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Range and Azimuth Determination of VLF Energy

CHARLES A. MARSH

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ELECTRONIC DEFENSE LABORATORIES

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RANGE AND AZIMUTH DETERMINATION OF VLF ENERGY

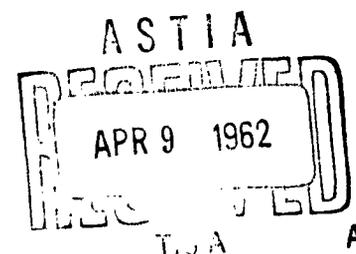
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SYLVANIA ELECTRIC PRODUCTS INC.



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RANGE AND AZIMUTH DETERMINATION OF VLF ENERGY

Charles A. Marsh

1. ABSTRACT.

A general theory to explain the propagation characteristics of very low frequency (VLF) waves which travel between the earth and the ionosphere is presented. From this theory, two methods for range determination are suggested by analyzing the received energy spectrum. The magnitude and the cause of the errors which can be expected in both range and azimuth measurements are predicted.

2. INTRODUCTION.

Determination of range and azimuth of unknown bursts of VLF energy has been solved to some extent by using radio direction-finders. A large number of stations for this purpose are now in operation. A basic disadvantage of radio direction-finding is the necessity of multiple fixes. Generally, the stations of a radio direction-finding network are spaced several hundred miles apart. There is, therefore, the problem of correlating the data arriving simultaneously at different stations.

The purpose of this paper is to report work on the determination of range as well as of azimuth of unknown bursts of VLF energy as they are received at a single station. The general approach is to study the individual waveshape characteristics of the VLF bursts.

Wait^{1, 2, 5, 6} has presented a theory which describes the characteristics of VLF propagation in the ionosphere. Using this theory and a study reported by Pierce and Crombie^{7, 8}, Wait was able to predict the diurnal height variations of the ionosphere. In the study made by Pierce and Crombie, the distance to the source of the VLF energy was accurately known. We propose, on the other hand, that Wait's theory can be used to determine the range of an unknown burst of VLF energy if we assume that the height of the ionosphere is known.

2. -- Continued.

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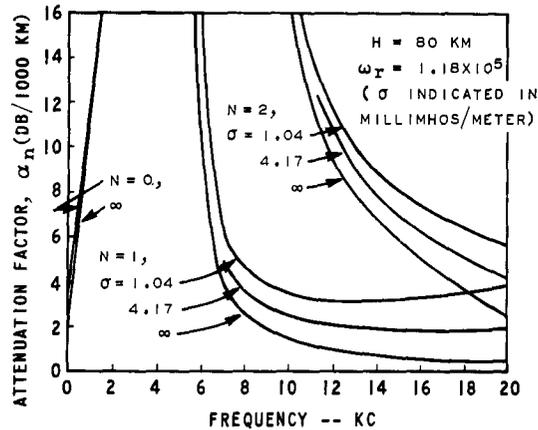
- (a) A general theory which reviews the waveguide mode theory for VLF energy is presented. Equations for group velocity and phase velocity are given.
- (b) Two methods for determining the range of VLF energy are discussed. The source and magnitude of the errors for these methods are predicted.
- (c) A study of the errors in determining the azimuth of thunderstorms is reviewed. This work is based on a study by Horner^{14, 15, 16} of the United Kingdom Direction-Finding Network.
- (d) An experimental atmospheric receiver is described. Measurements were made in the laboratory to study the waveshapes of atmospherics as an application of the VLF range-determination theory.
- (e) The paper is summarized and conclusions are made.

3. GENERAL THEORY.3.1 Waveguide Mode Theory.

At VLF the earth and the ionosphere can be considered as a waveguide with sharply bounded walls. It has been shown by Wait¹ that such a model satisfactorily explains most of the observed data in the VLF range. Wait presented a theoretical analysis^{1, 2} showing the characteristics of VLF propagation using waveguide modes. Some of the results indicated by this theory are presented in Figure 1, where

- h = separation in km between the ionosphere reflection layer and ground,
- σ = conductivity of ground in millimhos per meter,
- α_n = attenuation factor in db per 1000 km,
- n = waveguide mode index, and
- $\omega_r = \frac{(\text{plasma frequency})^2}{\text{collisional frequency}}$

3.1 -- Continued.



