Simulation of off-great circle HF propagation effects due to the presence of patches and arcs of enhanced electron density within the polar cap ionosphere

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Observations over recent years have established that large-scale electron density structures are a common feature of the polar cap F region ionosphere. These structures take the form of convecting patches and arcs of enhanced electron density which form tilted reflection surfaces for HF radio waves, allowing off-great circle propagation paths to be established. Numerical ray tracing has been employed to simulate the effects of these structures on the ray paths of the radio waves. The simulations have reproduced the precise character of experimental observations of the direction of arrival over a propagation path within the polar cap and of oblique ionograms obtained over the same path. INDEX TERMS: 2475 Ionosphere: Polar cap ionosphere; 6934 Radio Science: Ionospheric propagation (2487); 6964 Radio Science: Radio wave propagation; KEYWORDS: radio propagation at high latitudes, ionospheric propagation

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1. Introduction

Observations over recent years have established that large-scale electron density structures are a common feature of the polar cap F region ionosphere. During periods of southward directed Interplanetary Magnetic Field (IMF) (Bz < 0) and the associated high levels of geomagnetic activity, patches of plasma 100–1000 km across with electron density enhancements of up to a factor of 10 above the background densities have been observed in the high-latitude F region ionosphere. These drift antisunwards across the central polar cap at velocities of a few kilometers per second in the high latitude convection current flows [Weber et al., 1984; Buchau et al., 1983]. When geomagnetic activity is low and the IMF is directed northward (Bz > 0) (approximately 50% of the time), Sun-Earth aligned arcs of plasma with electron density enhancements of a factor of 2–3 above the background can occur which drift across the polar cap at velocities of a few hundred meters per second, generally in a dusk-ward direction [Buchau et al., 1983]. The plasma striations are elongated for thousands of kilometers in the transpolar noon-midnight direction but are much narrower (around 100 km) in the dawn-dusk direction. These features can persist for periods often in excess of one hour in the background F region ionosphere [Carlson et al., 1984] and have been found to be approximately twice as prevalent in the morning sector than in the evening sector. Intense arcs (greater than about 1 kR) are seen about 2% of the time [Gussenhoven, 1982], as well as the far more common weaker arcs (down to several tens or hundreds of Rayleigh) which are seen about 50% of the time [Valladares et al., 1994], and are associated with comparable F region electron density structures. Note that with such arcs present the half of the time that the IMF is northward, and patches present the other half of the time when the IMF is southward, the polar cap is persistently in one or other of the two states addressed in this paper [Carlson, 1994].

The electron density gradients associated with these large-scale electron density structures form tilted reflection surfaces for HF radio waves which allow off-great circle propagation paths to be established between the transmitter and the receiver. In order to investigate this type of propagation, a series of experiments [Warrington et al., 1997; Rogers et al., 2001] have been undertaken in which the bearings and signal character-
istics of a number of HF transmissions were measured by means of a wide aperture goniometric direction finding (DF) system located at Alert in northern Canada. Large quasi-periodic bearing variations of up to $\pm 100^\circ$ from the great circle direction were observed which were attributed to reflection from arcs and patches of enhanced electron density.

[4] When ionospheric conditions support off-great circle propagation, considerable problems can arise in a number of HF systems. Perhaps the most obvious example is that of direction finding in which the location of a transmitter is estimated by triangulation from bearing measurements made at a number of receiving sites. Large deviations in the direction of arrival from the great circle direction consequently lead to significant errors in the estimated locations of the transmitters of interest, often by many hundreds or even thousands of kilometers. In communications links employing directional antennas oriented along the great circle direction, a reduction in received signal strength and SNR may occur since the signals are not transmitted/received along the directions of the main lobes of the antennas. Furthermore, the off-great circle propagation mechanisms often support communications at times which are not predicted (i.e., when the signal frequency is above the predicted great circle MUF).

[5] While the experimental work reported by Warrington et al. [1997] and Rogers et al. [2001] has produced many useful results, they were obtained for a small number of paths and frequencies. In order to be able to develop tools to enable such effects to be considered in the design and operation of HF radio systems for which the signals impinge on the polar cap ionosphere, but for frequencies and paths not subject to experimental investigation, a ray tracing model has been developed. In this paper, the results obtained from the ray tracing simulations are presented together with examples of experimental observations. However, it is well known that the polar cap ionosphere is an extremely complex HF propagation environment and, therefore, precise agreement between experiment and simulation was not attempted and should not be expected.

2. Overview of Experimental Measurements

[6] Measurements were made over the 2100 km polar cap path from Iqaluit to Alert (see Figure 1) for a period of approximately 2.5 years (December 1993 to May 1996). In winter, the path remains in darkness for long periods and the converse is the case in summer. Consequently, there is a marked seasonal dependence of the signal behavior with large ($\sim 100^\circ$) bearing deviations observed during winter and equinoctial months and only small ($<10^\circ$) fluctuations for most of the time during the summer.

