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Analysis of Ionospheric Paths in Long-Range Propagation

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ABSTRACT. Based upon the author's previous work on ionospheric propagation, this paper describes new theoretical and technical methods of measuring and evaluating propagation paths over large distances. Following a detailed treatment of analysis by attenuation measurements and path diagrams, essential aspects of ionospheric path recorders are discussed with reference to modernized design and transistorization.

1. Introduction

After initial research on ionospheric wave propagation about three decades ago (Mitra 1952), the theoretical concept of long-range communication by means of a number of hops between ionosphere and earth's surface had been generally adopted as being valid. This "multihop theory" formed the basis for propagation predictions as they have now been known for about twenty years. Although some services employ slightly different systems, the consideration of two control points, one at each end of the great-circle path between transmitter and receiver (U.S. Bureau of Standards, 1948), proved to be a popular and undoubtedly simple approach. Assuming that ionospheric characteristics at these points are the more important factors, conditions at other locations along the path are supposed to have a negligible effect as far as general ionospheric predictions are concerned. With reference to the lowest-usable-high-frequency —LUHF—for communication along a certain path, this method makes use of an approximate calculation of signal strength at the receiving location, involving a simple formula for path attenuation as a function of distance, as follows—

$$\delta = \gamma \log D \qquad (1)$$

where δ = attenuation in db
γ = constant
D = distance in km

The constant γ accounts for attenuation due to ground reflections postulated by the multihop theory.

For the last two decades, predictions have yielded results sufficiently accurate for application in normal telecommunications of commercial and similar nature. Scientifically, however, the path actually taken by a ray between transmitter and receiver is definitely of such an interest that more precise investigations seemed to be justified. According to the distance involved, this type of research may utilize several methods. Whereas back-scatter systems (Eckersley 1940, Peterson 1951, Dieminger 1953, Shearman 1956) are suitable for maximum distances of the order of 10,000 km, longer paths require a different approach, namely, measurements of path attenuation on specially selected frequencies (Albrecht 1956a, 1957b). Each system shows optimum results in a certain frequency range. Considerations of practicability limit the range normally employed with back-scatter investigations to a minimum frequency of about 10 Mc/sec. As far as accuracy and reliability are concerned, both methods depend on precision and stability of the equipment utilized. With regard to operating economy, attenuation measurements have the advantage of rendering adequate results with less elaborate but equally reliable equipment.

TABLE 1

Station call-sign	WWV			JJY		WWVH		MSF	
Location	Washington			Tokio		Hawai		Rugby	
Carrier frequencies (Mc/s)	2·5	5	10	4	8	5	10	5	10
Audio frequencies(c/s)	1	440	600	1	1000	1	440	1	1000
Power of carrier (KW)	10			2		0·4		10	

2. Analysis by attenuation measurements

Path analysis by means of attenuation measurements requires the frequency to be such that interpretation and evaluation of data are as conclusive as possible (Albrecht 1956a, 1957b). Thus the frequency should be sufficiently high to be propagated by the ionosphere in a typical and representative fashion. In order to determine the maximum value allowable in each case, theoretical considerations have to decide on a frequency which is propagated by only one type of ionospheric layer with reasonably sudden commencement and end of the propagation period. For a number of years, the author has successfully used frequencies in the range between 2·5 and 7 Mc/sec.

The frequency having been selected, the signal level of a reliable communication station or, preferably, a station installed and operated for this purpose, is recorded by means of receiving equipment. Direction and distance of the transmitter are chosen in accordance with the great-circle paths to be investigated. The total path attenuation can be calculated as the first step towards path analysis, because the radiated power output of the transmitting station is known.

Much depends upon the stations selected for such recordings. Particularly suitable are time-signal stations operated by a number of services in the world. Table 1 gives relevant data of such stations, according to the latest information available to the author (Fetzer 1953). The list is limited to stations operating in the frequency range of interest for the propagation measurements mentioned. Inspecting the table it becomes obvious that, in certain parts of the world, interference from one of these stations upon the signal of another one operating on the same frequency makes serious measurements almost impossible if the equipment used is to be kept reasonably straight forward. With reference to the ionospheric path recorder to be described later in this paper, the receiving apparatus should be completely automatic in its operation and attendance of personnel should not be necessary.