THE ATTENUATION FACTOR AS A FUNCTION OF FREQUENCY FOR $H = 80$ KM AND $\omega_T = 1.18 \times 10^5$ AND VARIOUS VALUES OF GROUND CONDUCTIVITY WHICH ARE INDICATED ON THE CURVES IN MILLIMHOS/METER. J. R. WAIT

Figure 1

Results of Theoretical Analysis of Waveguide Mode Theory

Between 2 and 6 kc there is a pronounced absorption of VLF energy. For frequencies from 6 to approximately 16 kc, it appears that the mode labeled $n = 1$ is dominant and that attenuation at these frequencies is relatively small. For example, at 10 kc the attenuation factor is less than 2 db per 1000 km for infinite values of ground conductivity, the conductivity of sea water being effectively infinite. A typical value of land conductivity is 2 millimhos per meter; thus, at 10 kc the attenuation over land is twice as great as the attenuation over sea water. At frequencies higher than 16 kc, the higher waveguide modes become increasingly important. For extremely low frequencies (frequencies below 1 kc) propagation by mode $n = 0$ is dominant.

The curves in Figure 1 are representative of a large number of possibilities. The height, h , is known to vary considerably throughout the day, typically being 70 km during the daytime and 90 km at night. Experimental measurements³ indicate that ω_T is approximately 2×10^5 during the day and about 10^6 at night.

The pronounced absorption band centered at 4 kc is of special interest. This behavior is in accord with experimental observations of lightning strokes as recorded by Chapman and Mathews.⁴ One would expect that detection of VLF energy in this band at large ranges would be quite difficult.

3.2 Group Velocity and Phase Velocity.

Employing the theoretical model, a sharply bounded and isotropic ionosphere which is taken to be concentric to the surface of earth, and assuming that the source of the electric field is equivalent to a vertical (radially oriented) electric dipole, the group velocity for a mode of order, n , can be calculated⁵ by the equation

$$V_g \cong C \left(1 - \frac{(n - 1/2)^2 \lambda^2}{4h^2} \right)^{1/2} \left(1 - \frac{h}{2a} \right), \quad (1)$$

where

C = velocity of light in free space,
 h = height of the ionospheric reflecting layer,
 a = radius of the earth (6367 km), and
 λ = wavelength.

For frequencies in the range 6 to 16 kc, and for distances greater than 3000 km, the attenuation of the higher modes is such that only the mode corresponding to $n = 1$ need be considered.^{5,6} Letting $n = 1$, we find from equation (1) that

$$\begin{aligned} V_g &\cong C \left(1 - \frac{\lambda^2}{16 h^2} \right)^{1/2} \left(1 - \frac{h}{2a} \right) \\ &\cong C \left(1 - \frac{h}{2a} - \frac{\lambda^2}{32 h^2} + \frac{\lambda^2}{64 ha} + \text{smaller order terms} \right). \end{aligned} \quad (2)$$

Equation (2) shows that the group velocity is a function of both the ionosphere's height and frequency. At higher frequencies, V_g approaches $\left(1 - \frac{h}{2a} \right) C$; and as frequency decreases, the group velocity decreases.

The phase velocity for a mode of order, n , is given by equation (3)

$$V_p \cong C \left(1 - \frac{(n - 1/2)^2 \lambda^2}{4 h^2} \right)^{-1/2} \left(1 - \frac{h}{2a} \right). \quad (3)$$

3.2 -- Continued.

Assuming that $n = 1$, equation (3) becomes

$$V_p \approx C \left(1 - \frac{\lambda^2}{16 h^2} \right)^{-1/2} \left(1 - \frac{h}{2a} \right)$$

$$\approx C \left(1 - \frac{h}{2a} + \frac{\lambda^2}{32 h^2} + \text{small order terms} \right). \quad (4)$$

At higher frequencies, V_p also approaches $(1 - \frac{h}{2a}) C$; but as frequency decreases, the phase velocity becomes greater.

4. RANGE DETERMINATION.

4.1 Frequency Analysis Method.

Assuming distances which are 3000 km or greater, the group velocity of a VLF signal (in the range 6 to 16 kc) can be calculated by equation (2). If we assume that an unknown burst of VLF energy consists of many frequencies, then at a given receiver location the highest frequency component will be received first and the lowest frequency component will be received last. That is, the distance to the origin of the signal can be calculated by using equation (2) to obtain group velocity, by measuring the time difference in arrival between any two given frequency components of the unknown burst of energy. The time difference in arrival between two frequency components is

$$\Delta t = \frac{d}{V_{g2}} - \frac{d}{V_{g1}}, \quad (5)$$

where

Δt = difference of arrival time of two frequency components of the signal,

d = distance to the origin of the signal,

V_{g1} = group velocity of first frequency component,

and V_{g2} = group velocity of second frequency component.

