Radio Propagation Following World War II*

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Summary—**Since the early 1940's the development of new propagation modes has greatly increased man's ability to communicate. Some of the outstanding advances are briefly reviewed.**

Introduction

A REMARKABLE REVOLUTION has taken place since World War II in the field of radio propagation. In the early 1940's, the recognized modes of signal transmission useful for communications and broadcasting were principally 1) ground waves at MF and below, 2) ionospheric layer reflections, and 3) line of sight at VHF and above. These modes are still important, and many new developments have led to their more efficient use; however, a really surprising number of exciting new propagation modes have now arisen that enormously extend the communications capabilities that are open to us.

Orbiting Relays and Reflectors

Potentially the most significant development to radio propagation has been the growth of man's capability to launch artificial earth satellites. Using satellite relay stations, wide-band VHF and UHF communications become possible on a line-of-sight basis. The presence of signals depends only on the operation of man-made devices, and not upon ionospheric critical frequencies, or tropospheric conditions. The possible bandwidths are limited only by system sensitivity, so that such services as world-wide television are within reach.

Four principal forms of orbiting relays may be distinguished.[1] First is the active satellite repeater. This approach minimizes the power and sensitivity required by the ground transmitters and receivers and leads to the highest signal-to-noise ratios. If three such repeaters were placed in 24-hour orbits, communications would be possible between non-polar regions at all times. However, since a 24-hour orbit has an altitude of about 22,000 miles, a transmission delay of about one-half second would occur; such a delay would be objectionable for some applications. If an active satellite is placed in a lower and more easily achieved orbit, the time delay can be greatly reduced, but at the expense of reduced geographical coverage. However, a network of perhaps 100 active satellites in random polar orbits would make communication possible 99.9 per cent of the time and appears likely to be economically feasible.

A second form of satellite repeater has been achieved by orbiting a large, spherical, conducting balloon. Echo I, launched in August, 1960 by the National Aeronautics and Space Administration, was the first test of this technique. Because passive balloon reflectors of this type require high ground-system sensitivity, they lead to relatively small rates of information transmission. An alternative to the spherical balloon reflector is the use of resonant dipole elements. Several hundred million short resonant wires placed in orbit with slight differential velocities soon spread into an extended belt. The high reflectivity of the resulting belt of reflectors can be used to return signals near the resonant dipole frequency.

Although not man-made, the moon is an earth satellite which has been tested for communication purposes. Despite its great distance, its size makes usable signals possible. The moon has the merit of unique durability. However, the bandwidths are relatively limited, and reflected signals are delayed by nearly two-and-one-half seconds. When the moon is not in view, communication is impossible. Lunar reflections have been of importance principally in studies of propagation through the ionosphere, and in studies of the lunar surface.

Beyond-the-Horizon and Scatter Propagation

The applications of satellites as relays are just beginning to be felt. Tropospheric and ionospheric scatter propagation, on the other hand, have already assumed an important role in the communication scene.[2,3] Systems of meteor-burst propagation have been developed which promise certain advantages for some applications.[4]

Diffraction theory predicts that, at VHF and UHF, beyond-the-horizon signal strengths should attenuate very rapidly so that propagation over distances of several hundred miles should not be possible. During the early 1940's, as high power transmitters became available in these frequency ranges, it became apparent that beyond-the-horizon signals were well above the values predicted by diffraction. In some cases, the signals could be explained by trapping in an atmospheric duct or waveguide caused by certain meteorological conditions. However, in absence of ducting, a weak signal remained that has been attributed to scattering from ir-

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[1] J. R. Pierce, "Communication satellites," *Sci. Am.*, vol. 205, pp. 90–102; October, 1961.

[2] Scatter Propagation Issue, Proc. IRE, vol. 43; October, 1955.

[3] Joint Technical Advisory Committee, "Radio transmission by ionospheric and tropospheric scatter," Proc. IRE, vol. 48, pp. 4–44; January, 1960.

[4] Meteor-Burst Communication Papers, Proc. IRE, vol. 45, pp. 1642–1733; December, 1957.

regularities in the tropospheric dielectric constant. Tropospheric scatter communication has been found to be useful at distances up to about 600 miles, and with bandwidths of as much as several megacycles.

