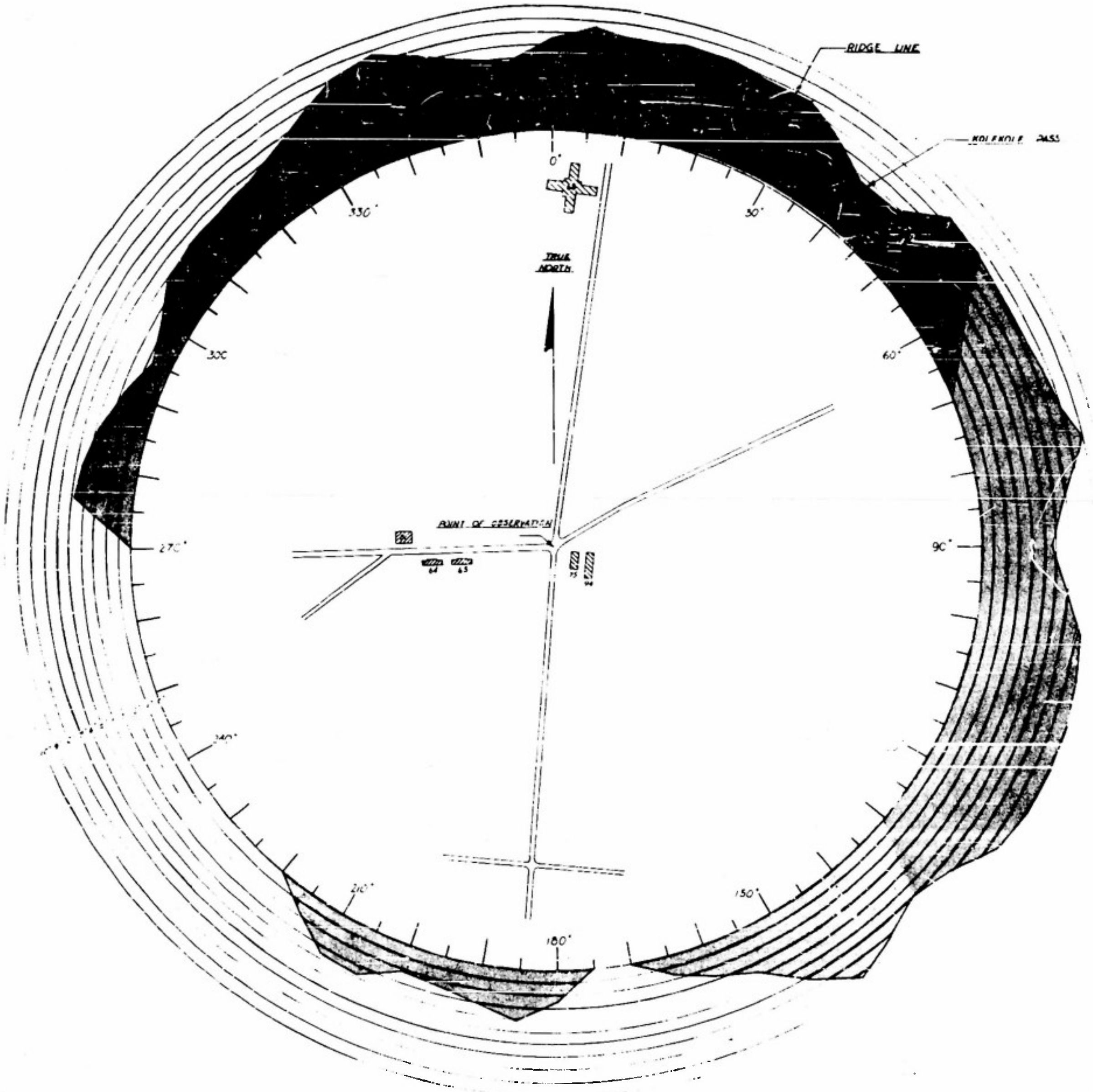

FIG 2

HORIZON PROFILE FROM U.S. NAVAL RADIO STATION (T) LUALUALEI, OAHU, T.H.

REF - 14th NAVAL DISTRICT DPWO NO DA-N11-466 observation. In this particular case, the skyline is elevated by angles between 5 and 8 degrees in almost all directions about the station, except for a gap toward the southwest. From points closer to the station boundary, angles of elevation as large as 13 degrees may be encountered. Since h-f transmissions over long distances make use of low angle sky-waves, desirable directions of propagation may be cut off by the mountains. When determining the location of directive antennas, the sites must be chosen so that the transmission paths are unobstructed in the required directions.

The outgoing signal traffic is divided into thirty-four circuits, according to the destination and the type of message transmitted. For the purposes of this report, only two different types of service need be distinguished — point-to-point circuits and broadcast circuits. For the former, highly directional antenna systems can be used, while for the latter, uniform coverage in azimuth is required.

None of the modulating signals for the transmitters are generated at the station. Voice, facsimile, frequency-shift telegraphic signals, and other information signals originate, for the most part, at Pearl Harbor and are transmitted to Lualualei over a v-h-f link. Some of the v-h-f channels on this link are used for order circuits over which routing and other instructions for the handling of the messages are sent. Instructions as to the frequency to be used for transmission over a given circuit are given to Lualualei over the same v-h-f link. At the transmitting station the proper demodulated signal from the v-h-f link modulates a transmitter tuned to the requested frequency. This transmitter must, of course, deliver its power output to an antenna suitable for this frequency as well as for the circuit over which the message is to be transmitted. Many of the transmitters are assigned to specific circuits and frequencies, and are therefore connected to the proper antennas over extended periods of time. They are thus ready to go on the air as soon as the particular circuit and frequency are requested.

As already stated, the bulk of the transmitters are installed in three buildings. The 500 kw v-l-f transmitter (TAWa) is presently on a standby status. It is put into operation for only a few hours every week. Normally, transmissions at these frequencies are sent out from the v-l-f station at Haiku Valley. Building No. 1 contains the transmitters for the point-to-point circuits to the east as well as transmitters for some of the broadcast circuits. Most of the l-f transmitters are located in this building, since

300-ft towers in its vicinity form suitable supports for the antenna required at these frequencies. A total of 23 transmitters are housed in Building No. 1; the terminal equipment for the v-h-f links is located in the basement. Building No. 68 is equipped with 68 transmitters; transmissions for the point-to-point circuits to the south and west, as well as many of the broadcast transmissions, emanate from here.

All the h-f transmitters of power output greater than 5 kw have balanced output circuits. They are fed into 600-ohm balanced parallel wire transmission lines and therefore require balanced antenna configurations. Most of the lower-powered transmitters, as well as the l-f and m-f transmitters, have unbalanced outputs. No transmission lines are used with these transmitters; the down-lead from the antenna is connected directly to the transmitter output terminal.

Three types of antennas are currently in use at the station. Marconi antennas for the transmitters with unbalanced output have just been mentioned. They consist of a single, preferably vertical, wire of a length depending on the output circuit of the particular transmitter to which the antenna is connected and on the frequency range over which it is to be used. The transmitters can usually be loaded into such antennas over a considerable band of frequencies. Rhombic antennas are used on the point-to-point circuits. With these antennas a VSWR of better than 2:1 can be maintained on the transmission lines at all frequencies required for the circuits. The radiation patterns, however, are not suitable for use of the antennas over the entire frequency range. Balanced antennas for the broadcast circuit consist of half-wave dipole antennas (doublets), or of simple arrays of such dipoles (folded dipoles, and lazy-H antennas). These antennas are matched to the transmission line by either short-circuited stubs placed across the line near the antennas, in which case the antennas are series fed, or by means of the parallel feed arrangement known as delta-match. In either case, the antenna and matching device have a narrow frequency-band characteristic. Such antenna systems can therefore be used only at frequencies close to the design frequency. In order to provide a balanced antenna system which correctly terminates a 600-ohm transmission line over a wide band of frequencies, three terminated folded dipoles are presently being used. All these antennas will be discussed in detail later in this report.

Some of the transmitters are connected to transmission lines that lead directly to the antennas. Others are connected to switching stations that permit the outputs of ten different transmitters to be connected to ten different antenna systems. These switching stations are located outside of the buildings; two such stations are in operation near Building No. 1 and four are being used at Building No. 68. The transmission lines leading to the antennas are arranged on an arc of a circle. The lines coming from the transmitter are stacked vertically on poles at the center of the circle. Connection is made by means of a short section of transmission line, one end of which is permanently connected to the terminals at the center poles while the other end can be mechanically linked to the required line leading to the antenna.

In addition to the transmitting station, there are two satellite installations for which Lualualei is responsible; one on Mauna Kapu and one at Kolekole Pass. The direct transmission paths between Pearl Harbor, Lualualei, and the receiving station at Wahiawa are obstructed by the Waianae Mountains; the receivers and transmitters of the satellite installation serve as a relay for the v-h-f links between the stations just mentioned.

CHAPTER 3

THE INFLUENCE OF PROPAGATION FACTORS ON TRANSMITTING STATION INSTALLATIONS AND OPERATIONS

A GENERAL PICTURE OF PROPAGATION BELOW 30 MC

Since the frequencies of interest in this study lie below 30 Mc, we are not concerned to any practical extent with tropospheric propagation or space-wave propagation. The only important mechanisms of propagation therefore are the surface wave and the ionospheric or sky wave.

The surface wave travels along the surface of the ground (or sea) and follows the curvature of the earth. It dies off rather slowly with height above the ground and rapidly with depth below the surface. The surface wave component is nearly always vertically polarized because the horizontal component of the electric field tends to be short-circuited by the conducting earth. The useful distance range of the surface wave increases with wavelength and is greater over sea than over land. Under the best conditions the useful range is limited to a few hundred miles at medium and high frequencies. However, at the extreme low end of the spectrum (in the neighborhood of 15 kc) distance ranges of several thousand miles are obtainable.

The sky wave is propagated to great distances by the ionosphere, which can produce essentially complete reflection at various heights between roughly 90 and 450 km. The effect of the ionosphere depends primarily on the presence of free electrons which are caused to vibrate by the passing radio wave. These moving electrons constitute an electric current which re-radiates energy much in the manner of a parasitic antenna. This re-radiated energy then adds to the original wave in such a way as to bend the direction of propagation away from regions of increasing electron density. If conditions are suitable, the direction of propagation eventually becomes horizontal and the wave is returned to earth. The higher the frequency the greater the electron density required for a given amount of bending.

The vibrating electrons frequently collide with other particles, losing all or part of the wave energy they were carrying before collision. This effect attenuates the wave and may in some cases cause almost total absorption of the wave. Such energy loss takes place in the lowest part of the ionosphere (the D-region) and the loss increases with the wavelength. This results from the fact that the velocity, and hence the kinetic energy, of the vibrating electrons increases with wavelength. At frequencies above about 2 or 3 Mc this type of attenuation, expressed in decibels, is inversely proportional to the square of the frequency.

The earth's magnetic field causes the vibrating electrons to travel in curved orbits since the force is at right angles to both the direction of electron motion and the direction of the earth's field. This produces a component of current flow not in the same direction as the electric field of the exciting wave and hence alters the polarization of the resultant wave. The net effect is that there are two "characteristic" waves which propagate independently, and exhibit different attenuation rates, group velocities, and polarizations. These are frequently termed the "ordinary" and "extraordinary" waves. An important practical result of the effect of the earth's field is that either vertically- or horizontally-polarized antennas may be used at either transmitter or receiver.

Most of the important features of h-f propagation can be represented by rays traveling from transmitter to receiver by means of one or more reflections from the ionosphere. Each transmission from earth to ionosphere and back is called a hop. When the straight line portions of this path are extended until they intersect, the resulting path is called the *equivalent path*. The height of the apex of the equivalent path above the earth is called the *virtual* height of reflection. The virtual height is always greater than the true height of the top of the actual path. If another signal is reflected at vertical incidence from the same actual height as the oblique signal, then the frequency of the oblique signal is equal to that of the vertical-incidence signal multiplied by the secant of half the apex angle of the equivalent path. This relation is commonly referred to as the *secant law*. From this relation it can be seen that the more glancing the path the higher the frequency that can be reflected from the layer. The highest frequency that can be transmitted over a given path at a given time is termed the ***maximum usable frequency*** (MUF). The corresponding ground distance is called the *skip distance*. Thus, as the operating frequency is increased, the skip distance will increase until the shadow of the earth intervenes. Beyond this point transmission to a receiver located on the earth is not possible by means of a single hop.

The virtual height can be measured by observing the delay time of a pulse reflected at vertical incidence. To obtain the virtual height, the frequency of the vertical-incidence sounder must be equal to the frequency of the oblique signal divided by the secant of the angle of incidence at the ionosphere. In practice, such sounders are swept through the h-f range (1-20 Mc) every half hour or so, yielding plots of virtual height vs. frequency. The frequency at which the sounding signal penetrates a layer is called the *critical frequency*, and is proportional to the square of the maximum electron density. These basic data constitute a complete description of the ionosphere as far as ray paths are concerned. From such data the characteristics of an oblique path whose reflection point lies over the sounder can be calculated. The cyclic nature of ionosphere characteristics allows fairly accurate predictions to be made. From data supplied by about 60 or 70 sounders scattered over the earth's surface, the characteristics at any given reflection point are determined by interpolation.

In most sky-wave transmission problems the propagation path can be represented by a number of symmetrical hops; i.e. hops in which the angles made by the ray at the surface of the earth are equal. There are then five geometrical characteristics of the equivalent path, which can be defined. They are (1) great-circle distance between transmitter and receiver, (2) virtual height of reflection, (3) equivalent path distance between transmitter and receiver, (4) angle of departure, and (5) angle of incidence at the ionosphere. A simple sky-wave transmission chart for solving any problem involving these five variables is presented in Appendix A. In connection with this study, the chart was used in determining the vertical angles discussed below.

There are three principal strata in the ionosphere, called the E, F1, and F2 layers. The E-layer lies at a height of about 110 km and has two components, the normal or regular E-layer, and the abnormal or sporadic E-layer. The normal component is produced by solar ultra-violet light and its critical frequency is essentially in phase with the hour angle of the sun. The maximum critical frequency occurs at local noon and, depending on the latitude, usually lies between 3 and 4 Mc. Reference to the sky-wave transmission chart (Appendix A) shows that the maximum one-hop distance is about 2200 km. Hence the highest maximum usable frequencies are less than 20 Mc.

At unpredictable times the E-layer produces partial and sometimes complete reflection at frequencies considerably in excess of the normal E-layer critical frequency. This phenomenon is called sporadic-E. Its cause is not understood. Sporadic-E MUF's as high as 80-100 Mc have been reported, although values of the order of 20-30 Mc are much more common. Sporadic-E is more prevalent in summer than in winter, and frequently determines the MUF over a short path (less than 2200 km). It is highly unpredictable and hence cannot be relied upon for regular transmission.

The F1-layer lies at a height of about 200 km and is similar to the E-layer in its variations. Its noon critical frequency lies between about 4 and 5 Mc in temperate latitudes. The maximum one-hop distance is about 3000 km. The F1-layer disappears at night.

The F2-layer is dominant in long-distance circuits since it generally has the highest MUF. Its height varies between about 250 and 450 km, depending on factors similar to those governing the MUF. The maximum one-hop distance is roughly 4000 km. F2-layer critical frequencies vary from less than 2 Mc to more than 15 Mc, depending on time and place.

B. USABLE FREQUENCIES AND REQUIRED TRANSMITTER POWERS

For a given set of conditions there is generally a limited range of frequencies that can be used for high-frequency communications. The upper limit is called the maximum usable frequency, as described above, and depends on the distance of transmission and the virtual heights and electron densities at the points of reflection. For the usual communication systems the MUF is nearly independent of the radiated power and the receiver sensitivity, depending almost entirely upon the height and electron density of the layer.

The lower limit of the useful range, on the other hand, depends on equipment characteristics as well as the propagation factors which affect the MUF. The principal reasons for the existence of a lower limit are

(1) The attenuation, in db, of a signal reflected by the ionosphere is approximately inversely proportional to the square of the frequency.

(2) The amount of available[*] atmospheric noise power is approximately inversely proportional to the square of the frequency.

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[*] By "available" is meant the total noise being produced on the earth's surface. How much of the total arrives at the receiver depends on the propagation characteristics of the many different paths involved.

Thus, the signal-to-noise ratio can be expected to increase with frequency, the exact relation depending on how much ionospheric absorption is present, and on the effect of a change of frequency on the propagation of atmospheric noise to the receiver.

In general, the frequency that gives the highest signal-to-noise ratio is the MUF. In practice, the optimum traffic frequency (FOT) is taken 15% below the MUF to allow for short-time fluctuations in the MUF.

To illustrate the absorption factor, consider a typical case in which the ionospheric absorption at 10 Mc over the San Francisco-Lualualei path is 20 db. If the frequency were reduced to 5 Mc, the absorption would increase by a factor of four, to a total value of 80 db. This reduction in frequency would therefore reduce the signal strength by 60 db for the same radiated power. If the signal level were to be maintained at its original level, the radiated power would have to be increased by a factor of 10^6. On the other hand, if the frequency were raised to 20 Mc, the absorption would be reduced by a factor of one-fourth, to a total value of 5 db. For the same radiated power, the signal strength would then be increased by 15 db. Or, conversely for the same signal strength, the required power would be reduced by a factor of 1/30.

Even when the ionospheric absorption is low, as it is at night, the lower frequencies require higher powers because of the greater atmospheric noise level. It is therefore important to design the transmitting antenna system to provide the highest power gain in the desired direction at the lowest frequency to be used, even at the expense of reduced gain at some higher frequencies.

The MUF can be predicted on an average basis for a particular month and path by the methods outlined in Ionospheric Radio Propagation,[1] together with the Basic Radio Propagation Predictions[2] issued three months in advance. Such predictions will give a useful indication of the frequency to use at any particular period of the day. However, they are limited by the fact that the MUF on any particular day may depart appreciably from the monthly average for that time. The smaller variations

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[1] National Bureau of Standards, Ionospheric Radio Propagation, Circular 462, June 25, 1948 (Superintendent of Documents, Washington, D.C.).

[2] National Bureau of Standards, Basic Radio Propagation Predictions, Central Radio Propagation Laboratory, Series D.

(in the neighborhood of ±15%) are more or less random, and hence unpredictable. Relatively large reductions in MUF (in the vicinity of 50%) are caused by ionosphere storms, which can be anticipated to some extent.[1]

The actual experimental determination of the MUF at any given time can now be carried out rather easily by means of a new measuring technique called scatter-sounding. This method makes use of pulses transmitted on the frequency of interest. If reflection from the ionosphere is possible, some of the energy is scattered back to the transmitter after reflection from the ground at a distance corresponding approximately to the skip distance at that frequency. The skip distance is determined simply by measuring the delay time of the leading edge of the back-scatter echo and applying a simple conversion factor. If the skip distance so measured is less than the length of the circuit path, then transmission will be possible on that frequency. The details of this technique are given in Appendix B.

A special problem arises when the transmission path is approximately 4000 km long. This distance is usually considered to be the maximum distance for one-hop propagation. However, under some conditions the one-hop mode may not be usable. It is then necessary to use a higher-order mode such as two-hop. The factors that can cause the maximum useful one-hop distance to be less than 4000 km are

(1) Low height of the F2-layer.

(2) Insufficient antenna response at low vertical angles.

(3) Obstructions, such as mountains or buildings, which cut off low angle radiation.

In such cases the MUF can be determined with sufficient accuracy by dividing the transmission path into uniform segments equal in number to the number of hops. The MUF for each segment is determined by the methods outlined in NBS Circular 462. The MUF for the entire path is then the lowest of the several values so calculated.

A practical example of a two-hop path of approximately 4000 km length is that from Lualualei to San Francisco. Here the Waianae mountains subtend an angle of about 6 degree in the direction of San Francisco. Reference to the sky-wave transmission chart of Appendix A shows that the

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[1] See, for example, the North Atlantic and North Pacific Warning Services, provided by Central Radio Propagation Laboratory of the National Bureau of Standards.

equivalent one-hop path with a take-off angle of 6 degrees must have a virtual height of 550 km. Since the virtual height of the F2-layer seldom reaches this value, the one-hop mode is cut off by the mountains most of the time. Actually, lower heights than that computed above will propagate the one-hop mode because of effects such as diffraction over the mountains, bending in the E-layer, and atmospheric refraction. An experimental check on the importance of the one-hop mode over this path was undertaken on September 2 and 3, 1953. Simultaneous recordings of NPM at Lualualei (15.65 Mc) and WWVH* (15.00 Mc) were compared with scatter soundings made on 17.31 Mc. The transmission paths from Lualualei to San Francisco, and from WWVH to San Francisco are almost identical. The one-hop ray path from Lualualei to San Francisco, however, is partially obstructed by the Waianae Mountains, while no such obstructions are present near WWVH. The two-hop paths are unobstructed in both cases. Signals were received from both stations, not only during times when the two-hop mode was active, but also when only the single-hop mode was possible. The data showed that the intensity of the signal from Lualualei, relative to that from WWVH, tended to be less on one hop than on two hop, indicating that the one-hop mode from NPM is less useful than that from WWVH. A study of several years of recordings of WWV and WWVH on 15.00 Mc, as received at the Stanford Radio Propagation Laboratory (near San Francisco, California), shows that although the one-hop mode is frequently present over both paths, it is often weaker and more variable in strength than the two-hop mode. It is concluded therefore that although the one-hop mode may at times provide adequate communication, it should not be relied upon for regular communications over such paths, particularly when the ray path is cut off by mountains or other obstructions.

To illustrate the nature of MUF variations with time of day, the MUF for November, 1953, for the Lualualei-San Francisco path was computed using the CRPL D-Series predictions made three months in advance. A two-hop mode was assumed, for the reasons given above. The MUF is plotted as a function of Greenwich Civil Time (GCT) in Fig. 3. Also plotted is the FOT, which is 85% of the MUF. The ratio of maximum MUF to minimum MUF is almost four to one, and it is clear that different frequencies must be used at different times of day if the effects of ionospheric absorption are to be minimized. A typical schedule for changing frequency is shown in the figure, assuming that the available.

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*WWVH is a transmitter of the National Bureau of Standards, located on the Island of Maui, T.H., which continuously transmits standard time and frequency signals on frequencies of 5, 10, 15, 20, and 25 Mc. WWV is a similar transmitting station located near Washington, D.C.

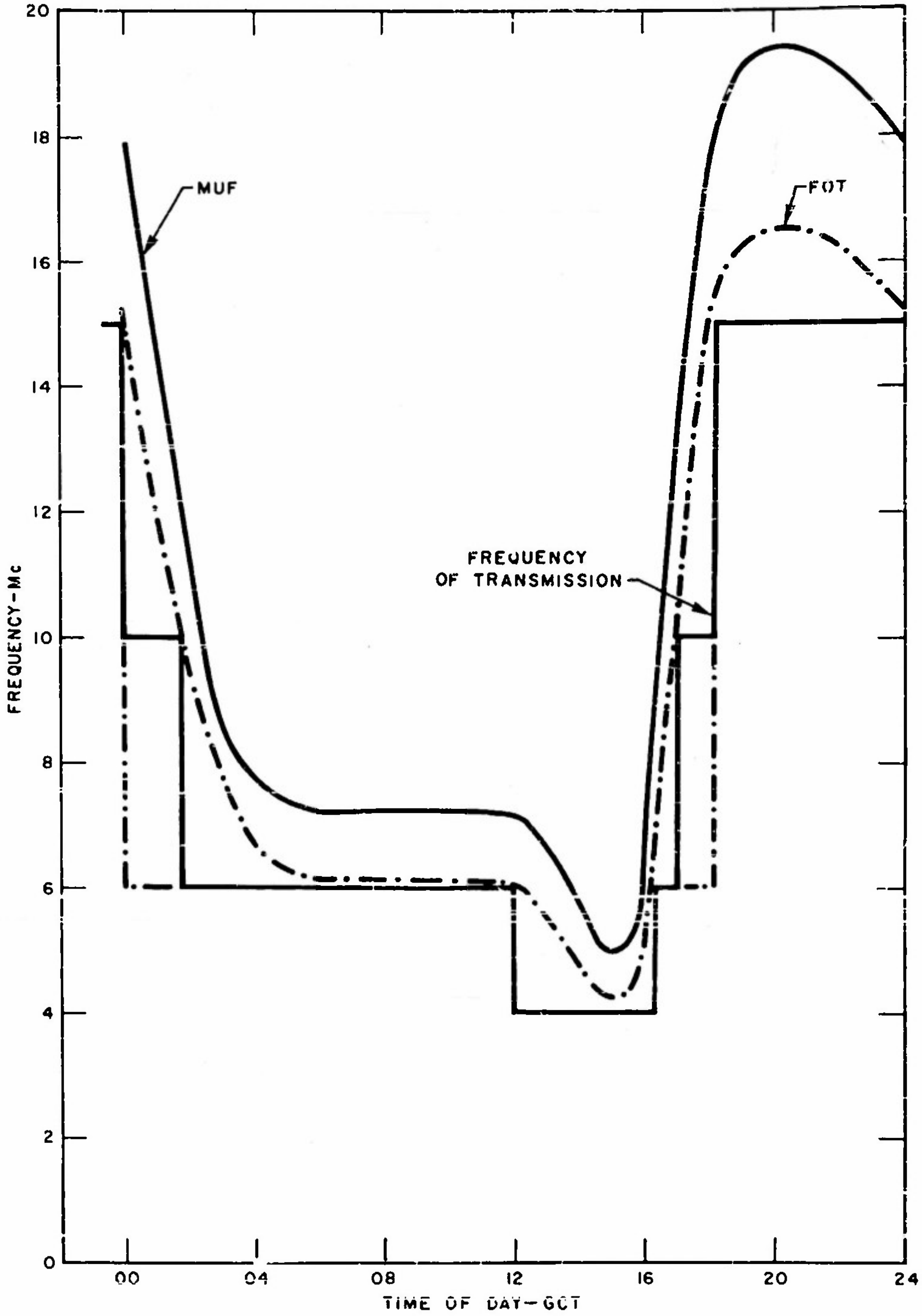

FIG. 3

OPTIMUM FREQUENCIES FOR THE LUALUALEI-SAN FRANCISCO PATH FOR NOVEMBER 1953

B-C92-F-12

frequencies are 4, 6, 10, and 15 Mc An alternative schedule is shown by the dotted line, in which only three frequencies, 4, 6, and 15 Mc, are used. The advantage of the three-frequency schedule is that outages associated with the mechanics of changing frequency are reduced in number. The disadvantage is that the ionospheric absorption will tend to be higher during those periods when the frequency in use is well below the FOT. Which of the two schedules would give the better results depends on the relative importance of the factors involved and can be discovered only by experiment.

Particular attention should be paid to the dip in the MUF curve which occurs just before sunrise. This dip is characteristic of most MUF curves and requires the use of a lower frequency just before sunrise, than was used earlier during the night. Since the required reduction in frequency occurs at a time when the absorption at the east end of the path is starting to rise, transmission conditions become very poor at this time. In actual practice there may be a tendency to raise the frequency of transmission to avoid the effects of absorption even though the MUF is dropping and communications can be maintained only by lowering the frequency.

Contrasting with the MUF curve for November is the curve for June 1953, which is characteristic of summer conditions (Fig. 4). Here the ratio of maximum MUF to minimum MUF is only 2. The number of frequency changes required each day is therefore smaller. Furthermore, since the number of daylight hours is greater in summer than in winter, the period of high daytime MUF is proportionately greater. The lowest frequencies are thus used a smaller percentage of the time in summer than in winter and the transmission difficulties associated with low frequencies are correspondingly reduced. For these reasons long-distance circuits, on the average, tend to be more efficient in summer than in winter.

The curves shown in Figs. 3 and 4 are characteristic of the minimum of the sunspot cycle. At the maximum of the sunspot cycle (the next maximum is expected in 1957-58) the MUF's are considerably higher. For example, the daytime value in winter will be increased by roughly 50% and the nighttime value by about 15%. On the other hand, in summer the daytime increase is only about 10%, while the nighttime increase is about 50%. These differences vary with the location of the path.

The most difficult time for transmission, particularly over an east-west path, is the sunrise period. This results from the fact that the effects of ionospheric absorption are felt at the east end of the path

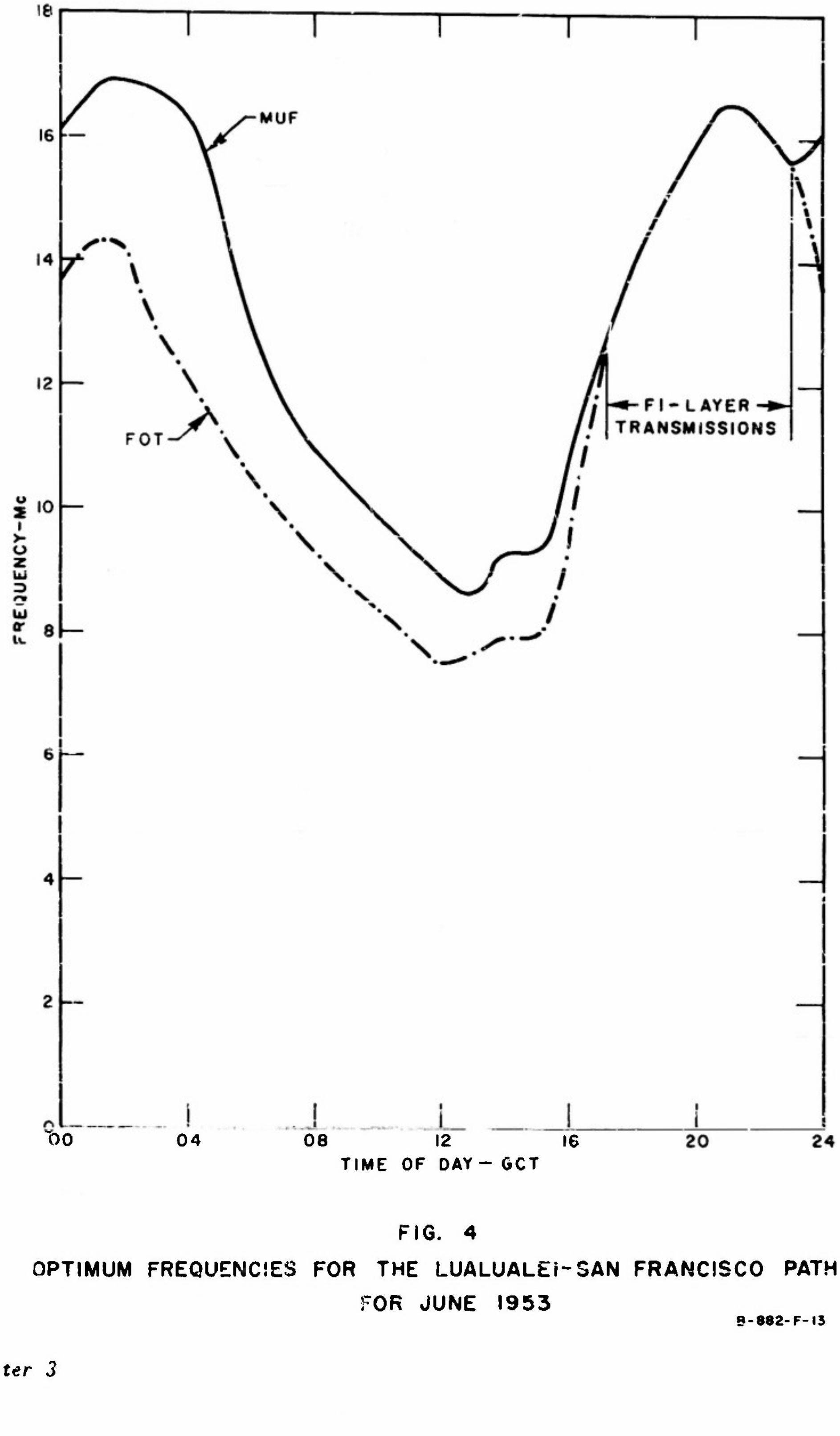

FIG. 4

OPTIMUM FREQUENCIES FOR THE LUALUALEI-SAN FRANCISCO PATH FOR JUNE 1953

B-882-F-13

before the MUF at the west end of the path has had a chance to rise. The MUF for the entire path is therefore low at this time, but the attenuation due to losses in the D-region has begun to increase. The longer the path (in an east-west direction) the longer is this period of transition and hence the more troublesome is the circuit.

C. USEFUL VERTICAL DIRECTION AS A FUNCTION OF REQUIRED COVERAGE AREA

The vertical angle of transmission for a sky-wave communication circuit depends on a number of factors such as the distance between transmitter and receiver, the height of the ionospheric reflecting layer, and the angle subtended by local obstructions such as mountains. The effects due to local obstructions do not change with time, nor does the distance between transmitter and receiver, for point-to-point circuits. The distance of transmission does vary, however, throughout a wide range, for the broadcast circuits. The height of reflection in the ionosphere also varies through rather wide limits with the time of day, with the season, and with the eleven-year sunspot cycle. The variation in height of reflection for the F-layer is in nearly all cases confined within limits of 200 to 500 km. For long distance circuits, that is for distances of transmissions greater than 2000 km, reflection normally takes place in the F2-layer, and hence it is this range of heights with which we must work when computing vertical transmission angles. The following discussion will consider point-to-point and broadcast circuits separately.

1. POINT-TO-POINT CIRCUITS

For a point-to-point circuit the distance of transmission is fixed, and for an assumed height of reflection the required angle of departure for the radio wave may be obtained from the transmission chart of Appendix A. For a particular assumed height of reflection a number of different angles of departure may be obtained, depending on the number of hops between the ionosphere and the earth. For example, consider the Lualualei-San Francisco path (3880 km). if reflection is assumed to take place at a height of 300 km, the one-hop path requires a takeoff angle of 0 degrees, the two-hop path requires 12.2 degrees and the three-hop path requires 21.0 degrees. Thus, some flexibility is permitted in the choice of a suitable departure angle for a given transmission path. The very lowest angles, near 0 degrees, are ordinarily ruled out by the inability of practical antennas to radiate efficiently at such angles. For the transmitting location at Lualualei, the height of the surrounding mountains places additional restrictions on the use of very low angles. For the Lualualei-San Francisco path, transmissions are limited to angles above about 6½ degrees because of the intervening mountains. Hence, for this path the one-hop mode would, in general, not be very useful and transmissions are best limited to the higher angles set by the two-and three-hop modes.

In general it is preferable to utilize transmissions which involve the smaller number of hops, when other considerations permit. An increase in the number of hops results in more absorption of the wave, due to the increased length of path in the absorbing region, and due to lower frequency of transmission necessitated by the higher angle of departure. However, when operating at a sufficiently high frequency, which is usually insured by working near the MUF, the change in absorption in going from one mode to a mode with the next higher number of hops is not prohibitive. An antenna such as a rhombic cannot be made to provide high-beam gain throughout the wide range of vertical angles and at all frequencies which would be necessitated if a single mode were to be used, irrespective of the height of the reflecting layer. If, for example, the two-hop mode were to be used at all times for the Lualualei-San Francisco path, a range of vertical angles from 6 degrees to 20 degrees would be required. If, for the lower heights of reflection, use is made of the three-hop mode, the required range of angles can be reduced to lie between 9 degrees and 19 degrees. The increased antenna gain, which is made possible by the smaller range of angles, offsets the increase in absorption brought about when changing from the two- to the three-hop mode.

Making use of the above considerations, it is possible to tabulate a set of useful vertical angles for different distances of transmission.

TABLE I

RANGE OF USEFUL ANGLES OF DEPARTURE FOR TRANSMISSION PATHS OF VARIOUS LENGTHS

LENGTH OF PATH		SUGGESTED RANGE IN VERTICAL ANGLES OF DEPARTURE
(Kilometers)*	(Nautical Miles)	
1500-2500	810-1350	12°-20°
2500-3500	1350-1900	6°-12°
3500-4500	1900-2450	9°-19°
4500-5500	2450-3000	9°-16°
5500-6500	3000-3550	9°-16°
6500 and beyond	3550 and beyond	6° 12°

* When dealing with problems involving ionospheric propagation, it is more convenient to use the kilometer as the unit of length. The ranges in nautical miles are obtained by the following conversion:

1 nautical mile ≅ 1.85 km.

This tabulation is based on average conditions and, as such, incorporates many compromises. When specific problems arise in the design of an antenna for a point-to-point circuit, improved performance may at times be achieved by an analysis based on the principles outlined above. For example, if a circuit is to be activated for a short period of time, it may be found that the range of variation of reflection height in the F-layer may be considerably smaller than the full range allowed for in the above tabulation. In this case, the range in vertical angles may be reduced and, as a result, increased antenna gain may be possible.

As a verification of the design criteria for antenna systems for the point-to-point circuits, a series of test transmissions were performed between the transmitter station at Lualualei, and Stanford University which is located in the vicinity of San Francisco, California. The transmissions took place on 15,665 kc. and on successive fifteen-minute periods utilized rhombic antennas RA-5 and RA-6. These two antennas were chosen because their major lobes lie at different vertical angles at the frequency used in the tests. The pattern of antenna RA-5 was centered around 12 degrees, while that of antenna RA-6 centered around 6 degrees. Vertical angle calculations show that for average F-layer reflection heights, antenna RA-5 radiates efficiently in the right range of vertical angles while the pattern of RA-6 falls below the proper range. The transmission tests of November 9 and 10, and of November 24 and 25, confirmed these expectations surprisingly well. The signals received while transmitting on RA-5 were about 10 db stronger, on the average, than when transmitting on RA-6. Differences as great as 16 db were observed at times. Using the known distance between Lualualei and Stanford, and obtaining the height of reflection in the F-layer from the Stanford vertical-sounding data, the takeoff angle expected during these transmissions was calculated. Using these calculated takeoff angles and the theoretical antenna patterns for the two antennas RA-5 and RA-6, the expected difference in received signal strength was obtained. This difference was compared with the measured field strength differences observed during the transmission tests. Rather close agreement was found, which indicated that the theoretical rhombic antenna patterns were being realized at the transmitter location at Lualualei, a result of considerable value when designing new antennas.

2. BROADCAST CIRCUITS

For broadcast circuits, a group of about five frequencies between 4 and 24 Mc are used simultaneously to cover an area extending from the transmitter location out to distances on the order of 4000 km in all azimuth directions. Ordinarily, it is not possible for any one of these frequencies to cover the full range of distances. At the lower frequencies, ionospheric absorption and atmospheric noise combine to limit the transmissions to relatively short distances. At the higher frequencies, the skip distance limits useful communications to the longer distances, in the daytime, and completely rules out their use at night. The range of vertical angles to be used depends on the height of the reflecting layers, on the distances to be covered, and on the frequency being used.

It is found that for frequencies near 4 Mc, ground-wave propagation can be relied upon to provide usable signals at all times out to distances of about 400 km over sea water. At that frequency and at a distance of 400 km the surface wave may be expected to be about 16 db below the free-space value. On a day of rather high ionospheric absorption the ionospheric wave will also be reduced about 16 db below the free-space value at a distance of 400 km. Hence, nothing is gained when high angles are included in an attempt to obtain sky-wave transmission at distances less than 400 km.

For the reflection at the highest F2-layer which is normally encountered, vertical takeoff angles of 55 degrees to 60 degrees are required in order for the sky wave to return to earth at 400 km. During much of the time, frequencies near 4 Mc will be reflected by the E-layer and much lower angles would suffice. Because of greater absorption at 4 Mc, signal strength at 8 Mc may frequently be greater at distances immediately beyond 400 km. Hence, antennas for 8 Mc should likewise radiate at angles up to 55 degrees or 60 degrees. At some times during the year or sunspot cycle, 8 Mc may also be called upon to cover the full range of distances out to 4000 km and beyond. As a result, the 8-Mc antenna should include radiation down to angles in the vicinity of 10 degrees. The ground wave at 8 Mc is relatively less important than at 4 Mc.

At the highest frequencies in the broadcast group (i.e. greater than 20 Mc), rather well-determined limits may also be set on required vertical angles. Because of rapid attenuation, the ground wave is unimportant at these frequencies. In addition, the F-layer critical frequency at vertical incidence does not often range to frequencies higher than 7-10 Megacycles. This corresponds to skip distances of about 2000 km at 20 Mc Thus, these transmissions would usually be limited to distances greater than 2000 km. At 2000 km the one-hop mode would be used, and at 4000 km the two-hop mode would prevail. Hence, for frequencies greater than 20 Mc, a limited range of vertical angles (8-30 degrees) is suggested and the possibility of some antenna gain in the vertical plane is indicated.

