Prediction of Long-Path Ionospheric Radio Propagation

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26 August 1992

Abstract - Prediction of ionospheric radio propagation in the 7 to 30 MHz range, over distances up to 20,000 km, can be done quite well using a constant-incident-angle hop-tracing method described by Davies and programmed by Fricker. Extending Fricker's method to include E layer refraction and reflections from the top of the E layer improves the predictions in the 1.8 to 7 MHz range, but the method still fails to predict long-path (over 20,000 km) propagation at low frequencies. A distinctly different approach is described that reduces the path into zones of homogeneous ionospheric type to determine whether propagation could occur in each zone. The zone method is quite successful in predicting propagation at times of actual observed long-path propagation on 3.8 and 7 MHz.

I. PREDICTION OF PROPAGATION BY FRICKER'S METHOD

Prediction of ionospheric propagation over short-path distances (up to 20,000 km) can be done with reasonable accuracy using the constant-incidence-angle fixed-hop-length approach described by Davies [2]. This approach assumes that propagation can be represented by a set of waveguide type modes, e.g. 2E3F (two reflections from the E layer, then 3 reflections from the F2 layer, with ground reflections in between). A computerized algorithm was devised by Fricker in his IONPRED computer program [3,4,5], to determine which of such modes is consistent with a mathematical model of the E and F2 layers. In this algorithm, rays are emitted at a specific takeoff angle and azimuthal bearing from the transmitter location and followed through the ionosphere, with reflections at the E and F2 layers and at ground modelled by the program along the path, until the receiver location is reached, or until failure of the mode occurs. This method assumes that perfect mirror image reflections occur throughout the path. Thus, a ray emitted at a particular takeoff angle would maintain a constant angle of incidence for all reflections at the E and F2 layers and the ray would finally arrive at the receiver at an arrival angle exactly equal to the original takeoff angle. Furthermore, in this method, changes in height of the F2 layer (which are actually predicted by Fricker's F2 equations [3,4]) are ignored such that hop lengths are predicted to remain constant. The assumptions of this approach clearly represent a greatly simplified model of the propagation path. In particular, the model neglects changes in incidence angle and hop lengths due to: changes in the apparent F2 height, ionospheric tilts, effects of the earth's magnetic field, and refractions instead of perfect reflections in the ionosphere.

The predictions of the author's modified version of Fricker's program, which uses the constant-angle fixed-hop-length approach, have been compared with actual propagation on amateur radio frequencies of 1.8 to 28 Mhz over the last few years. Short-path predictions generally corresponded quite well with observed propagation, both in predicted times of openings and in predicted signal strengths for frequencies above 7 MHz, for "good" days, i.e., when the magnetic field was quiet and there was low auroral zone disruption. The fact that short-path predictions with this method are as successful as they are suggests that ray deviation effects are often relatively unimportant and that the simplified model is relatively satisfactory over shorter path lengths, at least for frequencies above 7 MHz. The success of this approach results largely from the excellent mathematical model of the F2 layer developed by Fricker [3,4] which provides an algorithmic representation of empirical ionospheric data reported in the CCIR *Atlas* [1]. The microcomputer propagation prediction programs of Murray [6] and Shallon [7] both use Fricker's F2 model and adopt the simplified constant-angle fixed-hop-length assumptions.

Prediction of long-path propagation by the author's modified version of Fricker's IONPRED program, in stark contrast to the relatively good short-path predictions, was uniformly poor at all frequencies, however. For example, none of the long-path observations shown in Table 1 were predicted. (The only partial success was that an opening for observation #4 was predicted from 1230-1330, whereas the actual opening was 1330-1500.)

Insert Table 1 about here

II. EXTENSIONS TO FRICKER'S METHOD

In an effort to improve long-path prediction, Fricker's model was extended to include two additional possible ray trajectories, both of which are described by Davies [2]. The first extension was to allow reflections from the top of the E layer. Pure mirror image reflections were assumed with no loss other than the polarization coupling loss. This modification preserves all the simplifying assumptions, but incorporates the one major waveguide type mode that was not provided in Fricker's IONPRED program. The second extension was to allow non-mirror-image E layer refractions of the ray at two points in the path, i.e., at the first and last transits through the layer. Specifically, if the first and/or last transit of the E layer occurs at an angle corresponding to the critical frequency (where the ray is neither reflected at the mirror image angle nor passed through without deviation), then refraction of a higher takeoff angle into a low angle of incidence for the remainder of the path is assumed. This extended version of Fricker's algorithm followed the ray in the standard manner through E (top or bottom), F2 and ground reflections, maintaining a constant angle other than any refractions at the two ends of the path. As in Fricker's original program, constant hop lengths were assumed and success or failure of each ionospheric layer transmission/reflection was tested at each geographic location of contact with the layer. The result was that long-path predictions were somewhat improved, i.e., some observed 7 and 14 MHz long-path openings were now predicted by the program. (For example, for observation #4 in Table 1, the extended model now predicted an opening from 1300-1430, whereas the observed opening was from 1330-1500. None of the other observations were predicted.) Furthermore, short-path predictions on 1.8 MHz were much improved. In the latter case, it appears that many openings require relatively high takeoff angles to penetrate the E layer, but refraction to lower angles to allow fewer hops and lower losses. Long-path predictions, while better, were still unsatisfactory, however. A particular shortcoming was the failure to capture the effects observed under grayline conditions (i.e. when the great circle path between transmitter and receiver approximately coincides with the day/night terminator line). This failure was very apparent in the total inability of the program to predict observed long-path openings on 3.8 MHz, all of which were close to grayline.

