OBSERVATIONS OF THE TIME-OF-FLIGHT AND DIRECTION OF ARRIVAL OF HF RADIO SIGNALS ON A PATH AFFECTED BY THE MID-LATITUDE TROUGH

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ABSTRACT

Measurements of the time-of-flight and direction of arrival of an HF radio signal on a sub-auroral path between Sweden and the U.K. are presented. During the day, as expected, the signal arrives from the great circle path (GCP) direction. However, at night, especially during the winter and equinoctial months, the signal often arrives at azimuths displaced from the GCP by up to 40°. Azimuths which are deviated to the north of the GCP may arise as a result of the signal being scattered by irregularities embedded in the poleward wall of the trough.

INTRODUCTION

The trough is a region of depleted electron density in the night-time F-region ionosphere in which the critical frequencies drop by a factor of at least 2 and the altitude of the electron density peak rises by 100 km or more [1]. During the winter and equinoctial months the trough takes the form of a band a few degrees wide in latitude on the equatorward edge of the auroral oval, stretching in local time from dusk to dawn. In summer, the trough is much less pronounced and is confined to the hours around midnight. The location of the trough also depends on geomagnetic activity, the trough region moving equatorwards and the evening sector tending to move to earlier local times as the activity increases. The trough has been modelled on a statistical basis by various researchers (see, for example, [2], [3] and [4]). Recent developments in ionospheric tomography [5, 6] and observations made with EISCAT [7] have provided further experimental observations of the trough position and structure.

The presence of the mid-latitude trough has a significant impact on many radio systems, particularly those operating within the HF band where the signals are reflected from the ionosphere, but also systems operating at higher frequencies where the signals traverse the ionosphere. For HF systems, the electron density depletion within the trough region reduces the maximum frequency which can be reflected by the ionosphere along the great circle path (GCP). Additionally, the associated tilts in the electron density distribution frequently result in propagation well displaced from the great circle path by up to around 100° or more. These deviations impact not only on radiolocation systems for which estimates of a transmitter location are obtained by triangulation from a number of receiving sites assuming great circle propagation, but also on any radiocommunications system in which directional antennas are employed. For trans-ionospheric signals, the reduction in total electron content (TEC) over the trough region affects the time of flight of the signals which, for example, leads to timing and positional errors in satellite based navigational systems such as GPS and the proposed European Galileo system.

Reference [8] have investigated the effects of the trough on the azimuth-of-arrival of HF radio signals on two paths in the sub-auroral region, a long one between Halifax, Canada and Cheltenham, UK (4490 km, bearing 286°) and a shorter one between Halifax and Leitrim (near Ottawa), Canada (910 km, bearing 90°). For the longer path bearing deviations of up to 50° were commonly observed during October to March, while in the summer months bearing changes occurred infrequently, which is consistent with the well documented absence of the trough during the summer. The bearing deviations tended to occur earlier for increasing Ap which is consistent with the expected extension of the sub-auroral trough into earlier local times in the evening sector during enhanced geomagnetic activity. Some of these observations over this long path have been simulated using ray tracing techniques [9] and explained in terms of seascatter from regions far to the south of the trough.

On the shorter path very large bearing deviations of up to ±100° starting two or three hours after midnight UT were a common feature. The deviations were positive, negative or sometimes both even for geomagnetically quiet days. During disturbed times, the bearing deviations tended to start earlier with the time strongly related to Ap.

