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Technical Note No. 61

Boulder Laboratories

PROCEEDINGS OF THE 1960 CONFERENCE ON THE PROPAGATION OF E. L. F. RADIO WAVES

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

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NATIONAL BUREAU OF STANDARDS

Technical Note

61

PROCEEDINGS OF THE 1960 CONFERENCE ON THE PROPAGATION OF E. L. F. RADIO WAVES

National Bureau of Standards
Boulder, Colorado
January 26, 1960

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PROCEEDINGS OF THE 1960 CONFERENCE ON THE PROPAGATION OF E. L. F. RADIO WAVES

Preface

On January 26, 1960 a one-day conference on the propagation of extremely low frequency radio waves was held. Papers based on some of these oral presentations are being published in the July and September (1960) issues of the JOURNAL OF RESEARCH of the National Bureau of Standards, Section D. (Radio Propagation). The conference was organized by the following:

A.D. Watt (Conference Chairman)
R.C. Kirby (Chief of the Radio Communication and Systems Division)
J.A. Kemper, J.F. Brockman
Mrs. Winifred M. Mau, M.C. Weeg (Local arrangements)
J.R. Wait, Mrs. Eileen Brackett (Technical program and proceedings)
Mrs. Dorothea Lisle (Stenotypist)

For sake of completeness the titles and abstracts of these papers and other relevant material are listed in this report. An edited version of the oral discussions following the papers is also presented here.

James R. Wait
National Bureau of Standards
Boulder, Colorado
June 6, 1960

Contents

I. List of Titles and Abstracts

W.L. Anderson and R.K. Moore, Frequency spectra of transient e.m. pulses in a conducting medium. (To be published in Trans. Inst. Radio Engineers, AP-8, 1960.)

Abstract: The energy density spectra of transient electromagnetic fields generated by a pulsed ideal dipole source in an infinite conducting medium have been investigated for various distances from the source. A characteristic frequency ω_c, corresponding either to the peak of the spectrum or to its half-width, is defined and shown to vary inversely as the square of distance at large distances. The behavior of ω_c with distance is a measure of the behavior of the pulse energy. Thus at large distances it appears that the attenuation factor associated with

$$\omega_c, \quad \exp\left\{-r\sqrt{\frac{\sigma\mu\omega_c}{2}}\right\},$$

is independent of r, due to the constancy of the product $r\sqrt{\omega_c}$. From this point of view, the transient fields do not decrease exponentially as r, but as inverse powers of r.

This should not be construed as meaning the transient possesses an advantage over C.W. The attenuation for monochromatic components of the pulse is the same as for continuous waves of the same frequency, and at large distances the energy put into the high frequency components is wasted.

The phenomenon is illustrated by calculations that have been carried out for the case of pulses in sea water.

M. Balser and C. A. Wagner, Measurements of the spectrum of radio noise from 50 to 100 cycles per second, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 415-418, July/August 1960.

Abstract: Experimental spectra of radio noise in the band of about 50 to 100 cycles per second have been obtained by means of digital processing. Due to the long integration times which were used, the statistical uncertainty in the estimates of power was reduced to about 3 percent (0.13 decibel). It was hoped in this way to observe maximums in the spectrum due to excitation of higher resonant modes of the earth-ionosphere cavity (for the accuracy of these data, such peaks should be observed if the Q of the cavity were 10 or greater at these frequencies). No statistically significant evidence of these cavity effects was found.

Wallace H. Campbell, Natural electromagnetic energy in frequencies below slow tail sferics band, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 409-411, July/August 1960.

Abstract: The transition of natural signals from sferics slow tails to geomagnetic micropulsations was observed between 2.0 and 0.2 cycles per second. Micropulsations with periods of 5 to 30 seconds have characteristics which closely relate to solar terrestrial disturbance phenomena. The low latitude diurnal amplitude variation has maximums at 0945 and 1000 l.m.t. Similar groups of oscillations appear in Alaska and California. Simultaneous pulsation of λ 3914 aurora and magnetic field micropulsations has been observed in Alaska.

G.D. Garland and T.F. Webster, Studies of natural electric and magnetic fields, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 405-408, July/August 1960.

Abstract: Simultaneous measurements of short-period natural electric field variations across western Canada are reported. From these it is indicated that the effect of the varying depth to the Precambrian rocks is the dominant factor. Analysis of the simultaneous magnetic and electric measurements gives a resistivity for the Precambrian basement in excess of 30×10^5 ohm meters.