For reasons just mentioned, considerable difficulties may present themselves in Europe and America when WWV, WWVH, or MSF, respectively, are recorded. According to Table 1, only JJY seems to operate on suitable frequencies, because they are different from those of other time-signal stations. Interference from communication stations in the vicinity of the operating frequency of the recorder is generally not as severe and can be overcome by an appropriately selective receiver.

The author's research work on ionospheric path attenuation over long distances yielded the important result that its value appears to be independent of ground losses and generally lower than that hitherto accepted; in other words, very similar values of attenuation are displayed by great-circle paths differing largely in their electrical ground characteristics as, for instance, the paths between Eastern Australia and Western

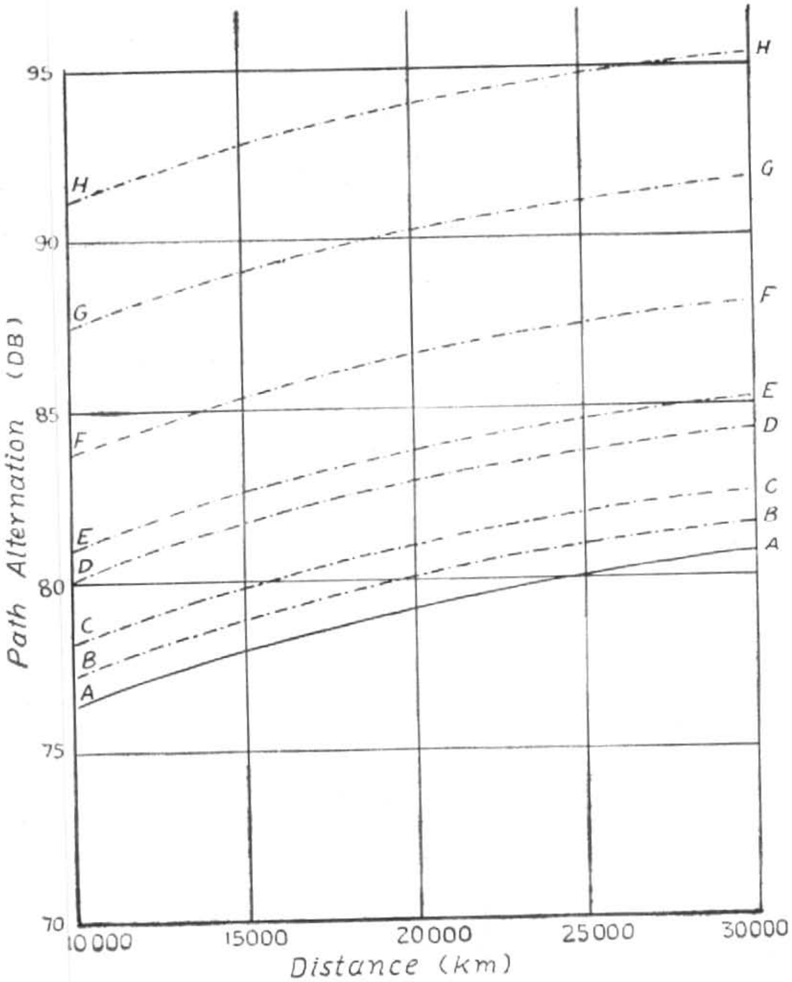

Fig. 1

Europe and, on the other hand, between Eastern Australia and North America. Thus the author found evidence for his "chordal-hop theory" of propagation (Albrecht 1956a, 1957b, 1958a, 1959). As the name implies, propagation takes place in chords along the ionospheric layer without necessarily touching the earth's surface between transmitter and receiver. Under such conditions, path attenuation can approximately be calculated by a new formula (Albrecht 1959):

$$\delta = 38 \cdot 2 \sqrt{\log D} \qquad (2)$$

where δ = attenuation in db and
D = distance in km.

