Observations of HF radio propagation at high latitudes and predictions using data-driven simulations

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ABSTRACT

Researchers at the University of Leicester, Lancaster University and St Petersburg State University have developed various models that can be employed in HF radio propagation predictions. Signal coverage predictions make use of numerical ray tracing to estimate the ray paths through a model ionosphere that includes various ionospheric features prevalent at high latitudes (in particular patches, arcs, ionisation tongue, auroral zone irregularities and the mid-latitude trough). Modelling of D-region absorption is also included. GOES satellites provide information on X-ray flux (causing shortwave fadeout during solar flares) and precipitating energetic proton flux which correlates strongly with Polar Cap Absorption (PCA). Solar wind and interplanetary magnetic field measurements from the ACE or DSCOVR spacecraft provide geomagnetic index estimates used to model the location of both auroral absorption and the proton rigidity cutoff boundary that defines the latitudinal extent of PCA during solar proton events (SPE). This paper presents measurements and associated modelling for a 9 day period.

1 INTRODUCTION

Space weather events can influence the ionosphere in a number of ways, and these can be particularly pronounced at high latitudes (i.e. within the auroral zone and polar cap). The most severe space weather events lead to a total loss of communications within the HF band (a radio blackout) via strongly enhanced D-region absorption. More commonly, events of intermediate severity can lead to disruption of communications that may be managed by appropriate frequency selection, relaying of messages, and possibly by spatial diversity if the operational configuration is such as to allow this.

Communications within the high latitude region is of growing importance for civil airlines operating trans-polar routes as these may form the shortest path between significant destinations (e.g. New York to Hong Kong), reducing travel time, cost and carbon emissions. In 2014, polar routes were operated by more than 10 major airlines, with over 12,000 cross-polar flights. However, in the polar cap above 82°N geostationary satellites lie below the horizon, and geographic and geopolitical considerations mean there are limited VHF radio air-traffic control facilities. Thus HF radio propagation via the ionosphere is of critical importance in maintaining communications. Adverse space weather conditions, leading to ionospheric disruption that in turn affects HF radio propagation, is of critical importance when considering whether polar routing is viable in the hours in advance of a flight (forecasting) and to the management of HF communications during a flight (nowcasting). Our research is currently directed towards the nowcasting and forecasting requirements. There are two aspects: (a) absorption, and (b) ray path characteristics.

The HF absorption estimates are determined either from the NOAA D-Region Absorption Prediction (DRAP) model [*Sauer and Wilkinson*, 2008; *Akmaev et al.,* 2010] that incorporates real-time X-ray and energetic proton flux measurements from the geostationary GOES-15 satellite, or the Polar Cap Absorption Model (PCAM) [*Rogers and Honary*, 2015; *Rogers et al.,* 2015] which is a modification of DRAP that assimilates direct real-time absorption measurements from high-latitude riometers.

Our ray-tracing model as previously reported [*Zaalov et al*., 2003; 2005] was based on measurements of azimuthal direction of arrival obtained in the 1990s. More recently, we have undertaken measurements of signals received over a number of paths (see Figure 1), including direction of arrival, time of flight (TOF) and signal strength with the specific aim of validating and developing our modelling procedures. In this paper we present a case study for a period displaying the effect of an intermediate-level absorption event - a series of M and X class solar flares and a relatively weak CME on HF radio performance from 6 to 13 January 2014. Significant ionospheric absorption was observed during this event, but - aside from a short period - were not sufficient to produce a radio blackout.