R. A. Helliwell, Whistler theory of ELF propagation.

Abstract: None.

A. G. Jean and W. L. Taylor, A proposed experiment to determine ELF propagation characteristics.

Abstract: A plan for establishing an experiment at the Boulder Laboratories to study the propagation of radio waves at extremely low frequencies (ELF) is described. The technique consists of receiving the same atmospheric at two or more stations situated approximately along a great-circle which passes through the source. The attenuation suffered by the atmospheric in propagating between two stations can be calculated from the spectra of the waveforms using methods developed at the Boulder Laboratories[1]. Recently, the analytical

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[1] W.L. Taylor, L.J. Lange, Some characteristics of VLF propagation using atmospheric waveforms, Recent Advances in Atmospheric Electricity, Pergamon Press, 1958.

techniques were extended to include calculations of relative phase velocities[2].

Recently, ELF recording stations were installed at Fairbanks, Boulder and Maui. Preliminary results obtained with this network confirm the feasibility of locating lightning discharges in certain areas of the Pacific Ocean and of obtaining two station waveform observations of sufficient quality to warrant performing detailed transient analyses.

G.V. Keller and F.C. Frischknecht, Electrical resistivity studies on the Athabasca Glacier, Alberta, Canada. (To be published in JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 5, September-October 1960 issue.)

Abstract: The use of electrical methods for measuring ice thickness and properties on the Athabasca Glacier, Alberta, Canada, has been studied by the U.S. Geological Survey. Two methods for measuring resistivity were tried: one, a conventional resistivity method in which current was introduced galvanically into the glacier through electrodes, and the other an electromagnetic method in which a wire loop on the ice was used to induce current flow. Results of the galvanic measurements showed large variations in the resistivity of the ice; in a surface layer several tens of feet thick the resistivity is between 0.3 and 1.0 megohm-meters, and under this layer, the resistivity of the ice is more than 10 megohm-meters. The resistivity of the surface ice is determined by its water content rather than by molecular resonance loss. The ice had no effect on the mutual coupling measurements in the frequency range from 100 to 10,000 cycles per second. As a consequence, the electromagnetic data could be interpreted simply in terms of ice thickness and bedrock resistivity.

Ronold W.P. King and Charles W. Harrison, Jr., Half wave cylindrical antenna in a dissipative medium: current and impedance, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 365-380, July-August 1960.

Abstract: An integral equation for the distribution of current along a cylindrical antenna in a conducting dielectric is derived. It is shown that the boundary conditions for an antenna in such a medium are formally the same as for an antenna in free space.

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2 A.G. Jean, W.L. Taylor and J.R. Wait, VLF phase characteristics deduced from atmospheric waveforms, Journal of Geophysical Research, Vol. 65, No. 3, March 1960.

The equation is solved for the current I and the driving point impedance Z by means of a technique that achieves sufficiently high accuracy in the leading terms of an iteration procedure so that the higher-order terms do not need to be evaluated. Moreover, these leading terms consist only of trigonometric functions with complex coefficients. The electromagnetic field in the infinite dissipative medium may be computed easily and in closed form since the current in the antenna is expressed in such simple terms.

A numerical analysis is made to determine the properties of an antenna with an electrical length of one-half wavelength in the medium with conductivity σ and relative dielectric constant ϵ_r. Universal curves are given of $I\sqrt{\epsilon_r}$ with $\sigma/\omega\epsilon_o\epsilon_r$ as the parameter and of $Z\sqrt{\epsilon_r}$ with $\sigma/\omega\epsilon_o\epsilon_r$ as the variable in the range $0 \leqq \sigma/\omega\epsilon_o\epsilon_r \leqq 0.4$. A table of numerical values of the impedance is given for media such as an isotropic ionosphere, dry salt, dry earth, wet earth, and lake water.

R. S. Macmillan, W. V. T. Rusch, and R. M. Golden, A very-low frequency antenna for investigating the ionosphere with horizontally polarized radio waves, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 1, pp. 27-35, January-February 1960.

Abstract: The advantages of a horizontal half-wave resonant antenna for very-low frequency propagation experiments lie in its relatively simple and inexpensive construction and in its radiation pattern which is maximum in the vertical direction. The radiation fields of this type of antenna located at the surface of a condcuting earth consist of: 1, A horizontally polarized space-wave field radiated in the perpendicular bisector plane of the antenna; and 2, a vertically polarized groundwave field radiated along the axis of the antenna. This vertically polarized field is zero at right angles to the antenna. These fields have been experimentally verified.