4.1 -- Continued.

Since group velocity is a function of h , the accuracy of such a system depends upon a constant knowledge of the height of the ionospheric reflecting layer. Let us assume that at a given receiver location the time difference in arrival is measured between the 15-kc component and the 6-kc component of an unknown burst of VLF energy. If an average value of $h = 80$ is used in equation (2) without correcting for the time of day of a specific measurement then one could expect maximum range errors of approximately ± 25 per cent due to the uncertainty of the correct value of h . To reduce this error, one would need either to measure the value of h hour by hour along the propagation path, or assume a better approximation for h than the constant value $h = 80$ km.

The diurnal variation of the time of arrival of a 16-kc signal has been studied by Pierce⁷ and Brombie.⁸ In these investigations the relative phase of the carrier signal from radio station GBR in Rugby, England, was investigated at Cambridge, Massachusetts, and at Wellington, New Zealand. Records were made showing the diurnal variation of the time of arrival of the carrier frequency. Figure 2 shows the basic results of the measurements made at Cambridge and represents a mean curve derived from several day measurements. The depth

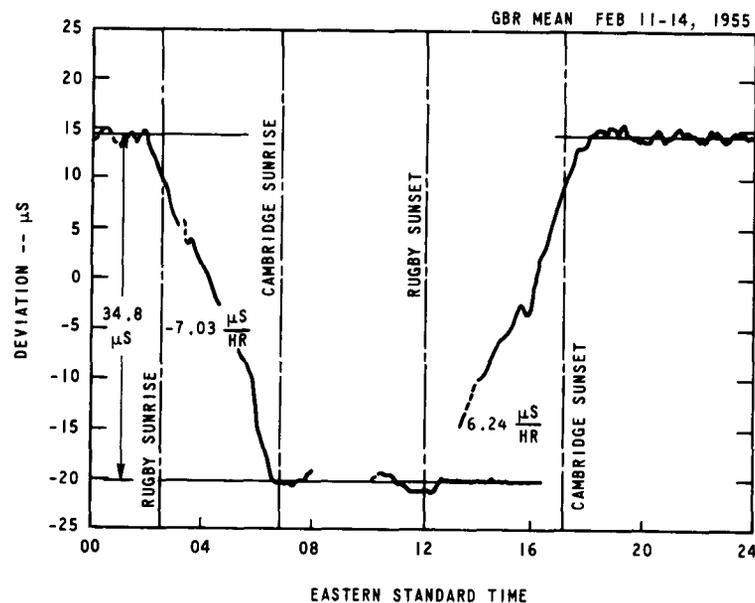


Figure 2

Diurnal Variation of the Time of Arrival
of the Signal from Station GBR, Rugby, England

4.1 -- Continued.

of this curve was found to be surprisingly constant throughout the year, being about 34 ± 1 microseconds.

It was noted that, for any particular day, the time of arrival would seldom stray more than ± 5 microseconds from the mean curve. With the use of such diurnal variation charts to correct for variations of the ionospheric height, the range determination error would be improved to approximately ± 5 per cent using 15-kc and 6-kc signals. It is to be noted that the transmission path for these tests was over sea water. It is expected that variations in the arrival time of a given signal for transmission paths over land would be comparatively greater.

4.2 Multireflection Method.

At distances less than 3000 km it is possible to determine range by studying the multiple reflections from the ionosphere. Referring to Figure 3, assume that a primary pulse of VLF energy is emitted at point A. Due to the mechanism of successive reflections between the ground and the ionospheric layer, energy will arrive at point B in a

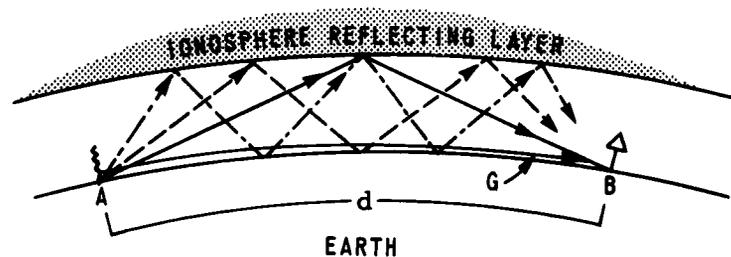


Figure 3
Multiple Reflections from the Ionosphere

4.2 -- Continued.

series of waves. The first wave to arrive at point B is the ground wave which travels directly from point A to point B. The next wave to arrive is reflected once from the ionosphere.

