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Radio-Wave Propagation in the Earth's Crust[1, 2]

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There is a reasonable basis for postulating the existence of a useful waveguide deep in the earth's crust, of the order of 2 to 20 km below the surface. Its dielectric is basement rock of very low conductivity. Its upper boundary is formed by the conductive layers near the surface. Its lower boundary is formed by a high-temperature conductive layer far below the surface, termed the "thermal ionosphere" by analogy to the well-known "radiation ionosphere" far above the surface.

The electrical conductivity of the basement rock has not been explored. An example based on reasonable estimates indicates that transmission at 1.5 kc/s might be possible for a distance of the order of 1500 km.

This waveguide is located under land and sea over the entire surface of the earth. It may be useful for radio transmission from the shore to a submarine on the floor of the ocean. The sending antenna might be a long conductor in a drill hole deep in the basement rock; the receiving antenna might be a vertical loop in the water.

In the earth's crust, there appears to be a deep waveguide that has not yet been explored. This waveguide extends under all the surface area, so it suggests the possibility of wave propagation under the ocean floor. This might enable communication from land to a submarine located on or near the ocean floor. If below a certain depth, it happens that the excess radio noise from electric storms would become weaker than thermal noise, and no other source of appreciable radio noise is recognized.

This waveguide comprises basement rock as a dielectric between upper and lower conductive boundaries. The upper boundary is formed of the well-known geological strata located between the surface and the basement rock, with conductivity provided by electrolytic solutions and semiconductive minerals. The lower boundary is provided by high-temperature conductivity in the basement rock.

In concept, the lower boundary is similar to the usual ionosphere, being formed by gradually increasing conductivity. In the usual ionosphere [Wait, 1957], caused by extraterrestrial radiation, the conductivity increases with height. In the present case, however, the conductivity increases with depth and is caused by the increasing temperature in the dielectric material. Therefore it may be designated as the "inverted ionosphere" or "thermal ionosphere."

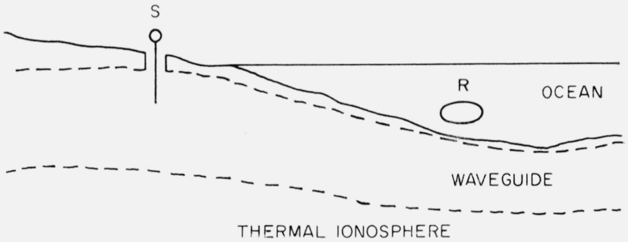

FIGURE 1. *Communication through the deep waveguide under the ocean.*

Figure 1 shows how this waveguide may be used for communication from a shore sending station (S) to an underwater receiving station (R). The latter may be a submarine on the bottom of the ocean. The sender launches a vertically polarized transverse-electro-magnetic (TEM) wave by means of a vertical wire projecting into the basement rock. The wave is propagated in the deep waveguide between the surface conductor and the thermal ionosphere. Some power from the wave leaks out of the waveguide into the ocean just above, and is sampled by an antenna at the receiver.

Figure 2 shows an arrangement for the sender antenna. It is a long conductor (pipe) sunk into a drill hole filled with oil insulation. The example shown has conducting material down to a depth of about 1 km. Through this layer of earth, there is an outer pipe which forms the outer conductor of a coaxial transmission line. This pipe is in contact with a conducting surface such as water or radial wires in the ground. Below this layer of earth, the inner conductor extends further about 2 km into the basement-rock dielectric. This extension radiates into the waveguide in the usual manner.

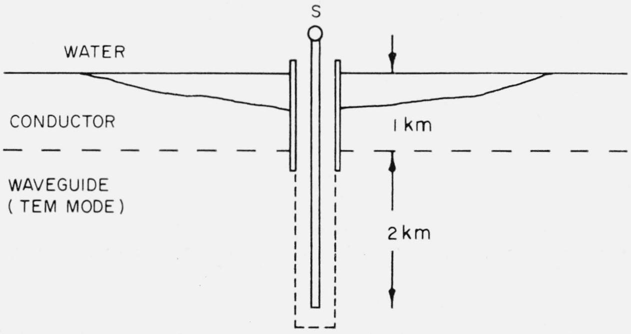

FIGURE 2. *Sender antenna in the deep waveguide.*

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[1] Contribution from Wheeler Laboratories, Great Neck, N.Y., and Developmental Engineering Corp., Leesburg, Va.

[2] Paper presented at Conference on the Propagation of ELF Radio Waves, Boulder, Colo., January 27, 1960.

