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A SURVEY AND BIBLIOGRAPHY OF RECENT RESEARCH IN THE PROPAGATION OF VLF RADIO WAVES

BY

JAMES R. WAIT

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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This report has been prepared at the suggestion of Professor R.A. Helliwell, Chairman of Commission IV of URSI (International Scientific Radio Union). A paper based, in part, on the subject matter will be presented at the 13th General Assembly of URSI to be held in London, England from Aug. 28 to Sept. 15, 1960.

A SURVEY AND BIBLIOGRAPHY OF RECENT RESEARCH IN THE PROPAGATION OF VLF RADIO WAVES

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1. Introduction

Although VLF (very low frequency) radio waves were used extensively in the early part of this century, interest in the subject waned. This was in spite of the fact that VLF waves propagate to great distances with extremely small attenuation. Recently, however, with the pressing need for long range navigational systems, long distance communication, and world-wide frequency standards the desirable transmission characteristics are again being utilized. Since lightning discharges are potent generators of VLF, storm centers may be located by using DF techniques. Such systems have been in operation in the United Kingdom and elsewhere for many years. It has been found that considerable energy at extremely low frequencies (ELF) is also radiated from lightning. While frequencies in this range (below 3 kc/s) have not yet found extensive application it is believed that they have considerable potential value in storm location.

It is the purpose of this paper to present a general, but brief, survey of the field. Attention is confined primarily to terrestrial propagation, and thus solar and exospheric phenomena are generally excluded although certain germane references dealing with these subjects are given in the bibliography.

First a brief description of recent advances of ground wave propagation is given. This is followed by sections on ray and mode concepts of ionospheric propagation. The research dealing with the waveforms of atmospherics is also considered. Finally some recent applications of VLF propagation are described. While the emphasis is on the theoretical approaches used, reference to corroborating experimental work is included. It is hoped that the shortcomings in a brief article of this kind are partially compensated by the inclusion of an extensive bibliography on the subject arranged under subject classification. While attention is confined primarily to the triennium (1957-1959) a number of basic references prior to 1957 are included.†

The VLF band is here defined as the decade 3 to 30 kc/s whereas the ELF band covers the range 1.0 c/s to 3 kc/s.

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† After this survey was written, the author's attention was directed to the review paper "Low and Very Low Frequency Propagation," by H. Poeverlein in Fortschritte der Hochfrequenztechnik, 4, 47, (1959). Among the topics considered were sferics, whistlers and exospheric phenomena. Also included were discussions of the lower ionosphere and noises at extremely low frequencies.

2. Theoretical Studies

For certain applications at VLF, particularly at short ranges, it is permissible to neglect the presence of the ionosphere. In fact, at frequencies of the order of 100 kc/s the ground wave may dominate the sky wave for ranges as great as 500 km. Furthermore, with the use of pulse-type transmission, such as used in the Cytac or Loran C navigation systems, the ground wave may be distinguished from the sky wave for distances as great as 2000 km [1 - Frantz, et al, 1957].† With this motivation a number of theoretical papers on ground-wave propagation have appeared in the literature dealing specifically with:

(i) amplitude and phase vs. distance curves [1 - Johler, et al, 1956; 1 - Wait and Howe, 1956]

(ii) land-sea boundary effects [1 - Wait and Householder, 1957; 1 - Wait, 1958]

(iii) propagation of electromagnetic pulses over the surface of homogeneous and inhomogeneous ground [1 - Johler, 1957 and 1958; 1 - Johler and Walters, 1959; 1 - Levy and Keller, 1958; 1 - Wait, 1957b, 1957c, 1957d and 1957e]

The penetration of ground-wave fields into the earth or sea has also been considered in some detail [1 - Keilson and Row, 1959; and 1 - Kraichman, 1960] and the influence of earth stratification on the attenuation rate of the ground wave has been given further attention [1 - Stanley, 1960; and 3 - Wait, 1958].