The third wave is reflected twice from the ionosphere and so forth. By measuring the time interval between the successive reflections from the ionosphere, the distance, d , between the source and the receiver can be calculated. The mechanics of multiple reflections between the ground and the ionosphere are given by equations (6) and (7).⁹

$$d = C t_g \quad (6)$$

$$C t_n = \left[d^2 \left(1 + \frac{h}{R} \right) + 4 n^2 h^2 \right]^{1/2}, \quad (7)$$

where

- t_g = time interval between the emission of the primary pulse by the discharge and the arrival at the receiver of the ground wave,
- t_n = time interval between the emission of the primary pulse and the arrival at the receiver of the wave that has undergone n reflections at the ionosphere,
- n = number of reflections at the ionosphere,
- d = great circle distance on the earth between the source and the receiver.

Tables of values which show related values of time delay between multiple reflections, distance, and height of the ionosphere are also presented by Wait.¹⁰

To evaluate d , a reference peak is selected on the waveform and the time interval between this peak and the same peak on succeeding waveforms is measured. If the peaks are sharply defined, the intervals between successive reflections can be measured with an accuracy of about ± 3 microseconds.⁹ If the peaks are broad, the accuracy of the measurement will probably degrade toward ± 10 microseconds. As in the case of the frequency analysis method, accuracy of range determination also depends upon a knowledge of the height of the ionosphere. If one assumes a constant value of $h = 80$ km, then maximum errors of at least ± 100 per cent can be expected without further corrections

4.2 -- Continued.

for h. Referring to equation (4) and taking differentials, it is seen that

$$\frac{\Delta V_p}{c} \approx \left(-\frac{1}{2a} - \frac{\lambda^2}{16h^3} \right) \Delta h, \quad (8)$$

where ΔV_p is a change in phase velocity resulting from a change of height Δh . The left side of equation (8) can be approximated by the ratio $\Delta T/t$, where ΔT is the corresponding change in phase (measured in seconds) and $t = \frac{d}{c}$. From the phase measurements made by Pierce⁷ the uncertainty of ΔT was found to be ± 5 microseconds over a distance of 5200 km. Substituting these values into equation (8), and assuming a frequency of 10 kc and $h = 80$ km, then the uncertainty of height, Δh , (that is, day-to-day variations from a mean curve after correction) is found to be about 1.5 km. Assuming that several reflections with sharp peaks are received and that the uncertainty of the ionospheric height is less than 1.5 km, then errors in range determination can probably be held within ± 10 per cent.

5. AZIMUTH DETERMINATION.

5.1 United Kingdom Network.

During the past twenty-five years, twin-channel cathode-ray direction-finders have been used to locate thunderstorms and have been a great aid in weather forecasting.^{11, 12, 13} The basic circuitry has not changed greatly, but continued efforts have been made to improve the equipment and the accuracy of azimuth determination. An extensive investigation of the accuracy of the United Kingdom Direction-finding Network has been made by Horner.^{14, 15, 16} The basic conclusion from this study is that if the direction-finding equipment is located on a level site and is free from obstructions, then polarization errors are likely to be the major source of error. The probable error in locating a storm center at a distance of 1000 km is about 20 km on a summer day, 50 km on a winter day, and 100 km on a winter night. A study of the errors in azimuth determination of thunderstorms by the United Kingdom Network provides a convenient background for the prediction of errors in azimuth determination for VLF energy in general.

5.2 Source of Errors.

Estimation of errors in determining the origin of lightning flashes is quite difficult because the actual location of the initial burst of energy is seldom known. Also, there are few commercial transmitters operating at these frequencies (about 10 kc) and construction of test transmitters for calibration purposes would be a difficult task. The magnitude of the errors given by Horner is deduced from measurements from visual observations made by two or more direction-finders and from observations made on fixed transmitter stations.