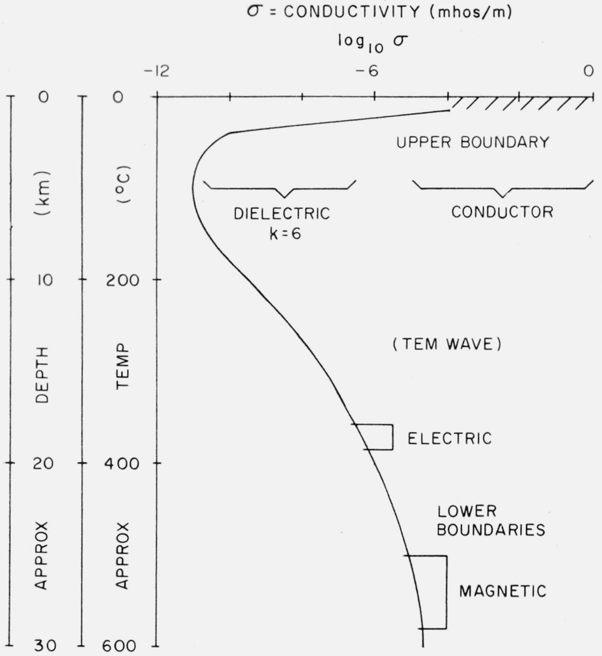

FIGURE 3. *Variation of conductivity with depth to form the deep waveguide.*

Figure 3 shows how the temperature and the resulting conductivity may vary with depth, especially in the basement rock at depths exceeding a few kilometers. This diagram will be used to explain the expected behavior of the deep waveguide. At depths of about 2 to 20 km, the basement rock is indicated to have such low conductivity that it is a dielectric suitable for wave propagation. Above and below this dielectric, the conductivity is high enough to serve the function of boundaries for the waveguide.

The upper boundary is fairly well defined, in a depth of the order of 1 km (perhaps down to several kilometers). Its conductivity, in the most common materials, ranges from a maximum of 4 mhos/m in sea water down to about 10^{-4} in rather dry nonconductive minerals.

The dielectric layer, shown between depths of about 2 and 20 km, may have very low conductivity, of the order of 10^{-6} to 10^{-11} mho/m. The lowest conductivity is observed in fused quartz, but probably is not found in nature. The present plan is useful if the conductivity is around 10^{-8} or lower. The dielectric constant is about 6.

The lower boundary has some unusual properties. (These are also characteristic of the ionosphere at frequencies below VLF.) The gradual increase of conductivity [Van Hippel, 1954] provides an effective boundary for each kind of field, that for the electric field being closer than that for the magnetic field. In each case, there is a sort of skin depth in the boundary [Wheeler, 1952]. Both of these boundaries make comparable contributions to the total dissipation factor of the waveguide, which determines the exponential attenuation rate.

The location of each boundary depends on the frequency, the conductivity, and the rate of change of conductivity with depth. In the example to be outlined, these boundaries occur at temperatures in the range of 300 to 600 °C.

As an example of the behavior that might be expected in this waveguide, the following numerical values are suggested.

Frequency	1.5 kc/s
Dielectric constant	6
Wavelength (in dielectric)	80 km
Effective boundaries of E field (depths)	1–18 km
Effective boundaries of M field (depths)	1–27 km
Skin depth for E field (lower boundary)	1.5 km
Skin depth for M field (lower boundary)	4 km
Length of radiator (in waveguide)	2 km
Reactance of radiator	1600 ohms
Effective length of radiator	1 km
Radiation resistance (in waveguide)	0.4 ohms
Other resistance	20 ohms
Radiation efficiency	0.02
Average power factor of E and M fields, about	0.1
Napier distance (for wave attenuation)	130 km
Decibel distance (for wave attenuation)	15 km
100–db distance	1500 km

If these values are to be experienced, communication ranges of the order of 1500 km will be possible under the surface of the earth.

The assumptions for this example are based on preliminary estimates of the best conditions that are at all likely to be realized. The high-temperature conductivity needed for the lower boundary is typical of quartz and other similar minerals. The extremely low conductivity at lower temperatures is unlikely, but need not be quite so low to provide a dielectric that could give the indicated performance.

As for the properties of the basement rock, it is very doubtful how low its conductivity may be. Its seismic properties are explored but not its electrical conductivity. Its principal chemical components are known, but apparently not its small content of "impurities" that may determine the conductivity. It seems that core samples have been made to only a small depth (less than 1 km) in the basement rock, presumably because there has been little prospect of valuable mineral products at a reasonable cost. It is notable that some tests show a trend toward lower conductivity (below 10^{-6}) in the transition from the surface layers into the basement rock. A continuation of this trend may enable such performance as is indicated in the example.

