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Research Memorandum 5 (Revised)

ORIENTATION OF LINEARLY POLARIZED HF ANTENNAS
FOR SHORT-PATH COMMUNICATION
VIA THE IONOSPHERE NEAR THE GEOMAGNETIC EQUATOR

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Prepared for:

UNITED STATES ARMY ELECTRONICS LABORATORIES
FORT MONMOUTH, NEW JERSEY

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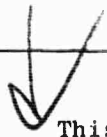
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PREFACE TO REVISED EDITION

This Research Memorandum has been revised and reissued to correct algebraic and typographical errors present in the first printing and to present some of the author's further thoughts on this subject.

ABSTRACT

 This report suggests that there is an optimum orientation for linearly polarized antennas used on short ionospheric paths near the geomagnetic equator. Consideration of the magneto-ionic theory and of its application to antenna-to-medium coupling problems indicates that aligning such antennas parallel to the earth's magnetic field will maximize signal strength while minimizing polarization fading on such paths. Linearly polarized antennas with such an orientation may intercept less interference than vertically polarized antennas. If this is true, the signal-to-noise ratio would be maximized and the orientation would be truly optimum. Experiments to test these hypotheses are outlined.



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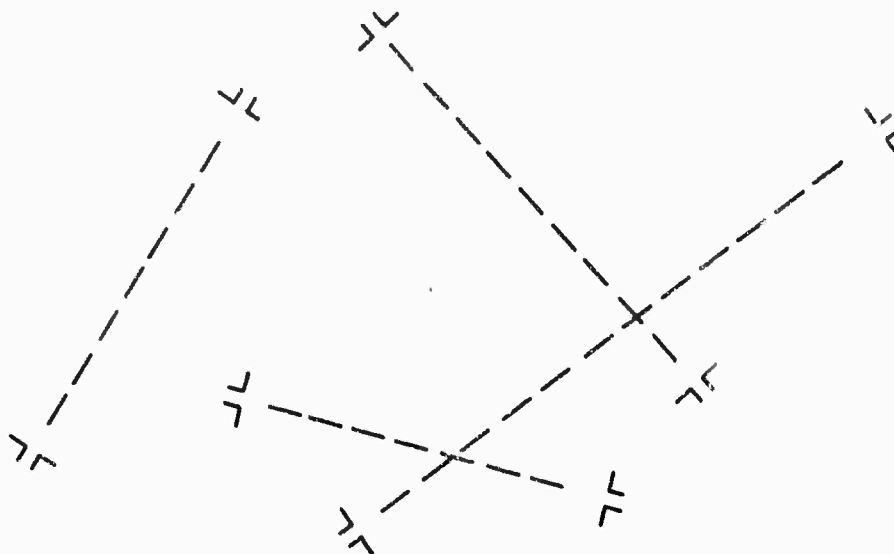
I INTRODUCTION

For communication via the ionosphere, it is normal procedure to orient dipole antennas orthogonal to the line joining their phase centers (see Fig. 1).^{1*} This orientation is usually preferred because of the radiation pattern of a horizontal dipole antenna (see Fig. 2) and is often thought of as "main-beam-to-main-beam coupling." Theoretical and experimental evidence indicates that such an orientation is not always the most desirable one, especially for short paths near the geomagnetic equator.²⁻¹⁰ The polarization of the downcoming ionospherically propagated wave and the differential absorption between ordinary and extraordinary waves account for this difference in preferred orientation. This report discusses the application of the magneto-ionic theory for describing wave propagation in the ionosphere to HF sky-wave propagation over short paths at low magnetic latitudes. Several experiments are outlined to test the application of the theory in order to determine the optimum alignment of linear antennas near the magnetic equator.

The height of the dipole above the earth is usually adjusted to maximize the radiation at the desired take-off angle for a given path.^{**} For $H < \lambda/4$, there is only one lobe, and $H = \lambda/4$ is optimum for a near-vertical take-off angle (short path) over perfectly conducting ground. For poor ground, the optimum height above ground level might be less than $\lambda/4$. For jungle terrain, noise considerations might indicate $H \approx 3\lambda/4$ as more nearly optimum by signal-to-noise criteria. The

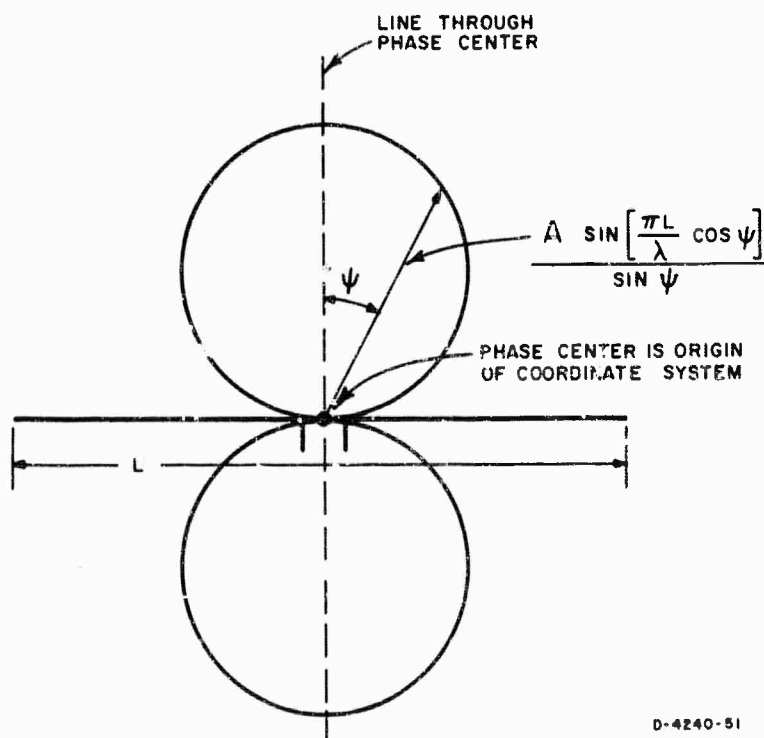
*References are given at the end of the report.

**Lobing of the vertical pattern is produced by reflections from the earth. The directivity pattern of the antenna in free space should be multiplied by approximately $2 \sin [2\pi(H/\lambda) \sin \alpha]$ for ground of reasonably high conductivity (e.g., $\sigma \approx 10^{-13}$ emu) to obtain the actual directivity in the presence of ground where H is the height of the phase center above the reflecting ground (electrical ground) and α is the elevation angle above the horizon.²⁰



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FIG. 1 TYPICAL ORIENTATION OF HORIZONTAL DIPOLE ANTENNAS FOR SEVERAL PATHS WHEN EFFECT OF GEOMAGNETIC FIELD IS NEGLECTED



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FIG. 2 RADIATION PATTERN OF A HORIZONTAL DIPOLE ANTENNA IN FREE SPACE

radiation pattern (directivity) in the azimuthal plane is relatively unaffected by the presence of the ground, provided the ground is smooth relative to a free-space wavelength. Under these conditions, a linear wave polarization is maintained in the far field (free-space radiation field) of such an antenna above the earth. Main-beam-to-main-beam coupling is achieved for very short ionospheric paths regardless of azimuthal orientation when $H < \lambda/4$.

The communicator tries to maximize signal-plus-noise-to-noise ratio $[(S+N)/N]$ in an attempt to minimize error rate for a given transmitter power, type of modulation, channel bandwidth, and noise environment. Other factors related to antenna alignment that affect $(S+N)/N$ are relative ionospheric absorption and relative antenna noise temperature in the absence of signal as functions of alignment. These factors are important when consideration is given to whether an antenna orientation is truly optimum. The communicator must consider signal "quality" as well as average power, $(S+N)/N$, relative to the noise environment. Antenna alignment may have great influence on fading of both the desired signal and the propagated noise. Indeed, the use of alignment may offer gains from a system employing polarization diversity that would be both technically and tactically superior to those from a single-channel system or those from a space diversity system. It may also offer significant reduction of the injurious effects of noise. Alternatively, a combination space-polarization diversity system may offer the greatest advantage, especially at frequencies above several megacycles.

While the Introduction uses dipoles as examples, the comments in the following sections apply to all linearly polarized antennas.²¹

II HISTORICAL BACKGROUND

A. HF SKYWAVE PROPAGATION IN TROPICAL AREAS

It became apparent early in World War II that the jungle path loss at HF and VHF limited portable radio sets to ranges of about one mile via ground wave. Apparently, the HF-VHF part of the spectrum was chosen because, below HF, antenna efficiencies were low and atmospheric noise high. (Broadcasting is done in the HF band in many tropical areas because of the higher noise levels at medium-wave broadcast frequencies.^{22*}) Above VHF, path loss is still increasing with frequency; this limits the useful frequency range on the higher end. Qualitative field reports of poor performance²³ were substantiated by quantitative measurements in Panama²⁴ and New Guinea.²⁵

While path loss in the New Guinea jungle was somewhat less than that in Panama, it was concluded that skywave should be used for ranges greater than approximately one-half mile. After the decision to use skywave had been made, Aikens, Tucker, and Chapman⁷ and others investigated antennas that were efficient in launching radio energy vertically. They concluded that the commonly used vertical-whip (Marconi) antennas were very poor whereas horizontal-dipole (Hertz) antennas were very good. They further concluded that, from interference considerations, a compromise (sloping-wire) antenna oriented nearly horizontally might receive better and transmit adequately. Antenna alignment in the tropics is discussed in Sec. II-B.

*The International Telecommunication Union's International Radio Consultative Committee (CCIR) Study Group XII is concerned with tropical broadcasting. Their objectives are: To study standards required for good quality service in the tropical zone, and for tropical broadcasting systems; interference in the shared bands; power requirements for acceptable service; design of suitable antennae for short-distance tropical broadcasting; optimum conditions for the utilization of frequency bands used for broadcasting in the tropical zone; other associated questions.

B. POLARIZATION STUDIES OF DOWNCOMING RADIO WAVES

Effects of the earth's magnetic field on the propagation of radio waves in the ionosphere, including polarization of downcoming waves, were first investigated theoretically by Appleton (1925),²⁶ Appleton and Barnett (1925),²⁷ and Nichols and Schelleng (1925).²⁸ Further work on polarization was done by Ratcliffe and White (1933),²⁹ Bailey (1934),³⁰ Booker (1934),³¹ Taylor (1934),³² and Martyn (1935).³³

In the mid-1930s Wells and Berkner performed a classical low-latitude experiment at Huancayo, Peru to test the validity of the magneto-ionic theory for describing radio wave propagation in the ionosphere.² Their single-frequency measurements revealed that the theory predicted the polarization of downcoming waves for vertical incidence near the magnetic equator, except perhaps near the ionospheric-layer critical frequencies. Near critical frequencies there appeared to be a slight departure from linearity, possibly due to coupling.

A review of the theoretical and experimental studies on the polarization of radio echoes was given by Martyn, Piddington, and Munro (1937).³⁴ Ghosh (1938) presented further considerations.³⁵

Eckersley and Millington, in a 1939 paper on limiting polarization of medium waves, presented a method of calculating the projection of the polarization ellipse on to the ground, including calculation aids.³⁶

Wells, in 1940, performed swept-frequency polarization measurements at vertical incidence at Huancayo, reconfirming his earlier F-region results and confirming the theory for the normal E region as well.⁴

The advantages of antenna alignment for short paths near the magnetic equator were recognized and utilized during World War II by several knowledgeable communicators in the Philippines.⁵ Possibly this was owing to the work of Norton,⁶ who was concerned with the effect of polarization

Does "alignment" mean parallel to magnetic field?

* A mathematical error in Norton's report was pointed out by workers at Harvard [see A. L. Aden, et al., "A Note on Ionospheric Radio Wave Polarization," Technical Memorandum 5, Cruft Laboratory, Harvard University (29 June 1949)].

on HF direction finding. Aikens, in an NDRC report published during World War II, briefly mentioned antenna alignment: "In the tropics, it may in some cases be advisable to orient sending and receiving half-wave horizontals approximately parallel; this is not necessary in the temperate zone. The source of this possible difference lies in effects of the earth's magnetic field in ionosphere."⁷ [That NDRC statement was quoted in an appendix of an RCA report (1963) without comment.⁸] The statement is ambiguous and incomplete but certainly suggests the possible importance of antenna alignment at low magnetic latitudes. Parallel to what?