At distances of roughly 600 to 2300 km, VHF signals can also be scattered in useful intensities from irregularities in electron density in the lower E region. Discovery of ionospheric forward-scatter signals was a result of a conscious search for a new communications mode, and was envisioned as an extension of the theory of tropospheric scatter to ionospheric irregularities.[5] Unlike tropospheric scatter, the irregularities in refractive index causing ionospheric scatter are strongly frequency dependent, so that frequencies from 25 to 60 Mc are preferred. Bandwidths of 40 kc are quite feasible. Ionospheric scatter circuits are relatively immune to the blackout and storm effects that plague HF ionospheric circuits. High power transmitters, large antenna gains, and diversity reception are the rule.

Ionospheric scatter signals are made up in part of reflections from a continuous background of ionized meteor trails. Also present are less frequent bursts of signal strength caused by relatively large meteors. Intermittent communication has been shown to be feasible by transmitting condensed bursts of information whenever the signal level exceeds an arbitrary high threshold level. Closed-loop systems are used to determine when transmission is possible. Since signals are sent only when the path loss is low, relatively low power is needed. Because of the aspect sensitivity of meteoric echoes, the antennas are not directed along the great circle. Meteor-burst communication is useful for distances out to about 2000 km, and at frequencies up to about 200 Mc. A transmission delay of a fraction of a minute is associated with the intermittent rate of meteoric incidence.

Higher-Order Scatter Systems

Tropospheric and ionospheric scatter systems depend on a second-order effect, the fluctuations in refractive index in the troposphere or ionosphere. Recently a third-order scatter mechanism has been experimentally demonstrated in the ionosphere,[6] and calculations show that communications possibilities exist.[7] It was shown by Gordon[8] that a neutral plasma containing electrons will scatter weakly because of the randomness in the positions of the individual electrons. More careful studies have shown that the electrons follow the positive ions, and the number of positive ions within successive regions separated by a fraction of a wavelength is unequal because of their random motion. Energy is scattered in proportion to the amplitude of the component of irregularity of scale equal to the effective space wavelength.[9] These "incoherent scatter" signals are very weak, and were first detected from the F layer using 5-Mw pulses and an antenna array of 1024 dipoles. Calculation shows that, at frequencies of 100 to 1000 Mc, communication would be possible at distances of over 4000 km. Using a million-watt transmitter and 1000 m^2 antenna apertures, an average of 100 teletype channels could be supported with an error rate of 1 in 10^3. Propagation would be relatively unaffected by ionospheric blackouts.

Developments in HF Communications

Great progress has been made in use and prediction of the properties of ordinary HF ionospheric layer propagation. Of primary significance has been the gradual evolution of a world-wide ionospheric sounding network. Since the war, the Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards has made predictions of radio propagation conditions based on results from the sweep-frequency ionosondes in the system. The development of the "f chart" has greatly improved reporting of data from individual stations.[10] CRPL is now adapting the prediction process to computers, thus reducing the subjective element. Predictions are made not only of the normal propagation frequencies but also of the probable occurrence of storm conditions and fade-outs.

Progress has also been made in measurement of propagation conditions as they occur. The scatter-sounding technique is important in this regard. Pulse signals are transmitted to a distant point by way of the ionosphere. Upon striking the ground, energy is scattered back along the original path to the transmitter site. Presence of echoes at given frequency and range thus indicates the possibility of communication on a given circuit.[11]

VLF Propagation

Despite the venerable place of VLF and LF propagation in the history of radio, important developments have occurred in the field. Greater theoretical understanding has arisen because of experimental and theoretical work.[12] The mode theory of propagation between earth and ionosphere has been carefully developed and

[5] D. K. Bailey *et al.*, "A new kind of radio propagation at very high frequencies observable over long distances," *Phys. Rev.*, vol. 86, pp. 141–145; April 15, 1952.

[6] K. L. Bowles, "Observations at vertical incidence scatter from the ionosphere at 41 Mc/sec," *Phys. Rev.* (letters), vol. 1, pp. 454–455; December 15, 1958.