Unfortunately, in cw systems and at distances as small as 100 km from the source, the sky wave may often interfere with the ground wave. Thus the total field may be considered as the resultant of a ground wave and a number of ionospherically reflected waves in the VLF band at moderate ranges (i.e., less than 1000 km or so) [4 - Johler and Walters, 1960; 4- Poeverlein, 1958a and 1958b; and

† The numeral preceding the cited authors refers to the appropriate section in the bibliography.

4 - Wait and Perry, 1957]. However, it appears to be more convenient to represent the total field as a sum of wave-guide type modes for VLF at great distances and, for ELF, at nearly all distances. In fact, for many applications only one or two modes need be retained since the higher modes are either "cut-off" or have severe attenuation. A number of papers on mode theory were presented at the VLF Symposium held in Boulder, Colo., January 1957 [6 - Budden, 1957; 10 - Liebermann, 1956b; 6-Wait, 1957c; and 9 - Wait, 1957]. In these, the ionosphere was represented by a sharply bounded and homogeneous ionized medium, and the influence of the earth's magnetic field was neglected. Also, since the frequency could be assumed to be much less than the effective collision frequency, the ionosphere was equivalent to an isotropic conductor. More recent investigations of mode theory have removed some of the earlier restrictions. For example, the influence of stratification in the D and E regions was accounted for by using layered and exponential models [6 - Shmoys, 1956; 6 - Wait, 1958b and 1960b; and 6 - Bremmer, 1959].

Alpert [6 - 1956] in the USSR has also pursued the mode theory of VLF propagation. In his work the influence of the earth's magnetic field is not considered and, in his initial formulation, the ionosphere is sharply bounded so that Fresnel-type reflection coefficients are used. He treats the effect of ionospheric stratification by using an Epstein model which is strictly valid only for horizontal polarization. By means of a semi-empirical "field-alignment" technique he uses the computed results of the reflection coefficient for horizontal polarization to evaluate effective values of the refractive index. Then, these are substituted into the appropriate (Fresnel) reflection coefficient for vertical polarization. In common with most other authors, he neglects the effect of earth curvature for purposes of computing the attenuation of the modes. Some time earlier Budden [6 - 1952] had obtained a first-order correction for earth curvature by using an earth-flattening type of approximation, and more recently Wait [6 - 1958a] had used a similar modification in some published curves of VLF transmission loss. From this work it appears that earth curvature has a negligible effect on the modes for frequencies less than about 10 kc/s, but for frequencies of the order of 20 kc/s the inclusion of curvature increases the attenuation by about a factor of two.

Actually, for frequencies at the upper end of the VLF band (i.e., 15 to 30 kc/s), it is necessary to abandon first-order curvature corrections and to introduce higher-order approximations for the spherical-wave functions which occur in the rigorous formulation. This aspect of the problem is discussed at length in a recent paper which includes an extensive discussion of related theoretical work [6 - Wait, 1960a].

The influence of the earth's magnetic field on the attenuation and phase of the modes is a difficult subject. However, if expressions for the plane-wave reflection coefficients for an anisotropic ionosphere can be derived, it is not too difficult to extend these to the computation of the modes [6 - Budden, 1952 and 6 - Wait 1960a]. Thus the results of Bremmer [6 - 1949], Yabroff [4 - 1957], and others [4 - Johler and Walters, 1960 and 4 -Wait and Perry, 1957] may be adapted for mode propagation between the curved earth and a doubly refracting ionosphere [6 - Wait, 1960a]. Using such an approach Crombie [6 - 1960] has adapted the result for plane-wave reflection with a transverse magnetic field to cover the case of mode propagation around the magnetic equator. This example, although based on a flat-earth model, clearly demonstrates non-reciprocity in VLF propagation. More recently Wait and Spies [6 - 1960] have considered mode propagation for a curved earth and a magnetic field of arbitrary dip angle. These latter results agree quite well with the recent experimental data of Taylor [9 - 1960] which also show that attenuation for west-to-east propagation is less than for east-to-west propagation.