Theoretical methods for obtaining the polarization parameters were given by Scott (1950, 1953).^{36,37} Also in 1950, Aden, de Bettencourt, and Waterman determined the correct relationship between the tilt angles of the major axes of the ordinary and extraordinary ellipses and pointed out the errors of several earlier workers (among them, Refs. 6, 32, and 33) owing to either neglect or inappropriate consideration of the effect of collisions.³⁸

Snyder and Helliwell (1952) plotted the complex wave polarization in the complex plane and gave nomograms useful for calculation.³⁹

Satyanarayana et al. (1956) made qualitative polarization measurements of sporadic-E (E_s) echoes at a low-latitude station and found the sense of rotation to be predominantly left-handed (ordinary wave dominant);⁹ and Verma and Roy (also 1956), using a more accurate technique, determined that polarization of echoes from thin E_s was often unstable.¹⁰

Piggott, in a 1959 DSIR report titled "The Calculation of the Median Sky Wave Field Strength in Tropical Regions," set the whole thing straight qualitatively at low latitudes by stating: "Directions for which the propagation is at right angles to the magnetic field are frequently more important and hence the direction and polarization of aeri-als are often more significant."¹¹ He also mentioned that "difficulties due to polarization phenomena when the propagation becomes transverse can be minimized by keeping the angle between the direction of polarization of the aerial and direction of the magnetic field as small as practical. At low latitudes this implies using horizontal

*Θ = angle between H_0 and $O-Z$
 $N =$ number of stations Davis, etc.*

aerials with their axes as near to the magnetic meridian as possible." Piggott presented many useful graphs to calculate Θ , the angle between the wave normal and the earth's magnetic field vector; one of these graphs is given in Sec. III of this report.

The measurements of Verma and Roy¹⁰ and others were reviewed in 1960 by Murty and Khastgir, who resolved some of the apparent discrepancies of previous experimental work that were due to difference in notation.⁴⁰

In 1962 C. Abhirama Reddy and B. Ramachandra Rao¹² observed that the extraordinary wave apparently had a greater partial reflection coefficient from E_s clouds and the polarization of echoes from E_s was unsteady. Their investigation of the regular layers in the ionosphere above Waltair, India (dip $\approx 20^\circ$ N) indicated that, in general, the magneto-ionic theory predicts the correct polarization.¹³ They observed a maximum of tilt angles at 0° and 90° as predicted by the theory, with approximately 85 percent of the measured values ($N = 426$) within $\pm 15^\circ$ of 0° for the ordinary and approximately 80 percent of the measured values ($N = 170$) within $\pm 15^\circ$ of 90° for the extraordinary. Their polarization measurements of E_s were used to deduce the structure of the E_s layer or cloud.^{12,14} Their data summary showed that the ordinary wave might be preferred for communicating via a blanketing E_s cloud while the extraordinary might be preferred for semitransparent and patchy E_s . The relative instability of the polarization of downcoming waves from E_s patches indicates that polarization diversity might be of more benefit when the E_s mode is used than for reflections via the regular layers, when antennas are aligned to generate pure ordinary and extraordinary waves. In a supplementary paper, C. Abhirama Reddy¹⁵ gave theoretical polarizations of HF waves at Waltair, India.

The author^{16,17} came, independently from all the foregoing, to the same general conclusion as Piggott.¹¹ Recent work by Davies¹⁸ explaining medium-wave propagation difficulties in equatorial Africa has added further evidence to the likelihood of antenna alignment being an important consideration on many equatorial ionospheric communication links.

Finally, recent preliminary measurements in Thailand, initiated at the author's suggestion, indicate that polarization may be important in the lower HF band on short paths in that country.¹⁹ The relevant mathematics and some useful graphs showing regions of applicability of the approximations are presented in Sec. III.

III WAVE POLARIZATION OF DOWNCOMING RADIO WAVES NEAR THE GEOMAGNETIC EQUATOR

Consider the case of a radio wave vertically incident on the ionosphere at the magnetic equator. By using the notation of Ratcliffe⁴¹ (see Appendix A: Definition of Terms), the geometry is as shown in Fig. 3.

The characteristic waves that will propagate in the O-Z direction with unchanging wave polarization have polarizations given by:

$$R = \frac{E_x}{E_y} = \frac{-1}{Y_L} \left\{ \frac{1/2 Y_T^2}{1 - X - iZ} \mp \left(\frac{1/4 Y_T^4}{(1 - X - iZ)^2} + Y_L^2 \right)^{1/2} \right\}$$

where

$$\left. \begin{aligned} Y_T &= \mu_0 H_0 e(m\omega)^{-1} \sin \theta \\ Y_L &= \mu_0 H_0 e(m\omega)^{-1} \cos \theta \end{aligned} \right\} \text{normalized gyrofrequency}$$

$$X = 4\pi N e^2 (\epsilon_0 m)^{-1} \omega^{-2} \quad \text{normalized plasma frequency squared}$$

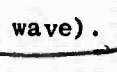
$$Z = \nu \omega^{-1} \quad \text{normalized collision frequency.}$$

θ = angle between wave normal and H_0 (see Fig. 3).

The upper sign corresponds to the wave least affected by the magnetic field (the ordinary wave); the lower sign corresponds to the extraordinary.

An investigation of this equation shows that for purely transverse propagation, $Y_L = 0$ (as shown in Fig. 3)

$R_{\text{upper sign}} = 0; E = E_y$ (ordinary wave) 

$R_{\text{lower sign}} = \infty; E = E_x$ (extraordinary wave). 

Therefore, if one launches E_y only (linear antenna parallel to the projection of the magnetic field), there is no magneto-ionic splitting, since the launched wave is a characteristic wave. This is likewise true if one launches only E_x , in which case the extraordinary wave is the only one propagating. The ordinary and extraordinary waves reflect

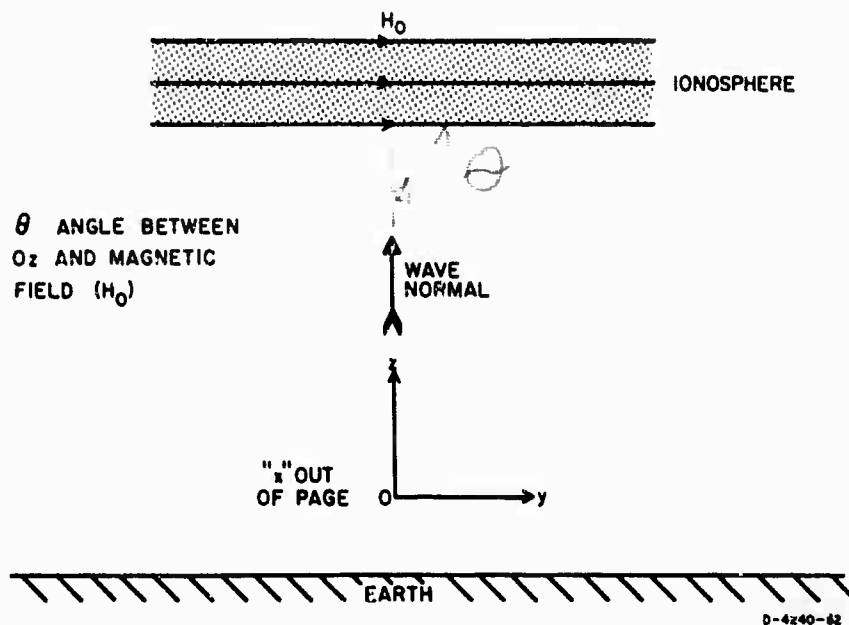


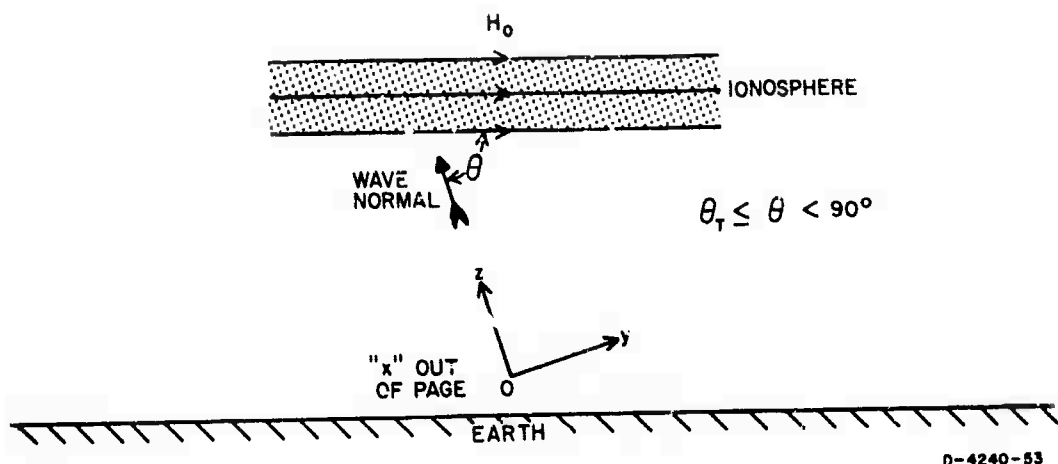
FIG. 3 GEOMETRY FOR VERTICAL INCIDENCE AT THE MAGNETIC EQUATOR

from different altitudes; when both are present, the resultant polarization depends upon the relative phase of these two components and is, in general, elliptical. (The resultant polarization will be linear only when the two linearly polarized downcoming waves are of the same relative phase.)

Now, imagine the wave normal inclined to the earth's field as shown in Fig. 4. For this case it is still possible to launch only one characteristic wave with a linear antenna, provided θ is greater than some θ_T . Propagation nearly transverse to the earth's field is, to a good approximation, similar to the purely transverse case if

$$\frac{Y_T^4}{4Y_L^2} \gg |(1 - X - iZ)^2|$$

This is termed the quasi-transverse (QT) approximation. Notice that this approximation depends on the plasma frequency, collision frequency, and gyrofrequency relative to wave frequency, as well as on the angle



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FIG. 4 GEOMETRY FOR NEAR-VERTICAL INCIDENCE AT THE MAGNETIC EQUATOR

the wave normal makes with the earth's field. (The ray path is identical with wave normal when collisions are negligible.) For this case of negligible collision frequency relative to the wave frequency (the usual case in the F region), this approximation is always good at the height of reflection of the ordinary wave.

More important, however, is the fact that if only one characteristic wave (linear polarization, for the case of interest here) is launched, the wave will emerge with the same polarization, provided the medium varies slowly enough to be considered locally homogeneous. This is equivalent to saying that no coupling is required between characteristic waves to satisfy the boundary conditions associated with any inhomogeneities; hence the characteristic wave that enters will emerge unaltered as far as polarization is concerned.*

It is the QT approximation in the region of entry into the ionosphere that must be satisfied if only one mode is to be excited and not the condition near the height of reflection, provided the medium can be

* A linearly polarized wave may alter its polarization along its path, but if the QT approximation holds for both entering and exit trajectories, the wave will emerge with the linear polarization with which it entered.

considered locally homogeneous. The conditions at entry must be satisfied at the same height that established the "limiting polarization" for the emerging wave.⁴²

The QT approximation can be rewritten:

$$\frac{Y_T^2}{4} \tan^2 \theta \gg f(X, Z) \quad .$$

But

$$Y_T^2 = \frac{\omega_H^2}{\omega^2} \sin^2 \theta \quad ,$$

where ω_H is the radian gyrofrequency.

Thus,

$$\frac{\omega_H^2}{4\omega^2} \sin^2 \theta \tan^2 \theta \gg f(X, Z) \quad .$$

Let

$$\frac{4\omega^2}{\omega_H^2} f(X, Z)$$

near the lower edge of the ionosphere be represented by A, then

$$\frac{\sin^4 \theta}{1 - \sin^2 \theta} \gg A \quad .$$

Let

$$\frac{\sin^4 \theta_T}{1 - \sin^2 \theta_T} = 10A \quad .$$

Solving this quadratic for $\sin^2 \theta_T$ gives:

$$\sin^2 \theta_T = \frac{-10A \pm \sqrt{100A^2 + 40A}}{2} \quad ,$$

or

$$\theta_T = \arcsin \left\{ -5A + \sqrt{5A(5A + 2)} \right\}^{1/2}$$

where

$$A = \left(\frac{2}{Y} \right)^2 | (1 - X - 1Z)^2 |$$

and Y is the gyrofrequency normalized by the wave frequency. Since X and $Z \ll 1$ at the base of the ionosphere at HF, $A \approx \frac{4}{Y^2}$, and the expression for θ_T can be rewritten in the form

$$\theta_T \cong \arcsin \left[1 - \frac{Y^2}{40} \right]^{1/2} \quad ,$$

which predicts too low by 13 minutes at $Y = 1$ and by 2 minutes for $Y = 1/2$ when collisions are negligible. The approximate formula for θ_T can be further simplified when $Y \ll 1$ by another expansion:

$$\left[\theta_T \approx \arcsin \left[1 - \frac{Y^2}{80} \right] \right]$$

13

$$Y = \omega_H / \omega$$

Normalized
gyrofreq.

The geometrical aspects of the QT approximation are shown in Fig. 5. Thus one sees that the approximation is good only very near transverse propagation for HF. Notice that for the lower frequencies QT holds for a smaller range of angles during the day than at night. This is because at the height determining limiting polarization for those frequencies, collisions are important during the daytime when the D region is present.