The use of a 50-kilocycle horizontal half-wave antenna for vertical-incidence ionospheric sounding experiments is described. The radiation pattern of this antenna is well suited for ionospheric soundings since a receiver located in the groundwave null receives only the reflected skywave signal.

Ground-resistivity measurements made at a number of locations in Central and Southern California were correlated with the geology of the terrain. This correlation showed that the ground resistivity is highest (a condition necessary for optimum antenna efficiency) in areas where the underlying rock formations are relatively unfractured. The amount of annual rainfall and other climatic conditions have little or no effect on the resistivity.

Finally, a unique antenna system is presented which employs resonant loading circuits to convert a section of an existing power line into a horizontal half-wave very-low-frequency transmitting antenna.

Elwood Maple, Sub-audio frequency (1 to 50 c/s) geomagnetic fluctuations at Denver, Colorado.

Abstract: Magnetic-tape recording of three components of the geomagnetic fluctuations in the 1 to 50 c/s range was begun at five field stations under IGY Project 3.10. The present progress report is based principally on six months of data from the Denver station. At playback, the recorded waveforms are filtered, rectified, and integrated to yield values of average magnetic-field strength in six frequency bands. A single value is obtained for the first fifteen minutes of each hour for each frequency band of each component. At the middle latitude station of Denver, almost all of the fluctuations throughout the 1 to 50 c/s range are judged to be of thunderstorm origin during most of the six-month interval. The wave-guide mode propagation theory is applicable down to frequencies of about 10 c/s, the minimum attenuation being reached at about 20 c/s. Below 10 c/s, the attenuation again increases; at still lower frequencies, the induction component of the field of the lightning discharge, rather than the radiation component, becomes the controlling factor. At frequencies below about 4 c/s, there are occasionally fluctuations which appear to be geomagnetic in the sense that they are related to the K indices. During winter, fluctuation levels at these frequencies are often near or below the instrument noise level. Meteor-shower effects in this frequency range are discussed in a separate paper.

R.K. Moore, Dipole radiation in a conducting half-space. (To be published in JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation.)

Abstract: The problem of communication between a transmitting and a receiving antenna, submerged in a conducting medium of sea water is analyzed as a dipole radiating in a semi-infinite conducting half-space, separated by a plane interface from a semi-infinite dielectric half-space. The theory is discussed for electric and magnetic dipoles for both horizontal and vertical antennas.

After a discussion of electromagnetic waves in a conducting medium, the Hertzian potential is derived for both electric and magnetic dipoles. The appropriate boundary conditions at the interface are applied such that the Hertzian potentials can be reduced to the Sommerfeld case in which both the dipole and point of observation lie in the interface. By investigation of

contours for the Hertzian potential integrals, the case of the dipole in the conducting half-space can be reduced to that of the Sommerfeld case of the antenna at the interface. Finally, the Hertzian potentials are used to determine the electric and magnetic field components for the four cases of the electric and magnetic, horizontal and vertical dipoles.

This analysis shows that the main path of communication is such that the transmitted wave travels perpendicularly to the interface, attenuating rapidly and exponentially; travels as a vertically polarized wave almost unattenuated along the surface, part of which refracts back into the conducting medium; and travels perpendicularly from the surface to the receiver, again attenuating rapidly and exponentially in the conducting medium.

K.A. Norton, Possible application of the system loss concept at ELF, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 413-414, July-August 1960.

Abstract: A brief description is given of the possible application of the system loss concept at ELF. A method for allowing for the effect of external noise levels is outlined.

E.T. Pierce, Some ELF phenomena, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 383-386, July-August 1960.

Abstract: Properties of the electric and magnetic fields in natural extremely low frequency (ELF phenomena) are briefly discussed. The ELF fluctuations in the electric field are then treated from two aspects; these are the electromagnetic changes associated with atmospherics and the electrostatic variations in atmospheric electricity. A final section attempts to integrate the general subject of ELF effects of natural origin.

L. Rawls, A practical underground transmitting antenna.

Abstract: None.

Gurdip S. Saran and Gedalia Held, Field strength measurements in fresh water. (To be published in JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 5, September-October 1960 issue.)

Abstract: Experiments were performed to measure field strength at a frequency of 18.6 kc/s in fresh water of conductivity 2.66×10^{-3} mhos/meter down to depths of 1000 ft using monopole and loop antennas. The experimental results verify the theoretical values of field strength attenuation with depth for all antennas and of the ratio of vertical to horizontal field strength for the monopole antennas.