While the mode theory would seem to be particularly appropriate at ELF, certain assumptions which are usually made become questionable. These longer wavelengths penetrate farther into the ionosphere so that the sharply bounded model must be modified [4 - Poeverlein, 1958b and 6 - Bremmer, 1959]. Another approach is to postulate an effective increase in the ionospheric height as the frequency decreases [6 - Pierce, 1960]. Even more important at ELF is the fact that distance from source to observer is usually comparable with the wavelength. Thus the numerical treatment of the mode series has been considered by Wait [6 - 1960c] for unrestricted distances, and in the same paper the relation of the shape of the ELF waveforms to the orientation of the lightning stroke is analyzed.

Again using the concept of modes, the propagation of both VLF and ELF pulses has also received considerable attention [10 - Liebermann, 1956b; 6 - Wait, 1960c and 7 - Wait, 1958]. Of some importance is the manner in which the quasi-half periods of the oscillatory waveform of the pulse vary with range and time [7 - Wait, 1958 and 9 - Taylor, 1960]. At large distances from the source (i.e., greater than 3000 km) the VLF portion of the waveform is usually a damped sinusoid of half-a-dozen or more cycles. The quasi-half period of a given cycle decreases with range in a regular manner. On the other hand, for a given range, the quasi-half periods increase in length with increasing time. These consistent and predictable properties of the waveform appear to offer great promise in range determinations using only a single recording station. Furthermore, the length of the individual periods and the particular manner in which they vary with range and time yield information about the source.

3. Analyses of Experimental Data

Since the observed characteristics of VLF and ELF propagation depend on so many factors, one should be careful in placing undue emphasis on any single experiment. In particular, the validity of a particular theoretical model cannot be established on a basis of experimental data obtained in a single geographical area and for restricted intervals of time. Nevertheless, certain experiments are crucial in the sense that they confirm the concept of the model. For example, if the measured dependence of VLF field strengths on distance and frequency are in general accord with theoretical predictions, one can say that, at least for those ionospheric conditions, the model is perhaps adequate in a phenomenological sense.

A crucial test of the wave-guide mode concept of VLF propagation was provided by Heritage, Weisbrod and Bickel [11 - 1957] in a series of airborne measurements of field strengths in the Pacific Ocean. They utilized transmissions in the frequency range of 16 to 20 kc/s from the United States, Hawaii and Japan. The daytime experimental data were in good agreement with the mode theory as indicated by Wait [6 - 1957c] ; however, the nightime data were highly variable and certain non-reciprocal effects were in evidence.

Phase variations of the 16 kc/s carrier signal of station GBR in England have been measured by Pierce [12 - 1955 and 1957] in Cambridge, Mass., and by Crombie, et al.[12 - 1958] in New Zealand. The diurnal variation of the change of the phase has been interpreted by Wait [12 - 1959] in terms of mode theory in a satisfactory manner. Phase variations of GBR have also been measured by Volland [12 - 1959] in Berlin. He indicates that the daytime reflection heights are between 69 and 76 km for 16 kc/s. During a solar flare it decreases.

Many studies of VLF propagation have been made using lightning strokes as a source of energy. For example, Watt and Maxwell [13 - 1957] showed that the propagation modified the spectral content of atmospheric radio noise in a manner which again was quite compatible with mode theory. In particular, the predicted absorption band [6 - Wait,. 1957c] at frequencies around 3 kc/s was confirmed. Attenuation rates at VLF have been deduced from the spectral analyses of atmospheric waveforms observed simultaneously at widely separated stations [9 - Taylor and Lange, 1959 and 9 - Taylor, 1960] . A similar technique has been developed for deducing phase characteristics of VLF propagation in a frequency range from 1 to 30 kc/s [9 - Jean, et al. ,1960] . Recently Obayashi [12 - 1960] indicates that a solar flare shifts the peak of the spectrum of the atmospheric upwards so that the peak is at frequencies around 25 kc/s.