These data (see Fig. 6) can, for example, be presented as a map of Thailand with contours showing the frequency above which the QT approximation fails for pure vertical incidence. This should be regarded as approximate, but it is based on the best dip-angle data available to the author (see Fig. 7).^{43,44} Piggott's chart (Fig. 8)¹¹ is useful to convert from vertical incidence to some oblique-incidence case when the dip angle is given by the map in Fig. 7, the azimuth specified by the path under consideration, and the take-off angle given by the geometry of the path (i.e., for E-region reflection, path height of 110 km assumed, etc.). The take-off angle can be determined more accurately when a vertical-incidence ionogram is available. The appropriate value of h' and corresponding take-off angle can then be determined by using a Newbern Smith slider.⁴⁵ An example of the calculation appears in Appendix B.

We must next investigate the angle, θ_L , at which the quasi-longitudinal (QL) approximation becomes valid. This investigation is important because it sets the lower limit of θ for which any improvement in signal might be obtained by alignment of linear antennas. A plot of θ_L and θ_T versus frequency indicates the band of angle-frequency combinations for which neither approximation holds (see Fig. 9). The QL approximation is given as

$$\frac{Y_T^4}{4Y_L^2} \ll |(1 - X - iZ)^2|$$

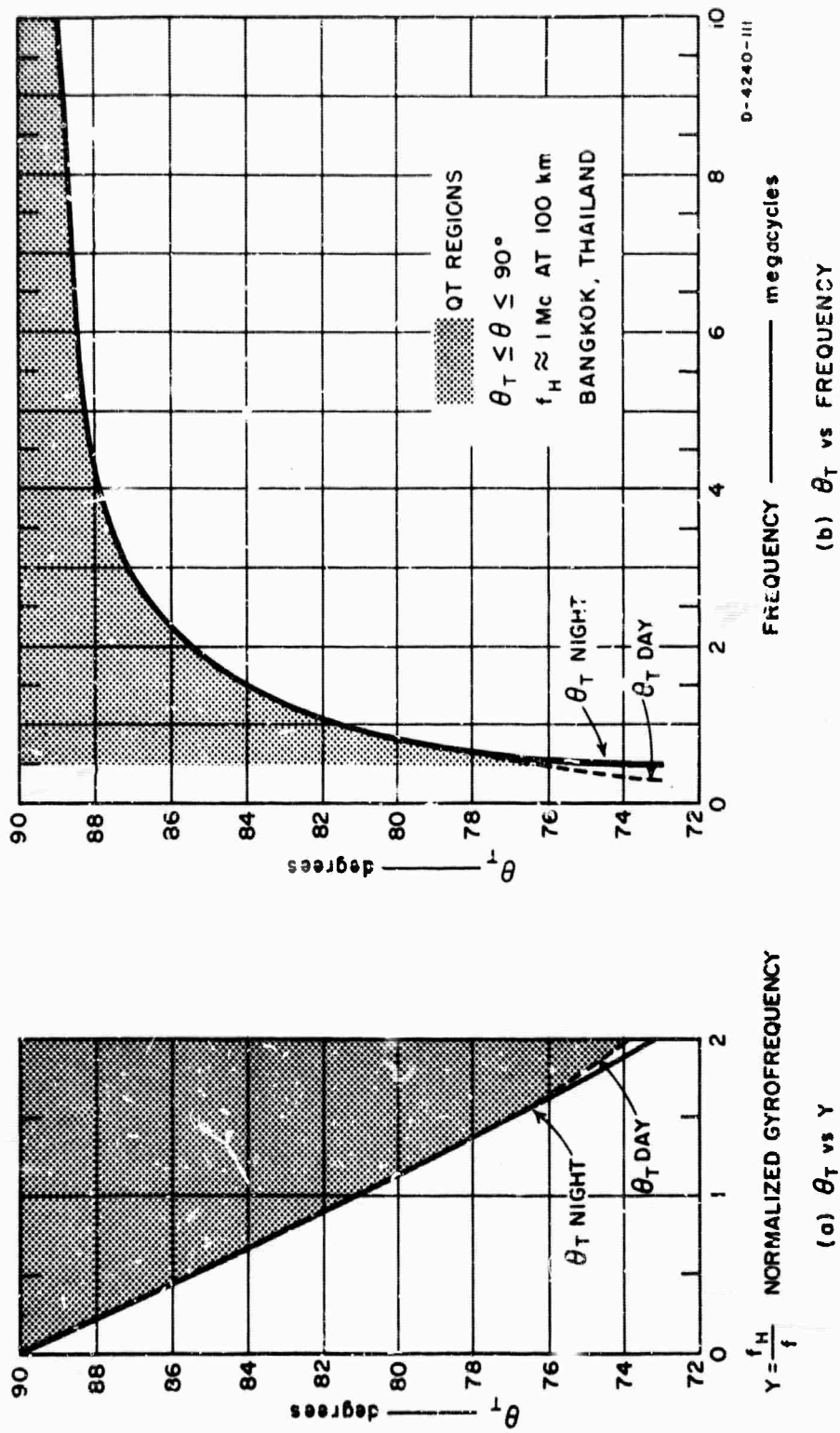


FIG. 5 GEOMETRICAL ASPECTS OF THE QT APPROXIMATION

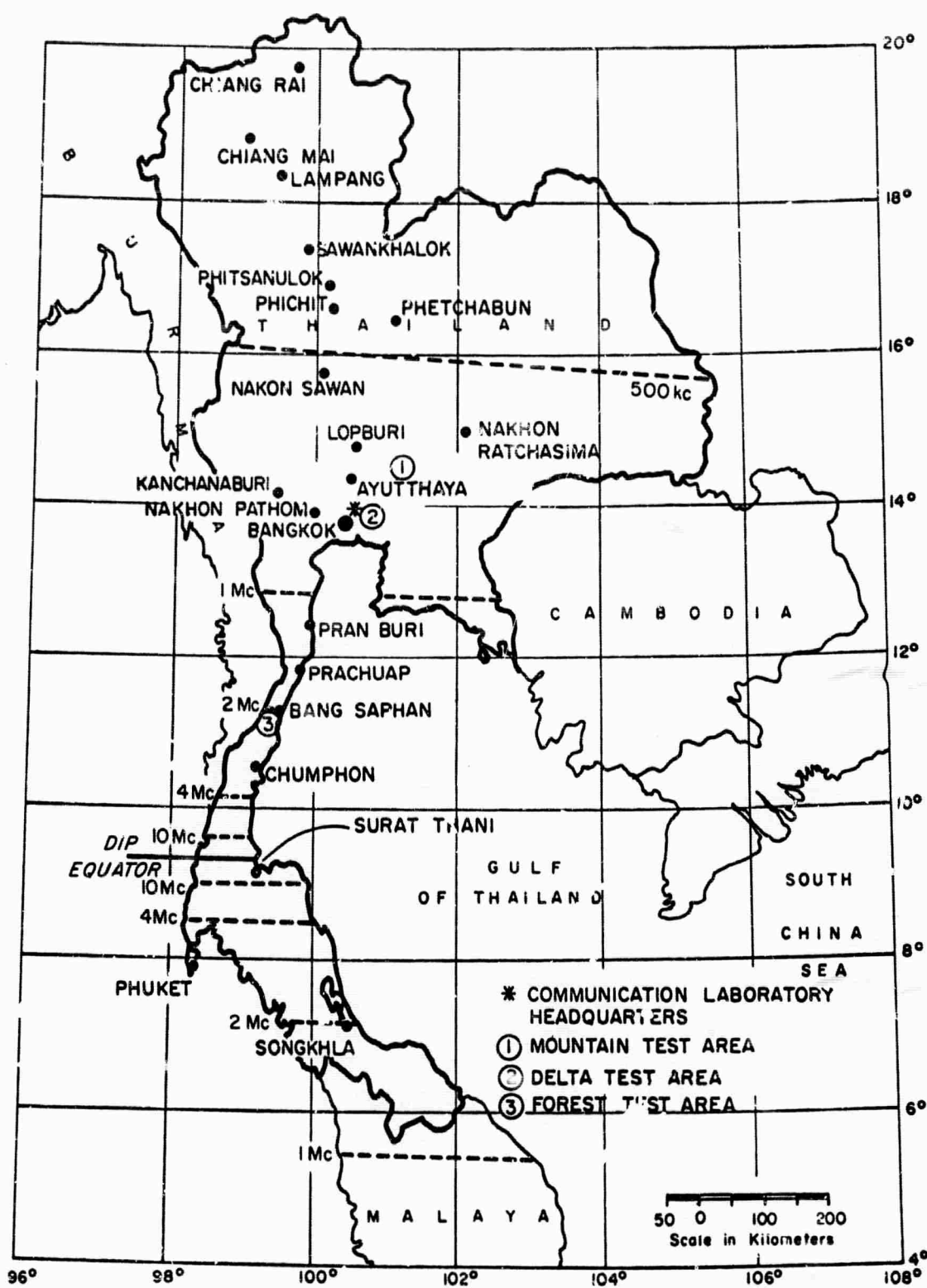


FIG. 6 VERTICAL-INCIDENCE QT MAP OF THAILAND

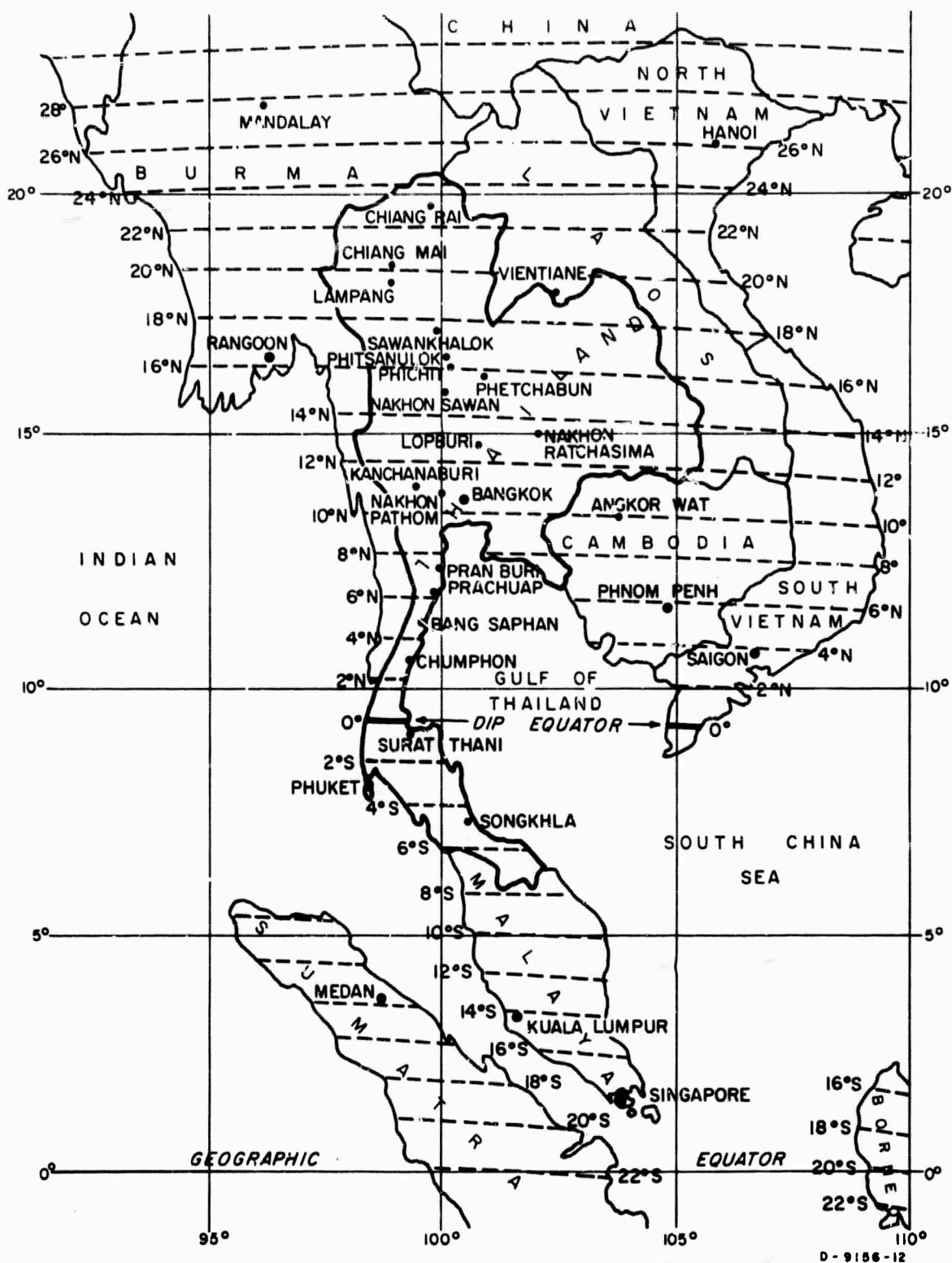


FIG. 7 DIP-ANGLE MAP OF SEA

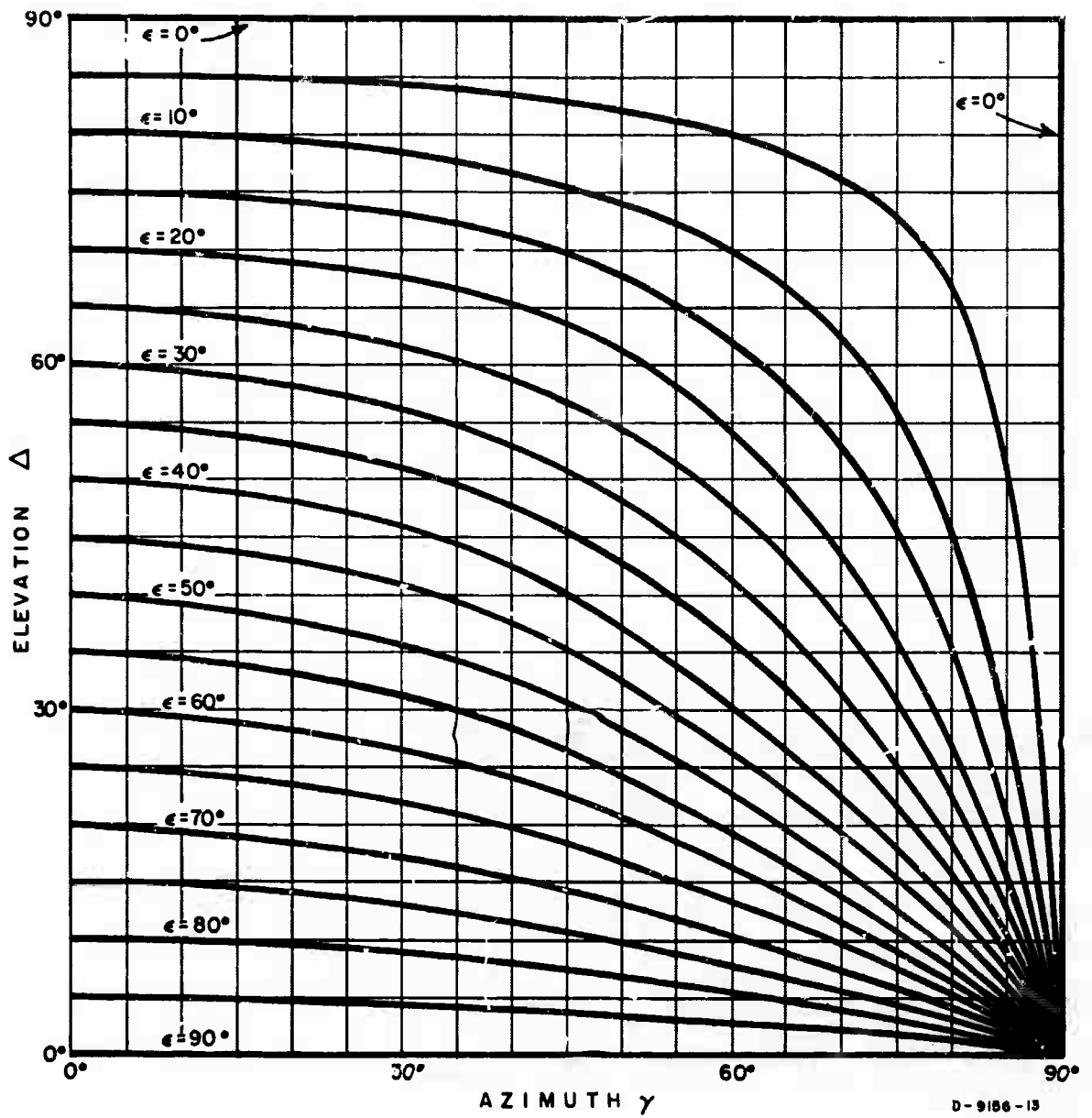


FIG. 8 DIRECTIONS FOR WHICH $\theta = 90^\circ$ FOR DIFFERENT DIP ANGLES, ϵ

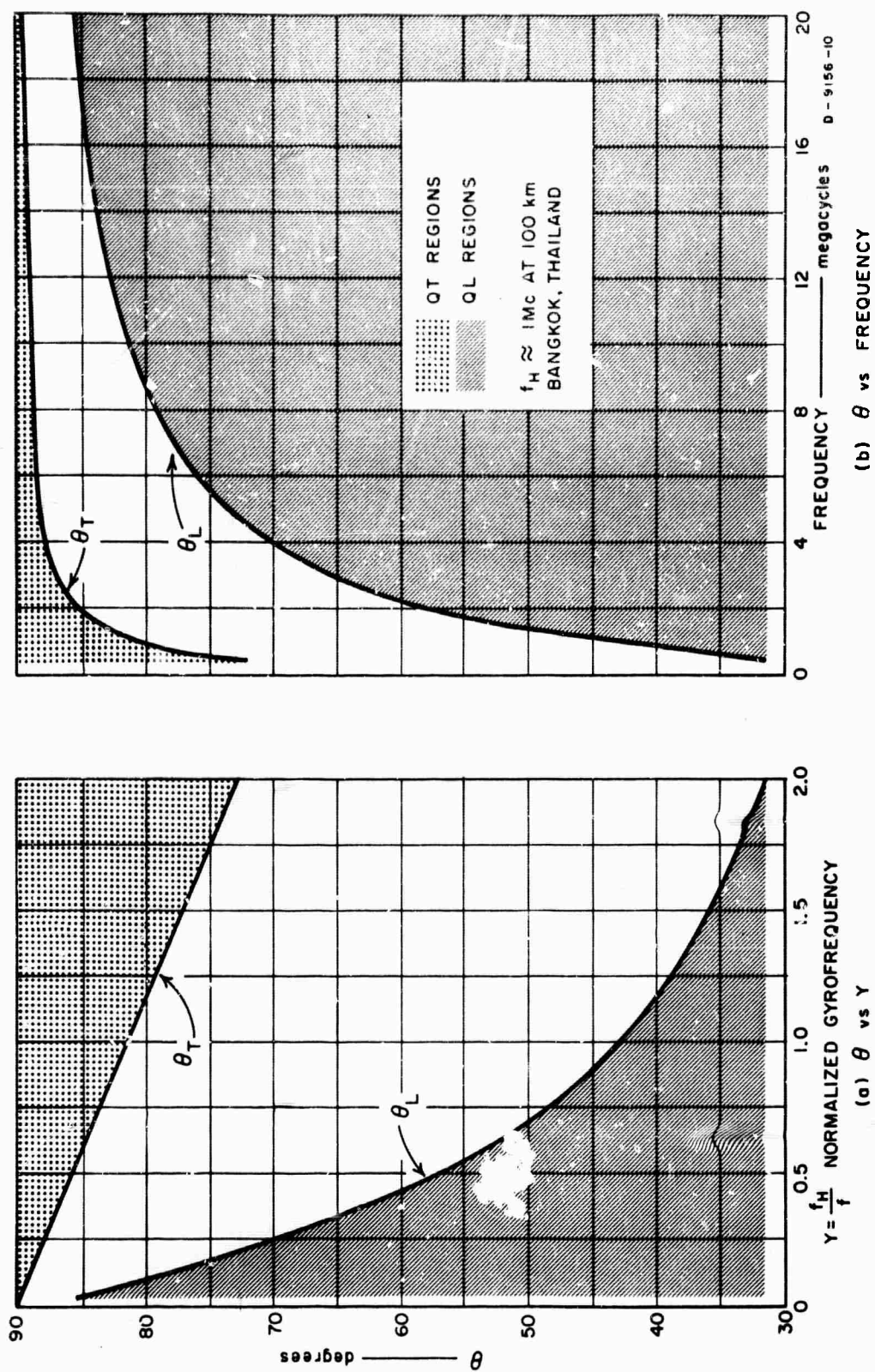


FIG. 9 QL AND QT REGIONS

and gives for the polarization equation:

$$R = \frac{E_x}{E_y} = \pm 1$$

where the upper sign represents the ordinary wave. This equation corresponds to circular polarization for the characteristic waves. The revised quartic is

$$\frac{10 \sin^4 \theta_L}{1 - \sin^2 \theta_L} = A$$

$$\sin^4 \theta_L + \frac{A}{10} \sin^2 \theta_L - \frac{A}{10} = 0$$

$$\sin^2 \theta_L = \frac{-A + \sqrt{A(A + 40)}}{20}$$

for 1 Mc, and $Y = 1$, $\theta_L \cong 43^\circ$, and

for 5 Mc, and $Y = 0.2$, $\theta_L \cong 73^\circ$.

For $\theta_L < \theta < \theta_T$, neither approximation holds, and the wave polarization of each characteristic wave is elliptical. It can be seen that in Thailand for 1 Mc, this region is roughly between 43° and 81° , and for 5 Mc the region has decreased to between 73° and 88° .