This relation is the basis of an attenuation diagram, an example being depicted in Fig. 1. Curve A represents eq. (2) while other lines are approximations to attenuation values when there remains evidence for a small number of ground reflections, as follows—

Curve A chordal-hop path (eq. 2).
- B path touches sea surface once.
- C path touches sea surface twice.
- D path touches land surface once.
- E path touches sea and land surface once.
- F path touches land surface twice.
- G path touches land surface three times.
- H path touches land surface four times.

The attenuation diagram is calculated theoretically for each great-circle path, assuming that the transmission angle, or the angle of arrival, respectively, is small and does not change appreciably. This sort of diagram is primarily intended to be a useful evaluation aid for the analysis of propagation paths and represents a continuation of the way indicated in the last-mentioned publication. Approximate values of electrical ground characteristics at eventual earth-touching points may be derived from geographical characteristics. These can be subdivided into three main groups, *viz.*, land surface—wet, land surface—dry, and sea surface (Albrecht 1959). Path attenuation due to remaining earth-touching points is determined by the ground reflection coefficient in the region concerned. In other words, each measured value of path attenuation (in db) approximately corresponds to a value on one of the curves at the particular distance. In an appropriately calculated attenuation diagram the definition of the curve then indicates the type of ground responsible for additional attenuation. This assists in finding the position of the touching point along the great-circle path. In conjunction with path diagrams to be discussed now, the exact propagation path taken by a ray can be traced in the majority of cases. This method has been used by the author in confirming his previous results and in providing further evidence for the chordal-hop mode of propagation.

3. Analysis by path diagrams

Path diagrams are obtained by plotting typical characteristics of the layer responsible for propagation as a function of distance along the great-circle path (Albrecht 1957b). Especially important are critical frequency, maximum-usable-frequency—MUF—, and variations in layer height. For the purpose of path diagrams, changes in the MUF-factor may, up to a certain degree, be regarded as being reciprocally connected to height variations.

Fig. 2 depicts a path diagram for typical propagation conditions in February 1954 between Eastern Australia and Western Europe at 1900 GMT with the critical frequency as variable. A path diagram for the MUF under the same conditions is shown in Fig. 3. The reliability of information contained in a path diagram is determined by the method utilized to obtain values of the characteristics. World-wide monthly values, as *e.g.*, published by the U. S. Bureau of Standards, may suffice for many applications. However, particular attention may be required with ionospheric points situated close to one of the boundaries of the three zones "E", "I" and "W" which were introduced to eliminate longitudinal effects (Mitra 1952). If an extreme or unlikely value results, that of the neighbouring zone has to be considered for the same latitude and time. Often their mean value may prove to be more representative and thus more suitable.

The chordal-hop propagation is defined as long-range propagation along chords to the ionospheric layer. With ray theory this means that an inclination in the layer provides for the ionospheric reflection to be such that the ray does not touch ground and describes a path of geometrically inscribed hops along the layer until its return to the earth's surface is caused by another appropriate ionospheric inclination. If frequency of operation and electron density at an ionospheric point permit the ray to penetrate into the layer for an appreciable distance, the horizontal distribution of the electron density

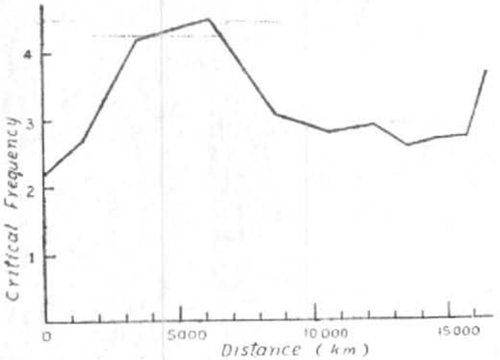

Fig. 2

in the layer can also affect the angle of return, as seen from the earth's surface.

