Electromagnetic Waves in Stratified Media

This book [1] was written at an important point in the development of applications of electromagnetic (radio) waves to communications, navigation, and remote sensing. Such applications require accurate propagation predictions for a variety of path conditions, and this book provides the theoretical basis for such predictions. The book is based on fundamental research in electromagnetic wave propagation that James R. Wait performed in the Central Radio Propagation Laboratory (CRPL) of NBS from 1956 to 1962. The mathematical theory in the book is very general, and the "stratified media" models are applicable to the earth crust, the troposphere, and the ionosphere. The frequencies of the communication, navigation, and remote sensing applications treated in this book range all the way from extremely low frequencies (ELF) to microwaves.

The mathematical theory of electromagnetic wave propagation is based on Maxwell's equations [2], formulated by James Clerk Maxwell in the 1860s. Experimental propagation studies in free space [3] and over the earth [4] also go back over 100 years. Research in radio science, standards, and measurements began in NBS in the early 1900s, and the long history of radio in NBS has been thoroughly covered by Snyder and Bragaw [5]. CRPL was moved to Boulder in 1954, and Wait joined the organization in 1955.

The mathematics of electromagnetic wave propagation in stratified (layered) media is very complicated, and progress in propagation theory in the early 1900s was fairly slow. Wait's book [1] included the most useful theory (much of which he developed) and practical applications that were available in 1962. A hallmark

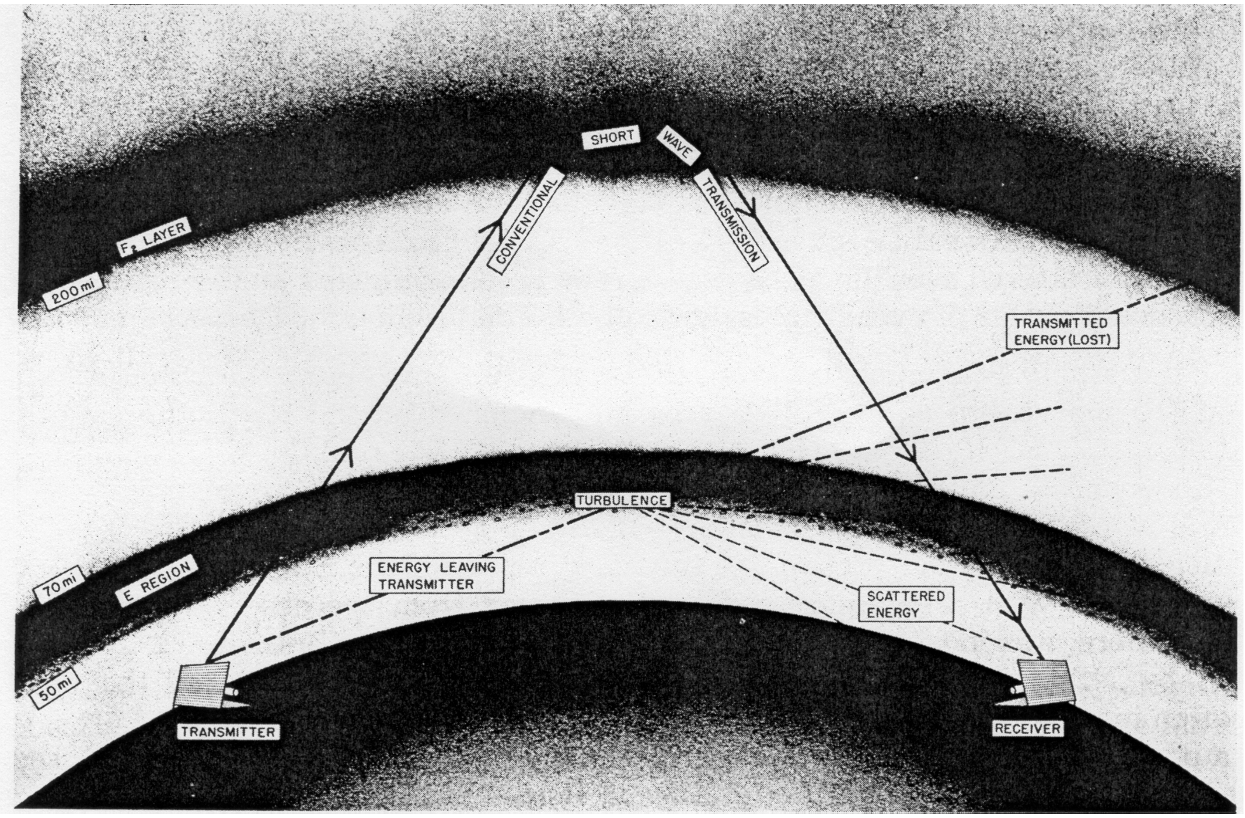

Fig. 1. What it's all about: In conventional transmission, short waves (in the range of 25 MHz to 60 MHz) are propagated beyond the visible horizon by reflection from the upper layers, or F region, of the ionosphere. In propagation by ionospheric forward scatter the energy of radio waves is scattered by small irregularities in the ionization of the lower ionosphere, i.e., the lower portion of the E layer and below this layer, providing for reception of signals much beyond the line of sight. The diagram is taken from the January 1956 issue of the NBS Technical News Bulletin.

of the book is that the theory was sufficiently general that it has served to guide further theoretical and experimental propagation research to this day. Continuing demand for the book led IEEE Press to reissue it in 1996.

Chapter I provides a general introduction to the book. Chapter II is fundamental to the entire subject because it covers reflection of electromagnetic waves from horizontally stratified media. The incident field can be either a plane wave (as from a distant source) or a spherical wave (as from a nearby antenna). The theory utilizes a novel iterative approach that matches the electric and magnetic field boundary conditions at each layer interface. Then the entire layered medium can be replaced by a single interface with an equivalent surface impedance (ratio of tangential electric and magnetic fields). This approach has been found very useful by many other researchers in simplifying the analysis of complex layered geometries [6], such as printed circuit boards.