It is unfortunate that the range of θ_T is so restricted at HF. However, for the case of interest in the present discussion (near-vertical propagation in the vicinity of the geomagnetic equator), the semi-major axis of the polarization ellipse for the downcoming waves should be oriented nearly in the y direction when the linearly polarized transmitting antenna is oriented parallel to the y direction, and nearly

in the x direction when the transmitting antenna is oriented parallel to the x direction. Actually, for the polarization-ellipse, semi-major axes are not, in general, exactly parallel to the x and y directions, as explained by Ratcliffe (Ref. 41, p. 67). In the northern hemisphere, the semi-major axes for both waves are in the northeast-southwest quadrants, but this canting should not be serious near the geomagnetic equator. Thus, even though the QT approximation does not hold exactly, it may be advantageous to align antennas as though it did hold for angles, θ , upon entry in the lower ionosphere greater than θ_L . Figure 9 shows the range of angles for which the QL approximation holds in the ionosphere above Thailand.

Figure 10 is a vertical-incidence QL map of Thailand (similar to Fig. 6, the QT map). The QL map shows the parts of Thailand at which the QL approximation begins to apply at vertical incidence. Near the equator, of course, very high frequencies would be required to satisfy the QL approximation. Near Bangkok, one would expect vertically down-coming waves of about 8 Mc and higher to be circularly polarized. Thus, at Bangkok, alignment would be important for the vertical-incidence case only for frequencies below about 8 Mc. At Chiang Mai (northern Thailand), alignment would be important only below 4 Mc for the vertical case.

In Figs. 6 and 10, "much greater than" ($\gg$) has been interpreted as 10 times in order to convert the inequality to an equation. This interpretation of $\gg$ is arbitrary [for example, Ratcliffe⁴¹ chooses 9, presumably because it has an integer square root, and Budden⁴² chooses to let $\frac{y_T^2}{2y_L}$ be $\geq$ or $\leq |(1 - X - iZ)|$] and implies "good enough for a specific purpose." An alternative approach to the mapping problem, suggested by Richard Silberstein, Assistant Scientific Director, U.S. Army Signal Radio Propagation Agency, Fort Monmouth, New Jersey, is to draw contours of frequencies for which 3 db or more signal power is available at the receiving antenna terminals by orienting the receiving antenna for one of the characteristic waves (the one the transmitting