Frequencies near 12 and 16 Mc would normally be used to cover somewhat shorter distances than the higher frequencies and, in addition, will be useful for distances out to 4000 km, or greater, at night. Hence, vertical angles between 8 degrees and 45 degrees may be desirable at various times during the day, year, or sunspot cycle. Use will be made of these results when deciding on the suitability of radiation patterns of existing and proposed broadcast antennas.

OUTAGE LOG ANALYSIS

Some of the characteristics of the Lualualei outage log data were studied for the purpose of establishing the primary causes of circuit outage. It was not considered within the scope of the contract to perform a full-scale statistical analysis of these data. However, some reduction of the data was made and the results were studied primarily on a qualitative basis. Some fairly pronounced trends appear and these form the basis for making a tentative selection of the primary causes of outage.

To get an overall picture of the outage situation, the yearly percent outage for the stations was compared. The results are expressed in terms of the percentage of the total time that the circuit was shut down, and are plotted as a function of the path distance in Fig. 5. A straight line

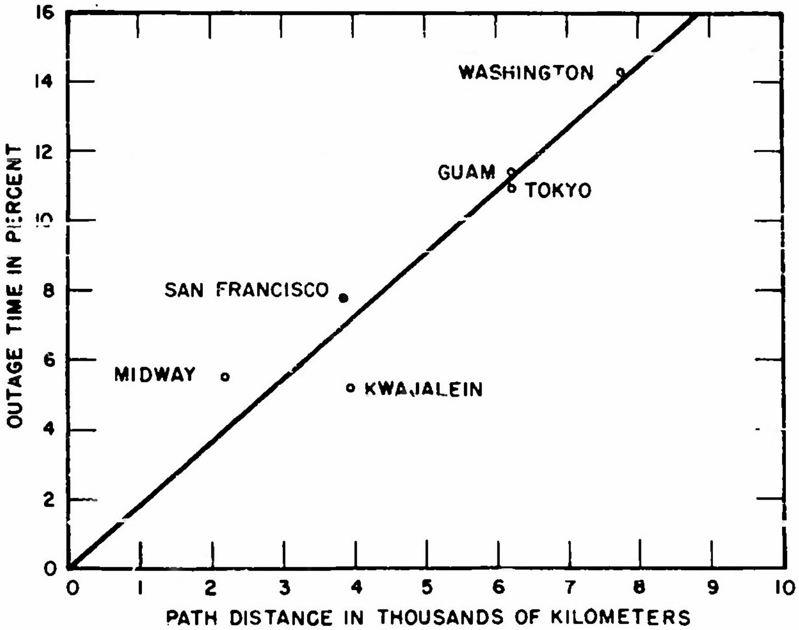

FIG. 5

LUALUALEI TRANSMITTING STATION

PERCENT OUTAGE VS. PATH DISTANCE FOR THE PERIOD
MAY 1952 THROUGH APRIL 1953

A-882-F-8

through the origin fits the points reasonably well, indicating that the total outage is roughly proportional to path distance The principal exceptions to this trend are the circuits to Midway and Kwajalein. A brief survey of the reasons listed for some samples of the outage data suggests that, in the case of Kwajalein, the relatively low total outage is connected with the relatively low incidence of outage caused by changing frequency. It is understood that on this circuit a separate transmitter can be placed in service on the new frequency before the existing one is shunt down. This factor may very well account for the low outage, although a detailed check of the operating procedures would have to be made to confirm this with certainty. The reason for the Midway outage being higher than that for Kwajalein is not clear. One possibility is the fact that the antennas used on this circuit are not of optimum design for the frequencies used. This causes the received signals to be weak. Also, the possibility of an unsatisfactory receiving installation should not be overlooked.

The indicated variation of total outage with path distance, shown in Fig. 5, is interpreted in terms of two factors. The first is the reduction in field strength with distance, caused by inverse distance attenuation and ionospheric absorption, which in general will reduce the signal-to-noise ratio. The second factor is the length of time during which night-time conditions prevail over one end of the path and daytime conditions over the other end. For example, consider an east-west path covering a time span of 3 hrs. For a two-hop path, the time difference between the point where the ray passes through the absorbing D-region at one end of the path and the point of reflection in the F2-layer at the other end will be about 2 hrs. Thus, in the morning the daytime absorption effect for this mode will commence about 2 hrs before the MUF for the path starts to rise. The sunset period is less difficult in this respect because the ionization in the F2-layer lags behind the hour angle of the sun, whereas the D-region ionization, and hence the absorption, is very nearly in phase with the sun's position

The existence of a period of poor transmission conditions in the vicinity of sunrise is well known. For example, recordings of WWV made at Stanford's Radio Propagation Laboratory on 5, 10, and 15 Mc show that the period when the highest available relative field intensity is a minimum, occurs approximately at the time of local sunrise at the midpoint of the path. The length of this period will, of course, increase with path distance in the east-west direction This effect is of much less importance on north-south paths since the local time is more nearly constant over such paths.

A pronounced seasonal trend can be seen in most of the data, the average outage tending to be much higher in winter than in summer. To illustrate this variation, the average outages for the months of June and July, 1953, and for the months of December, 1952, and January, 1953, were computed for each circuit. The ratio and difference of these quantities are listed in Table II below.

TABLE II

LUALUALEI OUTAGE DATA

CIRCUIT		DISTANCE FROM LUALUALEI	CIRCUIT OUTAGES		DIFFERENCE	WINTER AVG. / SUMMER AVG.
			Summer Average	Winter Average		
Washington D.C.	(NSS)	7750 km	66 hrs/mo	152 hrs/mo	86 hrs/mo	2.3
Guam	(NPN)	6200 km	52 "	94 "	42 "	1.8
Tokyo	(NDJ)	6200 km	64 "	87 "	23 "	1.4
Kwajalein	(NDJ)	3950 km	17 "	35 "	18 "	2.1
San Francisco	(NPG)	3850 km	17 "	79 "	62 "	4.6
Midway	(NQM)	2200 km	50 "	26 "	-26 "	0.52

With the exception of Midway, the outage in winter is greater than that in summer.

The diurnal variations in outage show a fairly consistent trend, being higher at night than during the day, with peaks at sunrise and smaller peaks at sunset. The sunrise and sunset peaks are explained by the fact that frequency changes are more numerous during these periods, while the general increase at night is explained by the fact that because the nighttime frequencies are lower, the noise is greater and at the same time antenna gains are down at the lower frequencies. These two factors combine to reduce the signal-to-noise ratio at night.

The increase of outage in winter is therefore believed to result from the increase in nighttime hours and also from the wider range of frequencies required during winter, as compared with summer. Thus, frequency changes are more numerous and the associated outage time is greater.

The chief reason given in the logs for outage appears to be frequency change. Therefore, any scheme which reduces the time lost during a frequency change should effect a marked improvement in the overall circuit performance. One means of improvement would be to use two transmitters at the time of frequency change, both operating until contact on the new frequency is clearly established. It is understood that this method may already be employed on the Kwajalein circuit, which shows the lowest average outage of the six circuits studied.

It is not clear from the log data whether the outage time associated with frequency change should be attributed to failure of the propagation path at that time or simply to the mechanics of changing frequency. If the first is the case, then the outage might be reduced by using some auxiliary method to determine when the frequency should be changed. One particularly easy expedient would be to monitor the broadcast circuits over the same path, and determine from the relative readability of the available frequencies when the point-to-point circuit should be shifted in frequency. Another method for determining the time to change frequency is scatter-sounding, described in Appendix B. Probably it would be helpful in determining the cause of outage associated with frequency change to record in the log whether any given outage occurring at the time of frequency change is primarily the result of failure of the transmission path, or is caused by the mechanics of changing frequency.

The nighttime outage data show a fairly large proportion of outages due to atmospheric noise (QRN). Such outages could be reduced by increasing the signal strength. The antenna usage data indicate that the effective radiated power is relatively low at the lower frequencies, the antennas having the greatest gain at higher frequencies where high power is not so important. It is concluded therefore that the antennas should be redesigned to favor the lower frequencies.

CHAPTER 5

DISCUSSION OF STATION LAYOUT AND TRANSMITTER BUILDINGS

A. THE LUALUALEI SITE AND THE SATELLITE INSTALLATIONS

Chapter 2 gave a brief description of the layout and operations of the transmitting station. Here, and in Chapter 6, the various parts of the installation will be examined in detail. The points brought out here, together with those discussed in the two previous chapters, form the basis for the recommendations and conclusions summarized at the end of the report.

Like many other long-distance radio communication station, the transmitting station at Lualualei was not planned and constructed in its present form, at any one time. On the contrary, starting with a few active circuits, new buildings, transmitters, transmission lines, and antennas were added as the need for them arose. Such a procedure, while largely unavoidable, unfortunately does not lead to the most efficient use of the available land. At Lualualei, for instance, the office buildings, mess hall, living quarters, electric power substation, power transmission lines, auxiliary power generating facilities, and many other service installations occupy the most desirable area for the location of high-frequency antennas. In order to conserve the remaining areas for antenna construction, additional buildings which might be constructed in the future should, insofar as possible, be located near the station boundary unless the contemplated building site is well within the already densely built-up area. The vicinity of the station boundaries nearest to the mountains is generally undesirable for the location of directive antenna systems, and, therefore, is suitable as service area. A site closer to the mountains for the v-l-f station would have led to better utilization of available space since the proximity of mountains is not an important factor at v-l-f. The choice of the present site was probably dictated, however, by the minimum allowable spacing between this installation and those of the Naval Ammunition Depot. The number of radiators which must be provided is prescribed by the number of circuits served by the station. The permanent man-made structures together with the other features of the terrain limit the maximum possible separation which can be achieved between adjacent antenna systems As will be pointed out presently, this separation will often have to be smaller than is desirable for the best operation of the circuits. In spite of these undesirable features the Naval Radio Station at Lualualei compares favorably with other such stations, both military and commercial, which were inspected in the course of this investigation.

As explained earlier, the transmitting station consists essentially of three separate locations: the v-l-f station, and Buildings No. 1 and No. 68 where the l-f, m-f, and h-f transmitters are housed. Little need be said about the v-l-f installation. The antenna system and transmitter were designed, erected, and tested as a unit and the installation appears to be working satisfactorily at the present time.

The relay stations for the v-h-f link also require little discussion. The installation on Mauna Kapu consists of two separate buildings. One of these contains the receivers and transmitters for the Pearl Harbor-Lualualei link, the other for the Wahiawa-Pearl Harbor link. The relay station at Kolekole Pass is used for v-h-f communications between Wahiawa and Lualualei. The latter link is required since keying of the transmitters at Lualualei, which are used for ship-to-shore communications, takes place at the Wahiawa receiving station. Except for the fact that the antennas are not sufficiently protected against corrosion, these relay links have operated with a high degree of reliability over a period of many years. The chief drawback of the system is the fact that further expansion of facilities in the 100-200 Mc range is virtually impossible. Plans are therefore currently in preparation for the installation of microwave links as replacements for the v-h-f equipment now in use. The new installation will have sufficient capacity to handle the increased traffic which may be required in the future.

Since industrially-generated r-f noise may interfere with the operation of the v-h-f links, a brief survey of possible sources of such noise was undertaken. The electric-power substation located at the western boundary of the Lualualei site was found to be the major source of r-f noise. Salt and dust deposits on the insulators cause leakage currents to flow over the surface of the insulators, and it is these currents that produce the noise. This was confirmed when, after a cleaning of the insulators, the noise disappeared. However, no interference with the reception over the v-h-f links has been observed in the past, and since such noise does not disturb any other functions of the station, the probable reappearance of this noise should not hamper operations of the station as long as it is utilized only for transmitting.

D. RADIO TRANSMITTER BUILDING (HF) (BUILDING NO. 1)

Building No. 1 is the earliest transmitter building at Lualualei. It is octagonal in shape, and therefore does not realize the best utilization of available space. Twenty-three transmitters are presently installed on the main deck. These serve the point-to-point circuits to the east as well as a number of the broadcast circuits. Two of the transmitters formerly installed at the center of the building have recently been moved to spaces nearer the outside walls. Before this rearrangement, three Marconi antennas for use at l-f and m-f frequencies passed through the cupola at the center of the roof. This resulted in coupling between the output circuits of the three transmitters feeding these antennas. With the new placement of transmitters, only a single Marconi antenna passes through the cupola, thus reducing by a considerable amount the undesirable coupling between circuits. The layout of equipment in Building No. 1, as at this time, is shown in Fig. 6. Terminal equipment for the v-h-f links is installed in the basement of the building.

The main point-to-point circuits for which equipment is now provided at Building No. 1, are those to Washington, D.C. and San Francisco. Both of these circuits make use of single-sideband (SSB) multiple channel teletype transmissions. Two transmitters (TEF) designed for this type of modulation are available, one for each of the two circuits. During routine maintenance, or in case of equipment failure, frequency-shift keying must be used, with a consequent reduction of the number of signal channels which can be multiplexed for simultaneous transmission at one carrier frequency. The SSB transmitters are rated at 2-kw power output. A 50-kw power amplifier (TPA) is available for use with the TEF transmitter. Such amplifiers are now in permanent use on the Washington and Guam circuits.

Changes in the division of circuits between Building No. 1 and Building No. 68 have recently been proposed by the staff of Lualualei. It is contemplated to move the Washington circuit from Building No. 1 to Building No. 68, and to move the Guam circuit from Building No. 68 to Building No. 1. Two additional SSB transmitters which are presently in in storage would also be installed in Building No. 1. One of these would

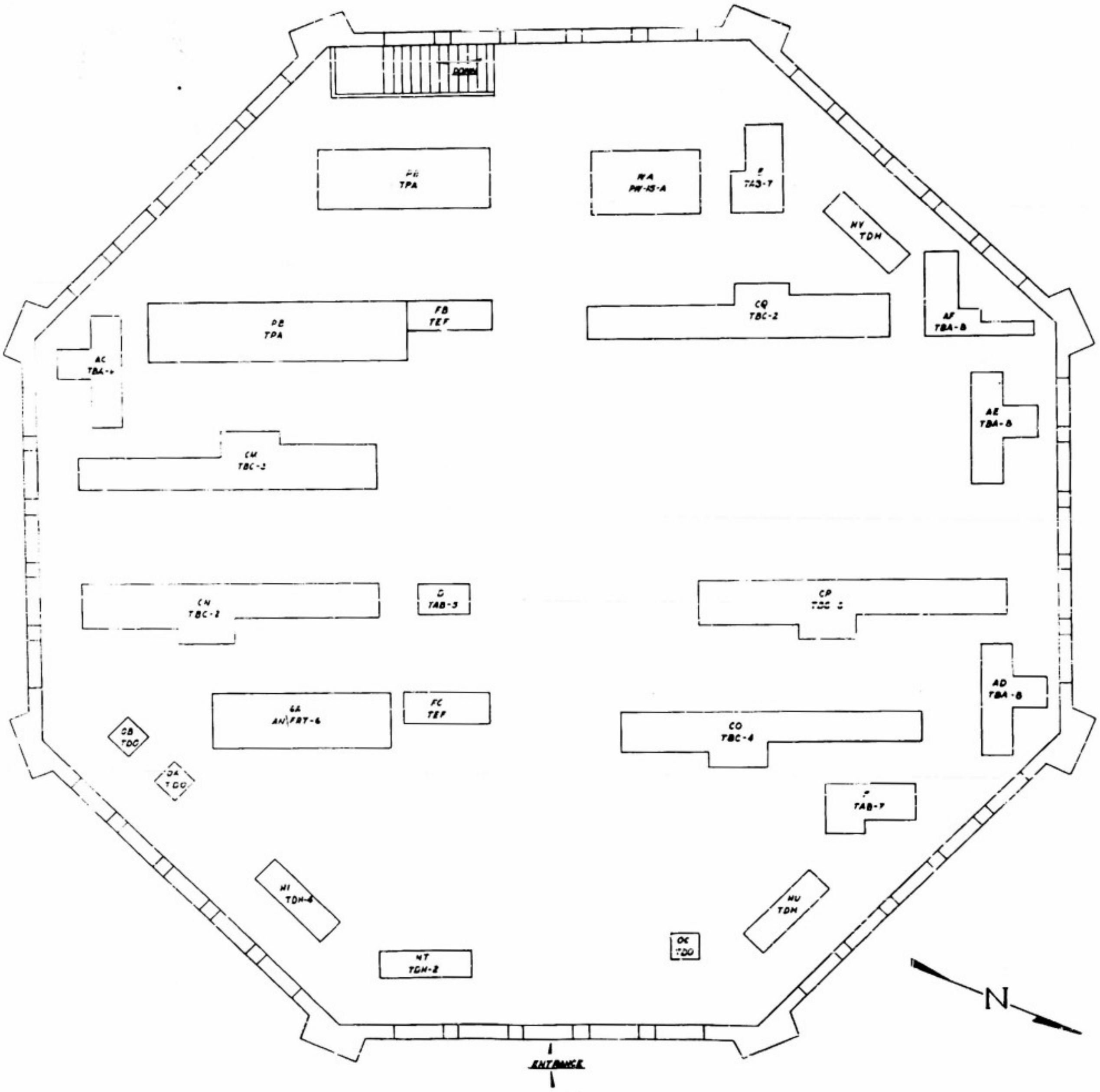

FIG. 6

EXISTING EQUIPMENT LAYOUT FOR BUILDING NO. 1

(RADIO TRANSMITTER BUILDING HF)

convert the Tokyo circuit to SSB operation. The fourth of the SSB transmitters would be available as a spare for any of the other three circuits during maintenance or breakdown of the normally used transmitters. A single power amplifier could be connected to any of the four transmitters if the need arose.

While the rearrangement of circuits and transmitters just outlined would provide more efficient use of the available SSB equipment it is recommended that these plans be modified in a number of respects Transmission paths to Washington from antennas located in the vicinity of Building No. 68 are intercepted by the mountains. Terminals for the circuits to the east should therefore remain at Building No. 1 Futhermore, Building No. 68 would still contain only one SSB transmitter and power amplifier with no available alternate SSB circuit in case of breakdown. Finally, the tying down of a power amplifier to a single circuit does not make the most efficient use of this equipment.

The contemplated changes do, however, suggest a rearrangement of equipments in Building No. 1, which would offer a number of advantages. It is proposed that all three SSB transmitters presently in operation as well as the two new SSB transmitters now in storage, be installed in this building The power amplifier now used for the Guam circuit in Building No. 68 would also be moved to Building No. 1 together with the TEF transmitter. In order to provide room in Building No. 1 for the additional power amplifier, one of the TBC transmitters (CP) could be moved to Building 68. Figure 7 shows the floor plan with the proposed changes in equipment layout. In summary, SSB transmitters for the Washington, San Francisco, Tokyo, and Guam circuits would all be located in Building No. 1. An additional SSB transmitter would be available for service on any of these circuits in case of breakdown of the regular equipments. The two power amplifiers would work in conjuction with any of the five SSB transmitter, whenever needed.

The concentration of all SSB transmitters and circuits in Building No. 1 has the following advantages:

(1) By proper scheduling of shutdowns for routine maintenance, a considerable reduction in the outages of the SSB circuits could be achieved since a spare SSB transmitter would be available.

(2) None of the power amplifiers would be permanently tied to a given transmitter as is presently the case for the Guam and

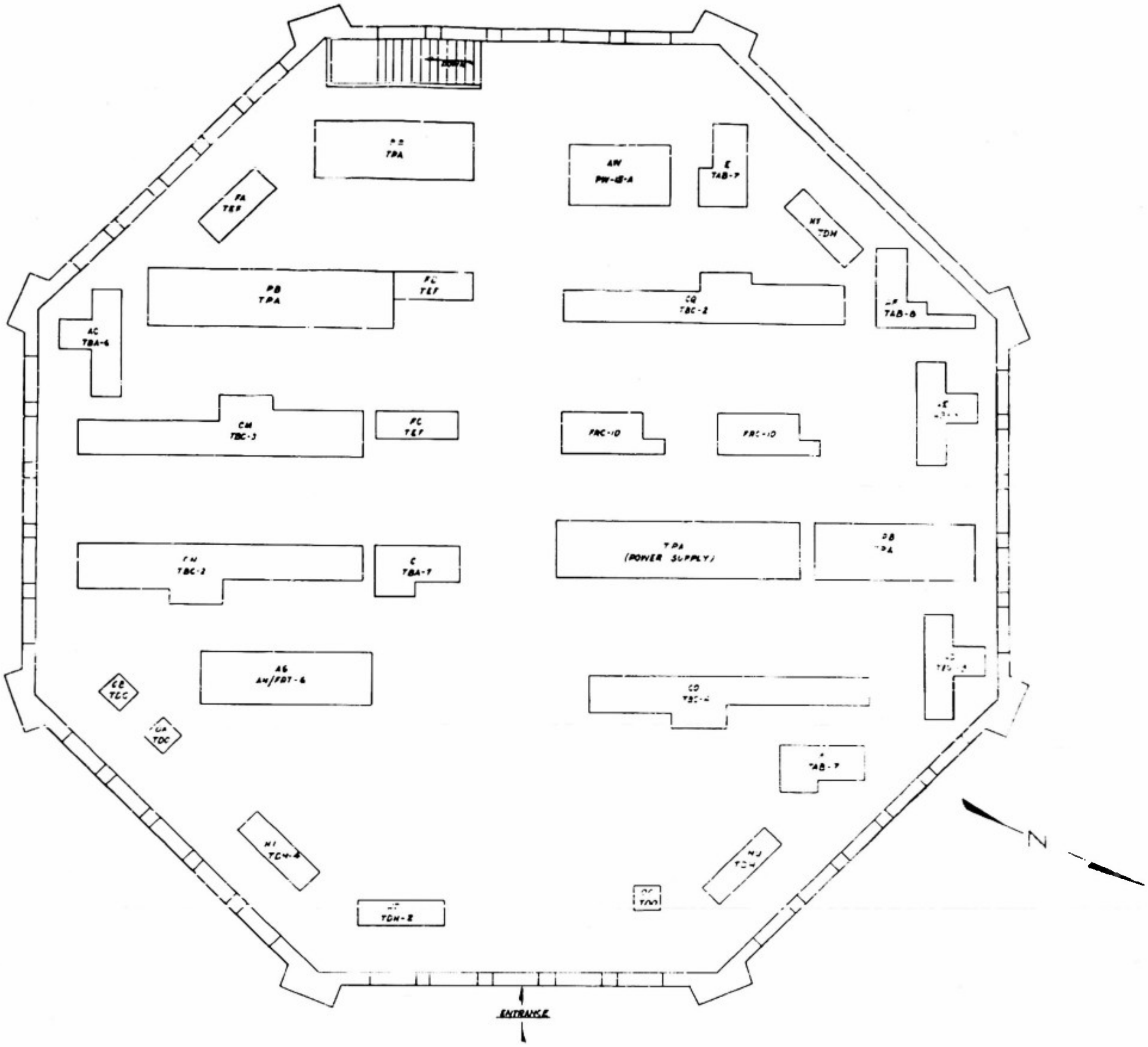

FIG. 7
PROPOSED EQUIPMENT LAYOUT FOR BUILDING NO 1
(RADIO TRANSMITTER BUILDING HF)

Washington circuits, or as would be required were the Washington circuit removed to Building No. 68. The sharing of power amplifiers between all possible circuits insures the most effective use of the 14-db power gain which can be achieved by these means. As explained in Chapter 3, it is quite possible that the additional power may be more urgently needed on a circuit operating at a low frequency over a relatively short range, rather than for transmissions at a higher frequency over longer distances. If the power amplifier is permanently made part of a single circuit, it may often stand idle or be used in cases where the extra gain does not enhance the reliability of the circuit.

(3) The concentration of the SSB transmitters in one location facilitates servicing of this rather specialized equipment.

(4) Space is available in the area about Building No. 1, for the additional directive antennas required in this relocation of circuits. At the same time, removal of point-to-point circuits from Building No. 68 would relieve the congestion of antennas in the vicinity of this building.

The antenna for the original l-f transmitter formerly housed in Building No. 1 was suspended from three steel towers. These 300-ft high towers are still standing, although the antenna for which they were intended has been removed. The base of the towers forms an equilateral triangle with sides equal to 750 ft, and the building is located half-way between Towers #2 and #3, as shown in Fig. 1. These three towers provide the only adequate support for antennas in the l-f range, no other supports of sufficient height being presently available anywhere else at Lualualei. It is therefore recommended that the m-f circuit now operating at a frequency of 500 kc from Building No. 1 be transferred to Building No. 68 where an antenna adequate for this frequency can be suspended from standard 120-ft poles. If it is desired to retain transmitter D for the 500-kc circuit, it should be moved to Building No. 68 and the l-f transmitter (C) now in this building could then be installed in Building No. 1. This change is indicated in Fig. 7. It should be noted that the three steel towers will support a maximum of three l f antennas. If more l f circuits are required additional structures of sufficient height should be erected.

Every transmitter must be provided with a good ground connection, as a safety measure for the operating personnel as well as to complete the electrical circuit. In practice, a grid of copper wires is buried under the building and this grid is continued out to a distance away from the building, sufficient for the currents in the wires to have reached negligible values. When vertical antennas are used, such as the Marconis, the system of ground conductors is required in order to increase the antenna efficiency.

The original l-f antenna suspended from the towers in the vicinity of Building No. 1 was provided with a ground system which is believed to be still in place. This ground system consists of a parallel grid of No. 10 B & S gauge copper wires spaced 12-½ ft apart. The grid covers a triangular area which reaches between 150 and 200 ft beyond the area formed by the base of the towers.[*] According to the drawing just referred to, this grid is continuous underneath Building 1 and in its immediate vicinity. The ground system in the building itself is made up of two parts. The first of these consists of thirteen, 1 × 1/8-in. copper straps that extend radially outwards from the center of the building to 10 ft beyond the building line.[**] A second ground system consisting of similar copper straps is laid in the drain trenches in the basement of Building No. 1. At the present time, the ground connections from the transmitters are made to the straps in the drain trenches. From the two drawings just mentioned is not clear if or how these three ground systems are interconnected, nor could this be ascertained during inspection of the site. Furthermore, parts of the ground system may have been changed without recording such changes Inspection of the basement of Building No. 1 revealed only about four of the indicated 13 radial conductors; it is not known whether the others are buried in the walls or have been removed entirely.

Apart from the uncertainty of the exact configuration of the ground system, the ground connections of the transmitters are unsatisfactory for two reasons. First, the transmitter deck is elevated by roughly 10 ft, with respect to the copper grid in the basement to which ground connections are made. Radio-frequency currents flowing between transmitter and ground set up fields which induce currents in the grounding straps of other transmitters. In other words, the whole transmitter floor is not only physically, but electrically above ground level by an appreciable amount as far as r-f energy is concerned. Currents from different transmitters, flowing to ground in close vicinity to each other, as is the case here, will produce strong coupling between the various equipments. It may be noted that such currents from transmitter to ground not only flow when unbalanced output circuits are used, but are also produced by any unbalance in the systems using nominally balanced outputs. Intercoupling between equipments is one of the chief causes for emissions at spurious frequencies and should therefore be avoided as much as possible, for this as well as other reasons.

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[*] See P. W. Drawing No. OA-N11-126 May 17, 1935, 14th Naval District, Pearl Harbor, T. H. "Ground System for High Frequency Antennas (Bldg. 1)," NRS Lualualei, Oahu, T. H.

[**] See Y & D Drawing No. 118,763, May 27, 1934, U. S. Naval Radio Station, Lualualei, Oahu, T. H. "Inter-and High-Frequency Transmitter Building Plans."

The second reason for considering the present ground system within Building No. 1 as inadequate is its geometrical structure, which consists of conducting loops and straight sections large enough to resonate at some of the frequencies used for transmission. This again produces coupling between transmitters as well as power loss. As a solution it is suggested that the present ground system within Building No. 1 not be used for r f ground connections. Instead it is proposed that the ceiling of the basement be completely covered with copper sheeting or a copper screen. All ground terminals of the transmitters should be connected to this sheet instead of making connections to the ground system in the basement. The copper sheet, in turn, must be joined to the existing ground grid outside the building. This can be done by utilizing copper straps laid out in the same fashion as the radial ground system shown in Y & D Drawing No. 118,763. Connections between these radial conductors and the parallel wire grid can be made at any convenient point outside the building. Care should be taken to connect each of the radial conductors to a different wire of the grid, to prevent the formation of new large conducting loops in the ground system.

In the discussion of the ground system outside of Building No. 1 it was assumed that the parallel wire grid is still in place and covers the area shown in Drawing No. OA-N11-126. From the date of the drawing one can conclude that this system of conductors has been buried in the ground for at least 17 years. The possibility that much of the system has disintegrated during this time through electrolytic action in the soil must not be overlooked. The ground grid may also have been damaged by excavations or plowing in the area. A check should therefore be made to ascertain the present status of the exterior ground grid.

The efficiency of the ground system for use with the l-f antennas can be increased by terminating each of the wires of the grid in ground rods which should reach to the permanent water level.[1] About 180 such rods would be required. However, no quantitative method is available to estimate the amount of improvement which could be achieved by the use of such rods, and since the l-f coverage appears to be satisfactory at the present time, the addition of the vertical rods to the ground system does not seem to be economically justified.

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[1] E. A. Laport, *Radio Antenna Engineering*, p. 50; McGraw Hill Book Co. Inc ; 1952.

The next topic which must be considered is that of switching between antennas and transmitters. Switching is required since it is impractical to connect each transmitter permanently to a given antenna. The switches that have been constructed at Lualualei work in conjunction with the balanced transmission lines and antennas. The lines from as many as ten transmitters are stacked vertically on an H-frame made of two poles. This frame is at the center of an arc of a circle, and the transmission lines to the antennas terminate at points on this arc. Lengths of transmission lines are used to connect the transmitters to the desired antennas. The links are permanently attached to the lines at the transmitter end of the switch, and connection at the antenna end is made by means of a hook and eye arrangement. This type of switch has many advantages: it is mechanically simple and rugged; a large number of different combinations of transmitters and antennas are possible; and, most important, adequate spacing of lines can be maintained throughout to prevent coupling between equipments. The switch suffers from one important disadvantage; a link attached at a higher point of the H-frame cannot readily be moved across a link attached at a lower point without disabling the circuit of which the lower link forms a part. From a purely topological point-of-view it is possible to pass either over or under intervening links in the switching operation and so avoid interrupting any of the circuits except the one which is being switched. In practice this may be difficult to carry out in a manner safe to both personnel and equipment. The study of a scheme whereby all switching could be performed without interruption of other circuits seems, however, to be clearly indicated.

Only two switching stations are now in operation near Building No. 1, neither of which is used to capacity. To implement the changes in circuit assignment and transmitter layout in Building No. 1, as described earlier, more switching facilities will be needed. At least one, and preferably two, additional ten-position switches should be constructed near the northern half of the building. To make full use of the potential interchangeability of SSB transmitters between the various circuits, means must be provided for interconnection of the switches. The following scheme for accomplishing this is suggested (Fig. 8). Position 10 on the antenna side of Switch No. 1 is permanently connected to the lowest position on the H-frame of Switch No. 2. Position 10 on Switch No. 2 is similarly connected to the lowest position on the H-frame of Switch No. 3. This is continued to complete the ring around the building. With the added

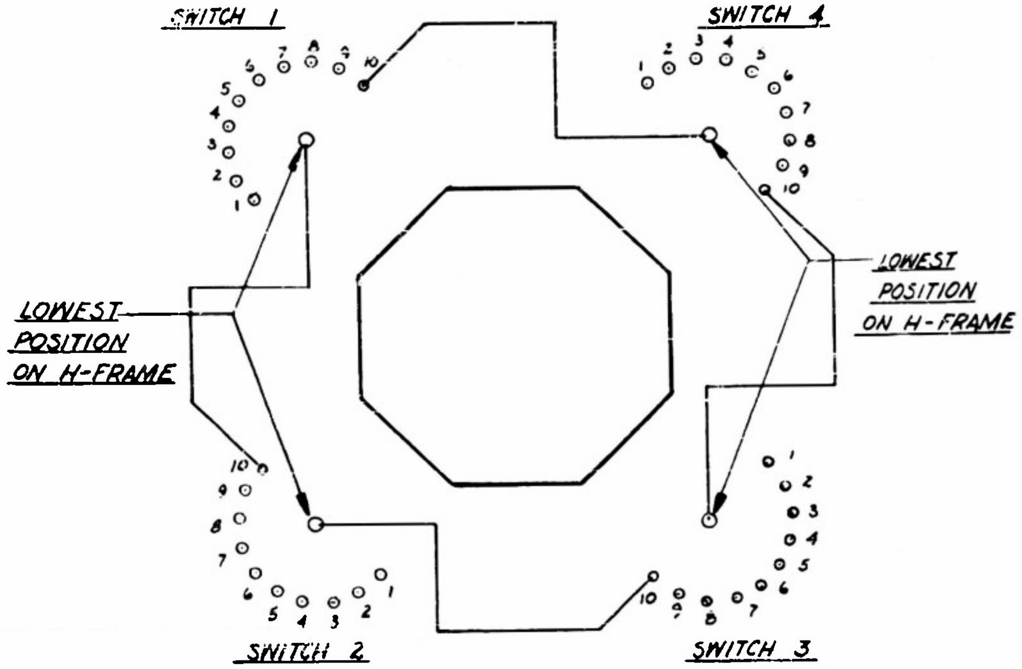

FIG. 8

INTERCONNECTION OF TRANSMISSION LINE SWITCHES

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switching capacity suggested above, a second such ring can be provided by connecting Position No. 9 to the second lowest position on the H-frame of the adjacent switch and so on. This arrangement will interfere, by the least amount, with the normal operation of each switch.

The arrangement of transmitters in Building No. 1, as described earlier, offers maximum advantages only if every one of the five SSB transmitters can be used in conjunction with the two power amplifiers. Additional switches must therefore be installed inside the building. The simplest type of switch for this purpose is the "Mare Island" switch, one of which is presently in use in Building No. 68.

C RADIO TRANSMITTER BUILDING (LU-4) (BUILDING NO. 68)

The Transmitter Building (LU-4) is both newer and larger than the HF-Building. The major share of the broadcast signals, as well as those signals for the point-to-point circuits beamed to the west are transmitted from here. The building consists of four wings in the shape of a cross. A large room at the center of the cross houses transmitters as well as the control console for the entire building. From this central hall every transmitter within the building can be seen. Although a total of 68 transmitters are housed in Building LU-4, ample clearance is maintained between equipments. As may be seen from this brief description, Building No. 68, in contrast to the Building No. 1, was carefully planned for the purpose for which it is used.

The layout of equipment is quite similar in each of the four wings of the building. This provides a considerable amount of flexibility in the assignment of transmitters to specific circuits. Two changes in equipment layout which are recommended have already been mentioned. These consist of the removal of the SSB transmitter (FA) and its associated power amplifier (PA) to Building No. 1. The space made available in the west wing by this move is to be filled by the transmitter (CP), for which room would no longer be available in the Building No. 1. The unsuitability of Building No. 68 for l-f transmitters has also been discussed. If use of the older transmitter (D) for emergency transmissions at 500 kc is to be continued, it should replace transmitters B or C, one of which would be removed to Building No. 1. Towers of adequate height should be constructed in the vicinity of Building No. 68 if it is to be permanently used for the housing of l-f transmitters. No other changes in the equipment layout seem indicated, even if the changes in antenna layout to be described later are carried through. Figure 9 shows a possible floor plan of Building No. 68, incorporating the changes in transmitter layout just mentioned.

The north wing of the building contains three banks of five transmitters each, (TDN), which require special attention. Each bank operates from a common power supply; balanced output terminals are provided at present, and since the transmitters are physically small in size, the five pairs of output terminals are very close to each other. Coupling between the five transmitters in a bank is so close that it is difficult to operate all of them simultaneously. Reference to the equipment instruction manual will show that these transmitters are basically designed for unbalanced outputs; an unbalance-to-balance network has been added to give

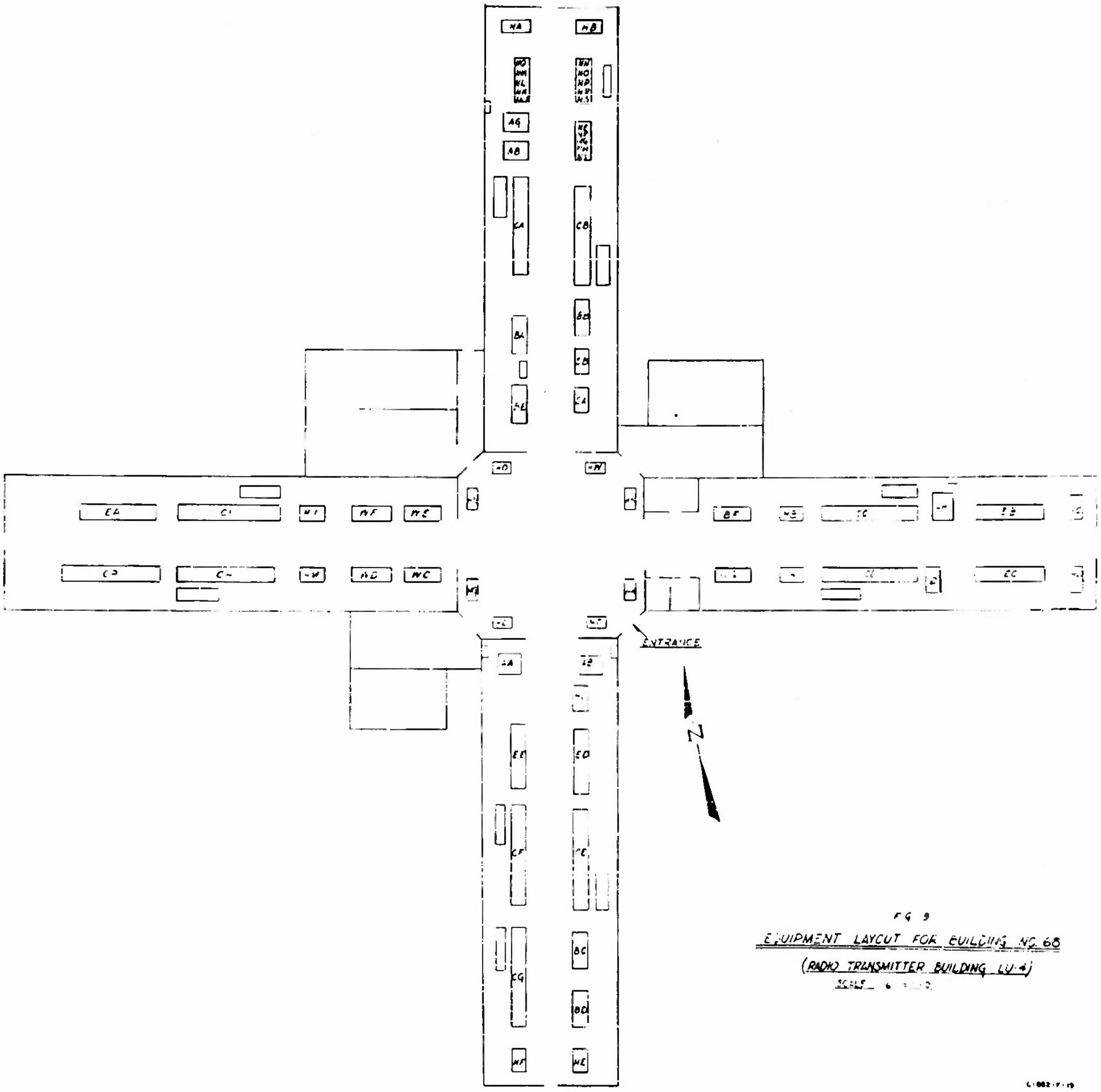

FIG 9

EQUIPMENT LAYOUT FOR BUILDING NO. 68

(RADIO TRANSMITTER BUILDING LU-4)

SCALE [illegible]

G-002-F-19

the present configuration Much of the inter-coupling is undoubtedly due not only to the close proximity of the output terminals, but also to the residual unbalance in the output circuit. It is therefore recommended that the TDN transmitters be converted to unbalanced output configuration. The r-f power delivered is only 2 kw so that coaxial cable can be used to feed the required vertical antennas. Cable with a characteristic impedance of 70 ohms, such as RG-85A/U is suitable for this purpose.

Detailed drawings of the ground system for Building LU-4 are available.* The exterior grid consists of radial wires spaced 5 degrees apart, which extend 265 ft away from the center of the building. The ground system inside the building is made of a rectangular grid of copper straps at the same level as the transmitter deck. The loops of this grid are too small to cause serious intercoupling between transmitters, provided good connections are maintained at all joints of the various members of the ground grid. A check for damages to the exterior grid has already been started.