Errors due to instrumentation are not a major factor. It is estimated that if the loop antennas and the amplifiers are carefully aligned, then the standard deviation of error due to instrumentation is less than 1 degree.¹⁴ With well-defined traces, the standard deviation of the observer error is about 1/2 degree.

The results of site-error investigations strongly indicate that irregularities in terrain can be a major source of error. As waves travel over a sloping ground the apparent direction of arrival tends to be deflected away from the direction of the steepest slope. For example, consider the ground to slope from north to south. Waves coming from a southeast direction appear to arrive from a ESE direction. Since the errors are several degrees, it is unlikely they are caused by a change in the direction of the travel of the waves. Horner suggests that it is probable that these errors are caused by a changing polarization of the waves.

The influences of surrounding hills have a noticeable effect on the accuracy of direction-finding. The apparent direction of the arrival of a signal is deflected towards the top of the hill. For example, a wave arriving from a direction about 40 degrees to the left of a hill-top may appear to arrive from a direction that is less than 40 degrees. It was found that such errors are as great as 6 degrees. It is suggested that this type of error can also be associated with changes in polarization introduced by the presence of the hills. In choosing a site, direction-finding equipment should be located on ground which is level for about a quarter of a mile, and there should be no well-defined hills subtending a vertical angle greater than 2 degrees at the direction-finder.¹⁴

It was found that errors as great as 30 degrees can be caused due to the influence of buried power cables. These errors may be caused by direct radiation from currents induced in the shield or armor of a

5.2 -- Continued.

cable buried in good contact with the ground.¹⁵ Such errors were present whether or not the direction-finding equipment was connected to the cable. If nonconducting pipe is used to carry the cables, error can be reduced to less than 1 degree. In cases where the power cables were buried together but were brought out of the ground several meters from the antennas, the errors were held within 1/2 degree.

Polarization errors seem to be predominant, especially at night. Polarization error is caused by the horizontal component of the wave. These errors tend to be greatest at short distances, being as great as 9 degrees from 250 to 500 km. Little information is available for long distances, but errors less than 3 degrees at distances greater than 1500 km are quite reasonable.

A source of error of a more fundamental nature is the error due to the interference between individual lightning flashes. The source of this error depends upon the amplitude and the rate of occurrence of these atmospheric. Experimental work by Horner suggests that errors less than 3 degrees are reasonable as long as the amplitude of the received atmospheric is greater than 2 millivolt per meter. For an average lightning discharge, this corresponds to distances up to about 6000 km.¹⁷ However, this type of error is random and is likely to become the limiting factor even at shorter distances (2000 km and greater).

The accuracy of the United Kingdom direction-finders is comparable to the system used in the United States. Direction-finders used at the National Bureau of Standards at Boulder, Colorado, measure the direction of the ground wave at distances less than 1000 km. Their accuracy is approximately 2 degrees due to scaling error and site error.

6. EXPERIMENTAL MEASUREMENTS.6.1 Atmospheric Receiver.

It has been shown that errors of range determination caused by the natural variations of the atmospheric conditions can be predicted and, therefore, reduced to a small per cent. For this study it was assumed that the initial frequency spectrum of the VLF energy was known. For

6.1 -- Continued.

the purposes of this paper, frequency spectrum is defined as the relationship between frequency and time at the source of the energy. Usually the exact initial frequency spectrum is not known on a pulse-to-pulse basis, but a "standard spectrum" can be assumed. A standard spectrum represents the average spectrum, or the best approximation of the initial frequency spectrum that can be made. It is necessary to know the maximum deviations between the standard spectrum and the individual initial frequency spectrums in order to determine the magnitude of the errors introduced. The degree of such errors depends upon the cause or source of the VLF energy. The energy spectrum of man-made radiation, such as radiation from electronic equipment could be very consistent, depending upon the electronic equipment. Radiation from natural sources, for example lightning, would probably vary considerably on a pulse-to-pulse basis. For range determination to be practical, using the frequency analysis method, it is necessary to determine the magnitude of the errors introduced by assuming a standard spectrum. An atmospheric receiver has been designed and constructed in the Laboratories for the purpose of studying the frequency spectrum of atmospheric. Figure 4 is a block diagram of the atmospheric receiver.