Lee R. Tepley, Slow tails from intra-cloud lightning discharges. Presented at Forty-First Annual Meeting of American Geophysical Union, Washington, D. C., April 27-30, 1960.

Abstract: It has been observed experimentally that a high percentage of slow tails (ELF sferics) are of negative polarity, whereas signals of positive polarity would be expected from most cloud-to-ground lightning discharges. It may be hypothesized that intra-cloud strokes are a prolific source of negative slow tails. An alternative hypothesis is that a polarity inversion occurs during propagation. In order to test the latter hypothesis, the polarity was measured for a large number of VLF ground-wave transients and their corresponding slow tails. It was found that the ground-wave and slow-tail polarities were almost always the same. Since there is no reason to expect a polarity reversal of the VLF ground wave, the latter hypothesis may be discarded. (However, it is still conceivable that a reversal in slow-tail polarity may occur if the wave propagates over a great distance. This possibility cannot affect the present results since the sferics considered here all originated at relatively short distances from the receiver, as is evident from the appearance of the VLF ground wave as a separate entity.) The wave form of the VLF sferic associated with the negative slow tail supplies some evidence in favor of the former hypothesis, since it is generally more ragged in appearance than the VLF wave form associated with the positive slow tail. This implies that the spectral energy maximum occurs at a relatively higher frequency as may be expected for radiation from an intra-cloud discharge. However, the difference in degree of raggedness for the two classes of VLF sferics is not great and their peak amplitudes are comparable. Hence, it appears that relatively more VLF energy is associated with intra-cloud discharges than was previously suspected to be the case. However, this last result must be considered as tentative since the peak amplitude and appearance of the waveform may lead to an incorrect estimate of both the energy distribution and the total energy in the sferic.

J.R. Wait, Mode theory and the propagation of E. L. F. radio waves, JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 4, pp. 387-404, July-August 1960.

Abstract: The mode theory of propagation of electromagnetic waves at extremely low frequencies (1.0 to 3000 c/s) is treated in this paper. Starting with the representation of the field as a sum of modes, approximate formulas are presented for the attenuation and phase constants. Certain alternate representations of the individual modes are mentioned. These are used as a basis for describing the physical behavior of the field at

large distances from the source, particularly near the antipode of the source. At the shorter distances, where the range is comparable to the wavelength, the spherical-earth mode series is best transformed to a series involving cylindrical wave functions. This latter form is used to evaluate the near field behavior of the various field components.

The effect of the earth's magnetic field is also evaluated using a quasi-longitudinal approximation. In general it is indicated that if the gyro frequency is less than the effective value of the collision frequency, the presence of the earth's magnetic field may be neglected for E.L.F. When this condition is not met the attenuation may be increased somewhat. The influence of an inhomogeneous ionosphere is also briefly considered and finally, the propagation of E.L.F. pulses are treated. It is suggested that certain observed characteristics of E.L.F. waveforms may be attributed to the inclination of the current channel in the lightning discharge.

A.D. Watt, ELF electric fields from thunderstorms. (To be published in JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 64D, No. 5, September-October 1960 issue.)

Abstract: The varying electromagnetic fields produced by thunderstorms and associated lightning discharges are examined. Calculated field variations produced by an assumed typical cloud-to-ground discharge model are found to agree well with observed fields. The magnitude of these vertical electric field changes are observed to decrease very slowly with distance from the source for values comparable to discharge channel heights. From 4 to 20 km a $1/d^3$ relation is observed, and beyond 30 km the field variations appeared to follow a $1/d$ relation.

The expected radiation field frequency spectra from 1 c/s to 100 kc/s are calculated employing models assumed to be typical of "long" and "short" discharges. The radiation spectra obtained from 1 to 100 kc/s for observed cloud-to-ground discharge field variations normalized to 1 km are seen to agree within expected limits with calculated values.

The models employed indicate that below 300 c/s "long" discharges produce much more energy than "short" discharges, and that inter- and intra-cloud discharges may produce as much energy as cloud-to-ground discharges. Anticipated variations of total vertical electric field frequency spectra as a function of distance based on the work of Wait, are shown for the frequency range from 1 c/s to 100 kc/s.

H. A. Wheeler, Useful radiation from an underground antenna. (To be published in JOURNAL OF RESEARCH of the National Bureau of Standards-D. Radio Propagation, Vol. 65D, No. 1, January-February 1961 issue.)