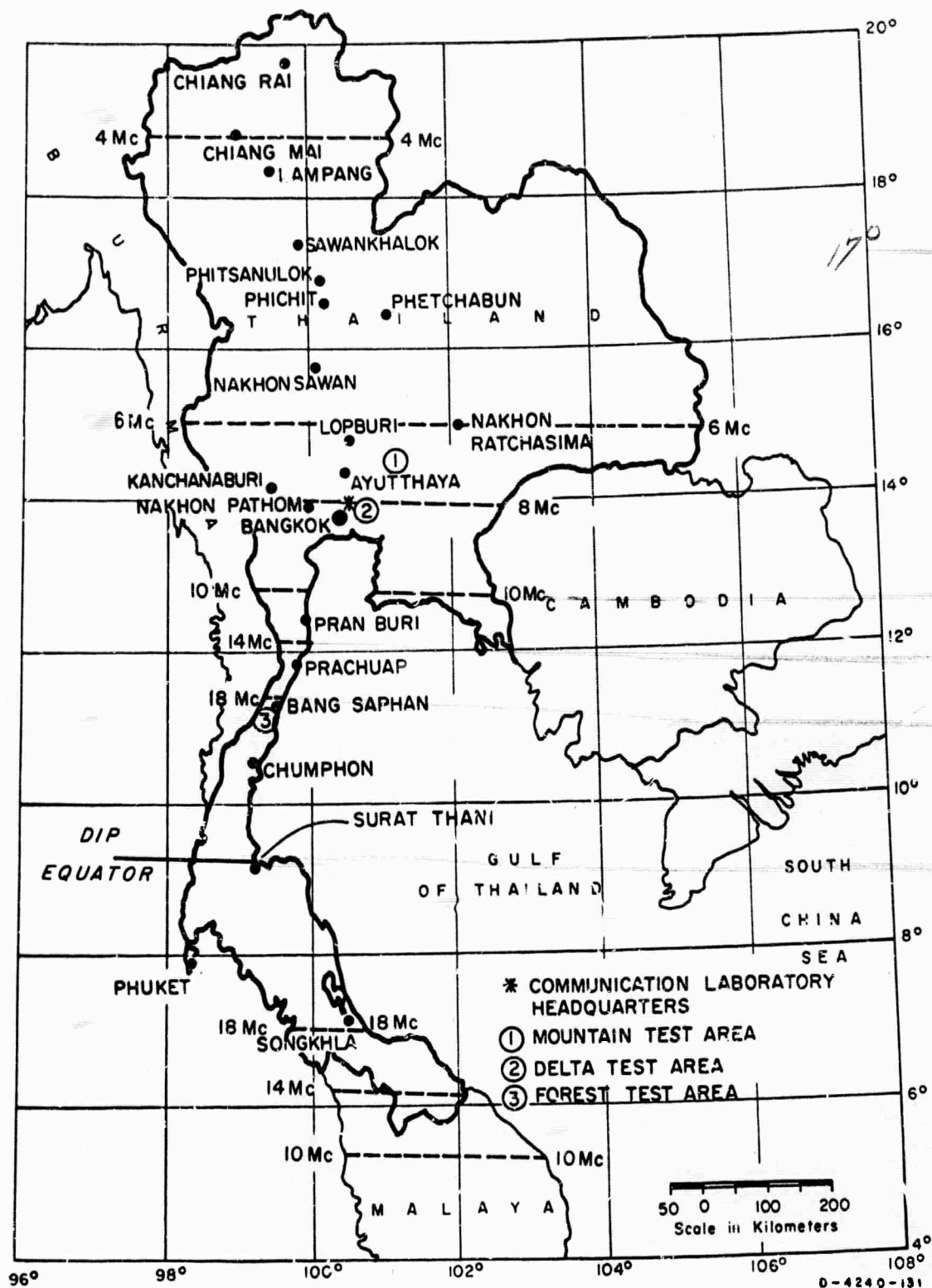


FIG. 10 VERTICAL-INCIDENCE QL MAP OF THAILAND

antenna is aligned to launch).^{*} This implies an axis ratio of 1.4:1. The contour for a given frequency on such a map would lie somewhere between those plotted as Figs. 6 and 10, but much nearer those of Fig. 10 than those of Fig. 6.

The author feels that the map of Fig. 6 shows too conservative an estimate of the benefits of alignment for the vertical-incidence case; whereas Fig. 10, while providing a lower theoretical limit, is probably too liberal. These maps should be regarded as rough guides only, for these reasons:

- (1) The theory has not been fully checked by experiment.
- (2) Few paths of practical importance are near enough to vertical to be considered so and thus make the map useful for specific application (especially at the high frequencies).
- (3) The dip of the magnetic field over Thailand is known to $\pm 1^\circ$ for the map of Fig. 7.

Until the theory is checked by experiment, antennas for use on short equatorial paths should be aligned to launch characteristic waves. On the basis of polarization considerations alone, the ordinary and extraordinary waves appear to be equally likely candidates for communication purposes.^{**} Further investigation might reveal that a 3-db contour map would indeed aid in "field manual" implementation of antenna alignment. For the present, it appears to the author that paths should be treated on an individual basis and that (excluding noise considerations) nothing is lost by alignment for characteristic waves.

Ordinary NS-NS
Extraordinary EW-EW

← This evidently means either
E-W E-W or
NS NS,

^{*} Richard Silberstein, private communication (July 1964).

^{**} There is experimental evidence that the ordinary mode is more stable with respect to tilt angle than the extraordinary and is therefore to be preferred by the communicator on stability considerations.¹³

IV ABSORPTION OF IONOSPHERICALLY PROPAGATED RADIO WAVES IN REGIONS WHERE THE QT APPROXIMATION IS VALID

To investigate the effects of absorption it is convenient to permit the refractive index to become complex. If the field quantity of interest is varying as $\exp \{i\omega[t - (nz/c)]\}$ as the wave propagates in the $+z$ direction, the exponent has the effect of introducing only a phase shift with distance. Allowing the refractive index, $n = \mu - i\chi$, to become complex permits the exponent a real part, which accounts for an amplitude decrease with distance in addition to any inverse distance attenuation to compensate for divergence with distance from the source of the wave. The wave then attenuates as $\exp \{-\kappa z\}$ where the "absorption" coefficient, κ , is given by $\kappa = \omega\chi/c$.

This form comes about by putting a viscous damping term in the equation of motion for an individual electron. The coefficient of the damping (velocity) term is proportional to an effective collision frequency, ν , and the constant of proportionality is the mass of the electron.

Ratcliffe⁴¹ shows that the equation for the refractive index becomes

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{1}{2} \frac{Y_T^2}{1 - X - iZ} \pm \left[\frac{1/4 Y_T^4}{(1 - X - iZ)^2} + Y_L^2 \right]^{1/2}}$$

Since $n^2 \triangleq (\mu - i\chi)^2 = \mu^2 - \chi^2 - 2i\mu\chi$, one can equate the imaginary part of the expression for the square of the complex refractive index, $2\mu\chi$, to the imaginary part of the above expression for n^2 and relate χ , and hence κ , to X , Y_T , Y_L , and Z .

In general, when this is done, κ is of the form:

$$\kappa = \frac{\nu}{2\mu c} \cdot f(X, Y, Z, \theta)$$

where Y is the normalized gyrofrequency and θ is the angle that the wave normal makes with the field.

In the ionosphere, the group velocity is given approximately by μc , when Z and $Y \ll 1$. Substituting this into the expression for κ gives some insight into the nature of the absorption coefficient:

$$\kappa \approx \frac{\nu}{V_{\text{group}}} (\text{const.}) f(X, Y, Z, \theta) \quad .$$

This says that the attenuation of the wave (in decibels) in traveling unit distance in the medium is proportional to the time it takes to traverse that distance and to the collision frequency applicable along the path. This relationship can, of course, be modified depending on $f(X, Y, Z, \theta)$ which, it will be seen, is usually directly proportional to electron density and approximately inversely proportional to frequency squared.

Ratcliffe⁴¹ shows (Chap. 4.4) that the QL approximation

$$\kappa_{\text{QL}} = \frac{\nu}{2\mu c} \cdot \frac{\omega_N^2}{(\omega \pm |\omega_L|)^2 + \nu^2} = \frac{\nu}{2\mu c} \cdot \frac{X}{(1 \pm |Y_L|)^2 + Z^2}$$

where ω_N is the plasma frequency and ω_L is the longitudinal component of the gyrofrequency. The upper sign corresponds to the ordinary ray and the lower sign to the extraordinary. For this case, $f(X, Y, Z, \theta)$ is given simply by

$$\frac{X}{(1 \pm Y \cos \theta)^2 + Z^2} \quad .$$

The κ expression for the QT approximation will be more complicated,¹⁷ as is indicated by the refractive index expressions:

$$n_{QT(\text{upper sign})}^2 = 1 - \frac{X}{1 - iZ + (1 - X - iZ) \cot^2 \theta}$$

$$n_{QT(\text{lower sign})}^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{1 - X - iZ} - (1 - X - iZ) \cot^2 \theta}$$

The expression for the upper sign (ordinary wave) leads to the following expression for κ :

$$\begin{aligned} \kappa_{QT(\text{upper sign})} &= \frac{\nu}{2\mu c} \cdot \frac{\omega_N^2 \csc^2 \theta}{\omega^{-2} (\omega^2 \csc^2 \theta - \omega_N^2 \cot^2 \theta)^2 + \nu^2 \csc^4 \theta} \\ &= \frac{\nu}{2\mu c} \cdot \frac{X \sin^2 \theta}{(1 - X \cos^2 \theta)^2 + Z^2} \end{aligned}$$

Notice that this result for the ordinary wave is independent of the magnetic field strength (gyrofrequency). This is to be expected because, for the ordinary wave in the QT approximation at HF, the electrons are accelerated nearly along the field and the $\vec{V} \times \vec{B}$ product is small. But κ is dependent upon θ , the angle that the wave normal makes with the static magnetic field, as would be expected, from inspection of the $n_{QT(\text{upper-sign})}^2$ expression, which is also independent of Y but a function of θ . This function of θ accounts for the effect of the small $V \times B$ electric field in the equation of motion for an individual electron.

At $\theta = 90^\circ$ (purely transverse),

$$\kappa = \frac{\nu}{2\mu c} \cdot \frac{\omega_N^2}{\omega^2 + \nu^2} = \frac{\nu}{2\mu c} \cdot \frac{X}{1 + Z^2}$$

This expression is quite simple. It is the expression for κ with the static magnetic field zero, which is identically true for the QL approximation at HF (i.e., when $\omega \gg \omega_H$), which, when $\omega \gg \nu$, becomes the familiar inverse-frequency-squared law for absorption at HF.

The κ expression for the lower sign (extraordinary wave) leads to a more complicated expression for $f(X,Y,Z,\theta)$:

$$\kappa_{QT}(\text{lower sign}) = \frac{-\nu}{2\mu c} \cdot \frac{\sin^2 \theta}{\cos 2\theta}$$

$$\frac{X \left[1 - \frac{\sin^2 \theta}{\cos 2\theta} \cdot \frac{Y_T^2}{(1-X)^2 + Z^2} \right]}{\left[1 - \frac{X \cos^2 \theta}{\cos 2\theta} + \frac{\sin^2 \theta}{\cos 2\theta} \cdot \frac{Y_T^2 (1-X)}{(1-X)^2 + Z^2} \right]^2 + Z^2 \left[1 - \frac{\sin^2 \theta}{\cos 2\theta} \cdot \frac{Y_T^2}{(1-X)^2 + Z^2} \right]^2}$$

For the region where $\mu \approx 1$ (nondeviative region), one can estimate relative differential absorption of the ordinary and extraordinary waves, at a given height in the ionosphere (db/km) by taking a ratio of the κ expressions and canceling μ . This predicts that the extraordinary suffers the greater attenuation in the nondeviative region and also that there is less differential absorption in the QT case than in the QL case.* No such simple comparison technique exists for the deviative region, and when collisions are important near the height of reflection, a full-wave solution is required to calculate total absorption (i.e., reflection coefficient of the ionosphere). The cumulative two-way absorption at

* This implies more severe fading due to beating of magneto-ionic components when the QT is valid than when the QL is valid for a random antenna orientation.

vertical incidence must be determined by integrating the κ expressions up to the true height of reflection ($X = 1$ and $X = 1 - Y$ for the ordinary and extraordinary, respectively) along the ray path:

$$\text{Two-way absorption (db)} = 17.36 \int_0^{h_{\text{true}}} \kappa(h) dh .$$

Calculations made with assumed $N(h)$ and $\nu(h)$ profiles indicate that deviative absorption is very dependent upon $\frac{dN(h)}{dh}$ and must be considered on an individual-case basis. In general, the ordinary wave suffered less absorption except when reflecting in a high-loss region (where the longer path in the lossy region caused greater total absorption) or when the height of reflection corresponded to a region of smaller increase of electron density with height than in the region of reflection for the extraordinary wave.

When collisions are important near the true height of reflection, the integral expression predicts too little absorption, and a correction must be added to account for the fact that the reflection is not total.⁴⁶ This added loss is important only for the vertical-incidence case.

V INTERFERENCE CONSIDERATIONS

Antennas launching characteristic waves for propagation transverse to the earth's field near the geomagnetic equator (short paths) would be horizontally polarized. This orientation would give the added feature of decreased sensitivity to interference propagated by the ground wave, which is predominantly vertically polarized at any distance from the source (at HF).⁴⁷

Workers at ACF Industries observed that a horizontal dipole above ground has a greater response for a vertically polarized ground wave off the end than it does broadside, because of the slight inclination of the ground-wave electric vector.⁴⁸ This comes about because of the requisite boundary conditions at the lossy boundary between the earth and free space. Thus, with dipoles oriented to utilize the ordinary wave, one would expect more discrimination against ground waves from east or west than from north or south.

In the absence of other information or data, it must be assumed that ionospherically propagated noise is randomly polarized. There is, however, reason to expect that it has a larger "effectively vertically polarized component" than horizontally polarized component as observed by ground-based antennas, especially at the lower frequencies. Should this be true, antennas oriented to launch the ordinary or extraordinary waves would be in a truly optimum orientation from a $(S+N)/N$ evaluation.