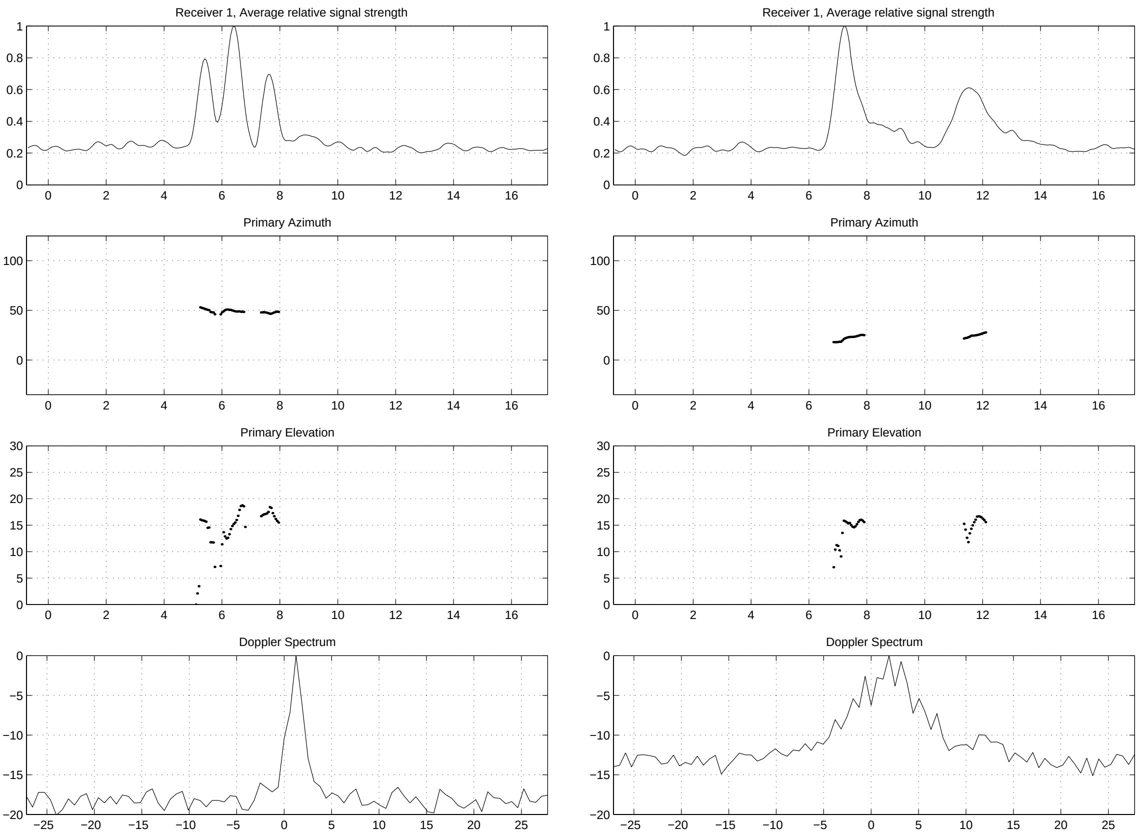

Fig. 1. Example measurements made at 11.12 MHz of signals received near Leicester on 23 November 2001 (day 327) for daytime (1134 UT, left) and night-time (0004 UT, right). From the top, the panels represent signal strength (linear, normalised) versus time-of-flight (ms), azimuth (°) versus time-of-flight (ms), elevation (°) versus time-of-flight (ms), and amplitude (dB) versus Doppler frequency (Hz).

OBSERVATIONS

In order to obtain additional information about the trough over northern Europe with the aim of improving the ionospheric models for this region, a new HF radio experiment has been established. This system (operational since October 2000), consists of a frequency-agile transmitter located in Uppsala, Sweden. The transmitted signals are received on a 6-channel superresolution direction finding system located south of Leicester, U.K. giving a 1400 km propagation path. Currently, the frequency (one of, 4.64, 6.95, 10.39, 11.12, 14.36, and 18.38 MHz) is changed every 30s. A 1667 baud, 13-bit Baker coded signal of 2s duration is employed in order to increase the signal-to-noise ratio of the received signal through a despreading process and also to act as an aid to signal recognition. Since both transmitter and receiver system clocks are synchronised to GPS, the direction-of-arrival can be measured as a function of absolute time-of-flight (TOF). As an additional diagnostic, a BR Communications chirpsounder system has also been deployed with the transmitter collocated with the main transmitter in Uppsala and the receiver at the University of Leicester.

Measurements typical of those found throughout the entire data set are presented in Fig.1. During the day, the signal strength (top-left panel) indicates that 1-hop, 2-hop and 3-hop F-region propagation is present. The azimuthal angle of arrival (second-left) is close to the GCP (46°) for each mode while the elevation angle (third-left) is just under 20°. The frequency spectrum shows a narrow peak (2 Hz at –10 dB). At night (top-right) two modes are present, a narrow one at a TOF of just under 8 ms (i.e. at about the same as the 3F daytime mode) and a second mode which occurs at a longer TOF and is more spread. The azimuthal direction of both modes is about 20° to the north of the GCP although there is a variation in the bearing with TOF. The elevation angles are again below 20°. The frequency spectrum is somewhat broader than the daytime case (~10 Hz at –10dB), the reasons for which will be discussed below.