Four ten-position switching stations of the type described above are located on the bisectors of the angles formed by the wings of the building; two more switching stations have been built but these are not yet in use. The capacity of these six switches appears to be adequate to provide the required flexibility in the operation of the circuits served by the transmitters in Building LU-4. It is suggested, however, that one of the switch positions be used for interconnecting the switches in the manner described earlier, so that alternate connections are available in case of serious breakdown of transmitter equipments.

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* P. W. Drawing No. OA-N11-338, 19 April 1944, "Naval Radio Station Lualualei, Oahu, T. H. Transmitter Building, Plan Ground Grid," 14th Naval District, Pearl Harbor, T. H.

CHAPTER 6

ANTENNAS AND FEEDER SYSTEMS

A ANTENNA AND FEEDER REQUIREMENTS

In fulfilling the Navy requirements for antenna systems a number of factors quite aside from purely electromagnetic aspects must be considered before the relative merits of possible configurations can be established These factors arise because the antenna is an element of a communications system and as such must be integrated into the system requirements If the system is complex then consideration must be given to the multiplicity of operational requirements Specifically, the following items should be examined as an aid in making a choice to determine if a particular antenna will satisfy a given set of requirements

(1) Polarization
  (*a*) Horizontal
  (*b*) Vertical
(2) Radiation pattern requirements
  (*a*) Azimuthal coverage
  (*b*) Vertical coverage
(3) Bandwidth (pattern and impedance)
  (*a*) Broadband
  (*b*) Narrow band
(4) Impedance level and power capability
  (*a*) Balanced feed
  (*b*) Unbalanced feed
(5) Efficiency
(6) Structural complexity and physical size
(7) Cost

As a consequence of the random polarization of ionospheric waves due to changes in transit, the polarization of the transmitting antenna need not be dictated by the characteristics of the remote receiving antennas

There are however several factors which must be considered when making the choice between a vertically or a horizontally polarized radiator. The first is the manner in which the radiation pattern characteristic is related to antenna configuration This is discussed in some detail in a following section A second factor to be considered is that of achieving short-range coverage (within several hundred miles) by the effective utilization of ground wave propagation Over sea water, which has the best conductivity afforded by nature substantial distances can be covered with frequencies up to 5 Mc or even higher This fact has often been utilized for inter-island communication and for short distance ship-to-shore-communication, particularly in harbors and estuaries In such applications vertical polarization gives best results and the station sites should be near the shore to avoid excessive attenuation over land

The principal difference between antennas utilized for broadcast and those used for point to point service lies in the required radiation pattern characteristics While the gain of 10 to 20 db that can be achieved through the use of directive arrays in point to point service does not overcome the vagaries of the ionosphere in its effect on signal transmission, it may often mean the difference between reliable and marginal communication In broadcast applications where the receiving stations are randomly disposed in azimuth and range such antenna gains are not possible if the general coverage requirements are met

It is well known that the radiation pattern characteristics of a particular antenna configuration are dependent upon frequency This imposes certain limitations on the bandwidth over which the antenna may be used Rhombic antennas for example have impedance characteristics that are very constant over an 8:1 range in frequency and yet variations in the vertical radiation pattern restrict the use of this antenna to bandwidths on the order of 2:1 Similarly with most other types of antennas whether horizontal or vertical pattern degradation imposes band limits on the range of operation

Pattern degradation is in general a relatively slowly varying characteristic when compared to limitations encountered by the terminal-impedance variation It is this latter characteristic that usually differentiates a narrow-band antenna from one that is considered broadband Since the antenna is often physically removed from the transmitter by distances ranging from a few wavelengths to many wavelengths some form of low-loss transmission line must be utilized for the feeder system This line will be an aperiodic system only when it is correctly terminated in its characteristic impedance. Thus, if the antenna impedance at the feed point differs from the characteristic impedance of the line, standing waves occur with resulting higher losses and high potential points on the line. Furthermore, the input impedance to the line seen from the transmitter will no longer be the line impedance but will be a function of the mismatch between the antenna and line. If this mismatch is such that a 2:1 voltage standing wave ratio (VSWR) appears on a 600-ohm line, then the transmitter must be capable of matching from 300 to 1200 ohms of resistance, including the reactance which is associated with such a load. This is a reasonable limit to impose on a two wire open line for power levels up to 50 kw. In solid dielectric coaxial cables such as RG-20A/U the added losses resulting from standing waves limit the power handling capability of the line. Such lines are capable of handling 12.5 kw with unity VSWR, while the maximum power under conditions of 3:1 VSWR is reduced to the order of 5 kw.

While it is possible to achieve a wide range of characteristic impedances in both balanced and unbalanced transmission lines, it is usually at the expense of having to choose complex multiple wire configurations. The advantage of the inherent simplicity of solid dielectric coaxial lines and two-wire open lines usually outweighs the disadvantage of the restricted impedance ranges they afford. Nominal characteristic impedances of 50 to 70 ohms are common in commercially available solid coaxial cable while 600 ohms represents an impedance level that is most common in open-wire balanced lines with conductor sizes and spacings that are capable of handling power levels of up to 50 kw.

The maximum intrinsic bandwidth and efficiency of a system involving an antenna and feeder usually occurs when the respective impedances are equal and therefore self matching. In many cases it is possible to design the antenna for an impedance that will fit a particular feeder impedance. When this cannot be fully achieved, it is sometimes possible to employ wide band coupling circuits between the antenna and line for impedance matching. In narrow-band applications, it is possible to obtain terminal matching by any one of a number of methods. The most common are

(1) Shunt stub sections
(2) Tapered transmission lines
(3) Lumped reactance networks
(4) Coupled line sections
(5) Series line sections of proper characteristic impedance

While there are numerous methods of accomplishing a balance-to-unbalance transformation in a feeder line, most of them introduce frequency selectivity. The obvious advantage of keeping the number of frequency-selective elements to a minimum leads to a natural selection of balanced feeders for balanced antennas, and an unbalanced line for unbalanced antennas, whenever possible. The other important factor which has been discussed previously is that of keeping the driving-point impedance of the antenna matched to the characteristic impedance of the line. Thus, for balanced antennas it is necessary to keep the driving-point impedance near 600 ohms, while for unbalanced antennas it should be kept near 50 or 70 ohms. (RG-20A/U has a nominal impedance of 50 ohms while RG-85A/U is a 70-ohm cable. These cables introduce approximately 1 db of attenuation per 100 ft at 10 Mc.)

In addition to losses imposed by transmission lines and matching devices, losses in the antenna proper must be accounted for in examining the system efficiency. Most resonant h-f antennas, whether broadband or narrow band, are inherently highly efficient; i.e. the ratio of power radiated to power dissipated is high. There are some notable exceptions to this, however: a vertical unbalanced antenna working against a poor ground system may induce very high losses in the soil, or an aperiodic antenna such as a terminated folded dipole in which lumped resistive loading is used to achieve broadband impedance characteristics, may dissipate more than 90% of the power in the load while radiating less than 10%.

The versatility of broadband antennas at radio stations having a large number of operating equipments and frequencies hardly needs emphasis. Use of these antennas, together with a well-engineered switching system, permits high equipment utilization and flexibility of station operations.

It is unfortunate that to a certain extent the structural complexity and cost of h-f antennas is directly related to their bandwidth. Simple dipoles pose no great design or installation problems. They are, however, virtually single-frequency radiators. Broadband radiators represent a much larger investment in effort, cost, and space than their narrow-band counterparts. The increased operational efficiency and versatility afforded by a well-integrated system of both narrow and broadband antennas at stations the size of Lualualei certainly justify the investment. With larger and larger traffic volumes to be handled, the compromises employed in the past for economic expediency may no longer be tolerable in the future.

B. BROADCAST ANTENNAS

In the preceding chapter certain factors which influence the choice of antenna configurations were discussed. In this section, specific configurations will be examined in detail, with respect to their advantages and shortcomings. While it is a little misleading to place general values on the bandwidth of any antenna and feeder system, it is advantageous to discuss the narrow and broadband systems separately. No general criterion has been established for the bandwidth requirements of a broadband antenna. However, there is a well-defined gap between simple radiators such as half-wave dipoles or folded dipoles, and the more complex structures such as quadrants or discones. These latter configurations have bandwidths in excess of five times that of the simple structures.

The geometry of sky waves has been discussed in detail. From this study, certain conclusions were drawn regarding favorable vertical-pattern requirements with emphasis on providing complete coverage from close range, to distances in excess of 4000 km at all azimuth angles. These conclusions must of necessity include all anticipated conditions of the ionosphere accounting for epoch of the sunspot cycle, time of year, and time of day. In summary, if frequencies of approximately 4, 8, 12, 16, and 20 Mc are simultaneously keyed to provide area coverage, we may generalize to the following extent:

(1) Frequencies below 5 Mc using ground-wave coverage
    Distance range: 0-400 km
    Vertical polarization. Desired vertical sector 0°-60°

(2) Frequencies between 4 and 8 Mc, mainly sky-wave coverage
    Approximate distance range: several hundred to over several thousand km
    Horizontal polarization. Desired vertical sector, 10°-60°

(3) Frequencies between 12 and 16 Mc, mainly sky-wave coverage
    Approximate distance range: 1200-4000 km or greater
    Horizontal polarization. Desired vertical sector, 8°-45°

(4) Frequencies above 20 Mc, mainly sky-wave coverage
    Approximate distance range: 2000-4000 km or greater
    Horizontal polarization. Desired vertical sector, 8°-30°.

Admittedly, ionospheric propagation is extremely complex and generalities are not reliable. Ionospheric turbulence, wave trapping, refractions and reflections, and scattering in space and at reflection points on the earth all contribute to unpredictability. However, it can be said that there is a sufficient amount of successful engineering experience available to justify the specification of desired vertical sectors, and to further stipulate that the radiation patterns within these sectors should be reasonably uniform and free of deep nulls.

The coverage requirements in the vertical directions at the various frequencies can, of course, not be met exactly without going to entirely uneconomical antenna structures. In general, vertical radiators less than a half-wavelength long provide good patterns for the launching of ground waves, and they give adequate coverage at all angles of elevation up to about 60 degrees from the horizontal. Such antennas are therefore most advantageous at l-f, m-f, and at the lower end of the h-f band. Some control of the radiation patterns of horizontal antennas can be achieved by varying the height above ground at which the antennas are suspended. A horizontal doublet elevated by a half-wavelength provides good vertical coverage from about 10 to 40 degrees, and adequate vertical coverage up to 60 degrees. Increased gain at particular angles can be obtained by raising the doublet more than this amount. This is achieved, however, at the expense of the breakup of the pattern into sharp lobes. A height of a half-wavelength above ground is therefore the best possible compromise.

1. NARROW-BAND ANTENNAS

a. DELTA-MATCH DIPOLE AND STUBBED SERIES-FED DIPOLE

A series-fed half-wave dipole has a driving point impedance which is approximately 70 ohms, but may vary from 60 to 100 ohms depending upon the height above ground. Like any resonant circuit, a half-wave dipole has a certain natural selectivity. This is, of course, manifested by the manner in which the resistance and reactance change with frequency in the operating range. The resistance is a much slower varying quantity than is the reactance. The fundamental bandwidth may be defined as the band of frequencies in which the magnitude of reactance does not exceed the resistance. It is more convenient, however, to define the bandwidth as the range of frequencies in which VSWR does not exceed some prescribed value. The selectivity is greatly affected by the conductor size, or more precisely by the ratio of length to diameter of the conductors forming the antenna. As a typical example, the use of No. 6 wire for half-wave dipoles will give a bandwidth of approximately 5% at 4 Mc. Such an antenna could therefore be used only at frequencies within 200 kc of this design frequency

Since the half-wave dipole is a balanced configuration and has a terminal impedance less than 100 ohms, some form of impedance transformation is necessary if it is to be driven from a 600-ohm balanced line. Either of two methods are commonly used: first, the so-called delta-match in which the antenna is shunt fed by fanning the feeders out to points equidistant from the center and approximately one-eighth wavelength apart for a 600-ohm line. A good match in general requires that final adjustment be made in actual operation, under reduced power. The disadvantage of this system is the critical nature of the dimensions involved, and the fact that it limits the operation to a narrow band of frequencies near the natural resonance of the antenna. Furthermore, unless careful adjustment is made at the tap points of the antenna, a shunt stub on the transmission line may be required to reduce the VSWR to a tolerable value. A second method of matching the non-resonant line to a half-wave dipole is through the use of a shunt stub at the appropriate point on the line. Again, final trimming must be accomplished by operation at the desired frequency, under reduced power. Both of the above systems require a good deal of time and effort if reasonable results are to be achieved. In addition, both suffer from the same limitations of being very narrow band devices.

Another limitation inherent in single-wire radiators is that of the power-handling capacity. In general, the power-handling capacity is increased by the same methods that are used to increase bandwidth, i.e. either increased conductor size or the use of multiple conductor configurations. Since power limitations are established by corona potentials, any reduction in potential gradients through the use of thicker elements permits increased power input.

A final important consideration, and one that is common to all balanced half-wave horizontally-polarized dipoles, is that of the radiation pattern characteristics. As previously discussed, the pattern requirements for the broadcast application are such that reasonably uniform azimuthal radiation is desired within a prescribed vertical sector. The limits of this conical sector are established by the range of distances to be covered and the geometry of the ionosphere. Since the vertical-plane radiation characteristics of a horizontal half-wave dipole are greatly influenced by the height above ground, it is important that this dimension be optimized for each installation. The ground constants have some influence on the pattern and field strength, but for these antennas with heights greater than 0.2 of a wavelength, the effects are of second order. For all requirements except those in which very low angle radiation is desired, a distance of a half-wavelength above ground is almost always optimum. It is therefore recommended that presently installed dipole type antennas be suspended at that height whenever possible. At the lower frequencies, poles of sufficient height may not be available. The height above ground of the antennas should then be the highest attainable. When wave angles of 5 degrees are important, the height may be increased to 0.6 or 0.7 of a wavelength. However, serious departure from omnidirectivity is coupled with low-angle radiation from this type of antenna. At wave angles of 15 degrees or less, very little radiation takes place in horizontal sectors off either end of the dipole.

b. FOLDED DIPOLES

The foregoing statements concerning pattern characteristics of half-wave dipoles also apply to half wave folded dipoles. The major differences and advantages of the latter are with respect to the ease in matching to high-impedance lines, the higher power-handling capability and the slightly greater natural bandwidth.

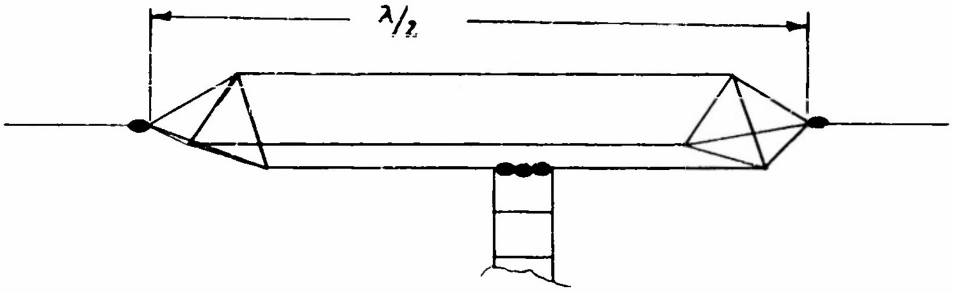
The driving-point impedance of a folded dipole is controllable over a relatively wide range by the appropriate selection of the number, spacing, and radii of the conductors. The two most common configurations are the simple two-wire and three-wire dipoles. These two types are illustrated in Fig. 10. It is most practical to use equal-radius wires and equal spacing. Using No. 6 wire and spacings on the order of 12 to 16 in. between elements, the two-wire version has a driving-point impedance of approximately 300 ohms, while the three-wire dipole has an impedance near 600 ohms. Both of these antennas have bandwidths which are slightly larger than single-wire dipoles, first because of their cage equivalence and secondly because a direct match is permissible to the feeder line, eliminating the necessity for frequency-selective impedance-matching elements.

The cage equivalent of the folded dipole improves the corona characteristics. Higher power handling capabilities result from the reduced potential gradients.

c. MARCONI ANTENNAS

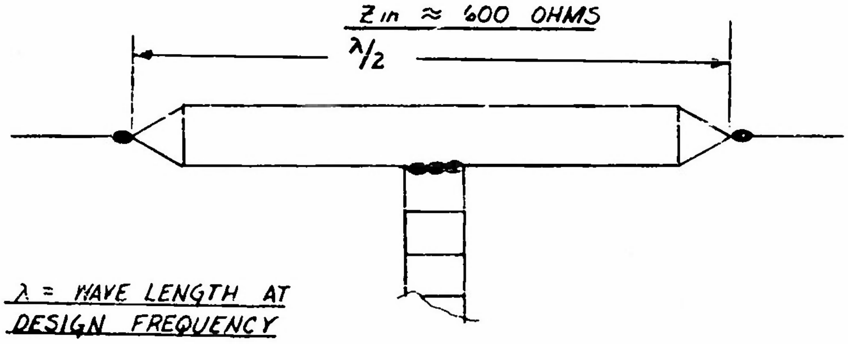
An end-fed slant or vertical conductor of arbitrary length is commonly referred to as a Marconi antenna. For high-frequency use, its chief virtue is the fact that no transmission line is required, so that the antenna can radiate power over all those frequencies at which the transmitter output circuit can provide a suitable match. The antenna must be in proximity to the transmitter, which results in a cluster of antennas at the transmitter house. In installations where this is the case serious intercoupling usually results. The effects of intercoupling manifest themselves by interaction in the tuning of the transmitters, and in the generation of spurious signals.

No pattern control is possible with the Marconi antennas since they may be used at nearly any frequency, irrespective of physical length. Furthermore, unless they are used with good ground systems, ground losses are high. It is therefore strongly urged that the use of Marconi antennas be restricted to l.f. and m.f. circuits. High frequency transmitters using



3 WIRE

Zin ≈ 600 OHMS



2 WIRE

Zin ≈ 300 OHMS

FIG. 10

FOLDED DIPOLE CONFIGURATIONS

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Marconi antennas at the present time should be converted to coaxial cable output. Antennas suitable for use with such cable are described below.

d. LAZY-H ANTENNA

The lazy-H is one of the simplest broadside arrays. It consists of two half-wave dipoles separated a half-wavelength and driven in phase. When erected in the vertical plane, this antenna gives a concentration of energy near the horizon. For broadcast applications, it suffers the same non-uniform azimuthal coverage as do the dipole configurations previously discussed. Other characteristics are similar to those listed for the delta-match and series-fed half-wave dipoles.

e. FOLDED MONOPOLE ANTENNA (GROUND-PLANE ANTENNA)

The folded monopole is an interesting application of u-h-f techniques applied to h-f antennas. It affords matching to 50-ohm coaxial cable and its radiation pattern is omnidirectional in the horizontal plane. It is inherently a narrow band antenna, and for nominal conductor sizes the bandwidth is limited to approximately 4 to 5%.

Structurally, it is a relatively simple device. Figure 11 illustrates this configuration. A single pole is required to support the vertical radiator. The length of this pole is approximately a quarter-wavelength plus the height of the resonant counterpoise. Four shorter poles, approximately 10 ft in length, are required to support each of the four ends of the counterpoise wire. The antenna may be fed from 50- to 70-ohm coaxial cable and it is therefore a suitable replacement for the Marconi antenna. It can also be used with the TDN-type transmitters, if they are reconverted to unbalanced outputs as suggested earlier.

2. BROADBAND ANTENNAS

a. DISCONE ANTENNA*

Very-high-frequency and u-h-f techniques have only recently been applied to the design of broadband h-f antennas. The discone is an interesting example of this application. The normally solid surfaces of the u-h-f configuration have been replaced by wires in the h-f counterpart.

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* A. G. Kandoian, "Three New Antenna Types and Their Applications," Proc. IRE, Vol. 34, 70W-75W, February 1946.

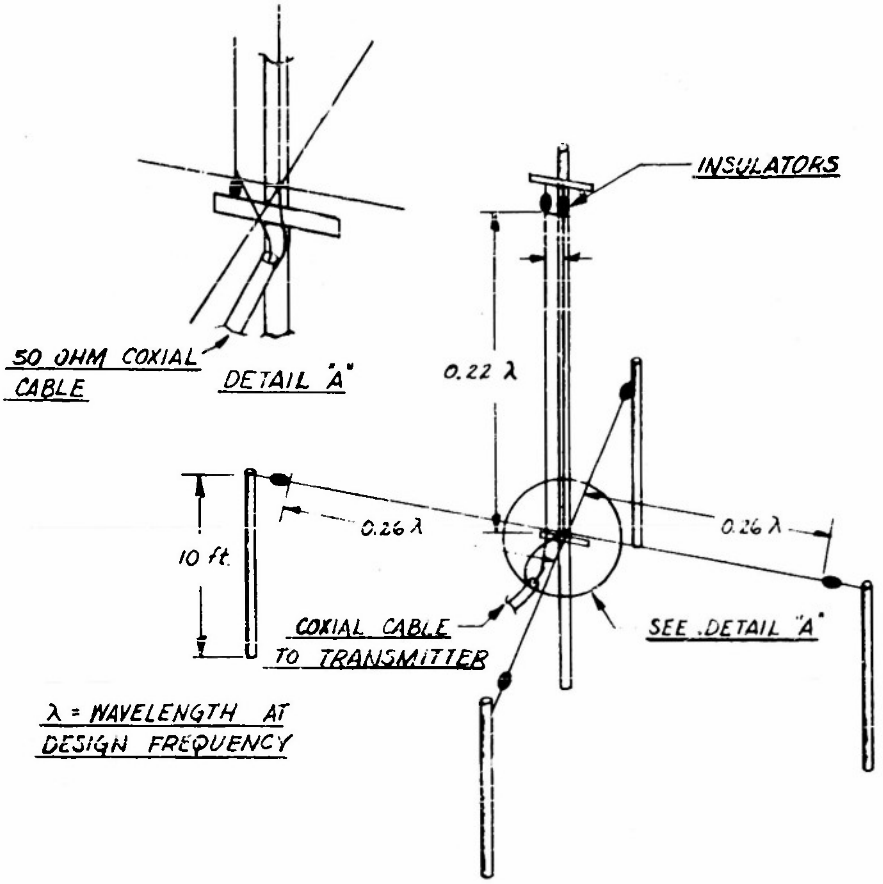

FIG. 11

FOLDED MONOPOLE ANTENNA

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The Electronic Division of the 9th Region of the Civil Aeronautics Administration in Honolulu, T. H., has a complete design* for an h-f discone. At least one of these structures has been erected in the Pacific area and is operating very successfully.

The discone is a vertically polarized radiator which requires no external ground system. A number of measurements were conducted at Stanford Research Institute, on a scale model of a structurally simpler

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* 9th Region CAA Drawings DR-9D-732-1, DR-9D-732-2, DR-9D-732-3, DR-9D-732-4, DR-9C-732-5.

version of the discone than the CAA antenna. The input of this antenna is suitable for connection to a 50-ohm coaxial cable and it can be operated over a bandwidth of approximately 4 to 1 with a VSWR of less than 2 to 1. Figure 12 shows the VSWR as a function of frequency, as measured on a $^1/_{43}$-scale model.

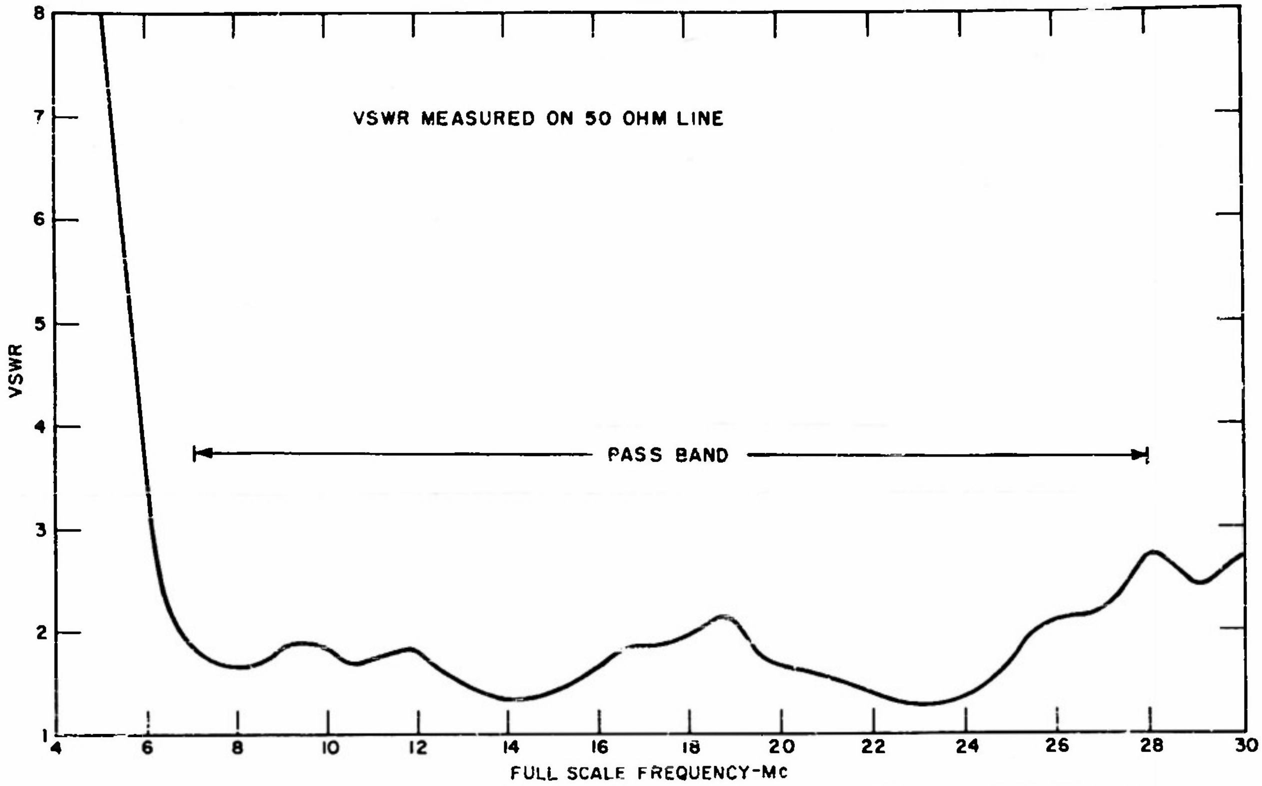

FIG. 12
DISCONE ANTENNA
VSWR AS A FUNCTION OF FREQUENCY

A-882-F-6

Like the vertical dipole, the discone antenna gives an omnidirectional pattern in the horizontal plane. Its distinctive characteristic, however, is that it may be operated over several octaves without substantial changes in the vertical pattern.

A sketch of the proposed antenna is shown in Fig. 13. The top disc consists of six equally-spaced wires, while the conical part of the antenna is made up of twelve slant wires terminated in insulators at a level of 12 ft above the ground. Only four poles are required for the suspension of this antenna. Details of construction may be taken directly from the CAA design.

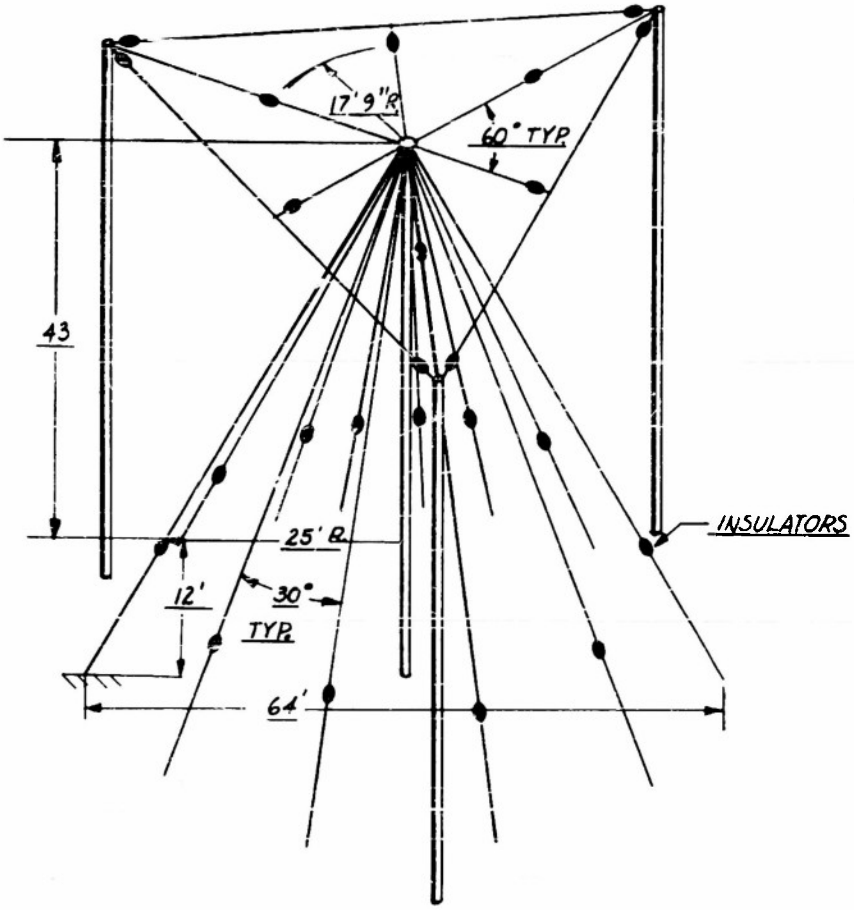

FIG. 13

A DISCONE ANTENNA FOR FREQUENCIES FROM
7 TO 28 MC

A-002-F-22

b. OPEN-SLEEVE ANTENNA*

Another very satisfactory scaled version of a u-h-f antenna for h-f applications is the open-sleeve antenna shown in Fig. 14. Again, the h-f configuration utilizes a curtain of conductors to simulate the solid surfaces of the u-h-f structure.

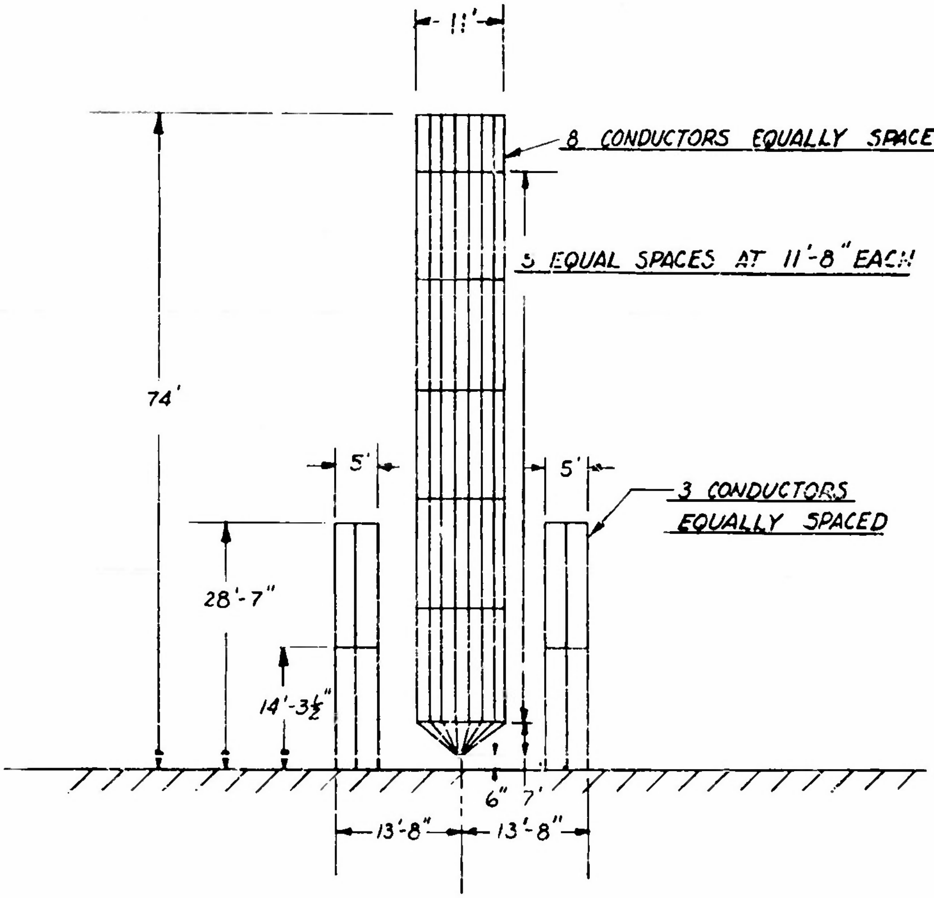

FIG. 14

OPEN SLEEVE ANTENNA FOR THE FREQUENCY RANGE FROM 3 TO 10 MC

A-882-F-23

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* J. T. Bolljahn, "Broad-Band Antenna," Patent No. 2505751, issued May 2, 1950; Stanford Research Institute, Stanford, California.

The open sleeve is structurally simpler than the discone and for this reason is to be recommended for use at the lower end of the h-f spectrum where physical dimensions of the radiators are large. The required pole construction is shown in Fig. 15. A disadvantage of this antenna is that it requires a rather extensive radial ground system (Fig. 16).

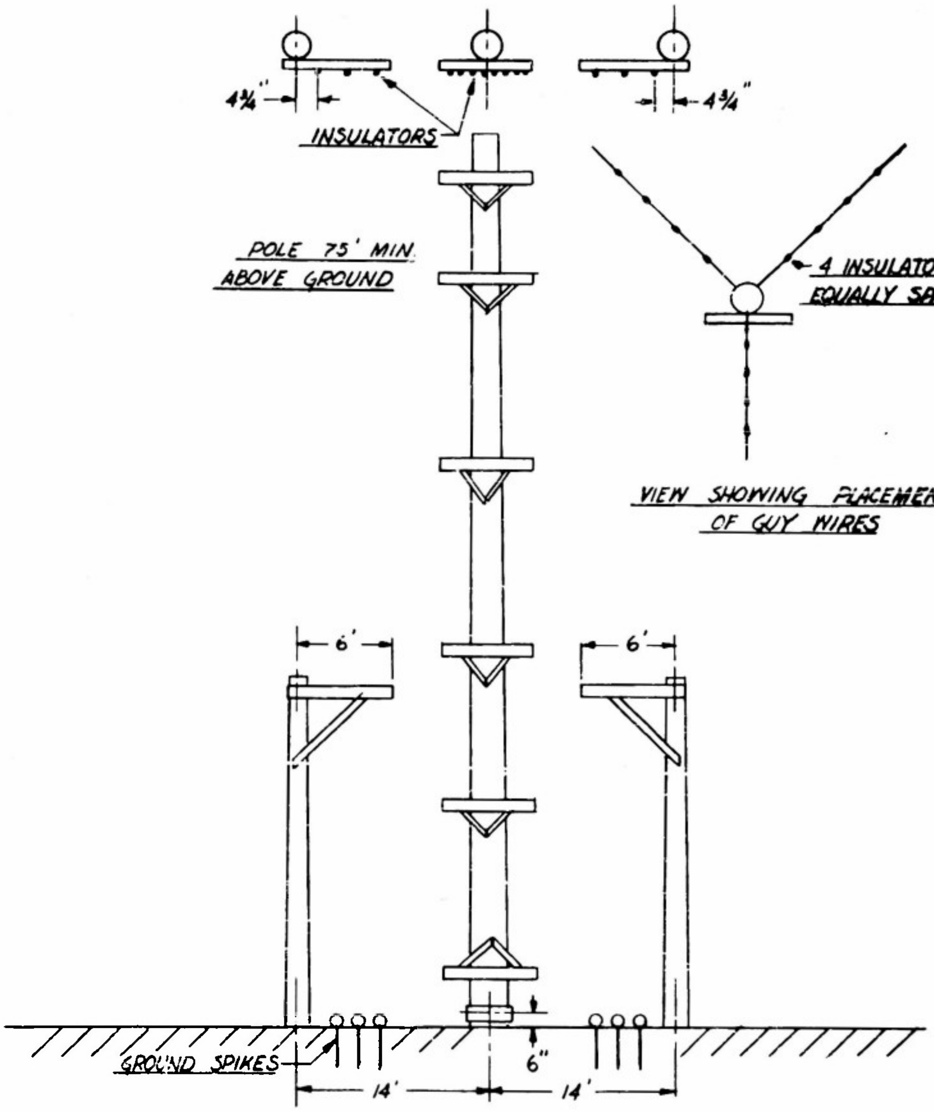

FIG. 15

POLE CONSTRUCTION FOR OPEN SLEEVE ANTENNA

A-1182-F-24

Measurements conducted on a $^1/_7$-scale version of this antenna indicate that satisfactory impedance characteristics are realized over a bandwidth of approximately 3.5:1. A VSWR of less than 2.8:1 is achieved over this bandwidth when the scaled version was fed from a 72-ohm coaxial line, as shown in Fig. 17. Figure 18 is a photograph of this model. The remotely controlled buried impedance bridge used for the measurements can also be seen in the photograph.

Pattern characteristics of this vertically-polarized radiator are known to be excellent over a 2:1 range in frequency at the low end of its pass band; however, no measurements have been made at the upper end.

c. QUADRANT ANTENNA[*]

The quadrant antenna shown in Fig. 19 has much to offer as a versatile efficient h-f radiator, although to date it has received little recognition in this country. It is simple to construct and has excellent radiation pattern and impedance characteristics over approximately a 1.5:1 range in frequency.

The quadrant antenna is a horizontally-polarized balanced full-wave radiator. Being a full-wave structure, its driving-point impedance is high permitting a relatively easy match to a 600-ohm open-wire transmission line. The elements are comprised of four conductors forming a cage to provide the required impedance level and to achieve the necessary broad banding. This also enhances the power handling capability of the radiator by reducing the potential gradients. Measurements on a scale model of this antenna showed that increased bandwidth could be obtained by means of a simple matching network. This network consists of a quarter-wave short-circuited transmission line stub of 600-ohms characteristic impedance, placed across the 600-ohm feed line a quarter-wave away from the antenna terminals. The design wavelength for the matching circuit is the center frequency of the band over which the antenna is to be used. When properly matched in this fashion, a bandwidth of 1.5:1 can be obtained, for which the antenna matches the 600-ohm transmission line within a VSWR of better than 2 to 1 (Fig. 20). Only five such antennas are therefore required for the entire frequency range from 3.16 to 24 Mc. The frequency range and design wavelength for these five antennas are listed in Table III.

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[*] N. Wells, "The Quadrant Aerial: An Omni-Directional Wide-Band Horizontal Aerial for Short Waves," Journal of the Institute of Electrical Engineers, Part III, pp 182-193; Dec. 1944.