Further development of the discrete hop tracing approach could attempt to include additional features, such as ionospheric tilt effects. However, this would be extremely difficult to model at the accuracy needed to follow ray deflections over great distances where a minor error in angle would have major consequences 20,000 km away. Furthermore, grayline conditions involve following a path where the ionosphere is for long distances in transition from dark to daylight conditions, a situation where no model could hope to depict the structure of the ionosphere in sufficient detail to predict the exact trajectory of a ray for 20,000 plus km. An alternative to the strict discrete hop-tracing approach is needed.

III. PREDICTION OF LONG-PATH PROPAGATION BY THE ZONE METHOD

A new method of predicting propagation was devised that differs in a fundamental manner from the discrete hop-tracing approach. The central characteristic of the new method is described in assumption 1 below.

1) Since prediction of the exact ray path along the rapidly changing ionosphere in the day/night terminator region appears to be unfeasible, the method will not attempt to determine whether a ray at a <u>certain</u> angle can traverse the entire path, nor will the method attempt to predict the exact set of discrete hops that will support propagation. Rather the method will ask whether a ray at <u>some</u> (unspecified) low angle can traverse each of a series of segments of the path and whether some number of hops could traverse each segment. The idea is, if it is possible

to traverse each segment, then there is at least the potential for a ray to traverse all segments. Since the initial path is illuminated at a continuous band of angles, this potential may actually enjoy a reasonable probability of success. This approach can be viewed as an attempt to predict an upper bound on the possibility for propagation. Thus, it is assumed that propagation can potentially occur if the path between transmitter and receiver consists of a set of zones of homogeneous ionospheric type, each of which can potentially support propagation.

Two additional assumptions were made to tailor the method for the needs of long path propagation.

2) Since a low-loss mode is necessary for long-path, it is assumed that propagation can potentially occur only if propagation can potentially traverse the path with no reflections from the bottom of the E layer. Such reflections would entail high absorption in the two passes through a highly ionized D layer.

3) Since a low loss mode is needed, very low angle propagation (i.e., few reflections with few polarization coupling losses) is assumed, except that high takeoff and arrival angles are allowed with immediate refraction at the E layer to low angles.

The implementation of the zone method includes the following heuristic features.

A) The F2 critical frequency is determined at a series of points along the path. If this is too low at any point (i.e., MUF too low), then no mode is possible. Otherwise, the possibility of good F2 reflections is assumed.

B) The lowest angle for penetration of the E layer at each end of the path is determined. If this is greater than 2 degrees, then refraction to a low angle is considered to occur at the angle corresponding to the E layer critical frequency.

C) The ionosphere structure along the path is analyzed using Fricker's (1988) theoretical models of E and F2 characteristics. This analysis divides the path into a series of discrete regions of three types. Type 1 is where transit of the E layer is possible, i.e., conventional reflections between F2 and ground can occur. Type 2 is where no reflection from or transit of the E layer is possible because the E layer critical frequency for low angle incident rays is close to the actual frequency. Type 2 regions can be skipped over if they are short enough, otherwise they prevent any propagation. Type 3 is where reflections between the top of E and F2 can occur.

D) The method determines whether a ray could traverse from the transmitter to the receiver by a series of possible propagation modes, without attempting to model the exact angles at which this would occur. Essentially, propagation is deemed potentially possible if the MUF is high enough, if penetration of the E layer can occur below 20 degrees at each end, and if no Type 2 region is too long to jump over.

E) A series of modes is reported. The possibilities are: "F" (for a Type 1 segment with reflections between F2 and ground), and "R" (for a Type 3 segment with reflections between F2 and the top of E. In each case, the minimum number of hops for the length of the segment is reported (assuming perfect mirror image reflections), e.g. "6F2R". The predicted mode is not arrived at by assuming a constant angle and hop length, rather the model assumes that angle and hop length likely is changing along the path, with the predicted "mode" representing a lower limit on the number of conventional reflections of each type. This mode report is not an essential part of the prediction of potential propagation, rather it provides a useful shorthand labelling of the path zone structure, and it is useful for predicting signal strength.