The TOF, signal strength, bearing and Doppler measurements made over three days in November 2001 at 10.39 MHz are shown in Fig.2. During the day, the signal exhibits several modes with delays typically in the range 5.5 to 8 ms,

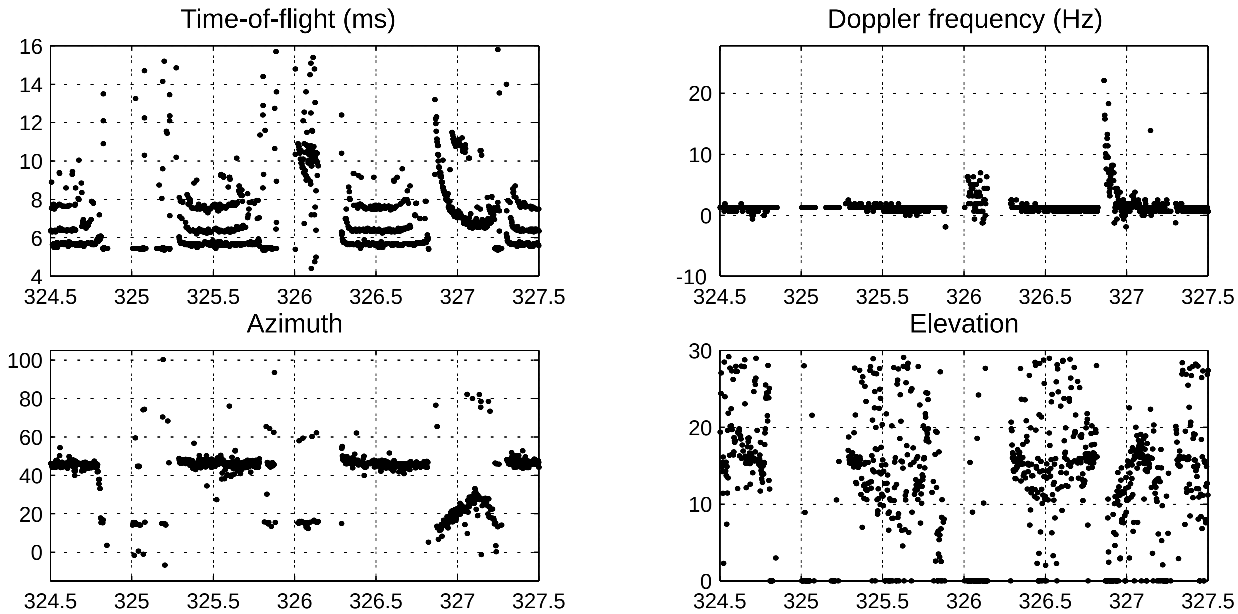

Fig. 2. Measurements made at 10.39 MHz between 20 November 2001 (day 324), 1200 UT to 23 November 2001 (day 327), 1200 UT. The panels represent, time-of-flight (ms, top left), Doppler shift (Hz, top right), azimuth of strongest mode (°, bottom left), and elevation of strongest mode (°, bottom right).

corresponding to propagation via 1F, 2F, and 3F modes, bearings close to the great circle (46°), and low Doppler shift and spread. At night, a wider variety of effects in both azimuth and TOF are observed. On the first night (i.e. day 324–325) intermittent propagation via an E-region mode at bearings of about 30° north of the GCP occurs. On the second night (day 325–326) just after midnight propagation is present on a mode with a relatively long TOF (8–10 ms) and bearings to both the north and, more weakly, the south of the GCP. The most striking behaviour can be observed on the third night (day 326–327) where a propagation mode appears at a long TOF (up to 13 ms) at about 2030 UT. Over the next six hours the TOF decreases reaching a steady value of about 7 ms by 0230 UT. At times around midnight a second mode at a longer delay (~11 ms) is present (also see Fig.1). The bearing deviation from great circle decreases as the TOF decreases from about 40° at 2030 UT to 20° at 0230 UT, while the elevation increases from about 10° to 15-20°. The rapid decrease in TOF is accompanied by a strong positive Doppler shift (~20 Hz).