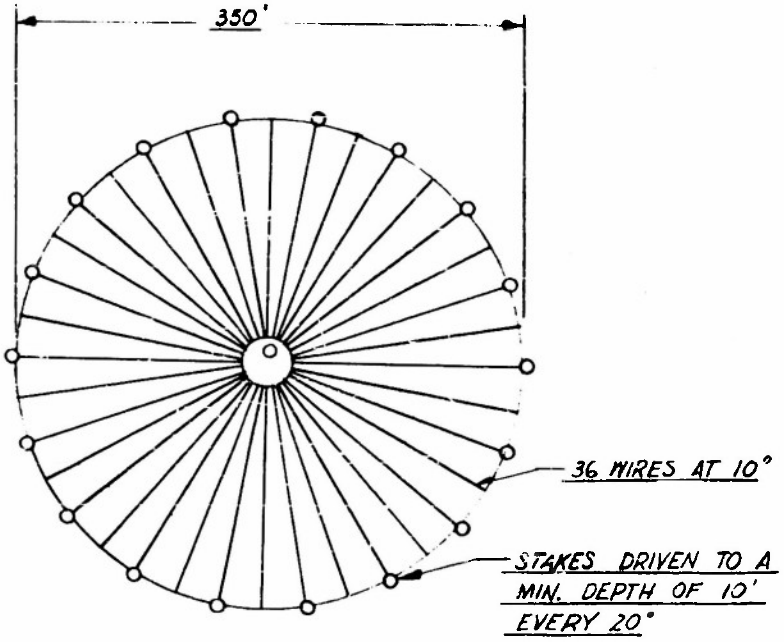


FIG. 16

GROUND SYSTEM FOR OPEN SLEEVE ANTENNA

A-822-F-25

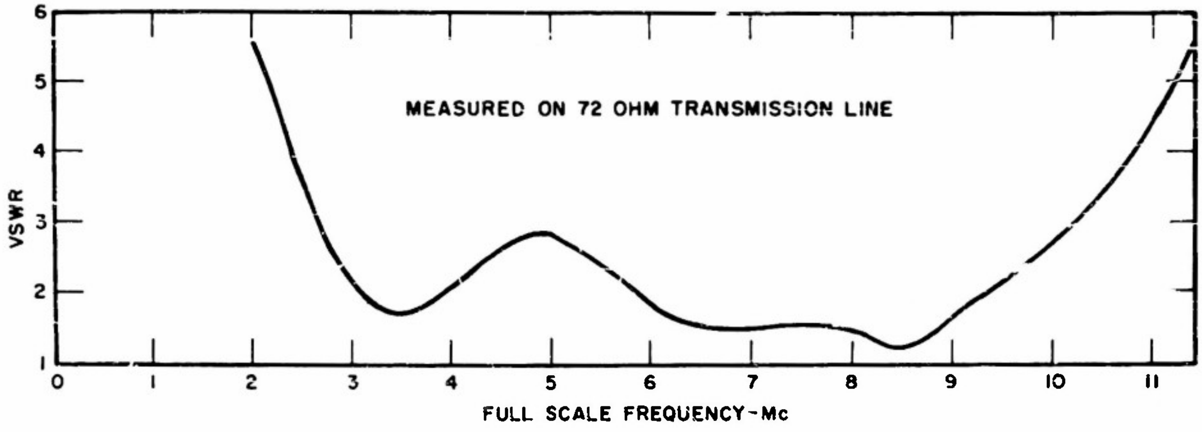


FIG. 17

OPEN SLEEVE ANTENNA

VSWR AS A FUNCTION OF FREQUENCY

A-882-F-5

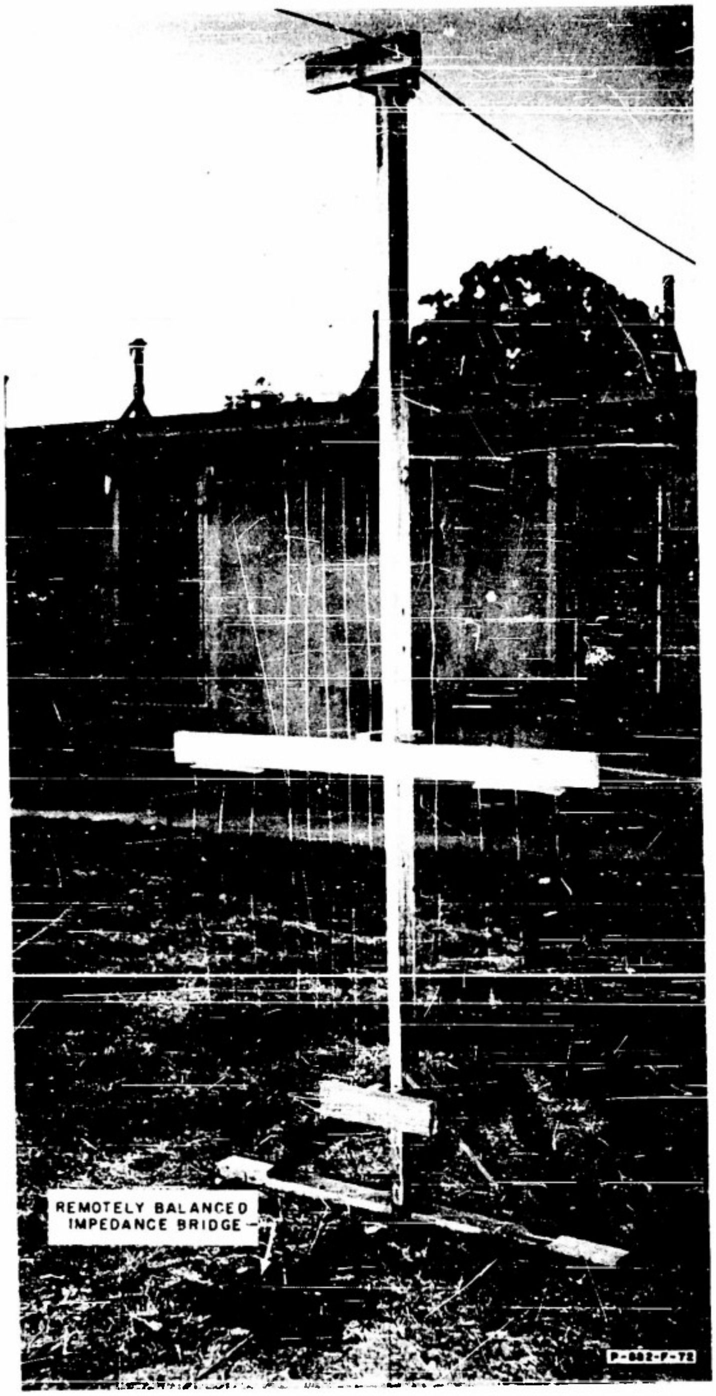
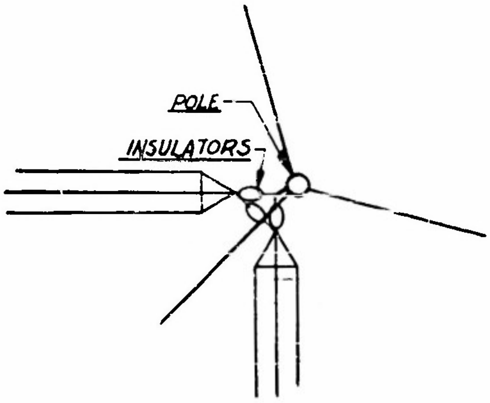


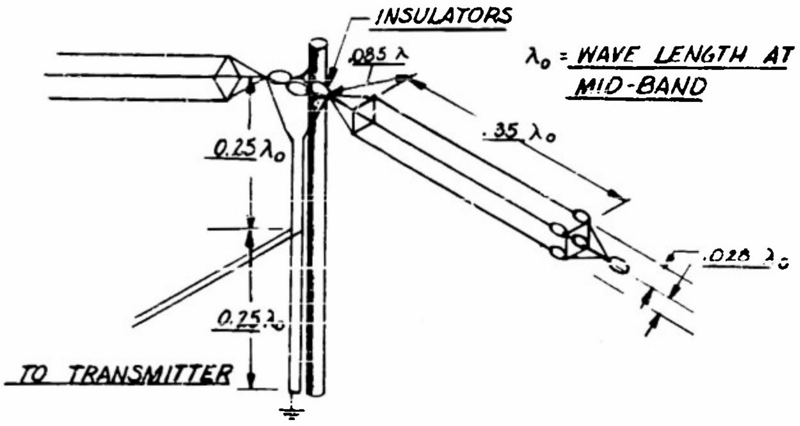
FIG. 18

OPEN-SLEEVE ANTENNA, $\frac{1}{7}$ SCALE MODEL



DETAIL 1 TOP VIEW

PLACEMENT OF GUY WIRES



DETAIL 2

TRANSMISSION LINE MATCHING STUB

FIG. 19

QUADRANT ANTENNA

A-082-Y-27

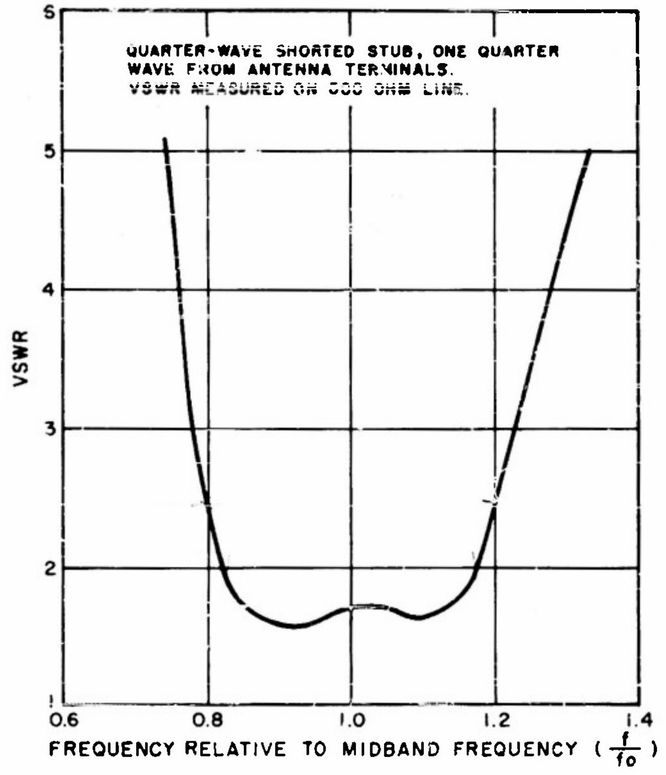


FIG. 20

STUBBED-QUADRANT ANTENNA

VSWR AS A FUNCTION OF FREQUENCY

A-882-F-4

TABLE III

FREQUENCY RANGE AND DESIGN WAVELENGTH FOR QUADRANT ANTENNAS

DESIGN WAVELENGTH (feet)	FREQUENCY RANGE (Mc)
260	3.16- 4.75
170	4.75- 7.10
115	7.10-10.70
76	10.70-16.00
51	16.00-24.00

The two half-wave cage elements are oriented to form a right angle to improve the radiation pattern characteristics. When placed a half-wavelength above ground at the center of its operating range, this antenna is very nearly omnidirectional in the horizontal plane at vertical wave angles from 5 degrees to 40 degrees.

The configuration of this antenna is such that four may be grouped together in a square with minimum requirements on the number of supporting poles (Fig. 21). The length of the diagonal of the square should be about twice the longest wavelength for which the antennas are to

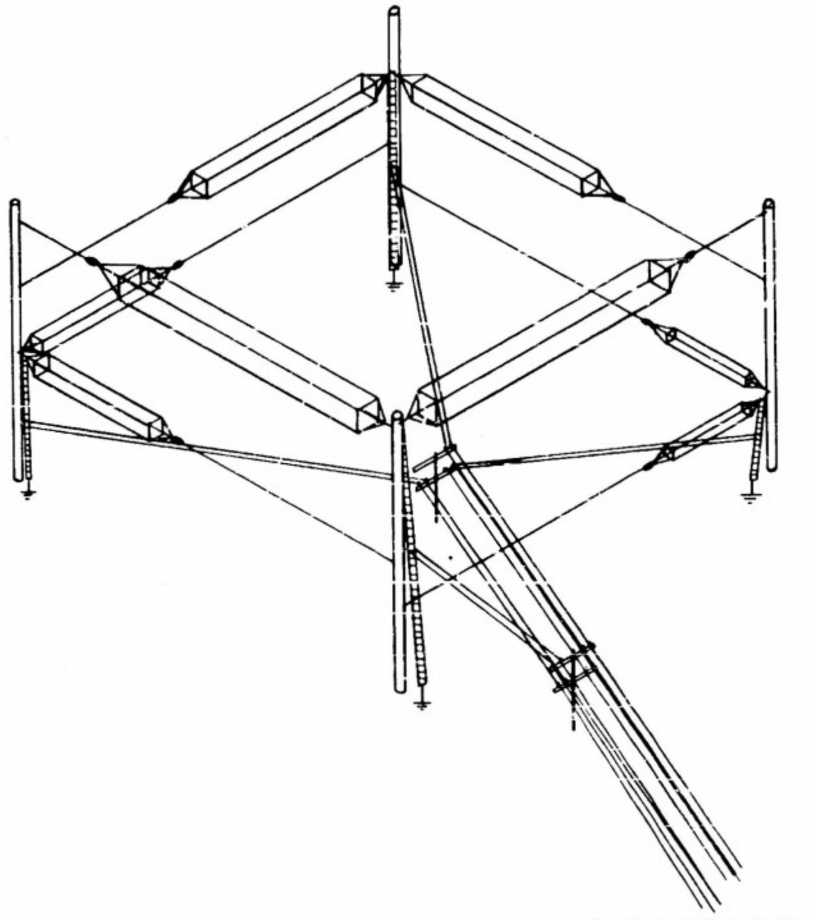


FIG. 21

GROUPING OF FOUR QUADRANT ANTENNAS IN A SQUARE

A-882-F-26

be used. Antennas for adjacent frequency bands are placed at opposite corners of the square, insofar as practicable. In this fashion, coupling between antennas can be made weak enough so that the energy lost by absorption in the adjacent antennas is negligible.

The quadrant antenna is ideally suited for broadcast applications in the high-frequency range. It is therefore recommended as a replacement for the existing types of doublet antennas.

d. SLEEVE AND PEDESTAL ANTENNA

Two interesting antennas have been developed at the U. S. Navy Electronics Laboratory at San Diego. These broadband antennas are vertically polarized and are designed to work from 50- and 70-ohm cable, respectively. Both are capable of operation over approximately a 3:1 range in frequency at VSWR's of 3:1 or less.

It is understood that NEL is preparing reports on these antennas and these reports will probably be available from that source.

e. TERMINATED FOLDED DIPOLE[1]

A further variation of the folded dipole that is akin to the rhombic antennas is a terminated folded dipole. In this form a terminating resistance equal to the characteristic impedance of the feeder is employed so that the radiating elements carry traveling waves and not standing waves. The radiation pattern is identical with that of a resonant dipole and therefore suffers the same limitations; however, tilting tends to improve low-angle coverage.

A somewhat wider bandwidth is obtainable at the expense of greatly reduced efficiency. A curve of efficiency as a function of relative operating frequency is given in Fig. 22. The efficiency was computed using the formulas given by Tai.[2] It will be noted that the efficiency never reaches 50% and is very much lower than that over most of the band. The VSWR reaches a value of 3:1 within the frequency ranges suggested by the author. Use of this antenna as a broadband radiator is therefore not recommended.

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[1] G. L. Countryman, "An Experimental All-Band Nondirectional Transmitting Antenna," QST, Vol. 33, pp. 54-55, June 1949.

[2] C. T. Tai, "Coupled Antennas," Proc. IRE, Vol. 36, pp. 487-500, April 1948.

It might be noted that, according to the sketches supplied by Lualualei, the folded dipoles constructed there are only half as long as required by the design given in the reference. Using these shorter dimensions, very low VSWR's should be obtained over most of the 5 1 frequency range for which this antenna is being used. On the other hand, the percentage of input power radiated seldom exceeds 5% under these circumstances. If temporary use of these antennas is contemplated their length should be adjusted to the proper values. It is, however, recommended that the folded, terminated dipoles be replaced as soon as possible by quadrant antennas.

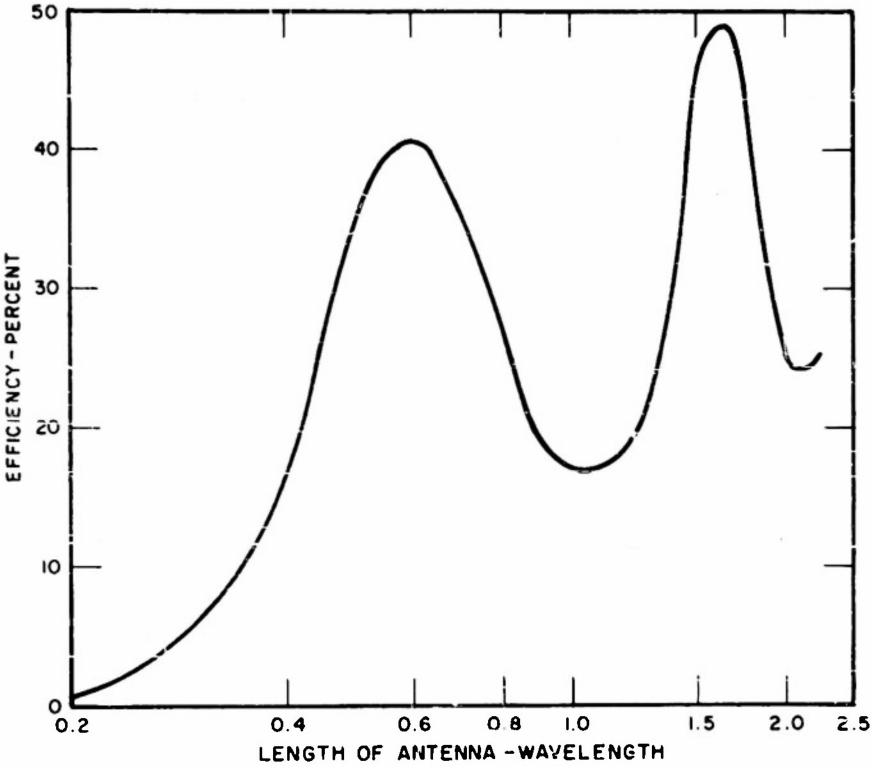

FIG. 22

EFFICIENCY OF TERMINATED FOLDED DIPOLE

A-882-F-9

3. Low- and Medium-Frequency Broadcast Antennas

The treatment of the engineering problems of l-f and m-f broadcast antennas differs considerably from that of h-f antennas. In the lower frequency range, antenna engineering is principally a problem in circuits and involves obtaining maximum efficiency from an electrically-short antenna.

Low-frequency and m-f antennas are vertically polarized. The usual antenna configurations for operation in this frequency range are towers, vertical wires, and top-loaded wires and towers. Because of the relatively large dimensions involved, and because of the greater penetration of the soil by these low frequencies, rather extensive ground systems are required if reasonable efficiency is to be obtained.

Three towers of 300-ft height are available at Lualualei for the suspension of antennas for these frequencies. The possibility of shunt exciting the towers themselves was considered. This scheme did not prove to be practical, because the various structural members of the towers are not properly bonded electrically, and hence cannot be used to carry r-f currents. Three wires used as l-f and m-f antennas are presently suspended from horizontal wires stretched between the towers. Improved efficiency can be obtained by top-loading these antennas.

No other supports for l-f antennas are presently available at Lualualei. The l-f antennas now used at Building No. 68 are highly inefficient. Antennas of the Beveridge type are not suitable as transmitting antennas except in locations where the ground resistivity is extremely large. This precludes their use at the Lualualei site. It must therefore be concluded that, except for the three l-f antennas already in use at Building No. 1, no other such antennas can be installed at the present time.

In the m-f range, antennas can be suspended from the 120-ft high poles available at the site. Here again top-loading of the antennas will be found to be advantageous.

C ANTENNAS FOR POINT-TO-POINT CIRCUITS

As the name implies, point-to-point circuits operate between fixed transmitting stations and fixed receiving sites. Distances over which transmissions from Lualualei take place range from 1800 km to 11,000 km. High frequencies are used for all the transmissions so that the signal travels via the sky wave. The ionosphere dictates the choice of frequency, the required power rating of the transmitters, and the best radiation pattern for the antennas. These factors were discussed in Chapter 3. In this chapter we shall show how far the requirements on the antennas, dictated by the ionosphere, are met in the Lualualei installation.

Recommendations are made which will lead to a more effective use of existing facilities, and designs and plans for improved antenna systems and a better layout of these antennas are presented.

One of the main distinctions between the point-to-point circuits and the broadcast circuits is the fact that the fixed location of transmitters and receivers permits the use of highly-directional antenna systems. Many designs for such antennas have been developed in the past; the most widely used type at the present time is the rhombic antenna. The chief advantages of this antenna are its simplicity of construction, its favorable impedance characteristic, and the high gain which can be achieved over a considerable band of frequencies. Rhombic antennas are the only kind of high-gain antenna used at Lualualei, and their continued use is recommended. Before proceeding with the discussion of the Lualualei installations, therefore, the characteristics of rhombic antennas must be considered in some detail.

Rhombic antennas consist of four straight wires arranged in the form of a rhombus, or of four systems of wires similarly arranged. For most h-f applications, the antenna is suspended horizontally from four poles at a height determined by the desired vertical angle for maximum radiation. The sides are usually long, compared to a wavelength, and one of the acute ends of the rhombic is terminated in an impedance such that current waves on the wires are essentially traveling waves. Power is delivered to the antenna from a transmission line connected to the opposite apex.

The most important characteristics of an antenna for the present purposes are its impedance and its radiation pattern. Let us consider the impedance first. A correctly terminated rhombic antenna presents an essentially constant impedance at its input terminals. Measurements in the frequency range from 7 to 20 Mc on a single-wire rhombic antenna terminated in an 815-ohm resistor, showed variations in the resistive component of the input impedance from a minimum of 660 ohms to a maximum of 830 ohms.[1] This antenna would provide an adequate match for a 600-ohm transmission line over this frequency range, the maximum VSWR being about 1.5:1. A better match to a 600-ohm transmission line is obtained by making each leg of the rhombus consist of two or more wires connected in parallel, the spacing between wires being larger at the corners than at the apex. The characteristic impedance is thereby lowered while it is, at the same time, kept more

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[1] E. Bruce, A. C. Beck, L. R. Lowry, "Horizontal Rhombic Antennas," Proc. of the IRE, Vol. 23, pp. 24-27; January 1935.

uniform along the length of the antenna. In practice, the improvement in antenna gain achieved by multi-wire construction is only between 0.5 and 1.5 db.[1] Since this additional gain can be achieved at relatively low cost, and since other advantages accrue from the use of a "flat" feeder system, the two- or three-wire construction of rhombics may be preferable to the single-wire type, especially when the transmitter power output is as high as 50 kw. The further improvement obtained from the use of a fourth wire seems entirely negligible. Avoidance of sharp corners where the feeder and termination line attach to the antenna also improves the impedance match of the antenna to the transmission line.[2]

The terminating impedance of rhombic antennas is usually resistive. For the transmitting antennas in which as much as 25 kw may have to be dissipated, a lossy transmission line is commonly used for the termination. The exponential dissipation line described in the Philco training manual[3] is a suitable design for this purpose. By progressively reducing the characteristic impedance in an exponential fashion, power dissipation is uniformly distributed along the line. In a line of uniform characteristic impedance most of the power dissipation occurs at the beginning of the line which must therefore be capable of withstanding considerable heating. The exponential line described in the Philco manual seems to be based on a design by Christiansen.[4]

Some trouble in the form of burnouts had been experienced at Lualualei, with more recently constructed dissipation lines. In order to investigate the cause of this failure, an exponential termination line was built at Stanford Research Institute, with the same stainless steel wire as that in use at Lualualei. The impedance of this line was found to be highly reactive. Further checks showed the wire to be of the non-ferromagnetic type. The surface resistivity of this wire at 10 Mc was found by measurement to be 6.2 milliohms. A sample of the American Iron and Steel Institute No. 410 stainless steel wire was obtained, for which the surface resistivity was measured to be 38 milliohms at 10 Mc. The latter type of wire is ferromagnetic

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[1] S. A. Schelkunoff, H. T. Friis, *Antennas: Theory and Practice*, p. 469; John Wiley & Sons; 1952.

[2] Laport, *op. cit.*, p. 333.

[3] Philco Service, Training Manual on Antennas, p. 166; Philco Corporation; 1948.

[4] W. N. Christiansen, "An Exponential Transmission Line Employing Straight Conductors," A. W. A. Technical Review (Australia), Vol. 7, pp. 229-241; April 1947.

and it is commonly used for the construction of dissipative lines. A more than sixfold increase in attenuation is obtainable when using ferromagnetic wire instead of non-ferromagnetic wire, or, conversely, a line only one-sixth as long is required for a given amount of power dissipation. It can therefore be seen that, in practice, it is essential to use ferromagnetic stainless steel wire in the construction of dissipation lines. The American Iron and Steel Institute Wire No. 410 (United States Steel No. 12) is recommended for this purpose. It was noticed that No. 12 B & S gauge wire was used instead of No. 14 as called for by the design given in the Philco manual. Use of the larger diameter wire reduces the attenuation and may also cause appreciable changes in the impedance since the spacing between conductors is quite small over some portions of the line. To insure that the correct terminating impedance is being used, newly constructed rhombic antennas or terminations should be checked by measuring the VSWR on the transmission line, over the entire frequency range for which the antenna is to be used. Adjustments of the terminating load may be required in order to obtain the best possible impedance match.

It is not difficult in practice to match a rhombic antenna to a 600-ohm transmission line within a VSWR of better than 1.5:1 over a 6:1 range in frequency. From this point of view alone, such an antenna is a broad-band radiator. When the radiation pattern is considered, however, the useful frequency range over which a given rhombic antenna can operate is considerably smaller. Figure 23 illustrates this point. One of the curves shows the angle of elevation above the horizontal, of the main lobe of the radiation pattern of a particular rhombic antenna, as a function of frequency. The other curve gives the antenna power gain[*] in the direction of the principal lobe, also as a function of frequency. The antenna (RA-5) for which the curve of Fig. 23 has been computed is used for the San Francisco circuit. The angles of departure for this path range from about 9 to 20 degrees. Depending on the frequency of transmission, the main lobe

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[*] The power gain is here defined with respect to an isotropic radiator. It is given by

$$G(\theta,\phi) = 10 \log_{10} \frac{4\pi P(\theta,\phi)}{P_t}$$

where

$G(\theta,\phi)$ = power gain of antenna in the direction (θ,ϕ) (in db)
$P(\theta,\phi)$ = power per unit solid angle radiated in the direction (θ,ϕ)
P_t = power input to antenna at antenna terminals.

It will be noticed that for the case of the rhombic antenna this definition of gain takes account of the power lost in the termination.

of the radiation pattern may be 20 degrees or more above the required angle, or more than 10 degrees below it. While the gain in the direction of the principal beam remains fairly constant, the gain of the rhombic in the required directions may be very small indeed. In Fig. 24 the gain of the same rhombic antenna is plotted as a function of frequency for *fixed* directions of propagation. At a frequency of 6 Mc the gain of the antenna is between 8 and 23 db below the maximum achievable gain. In comparison, a horizontal dipole cut for the required frequency and suspended at the proper height above ground, has a power gain of about 7.5 db. The performance of the rhombic antenna considered in this illustration may therefore in many cases be very much worse than that of a simple doublet antenna.

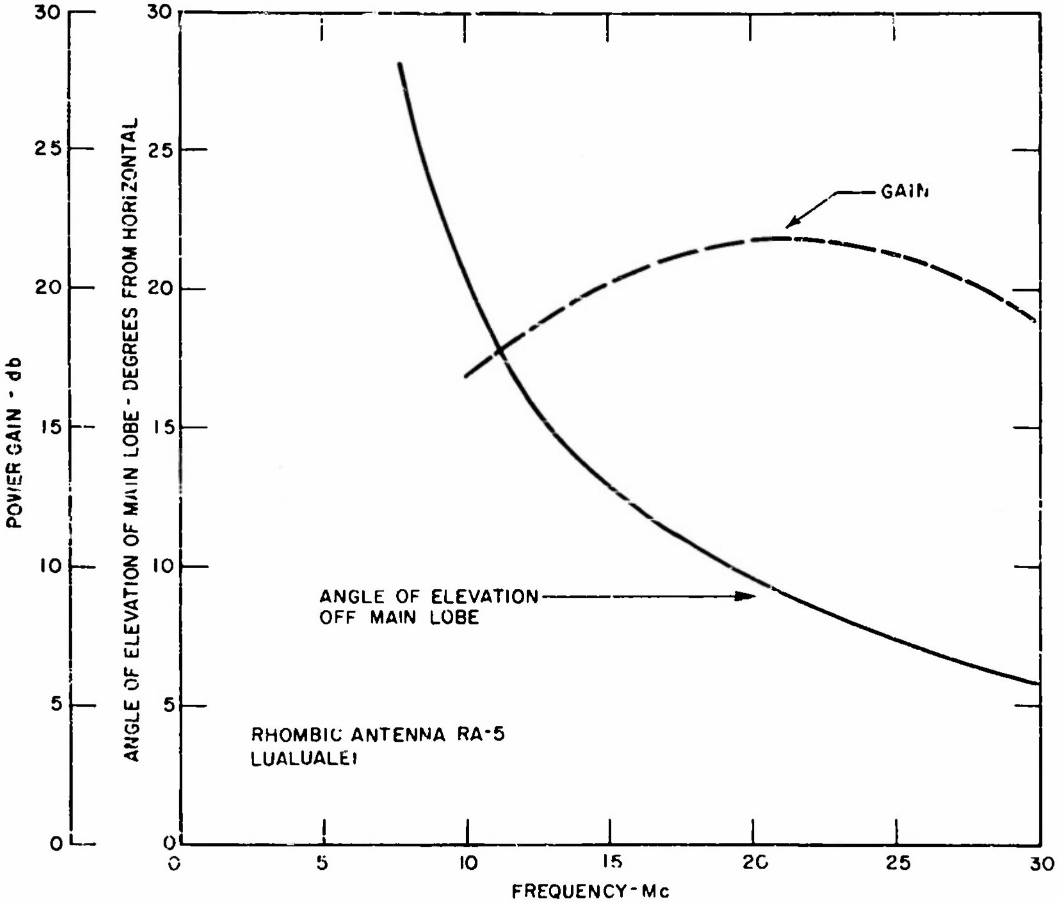

FIG. 23

VARIATION OF RADIATION PATTERN OF A RHOMBIC ANTENNA
WITH FREQUENCY OF TRANSMISSION

B-882-F-11

In general, the radiation pattern in the vertical plane limits the useful frequency range of rhombic antennas to about 2:1. This fact has been pointed out in many places,[1] yet it is often overlooked in the actual use of such antennas. At Lualualei, rhombic antennas directed at a given station are used at any of the frequencies assigned to this circuit, that is over a frequency range of as much as 6:1. Satisfactory communications may be obtained despite this procedure, at least part of the time because of the following reasons:

(1) The r-f power available from the transmitter may be sufficient to make up for the decrease in antenna gain.

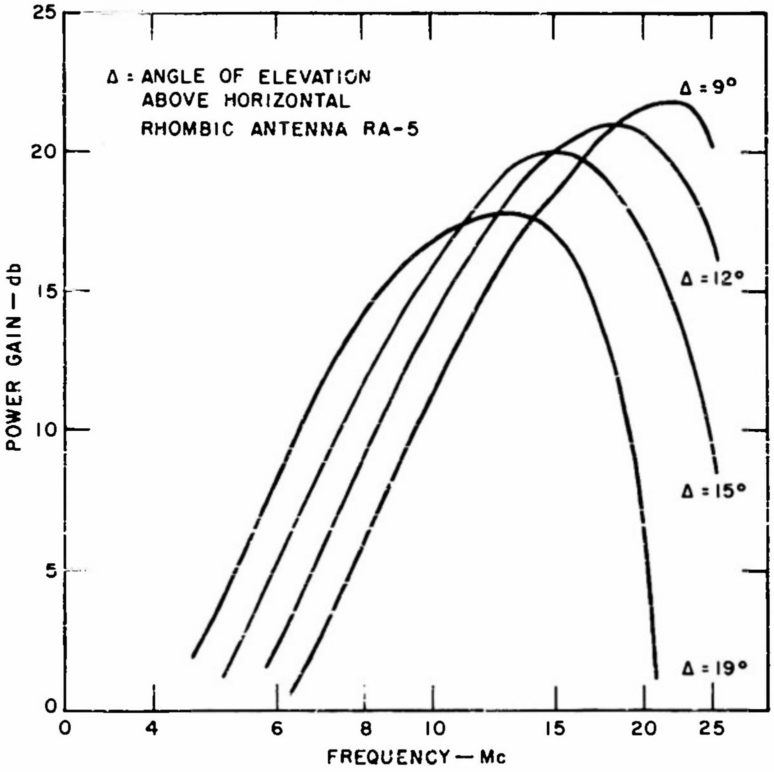

FIG. 24

GAIN OF A RHOMBIC ANTENNA IN FIXED DIRECTIONS AT DIFFERENT FREQUENCIES

A-882-F-2

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[1] See for instance, F. E. Terman, *Radio Engineers' Handbook*, p. 805, McGraw-Hill Book Co., Inc., 1943.

(2) One of the numerous secondary lobes of the antenna pattern may launch a signal over transmission paths with a higher number of hops. Such paths, however, usually offer higher attenuation than those using a smaller number of hops.

A considerable share of circuit outage must, however, be attributed to this type of usage of rhombic antennas. In order to decrease the occurrence of circuit outages it is recommended that the rhombic antennas be used over a more restricted range in frequencies than is the current practice. The practical application of this recommendation to the existing rhombic antennas will be discussed below.

Rhombic antennas are more directive in the horizontal plane than in the vertical plane. Therefore, they should not be used for transmissions deviating by more than 5 to 10 degrees from the direction of the major axis of the rhombus. Figure 25 is a typical example of the behavior of the radiation pattern in the horizontal plane. The curves show the gain of the rhombic in off-course directions relative to the gain in the forward direction, as a function of the length of one of the legs of the antenna. The leg length is given in wavelengths so that this scale is proportional to frequency. At a frequency corresponding to a leg length of 5.5 wavelengths, there is a null in the radiation pattern at 10 degrees from the main axis of the antenna. For angles 20 degrees removed from the major axis of the rhombic, the null occurs at a lower frequency, corresponding to a leg length of 3.5 wavelengths. The apparent gain in the directions off the side for leg lengths above about 7 wavelengths is due to the fact that the main lobe in the forward direction splits into two parts at the corresponding frequencies. A rhombic antenna should, of course, never be used at the frequencies where this takes place. Figure 25 is presented as an illustration only. Details of the curves depend on the tilt angle of the antenna and on the vertical elevation of the principal lobe. In general, the horizontal beam width decreases with increasing frequency; this should be borne in mind when making use of rhombic antennas for transmissions in directions other than that of the major axis.

Thirty-one rhombic antennas are presently installed at Lualualei. The question of how far apart these antennas must be placed in order to produce negligible interference is therefore an important one. Little quantitative information is available as to the minimum allowable spacing between antennas. Measurements have shown that the radiation patterns of two rhombic antennas using a common corner pole are essentially

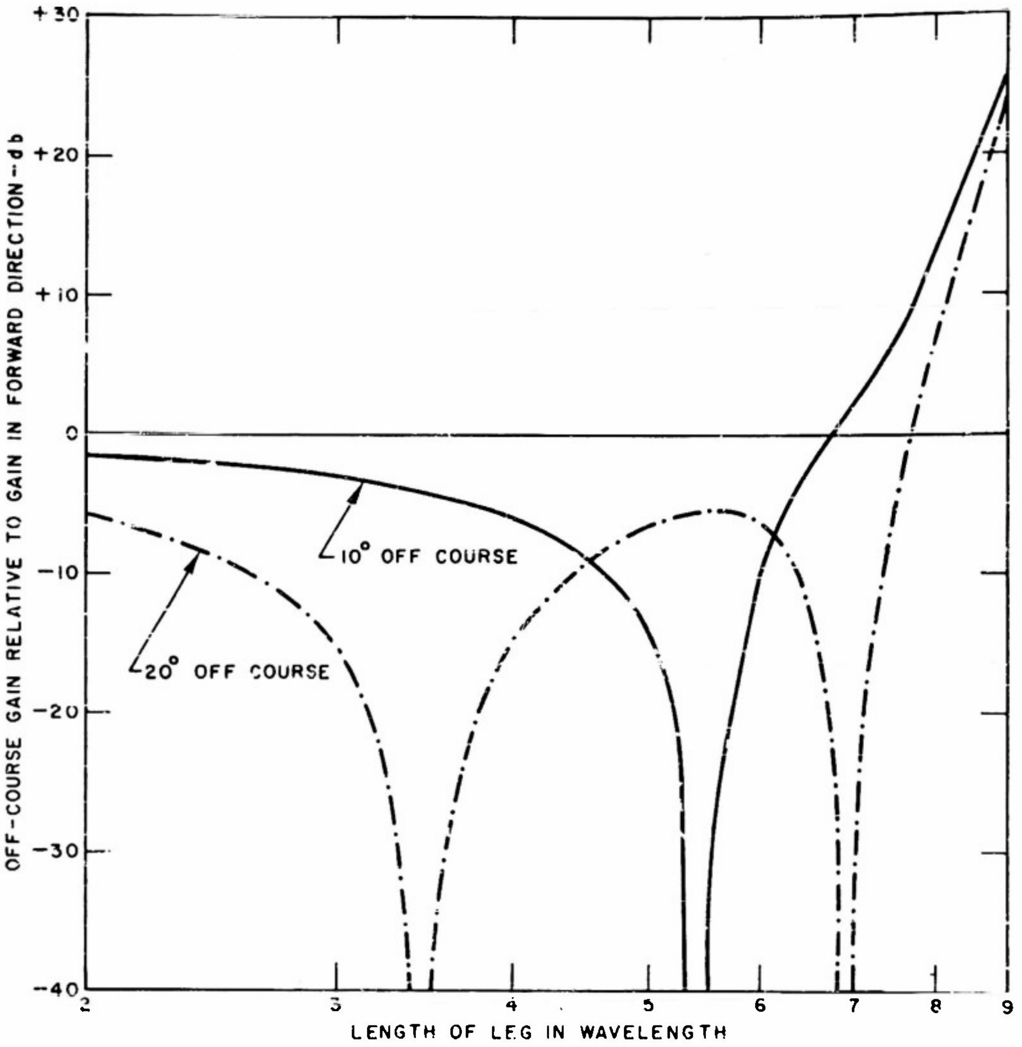

FIG. 25
GAIN OF RHOMBIC ANTENNA IN HORIZONTAL PLANE

A-882-F-5

undisturbed.[1] In the case just mentioned, the major axes of the two antenna were almost parallel to each other. One may infer from this that rhombics should be so arranged that the major axes are as nearly parallel to each other as possible. The more closely the legs of two rhombics approach to being parallel, the wider should be the spacing between the

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[1] J. DuFour, "Reception Diagrams of Rhombic Antennas in a Vertical Plane," Technische Mitteilungen der Schweizerischen Telegraph und Telephon Verwaltung, Vol. 31, pp 65-72, March 1, 1953

antennas. Placing one rhombic antenna directly in the main beam of another should be avoided. The presence of the Waianai Mountains as well as the limitations imposed by the existing structures make it impossible to strictly adhere to these rules for all the antennas required at Lualualei.

A final word should be added about the terminating impedance of rhombic antennas. The radiation pattern in the forward direction is very little affected by the presence or absence of the termination. Radiation in the backward direction, on the other hand, is directly dependent on whether or not power is being absorbed at the forward end of the antenna. In the absence of a termination, with the apex either open or short-circuited, a reflected wave is set up on the antenna which radiates in the backward direction. To a first approximation, about half of the power is in the forward traveling wave and half in the backward traveling wave, when no termination is used. A resistive termination absorbs power for the backward traveling wave and therefore reduces the radiation in the backward direction only. Suppression of the back lobe is desirable, however, since signals from a high-power r-f source over a high-gain antenna may cause interference many thousands of miles away from the transmitting station. The chances for mutual effects between antennas on the site are also greatly increased. For these reasons, as well as for proper matching of the transmission lines, rhombic antennas should be carefully terminated.

Let us now consider the rhombic antennas installed at Lualualei, and the way in which they are arranged on the site. There are 31 rhombic antennas available for transmissions in 21 different directions about Oahu. Seven of these are directed to San Francisco or Washington both of which lie on the same great-circle path, three are beamed toward Guam, two to Kawajalein, two to Tutuila, two to Tokyo or Midway; three to Australia, two to New Zealand, two to Alaska; and the remaining ones, in various other directions mainly to the west. Figure 26 shows the circuits for which rhombic antennas are currently available. Frequencies of transmissions range from about 6 to 20 Mc. Over a period of about six to eight years, frequencies within the entire range from 4 to 24 Mc will have to be used for transmissions over most of the circuits. The present practice at Lualualei is to use a rhombic facing in the right direction for all frequencies assigned to a circuit. This practice is not recommended, since the antenna gain in the desired direction will be entirely inadequate at some of the frequencies.