[7] A. M. Peterson, "Free Electron Scatter as a Communication Mode," Paper no. 31/3, presented at WESCON, San Francisco, Calif.; August 22–25, 1961.

[8] W. E. Gordon, "Incoherent scattering of radio waves by free electrons with applications to space exploration by radar," Proc. IRE, vol. 46, pp. 1824–1829; November, 1958.

[9] T. Hagfors, "Density fluctuations in a plasma in a magnetic field with application to the ionosphere," *J. Geophys. Res.*, vol. 66, pp. 1699–1712; June, 1961.

[10] W. R. Piggott and K. Rawer, "URSI Handbook of Ionogram Interpretation and Reduction," Elsevier Publishing Co., distributed by D. Van Nostrand Co., Inc., Princeton, N. J.; 1961.

[11] O. G. Villard, Jr. and A. M. Peterson, "Scatter-sounding: A technique for study of the ionosphere at a distance," IRE Trans. on Antennas and Propagation, vol. AP-3, pp. 186–201; August, 1952.

[12] K. G. Budden, "Radio Waves in the Ionosphere," Cambridge University Press, London, England; 1961.

used to explain the experimental results. Pulse soundings of the ionosphere were made at LF for the first time soon after the war,[13] and quite recently the resonant properties of the concentric earth-ionosphere cavity has been demonstrated for the low order modes.[14] It is of interest that the fundamental frequency is about 7.8 cps, and the Q is about 4.

Study of the waveform of signals from lightning discharges led to detailed analysis of "whistlers," a highly dispersed form of atmospheric with energy return spread over a second or more. These signals were shown to propagate between northern and southern hemispheres along a dispersive guided path controlled by the geomagnetic field. Thus the signals extend several earth radii into space.[15] Man-made signals have also been transmitted using this mode.

Underlying Research

Back of the salient developments in propagation discussed above has been a tremendous and growing research effort, directed in large part to the physics of the troposphere and ionosphere.[16] One might draw fleeting attention to the development of refractometer techniques of tropospheric study, the enormous amount of work devoted to study of auroral ionization and polar propagation, and the study of ionospheric storms and polor blackouts. One should not ignore the development of techniques to measure ionospheric winds using drifting meteor trails, the fading properties of radio signals, or the drift and expansion of rocket-borne chemical releases. Nuclear detonations both below and above the ionosphere, as in the ARGUS experiment, have had farreaching effects. Detailed study has been made of ionospheric layer formation, ionospheric composition, electron concentration, and the incident solar radiation. Rocket data has played a key role in the latter experiments. The list seems endless, and the literature is enormous.[17]

[13] R. A. Helliwell, "On the measurement of ionospheric virtual height at 100 kilocycles," *Phys. Rev.*, vol. 73, p. 77; January, 1948.
[14] M. Balser and C. Wagner, "Observations of earth-ionosphere cavity resonances," *Nature*, vol. 188, pp. 638–641; November 18, 1960.
[15] R. A. Helliwell and M. G. Morgan, "Atmospheric whistlers," Proc. IRE, vol. 47, pp. 200–208; February, 1959.
[16] J. A. Ratcliffe, "Physics of the Upper Atmosphere," Academic Press, New York, N. Y.; 1960.

The Future

Very few of the developments of the past fifteen years were foreseen in advance. None the less, certain trends seem likely to continue. With the use of computers, communications channels are likely to be used by adaptive systems which control type of modulation, frequency, and directivity to match the propagation conditions. Computer control will be a must in organizing the use of satellite relays. The properties of the interplanetary environment and the ionospheres of other planets will be studied, and communications techniques adapted to the scale of the solar system. Our understanding of sun-earth relationships will grow, and with it an elucidation of ionospheric storm and auroral mechanisms. Finally, we will probably not leave the atmosphere as nature made it, but will find new ways to modify its propagation properties to suit our needs; already we have seeded the ionosphere with chemicals, shocked it with bombs, heated it with radio waves, and filled it with satellites. Next? Only dreams will tell.

[17] L. A. Manning, "Bibliography of the Ionosphere—An Annotated Survey through 1960," Stanford University Press, Stanford, Calif., 1962.