In the jungle, where path loss for ground waves is high, one would expect the noise to be less in the direction of thick jungle at zero take-off angle. Likewise, one would expect noise to be at a minimum near the zenith during the day, because energy arriving at high angles would generally require more D-region penetrations than energy arriving at some intermediate range of angles. Figure 11 shows noise temperature versus elevation angle--for day and for night--that might be expected at a tropical jungle site. If this conjecture is correct, vertical-looking, horizontally polarized antennas ($H < \lambda/4$) should be

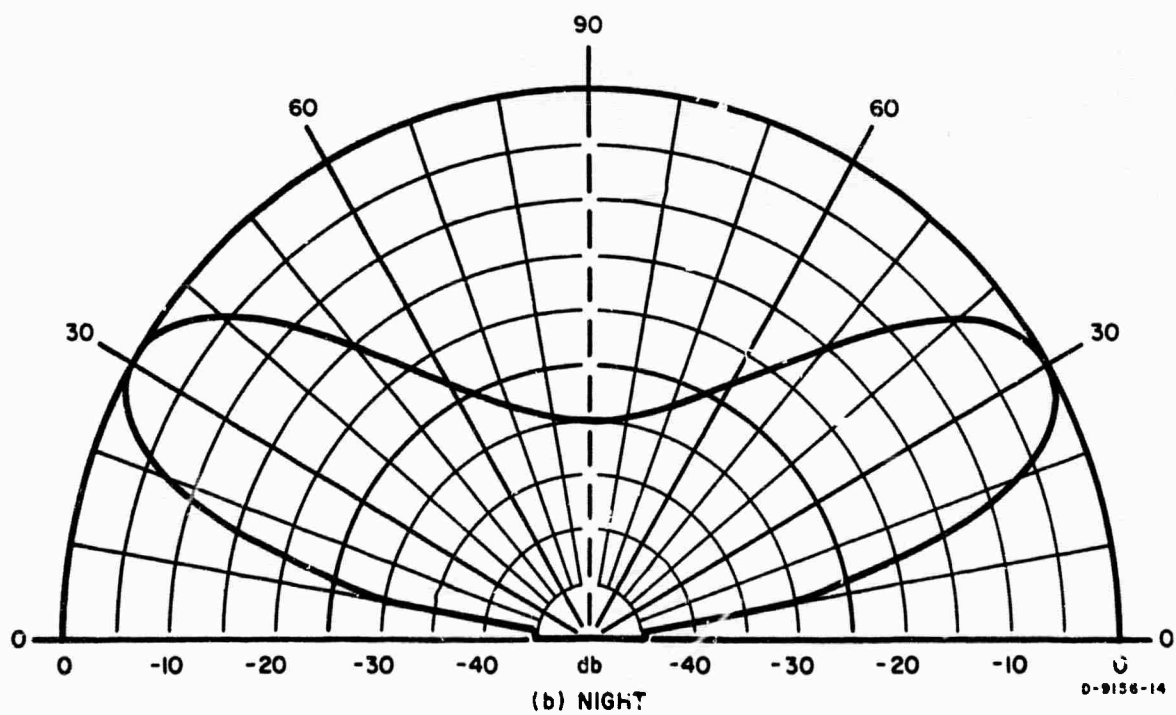
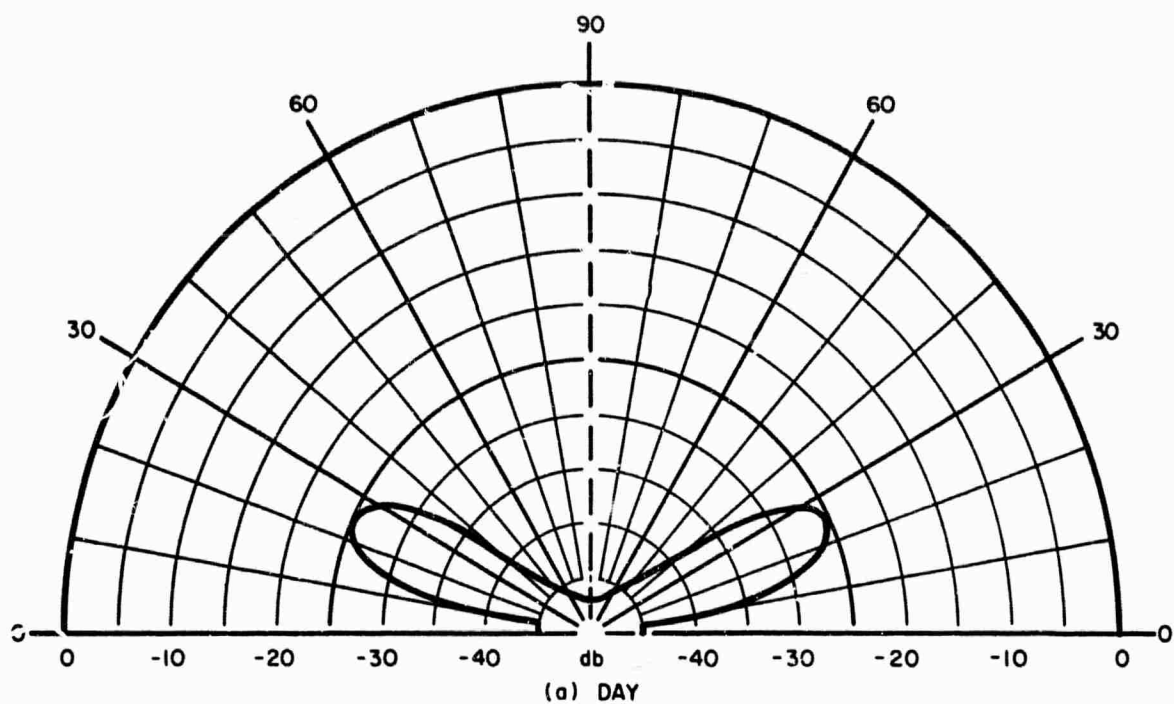


FIG. 11 RELATIVE NOISE POWER INCIDENT ON A GIVEN JUNGLE RECEIVER SET

less noisy than horizontally polarized antennas with main beams at lower elevation angles. Also, it might be desirable to increase the height (if frequency is sufficiently high for this to be practical) to give a receiving antenna pattern such as that shown in Fig. 12. This would take advantage of the jungle path loss for noise at low angles at permanent receiving locations (or when noise conditions are extreme) and place



FIG. 12 OPTIMUM HALF-WAVE DIPOLE ANTENNA HEIGHTS (H) AND PATTERNS

a null in the antenna-elevation-angle response pattern near the anticipated maximum in the noise pattern. The height of a horizontal, balanced half-wave antenna might be adjusted around $H = \lambda/4$ or $H = 3\lambda/4$ to obtain the best signal-to-noise ratio. Such adjustment around $H = 3\lambda/4$ would be especially desirable for receiving in a jungle valley but would probably be undesirable on hilltops or mountain peaks.

It should be observed that the common doublet antenna constructed (or fed) from coax shield and center conductor is an unbalanced structure. The *slight* loss (and hence increase in antenna noise temperature) incurred by the use of a balanced transformer with such an antenna could be more than overcome by the polarization rejection of interference, if such a preferred polarization of interference actually exists.

Experiments should be performed in Thailand to determine whether such polarization effects exist and whether the added expense and complexity of balanced transformers for use with radio sets having an unbalanced input is justified for field use. It would further appear that sets designed for short-ionospheric-hop use at low latitudes might be more versatile with both balanced and unbalanced inputs. For such an arrangement, a dipole could be fed with balanced line, and no balun would be required. A whip could be fed into the coax connector when required.

VI PROPOSED EXPERIMENTS TO VERIFY ANTENNA ORIENTATION SUGGESTIONS

A. INTRODUCTION

The theoretical presentation in the earlier sections of this report should be investigated by experiments in Thailand.* Effects that should be examined include:

- (1) Polarization of desired signal
- (2) Polarization and angle of arrival of interfering signals and noise
- (3) Absorption
- (4) Fading.

Items (1) and (3) can be checked most easily with a pulse experiment; (2) and (4) are most easily checked with CW experiments, in the case of (4) performed simultaneously with a pulse experiment (to obtain an oblique-incidence ionogram that defines the mode structure causing the fading observed on the CW transmission). Fading effects of individual modes (one-hop ordinary or extraordinary) should also be examined to see whether polarization diversity would be useful. These effects are most easily observed by using pulse techniques.⁴⁸

B. POLARIZATION EFFECTS

1. Desired Signal

This experiment consists of determining the polarization of downcoming radio waves on short paths near the geomagnetic equator when

* The polarization effects have already been checked at Huancayo, Peru,^{2,4} in the mid-1930s and early 1940s. The absorption effects have received a preliminary check.¹⁹

the transmitted wave is launched by linearly polarized antennas aligned parallel to or orthogonal to the projection of the earth's geomagnetic-field vector (at the bottom of the ionosphere) upon the earth. Such antennas will launch characteristic waves (ordinary and extraordinary, respectively) which are linearly polarized when the magnetic-field dip angle at ionospheric heights is not too great and the path is short enough (i.e., the QT approximation holds near the entry region in the lower ionosphere--see Sec. III). As previously stated, the critical parameter in determining the validity of this approximation is usually Θ , the angle that the wave normal (perpendicular to planes of constant phase) makes with the earth's static magnetic field.

A primary objective of this measurement program would then be to determine the region on the ground where the emerging polarization is linear (i.e., where the QT approximation holds) as a function of path length, frequency, and local time.* Such measurement would indicate whether there is an optimum orientation from a signal-polarization standpoint. A few transmissions might be made with the transmitting antenna aligned to launch the ordinary component and the receiving antenna aligned to receive the extraordinary, to illustrate that there exist truly non-optimum orientations and that one might, under these conditions receive no signal (or at best a very weak signal--the approximately 20-db cross-polarization response of a dipole, for example). Preliminary measurements in Thailand indicate that this is very approximately true.¹⁹

Pulses are required to separate the received ordinary and extraordinary components generated; it is proposed to measure the axis ratios of both ordinary and extraordinary and also the ratio of the

*The diurnal change of h' for a given path and frequency corresponds to a change in Θ . This should be a significant effect at frequencies above several megacycles per second on long north-south paths or on short paths relatively remote from the equator.

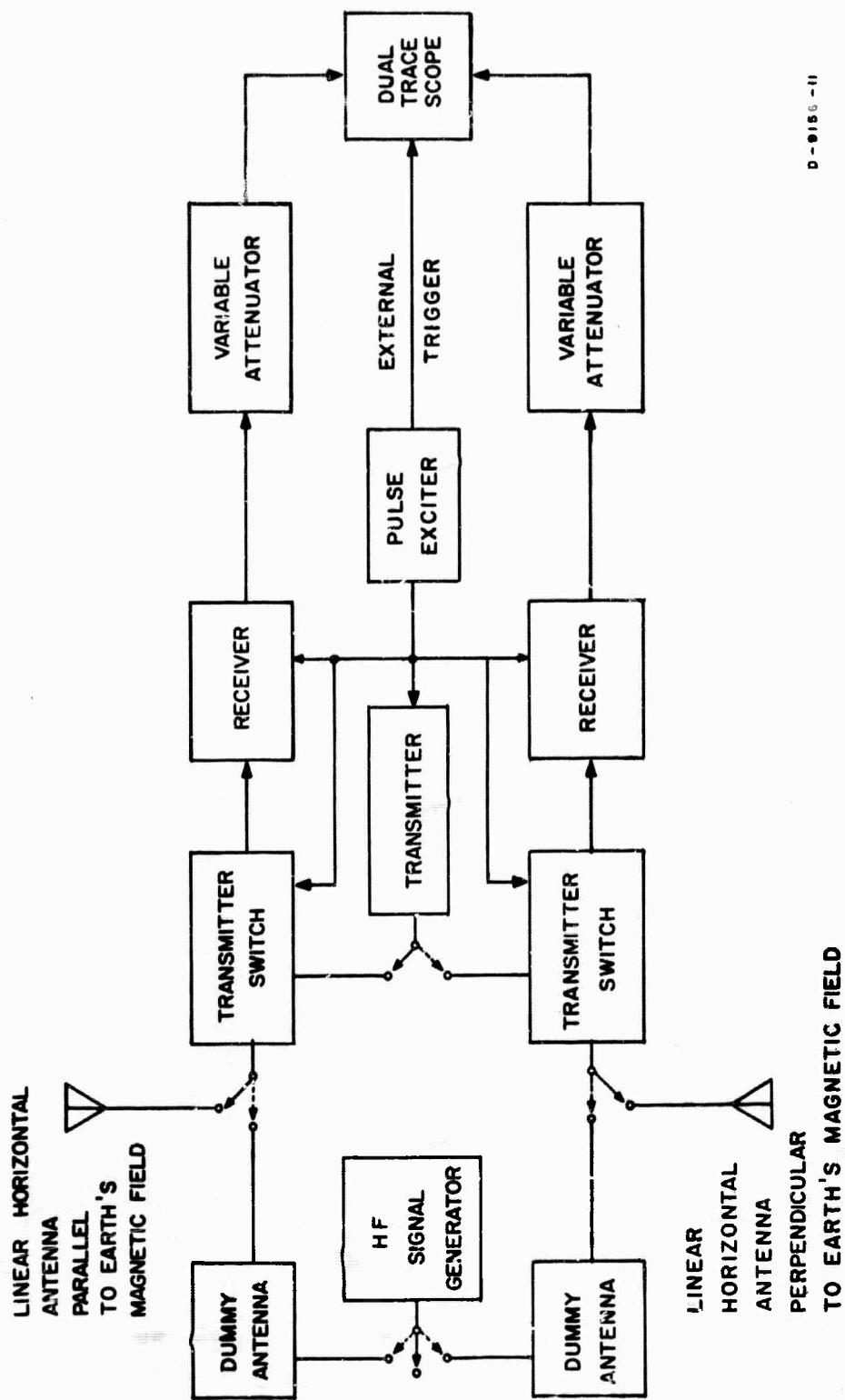
ordinary and extraordinary semi-major axes, which will give absorption information when both transmitting orientations (parallel and perpendicular to the earth's field) are utilized in reasonably swift succession. Measurements of the sense of rotation of the polarization ellipse are not suggested at this time, but a check of the relationship $R_u R_l = 1$ would be interesting and might be pursued later.^{13,41}