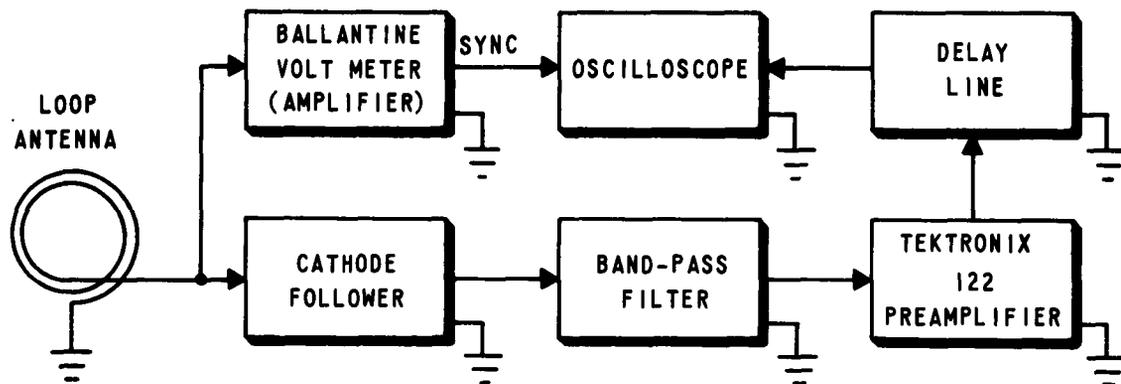


Figure 4

Block Diagram of Atmospheric Receiver

6.1 -- Continued.

The antenna is a circular loop, approximately 67 inches in diameter and wound with 100 turns of No. 17 copper wire. It is tuned to 10 kc and shunted with 1000 ohms to broaden the pass band. The output of the antenna is fed to a cathode follower which provides a low impedance source for a band-pass filter. The 3-db pass band of the filter is approximately 1.5 to 18.5 kc. The main purpose of the filter is to eliminate the radiation of 60 cycles and the harmonics of 60 cycles from nearby power lines and to filter out the higher frequencies of nearby VLF communication transmitters. The strongest interfering signal is 18 kc from NPG in San Francisco. Since this is in the pass band of interest, it was eliminated by turning the antenna to null out this interference. The amplifier is a Tektronix Type 122 Preamplifier. The 3-db pass band of the preamplifier is 1 to 40,000 cps and the voltage gain is 1000.

The properties of this amplifier which were considered most important were frequency response, harmonic distortion, intermodulation distortion, and dynamic range. The amplifier is battery-powered making it portable. Because of the magnitude of the electric field radiated from lightning flashes, sensitivity was not a consideration for this receiver. For this reason, a matching transformer was not needed to match the antenna to the preamplifier. The output of the amplifier is connected through a 150-microsecond delay line to the vertical deflection plates of an oscilloscope. An additional output is taken from the antenna and amplified by a Ballantine Voltmeter Model 314, then applied to the external sync of the oscilloscope. The trigger level of the scope can be adjusted so that only signals of the desired amplitude will be observed. The purpose of the delay line is to delay the atmospheric so that the leading edge can be observed on the oscilloscope.

6.2 Atmosphericics.

It is known that the type of atmospheric waveform can be classified somewhat as to the geographical location of the source.^{9, 18} To determine the range of an atmospheric using the frequency analysis method, one must assume an initial frequency spectrum of the atmospheric; that is, a relationship between frequency and time. If the method is to be useful, the frequency spectrum of individual lightning flashes for a given area must be consistent. Ia. L. Al'Pert^{19, 20} observes that great numbers of atmosphericics possess sufficiently

6.2 -- Continued.

universal properties so that a standard atmospheric can be assumed. It is further observed by Ia. L. Al'Pert that, for the most part, there is good agreement between the experimental data obtained and the theoretical synthesis of atmospherics.

Photographs of atmospherics were taken in the laboratory to study their frequency spectra.