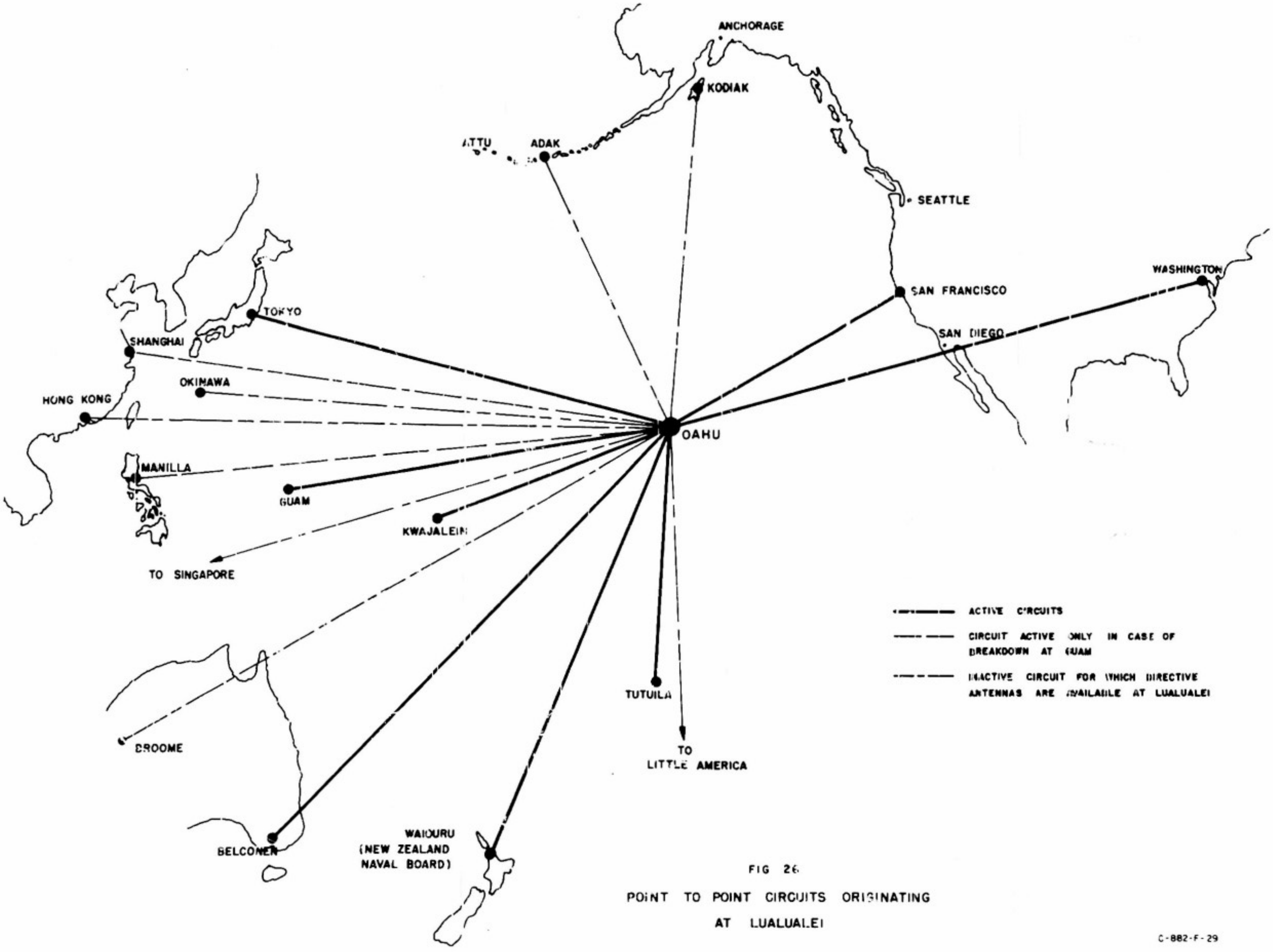


FIG 26
POINT TO POINT CIRCUITS ORIGINATING AT LUALUALEI

The existing rhombic antennas can be used much more effectively by making a selection on the basis of frequency of transmission. The radiation patterns of these rhombics are shown in Appendix D. It can be seen there that for some of the circuits, pairs of antennas are available which, together, give much more adequate coverage over the required frequency range. Table IV lists various possible combinations of rhombics for the different circuits and the frequency range over which they should be used.

TABLE IV

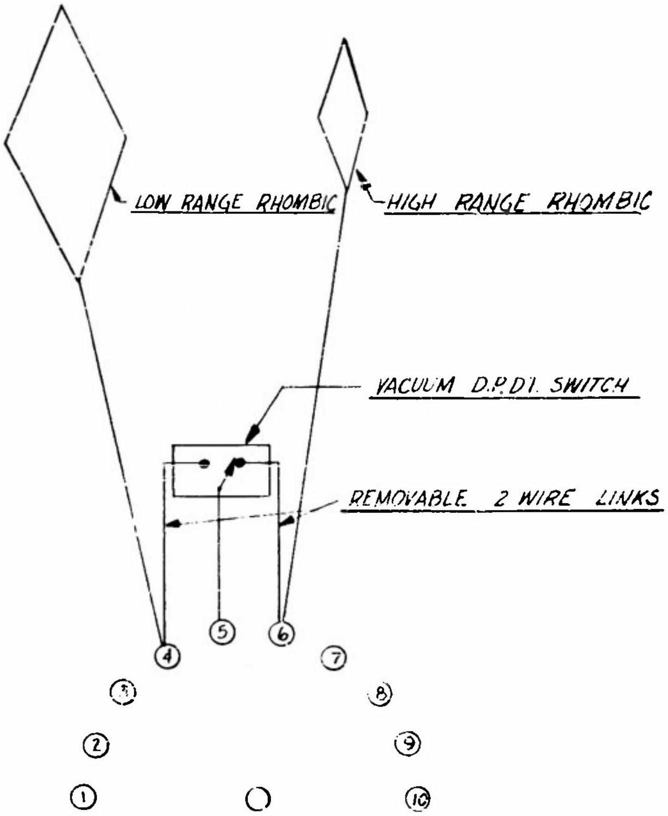
SUGGESTED FREQUENCY RANGES FOR
EXISTING RHOMBIC ANTENNAS

Circuit	Rhombic	Frequency Range (Mc)	Rhombic	Frequency Range (Mc)	Frequency Range over which Either Antenna May be Preferable (Mc)
Washington, D. C.	RA-1 RA-3	4 - 12	RA-2	14 - 24	12 - 14
	RA-6	4 - 13	RA-5	17 - 24	13 - 17
San Francisco	RA-1 RA-3	4 - 9	RA-2	12 - 24	9 - 12
	RA-6	4 - 9	RA-5	12 - 24	9 - 12
Guam	RA-12 RA-21	4 - 11	RA-18	16 - 24	11 - 16
Kwajalein	RA-10	4 - 10	RA-24	14 - 24	10 - 14
Tutuila	RA-22	4 - 9	RA-22	14 - 24	9 - 14
Tokyo	RA-19	4 - 11	RA-4 RA-9 RA-14	16 - 24	11 - 16
New Zealand	RA-22	4 - 11	RA-27	15 - 24	11 - 15
Broome, Australia	RA-10	4 - 15	RA-24	18- 24	15 - 18

For each of the listed pairs there is a region where either may give a stronger signal at the receiver. The best antenna for these frequencies depends on unknown ionospheric conditions and can therefore be determined by actual trial only. The rhombic antennas not listed in the table usually provide insufficient gain at the low end of the frequency range. Many of the antennas, even some of those listed in the table, were designed for transmissions at the geometric mean of the total frequency range, that is for use around 10 Mc. Poor performance can therefore be expected at both the low end and the high of the band. From the discussion of Chapter 3 it is seen that antenna gain is especially important for frequencies of transmission below about 10 Mc. Many of the existing rhombics are therefore unsatisfactory for use at the lower frequencies. A significant reduction of circuit outages may often be achieved by using rhombic antennas designed specifically for the frequencies below 10 Mc. Designs suitable for this purpose will be discussed presently.

The selection of rhombic antennas on a frequency basis requires additional switching facilities. In some cases simultaneously keyed transmissions take place over the same circuit at two different frequencies. This practice is highly advantageous during periods of rapid changes in the MUF for the path, such as during dusk and dawn. Provisions should therefore be made to feed both antennas of the rhombic pair from two different transmitters. On the other hand, when the transmitting frequency is such that either antenna of a complementary pair provides superior gain, or when only one transmitter is used at any one time, it is desirable to have some means of rapid switching between the two rhombics. A vacuum type double-pole-double-throw switch can be used here to advantage (Appendix E). To provide for separate excitation of both antennas, or for the rapid changing of the antennas just mentioned, the switching scheme shown in Fig. 27 is suggested. Transmission lines connect each of the two rhombic antennas to a position on one of the hand-operated switches. A third position on the hand-operated switch is connected to the "pole" of the vacuum switch. The two throw position of this switch can be connected by means of removable links to the transmission lines leading to the antennas. Connection of the links can be accomplished by the same hook and eye arrangement as that used for the hand-operated switch. When these links are removed, the transmitters can be connected to either antenna separately, or by connecting the transmitter to the double-pole-double-throw switch and inserting the two links, rapid switching between the two rhombics may be accomplished by means of the relay-operated vacuum switch.

The location of the 31 rhombic antennas now installed at Lualualei is shown in Fig. 28. With the exception of the antennas directed to Alaska, all rhombics are located so that the most useful transmission paths clear



LUALUALEI HAND OPERATED SWITCH

FIG. 27

SWITCHING CIRCUIT FOR RHOMBIC PAIRS

A-882-F-30

the mountains. The spacing between antennas is somewhat closer than necessary or desirable. Some improvement in this situation may be achieved by removing all those antennas which will not be put to use within the foreseeable future.

It has been shown above and in Appendix C that many of the presently used rhombics do not radiate a sufficient amount of power in the required direction at all the frequencies which may be used for transmission. It was also pointed out that changes in radiation pattern limit the useful bandwidth of rhombic antennas to a frequency range of 2:1. For best coverage at all frequencies between 4 and 24 Mc a minimum of three rhombics would therefore be required for each of the circuits. The multitude of

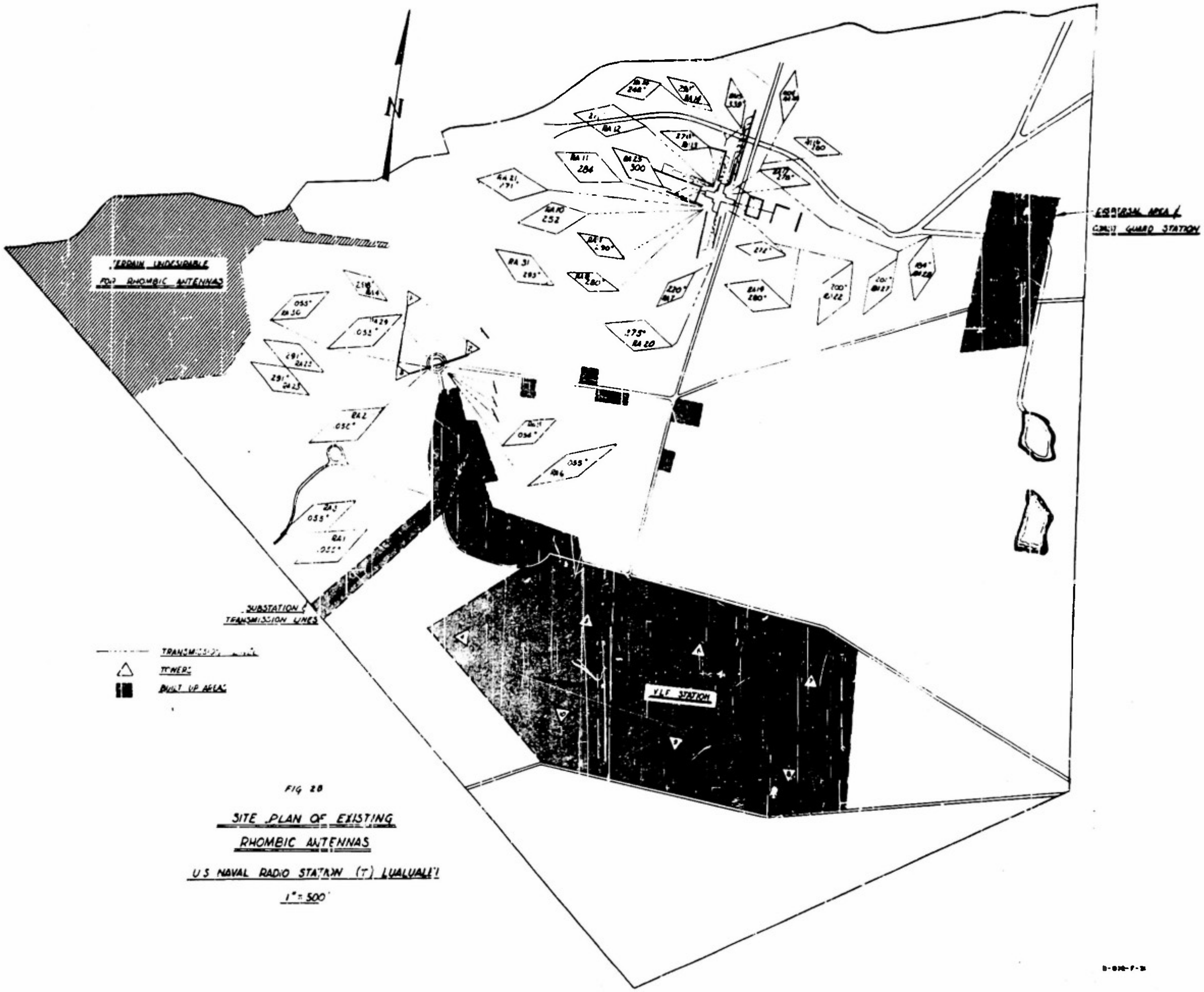


FIG 28

SITE PLAN OF EXISTING RHOMBIC ANTENNAS

U S NAVAL RADIO STATION (T) LUALUALEI

1" = 500'

circuits and geographical limitations of the site would make it difficult to provide this number of rhombics for every circuit. A compromise design has therefore been prepared in which two antennas are used for each circuit: Part A for the lower end of the band, and Part B for the upper end. Three such pairs are required to provide satisfactory gain in all desired vertical directions. Table V lists the frequency and distance ranges for which each antenna is intended. The range of vertical directions for which coverage must be provided when transmitting over a given distance is given by Table I in Chapter 3. A detailed discussion of these antennas will be found in Appendix D. It should be noted here that the use of only two rhombics for the entire frequency range necessarily requires some compromise. What has been done in the new designs is to provide more gain at the lower frequencies where it is most needed. This entails some reduction in gain at frequencies intermediate to those for which the two antennas of a pair were designed. The size of optimum rhombic antennas for use at the lowest frequencies in the h-f range becomes entirely excessive. It was assumed here that the maximum average height above ground at which the antennas can be suspended is 110 ft, and the maximum length of one leg was taken to be 600 ft. These maximum dimensions limit the power gain which can be obtained at the low end of the band.

TABLE V

PROPOSED RHOMBIC-PAIR DESIGNS
FREQUENCY BANDS AND DISTANCES OF TRANSMISSION

PAIR No.	DISTANCES OF TRANSMISSION (kw)	PART A	PART B	FREQUENCY RANGE OVER WHICH EITHER ANTENNA MAY BE PREFERABLE (Mc)
		Frequency Range (Mc)	Frequency Range (Mc)	
1	1500 - 2500	4.0 - 9.5	12.5 - 24.0	9.5 - 12.5
	3500 - 4500	4.0 - 9.5	14.5 - 24.0	9.5 - 14.5
2	4500 - 6500	4.0 - 10.0	13.5 - 24.0	10.0 - 13.5
3	2500 - 3500 or beyond 6500	4.0 - 9.0	10.5 - 24.0	9.0 - 10.5

Figure 29 shows a possible way of arranging these rhombic pairs about the two transmitter buildings. The number of rhombic pairs provided for

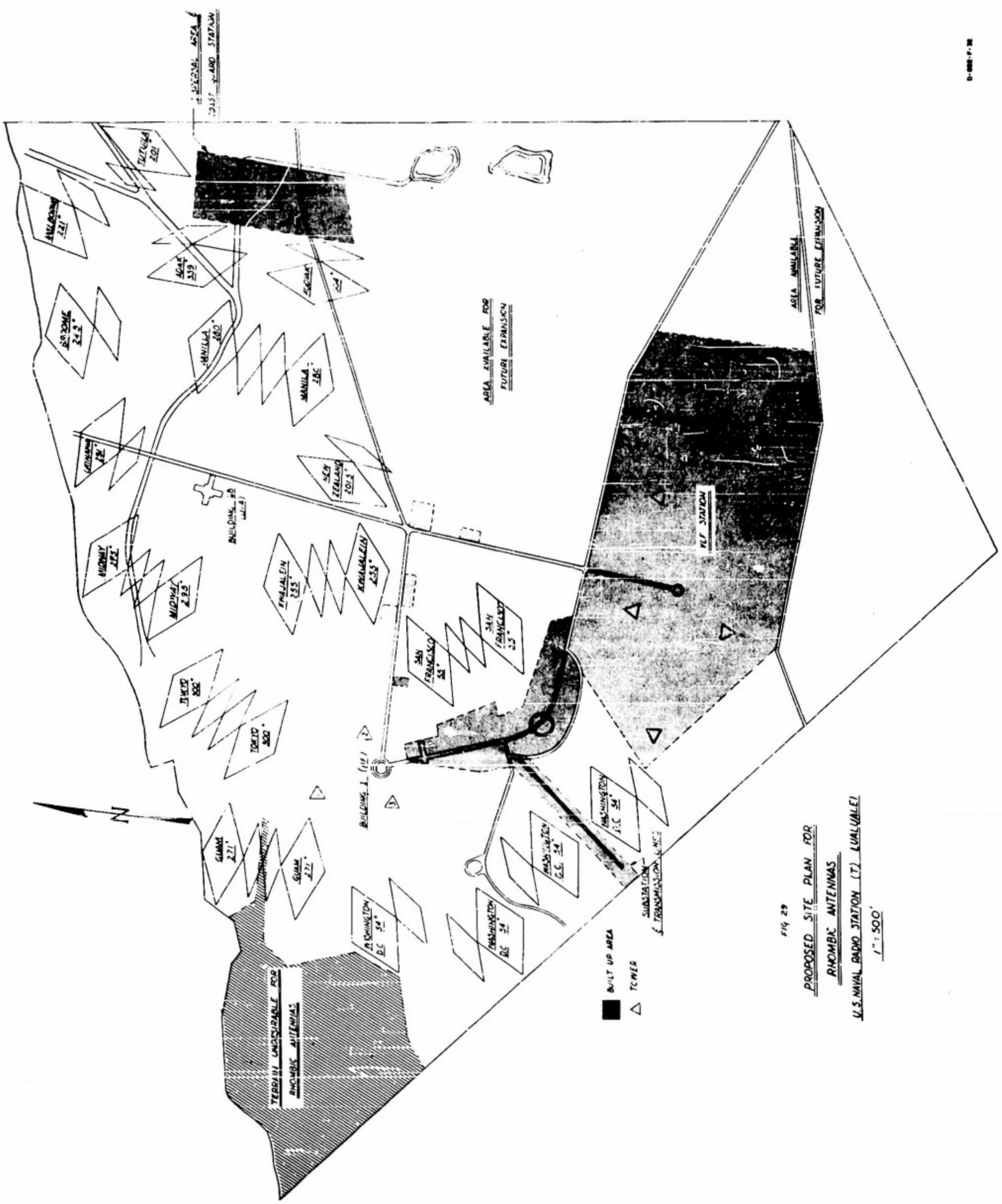


FIG 29

PROPOSED SITE PLAN FOR
RHOMBIC ANTENNAS
U.S. NAVAL RADIO STATION (T) LUALUALEI
1" = 500'

each circuit corresponds approximately to the number of antennas available at the present time. It cannot be determined at this point whether all the antennas shown in the figure will actually be needed, nor is it known whether enough antennas are shown for each of the circuits. The layout does provide a guide to a more favorable location of rhombic antennas. The aim has been to obtain as much separation between antennas as can be achieved practicably. In no case are transmission paths obstructed by the mountains. The length of transmission lines was kept to less than 3500 ft in order to avoid excessive power loss in the feeders. At the same time, more room than presently available is provided in the vicinity of the transmitter buildings, for the construction of broadcast antennas. It is felt that use of the proposed designs of rhombic pairs located as shown will provide improved communications over the point-to-point circuits, and better utilization of the available land area.

D. FEEDER SYSTEMS

With few exceptions, transmission lines, or feeders must be used to convey the energy between transmitters and antennas. The only type of feeder used at Lualualei at the present time is the balanced parallel wire transmission line. All transmitters with unbalanced output circuits utilize Marconi antennas which are connected directly to the output terminal.

The transmission lines used at Lualualei consist of two parallel conductors of No. 6 B & S gauge copper wire spaced 12 in. apart, giving a characteristic impedance of 600 ohms. Considerable variations in spacing between the conductors can be tolerated without seriously affecting the VSWR on the line. This is illustrated in Fig. 30 which shows the characteristic impedance of a two-wire line made of No. 6 wire, as a function of line spacing. If, for instance, the spacing between the conductors of a matched 600-ohm line were suddenly reduced from 12 in. to 6 in., beginning at some point along the line, the VSWR on the 6-in. line would be changed from unity to only 1.16:1. The VSWR is obtained from

$$\text{VSWR} = \frac{600}{525} = 1.16 ,$$

where 525 ohms is the characteristic impedance of a two-wire line made with No. 6 conductors spaced 6 in. apart, as seen from the curve of Fig. 30. Sudden changes in line spacing do, however, produce possible points of

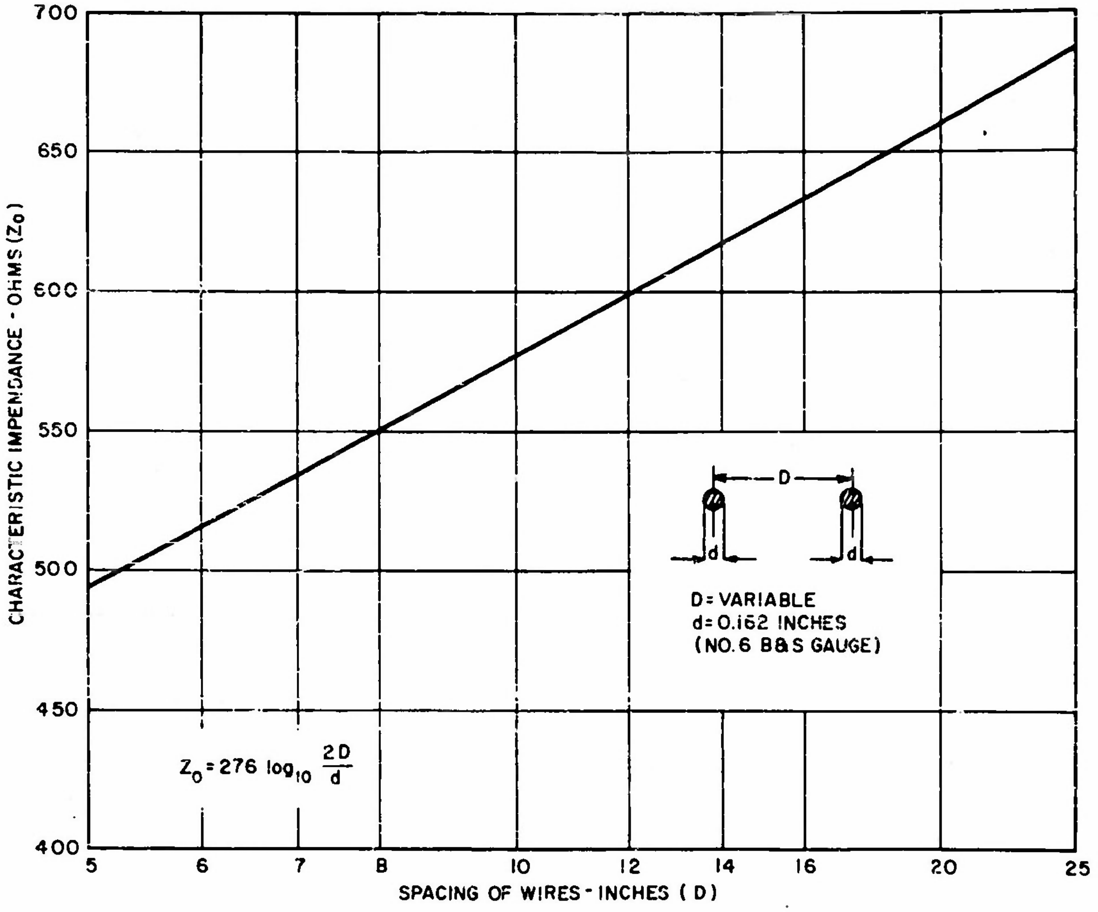


FIG. 30

CHARACTERISTIC IMPEDANCE OF PARALLEL WIRE LINE
MADE OF NO.6 B&S GAUGE WIRE

A-882-F-10

corona formation as well as power losses in the form of radiation, and should therefore be avoided whenever possible. Of more importance, because it is overlooked more often, is the requirement of keeping the total length of the two wires in the balanced feeder system exactly equal.[1] This especially should be watched for with the sections of feeder passing from the transmitters to the outside of the building, in the switches, and at bends or turns in the line. Wire loops may be inserted at bends and other critical points to insure that both wires remain of equal length; or the plane of the line may be turned through 90 degrees before making the turn, and brought back to the horizontal for the next straight run.[2]

Some of the power delivered to the feeder by the transmitter is dissipated in the form of ohmic losses in the wire and on conduction through the supporting insulators; radiation losses are usually negligible. The attenuation of two-wire line made of copper, including losses through the insulators is given by:

$$a = \frac{14.4 \sqrt{f}}{d z_0} \text{ db/1000 ft}$$ [3]

where

a = attenuation in db per 1000 ft of two-wire line
f = frequency in Mc
d = diameter of conductors in inches
z_0 = characteristic impedance of line in ohms.

The attenuation of the 600-ohm line using No. 6 conductors is plotted as a function of frequency in Fig. 31. It will be noted that such a line is highly efficient, so that relatively long runs may be tolerated when this is required for proper spacing of the antennas. The longest feeder length recommended in the layout of antennas discussed below is 3500 ft, which corresponds to a line loss of 3 db at 24 Mc. A loss of that magnitude at this frequency can be tolerated in a transmission link which utilizes the ionosphere. It is obvious, of course, that the feeders should not be made longer than strictly required. Work at Lualualei is now in progress to remove unnecessary bends and turns in the feeder system,

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[1] F. E. Lutkin, R. H. J. Cary, G. N. Harding, "Wideband Aerials and Transmission Lines for 2 to 35 Mc/s;" Journal of the I.E.E., Vol. 93, Part IIIa, p. 552; 1946.

[2] E. A. Laport, *Radio Antenna Engineering*, pp. 395-397; McGraw-Hill Book Co., Inc.; 1952.

[3] *Ibid*; p. 396.

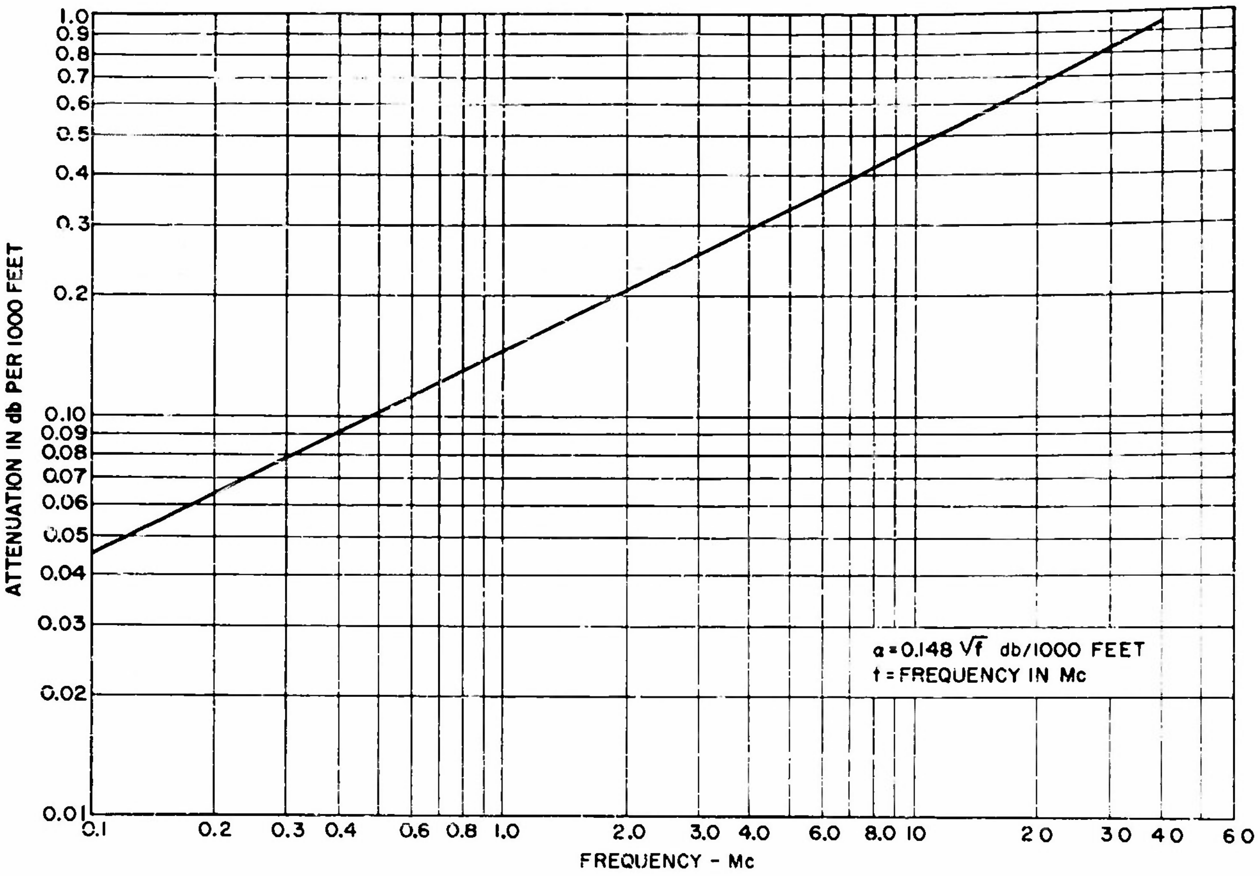

FIG. 31
ATTENUATION OF 600 OHM PARALLEL WIRE TRANSMISSION LINE
MADE OF NO 6 B&S GAUGE COPPER WIRE

B-882-F-7

resulting in considerable shortening of the length of some feeders. If the line is mismatched at the antenna end, additional losses are introduced. For properly terminated rhombic antennas this additional loss is entirely negligible; for a line length of 3500 ft and a frequency of 24 Mc the additional loss due to a mismatch corresponding to a VSWR of 2 1 is only 0.4 db.[1] In all cases considered here, therefore, the curve of Fig. 31 may be taken to represent the entire losses introduced by the feeder system. It has been assumed that the feeders are suspended at a sufficient

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[1] *Reference Data for Radio Engineers*, Federal Telephone and Radio Corporation, p. 329; J. J. Little & Ives Co., N. Y., 1949.

height from the ground so that ground losses may be neglected. A safe height between line and ground, for which this assumption holds, is ten times the line spacing, that is 10 ft for the lines at Lualualei.[1]

In an installation of the size discussed here, it is inevitable that several feeders may run parallel to each other over considerable distances. In the past, two or more transmission lines at Lualualei were supported close to each other. This practice not only produces coupling between adjacent circuits but also unbalances the feeder systems. The two wires of the feeder then form one side of an unbalanced line, the other side of which is formed by the ground. Losses in the feeder system are thereby greatly increased. During the past months, work has been started at Lualualei to rectify this condition. As a general rule, two-wire balanced transmission lines should be spaced apart by at least six times the spacing between conductors of a single pair of lines,[2] that is 6 ft in the present case. This still permits the use of a single pole and cross-arm construction to support two pairs of lines; additional feeders can be run in parallel if more elaborate supports are used.

Up to this time, no coaxial transmission line systems have been used at Lualualei. If Marconi antennas are to be avoided, such cables will have to be used in the future. Conversion of the TDN transmitter to unbalanced outputs was recommended earlier so that here too, coaxial transmission lines will be required. Fortunately none of the transmitters with unbalanced output circuits has a power output larger than 5 kw. This permits the use of standard flexible coaxial lines, as long as the VSWR is kept within reasonable limits. As discussed in the section on broadcast circuits, cables with characteristic impedances of both 50 ohms and 70 ohms will be required. The following types of standard cable are recommended:

RG-20A/U — characteristic impedance: 50 ohms
RG-85A/U — characteristic impedance: 70 ohms

Both of these types are armored so that they can be buried directly in the ground. The losses are low for this kind of transmission line, but they are approximately three times as large as those of the two-wire balanced feeders. The antennas fed by coaxial cables should therefore be kept as

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[1] F. C. McLean, F. D. Bolt, "The Design and Use of Radio-Frequency Open Wire Transmission Lines and Switchgear for Broadcasting Systems," Journal of the IEE, Vol. 93 (Part III), pp. 191-210; 1946.

[2] F. C. McLean, *et al*; *loc. cit*.

close to the transmitters as is practical, while maintaining the required separation between antenna systems. The VSWR should be less than 3:1 for safe, continuous operation at 5 kw power input.

A continuous check should be kept on the operation of the feeder system. The only continuous monitoring devices used at the present time are r-f ammeters inserted in series with the transmission lines. By using one such meter in each leg of the two-wire lines, the transmitters can be adjusted for balanced current input to the feeder system. It was noted, however, that in many cases the meters used were too insensitive to give a readable indication of r-f line current. These meters should be replaced with instruments of smaller current range so that the readings fall within the more sensitive part of the scale. A continuous check of the VSWR and power input to the coaxial cables is essential to prevent overloading and breakdown. The "Micro Match," manufactured by the M. C. Jones Electronics Company, 96 North Main St., Bristol, Conn., can be used for this purpose.[*] The same type of instrument is also available for use with balanced transmission lines. Such instruments are available for measuring powers up to 50 kw in the h-f range. Their use for monitoring VSWR and power input to the balanced feeders should be seriously considered, although the existing trolley meters are adequate for this purpose.

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[*] Before using the instrument a reading of "reflected power" should be taken when the transmitter connected to the transmission line is cold. This will indicate possible cross coupling between the circuit under test and adjacent circuits

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

In the preceding chapters the installations and operation of the Naval Radio Transmitting Station at Lualualei were critically examined. Wherever it was found that improvements could be achieved by changes in existing equipment or practices these have been mentioned together with reasons leading to the recommendation of such changes

Before proceeding with a summary of the conclusions and recommendations, certain general aspects of the investigation, which have been brought out in this report, should be repeated here. The station and its satellite installations are in perfectly sound operating condition. Many of the points raised in this investigation can therefore be regarded as desirable aims to be achieved whenever practical In general, then, this report presents a guide to future planning, rather than a list of faults in urgent need of correction.

Although the choice of frequencies of transmission and the examinations of the outage logs are not wholly the responsibility of the transmitting station, they profoundly influence the design and the operations of the station. It was therefore necessary to devote considerable attention to these problems. For instance, the careful tuning of a large transmitter is time consuming and it would be helpful in reducing outage to be able to anticipate changes in transmission frequencies at the transmitting station. The scatter-sounding technique described in Appendix B presents a scheme which makes possible a correct choice of frequency at the transmitter. An even simpler method of accomplishing this was described at the end of Chapter IV. This latter scheme would consist of monitoring, at the receiving site, the broadcast transmissions sent out from Lualualei at evenly spaced frequencies throughout the h-f band, and thus determining directly the best frequency for the path at any given time.

It might prove helpful in the future to keep a more complete record of operations. Data to be recorded should include the frequency of transmission, the transmitter and antenna used, and the power output of the transmitter. If such data were available, together with a more precise recording of the reason for circuit outage, additional information on the causes for breakdowns could be obtained. A detailed record of the dimensions of all antennas, ground systems, and feeder lines, kept up-to-date to include all subsequent changes, should also prove of great value.

A list of more specific recommendations and conclusions follows. The *nature* of these will make clear the relative importance and urgency of each of the points mentioned.

RADIO TRANSMITTER BUILDING NO. 1(HF)

(1) It is suggested that all SSB circuits be brought to this building in order to make more effective use of the available equipment. This rearrangement of equipment would require the installation of "Mare Island" type switches within the building so that the spare transmitter and the power amplifiers could be used on any of the circuits involved. In general it will be found that the power amplifiers used with the SSB transmitters are most urgently needed for transmissions at the lower frequencies, regardless of the path length of transmission.

(2) The present facilities in the neighborhood of Building No. 1 are sufficient for only three active low-frequency circuits.

(3) The existing ground system within the building should not be for r-f ground connections. It is recommended that the ceiling of the basement be covered with copper sheeting which, in turn, should be connected to the external ground grid in the proper fashion. Ground connections from the transmitters should be made to this copper sheet.

(4) The external ground system should be examined for existing faults and be repaired wherever necessary.

(5) An increase in switching facilities and increased use of the switches should prove advantageous. In this respect, changes in the design of the hand-operated switches might be investigated, which would make it possible to perform the switching operations without interruption of any but the circuit directly involved.

The switches should be interconnected in the manner described in Chapter VI.

RADIO TRANSMITTER BUILDING NO. 68(LU-4)

(1) Without the erection of additional towers this building is not suitable for the housing of l-f circuits and transmitters. Antennas for m-f transmissions can, however, be erected near

Building No. 68 so that m-f transmitters may be housed in the building.

(2) The ground system inside the building should be checked to insure that the various members of the system are properly bonded. Faults in the radial grid in the vicinity of the building should be repaired.

(3) Present switching facilities, together with those now under construction, appear to be sufficient. It is suggested that the switches be interconnected in order to increase the flexibility of operations.

TRANSMITTERS

(1) All h-f transmitters presently used with Marconi antennas should be converted to coaxial cable output. Either 50- or 70-ohm cable may be used with these transmitters.

(2) The TDN-type transmitters should be reconverted to unbalanced outputs. Cable of 70-ohm characteristic impedance should be used with these transmitters.

FEEDER SYSTEMS

(1) The two-wire balanced transmition lines should be suspended at least 10 ft above the ground in order to minimize ground losses.

(2) When running two or more such lines parallel to each other they should be spaced at least 6 ft apart to prevent coupling between circuits.

(3) When constructing parallel-wire lines it is important that the two sides of the line be of exactly equal length.

(4) The following types of standard coaxial cable are capable of carrying up to 5 kw of r-f power as long as the VSWR is kept to less than 3:1.

RA-20A/U — Characteristic Impedance 50 ohms
RA-85A/U — Characteristic Impedance 70 ohms

Both of these cables may be directly buried in the ground.

(5) The power input to the coaxial cables and the VSWR should be monitored continuously. The "Micro Match" can be used for this purpose. "Micro Matches" are also built for use with balanced transmission lines.

(6) Whenever new antennas are put into service or alterations are made on existing antennas, the VSWR on the transmission lines should be checked at several frequencies within the range over which the antennas are to be used. In particular, checks of the VSWR should be made at the extreme ends of the intended frequency range.

(7) Radio-frequency ammeters presently inserted at the input ends of the two-wire lines are in many cases too insensitive to provide readable scale deflections. These meters should be replaced with more sensitive instruments.

BROADCAST ANTENNAS

(1) Doublet antennas should be suspended at a height of a half-wavelength above ground. When the wavelength is too great to make this feasible they should be suspended at the maximum practical height.

(2) The quadrant antenna is a much more suitable type of broadcast antenna than any of the doublet antennas now in use. The gradual replacement of all existing types of doublet antennas by quadrant antennas is therefore recommended.

(3) The folded, *terminated* doublet antenna is a highly inefficient radiator. If use of this type of antenna is to be continued for the time being, its overall length should be increased to one-third wavelength at the lowest frequency for which it is intended. It is recommended, however, that this type of antenna be replaced by quadrant antennas as soon as possible.

(4) It is strongly urged that the use of Marconi antennas be discontinued except for use with l-f and m-f circuits. Clusters of these antennas are responsible for much of the intercoupling of equipments and the consequent emissions at spurious frequencies, presently experienced.

(5) The folded monopole antenna is a suitable replacement for some of the Marconi antennas, and for use with the TDN transmitters after reconversion to unbalanced outputs. This type of antenna can be used at the design frequency only, and it must be carefully adjusted for minimum VSWR on the transmission line.

(6) The open-sleeve antenna is recommended as a broadband radiator for the frequencies from 3 to 10 Mc.

(7) The simple discone antenna investigated at Stanford Research Institute can be used for frequencies between 7 and 28 Mc. This antenna should be used in preference to the folded monopole antenna, whenever cost and space permit.

(8) Vertically-polarized antennas should be separated by no less than one wavelength at the lowest frequency at which they transmit. The spacing between horizontally-polarized and vertically-polarized antennas is not critical, and it may be found convenient to use common poles for such antennas in some cases.