Experimental studies at ELF have been primarily devoted to the recording of theELF or "slow tail" portion of the atmospheric waveforms [10 - Liebermann, 1956a; 14 - Holzer, et al, 1957; and 9 - Tepley, 1959; 10 - Hepburn and Pierce, 1953; and 10 - Hepburn, 1958] . In many cases it appears that this ELF part of the waveform is a highly damped pulse with seldom more than two half cycles and with periods of the order of several milliseconds.

Apparently, Watson-Watt, et al.,[10 - 1937] were the first to make a study of the ELF portion of atmospheric waveforms. They observed that the separation between the higher frequency oscillatory head and the slow tail increased as the distance to the source became greater. A partial theoretical explanation for this effect was proposed by Hales [10 - 1948] . Using this theory, Hepburn and Pierce [10 - 1953] and Hepburn [10 - 1957] deduced effective values of the conductivity of the lower edge of the ionosphere from their own experimental results. These authors assume that the mean separation of the oscillatory head and the maximum amplitude of the slow tail was a linear function of the distance from the source. This was probably done to facilitate the interpretation in terms of the theory of Hales [10 - 1948] . It should be pointed out, however, that the group delay derived by Hales is only valid when the signal contains a narrow band of frequencies. Predictions from such a quasi-monochromatic theory have only a qualitative value if the signal contains many spectral components [7 - Wait, 1958]. This fact is probably sufficient to reconcile certain apparent discrepancies between the results of Hepburn [10 - 1957] and those of Liebermann [10 - 1956a and 1956b]. This latter author treated slow-tail propagation on the assumption that the source could be represented by an impulse. While not explicitly stated, Liebermann computed the resulting waveform for the vertical electric field component which he then compares with his observations of the horizontal electric field component. Since the ratio of the frequency spectra of these two components is proportional to the square root of frequency, some of Liebermann's deductions could be questioned. Another disturbing factor is that Liebermann's amplifier response is not at all flat. It is just possible, however, that the amplifier response characteristic could partially compensate for the antenna characteristics. Actually, full compensation would require an amplifier with an amplitude response which varied as the inverse square root of frequency. Despite these questions, it is probable that Liebermann's conclusions are generally valid. In a recent paper, Wait [10 - 1960] has shown that Hepburn's experimental data for the slow-tail separation could be interpreted in terms of a source whose duration is finite. Values of effective ionosphere conductivities for day and night deduced from this analysis were consistent with earlier results for the VLF band.

Extensive experimental studies of ELF propagation have been carried out at the Institute of Geophysics in the University of California. Certain aspects of this work have been described by Holzer and Deal [14 - 1956], Holzer [14 - 1958] and Tepley [10 - 1959]. An excellent and complete account of the analysis of slow-tail waveforms obtained by this group is included in a recent thesis of Smith [10 - 1960]. Employing waveforms records in Hawaii and Los Angeles an attempt was made to deduce attenuation rates in the frequency range from 50 - 150 c/s. Difficulty in the analysis occurred when it was indicated that the attenuation coefficient varied in a regular manner from one path to another. This geographical dependence was consistent with the hypothesis that transmission is better for propagation from south-to-north than from east-to-west. Evidence based on the observed dispersion of the ELF waveforms also supported this hypothesis. Unfortunately, as Smith points out, theories dealing with the influence of the earth's magnetic field, appear to be unable to account for the effect. In fact, Wait and Carter [6 - 1960] have shown that ELF attenuation is hardly influenced at all by a magnetic field. It should be mentioned, however, that the direction of propagation may not be the controlling factor; the same results could also be attributed to a dependence on geographical latitude. In fact, Smith suggests that if the ELF waves experience increased attenuation in the vicinity of the equator, his observations could be rather simply accounted for. For example, if the height of the ionosphere varied with the zenith angle of the sun, increased absorption would indeed be observed at equatorial latitudes in the daytime but not at night. This is just what Smith finds!