Figure 5 shows photographs of three atmospherics received with the atmospheric receiver. To take these photographs, the camera shutter was opened during a time when no signal was present. After a signal appeared on the oscilloscope, the camera shutter was closed. Sometimes several signals would be photographed before the shutter closed, as seen in Figure 5 (B and C). The band-pass of the receiver filters out the highest frequency components of the atmospherics. Figure 5A is a typical example of the atmospherics which were received. The wave reveals that the high frequency components of the wave are received first and the lower frequency components are received last. This is in agreement with equation (2). It is interesting to note that of the three atmospherics shown in Figure 5C, two are almost identical

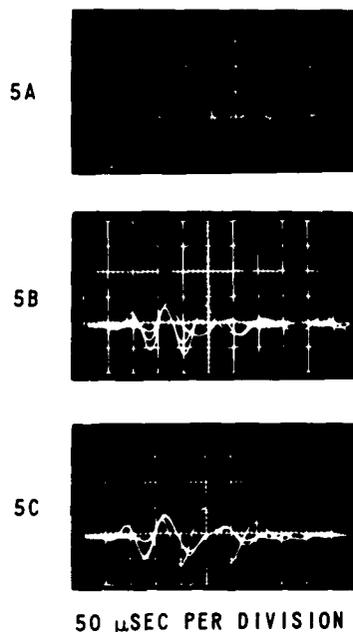
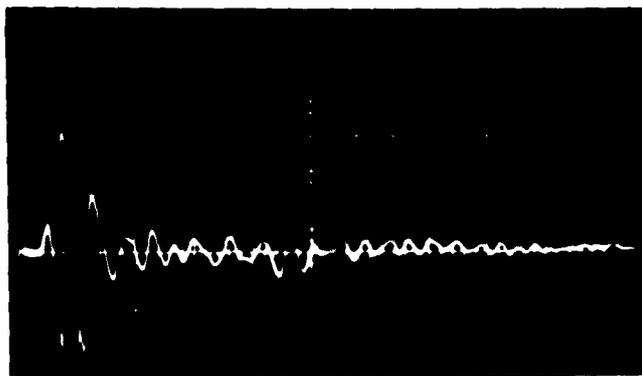


Figure 5
Atmospheric Waveforms

6.2 -- Continued.

in every detail. If it could be assumed that both atmospherics originated from the same geographic area, then it would seem that a standard atmospheric could be assumed that would give consistent measurements.

Range determination by the frequency analysis method cannot be studied for waveforms of the type shown by Figure 5A, because the geographic origin of such signals are not known. It is necessary to know the geographic origin in order to study the initial frequency spectrum of the atmospheric. Figure 6 represents the waveform of an atmospheric where multiple reflections are obtained. Using the multiple reflection method (equations 6 and 7) and assuming a value for h , a first order approximation of range can be determined. Eight photographs of atmospheric waveforms which showed multiple reflections were carefully examined. These were selected from the same storm center, which originated at about 500-km distance. A first-order approximation between waveforms can be made by comparing time relationships between the peaks of the waveforms and the zero crossings. From the eight waveforms, a standard atmospheric was assumed and measurements were made to compare the ground wave of each atmospheric to the standard.



200 μ SEC PER DIVISION

Figure 6

Atmospheric Waveform Showing Multiple Reflections

6.2 -- Continued.

The standard atmospheric approximates the average of the eight atmospherics. For a first approximation it can be assumed that the ground wave of each pulse train approximates the initial frequency spectrum of the atmospheric. The standard atmospheric is shown by Figure 7. It shows the relationship of frequency and time for the initial atmospheric frequency spectrum for frequencies between 15 and 9 kc.

Also shown by Figure 7 is a first order approximation of the initial frequency spectrum of one individual atmospheric received. It is noted that the variation between this atmospheric and the standard atmospheric is considerable. Such variations between individual lightning flashes is the same order of magnitude as that indicated by equation (5) for propagation distances of several thousand kilometers. Therefore, due to the variations between individual atmospherics, errors of at least 5000 km are predicted for range determination of lightning flashes using the frequency analysis method.