A possible setup for a vertical-incidence test (monostatic operation) is shown in Fig. 13. Another system has been described by Busch and Green.⁴⁹

For bistatic tests, the setup must be rearranged. When the ground wave is large enough, it can be used as a synchronizing pulse. However, when this wave is greatly attenuated (the usual case in jungle operations), synchronization must be achieved by other means. Since the true delay between the ordinary and extraordinary waves is usually unimportant, the scope internal trigger with fine adjustment can be used to display the pulses. Such an arrangement is shown in Fig. 14. Busch and Green of ACF have indicated that peak pulse powers on the order of milliwatts and pulse lengths of several hundred microseconds should produce useful echoes at vertical incidence.⁴⁹

The monostatic system shown in Fig. 13 could also be used with a rotating dipole antenna for both transmitting and receiving. Such an experiment would show the changing energy distribution in the two modes as the angle of the dipole to the magnetic field changes.* This could best be done at night when differential absorption effects are minimum and low power could be used. One slowly rotating horizontal dipole might be used to both transmit and receive. For convenience, a fore-shortened (loaded with lumped elements) dipole might be used. The

* An equivalent experiment was performed by Wells⁴ near Huancayo, Peru; it gave the expected results.



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FIG. 13 TEST SETUP FOR VERTICAL INCIDENCE (MONOSTATIC)

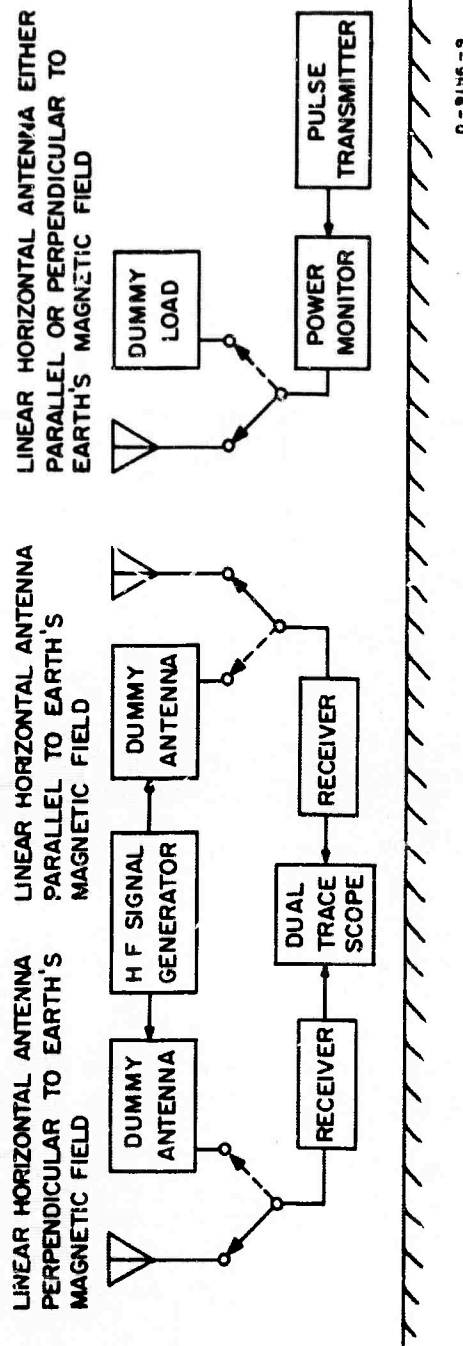


FIG. 14 TEST SETUP FOR OBLIQUE INCIDENCE (BISTATIC)

A-scope displays to be expected on an oscilloscope as a function of dipole angle to the magnetic field during transmission of short pulses (200 μ sec or so) are shown in Fig. 15. Alternatively, the bistatic system depicted in Fig. 14 could be used, and the transmitting dipole could be rotated.

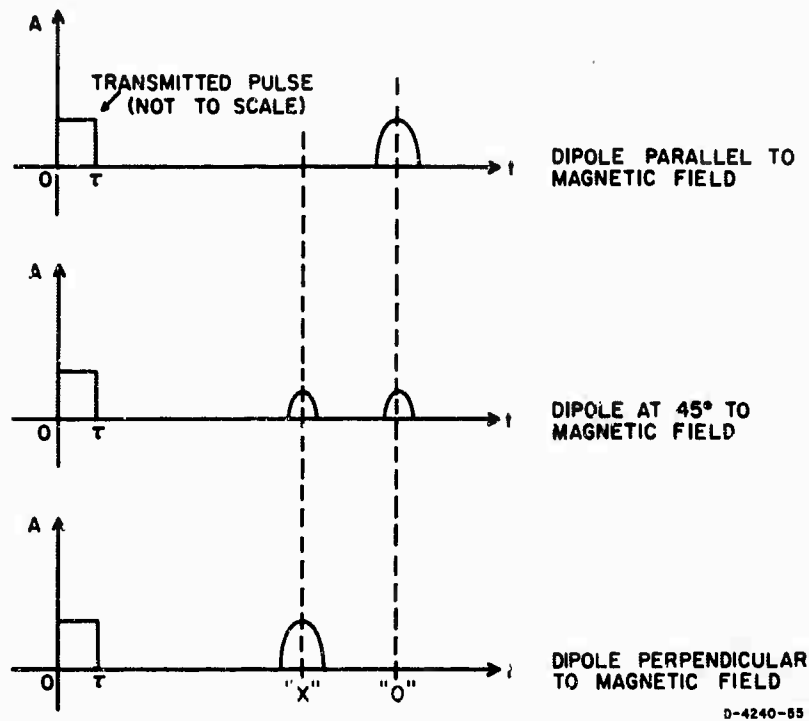


FIG. 15 A-SCOPE DISPLAY FOR ROTATING DIPOLE EXPERIMENT

It would also be possible to use a slowly rotating loop, as described by Snyder.⁵⁰ The "polarimeter" described by Benner⁵¹ might be used. Alternatively, a combined four-element Adcock and crossed-loop direction finder could be used to specify completely the characteristics of the downcoming radio wave (i.e., angle of arrival, etc., as well as polarization).⁵² All of these systems could be calibrated to provide accurate absorption data.^{53,54}

2. Interfering Signal

To the communicator, the error rate for a given information transmission rate is most important. This is usually related to the signal-to-noise ratio at the receiver output, although not necessarily in a straightforward manner.⁵⁵ There is reason to suspect that both ground-wave and sky-wave interference are predominantly vertically polarized in the HF band, especially at the lower frequencies. This has a direct effect on the choice between possible antennas where the system limitation is noise or interference (i.e., low-power radio transceivers in a noisy environment), and it should be checked by experiment.

The bandwidth of the tuned RF amplifier should be on the order of hundreds of cycles (e.g., about 200 cps), with the pass band centered in a portion of the spectrum containing no strong local carriers. The detector-recorder time constant should be long enough to provide adequate averaging. A variable time constant might be desirable. Wide dynamic range amplifiers (greater than 80 db) would be desirable to avoid saturation effects and to provide proper averaging.

Another reason for taking atmospheric noise data is to obtain a factor for converting existing radio noise data⁵⁶ taken on a 21.75-foot vertical monopole antenna above a ground plane (used to calculate noise grade, etc.) to a value for use with horizontally polarized antennas. The conversion factor is often assumed to be unity, but this assumption is probably in error by tens of decibels⁵⁷ and should be checked near the magnetic equator. It would be desirable to measure the conversion factor for representative center frequencies for several times of day during various seasons.

It would also be interesting to check the noise voltages induced at the terminals of two horizontal dipoles, one parallel to and one perpendicular to the earth's magnetic field near the equator, as a function of antenna height. One might expect the antenna parallel to the earth's field to pick up more interference, because more atmospheric interference should come from the east and west (the storm belt near the

equator) than from the north and south, except when local conditions control the atmospheric noise picture. The alignment of the linear antennas relative to the polarization of the propagating interference and the actual source distribution at the time of measurement could modify this expectation considerably, however.

C. FADING EFFECTS

When signals arrive at a receiving antenna via several paths (e.g., ordinary and extraordinary, upper and lower ray, E- and F-region reflections, sky-wave and ground-wave, etc.), the resultant induced voltage at the antenna terminals varies with time when the relative phases (or amplitudes, or both) vary with time. The fading condition produced, termed multipath by communicators, is generally undesirable. Under certain conditions, a communication channel may be rendered unusable by such fading. If magneto-ionic splitting can be eliminated, one of the several possible causes of multipath on HF circuits can be eliminated,¹⁰ with accompanying reduction of the required "fading margin" used in lowest-useful-frequency calculations.

Fading due to the ordinary and extraordinary waves beating together is usually most noticeable when the operating frequency is near the MUF for the path. Such fading tends to be periodic and is observed when the MUF is changing (early morning or late afternoon).⁵⁸ Since the extraordinary is generally subject to more absorption than the ordinary, such fading rarely nulls to zero.

The effect of ordinary and extraordinary fading could be determined by so choosing an operating frequency for a given path that the low-ray ordinary and extraordinary waves were the only contributors to the multipath. This could be determined by using pulses of length short enough to give resolution of the propagating modes. Then, with the cause of the multipath determined, a CW measurement could be performed to check the effect. This would correspond to a measurement of the relative phase (and amplitude) stability of the modes. Such an experiment could be performed simultaneously with a test of a diversity combining receiver to check the possible usefulness of polarization diversity.

The test setup shown in Fig. 14 could be used to define the propagating modes; the setup shown in Fig. 16 could be used to perform the CW experiment. The time constant of the recorder should be short enough to capture the most rapid fading of interest. It might be possible to correlate the CW measurements with ionograms simultaneously taken with a step-frequency oblique-incidence sounder.

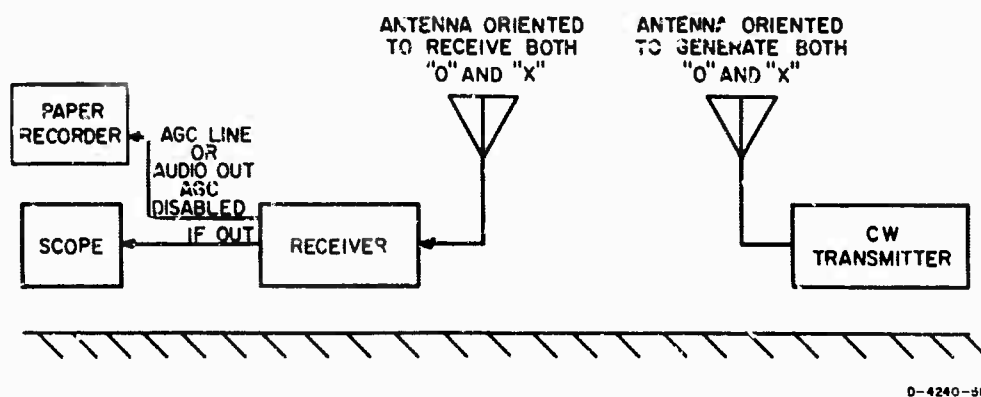


FIG. 16 TEST SETUP FOR CW EXPERIMENT

Multipath from another source on HF ionospheric paths near the magnetic equator deserves passing mention: equatorial flutter fading.⁵⁹ This is a nighttime effect (often termed sunset effect) associated with equatorial spread F as observed on a vertical-incidence sounder.^{60,61} Such fading is especially noticeable at the equinoxes; it appears more serious shortly after sunset at the receiving station during sunspot maxima. It is doubtful that alignment of antennas will be of benefit in combating the effects of this type of fading (the theory on which the alignment arguments are based requires a slowly varying refracting medium rather than a swiftly varying reflecting or scattering medium), but performance of the CW experiment would help to define these effects. The author believes the effect to be primarily an F-region phenomenon (oblique-incidence manifestation of equatorial spread F) associated with a rise of the F region after sunset in the ionosphere. Therefore, outages due to flutter fading could be avoided on HF circuits by using

frequencies low enough to be reflected by the nighttime E region or by E_s . Experiments to determine the effect of flutter fading on long paths have been conducted in South America and Africa by the National Bureau of Standards, Boulder,⁵⁹ and by several workers in Africa.⁶⁰ The author feels that experiments on shorter paths and lower frequencies in the HF band could be performed in Thailand that would supplement existing data and give information useful in radio set design as well as propagation studies.