F) The signal strength is predicted for the final mode sequence. Fricker's (1988) equations are used to model all path losses and gains that are represented in his program (spatial attenuation, horizon focussing, antipodal focussing, D layer non-deviative absorption, polarization coupling loss, and ground reflection loss). The resulting signal strengths were greater than observed in most cases. An additional loss factor was introduced in which the loss increases with the amount of E layer refraction, but with a frequency scaling such that less loss occurs for a given refraction amount at lower frequencies. The equation used is:
$k = 20 \log(\cos^{-3}(a(f/7)))$, where k is loss in dB, a is the angle of refraction, and f is the operating

frequency. I suggest that this factor represents deviative absorption, which is described by Davies [2], but not included in Fricker's model. Deviative absorption would become significant precisely under conditions of E layer refraction when the ray is penetrating at close to the E layer critical frequency. The exact form of this loss factor was chosen to accord with empirical observations. However, this form is plausible on the basis that a) greater refraction ("a" larger) means being closer to the critical frequency, thus longer occupation of the ionized region with consequently greater loss, and b) refraction of higher frequencies ("f" larger) at the same angle means that the ionization level must be higher (otherwise the ray would pass through without refraction), hence greater loss. The angle "a" itself is determined from Fricker's [4] formula for the E layer critical frequency, i.e. "a" is the angle such that f = foE(sec(a)), at the location of transit through the E layer. This assumes that a ray with a takeoff or arrival angle of approximately "a" will refract to essentially zero degrees incidence when the frequency is at the critical frequency. (Some angle close to this <u>must</u> experience such refraction, as lower angles are reflected and larger angles are transmitted.)

The result was that the zone method predicted observed long-path openings considerably better than did the discrete-hop-tracing method. In particular, grayline and 3.8 MHz openings were captured quite well. All of the observed long-path propagation examples in Table 1 were predicted. For observation #4 the predicted opening corresponded exactly to the observed time range of 1330-1500. For all six of the long-path observations described in Table 1 the paths consisted, at least in part, of zone type 2 (reflections between the top to the E layer and the F2 layer). The predicted mode for observations 1, 2 and 3 was for the entire path length to consist of reflections between these two layers with no ground contact intervening between the transmitter and receiver. The model also predicted E layer refraction at one or both ends of the path for the 3.8 and 7 MHz observations. Thus, prediction of long-path propagation at lower frequencies would appear to require modelling E layer refraction and reflections between E and F2 layers. Including these latter features in the extended discrete hop-tracing model was not sufficient, however. Including these features together with the zone analysis approach provides a more practical prediction system.

Table 1. Instances of observed long-path propagation. For all observations, the author's version of Fricker's IONPRED method found no useable propagation mode, while the zone method did predict propagation.

Obs. #	Date (D/M/Y) Distance	Time (UTC) Flux	Freq (MHz)	Transmitter (Lat., Long.)	Receiver (Lat., Long.)
1.	23/1/92 31022 km	1530 165	3.8	Belgrade (44.83N, 20.49E)	Victoria, BC (48.47N, 123.33W)
2.	15/12/91 28257 km	1530 180	3.8	Saudi Arabia (24.63N, 46.71E)	Victoria, BC (48.47N, 123.33W)
3.	16/1/92 28086 km	1540 165	3.8	Oman (23.61N, 58.58E)	Victoria, BC (48.47N, 123.33W)
4.	3/5/92 23338 km	1400-1500 134	7	Lesotho (29.46S, 27.49E)	Vancouver, BC (49.28N, 123.11W)
5.	24/5/92 28626 km	0500 100	7	Lesotho (29.46S, 27.49E)	New Zealand (41.3S, 174.76E)
6.	16/1/91 1500 30920 km	235	14	Odessa (46.1N, 29.8E)	Guemes Is., WA (48.5N, 122.6W)

Note: All observations are of two-way communication between amateur radio operators with directional antennas which confirmed long-path azimuth.

Acknowledgment - The author thanks Dr. Robert Brown for his assistance in the development of the modified version of Fricker's program and for the suggestion to include E layer refraction.

REFERENCES

[1] CCIR. *Atlas of Ionospheric Characteristics. CCIR Report 340*. International Telecommunication Union, Geneva, 1983.

[2] Davies, K. *Ionospheric Radio Propagation.* National Bureau of Standards Monograph 80. Washington, D.C.: U.S. Government Printing Office, 1965.

[3] Fricker, R. *A Microcomputer Program for the Critical Frequency and Height of the F-layer of the Ionosphere.* IEE Fourth International Conference on Antennas and Propagation, Coventry, England, 1985.

[4] Fricker, R. *COMB 7b: Combined Modes Propagation Programme.* September 1987.

[5] Fricker, R. *A Microcomputer Method for Predicting the Field Strengths of H.F. Broadcast Transmissions.* BBC External Services Engineering, London, 1988.

[6] Murray, D. P. *MAPPER86/87 .. A DX MAP Drawing and Propagation Program for IBM PC Compatibles with Graphics Capability, Version 8.0.* D. P. Murray, 11165 McDonald Street, Culver City, CA, 90230, 1992.

[7] Shallon, S. *MINIPROP Propagation Program, Version 3.0.* W6EL Software, Los Angeles, CA, 1988.