Chapter III treats the case where the electromagnetic properties of the reflecting medium vary smoothly, rather than discontinuously as in a multi-layered medium. For some special profiles, such as linear or exponential, the solutions can be given exactly in terms of known mathematical functions. This type of treatment has been particularly useful in obtaining solutions for reflection of pulses from the ionosphere [7].

Whereas the methods in Chapters II and III are exact, approximate methods are developed in Chapter IV. These methods are less accurate, but they have the advantages of simplicity and physical interpretation. In general, these methods track the fields in a manner similar to ray tracing. The approximate methods have been found to be particularly useful for calculating reflections from complex ionospheric profiles [8].

Chapter V brings curved boundaries into the theory by treating wave propagation along a spherical surface. This theory is particularly important for analyzing ground-wave propagation along the surface of the earth [9]. The most important effect that can be predicted using this theory is the rapid attenuation of field strength beyond the shadow boundary. For example, the extent of daytime AM radio coverage can be determined if the ground properties are known. The most general theory can make use of the impedance boundary condition developed in Chapter II to predict field strength as a function of distance even when the curved earth model includes layering [10].

When the ionosphere is added to the curved earth model, mode theory is required to calculate field strength in the earth-ionosphere waveguide. Chapter VI presents a self-contained treatment of mode theory that starts with very complex mathematics and ends with fairly simple and convenient approximations. The formulations are very general, and the transmitting antennas can be electric or magnetic dipoles of arbitrary orientation. At low frequencies, the earth-ionosphere waveguide acts like a cavity that can resonate [11] and enhance the background noise (typically due to lightning).

The very low frequency (VLF) band is particularly useful for long distance communication and navigation [12] because of the low attenuation rates of the earth-ionosphere waveguide modes. Chapter VII presents VLF approximations that are particularly useful in simplifying the general mode theory of Chapter VI. Numerous attenuation and phase velocity calculations are presented for use in communication and navigation system calculations, and the effects of earth or sea water conductivity are also included. Antenna height is also shown to be important.

The ionosphere is an ionized medium, or plasma. The earth's magnetic field alters the electromagnetic properties of the ionosphere, in particular making it anisotropic. Chapter VIII covers electromagnetic propagation effects encountered in such a magneto-plasma. Again both layering and curvature are taken into account, and practical VLF propagation effects are analyzed in detail. These results have direct application to navigation systems [13].

Chapter IX contains extensive comparisons of theory and measurement at VLF. Interesting effects such as direction of propagation (important because of the earth's magnetic field) and time of day are shown by both theory and experiment [14]. The sources can be either antennas or lightning strikes, and attenuation rates of theory and experiment are generally in good agreement [15].

Chapter X continues in the spirit of Chapter IX except that it covers extremely low frequencies (ELF). Different mathematical approximations are required to fit this lower frequency range (1 Hz to 3000 Hz) even though propagation is still primarily due to a waveguide mode. At this frequency range, the fields can penetrate sea water allowing communication with submarines [16]. Good agreement between theory and experiment [17] is again obtained.

The relationship between waveguide modes and rays is clearly developed in Chapter XI. This provides very useful insight because the ionosphere "sky wave" is often interpreted as an ionospheric reflection for a particular ray path. The mathematical results are sufficiently general that they can be applied to a variety of layered media problems [18].

Chapter XII is particularly important for current applications because it covers propagation of microwaves in the troposphere. General mathematical formulations are obtained, and tropospheric ducting is covered in detail. Microwave propagation in personal communication systems [19] is one of many possible current applications of the theory.

Wait's book synthesized the results of a large number of observations and experiments, some of which had been carried out at the Bureau over the years [5]. Louis W. Austin's investigations on radio wave propagation for the Naval Wireless Telegraphic Laboratory (in close association with, and located at NBS) dated back to 1909. In a Bureau publication of 1911, Austin accounted for anomalies in his observations as being due to absorption of radio signals in the ionized layer above the Earth. In a 1913 paper he explained the increased strength of nighttime signals by reflection from an ionized layer that is less uniform during the day.

The fading of radio signals was of much concern to the Radio Laboratory at NBS and was a puzzlement to operators and scientifically minded observers from the very beginning of radio. In 1920 a cooperative program was initiated by the Radio Laboratory with the American Radio Relay League (ARRL) in a broadside approach by enlisting a large number of radio amateurs to observe fading effects. The vagaries of transmission observed by the growing multitude of listeners in the broadcast frequencies gave added incentive to study fading phenomena. The cooperative program on fading studies with the ARRL and later with several universities and radio stations continued until 1927.

The Bureau's first measurements of the height of ionosphere layers were made in February 1929 by T. R. Gilliland, using a pulse technique. Transmissions came from the Naval Research Laboratory in southeast Washington, with reception at a Kensington, Maryland, field site 5 miles north of the Bureau grounds. By 1930 an organized study of the ionosphere was underway. Thereafter came the many-faceted and extensive program of probing the secrets of the ionosphere and the vagaries of radio propagation under the able direction of John H. Dellinger, who later became Chief of the NBS Central Radio Propagation Laboratory.

James R. Wait (1924–1998) was born in Canada and received his Ph.D. from the University of Toronto in 1951. He joined the Central Radio Propagation Laboratory in Boulder in 1955 and remained in the Boulder Laboratories until 1980. He was a professor at the University of Arizona from 1980 to 1998. He published 8 books and more than 800 papers on electromagnetics in his long career. Of his many awards, he received IEEE Heinrich Hertz Medal, primarily for the research reported in this book [1].

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