Abstract: An underground antenna delivers power to the surrounding conductive medium, and a fraction of the power goes out as radiation above the surface. This fraction is denoted the "radiation efficiency." It is expressed in simple terms for two types of underground antennas. The first and simplest is a vertical loop in a submerged spherical radome. The second is a submerged horizontal insulated wire with each end connected to a ground electrode. In each case, the efficiency is the product of three simple factors: the first depending on the index of refraction between air and ground; the second proportional to the size (radius of the radome or length of the wire); the third giving the attenuation with depth. An example for 1 Mc gives an efficiency of .0014 for an underground wire of specified dimensions. The radiation efficiency is applicable to sender or receiver.

II. Discussions in Morning Session

R. C. Kirby opens session with welcoming address.

E.T. Pierce speaks.

Wait (moderator) Are there any questions on the paper by Pierce?

Wait: I would like to ask one question. Have you observed non-reciprocity in E.L.F. propagation?

Pierce: No.

Wait: Any more questions? If not, we shall proceed.

Garland speaks.

Wait: Any questions?

Wheeler: I didn't get it clear about how deep you had to go before the conductivity starts to rise.

Garland: In that connection the change in conductivity suggested by Niblett was at the base of the crust which in this part of Alberta was at 40 kilometers.

Wheeler: Any idea of when it starts to increase?

Garland: Down through crust the resistivity seems to be on the order of 10^6 ohm-meters. This seems to persist about 40 kilometers and then the decrease starts.

Wheeler: You don't associate this with temperature?

Garland: Undoubtedly this has some effect.

Wheeler: Suppose it could be caused by moisture or by nature or what?

Garland: It is not clear whether the change in conductivity at the base of the crust is due to a change in composition of the rock or to other factors.

Wait: Have you tried using 3-layer correction curve rather than a 2-layer?

Garland: We didn't because of the lack of a broad enough spectrum of disturbance to get enough character in the plot of the apparent resistivity.

Wait: Are the range of the periods limited?

Garland: We think this is a limitation of the method of frequency analysis. What is really needed is a complete spectral analysis by digital recording and machine computation.

Pierce: I think you considered horizontal currents only. We know also that an air earth current flows vertically at the earth's surface.

Garland: I qualified that.

Pierce: It is a question of orders of magnitude?

Garland: The potential gradient of 100 volts per meter as measured in the atmosphere would correspond to a vertical gradient below the limit of measurement in the earth because of the ratio of conductivities.

Pierce: It would seem to be legitimate to neglect air-earth currents in fair weather by comparison with earth currents, but not necessarily correct to do so under stormy conditions. In amperes/cm^2 the vertical earth currents are of the order of 10^{-13}; fair-weather air-earth currents are 10^{-15}, increasing to 10^{-11} during storms.

Garland: In fact, we hope to set up an atmospheric gradient recorder and see if any of the pulsations are related to the horizontal currents.

Wait: We should be getting on with the next series of papers.

Campbell gives paper.

Wait: Any questions?

Tepley: There was an article in Time magazine about some measurements at frequencies comparable to those considered in your investigation. This had to do with a Signal Corps project during the Argus series. They reported a large pulsation associated with the arrival of a hydromagnetic wave and also a second and third maximum at somewhat later times. These were supposedly associated with waves moving back and forth in an ionospheric duct. I wonder if this is the same type of thing that you have indicated on your slides?

Campbell: Perhaps. It may be a related type of phenomena. On the first of August 1958, we did receive pulsations which we interpreted as due to the high altitude Johnston Island nuclear explosion. There was no indication of signals from any of the other shots.

Tepley: Referring to the Signal Corps project again. I believe that the waves were reported to travel with something like sonic velocity. Did the pulsation that you recorded appear to travel with comparable speed?

Campbell: The velocity we are thinking of is in the 10 kilometers per second range.

Wheeler: You didn't say very much about the maximum in 100 cycles. Do you have any idea as to why 100 cycles?

Campbell: The loop antenna was used up to 20 c/s. A vertical antenna was used from 3 c/s to 1,000 c/s. The maximum at 100 c/s is typical of the sferics slow tails.

Taylor speaks.

Lehan: Are there any plans to extend your frequency range below 10 cycles down?

Taylor: Presently we only plan on going down to ten cycles per second with vertical antennas. Trying to get much lower is extremely difficult with vertical antennas.

Lehan: Trying to get much lower than that you would probably want to use a horizontal antenna?