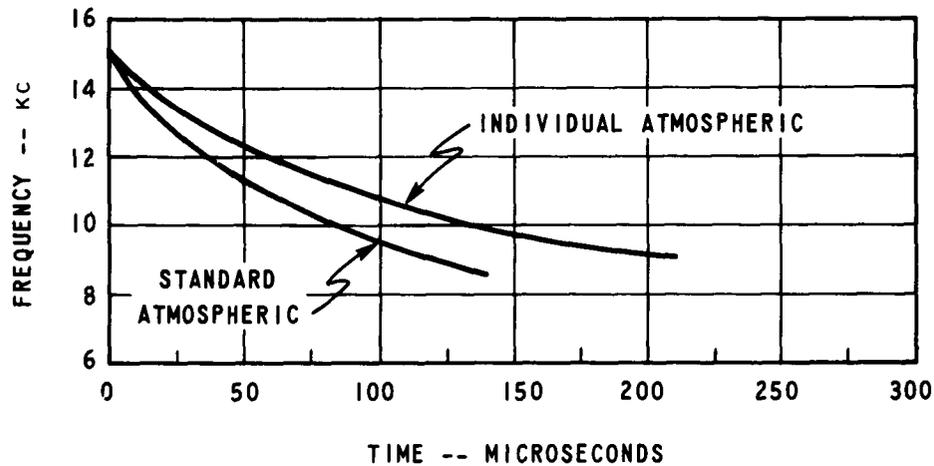


Figure 7

Comparison of Individual Atmospheric to the "Standard" Atmospheric

7. SUMMARY AND CONCLUSIONS.

The limitations of range and azimuth determination of VLF energy are largely due to natural variations of atmospheric conditions. The magnitude of these variations is extensive. However, a more careful study shows that these variations often are cyclic and can be predicted. This is true for errors which are caused by variations in the height of the ionosphere reflecting layer. The study by Pierce and Crombie on intercontinental VLF radio transmissions indicates that the diurnal variations of the ionosphere are surprisingly constant throughout the year and can be predicted on a long-term basis. Therefore, it is probable that errors in determining the range of VLF energy can be reduced by using charts to predict the ionospheric height on an hourly basis.

The range accuracy of the frequency analysis method depends upon the knowledge of the initial frequency spectrum of the VLF energy. The waveshapes of eight atmospheric were studied to determine their initial frequency spectrum. Since multiple reflections could be distinguished for each atmospheric, the range to the energy source (or storm center) could be estimated. For the eight waveshapes studied it was assumed that the ground wave, or the first wave to reach the receiver, approximated the initial frequency spectrum of that atmospheric. It was found that on a flash-to-flash basis, the initial frequency spectrum between different lightning flashes varied considerably. Using the frequency analysis method, errors in range determination of at least 5000 km are predicted. It is noteworthy that these calculations are based on the extreme deviations of the individual frequency spectrums. It may be possible that a large enough number of atmospheric possess sufficiently universal properties to provide useful range data. That is, the study of a large group of atmospheric could be made to determine the general storm centers. This is verified to a degree by Ia. L. Al'Pert and Borodina who observed that atmospheric possess sufficient universal properties so that statistical processing of large numbers permits sufficient accuracy to study certain characteristics of the ionosphere.

Most of the assumptions made in this paper are based on the results of experimental measurements. However, propagation data are not available for the complete VLF range of frequency. For this reason, the extrapolation of the existing data to the unexplored areas of VLF propagation may induce further error.

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<p>AD Electronic Defense Labs., Mountain View, Calif. RANGE AND AZIMUTH DETERMINATION OF VLF ENERGY - Charles A. Marsh. Technical Memorandum EDL-M364, 12 February 1962. (Contract DA 36-039 SC-87475) UNCLASSIFIED Report.</p> <p>A general theory to explain the propagation characteristics of very low frequency (VLF) waves which travel between the earth and the ionosphere is presented. From this theory, two methods for range determination are suggested by analyzing the received energy spectrum. The magnitude and the cause of the errors which can be expected in both range and azimuth measurements are predicted.</p>	<p>AD Electronic Defense Labs., Mountain View, Calif. RANGE AND AZIMUTH DETERMINATION OF VLF ENERGY - Charles A. Marsh. Technical Memorandum EDL-M364, 12 February 1962. (Contract DA 36-039 SC-87475) UNCLASSIFIED Report.</p> <p>A general theory to explain the propagation characteristics of very low frequency (VLF) waves which travel between the earth and the ionosphere is presented. From this theory, two methods for range determination are suggested by analyzing the received energy spectrum. The magnitude and the cause of the errors which can be expected in both range and azimuth measurements are predicted.</p>	<p>UNCLASSIFIED</p> <ol style="list-style-type: none"> 1. Propagation 2. Very-low-frequency 3. Wave 4. Range 5. Azimuth <p>I. Charles A. Marsh II. Contract DA 36-039 SC-87475 8. 6/2. 7</p>	<p>UNCLASSIFIED</p> <ol style="list-style-type: none"> 1. Propagation 2. Very-low-frequency 3. Wave 4. Range 5. Azimuth <p>I. Charles A. Marsh II. Contract DA 36-039 SC-87475 8. 6/2. 7</p>
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