Summarizing, the overall picture of a long-range propagation path is obtained from an accurate attenuation measurement and the attenuation diagram. These serve, in conjunction with path diagrams of as many as possible ionospheric characteristics, to determine more precisely where the ray touches the layer and, eventually, the earth's surface. With particular reference to the chordal-hop theory, the non-existence of propagation to and from ground points between transmitter and receiver may often be a helpful indication, in addition to the complete analysis described above.

4. Modern equipment for ionospheric path recorders

According to what has been said earlier in this paper, the equipment of an ionospheric path recorder, *i.e.*, a passive ionospheric station, should be economic in its operating requirements, universal in its applications, and absolutely stable as far as frequency of operation and calibration of field-strength measurements are concerned.

Although these essential conditions can be satisfied by orthodox type of equipment, complete or at least partial transistorization considerably improves permanent stability and operating economy. During the last few years, the author has evaluated and clarified design aspects for transistorized apparatus of this kind (Albrecht 1958c). Extremely critical is the question of frequency stabilization and temperature compensation. The application of the superheterodyne principle being absolutely necessary, oscillators in the receiver have to be stabilized such that fluctuations of the signal strength recorded cannot be caused by a frequency shift of oscillator circuits employed in the path recorder. Due to the nature of the investigations under discussion, recordings are taken on a number of selected fixed frequencies and thus oscillator circuits may be stabilized by quartz crystals with a nominal precision of one part in 10,000. If a larger stability is required, effects of the transistor itself may be eliminated using the author's method of frequency stabilization of transistor oscillators (Albrecht 1957c). All amplifier circuits in the receiver should be stabilized to a sufficient degree, even at the expense of a slight increase in overall consumption. In other words, the resistance stabilization described in original literature on transistor circuits (Shea 1955) is recommended with values of the stability factor chosen for each stage according to the requirements of receivers for measuring purposes (Albrecht 1957a, 1958c).

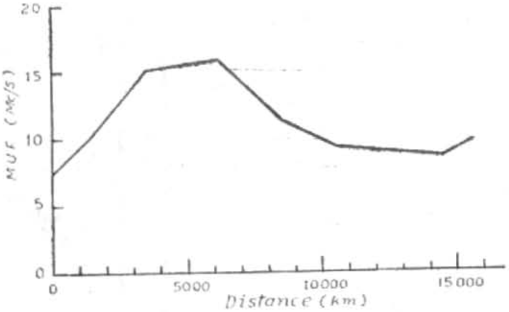

Fig. 3

As an example, Fig. 4 shows the schematic diagram of receiving equipment for recordings on two frequencies, namely, 5 and 10 Mc/sec. Commencing with a description of the antennae, it has to be pointed out that their characteristics should display no variation even under extreme changes of weather conditions; therefore they have to be erected at locations with free surroundings or, at least, under ambient conditions which are

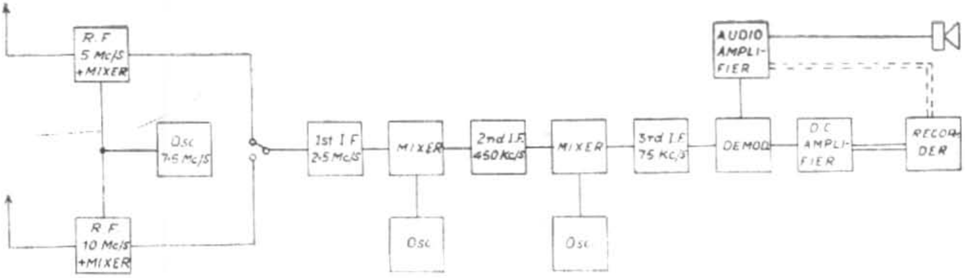

Fig. 4

not subject to weather changes. The location must also be considered for the other essential requirement of keeping the level of interfering signals at a minimum. For frequencies below about 10 Mc/sec and particularly at the lower limit of the range, approximately 2·5 Mc/sec, antennae can hardly be designed to be directional with distinct radiation patterns in the horizontal plane. Nevertheless, there may be more or less pronounced radiation lobes in the directions of interest. The effect of such lobes on the signal strength measured has to be determined and controlled at regular intervals. In order to reduce interference from local man-made noise, a shielded transmission line should be used to connect the antennae to the RF-amplifiers on 5 and 10 Mc/sec, respectively.