(1) From the point-of-view of *impedance alone* the rhombic antenna can be used over an extremely wide band of frequencies. In practice, the bandwidth is limited by the radiation patterns to a 2 1 range in frequencies.

(2) The rhombic antenna should be properly terminated. The exponential dissipation line now used at Lualualei is well suited for this purpose. This line should be constructed of No. 14 A.W.G. stainless steel wire. The wire must be ferromagnetic, such as American Iron and Steel Institute stainless wire No. 410. The stainless steel wire presently stocked at Lualualei is non-ferromagnetic and should not be used.

(3) The VSWR on the transmission line leading to the antenna should be checked after construction of the antenna or termination, and the termination should be adjusted, if necessary, to provide the best possible impedance match over the required frequency range.

(4) The two- or three-wire rhombic construction has some advantages over the single-wire type. The addition of a fourth wire is not necessary.

(5) Rhombic antennas should be used for transmissions over the great circle path to which they point, whenever possible. In no case should the transmission path deviate from this direction by more than 10 degrees for the lower frequencies of transmission, and should deviate even less than that amount at higher frequencies.

(6) It is recommended that existing rhombics be selected on the basis of frequency of transmission as outlined in Table IV. Switching between rhombics is greatly simplified if relay-operated vacuum switches are used.

(7) Dimensions for the construction of new rhombic antennas have been presented. These antennas provide higher gain in the required directions than the existing rhombics at almost all frequencies between 4 and 24 Mc, but especially so at the lower frequencies where such increases are most desirable.

(8) The general layout of rhombic antennas given here provides better spacing between adjacent antennas and more room for the construction of broadcast antennas. It is therefore suggested that this plan be followed in new construction or in the relocation of existing antennas.

Modifications and checks of the ground system, the replacement of Marconi antennas by antennas connected to the transmitter through coaxial cables, and the relocation of the two-wire transmission lines wherever they run too closely in parallel to each other, should largely eliminate deleterious coupling between different circuits. In these cases, immediate improvements can be expected when carrying out the recommended changes. In general, however, and in common with all systems relying on the ionosphere for communications, increases in circuit reliability will not necessarily be immediately apparent from the use of systems with more favorable overall gain. The benefits resulting from the recommendations made in this report will be found by an analysis of outages over periods of months and years. The day-to-day operations are subject to the vagaries of the ionosphere which can produce changes in signal strength many orders of magnitude larger than those due to changes in power gain of any physically realizable transmitting system. For h-f transmissions, careful choice of the best frequency of transmission and strict adherence to best operating practices will usually lead to improvements in circuit reliability, many times larger than those achievable by changes to existing facilities.

APPENDIX

GRAPHICAL SOLUTION OF SKY-WAVE PROBLEMS

THE DETERMINATION OF OPTIMUM FREQUENCIES OF TRANSMISSION BY MEANS OF SCATTER SOUNDING

THE POWER GAIN OF RHOMBIC ANTENNAS INSTALLED AT LUALUALEI

DESIGN OF RHOMBIC PAIRS FOR TRANSMISSIONS OVER DISTANCES GREATER THAN 1500 KM

TRANSMISSION-LINE SWITCHING

APPENDIX A

GRAPHICAL SOLUTION OF SKY-WAVE PROBLEMS[1]

In radio communication problems involving transmission by means of sky waves reflected from the ionosphere it is often necessary to relate: (1) great-circle distance between transmitter and receiver, (2) virtual height of reflection, (3) equivalent path distance between transmitter and receiver, (4) angle of departure, and (5) angle of incidence at the ionosphere. It is the purpose of this appendix to present a simple graphical method whereby these factors can be determined rapidly without recourse to the analytical expressions. If any two factors are given, the other three can be found.

It is assumed that propagation can be represented by a ray and that the characteristics of the actual path of the ray can be represented with sufficient accuracy by the so-called "equivalent" path, shown in Fig. A-1 as the lines *AB* and *BC*. The height h', of the apex *B* is called the virtual height. *D* is the great circle distance between the end-points *A* and *C*. β is the angle between *AB* and the tangent at *A*, and is called the vertical angle or angle of departure. The ionosphere is assumed to be horizontally stratified and earth's magnetic field effects are neglected. The path is therefore symmetrical about the mid-point, and the angle of arrival is equal to the angle of departure.

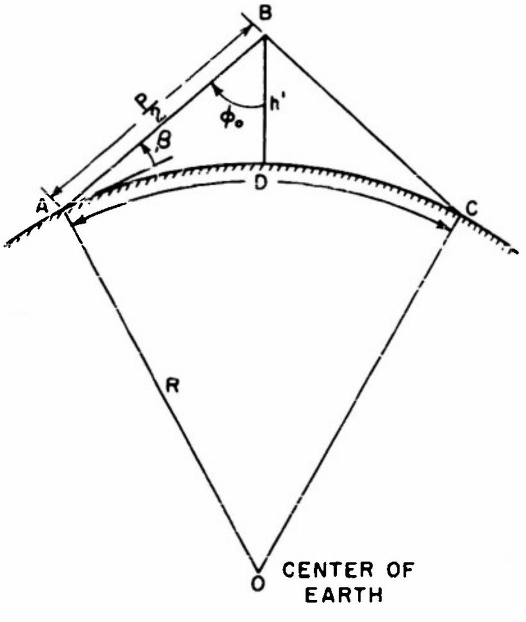

FIG. A-1

RAY-PATH GEOMETRY

A-882-F-33

Graphical computations are facilitated with the aid of the sky-wave transmission chart shown in Fig. A-2. This is simply a

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[1] R. A. Helliwell, "Electronics," p. 150 February 1953.

vertical cross-section of the earth's atmosphere up to a height of 600 km. Great-circle distance D, on the earth's surface is given by the lower scale and virtual height h', by the left-hand scale. The vertical angle β, is determined by aligning a straight edge with the origin and the mid-point of the equivalent path (coordinates h' and $D/2$) and reading the upper scale. The angle of incidence ϕ_0, is interpolated in the family of curves of constant ϕ_0 plotted on the chart. Sec ϕ_0 is read from the conversion chart below the main chart.

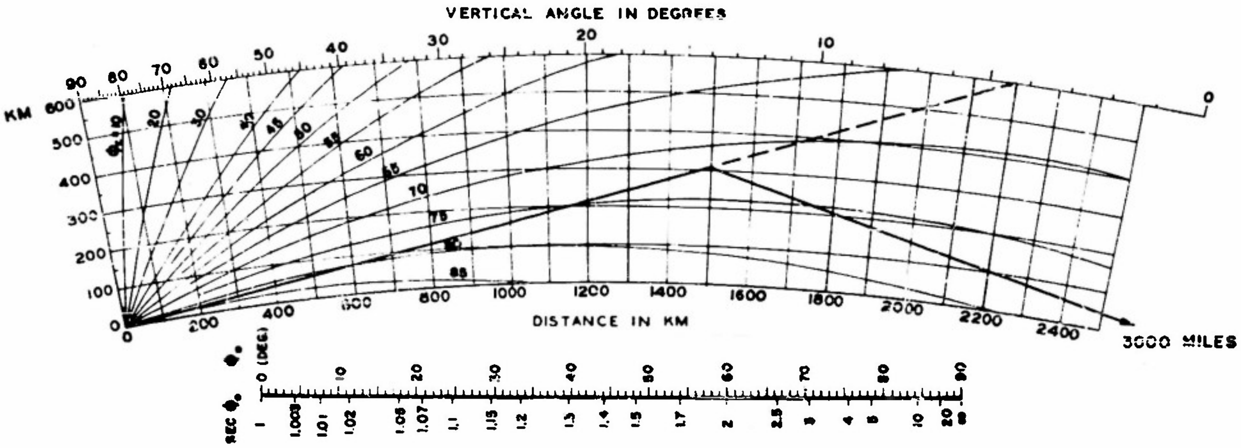

FIG. A-2

SKY-WAVE TRANSMISSION CHART

(EARTH RADIUS = 6357 KM)

A-882-F-34

Since there are five basic variables (D, P, h', β, and ϕ_0), only two of which can be independent, there are ten possible combinations of independent variables. For any given pair of variables, the other three are determined from the chart. The procedure is illustrated in the following example for a selected pair of variables (D and h').

Problem: Given a great-circle distance, D, of 3000 km and a virtual height, h', of 310 km, find the vertical angle β, and the angle of incidence ϕ_0, at the ionosphere, sec ϕ_0, the path distance P, and the transmission time t.

Solution: Locate the apex of the path at $D/2$ - 1500 km and h' = 310 km on Fig. A-2. Align straight edge with origin and apex. Read β = 4.5 degrees on the upper scale. Read ϕ_0 = 72 degrees by interpolating in family of curves of constant ϕ_0. Obtain sec ϕ_0 = 3.2 from conversion scale. Obtain P = 3140 km by measuring distance from origin to apex with 30-to-the-inch engineer's scale (or use height scale on chart) and multiplying result by 2. The transmission time $t = 10{,}470 \times 10^{-6}$ seconds is obtained by dividing the path distance P, by the speed of light (3×10^5 km/sec).

Some of the more important analytical expressions, based on Fig. A-1, are given below for reference. Others can be derived readily.

$$\phi_0 = \tan^{-1} \frac{\sin \frac{D}{2R}}{1 - \cos \frac{D}{2R} + \frac{h'}{R}}$$

$$\beta = 90 - \phi_0 - \frac{D}{2R} \, \frac{180}{\pi}$$

$$h' = R \left[\frac{\cos \beta}{\cos \left(\frac{D}{2R} \, \frac{180}{\pi} + \beta \right)} - 1 \right]$$

$$D = 2R \left[\cos^{-1} \left(\frac{R}{R + h'} \cos \beta \right) - \frac{\pi}{180} \beta \right]$$

$$P = 2 \sqrt{2R\left(R + h'\right) \left(1 - \cos \frac{D}{2R} \, \frac{180}{\pi}\right) + h'^2}$$

APPENDIX B

THE DETERMINATION OF OPTIMUM FREQUENCIES OF TRANSMISSION BY MEANS OF SCATTER SOUNDING

Scatter sounding[1,2,3,4,5] is a new technique for determining the geographical areas to which ionosphere-propagated transmissions may be maintained at any given time and frequency. It is possible from a single location to determine the optimum frequency for transmission to points in the surrounding region out to distances of several thousand miles. The correct frequency varies with time of day, with season, and with sunspot cycle in a manner which is never entirely predictable. It is ordinarily desirable to operate near but slightly lower than the MUF for the given distance. Or, stated slightly differently, the optimum frequency is one which makes the actual transmission path slightly longer than the skip distance. In the past, the ionosphere has been studied by the use of vertical-incidence sounders which study the ionosphere directly over the sounder. The height of reflection as a function of frequency, as determined at vertical incidence, may then be manipulated mathematically or graphically to yield the skip distance or the MUF at oblique incidence. This method of investigation is very successful in determining the average behavior of the ionosphere, and data gathered by a large number of such stations throughout the world form the basis for the advance predictions of transmission conditions supplied by the CRPL and other

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[1] A. M. Peterson, "The Mechanism of F-Layer Propagated Backscatter Echoes," Journal of Geophysical Research, Vol. 56, No. 2, pp. 221-237: 1951.

[2] O. G. Villard, Jr., and A. M. Peterson, "Scatter-Sounding: A Technique for Study of the Ionosphere at a Distance," "Transactions of the I.R.E. Professional Group on Antennas and Propagation," PGAP-3, pp. 140-142.

[3] O. G. Villard, Jr., and A. M. Peterson, "Scatter-Sounding: A New Technique in Ionospheric Research," Science, Vol. 116, No. 3099, pp. 221-224; August 1952.

[4] O. G. Villard, Jr., and A. M. Peterson, "Instantaneous Prediction of Radio Transmission Paths," QST, Vol. XXXVI, No. 3, pp. 11-20; March 1952.

[5] L. C. Edwards, "Communication Zone Indicator." ELECTRONICS, Vol 26, No. 8, pp. 152-155; August 1953.

similar agencies However, conditions over a particular path and for a particular time are found to depart widely from average conditions. Vertical-incidence sounders have not to date been particularly useful as an aid to choosing the right frequency for a particular time of day. Scatter sounding, on the other hand, makes use of the same oblique paths which are utilized for communication, and the skip distance is obtained by a simple conversion of the observed time delay.

In scatter sounding an echo is received not from the ionospheric layer itself but from distant portions of the earth's surface which have been illuminated by energy bent back to earth by the layer. In briefest outline, the method consists of noting the time delay between the transmission of a short burst of transmitted signal and the return of a small fraction of its energy scattered back to the transmitter when the outgoing signal strikes irregularities on the surface of the earth. Figure B-1 is a simplified diagram showing how this scattering occurs. The backscattered energy produces an echo at the transmitter location, which may be

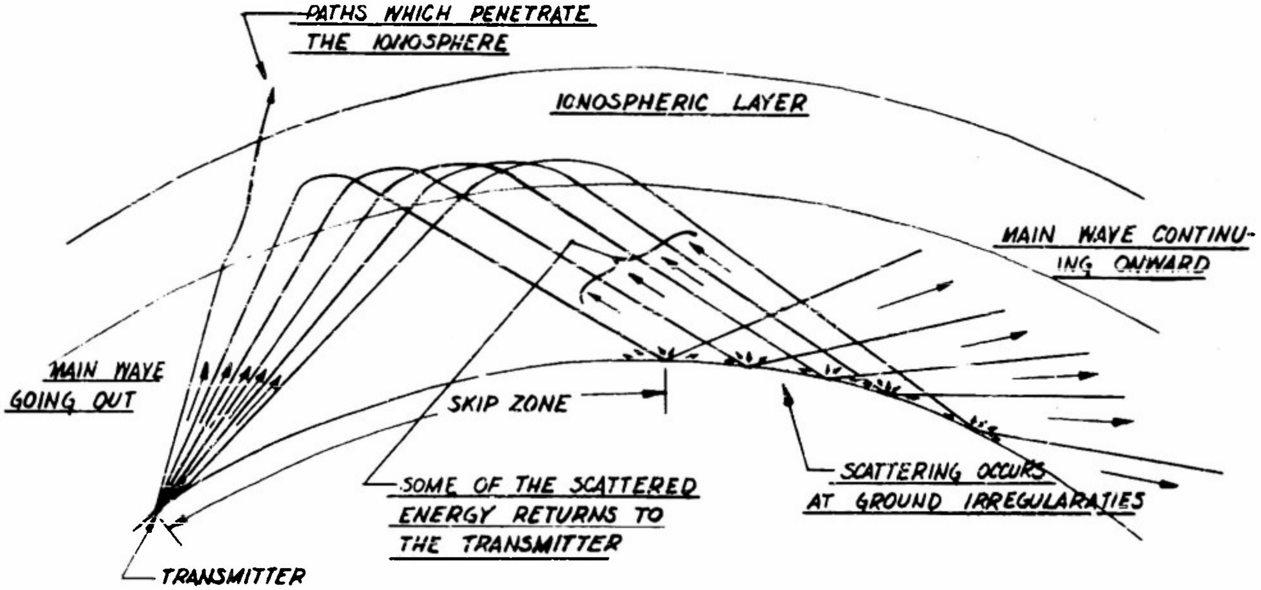

FIG. B-1

BACKSCATTERING BY IRREGULARITIES AT EARTH'S SURFACES

A-882-F-35

detected on a near-by receiver. A sketch of a typical oscilloscope indication (amplitude-time, or "A scope") is shown in Fig. B-2. From the delay time indicated on the sketch (the interval t_1) the ground distance to the scatter source may be obtained by the use of a conversion chart.* An echo resulting from a second hop is also illustrated in this sketch, with time delay t_2.

When a rotatable directional antenna is used it is possible to obtain a range-azimuth or plan-position-indicator (PPI) type of display of those areas on the earth's surface which are being strongly illuminated by the transmissions at the particular time and frequency. The PPI display is convenient for a study of conditions over a large number of paths. If the primary interest is in a particular path, the A-scope display will ordinarily be satisfactory. In either case, since ionosphere conditions are seldom the same in all directions from a given point of observation, a directive antenna is essential in order to avoid ambiguity. If the same antenna is used for transmitting and receiving the directivity is effective both on transmitting and receiving. When an omnidirectional antenna is used for transmitting, a more directive receiving antenna will

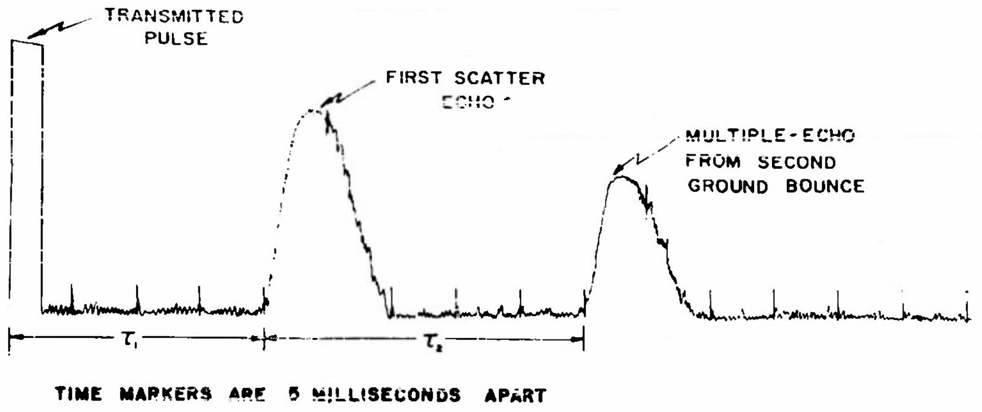

FIG. B-2

SKETCH ILLUSTRATING THE APPEARANCE OF SCATTER-ECHOES ON AN A-SCOPE

A-802-F-36

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*See Fig. B-9.

be required. A three-element Yagi array of the type common in amateur radio installations has been found very useful for scatter-sounding purposes when used for transmitting and receiving. The PPI photograph of Fig. B-3 represents a sample of the scatter-sounding records obtained

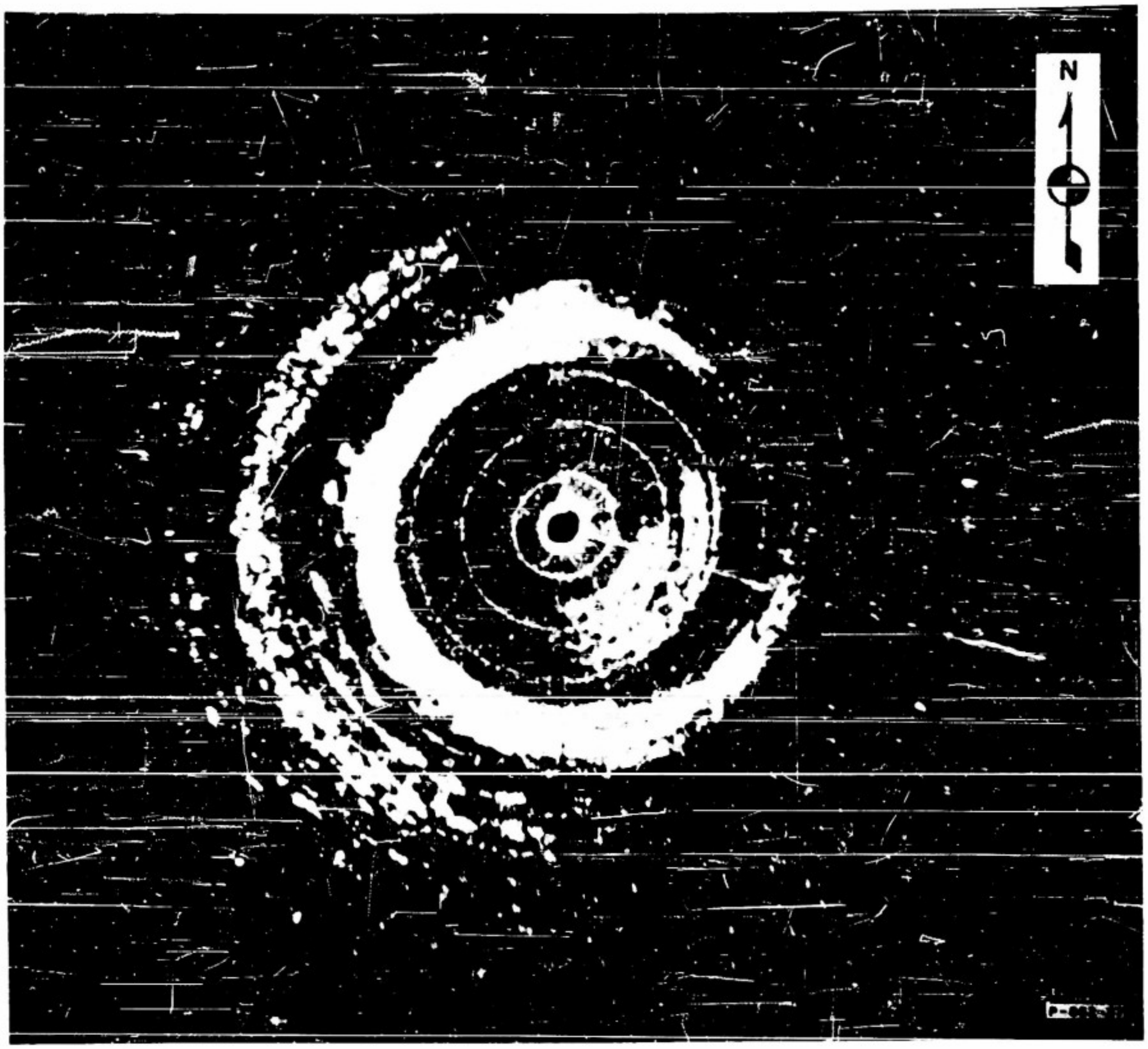

FIG. B-3

PLAN-POSITION DISPLAY OF GROUND-SCATTER ECHOES
PROPAGATED BY BOTH F AND SPORADIC E-LAYERS
LOCAL TIME: 1825

using a rotatable three-element Yagi. In this picture, north is at 12 o'clock, east at 3 o'clock, etc. Time-delay circles are spaced 3.33 ms of time delay apart. The record was made at Stanford University, on a frequency near 14 Mc. At the local time indicated, F2-layer propagation to the east has failed but is still possible to the north, west, and south. The crescent of echoes in these directions represents ground-scattered echoes propagated by the F2-layer. The multiple echoes to the west result from additional hops between earth and ionosphere. The patch of echoes at close range to the southeast indicates the presence of a cloud of sporadic-E ionization Though communication via these sporadic E patches is possible, they occur at times and with intensity which cannot be predicted.

SCATTER-SOUNDING EQUIPMENT

A specially constructed scatter-sounder capable of supplying PPI displays at several frequencies in the range between 4 Mc and 24 Mc would be a very useful apparatus for continuous monitoring of propagation conditions in the region surrounding a communication station. Equipment of this type has been designed and operated for nearly two years at Stanford University,[1] for ionospheric research purposes. On the other hand, scatter sounding can be successfully accomplished by relatively minor modification of existing communications equipment. The apparatus required for scatter sounding of the ionosphere is essentially the same as that used for long-distance communication purposes. The five major items are: (1) a transmitter capable of high-speed keying, (2) a sensitive communications receiver, (3) suitable antennas, (4) a keyer for generating the keying impulses, and (5) an oscilloscope for observing the echoes. Figure B-4 is a block diagram that demonstrates the interconnection of these components to form a complete scatter sounder. Figure B-5 shows an oscilloscope photograph obtained at Lualualei, using TBC transmitters, rhombic antennas, and an SP600 receiver. A strong first-hop echo and a weak second-hop echo are present in this photograph. These scatter soundings were undertaken to study the effect of the mountains which surround the transmitter site and to indicate the effectiveness of the rhombic terminations.

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[1] A. M. Peterson, A Scatter-Sounder For The Study of Sporadic Ionization in the Upper Atmosphere, Technical Report No. 1, September 1953, Office of Ordnance Research Contract DA-04-200-ORD-181.

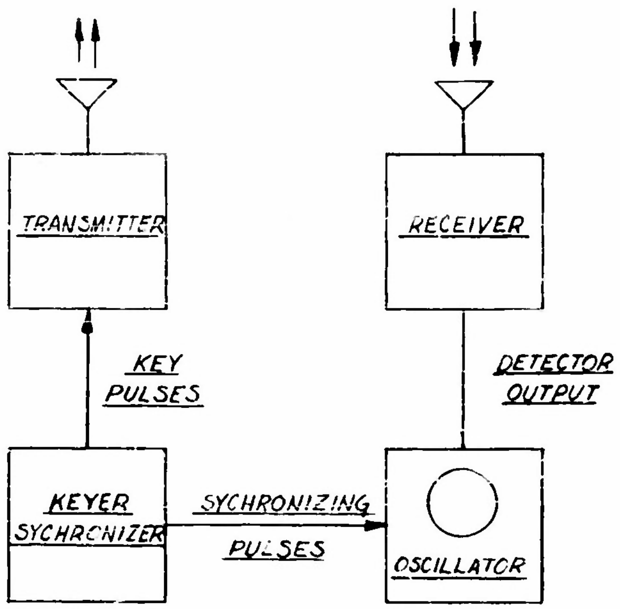


FIG. B-4

BLOCK DIAGRAM OF COMPLETE SCATTER SOUNDER

A-882-5-38

Transmitter requirements for scatter sounding are relatively modest. One or two kilowatts of transmitted power is sufficient for most purposes, though higher power may be advisable in the interest of improved reliability. For simplicity in keying, the transmitter should preferably utilize vacuum tube keying circuits. Experiments at Lualualei indicate that the Navy type TBC transmitter meets all of these requirements and seems to be nearly ideal for scatter sounding without modification. Successful keying or "pulsing" may be accomplished by using a special keyer (to be described later) with the TBC in the d-c keying position.

Nearly any sensitive communications receiver can be used as a receiver for scatter sounding purposes. Somewhat better than the usual overload characteristics are necessary in order that the full sensitivity be recovered quickly, following a transmitted pulse. The SP-600 receiver has proven satisfactory for these purposes without special modification. Further desirable features of this receiver are the variable i-f selectivity (3 to 16 kc) and the availability of a direct output from the final detector (d-c connection). Though for most scatter-sounding tests the receiver will be run in the narrowest of the regular i-f bandwidth positions (not crystal, since excessive ringing takes place), the availability of the wider bandwidths proves useful in examining the details of the echo. The direct connection to the detector is usually essential

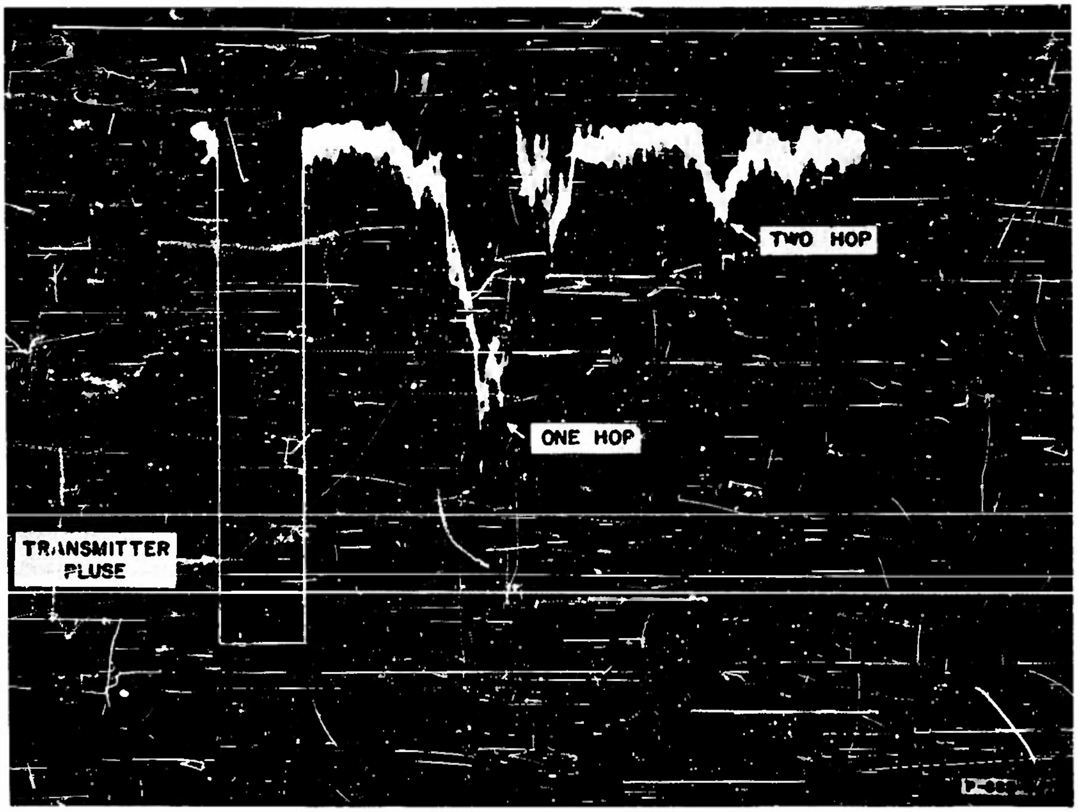


FIG. B-5

A SCOPE PHOTOGRAPH OF SCATTER ECHOES OBTAINED WITH STANDARD COMMUNICATIONS EQUIPMENT AT LUALUALEI. FREQUENCY: 16, 940 KC. TIME: 1530 HST, 24 JULY 1953.

since normal headphone or speaker outputs follow amplifiers whose frequency response is inadequate to pass the scatter-sounding waveforms without distortion. Other types of receivers may require minor modifications, such as decreasing the RC time- constant values in the r-f and i-f amplifiers (detector filter time constant may also require attention in some cases). The RC product of all circuits which contain capacitors that are charged by grid-current flow during transmit time should be made small (RC $\approx$ 200 μs). If this is not done, the capacitors may remain charged for long intervals following the transmitted pulse, with resultant loss of receiver sensitivities. In addition to these modifications, a direct connection to the detector output should be made available.

An oscilloscope is required for examining the output from the receiver. Nearly any oscilloscope is satisfactory as long as the sweep circuits function well in the 10- to 20-cps region. The Dumont types 304H or 304A oscilloscopes have proven very useful for scatter-sounding work. A long-persistence P7 screen is desirable as an aid to viewing and study of the echoes.

The choice of antenna will depend on the purposes for which the scatter soundings are being taken. For a point-to-point circuit the best antennas may be the ones actually used for communications. The transmitter might well be fed into its usual antenna, probably a terminated rhombic, since this tests the path under actual conditions. For receiving, it is possible to use the same antenna by making use of a transmit-receive (TR) apparatus. This sort of operation is probably undesirable for the conditions which exist at a transmitter station such as Lualualei, since a large variety of transmitters and antennas are used. If, however, a completely separate installation is contemplated, the use of a TR and a common antenna for both transmitting and receiving may be advisable. For point-to-point circuits, an additional antenna of the same type as used at the transmitter would make a very satisfactory receiving antenna. If this is not available, a simple directive antenna aimed in the proper direction, or even non-directional dipoles, may be used. With non-directional receiving antennas, care must be taken to properly interpret the echoes, since more possibility exists for echoes arising from side or back-lobe radiation at the transmitter antenna to be detected.

For broadcast use, the communications transmitter will normally be connected to a non-directional antenna. If a non-directional antenna is also used for receiving, an echo arriving from one direction will mask the lack of echo from another direction. Consequently, if it is desirable to know that a particular area is being illuminated by a broadcast transmission, some form of directive antenna array should be used for receiving. One possibility is a group of rotatable Yagi antennas, each tuned to one of the frequencies used for broadcast purposes. Alternatively, a number of broadband directional antennas, such as rhombics, can be used to observe the echoes in each of several azimuth directions. One form of antenna which has proven effective for this purpose is a group of sloping "Vee's" all suspended from a central pole. Twelve wires, èach some 600 ft in length, may be arranged at 30 degrees intervals around the central pole with the lower end sloping off gradually to ground level. With this arrangement, a switching box may be mounted atop the pole and a single transmission line may be used to feed the 12 wires in pairs as Vee antennas. At the higher frequencies (10 to 20 Mc), the pairs are formed by connected adjacent wires (30 degrees apart) to the transmission line to form the Vee antenna. At the lower frequencies (5 to 10 Mc), pairs are made from wires 60 degrees apart, that is by skipping one wire in between the two active wires. In this manner the Vee's can be made to function with more nearly the optimum angle between wires at all frequencies. In each case, this antenna array provides for examination of echoes in twelve different directions. The use of this type of antenna array when transmitting on non-directional antennas should permit determination of the areas which a particular broadcast transmission is effectively illuminating at any particular time. It would thus be possible to insure complete coverage of the desired areas while at the same time permitting the securing of those transmissions at frequencies which were ineffective at a particular time.

A pulser is required for keying on the transmitter for a short time at regular intervals. This pulser is a sort of electronic "dot wheel." Investigations have shown that the optimum length of transmitted impulse is 1-2 ms. The interval of time between pulses is determined by the time it takes the most distant echo to return to the transmitter. A distance of 12,000 km is a fairly representative upper limit. This requires a time interval between pulses of 1/12.5 sec, or a pulse repetition rate of 12.5 pulses per second.

Perhaps the simplest form of keyer is the two-tube circuit illustrated in Fig. B-6. This consists of a triggered multivibrator and a cathode

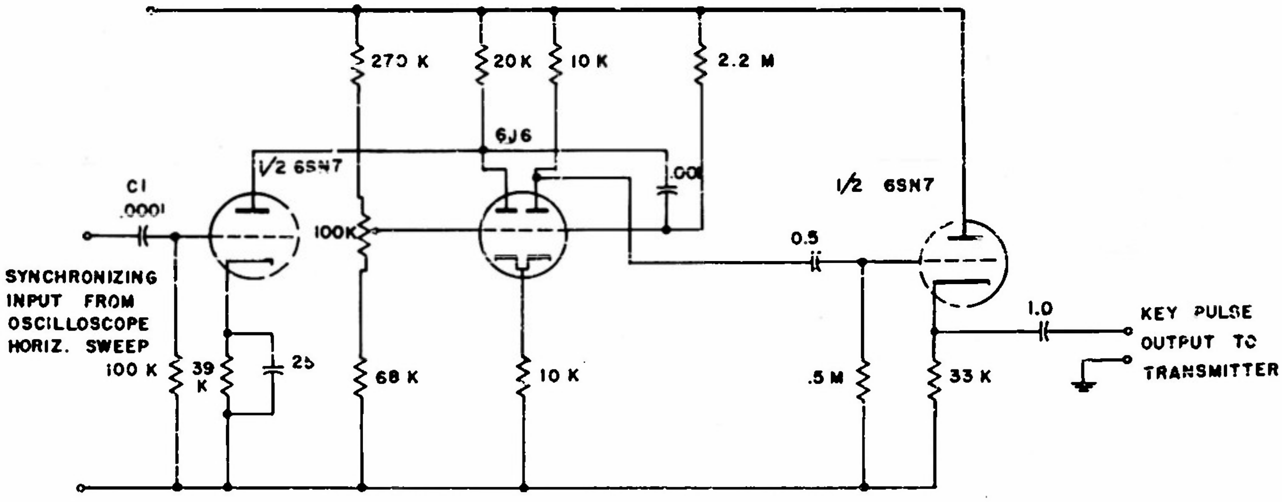


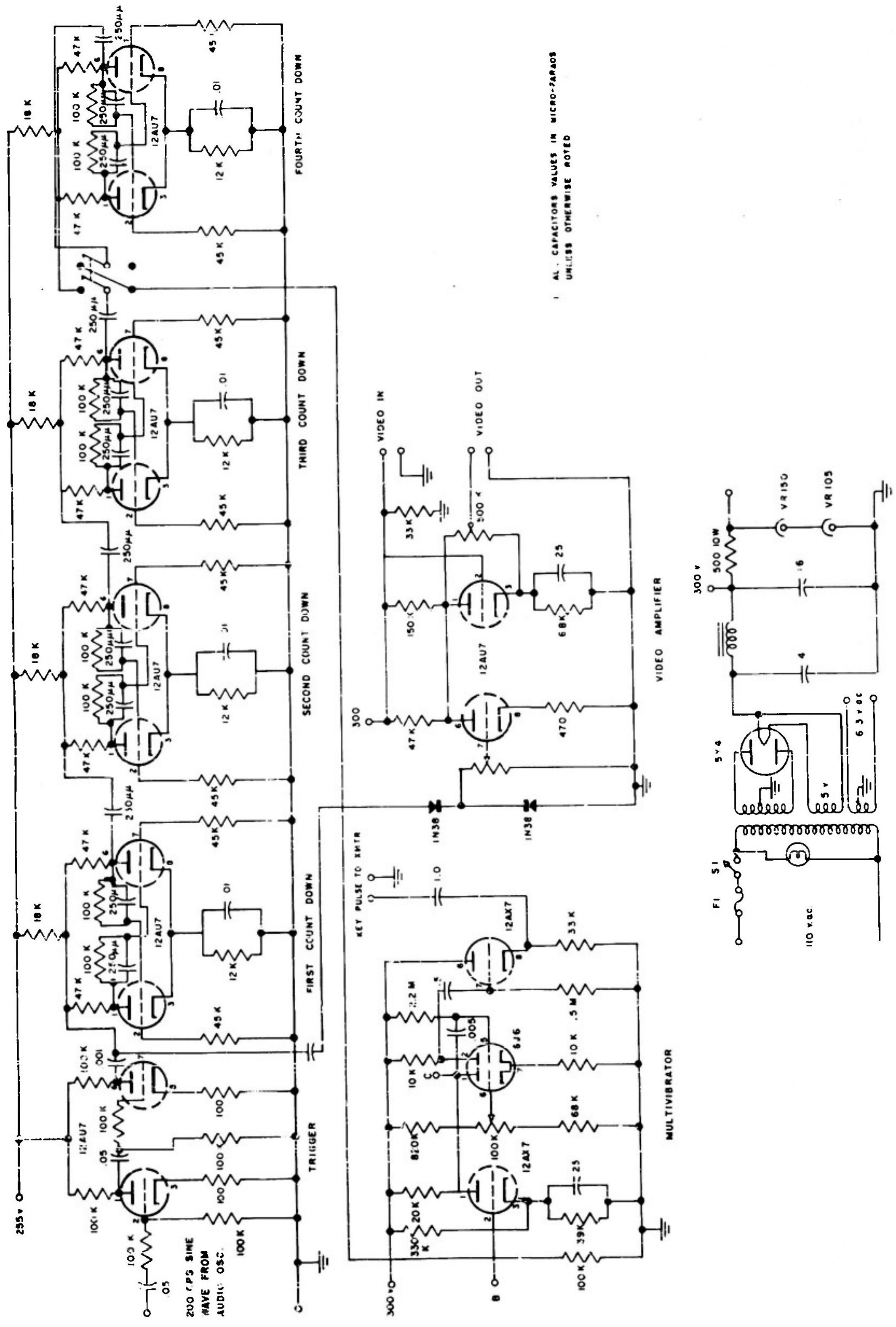
FIG. B-6

SIMPLIFIED PULSER FOR SCATTER-SOUNDING

A-882-F-40

follower. This type of keyer was constructed while the S.R.I. group was at Lualualei, and functioned quite satisfactorily during a series of scatter-sounding tests. In this unit, a 6J6 tube functions as a cathode-coupled multivibrator generating pulses whose duration can be varied by means of potentiometer R-3. The two sections of a 6SN7 function as a trigger amplifier and a cathode follower, respectively. The cathode follower provides the required low output impedance for working into keying lines to key the transmitters. The trigger voltage for this simple pulser was obtained from the horizontal sawtooth sweep voltage of a small test oscilloscope by attaching between one of the scope plate connections and ground. These terminals are usually available at the back of the oscilloscope. Capacitor C1 and resistor R1 at the input of the pulser comprise a differentiator circuit which forms a short trigger pulse at the flyback time of the sawtooth voltage.

In using this simple pulser, the time interval between pulses is set by varying the rate at which the multivibrator is triggered. Using the oscilloscope trigger, this is accomplished by varying the sawtooth sweep frequency. For example, a sweep frequency of 20 cps allows 1/20 sec = 50 ms between pulses, and 12.5 cps allows 1/12.5 = 90 ms between pulses. Time intervals along the sweep length can be measured by



1. ALL CAPACITORS VALUES IN MICRO-FARADS UNLESS OTHERWISE NOTED

FIG B-7

PULSER-SYNCHRONIZER FOR SCATTER SOUNDING

Appendix B

subdividing the oscilloscope sweep length into equal length segments. For example, a scale which divides the 1/20 sec sweep into 5 equal lengths yields 1/5 × 1/20 = 10 ms intervals. Using this technique the time interval between transmitted pulse and received echo can be measured when the receiver output is applied to the vertical deflection plates of the oscilloscope.