Taylor: Yes, another type, possibly a horizontal wire between ground stakes.

Lehan: You people are not planning to do this?

Taylor: No, not below 10 cycles. One comment I would like to make. I recently returned from talking with Dr. Mark Brooks at Socorro, New Mexico. He has some beautiful lightning discharge records separating individual lightning channels by moving the camera as the flash occurs. It becomes obvious upon examining these pictures that a cloud-to-ground stroke may not be a distinct discharge of only a few hundred microseconds. Sometimes a continuous glow continues in the channel for as long as a half-second and often characterized with some minor pulsations in illuminating during this period. With sufficient current flowing in a discharge channel to produce this illumination means that a very large total current was associated with this type of discharge. It may be that the longer duration discharges of this general type are more efficient sources of ELF energy than the conventional type of discharges that last for only a hundred microseconds or so.

Pierce: May I comment on that last point? I do think it is rather dangerous to consider the return stroke as the only thing in the lightning flash. It is well established that about 100 microseconds is occupied by a return stroke. Then as Bill Taylor pointed out, there normally is something like a quarter of a second of electrostatic field change occurring afterwards, so the lower down in frequency we go, the more we have to take account of the whole discharge; of the leader, of the following return stroke, and of any continuing current afterwards. Equally, I think that a cloud discharge in which we have no return stroke at all could be a very potent source of ELF of the order of cycles per second.

Tepley speaks. (No questions after his talk.)

Maple speaks. (This is based on a paper, "Audio-Frequency Fluctuations of the Earth's Magnetic Field," to be published in Journal of Geophysical Research.)

Wait: Any questions?

Goldberg: Did you see anything like you have observed in the past, such as a 7-hour precursor, in the 1 to 50 cycles per second activity?

Maple: No, I haven't yet analyzed any data on our present project from a high latitude station where I would expect to see the precursor.

Campbell: Can't you explain the sudden rise the day before an activity as being attributed to increase in E layer ionization and still be recorded as spherics?

Maple: I don't think so. The diurnal variation of the precursor signals doesn't suggest this. Also, decreasing the already low attenuation rate over only a part of the propagation path wouldn't raise the signal level by a large factor.

Campbell: Can you attribute the sudden increase in your activity the day preceding magnetic storms to an increase in E layer ionization affecting the sferics slow tails received?

Saran presents paper.

No questions.

Goldberg presents paper.

Wait: We have time for one question or so.

Tepley: You presented one slide in which the magnetic field intensity was plotted against frequency. Campbell presented a slide in which the same quantities were plotted. However, the two curves were not at all similar. Could you comment on whether or not there appears to be a discrepancy between the two curves?

Campbell: Yes. I recorded up to 20 c/s with the loop antenna and then with vertical antenna I went from 1,000 c/s down to 3 cycles per second.

III. Discussions in Afternoon Session

Moderator: A.D. Watt

M. Balser (from MIT) speaks. (No questions.)

Wait speaks.

Watt: Any short questions on the paper?

Tepley: Is there a dependency on the earth's magnetic field?

Wait: Of course, if you accept the quasi-longitudinal approximation, in the normal sense it essentially means that the propagation will be reciprocal. However, if you use this Q. L. approximation in a special way, the effective component of the gyro-frequency is slightly different for north-south and south-north propagation. For propagation from east-to-west or west-to-east, the earth's magnetic field should produce the maximum non-reciprocity, but even in this case it appears to be a very small effect. It is possible, however, that the presence of heavy ions could produce non-reciprocity at E. L. F. In fact this would be a good way to test for their significance.

Crombie: I have made a calculation, and it appears that in the ELF region no non-reciprocity as far as attenuation is concerned to first order of approximation. There is no effect whatsoever on attenuation - but a slight effect on phase velocity.

Wait: That's an interesting point since it might affect cross-over time on slow tails.

Helliwell speaks. (The paper dealt with the ELF spectrum of whistlers and related sferics).

Watt: Any questions?

Goldberg: Do you notice much difference between day and night in the lower cut-off region?

Helliwell: Yes, the day-to-night variation is quite marked and regular. The sharp cut-off is limited to nighttime. Let me qualify; I never see it over a daytime path. You may see it around sunrise or sunset by looking at a source from the night side.

Campbell: For the cases in which you observed the whistlers continuing down into the ELF range; did the accompanying sferics also continue down into the ELF range?