4. Recent Applications of VLF Propagation

Research in VLF propagation has been prompted by many important applications. In particular, the low attenuation and high phase stability of VLF signals make it feasible to set up a world-wide frequency standard employing only one transmitter. A careful study of this problem by Watt and colleagues [11 - Watt and Plush, 1959] indicates that a minimum radiated power of 10 to 100 kw for frequencies of 20 kc/s would be required. Minimum observation times of 15 to 30 minutes would be needed to obtain a precision of frequency of 1 part in 10^9. Another application is to long-range navigational systems such as the Radux-Omega in which the phase difference between two widely separated transmitting stations is measured. Frequencies used in this system are in the range 10 to 18 kc/s with typical phase stabilities on a path of 8000 km of 4 μ secs.

in day and 5 μ secs. at night [12 - Casselman, et al., 1959].

Within the past few years numerous reports in the press have been concerning the electromagnetic signal emitted from a nuclear detonation. This provides the basis of a method of detection. The phenomenon has been discussed at the "Conference of Experts" [15 - United Nations, 1958] held in Geneva at various intervals since the summer of 1958. Kompaneets [15 - 1958] shows that the duration of the current due to the electronic current produced is of the order of 1 or 2 μ secs. The length of the half-cycles of the electromagnetic oscillations is approximately ten times as large. On the basis of this calculation the frequency spectrum of the signal should peak around 30 kc/s.

Actually, the electromagnetic signal radiated from nuclear explosions is quite similar to that produced by lightning, thus the atmospherics act as a source of interference to this method of detection of explosions.

5. Suggestions for Further Work

While the mode theory in its present form appears to explain the gross features of VLF propagation, additional refinements are still needed. In particular, the influence of stratification in the D region requires further study. It would also be worthwhile to extend the calculations of field strength to heights extending right up to the D region. In fact, both the analysis and explicit formulas are already available. A preliminary examination would indicate that just below the D region the vertical field in the V.L.F. range should decrease rather abruptly. It would also be expected that the field strength vs. distance curves at great heights would be very different in form to those at low heights or on the ground since the higher-order modes play a more important role. It would also be of great interest to compute the field within the ionosphere corresponding to a mode in the earth-ionosphere waveguide. However, some caution should be exercised in drawing any conclusions from such an analysis since the results will be critically dependent on the nature of the profile assumed at the lower edge of the ionosphere. Nevertheless, such a study might shed some light on the difficult problem of whistler generation.

It might also be worthwhile to investigate the influence of the ionosphere on the impedance of a V.L.F. antenna. For the common ground-based monopole, it is usually assumed that the radiation resistance is the same as an antenna in the absence of an ionosphere. Preliminary calculations would indicate that the input impedance of a ground-based antenna could be dependent on ionospheric height changes such as may occur during a solar flare. In particular, it would be interesting to estimate the changes of the impedance on a missile-borne antenna as it proceeds on its journey from the ground towards the ionosphere. This might provide a theoretical basis for an experimental method to investigate the D region.

There are many investigations at ELF which should be carried out. For example, the mode theory could be generalized to include the effect of heavy ions in the D and lower E region. Since the frequencies are of the same order as the ion gyro frequencies their influence may be great. Much additional experimental data are also required in this frequency range. The relatively meagre data which are available indicate that the attenuation rate and waveform dispersion depend on the particular path. Further measurements, with an accurate technique for source location, are urgently needed to show whether the path dependence is a geomagnetic or a geographical effect.

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U.S. DEPARTMENT OF COMMERCE
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THE NATIONAL BUREAU OF STANDARDS

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Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer. Concreting Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

• Office of Basic Instrumentation. • Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Radio Warning Services. Airglow and Aurora. Radio Astronomy and Arctic Propagation.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

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