A more complicated form of pulser, though one which is much easier to use operationally, is shown in Fig. B-7. In this circuit, time-delay marks are provided at 5-ms intervals to be used in measuring the time delay between transmitted pulse and received echo. These marks are derived from a 200-cps sine-wave oscillator voltage. The multivibrator and cathode follower portion of this unit are the same as that of the simple pulser but the trigger voltage is obtained from the 200-cps sine-wave source. This is accomplished by the use of a series of Eccles-Jordan count-down stages. In this manner the 5-ms time-delay markers are permanently synchronized with the transmitted key pulse. The two halves of the 12 AU7 tube in the video amplifier stage amplify the receiver output and provide a means for mixing with the time-delay markers. The synchronizer pulse output is used to synchronize the oscilloscope sweep to the key pulse output. In this unit the key pulse rate is normally set at 1/16 of 200 cps, or 12.5 sweeps per second. The interval between pulses is 80 ms with sufficient time delay to allow for echoes arriving from distances as far away as 12,000 km (7440 miles). Switch S1 permits the pulse rate to be changed to 25 pulses per second and the range interval to 6000 km (3720 miles). This higher rate is sometimes advantageous when only short-range echoes are being investigated. For broadcast use, this shorter range interval would ordinarily be adequate. The type of indication obtained when using this improved synchronizer-pulser is illustrated in Fig. B-2.

ECHO INTERPRETATION

Although the details of scatter-echo production are complicated, the method of obtaining the MUF or the skip distance by scatter sounding is quite straightforward. For simplicity in interpreting the echoes, assume that the geometry of Fig. B-8 applies. In this sketch the actual F-layer is replaced by a spherical sheet at an average equivalent height, *h*, above the earth. Propagation may be assumed to take place following triangular paths such as those illustrated in Fig. B-8, with reflection at height *h*.

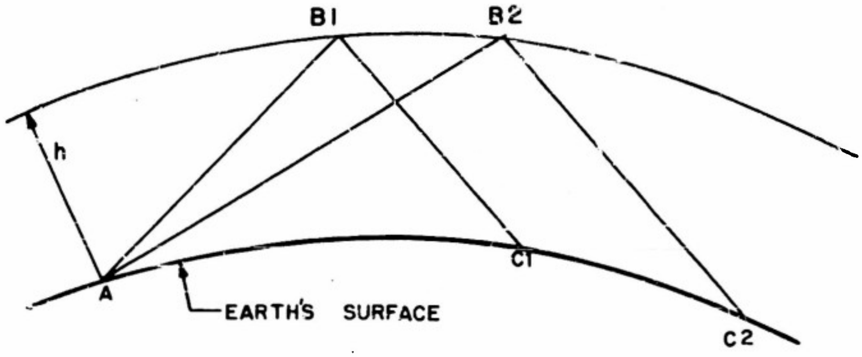


FIG. B-8

SKETCH ILLUSTRATING TRANSMISSION-PATH GEOMETRY

A-882-F-42

The energy strikes the earth at point C_1 and some of it is scattered back to the transmitter location from this point. Under these conditions the ground distance $D_1 = AC_1$, can be very simply related to the time delay taken to travel over the equivalent triangular path AB_1C_1 and back. AB_2C_2 illustrates another possible path. If all echoes at all time delays are assumed to result from propagation involving this sort of path, with reflection at height h above the earth, curves such as those of Fig. B-9 can be constructed which will relate the distance, D, at which the signal returns to earth to the time delay, τ, along the equivalent triangular path. For F-layer propagation it is assumed that $h = 300$ km, and for E-layer propagation $h = 100$ km. Curves for these two cases are plotted in Fig. B-9. To determine the skip distance, the time delay in milliseconds between the leading edge of the transmitted impulse and the leading edge of the returned echo is measured. With the measured value of time delay, the corresponding value of skip distance, D, can be read from Fig. B-9. Though approximations are made in using this simplified technique, the resulting distance is a very good index of the actual skip distance for propagation via the F-layer, provided the measured time delay, τ, is greater than about 6 ms. This corresponds to a skip distance of about 800 km. For distances shorter than 800 km, the thickness of the actual F-layer and its variations in height begin to make corrections to the simple method outlined above more important. As described in Chapter 4, ground-wave propagation at frequencies near 4 Mc provides communication at all times for distances out to 400 km or more. Scatter soundings are therefore not required for distances less than this. For distances between 400 km and 800 km, when propagation is via the F2-layer, the

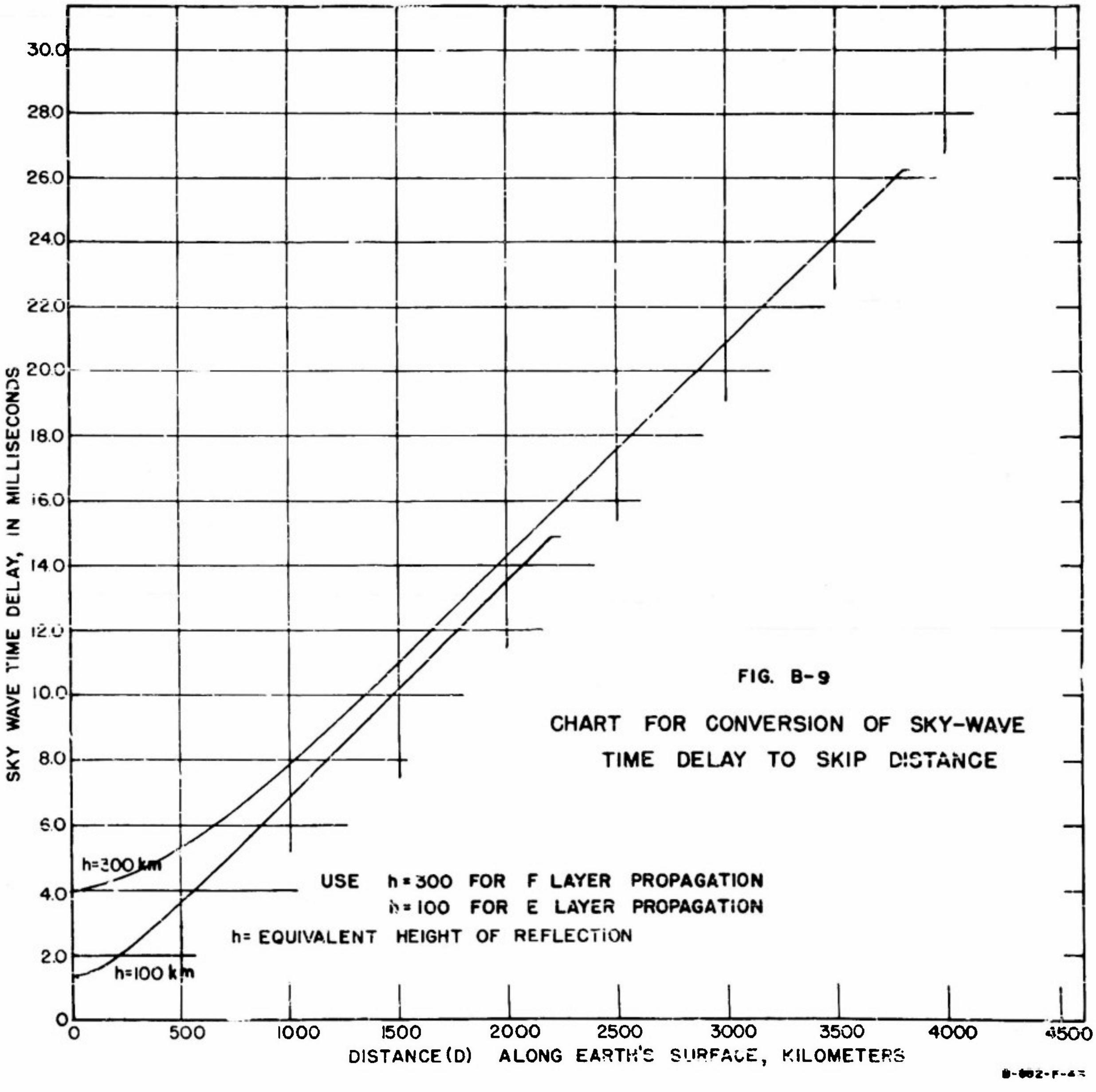


FIG. B-9

CHART FOR CONVERSION OF SKY-WAVE TIME DELAY TO SKIP DISTANCE technique outlined in this discussion will ordinarily indicate a satisfactory transmission frequency, though it will be somewhat lower than the MUF.

When the scatter echo results from E-layer propagation, the curve for *h* = 100 in Fig B-9 is used to convert time-delay to skip distance. Echoes of this type produced by a sporadic-E cloud are illustrated on the PPI record of Fig B 2 as a compact clump of echoes at a short range in the southeast Sporadic-E echoes normally occur as patches of limited extent when observed at a given frequency. The change in echo time-delay is much slower with changes of frequency than is the case for F-layer echoes Sporadic-E echoes are found to occur at unpredictable times, with echo delays ranging to a maximum of about 15 ms. This corresponds to distances of transmission up to 2200 km. These characteristics of sporadic-E echoes, along with a knowledge of the relatively well behaved F-layer echo characteristics, permit a separation of the two types of scatter echoes during times when sporadic-E echoes are present.

As an illustration of the determination of the skip distance by scatter sounding, consider the sketch of Fig. B-2. In this case the echoes can immediately be said to result from F-layer propagation since the time delay is greater than 15 ms. Two echoes are shown, which result from a first and second hop between earth and ionosphere. Assume the scatter soundings were taken at a frequency f_1. The first hop time delay, τ_1, is read as 20 ms and the second hop delay as 25 ms. The skip distances are obtained from the chart of Fig B-9 as 2875 km for the first hop and 3125 for the second hop. Or, conversely, the frequency, f_1, is the MUF for a distance of 2875 km by one-hop F-layer propagation of 6000 km for two hops. In order to allow for short-term variations in layer conditions, a frequency about 10% lower than the MUF would be used for a communication circuit.

APPENDIX C

THE POWER GAIN OF RHOMBIC ANTENNAS INSTALLED AT LUALUALEI

In Figs C-1 to C-26 the gain of the presently installed rhombic antennas has been plotted as a function of frequency. These curves can be used to determine whether or not a oarticular antenna is suitable for transmission over the circuit at a particular frequency. The gain is given relative to that of an isotropic radiator. On this scale the gain of a horizontal doublet antenna suspended at optimum height above ground is about 7.5 db. Several curves are given for each of the antennas, each for a different fixed angle of elevation above the horizontal. Under most ionospheric conditions, the transmission path for a given circuit will fall within the range of vertical angles for which gain curves are presented. A glance at these figures will show that for many of the circuits, different rhombic antennas were designed for different parts of the frequency range from 4 to 24 Mc. As an example, Fig. C-1 shows the gain of rhombic antennas RA-1 and RA-2, which are used for the Washington circuit. It is apparent that RA-2 has very poor gain at frequencies below 6 Mc while RA-2 is not suited for transmissions above 19 Mc. These two antennas should therefore be used as a compelementary pair, RA-1 for frequencies between 4 and 12 Mc, RA-2 for those between 14 and 24 Mc. Either antenna may be better for use at any given time between frequencies of 12 and 14 Mc, depending on ionospheric conditions. Similar pairs of antennas are available for some of the other circuits. These were listed in Table IV.

The gain of the remaining rhombics is usually small at the low-frequency end For instance, at frequencies below about 7 Mc the performance of RA-31, used for the Midway circuit, is poorer than that of a simple doublet antenna (Fig. C-15). This may explain some of the excessive outages experienced on this circuit.