Helliwell: No. A plausible explanation is that the whistler path begins at the location of the originating discharge and ends at the receiver, so that waveguide cut-off effects cannot develop. The atmospheric, on the other hand, travels a considerable distance in the waveguide, and hence will be modified by transmission properties of the guide.

Anderson speaks.

Watt: Any questions?

Wait: This is based on a plane wave and an infinite homogeneous medium?

Anderson: Yes.

Wait: This is changed quite a bit in the presence of an interface?

Anderson: Yes, I am sure.

Norton speaks.

Watt: Any questions on Mr. Norton's paper?

Wheeler: In the case of the waveguide modes an interesting question comes up. Should you regard the transmitter antenna as radiating in half-space and then put the waveguide on it, or should you go right to the transmission behavior in the waveguide mode, which of course would give a different radiation resistance. Had you thought about that?

Norton: I think that you should determine the transmitting antenna radiation resistance with the receiving antenna terminals open and then separately calculate the mutual impedance which contains all of the propagation. It's as simple as that. All of the propagation is in the mutual impedance but, of course, this method of looking at the problem does not necessarily alleviate any of its inherent difficulties.

Wheeler: The self-impedance of the antenna does reflect the waveguide boundaries, so you might be interested in the rule of thumb that I have been using. If it is single-mode propagation in waveguide, which in general means only one mode excited by the antenna, then I say the radiation resistance is the resistance that it has in that mode of propagation, and that cuts out one factor. If, however, the waveguide is in a multi-mode propagation region - an example would be 15 kc - then I prefer to write the radiation resistance of the antenna in half-space and apply an ionospheric gain factor when we take the mode that is actually the prevalent mode in propagation. Both of those do work very well.

Wait: I think the simplicity of the original presentation is lost in Dr. Wheeler's modification. The mutual impedance term actually involves the complete mode series.

Wheeler: That is true if the waveguide is a lossy waveguide. When you get down to below 10,000 cycles (1) the waveguide doesn't have single mode propagation and (2) it is not a lossy waveguide so it does affect the impedance of the transmitter antenna and that's the reason for it.

Harrison speaks.

Watt: Any questions?

Lehan: Is the model antenna you are discussing actually in contact with the dissipative medium?

Harrison: It is in contact with the medium; no insulation being assumed in the theory. In practice the feed line and a portion of the antenna in the immediate vicinity of the input terminals would be insulated, I suppose.

Wait: I understand that the infinite susceptance across the drive point that results from the assumption of a delta-function generator is effectively subtracted out in the iterative scheme you are using - - but how do you take into account the shorting effect of the conducting dielectric across the slice generator?

Harrison: I would prefer not to discuss this point. Since the knife edges between the idealized halves of the antenna are separated by zero distance, and are in contact with the dissipative medium, the conductance and capacitance are infinite. But if the integral equation is solved in terms of continuous functions by the usual method of iteration, the driving point current actually obtained is essentially that maintained by the delta-function generator minus this infinite gap current. Prof. Tai Wu of Harvard[1], and more recently Prof. R. H. Duncan of New Mexico State University[2], have discussed this point at some length as

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1 Tai Wu and R.W.P. King, Driving point and input admittance of linear antennas, Jour. Appl. Phys., 30, 74 (1959).

2 R.H. Duncan and F.A. Hinchley, Cylindrical antenna theory, Jour. Res. N.B.S., 64D, Sept./Oct. 1960. (in press)

applied to antennas in free space.

Held: It appears to me that you are getting the familiar sinusoidal current distribution, yet you say that the antenna is not insulated from the medium.

Harrison: It is true that the integral equation, which is valid in a dissipative medium as well as in free space, yields sines and cosines. But when the medium is dissipative, sines and cosines of complex arguments are involved, bringing in the hyperbolic functions. In free space the sines and cosines are of real arguments.

Bearce: Have you taken into consideration the effect of a magnetic field on antennas in lossy media?

Harrison: No. We have only considered the case of an antenna immersed in an infinite homogeneous dissipative medium.

Macmillan speaks.

Watt: Any questions?

Wheeler: Do you have any idea what modes are getting through to Cambridge?

Macmillan: No, I would be interested.

Wheeler: I have a suspicion it was probably the TE_{01} mode which is one not used normally at all and which takes advantage of the oblique propagation upward which has a rather low attenuation.

Macmillan: It is very possible.

Wait: What direction was the launching plane relative to the path of Cambridge?

Macmillan: I would say that it would be 30° or so off axis.

Wait: This would give fairly efficient launching into the TM mode, although the maximum launching would be right off the end.