Returning to the waveguide properties, the TEM mode (with vertical polarization) is the one that has the greatest probability of enabling long-range communication. It is the only propagating mode at frequencies below about 2 kc/s (including the above example).

This preliminary study has indicated that the deep waveguide is probably a definite physical phenomenon. The properties of its dielectric and boundaries are not known quantitatively, so it is uncertain to what distances this waveguide may be useful for communication or related purposes. Some rather optimistic assumptions as to these properties lead one to speculate on distances of the order of 1500 km. While the deep waveguide extends under the entire surface of land and sea, it is most needed for radio transmission to a submarine on the ocean floor, because this location is shielded from the usual radio waves above the surface.

This concept occurred to the writer recently during discussions with Lester H. Carr and his associates in Developmental Engineering Corporation, notably L. E. Rawls, G. F. Leidorf, and their geological consultant, P. Parker. The opportunity of working with this group is acknowledged with appreciation.

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(Paper 65D2–119)

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Selected Abstracts

Use of the incoherent scatter technique to obtain ionospheric temperatures, T. E. VanZandt and K. L. Bowles, *J. Geophys. Research* **65,** *No. 9, 2627–2628 (Sept. 1960).*
If the ion-electron gas is in diffusive equilibrium on the topside of the F layer, then the electron density decreases exponentially with height, and its logarithmic decrement is proportional to the neutral gas temperature. From an electron density profile obtained by the scatter radar technique, it is shown that this interpretation is consistent. Moreover, the deduction of ionospheric temperatures in this way from scatter radar electron density profiles has several advantages over other methods.

Correlation of an auroral arc and a subvisible monochromatic 6300 A Arc with outer-zone radiation on November 28, 1959, B. J. O'Brien, J. A. VanAllen, F. E. Roach, and C. W. Gartlein, *J. Geophys. Research* **65,** *No. 9, 2759–2766 (Sept. 1960).*
During a severe geomagnetic storm on November 28, 1959, two Geiger tubes on satellite Explorer VII (1959 iota) found anomalies in the outer radiation zone at an altitude of about 1000 km which appear to be correlated in space and time with optical emissions from the atmosphere beneath. Very intense narrow zones of radiation were detected over a visible aurora during one pass. The radiation in three such zones was harder toward low latitudes. On three subsequent passes the radiation zone was deduced to be over a subvisible 6300 A arc, whose brightness diminished as the radiation zones became less intense. The correlation is discussed.

Seasonal variations in the twilight enhancement of [OI] 5577, L. R. Megill, P. M. Jamnick, and J. E. Cruz, *J. Atmospheric and Terrest. Phys.* **18,** *No. 4, 309–314 (Aug. 1960).*
Measurements of the twilight enhancement of [OI] 5577 were obtained during the period September 1957 to December 1958 at Rapid City, S.D. All these measurements were normalized to the intensity at sunset or sunrise at a height of 100 km. The results obtained indicate that there was a seasonal dependence of the twilight enhancement of [OI] 5577 emission. The enhancement occurred most frequently in the autumn and winter months, the maximum occurring about 1 November. The enhancement almost never occurred during the spring and summer months.

Some magnetoionic phenomena of the Arctic E-region, J. W. Wright, *J. Atmospheric and Terrest. Phys.* **18,** *No. 4, 276–289 (Aug. 1960).*
Several unusual phenomena of E-region ionogram echoes obtained at Thule, Greenland (mag. dip 85.5°) are described. They are explained as the effects of electron collisions on the propagation of radio waves at high-magnetic latitudes. The third magnetoionic component (Z-echo) is explained in this way and several of its distinguishing features are explained and illustrated. New phenomena demonstrate the existence of an E-pause (valley above $h_{\max} E$), and permit the measurement of electron densities and collision frequencies therein.

Widely separated clocks with microsecond synchronization and independent distribution systems, T. L. Davis and R. H. Doherty, *IRE Wescon Conv. Record* **4,** *pt. 5, 3–17 (1960).*
In a majority of timing applications, a problem exists in setting two or more clocks to agree with one another. Present techniques using WWV or other high frequency broadcasts allow clocks to be synchronized within one millisecond. This paper offers an improvement in synchronization of three orders of magnitude.
Microsecond synchronization is obtained by use of the Loran-C navigation system as the link between a master clock at Boulder, Colorado, and any slaved clock anywhere in the Loran-C service area.
The timing system also includes a unique method for distribution of several time code formats on a single UHF channel.