A detailed description of amplifier and oscillator circuits does not seem to be justified, because the design procedure is straight forward, apart from the stabilization requirements discussed earlier in this paper. However, the following general comments may prove to be useful in connection with an ionospheric path recorder of the type depicted in Fig. 4.

The receiving equipment uses the multi-conversion principle which improves the reliability of operation although additional stages have to be included with a corresponding increase in power consumption. An oscillator on 7·5 Mc/sec conveniently allows an intermediate frequency (IF) of 2·5 Mc/sec to be obtained with either of the two operating frequencies. The change-over is achieved by an automatic switch which is controlled by the colour change in the recorder. Another pair of contacts should be used to earth the input of the RF-amplifier which is not in operation. Synchronism between the automatic switch and the recorder may be transferred mechanically by a lever system or electrically, using a relay circuit. Frequencies suitable as 2nd and 3rd IF are 450 kc/sec and 75 kc/sec respectively. Appropriate mixer stages change the signal from one IF-channel to the other. Mixer oscillators are preferably stabilized by quartz crystals.

The IF-part of the receiving equipment is followed by the demodulator stage with its two output signals, one representing the signal strength and the other being an audio signal according to the tone modulation of the transmission. The d.c. signal is amplified by a direct-coupled amplifier, its gain depending upon the sensitivity of the recorder. Its stabilization has to be absolutely secure. Recommended is a superimposed bridge circuit of the type designed and employed by the author some time ago for geophysical measurements (Albrecht 1956b, 1958b). Having been amplified in an audio amplifier, the tone signal is passed to an acoustic indicator, *e.g.*, a loudspeaker. In order to investigate eventual changes in modulation percentage or frequency distortion, an appropriately treated part of this signal may be recorded, using an additional colour in the recorder.

As recorder, any apparatus of good quality is suitable. The recording should be continuous. For this reason, operating economy of the entire equipment is important. As far as the receiver is concerned, this has been achieved by complete transistorization, thus enabling it to be powered by a power supply connected to the line or, alternatively, by a battery assembly. It is obvious that these advantages should not be jeopardized by the type of recorder used.

The schematic diagram in Fig. 4 has been discussed as an example of a transistorized ionospheric recorder for path analysis in long-range propagation. Operating frequencies and amplification requirements can be changed in order to secure optimum conditions for such research work.

5. Conclusions

This paper has described a new method of determining the ray paths of short-wave signals in long-range propagation. For a number of years, attenuation measurements and path diagrams have been successfully used by the author as a way to investigate the behaviour of the ionosphere with regard to short-wave propagation up to frequencies of the order of 10 Mc/sec. Then standardization of evaluation procedure and more precise definition of path analysis have led to the present paper in which the method is for the first time, described as a general and sufficiently accurate approach to long-range propagation research.

Apart from the fact that beyond distances of the order of 10,000 km other methods often fail to yield definite results, the system dealt with in this publication requires relatively simple equipment. The necessity of modernization and permanent reliability have caused the author to present essential aspects of a completely transistorized ionospheric path recorder. Special design considerations have been discussed in detail where it was felt that the procedure differs from the normal design method. With a total power consumption of about 200 milliwatts at a low d.c. voltage (if a clockwork-driven recorder is employed) equipment of the kind described can be operated at any suitable location. Low costs of construction and operation permit the number of such path recorders to be increased in order to obtain a well-distributed network of passive ionospheric stations for still more conclusive investigations on ionospheric propagation.

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