[7] During the winter and equinoctial months, there is an underlying tendency for propagation to deviate to the west of the great circle path (GCP) (high bearing angles) in the evening sector (local midnight at the GCP midpoint is 0430 UT) with propagation returning from the east of the GCP (low bearing angles) in the morning. This probably arises from very large-scale ionospheric gradients in the polar cap associated with the solar terminator. More rapid bearing swings with periods of about 30 min are often superimposed upon these trends which are attributed to the presence of convecting patches or arcs of enhanced electron density.

[8] An example period illustrating the rapid bearing swings observed at 9.292 MHz for the period 21–24 February 1994 is presented in Figure 2 together with values of the 3-hourly ap index and the By and Bz IMF parameters. A geomagnetic storm is evident on 21–22 February. The principal bearing swings on the night of the 21–22 February, a period of southward IMF and high ap values, have a decreasing bearing angle and occur in the six hour period before local midnight (0430 UT), whereas the principal bearing swings on the following night, a period of northward IMF and low ap, have an increasing bearing and occur principally in the hours following local midnight.
Figure 2. Bearings measurements for the 9.292-MHz transmission from Iqaluit received at Alert for the period 21–24 February 1994. Three-hourly ap values and the IMF By and Bz values are also shown. Bearings are measured in degrees clockwise from north, and the times/dates are in UT.
Reference to the expected convection flow patterns (see Figure 3 reproduced from Lockwood [1993]) suggests that when the IMF is directed southward ($B_z < 0$), patches of ionisation drifting antisunwards would lead to a preponderance of decreasing bearing angle swings in the premidnight hours and increasing bearing angle swings in the hours after midnight. Figure 2 shows this to be the case where $B_y < 0$, although where $B_y > 0$ there is a distinct lack of decreasing swings in the premidnight sector. It is important to note, however, that the convection flows illustrated in Figure 3 are sketches of the overall form of what may be expected. On any particular occasion, the actual flow patterns may differ significantly from those in the illustration. When the IMF is directed northwards ($B_z > 0$), the principal large-scale electron density structures within the polar cap ionosphere are Sun-aligned arcs (plasma striations extending for thousands of kilometers in the transpolar noon-midnight direction, but much narrower with scales around 100 km in the dawn-dusk direction [Buchau et al., 1983]). A series of arcs drifting steadily across the polar cap from dawn to dusk would lead to the expectation that increasing bearing swings would be observed during the time sector 1800 to 0600 LT, with the largest swings expected in the midnight sector. Decreasing bearing swings would be observed in the local time sector 0600 to 1800 with the largest swings in the noon sector.

3. Simulation

The simulations make use of a numerical ray tracing code [Jones and Stephenson, 1975] to estimate the ray paths through a model ionosphere comprising two Chapman layers, the main parameters of which (critical frequency, critical height, vertical scale height of each layer) are based on values obtained from the International Reference Ionosphere (IRI) [Bilitza, 1990]. The IRI model was chosen since it provides a reasonable model of the background ionosphere from the point of view of long-term predictions, but it is, of course, possible to use other models or even experimental data, if available. Marked day-to-day deviations from the average background ionosphere are to be expected. In order to introduce some flexibility in the ionospheric models and to significantly improve the computational speed, some analytical approximations were made to the longitudinal and latitudinal gradients of electron density based on magnitudes of the critical frequencies of the main layers ($E$, $F_2$) at five reference points (North Pole, two points near midnight and two points near noon). Localized, time-varying perturbations in the electron density are then applied to the background model to represent the convecting patches and arcs of enhanced electron density.

3.1. Sun-Aligned Arcs

The shape of each Sun-aligned arc is defined within the model by a small number of three-dimensional Gaussian perturbations in electron density of different spatial scales (altitude, longitude and latitude) randomly distributed near to the center of the arc. Several Gaussian perturbations were combined in defining the shape of each modeled arc in order to prevent the shapes of the arcs being too stylized. For all arcs away from close proximity to the dawn or dusk auroral oval, the plasma strands are elongated for several hundreds or thousands of kilometers with a latitudinal scale which is significantly larger than the longitudinal scale. Many such arcs can be included in the simulation with their positions being randomly distributed in an area centered on the geomagnetic pole and bounded by the auroral oval. The magnitude of the electron density perturbation of each of the elements forming the arcs is randomly distributed about a specified average value. Evolution of the structures relative to the propagation path is determined by the rotation of the Earth beneath the arcs and by the movement of the arcs in the dawn-dusk direction.