Comment on models of the ionosphere above $h_{\max} F_2$, J. W. Wright, *J. Geophys. Research* **65,** *No. 9, 2595–2596 (Sept. 1960).*
Evidence for a gradient of scale height in the F region is shown, and discussed in relation to a simple Chapman model of the F region above $h_{\max}F_2$. It is suggested that a similar model, but allowing for a scale-height gradient, may give somewhat better agreement with recent observations.

Improvements in radio propagation prediction service, W. B. Chadwick, *Elec. Eng.* **79,** *721–724 (Sept. 1960).*
Data from world-wide ionospheric and solar stations permit close observation of the changing state of the ionosphere so that the maximum usable frequency for radio communications between any two points in the world can be accurately predicted 3 months in advance.

Other NBS Publications

Journal of Research, Vol 65A, No. 1, January–February 1961. 70 cents.

- Faint lines in the arc spectrum of iron (Fe I). C. C. Kiess, V. C. Rubin, and C. E. Moore.
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- Heat of formation of *N*-dimethylaminodiborane. W. H. Johnson, I. Jaffe, and E. J. Prosen.
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- Reaction of sulfur, hydrogen sulfide, and accelerators with propylene and butadiene. F. J. Linnig, E. J. Parks, and L. A. Wall.

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- An ultra low frequency bridge for dielectric measurements. D. J. Scheiber.
- The ephi system for VLF direction-finding. G. Hefley, R. F. Linfield, and T. L. Davis.
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This course is designed to provide a discussion of the fundamentals of radio propagation, the latest advances in the state of the art, and the application of this knowledge to the design and development of communication systems. Tropospheric Propagation and Ionspheric Propagation will be considered in two separate sections which may be taken individually or in succession. Details of this course may be obtained from the Educational Director at the address given below.

The course will consider communication via the entire range of useable radio frequencies and will extend into the modes of propagation which are being explored for the future. In both sections the continuing emphasis will be on those elements of propagation which affect system design and frequency allocation.

In addition to the subject matter mentioned above the two sections will include discussion of the following:

Tropospheric Propagation (**July 31-August 4, 1961**)

The effect of atmospheric turbulence, and of both normal and unusual atmospheric stratification, upon the refraction and attenuation of radio waves . . . Climatology of the atmospheric radio refractive index and its measurement by refractometers or weather data . . . Diffraction and reflection from irregular terrain and absorption by trees and buildings . . . The phase stability of microwave signals and its effect upon systems of tracking, guidance, and geodetic measurement . . . Mechanisms of tropospheric propagation . . . Variability of transmission loss and the theoretical basis for transmission loss prediction . . . Modulation studies and techniques . . . Methods for predicting the probability of satisfactory point-to-point communication, broadcast coverage, and communication via satellites.

Ionospheric Propagation (**August 7-18, 1961**)

Theory of radio wave propagation via the ionosphere, from the very lowest frequencies to microwaves . . . The distorting effects of ionospheric irregularities and dispersion on broad-band radio signals . . . A description of the ionosphere—its spatial and temporal variations and their predictability . . . Transmission loss and its variability as a function of frequency and other system parameters . . . Special problems of earth-space communication . . . Statistical character and average power of atmospheric, cosmic, and artificial radio noise . . . Characterization of the propagation medium as a time-variant communication channel . . . Consideration of perturbations of amplitude and phase, multipath propagation, and noise as factors affecting modulation techniques, and the capacity and reliability of systems . . . Prediction of performance of ionospheric radio systems for communication, detection and positioning, navigation and timing.

Prerequisites:

A bachelor's degree in Electrical Engineering, Physics, or other suitable academic or practical experience.

Tuition:

Tropospheric Propagation—$100
Ionospheric Propagation—$200
Entire course—$300

Registrations will be limited and early application should be made to ensure consideration. Further details of the course and registration forms will be available March 1, 1961, from: Edmund H. Brown, Educational Director, Boulder Laboratories, National Bureau of Standards, Boulder, Colorado.

Editorial Notice

Conference on Transmission Problems Related to High-Frequency Direction Finding

This issue includes a group of papers presented in June 1960 at a conference sponsored by the University of California at Los Angeles in cooperation with the Office of Naval Research. The purpose of the conference was to discuss the aspects of long-range high-frequency radio propagation that affect radio location and direction finding, and the related problems of measurement and analysis.

A comprehensive bibliography of published work on direction finding and related ionospheric propagation topics for the period 1955–1959 has been prepared by the Numerical Analysis Research Staff of the University of California at Los Angeles. This bibliography will be edited by the Radio Systems Division of the NBS and published as a Technical Note of the NBS.

THOMAS N. GAUTIER, *Associate Editor*.