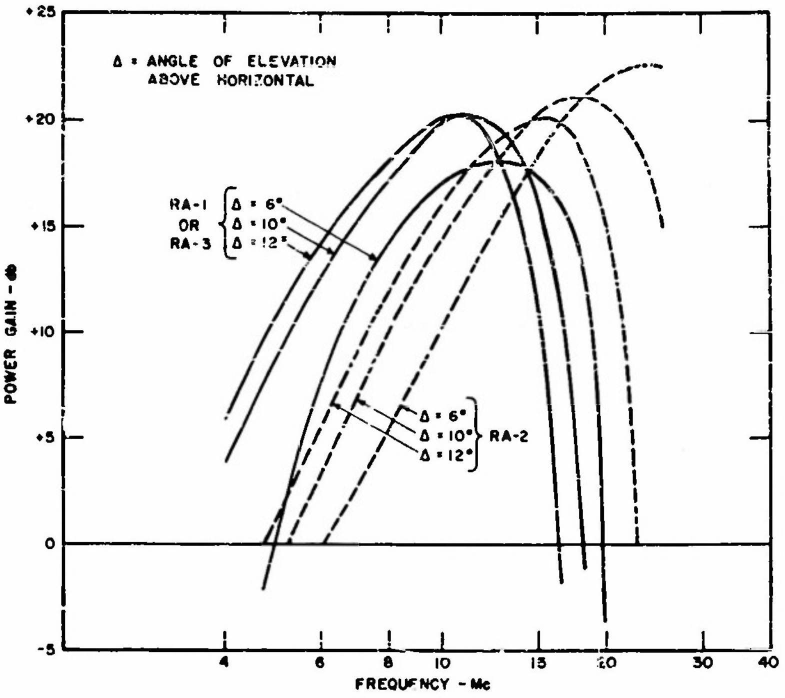


FIG. C-1

GAIN OF RHOMBIC ANTENNAS RA-1 OR RA-3, AND RA-2
FOR WASHINGTON, D.C. CIRCUIT

A-882-F-45

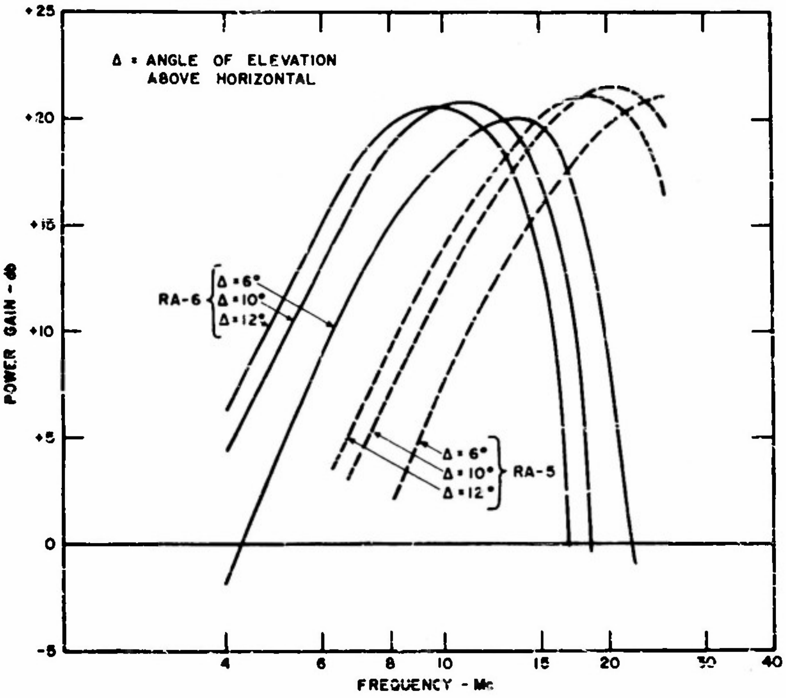


FIG. C-2

GAIN OF RHOMBIC ANTENNAS RA-6, AND RA-5
FOR WASHINGTON, D.C. CIRCUIT

A-882-F-43

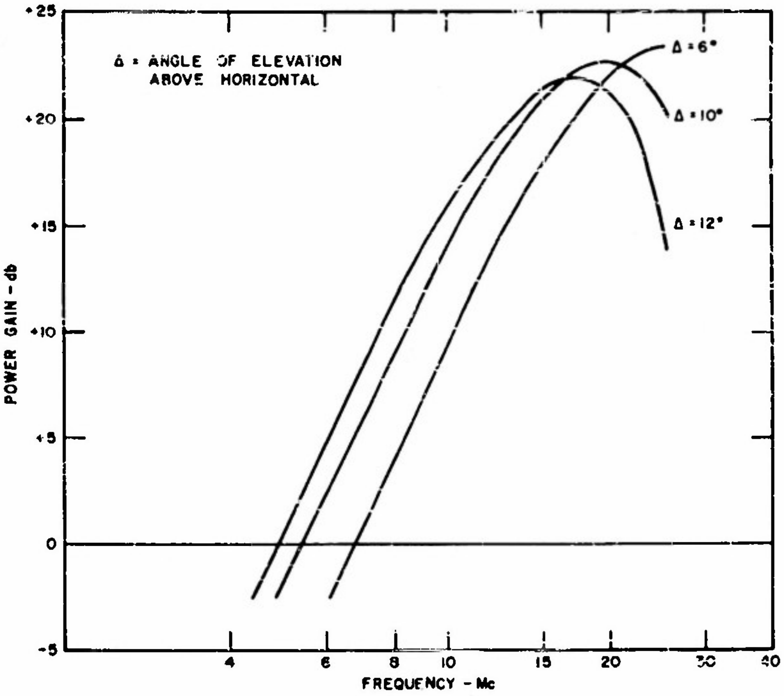


FIG. C-3

GAIN OF RHOMBIC ANTENNA RA-29
FOR WASHINGTON, D.C. CIRCUIT

A-882-F-47

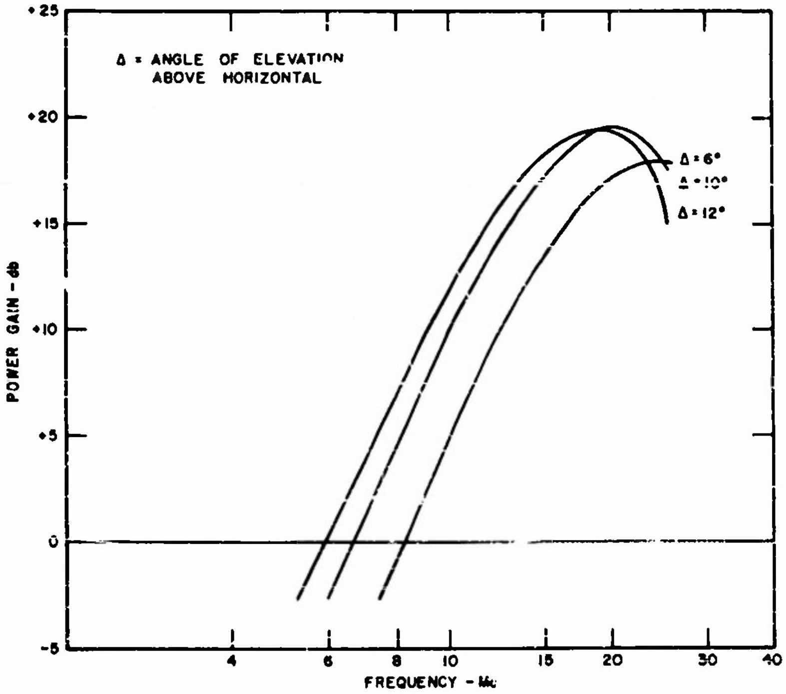


FIG. C-4

GAIN OF RHOMBIC ANTENNA RA-30
FOR WASHINGTON, D.C. CIRCUIT

A-882-F-48

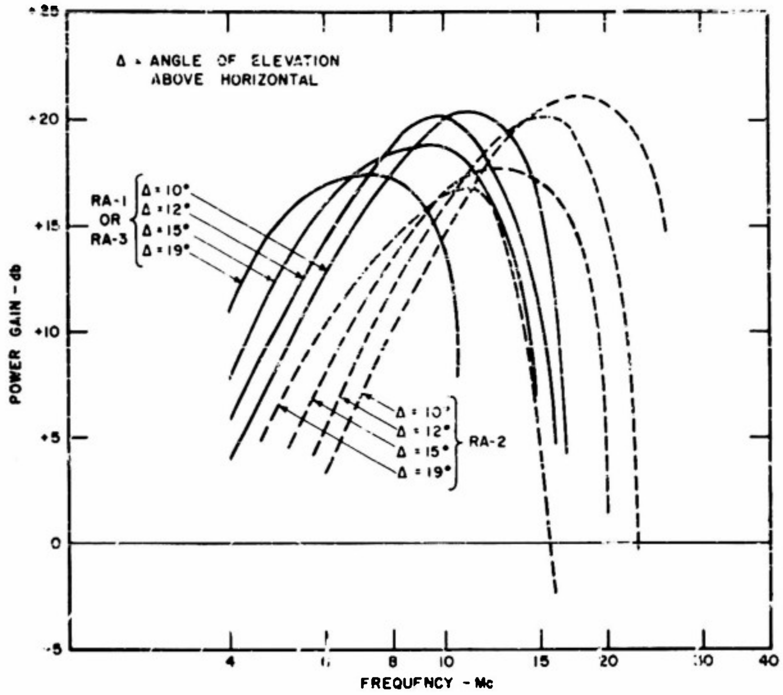


FIG. C-5

GAIN OF RHOMBIC ANTENNAS RA-1 OR RA-3, AND RA-2 FOR SAN FRANCISCO CIRCUIT

A-882-F-49

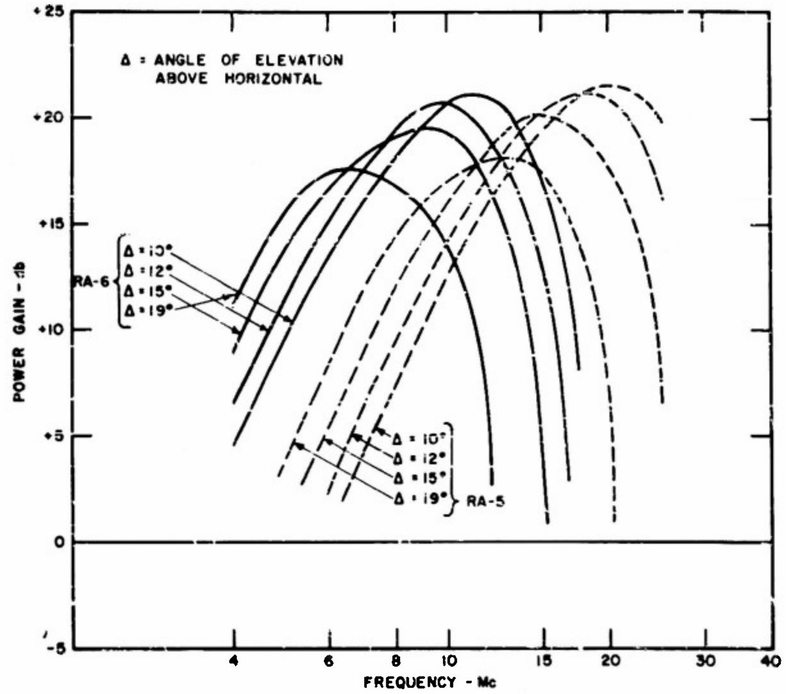


FIG. C-6

GAIN OF RHOMBIC ANTENNAS RA-6 AND RA-5 FOR SAN FRANCISCO CIRCUIT

A-882-F-50

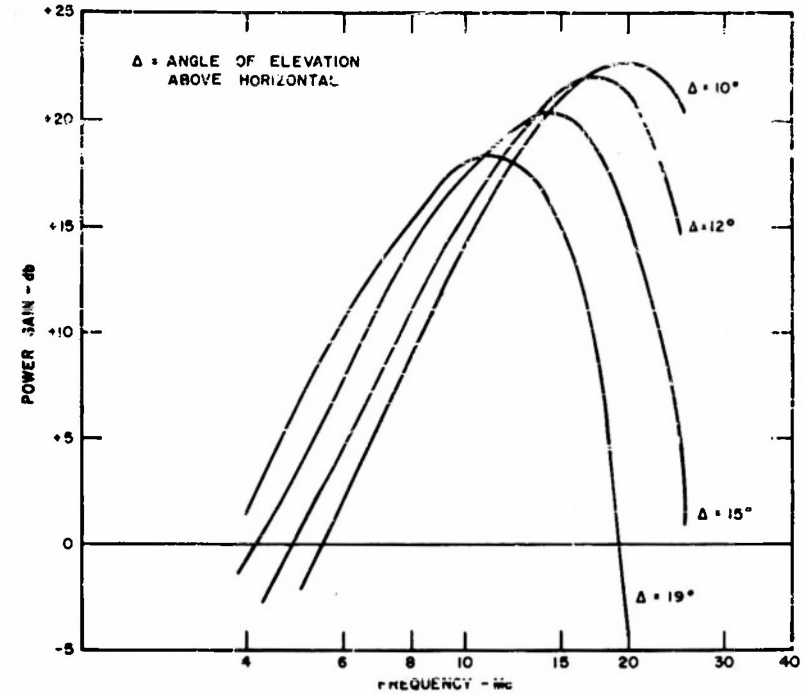


FIG. C-7

GAIN OF RHOMBIC ANTENNA RA-29
FOR SAN FRANCISCO CIRCUIT

A-882-F-51

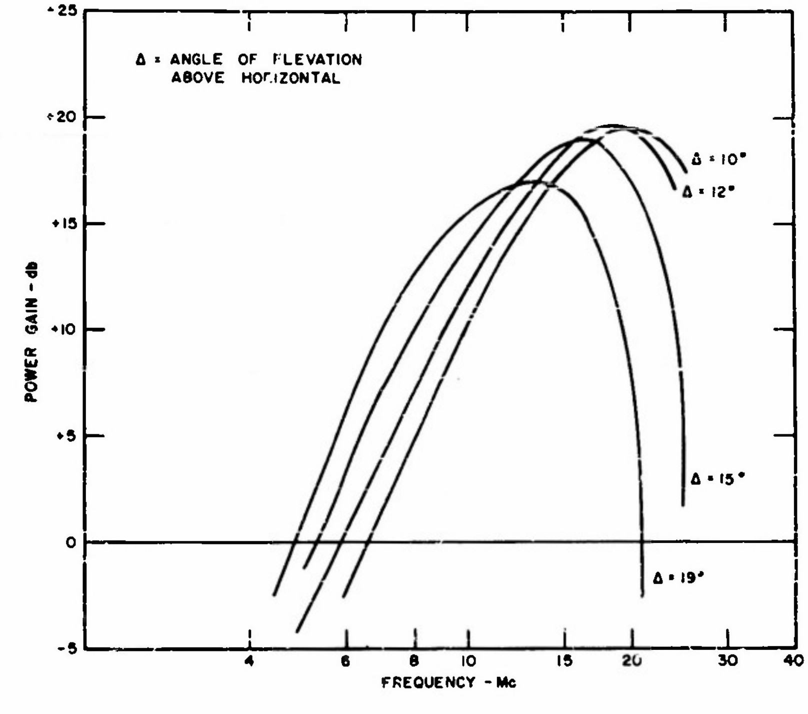


FIG. C-8

GAIN OF RHOMBIC ANTENNA RA-30
FOR SAN FRANCISCO CIRCUIT

A-882-F-52

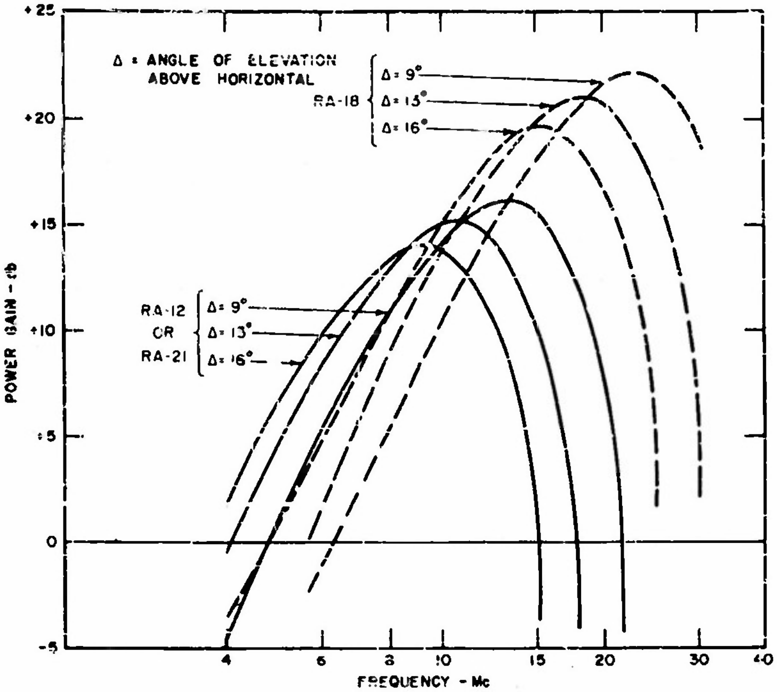


FIG. C-9

GAIN OF RHOMBIC ANTENNAS RA-12 OR RA-21, AND RA-18 FOR GUAM CIRCUIT

A-882-F-53

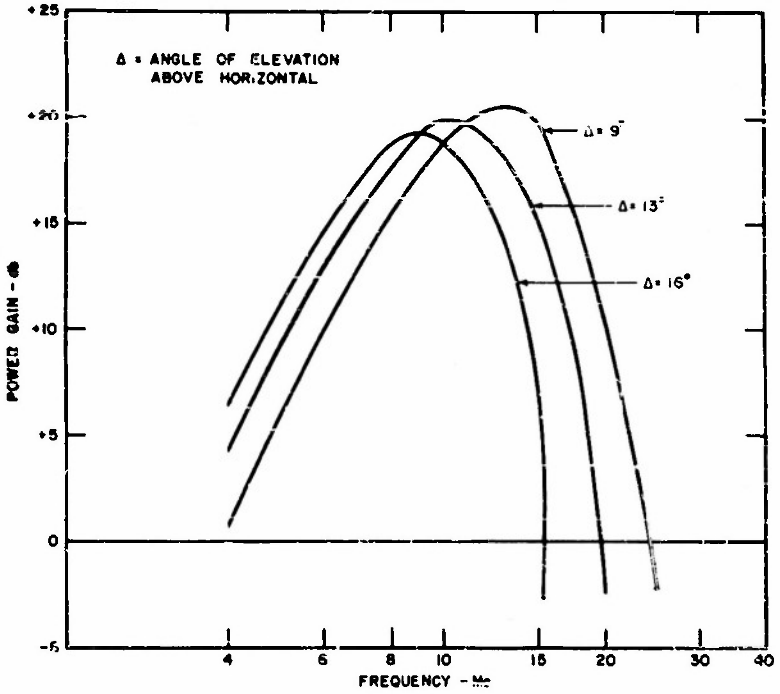


FIG. C-10

GAIN OF RHOMBIC ANTENNA RA-21 FOR GUAM CIRCUIT

A-882-F-54

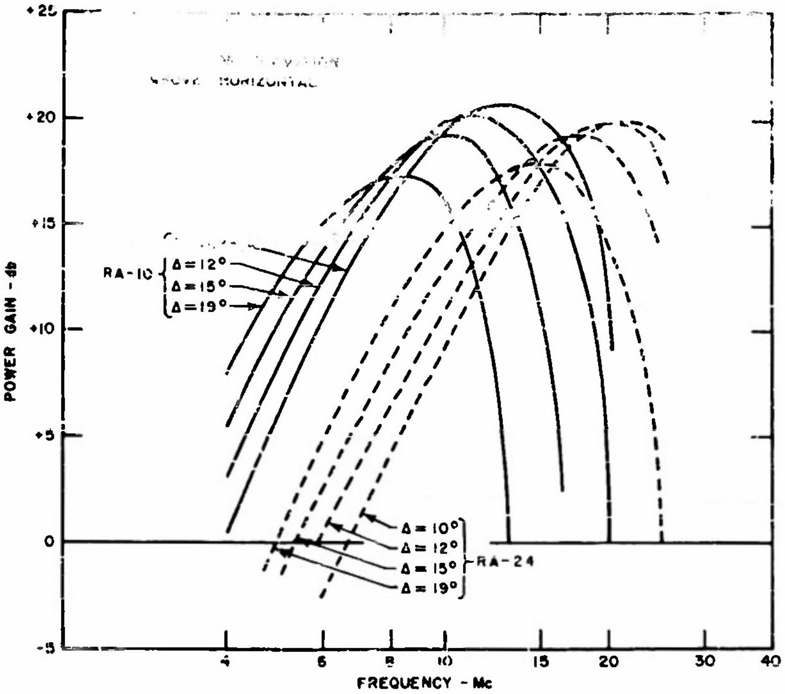


FIG. C-11

GAIN OF RHOMBIC ANTENNAS RA-10 AND RA-24 FOR KWAJALEIN CIRCUIT

A-662-F-65

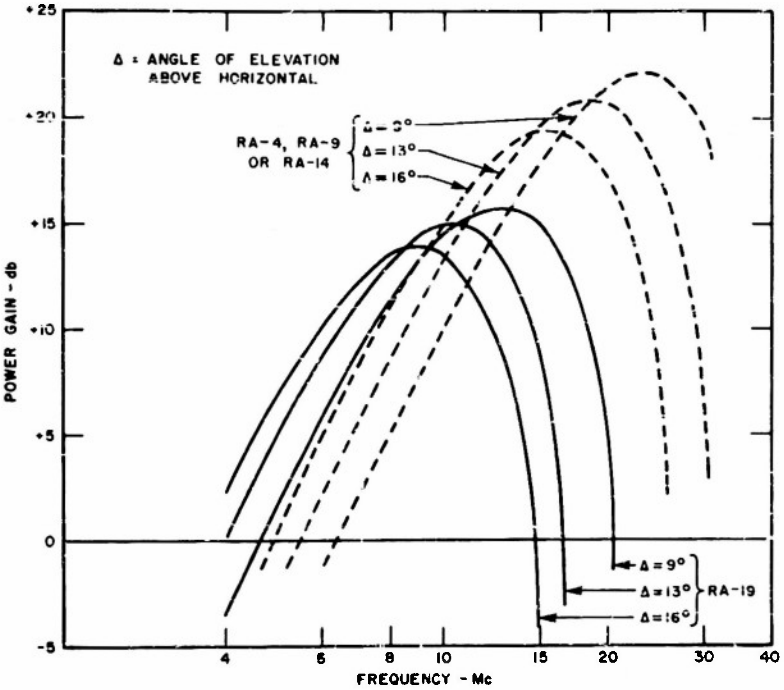


FIG. C-12

GAIN OF RHOMBIC ANTENNAS RA-4, RA-9, OR RA-14, AND RA-19 FOR TOKYO CIRCUIT

A-662-F-66

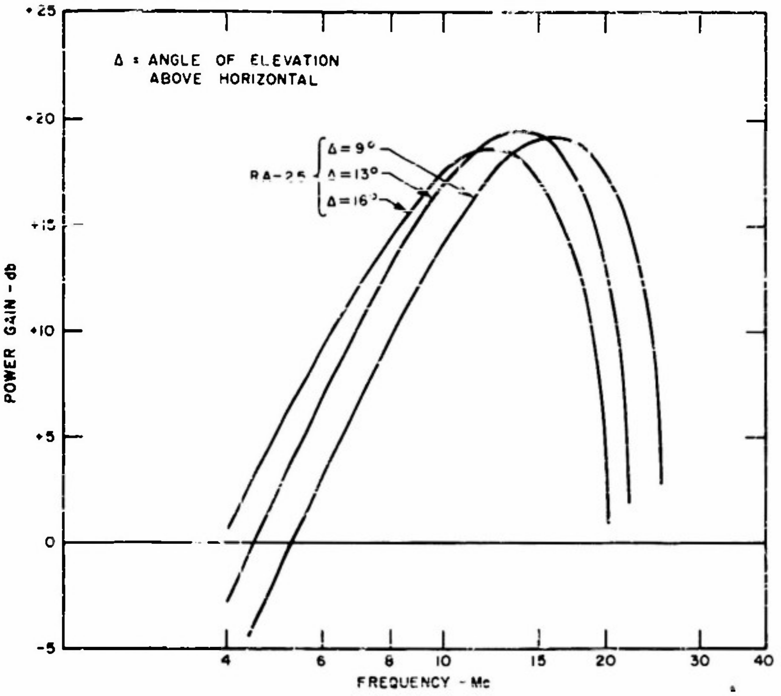


FIG. C-13

GAIN OF RHOMBIC ANTENNA RA-25 FOR TOKYO CIRCUIT

A-882-F-57

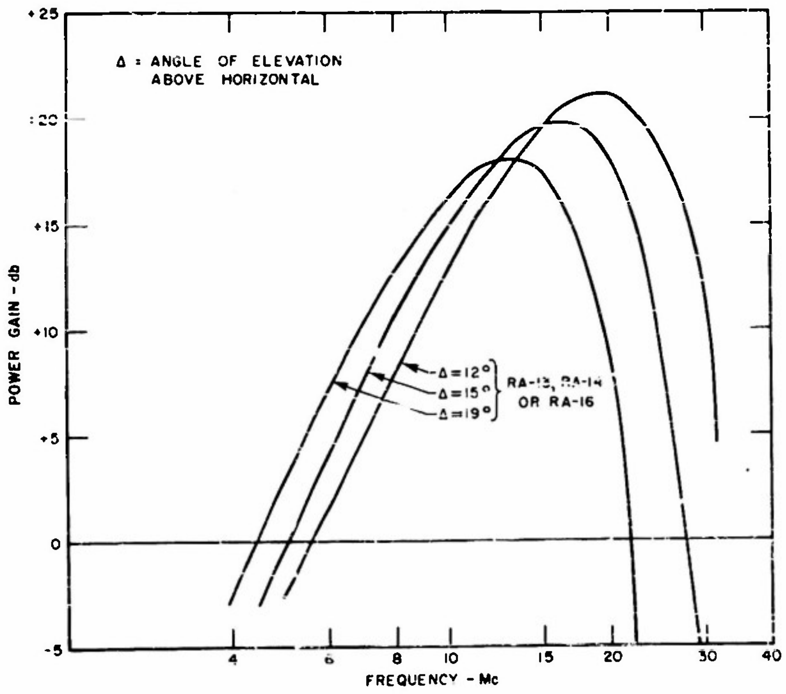


FIG. C-14

GAIN OF RHOMBIC ANTENNA RA-13, RA-14, OR RA-16 FOR MIDWAY CIRCUIT

A-882-F-58

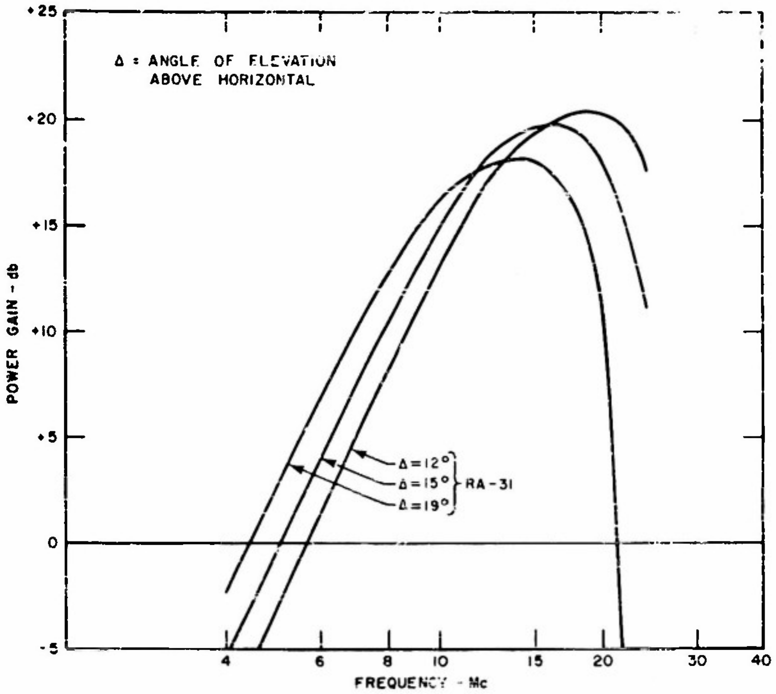


FIG. C-15

GAIN OF RHOMBIC ANTENNA RA-31 FOR MIDWAY CIRCUIT

A-882-F-59

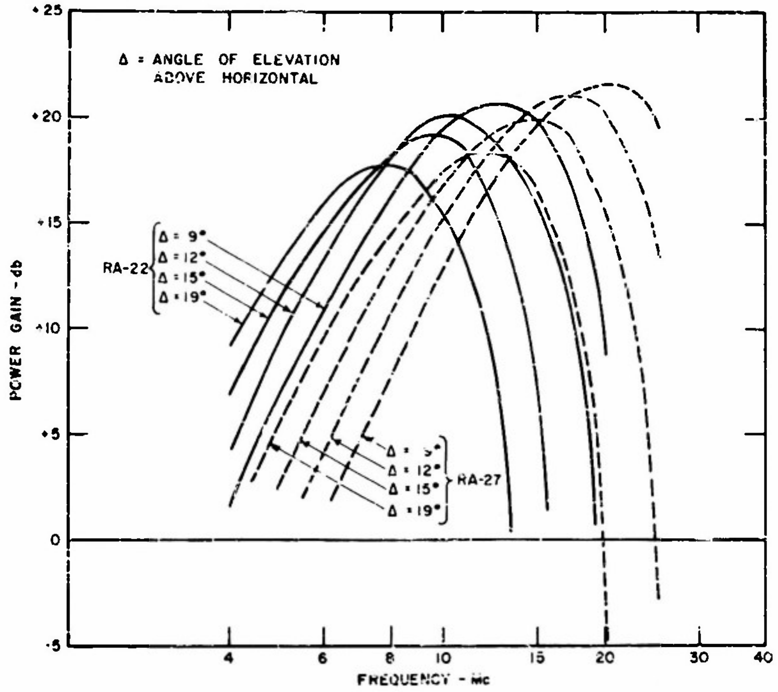


FIG. C-16

GAIN OF RHOMBIC ANTENNAS RA-22 AND RA-27
FOR TUTUILA CIRCUIT

A-882-F-60

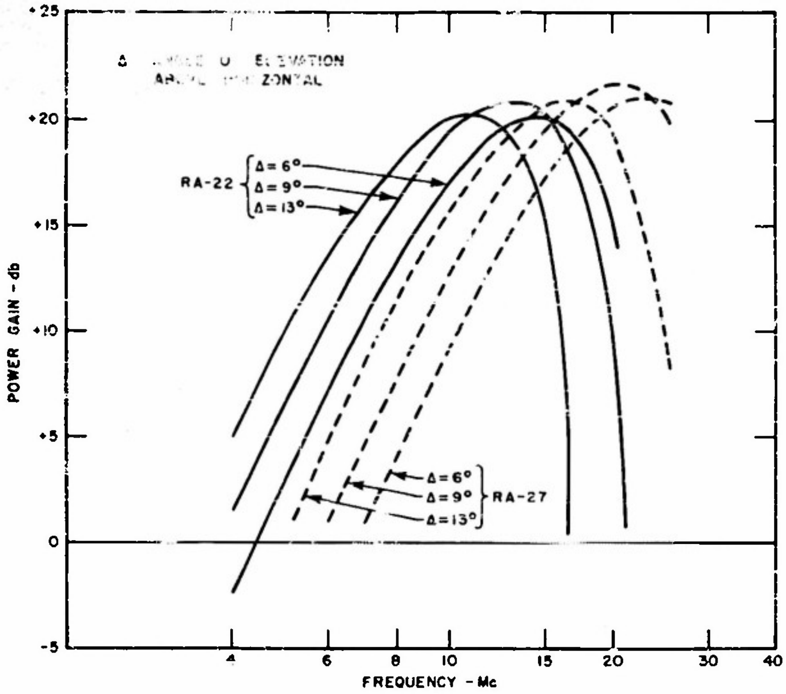


FIG. C-17

GAIN OF RHOMBIC ANTENNAS RA-22 AND RA-27 FOR NEW ZEALAND CIRCUIT

A-882-F-61

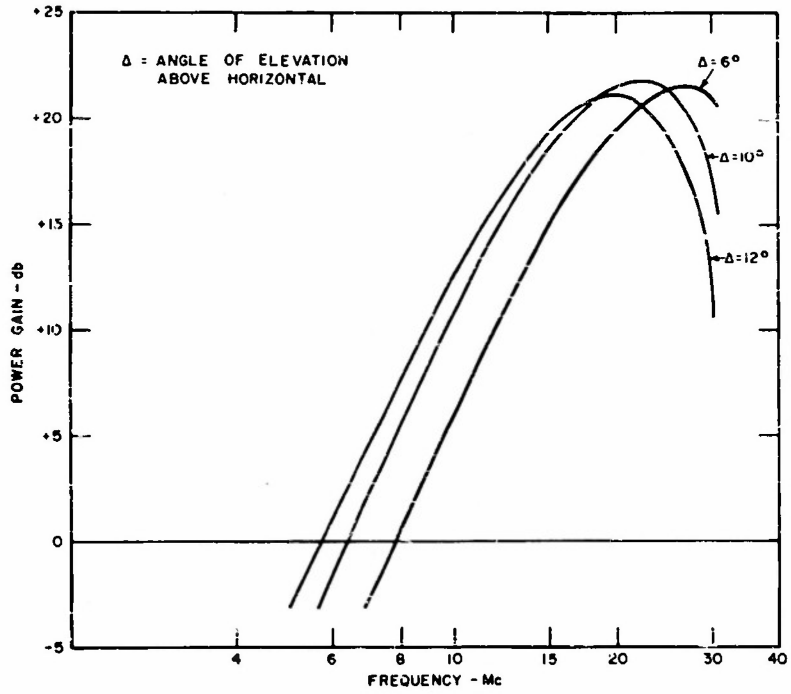


FIG. C-18

GAIN OF RHOMBIC ANTENNA RA-8 FOR MANILA CIRCUIT

A-882-F-62

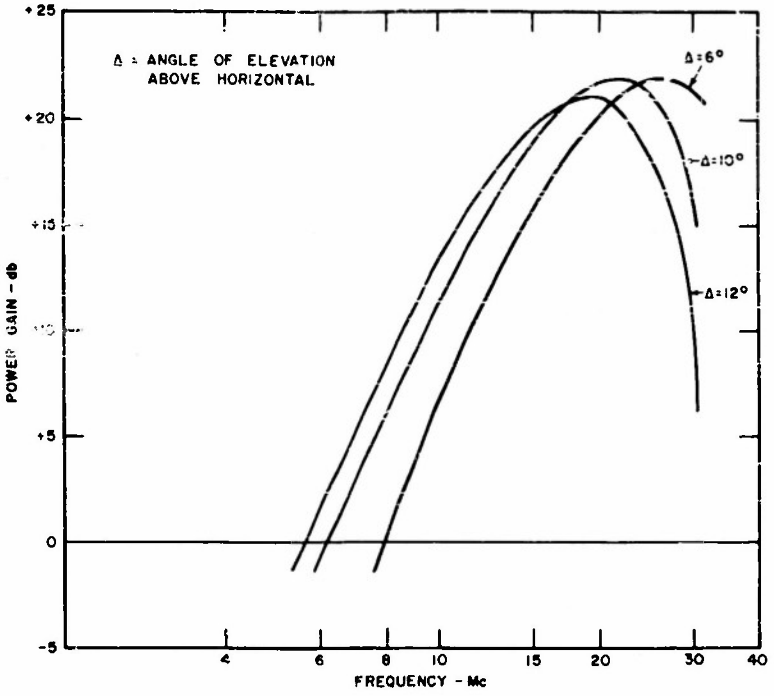


FIG. C-19

GAIN OF RHOMBIC ANTENNA RA-16 FOR MANILA CIRCUIT

A-882-F-63

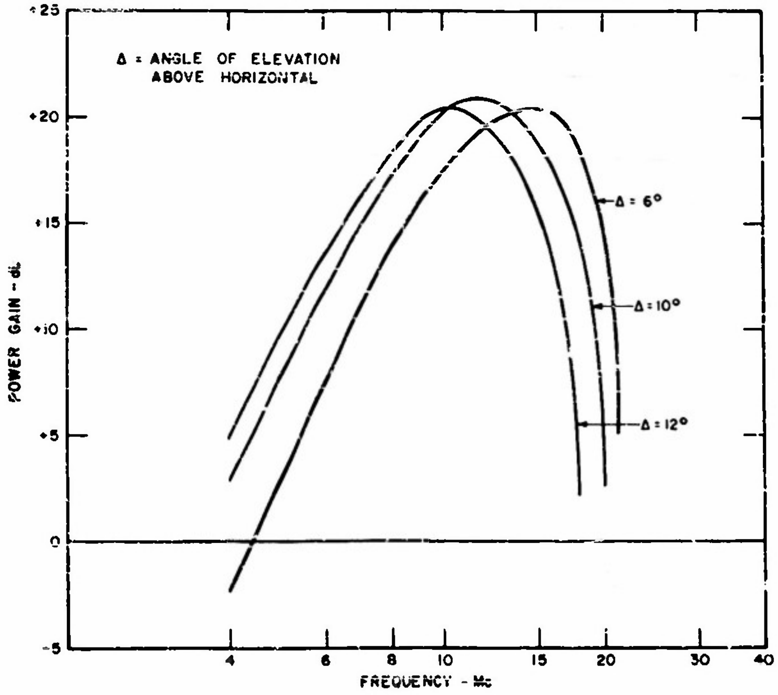


FIG. C-20

GAIN OF RHOMBIC ANTENNA RA-19 FOR MANILA CIRCUIT

A-882-F-64

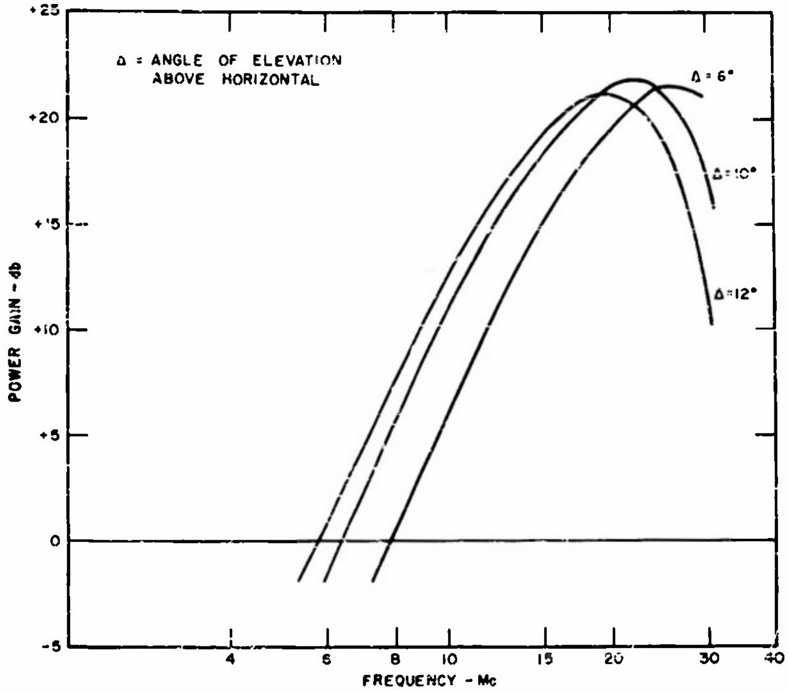


FIG. C-21

GAIN OF RHOMBIC ANTENNA RA-7
FOR MELBOURNE CIRCUIT

A-882-F-63

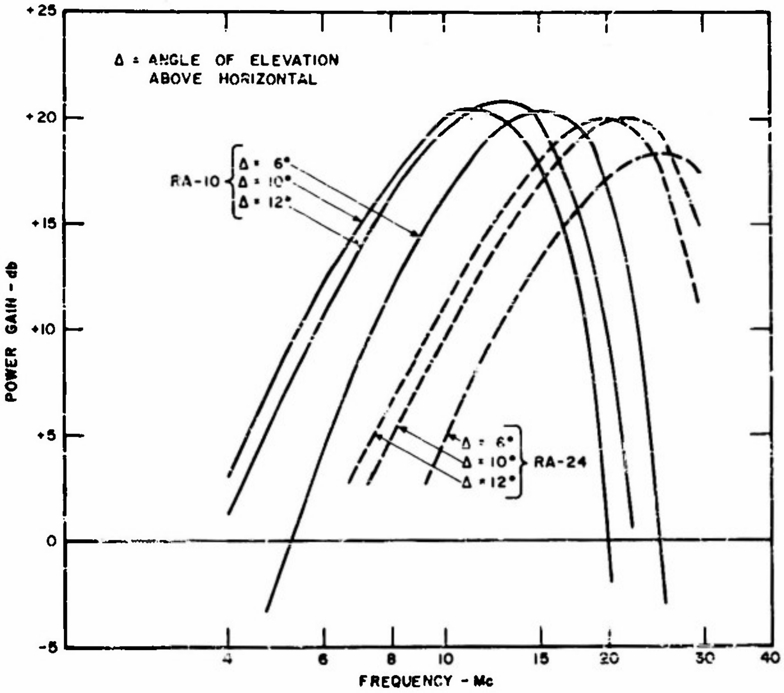


FIG. C-22

GAIN OF RHOMBIC ANTENNAS RA-10 AND RA-24
FOR BROOME, AUSTRALIA CIRCUIT

A-882-F-66

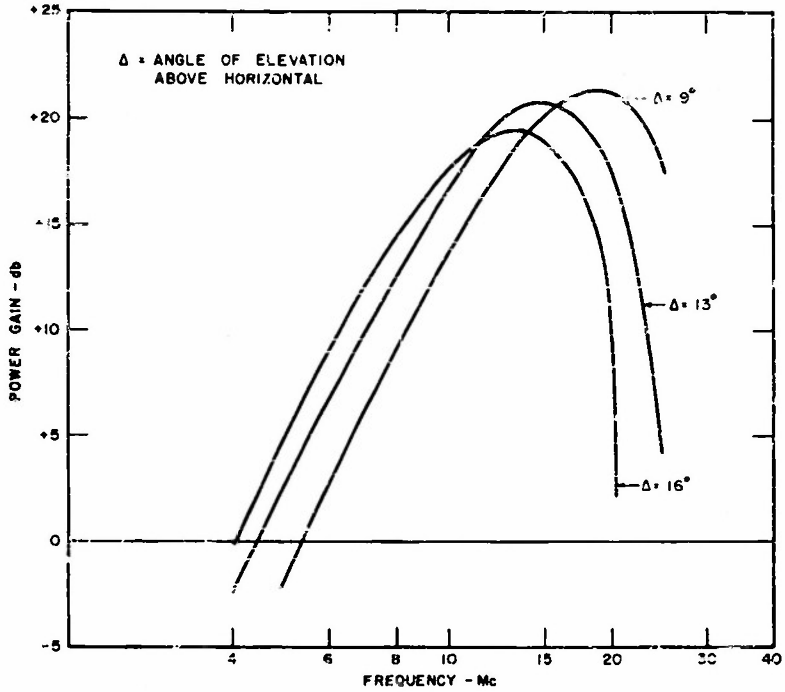


FIG. C-23

GAIN OF RHOMBIC ANTENNA RA-23 FOR OKINAWA CIRCUIT

A-882-F-67

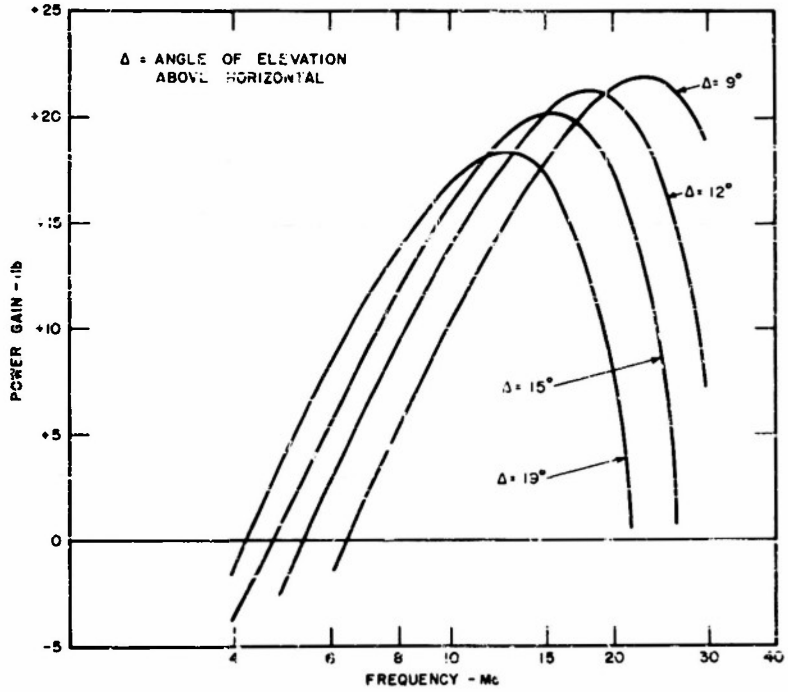


FIG. C-24

GAIN OF RHOMBIC ANTENNA RA-13 FOR ADAK CIRCUIT

A-882-F-77

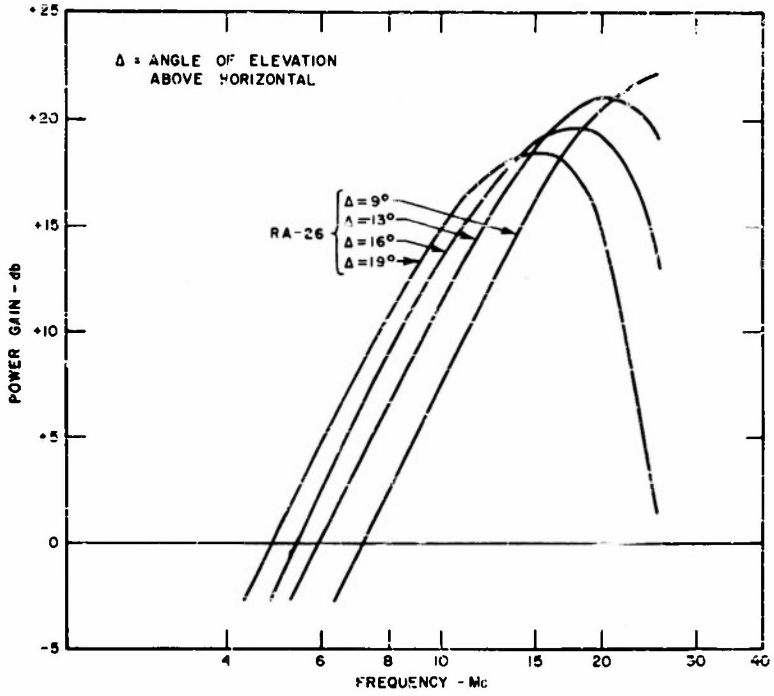


FIG. C-25

GAIN OF RHOMBIC ANTENNA RA-26 FOR KODIAK CIRCUIT

A-882-F-78

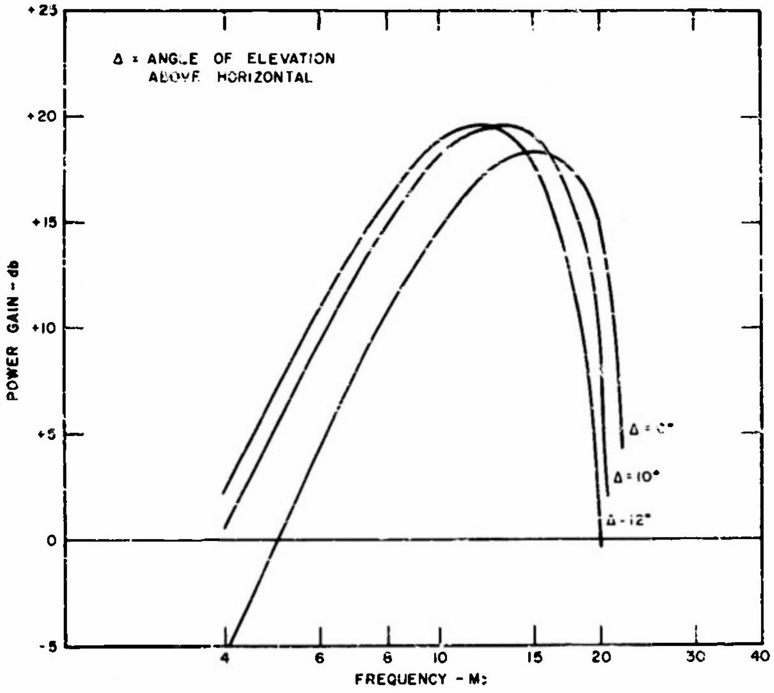


FIG. C-26

GAIN OF RHOMBIC ANTENNA RA-20
FOR SINGAPORE CIRCUIT

A-882-F-79

APPENDIX D

DESIGN OF RHOMBIC PAIRS FOR TRANSMISSIONS OVER DISTANCES GREATER THAN 1500 KM

The required coverage in vertical directions for transmissions over various distance ranges was discussed in Chapter 3. Three pairs of rhombic antennas were designed which, together, provide adequate power gain at all frequencies and in all required vertical directions. The distances and frequencies of transmission for which each antenna is to be used are listed in Table V of Chapter 5.

The following design procedure was adopted. At the extreme ends of the frequency range for which the rhombic is to be used, the power gain in the most unfavorable vertical direction is to be greater than that obtainable by the use of a doublet antenna suspended at the optimum height above ground. At the high end of the frequency band the gain is lowest at the largest angles of elevation relative to the ground, while at the low end of the range, high-power gains at angles close to the ground are most difficult to achieve.

The "alignment design method" was used for the high-frequency part of the rhombic pair, in preference to the "maximum output design method." The former method provides better broadband characteristics at a slight loss in maximum gain.[1] Use of the same design method for the low-frequency part would lead to rhombic antennas of entirely too large dimensions. It was assumed here that the maximum average height of suspension is limited to 110 ft and the major axis of the rhombics was kept to less than 1100 ft. The compromise design method described by Bruce, Beck, and Lowry[2] was used to evaluate the best apex angle under the imposed restrictions.

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[1] W. N. Christiansen, "Directional Patterns of Rhombic Antennae", AWA Technical Review (Australia), Vol. 7, pp. 33 53; Sept. 1946.

[2] E. Bruce, A. C. Beck, and L. R. Lowry, "Horizontal Rhombic Antennas", Proc. IRE, Vol. 23, p. 30; January 1931.

The design parameters which have to be determined for each of the rhombics are shown in Fig. D-1. Table D-I lists the dimension of rhombic antennas designed in the manner just described. It will be noted the low frequency antenna of pairs No. 1 and 2 are identical, so that five different rhombics are sufficient for the entire range of frequencies and vertical directions to be covered.

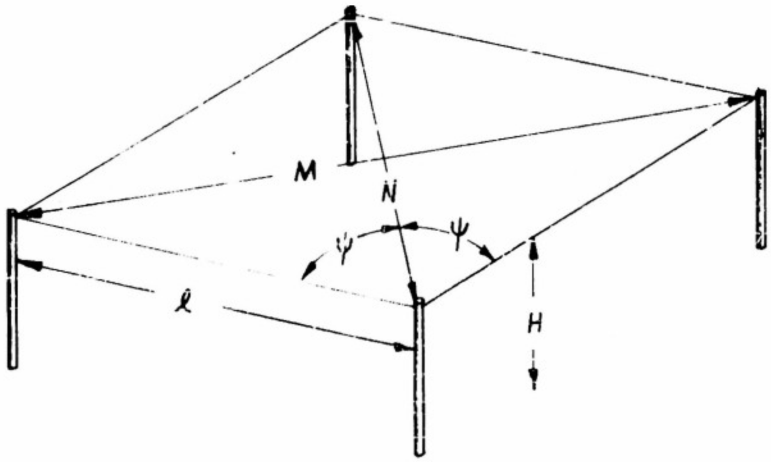

FIG. D-1

DESIGN PARAMETERS OF RHOMBIC ANTENNAS

A-882-F-68

The gain of these antennas in different vertical directions is shown as a function of frequency in Figs. D-2, D-3, and D-4. The gain of a horizontal dipole suspended at optimum height above ground is also shown in these figures to provide an estimate of the improvement that can be obtained by the use of rhombic antennas. The gain of the suggested new designs of rhombic antennas should be compared with that of the existing antenna given in Appendix C. It will be found that considerable improvement has been achieved with the new designs, especially at the low end of the frequency range. On the other hand, it should be remembered that the use of only two rhombics for the range from 4 to 24 Mc necessarily requires each of the two antennas to operate over a somewhat wider band than

TABLE D 1

DIMENSIONS OF SUGGESTED RHOMBIC-PAIR DESIGNS

Pair No.	1		2		3	
Distance Range of Transmission (Nautical miles)	810 - 1350 1900 - 2450		2450 - 3550		1350 - 1900 beyond 3500	
Part No.	A	B	A	B	A	B
Approximate Frequency Range (Mc)*	4-10	10-24	4-10	10-24	4-10	10-24
Length of Major Axis (M in ft)	1104	610	1104	856	1070	854
Length of Minor Axis (N in ft)	468	166	468	198	544	278
Leg Length (l in ft)	600	321	600	440	600	450
Average Height above Ground (H in ft)	111	56	111	66	111	83
Half-Angle at Corner of Rhombus (ψ in degrees)	67	75	67	77	63	72

* For details see Table V of Chapter VI

desirable. At some frequencies therefore, usually between 10 and 15 Mc, some of the existing antennas have more gain than the proposed designs. This excess in gain hardly ever exceeds about 5 db, which is not a serious defect at frequencies above 10 Mc.

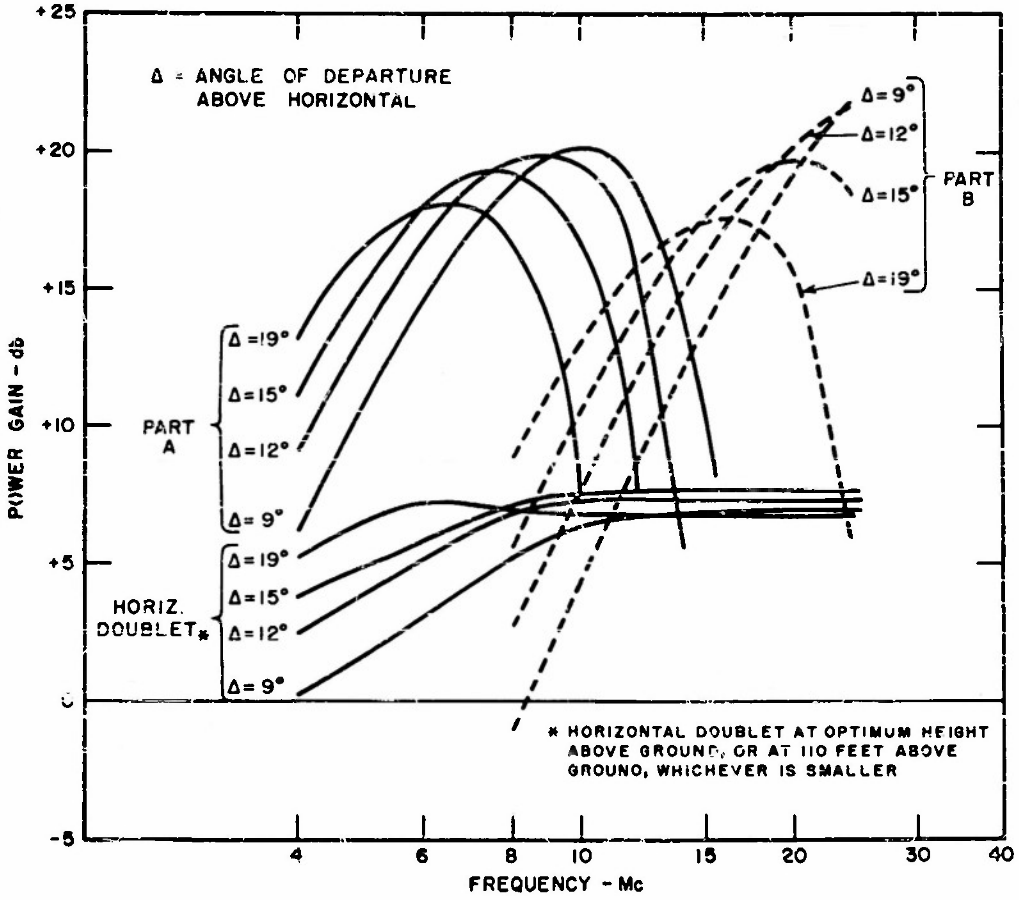

FIGURE D-2

RHOMBIC ANTENNA PAIR NO. 1

POWER GAIN AS A FUNCTION OF FREQUENCY

A-882-F-69

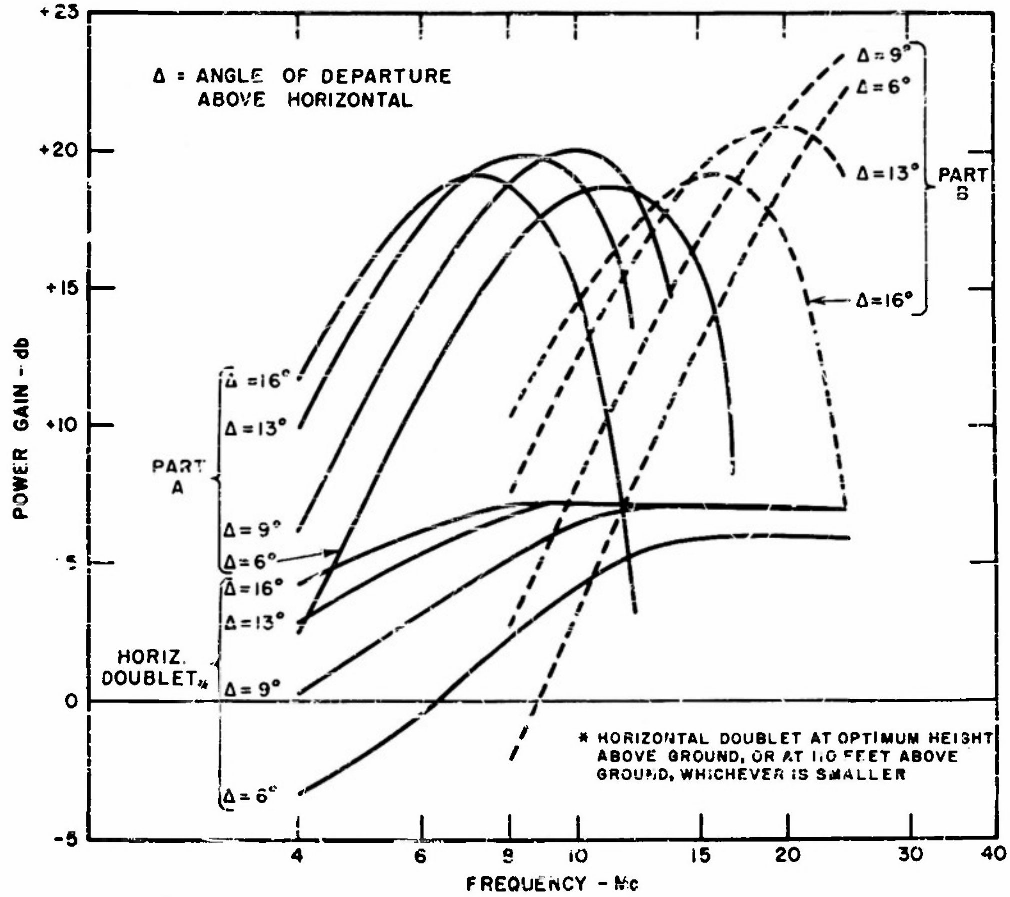

FIGURE D-3

RHOMBIC ANTENNA PAIR NO. 2
POWER GAIN AS A FUNCTION OF FREQUENCY

A-882-F-70

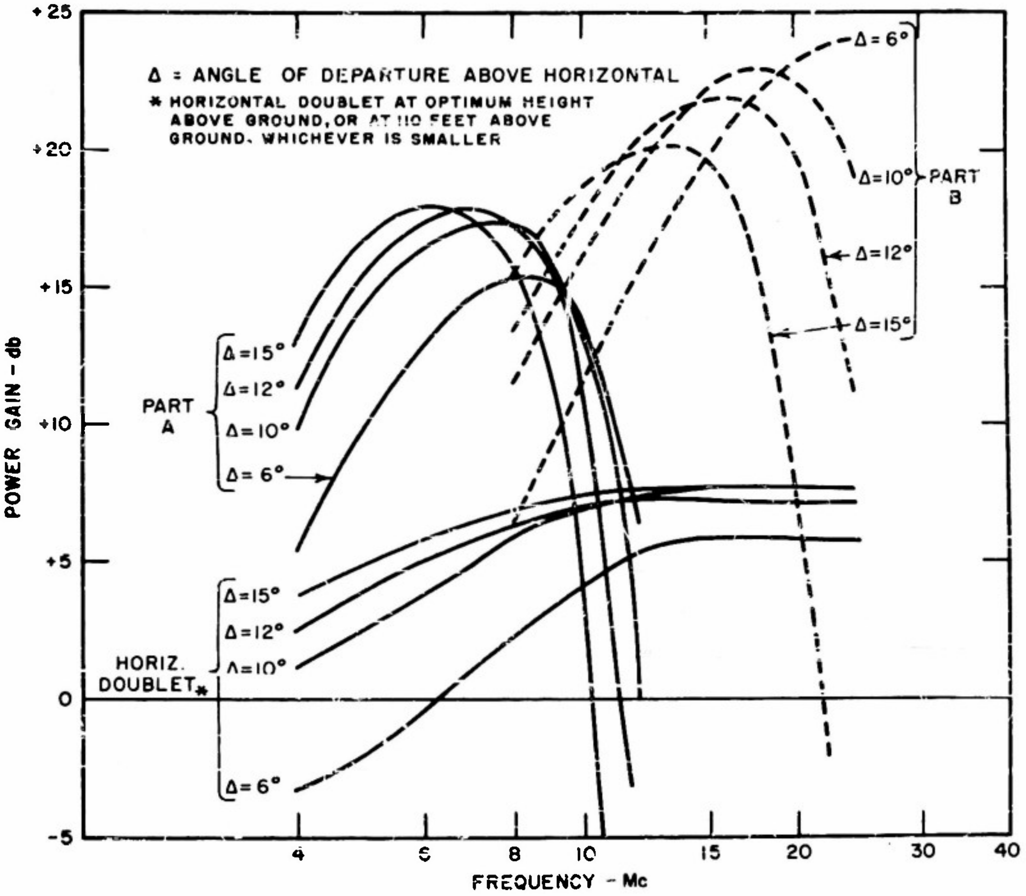

FIGURE D-4

RHOMBIC ANTENNA PAIR NO. 3
POWER GAIN AS A FUNCTION OF FREQUENCY

A-882-F-71

APPENDIX E

TRANSMISSION-LINE SWITCHING

A well-engineered transmission line switching system is an important requisite in h-f transmitting stations if best utilization of equipment and antennas is to be achieved. The frequent changes in working frequency over a given circuit during the day, together with changes in traffic capacities place demands of versatility on the installations. In general, the degree of complexity of the switching system increases rapidly with increased flexibility; therefore the goal should be one of limited flexibility which is tailored to meet operational requirements. Other important considerations which add to the general complexity of switching schemes include the requirements for maintenance of regularity in characteristic impedances of the lines retaining balance of lines to ground, and preventing any dead-end sections of line from appearing across active circuits.

Numerous types of switching devices have been developed and are currently being used in h-f installations throughout the world. These include both coaxial and balanced, manual and automatic, low and high power, and indoor and outdoor types. Certain of the configurations lend themselves well for application to the Lualualei installation.

Although the stacked-boom switch presently being used at Lualualei suffers certain severe limitations, such as the inability to switch one circuit while others are active, it is electrically sound and mechanically simple. To accomplish the same function automatically using electrically-actuated contactors is an extremely complex task involving many switches. In general, therefore, automatic switching does not seem to be feasible using presently available equipment.

Three- or four-pole boom-type switches[1] can be constructed which will permit switching of one circuit while others are active, without danger

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[1] Laport, *op. cit.* p. 437

to personnel or equipment. The actual design of such a structure is beyond the scope of this investigation, but it is recommended that this type of switch be further investigated for possible application at Lualualei.

Another class of switch, which would find immediate application at the station, is the remotely-operated vacuum switch.* These switches are physically small but are capable of operation at very high power levels. Open-wire and coaxial types are available, and both are capable of remote control using either pneumatic or electrical actuation.

Figure E-1 shows the basic single-pole-double-throw open-wire type which is capable of operation at a power level of 200 kw. This type may be paired to form a balanced 600-ohm open-wire switch as shown in Fig. E-2. The two switches are shown mounted in a waterproof molded Fiberglas housing with the appropriate spacing for 600-ohm open-wire line operation. A smaller double-pole-double-throw switch is shown in Fig. E-3. Use of this switch would be appropriate at the two- to five-kw level.

Many of the recent developments of vacuum switches have been in the coaxial configuration. Figure E-4 shows a pneumatically-operated high-power coaxial switch for 3-in. line. Others are in development for smaller diameter lines and for electrical actuation. At Lualualei, however, sufficient flexibility in switching coaxial feeders can usually be achieved by the use of simple patch panels.

Of the switches shown, the balanced 600-ohm double-pole-double-throw configuration would lend itself well for remote selection of the paired rhombic antennas for the various point-to-point circuits. This was discussed in Chapter 6.

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*Manufactured by Jennings Radio Mfg. Co., San Jose, California.

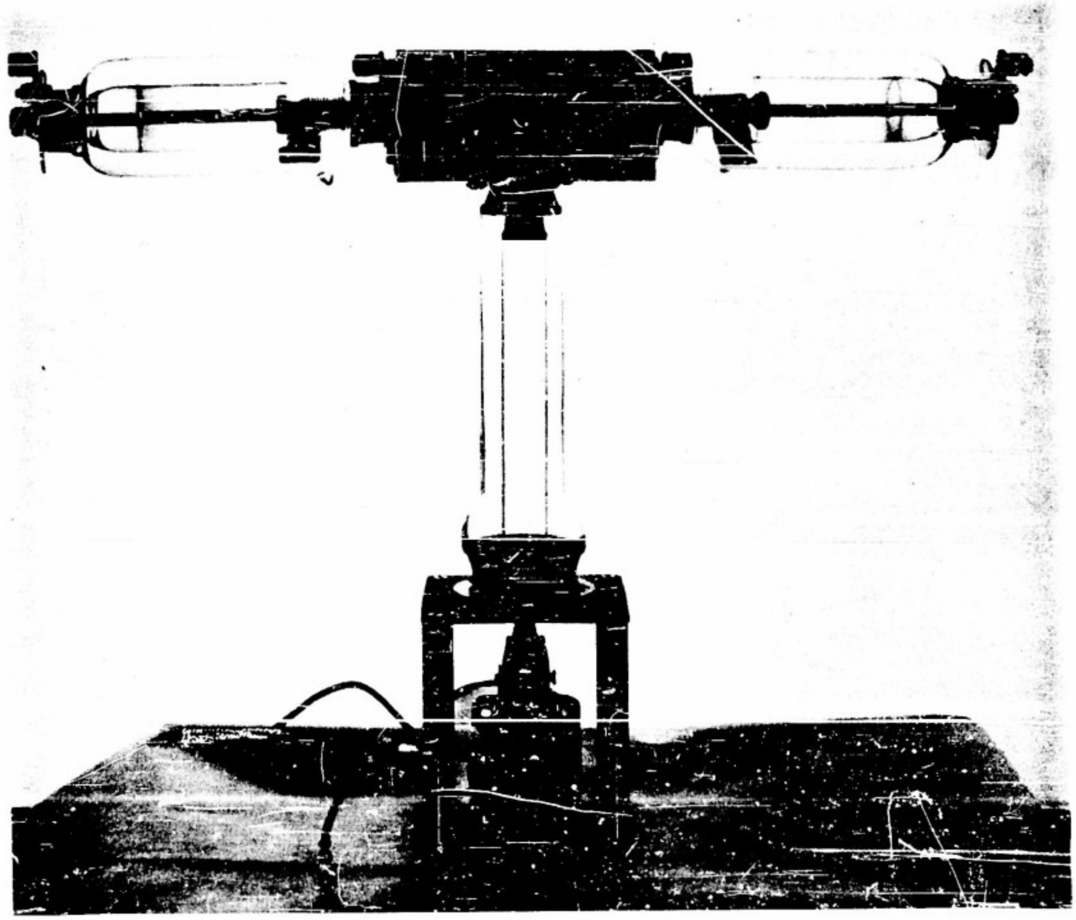

FIG. E-1

VACUUM TYPE SINGLE-POLE-DOUBLE-THROW SWITCH

P-882-F-74

FIG. E-2

SOLENOID ACTUATED DOUBLE-POLE-DOUBLE-THROW SWITCH