Helliwell: Weren't there some measurements of attenuation for the experiment?

Macmillan: No! This was done in March just when the signal is not sufficient to judge attenuation measurements. We are replacing the crystal oscillator and receiving equipment so we hope to be able to do that and operate at a higher power.

Keiser: Do you have any evidence of a second bounce transmission for this?

Macmillan: We hope to investigate this.

Keller presenting Frischknecht paper.

Watt: Any questions? I would like to make one comment, that is, it is quite nice to sit here and look at these figures, but to stop to think what went into getting them. We tried to make similar measurements and at times the weather and other conditions were quite adverse.

Moore speaks.

Watt: Any questions?

Wait: Regarding the approximation you made in the Hankel function. Did you not estimate it by the first term of its asymptotic expansion? If so, this would require that the distance is quite large compared to the wavelength.

Moore: Not quite true. ρ is the distance in (free space wavelengths)/2π. For the frequencies I considered, and the conductivity of sea water, this approximation is valid down to ρ equals 0.01. The reason is that the asymptotic series for the Hankel function is used in the integration along BL1 where the product $\psi\rho$ is always large even for fairly small ρ. The asymptotic expansion is not used close to BL2 and Pole 1. I did not present the discussion of the part of the integration near the pole and branch point number 2 here since it has been carried out by Sommerfeld and others.

Wait: I believe your result is restricted to distances which are large compared to the sum of the respective depths. However, in certain cases of practical interest the horizontal range and the depths are comparable. Furthermore, significant distances in the conductor at extremely low frequency may be of the order of the skin depth. Under these conditions your results are not applicable.

Moore: That is true for some of the cases you have discussed. On the other hand, this approximation is valid in many cases where ρ is relatively small because the algebraic factor and the Hankel function both tend to get small fairly rapidly along BL2 as we go away from the axis of reals; thus one can make this statement as long as $\sigma/\omega\epsilon$ is large so that ψ must be considered in the square root only for large values. Since ψ appears in the Hankel function multiplied by ρ the approximation is reasonable as long as the product $\psi\rho$ is of fairly large size for a value of ψ equals the $\sqrt{\sigma/\omega\epsilon}$. Of course, if ρ is <u>extremely</u> small the approximation is not valid.

Wait: I might mention at this stage that an almost exact treatment of the problem may be carried out if the horizontal range is small compared to a free space wavelength. In this case the integrals may be evaluated in closed form (see for example, J.R. Wait, Jour. Geophys., Res. 58, pp. 21-28 and pp. 167-168, 1953).

Wheeler and Rawls talk.

Watt: Any questions on both papers?

Moore: I would like to comment on three things. First, in Mr. Rawls' paper he did not point out that there is some question about using my approximations at frequencies as high as 1 megacycle for ground conductivities as small as he quotes. I am sure, of course, that he is aware of this, and I merely point this out so that others will be cautious in using this approximation under other conditions than the ones I used it for. Under some conditions at frequencies of 1 megacycle, the conduction current in the ground may actually be smaller than the displacement current.

Another thing that might be worth mentioning is that, in the case of a high conductivity medium such as sea water, there is an effect of the high attenuation on the noise considerations. For any significant depth it is necessary that the transmitter lay down such a strong signal at the surface above the receiving submarine antenna that it will always be stronger than any noise signal, thus the effect of noise considerations in the case of antennas under the sea might be quite different than in the case of the antenna in the ground as considered by Mr. Rawls.

Wheeler: In the ground I assumed the conduction current is about five times the dielectric current.

Moore: I am sure you checked them, but I would certainly think that one would have to check the approximations quite carefully each time he used them in such a different situation. The other point I wish to discuss has to do with Dr. Wheeler's very interesting paper. The picture he drew on the blackboard is essentially that of Weyl's treatment of 1919. Unfortunately, for a conducting medium complex angles of incidence, reflection, and transmission occur which tend to confuse the issue. As a matter of fact, Mr. Williams is currently working on a physical interpretation of this very picture for the case of the complex angles of incidence that come up in resolution of the dipole source.

Wheeler: My study shows rather quickly that there isn't any additional complication if you use the receiver method of analysis.

Wait: This is quite an interesting remark that Wheeler made. By reciprocity I can see how we can get the mutual impedance in the system by using this method, but I don't see how you get the input impedance in the loop using a plane wave.

Wheeler: We do require a different method for the self impedance.

IV. List of Participants

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

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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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