The feature observed on day 326–327, where a long TOF accompanied by bearing deviations of up to 40° and Doppler shifts is a relatively common occurrence (see Table 1). In the non-summer months, this phenomenon is observed on over 40% of nights, while in the summer it is comparatively rare. Examination of Table 1 also reveals that bearing deviations to the north of the GCP are more likely to occur than those to the south for all seasons and that the VOACAP prediction programme underestimates how often propagation takes place.

Two ionograms observed on the morning of day 327 are presented in Fig. 3. In the left panel, the ionogram taken on the Uppsala-Leicester path exhibits the normal ionospheric F-layer at a relative delay of about 2 ms and a critical frequency of just over 4 MHz. However, at frequencies up to about 14 MHz a more diffuse set of echoes is present. In the short-path ionogram (right panel) taken shortly beforehand a similar feature can also be found. These diffuse echoes, together with the bearing deviations, the TOF variation and the increased Doppler shift and spread are consistent with the signal scattering from irregularities in the poleward wall of the trough. Preliminary ray tracing studies have shown that this mechanism can lead to azimuth deviations similar to those observed.

Table 1. Occurrence statistics by mode and bearing (% of nights) for 10.39 MHz signal between October 2000 and October 2001

	VOACAP	Propagation mode		Bearing		
	No prop	No prop	Long TOF	GCP	North	South
Spring	67	42	43	17	38	22
Summer	44	4	15	84	16	9
Autumn	86	19	52	26	54	23
Winter	100	30	57	13	45	36

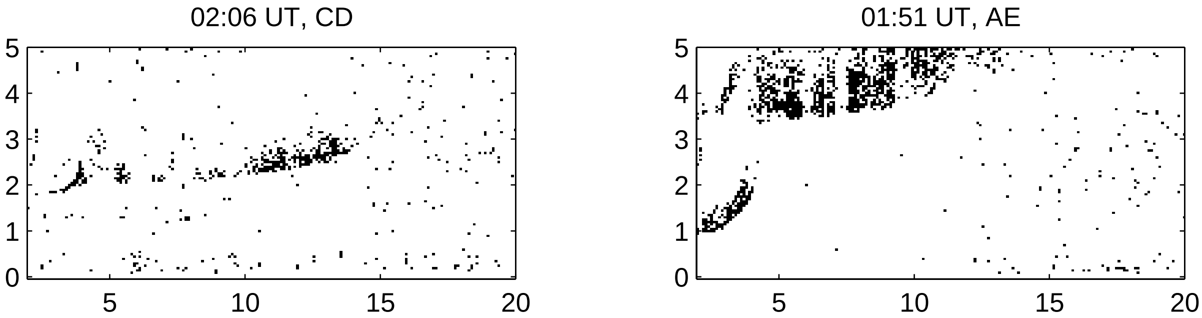

Fig. 3. Ionograms taken around 0200 UT, 23 November 2001 (day 327). Left panel is over an oblique path from Uppsala-Leicester, the right panel is for a short path

CONCLUDING REMARKS

In order to obtain additional information about the trough over northern Europe, a new experiment has been established between Uppsala, Sweden and Leicester, U.K., the particular aim of which is the improvement and development of the ionospheric trough models for this region. Unlike the earlier experiments [8] in which the signal azimuth, amplitude and Doppler frequency characteristics were recorded, the new measurements include the elevation angle of arrival and since they are of a time synchronised pulsed transmission TOF characteristics may be incorporated in the analysis. During the day the observations do not exhibit any unexpected characteristics – the bearing is largely on-GCP and various F-region modes are commonly supported. However, at night, especially in non-summer months, propagation at long TOF and with bearings displaced from the GCP often occurs. This propagation is consistent with the received signals scattering from irregularities in the poleward wall of the trough.

Further analysis of the measurements will initially be directed towards (a) experimentally determining the accuracy of the currently available models of the trough by a comparison of ray tracing simulations with the measurements, and (b) improvement of the accuracy of the models by imposing physically realistic refinements to give a better fit to the experimental data.

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