VII CONCLUSIONS

It may be advantageous to the communicator to launch only one characteristic wave (a wave that propagates with locally unchanging wave polarization) in order to minimize magneto-ionic effects including polarization fading⁵⁸ and to minimize absorption in the ionosphere.¹⁷ For paths where the QT approximation holds for entry to the ionosphere, a characteristic wave can be launched with a linearly polarized antenna. Such a wave can be launched with electric vector parallel to or orthogonal to the earth's magnetic field. Only one characteristic wave will emerge when there is no mode coupling* within the ionosphere and conditions at emergence are the same as those at entry. There exists, then, an optimum orientation, based upon polarization considerations, for both transmitting and receiving antennas under these conditions. Notice that, for short paths near the magnetic equator, such an optimum orientation corresponds only to east-west or west-east paths (ordinary wave) and north-south or south-north paths (extraordinary wave), for the rules of alignment illustrated in Fig. 1. However, for the large elevation angles associated with short paths, when horizontal dipoles adjusted to appropriate heights above ground are used, the directivity itself is not seriously affected for any axis orientation, so the argument used to generate the rule on which Fig. 1 is based does not apply. It can be concluded, therefore, from polarization considerations, that appropriate alignment for linearly polarized communication antennas for use on short

* Cohen points out that quasi-transverse propagation regions are precisely where mode coupling should be most expected, essentially because in these regions the characteristic polarizations change rapidly with changes in propagation angle, electron density, and magnetic field strength.⁶² He says that when propagation is nearly transverse ($\Theta = 90^\circ$), the possibility of mode coupling should be investigated, especially when empirical data do not appear reasonable on the basis of uncoupled modes.

ionospheric paths near the geomagnetic equator is either parallel to or perpendicular to the projection on the earth's surface of the geomagnetic field in the lower ionosphere. Figure 5 indicates that such alignment will be most useful on short paths in the lower part of the HF band (say below 5 Mc) except for very nearly pure-transverse propagation. Appendix B illustrates the calculation when the QT approximation is likely to hold for a given path.

The theory does not necessarily apply to reflections from E_s or other inhomogeneities. Indeed, the full-wave theory predicts there may be mode conversion at the boundary of the inhomogeneity. Measurements by C. Abhirama Reddy and B. Ramachandra Rao¹² indicate that the theory holds somewhat for E_s reflections but that the reflection properties depend upon the type of E_s cloud. Thin clouds tend to reflect the extraordinary wave more strongly than the ordinary, but the extraordinary is more absorbed. It seems that determination of the polarization of E_s echoes very near the magnetic equator where the QT approximation clearly holds would supply valuable supplementary information. Absorption and mode conversion efficiency would be simultaneously determined.

A consideration of the relative absorption (see Sec. IV) of the two characteristic waves indicates that the extraordinary wave will suffer more absorption than the ordinary wave. When the wave frequency approaches the gyrofrequency for electrons, absorption is high for both ordinary and extraordinary waves, because the wave frequency is low relative to the collision frequency for electrons. The theory predicts that the extraordinary wave will, however, be almost completely absorbed as evidenced by the "pole" at $Y = 1$ in the expression for κ . Thus it is usually advantageous to use the ordinary wave for communicating, as surmised by Piggott.¹¹ Even if a "pure" ordinary wave is not launched, the differential absorption should accomplish some "mode purification," which will be helpful in reducing the amplitude of polarization "fades."

It appears that launching either the ordinary or the extraordinary wave with carefully balanced horizontal antennas will minimize atmospheric noise at the terminals of a similarly aligned receiving antenna;

however, one does not know which orientation is more discriminating against the noise. Furthermore, whereas the orientation for the ordinary may be preferred from the standpoints of signal (absorption) and stability of tilt angle, that for the extraordinary may actually yield a larger signal-to-noise ratio at the receiver output and consequently be a more useful orientation. This can be checked at a given location, season, and frequency by setting up two antennas and observing which has the greater equivalent noise temperature ($P_n = k T_{eq} B_n$).

If significant energy is propagating in only one magneto-ionic component, fading due to magnetic field effects (splitting) will be eliminated or minimized, and polarization diversity would provide no improvement in system performance. However, should fading of individual modes^{63,64} prove to be time uncorrelated or correlated in a usable manner, then polarization diversity might still offer improvement under special conditions, especially when E_s reflection is the dominant mechanism and the wave polarization is unsteady.^{12,13,14} Polarization diversity might also be helpful in minimizing fading due to multiple hops. Perhaps a combination polarization/space diversity system employing noise-canceling techniques is more nearly optimum for short-path communication via the ionosphere near the geomagnetic equator.

APPENDIX A
DEFINITION OF TERMS

The terms used in this paper (with several exceptions) follow the notation employed by Ratcliffe:⁴¹

c = free-space velocity of electromagnetic waves

e = charge on an electron (When numerical values are inserted, this will be negative.)

H_0 = magnitude of the imposed magnetic field

ϵ = magnetic-field dip angle

μ_0 = permeability of vacuum = 10^{-7} henry/meter

ϵ_0 = permittivity of vacuum = $4\pi \cdot 8.855 \times 10^{-12}$ farad/meter

m = electronic mass

n = complex refractive index = $\mu - i\chi$

N = number density of electrons

x, y, z = position coordinates

E = electric wave field

H = magnetic wave field

f = wave frequency

ω = angular wave frequency = $2\pi f$

μ = refractive index = real part of n

κ = absorption coefficient

χ = $\kappa c / \omega$ = absorption index = negative imaginary part of n

θ = angle between H_0 and O-Z

ν = frequency of collision of electrons with heavy particles

R = wave polarization.

The following symbols are recommended by the Union Radio Scientifique Internationale (U.R.S.I.):

$$\omega_N^2 = 4\pi N e^2 / \epsilon_0 m = \text{plasma frequency squared}$$

$$\omega_H = \mu_0 H_0 |e| / m = \text{radian gyrofrequency}$$

$$\omega_L = (\mu_0 H_0 e / m) \cos \theta \text{ longitudinal-component radian gyrofrequency}$$

$$\omega_T = (\mu_0 H_0 e / m) \sin \theta \text{ transverse-component radian gyrofrequency}$$

$$X = \omega_N^2 / \omega^2 \text{ normalized plasma frequency squared}$$

$$Y = \omega_H / \omega \text{ normalized gyrofrequency}$$

$$Y_L = \omega_L / \omega \text{ longitudinal-component normalized gyrofrequency}$$

$$Y_T = \omega_T / \omega \text{ transverse-component normalized gyrofrequency}$$

$$Z = \nu / \omega \text{ normalized collision frequency.}$$

Other symbols used in this report follow:

$$\Delta = \text{take-off angle}$$

$$\gamma = \text{magnetic azimuth}$$

$$h' = \text{virtual height}$$

$$D = \text{great-circle distance}$$

$$P_n = \text{noise power}$$

$$k = 1.38 \times 10^{-23} \text{ joule/degree Kelvin} = \text{Boltzmann's constant}$$

$$T_{eq} = \text{equivalent noise temperature}$$

$$B_n = \text{equivalent noise bandwidth.}$$

APPENDIX B

EXAMPLE CALCULATION

The charts presented in this report should be more meaningful when illustrated with an example. To check a given path, frequency, date, and local time to ascertain whether the QT approximation holds, complete the following steps:

- (1) List path endpoints and geographic coordinates, e.g., Bangkok ($13^{\circ}44'N$, $100^{\circ}30'E$) and Ayutthaya ($14^{\circ}20'N$, $100^{\circ}35'E$).
- (2) Calculate azimuth and great-circle distance. The azimuth and great-circle distance can be calculated by the following formulas or measured from a map: Let A and B be two points on the earth's surface whose coordinates are known, with A closer to the equator. Let L_A be the latitude of A, L_B the latitude of B, and C the difference in longitude between A and B. Let ϕ and ζ be the angles at A and B of the great circle passing through the two points, and let η be the distance between A and B. We desire to calculate ϕ , ζ , and η (actually, for our example, only ϕ and ζ are required because the transmitter is assumed to be located at A):

$$\tan \frac{\zeta - \phi}{2} = \cot \frac{C}{2} \frac{\sin \frac{L_B - L_A}{2}}{\cos \frac{L_B + L_A}{2}}$$

$$\tan \frac{\zeta + \phi}{2} = \cot \frac{C}{2} \frac{\cos \frac{L_B - L_A}{2}}{\sin \frac{L_B + L_A}{2}}$$

These equations are solved for ϕ and ζ by simultaneous solution of the equations for $\frac{\zeta - \phi}{2}$ and $\frac{\zeta + \phi}{2}$:

$$\frac{\zeta + \phi}{2} + \frac{\zeta - \phi}{2} = \zeta \quad ; \quad \frac{\zeta + \phi}{2} - \frac{\zeta - \phi}{2} = \phi \cong 7^\circ 22'$$

$$\tan \frac{\eta}{2} = \tan \frac{L_B - L_A}{2} \frac{\sin \frac{\zeta + \phi}{2}}{\sin \frac{\zeta - \phi}{2}}$$

$$\eta \cong 37'$$

η in degrees is converted to kilometers by multiplying by 111.195. This gives 68.5 km.

Note: North latitudes are taken to be positive and south latitudes negative.

- (3) Convert to magnetic azimuth by using declination (approximately zero in Thailand). This is done by adding or subtracting the magnetic declination, which can be obtained from maps.⁴⁴
- (4) Read dip angle for region of entry into ionosphere from map (Fig. 7) or other source.⁴⁴ $\epsilon \approx 10^\circ$ for the Bangkok-Ayutthaya path.
- (5) Estimate or calculate the virtual height of reflection for the time of day and frequency of interest. (Note: This is most easily done when one has a vertical-incidence ionogram and a Newbern Smith slider--then one can get the takeoff angle rather exactly. Alternatively, one might estimate h' for E, F_1 , or F_2 layers).
- (6) Calculate the take-off angle, Δ , for a specified frequency, given the virtual height and great-circle

distance, by using the formula $\Delta = \arctan \frac{2h'}{D}$. Alternatively, one can use Helliwell's skywave transmission chart.⁶⁵

- (7) Given the azimuth, dip angle, and take-off angle, calculate Θ at entry into the ionosphere. (The angle the wave normal makes with the static magnetic field is very nearly the angle the ray direction makes with the static magnetic field in the HF approximation, $Z \ll 1$.) Figure 8 can be used to get the directions for which $\Theta = 90^\circ$. The difference between the dip angle for which $\Theta = 90^\circ$ and the dip angle for the case of interest gives the angle by which Θ differs from 90° . Table B-I gives the output of such calculations for the Bangkok-Ayutthaya path. Notice that h' changes with local time for a given frequency. This implies that, especially for the higher frequencies, the QT approximation may only hold for part of the day for a given path.
- (8) Given Θ and f , check Fig. 9 to see whether the QT approximation holds; if it fails, estimate by how much. The QT clearly holds for $h' = 180$ km through 350 km (approximately 20:00 through 04:00 hours local time) for 1.7 Mc during sunspot minimum assuming flat earth, ionosphere, no ionospheric tilts, and no anomalous reflections (E_s). The QT approximation is only appropriate at 12 Mc for a ± 25 -km range of h' around 200 km. Other cases can be checked as required using the techniques illustrated in this Appendix. It should be kept in mind that such calculations are only as good as one's knowledge of the earth's magnetic field and that alignment becomes more critical for the higher frequencies in the HF band.

Table B-I

APPROXIMATE θ vs. h' FOR BANGKOK-AYUTTHAYA PATH

h' (km)	β (degrees)	θ (degrees)
100	71.2	81.2
175	78.9	88.9
200	80.3	89.7
225	81.4	88.6
250	82.2	87.8
300	83.5	86.5
350	84.4	85.6

For this path, which is nearly south-north,

$$\Delta \cong \arctan \frac{h' \text{ (km)}}{34.25}$$

$$\theta \cong \Delta + \epsilon = \Delta + 10^\circ \quad .$$

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