The results of some typical simulations for the Iqaluit to Alert path are presented in Figure 4. In this and subsequent figures, the darkness of the traces indicates the intensity of the received signal based on the ray density on the ground around the receiver site. Large (in this case $80^\circ$ positive) bearing swings are apparent which are reminiscent of the observations reproduced in Figure 2 and others reported by Warrington et al. [1997]. The model also enables ionograms to be simulated, examples of which are presented in Figures 5 and 6 corresponding to two instances from Figure 4. For the case of Figure 5, reflections from the background ionosphere appear on the ionogram as the usual one hop trace with a MUF of around 8 MHz together with a two hop
A detached feature is evident on the ionogram between about 8 and 11 MHz which is due to the presence of the arcs. The bottom frame of this figure displays the direction(s) of arrival as a function of signal frequency. It is interesting to note that the signal energy associated with the arc reflections is displaced from the GCP by between $20^\circ$ and $60^\circ$. Different characteristics are evident in the example given in Figure 6. In this case a long, horizontal “nose extension” to the 1-hop $F$ region trace occurs which is associated with signal energy arriving from around $15^\circ$ to $20^\circ$ from the great circle direction. In particular, it should be noted that the thin traces are a common feature on ionograms for paths through ionospheres containing arcs [see Rogers et al., 2001].

3.2. Convecting Patches

Patches of enhanced electron density (patches) associated with high geomagnetic activity are modeled as an arbitrary number of Gaussian distributions with approximately equal longitudinal and latitudinal scale. The temporal evolution of the patches relative to the propagation path is simulated by means of a convection flow scheme coupled with the rotation of the Earth beneath the convection pattern, the precise form of which depends upon the components of the IMF (see the stylized sketches in Figure 3 and Lockwood [1993]). In practice, the shape, size and number of patches in the convection flow area depends upon many geophysical parameters, not only upon the instantaneous values but also upon their history. By using up to four vortices based on the modeled convection flow patterns associated with the various IMF orientations presented by Lockwood [1993], many realistic situations may be simulated.

Examples of the azimuth deviations produced by the presence of patches are given in Figure 7 for convection patterns associated with values of $B_y < 0$ and $B_y > 0$. In this example, there were 28 patches of enhanced electron density with a maximum critical frequency of approximately 9 MHz. Only those patches that

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**Figure 4.** Two examples of the time history of the direction of arrival (azimuth only) of a 9.3 MHz signal propagating through a model ionosphere containing arcs of enhanced electron density.

**Figure 5.** Oblique ionogram produced by ray tracing simulations through an ionosphere containing arcs of enhanced electron density (0700 UT for the simulation of the top frame of Figure 4).
relatively close to the propagation path influence the structure of the received signal, but as the patches evolve and move following the modeled convection flow patterns, the number and positions of those patches influencing the signal changes. As with the modeled arcs, large bearing deviations are evident but it is clear that the nature of the deviations varies with time and that it is also dependent upon the convection flow pattern (and hence the value of $B_y$). Two ionograms simulated for an ionosphere where enhanced patches are present are given in Figures 8 and 9. The first is an example of a "nose extension" to the normal ionogram trace in which energy is received at frequencies above the junction frequency (i.e., above the great circle path MUF). In the simulated ionogram presented in Figure 9, the nose-extension feature has become detached from the main trace, and again this is a feature commonly present in the ionograms obtained in practice [see Rogers et al., 2001].

4. Concluding Remarks

[15] A wealth of knowledge resulted from the investigations into gross deviations from the great circle path (GCP) outlined by Warrington et al. [1997]. As part of this work, the magnitude and variances of the deviations from the GCP were quantified and the associated geophysical conditions and signal characteristics identified. In order to extend the results of this work to paths and frequencies which were not the subject of experimental investigation, a ray-tracing model has been developed. The results obtained from the ray tracing simulations,

**Figure 6.** Oblique ionogram produced by ray tracing simulations through an ionosphere containing arcs of enhanced electron density (0500 UT for the simulation of the bottom frame of Figure 4).

**Figure 7.** Time history of the direction of arrival (azimuth only) of a 9.3 MHz signal propagating through a model ionosphere containing patches of enhanced electron density. (top) $B_y < 0$; (bottom) $B_y > 0$. 
examples of which have been presented in this paper, are very reminiscent of the experimental measurements which (1) support the experimental evidence as to the effects of the patches and arcs on the direction of arrival of signals propagating in the polar cap ionosphere, and (2) suggest that useful estimations may be made of the likely effects on other paths and at other frequencies. Of course, the specific structure of the simulated signals depends on the number of arcs or patches present, their size and shape, their positions and the shape and size of the convection flow patterns. It is, therefore, important to note that owing to the complex nature of the polar cap ionosphere, an identical match between the experimental data and the simulations was neither attempted nor expected.

[16] Following on from this work, procedures will be developed through which the influence of the off-great circle propagation mechanisms on specified communications links, radiolocation systems and HF radars may be estimated. Since ray tracing simulations are computationally very intensive, it is anticipated that the procedures will take the form of a set of rules (a “rule base”)

which will then be the incorporated into computer code which may then be integrated with various prediction codes currently in use to allow proper consideration to be given to the off-great circle propagation mechanisms.

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