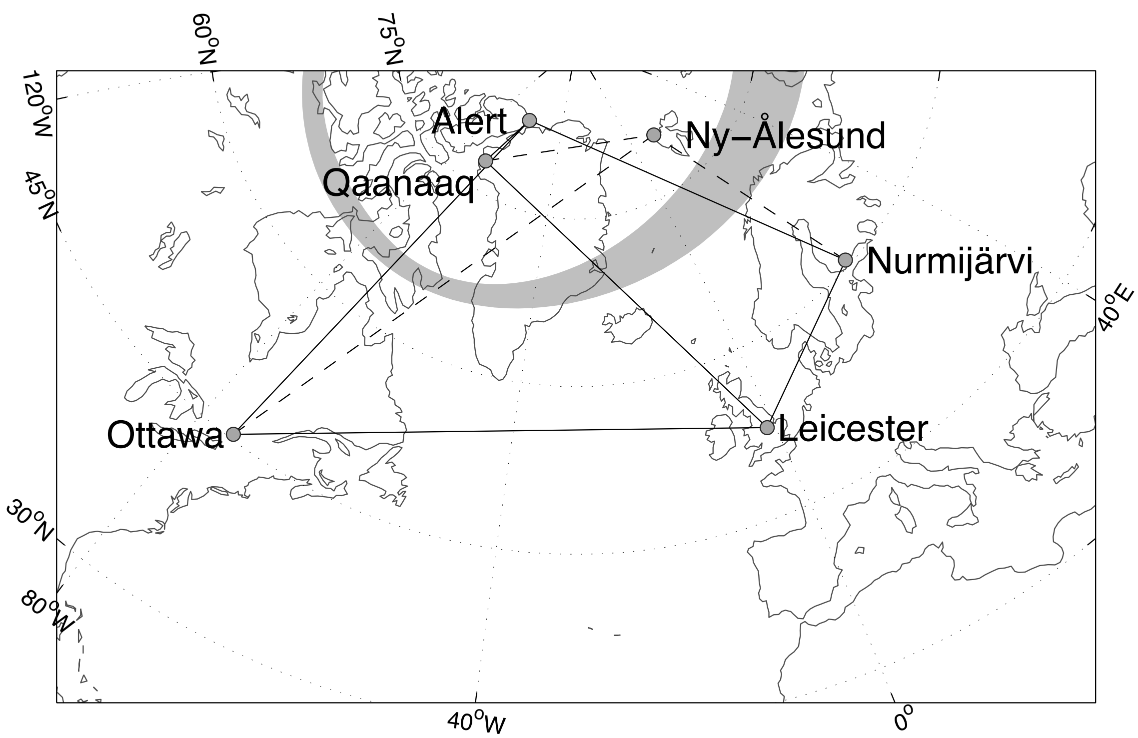

Figure 1. Map indicating our experimental configuration. Transmitters are located at Nurmijärvi, Qaanaaq and Ottawa, direction finding receivers at Alert and Leicester, and single channel receiver at Ny-Ålesund. The solid lines indicate the paths for which directional measurements are available, and the dashed lines those paths where only signal strength measurements are made.

2 PROPAGATION MODEL

Typically, at mid-latitudes, HF signals propagate on paths close to the great-circle between transmitter and receiver. However, at high latitudes the presence of various ionospheric features alters this behaviour. For example, the presence of patches of enhanced ionospheric electron density may reflect the signals into unexpected areas and can also shield particular regions from a given transmitter site. To estimate ray paths, and hence signal coverage, we use an ionospheric ray-tracing model, in conjunction with HF sounding and other geophysical measurements as inputs to define a model ionosphere suitable for use with the ray tracing code. A realistic background ionosphere based on observations, localised ionospheric features (e.g. the mid-latitude trough, the tongue of ionisation in the polar cap and polar patches and arcs), D-region absorption inferred from satellite measurements (DRAP) with inputs from real-time riometer measurements, HF-transmitter/receiver antenna patterns are used to predict radio propagation behaviour. The area coverage to be expected from a transmitter at a given location is then estimated by ray-tracing through the model ionospheres. A large number of rays launched in an azimuth / elevation grid from the transmitter are traced through the model ionosphere. Each ray is assigned a power depending upon the transmitter power and antenna radiation pattern, absorption is added for each transit of the D-region taking into account the location of the transit, and the signal strength at the receiver estimated summing the ray power in the area around the receive antenna.

3 MEASUREMENTS AND SIMULATIONS: 6-15 JANUARY 2014

For the measurements reported in this paper, a nominal power of 100 W was fed to a commercial end-fed V broadband antenna. This antenna incorporates a resistive load as part of its design and is not expected to be as efficient as a resonant antenna. However, it was not possible for us to determine the precise efficiency of the antenna. Furthermore, the signal loss through various distribution systems at the receiver is unknown. To account for these two sources of loss, the nominal transmit power in the simulations and VOACAP [*Sweeney et al.,* 1993] predictions has been reduced by 12 dB at Qaanaaq, this value giving good agreement between received signal power, VOACAP predictions and signal strength predictions from our simulations presented in subsequent sections of this paper. Received signal strength is presented as S-units, the scale commonly used on HF communications receivers with S1 being very weak (-121 dBm), stepping in 6 dB increments per S-unit to S9 (-73 dBm) indicating a relatively strong signal, and then in dB exceeding S9.

This period is one during which the absorption in the polar cap increased, but not such that a complete HF blackout occurred. Figure 2 indicates various parameters observed for a 7.0 MHz signal from Qaanaaq to Alert during this period, namely (a) time of flight, (b) direction of arrival, (c) signal strength, (d) absorption predicted by the PCAM and DRAP models corrected for the oblique path, and (e) the lowest frequency (f_{min}) observed on the Qaanaaq ionosonde.

A clear variation in signal strength (Figure 2(c)) with a strong diurnal component is evident. At times away from the absorption event, there is good agreement with VOACAP on the maximum signal strengths observed around local noon but the magnitude of the variation is under estimated. Furthermore, (as expected) VOACAP, being based on a statistical model, does not show any day-to-day variation over the period. Much reduced signal strength was observed for 8/9 January 2014, and less so on 10 January, corresponding to times of relatively high absorption but not so high as to completely absorb the signals.

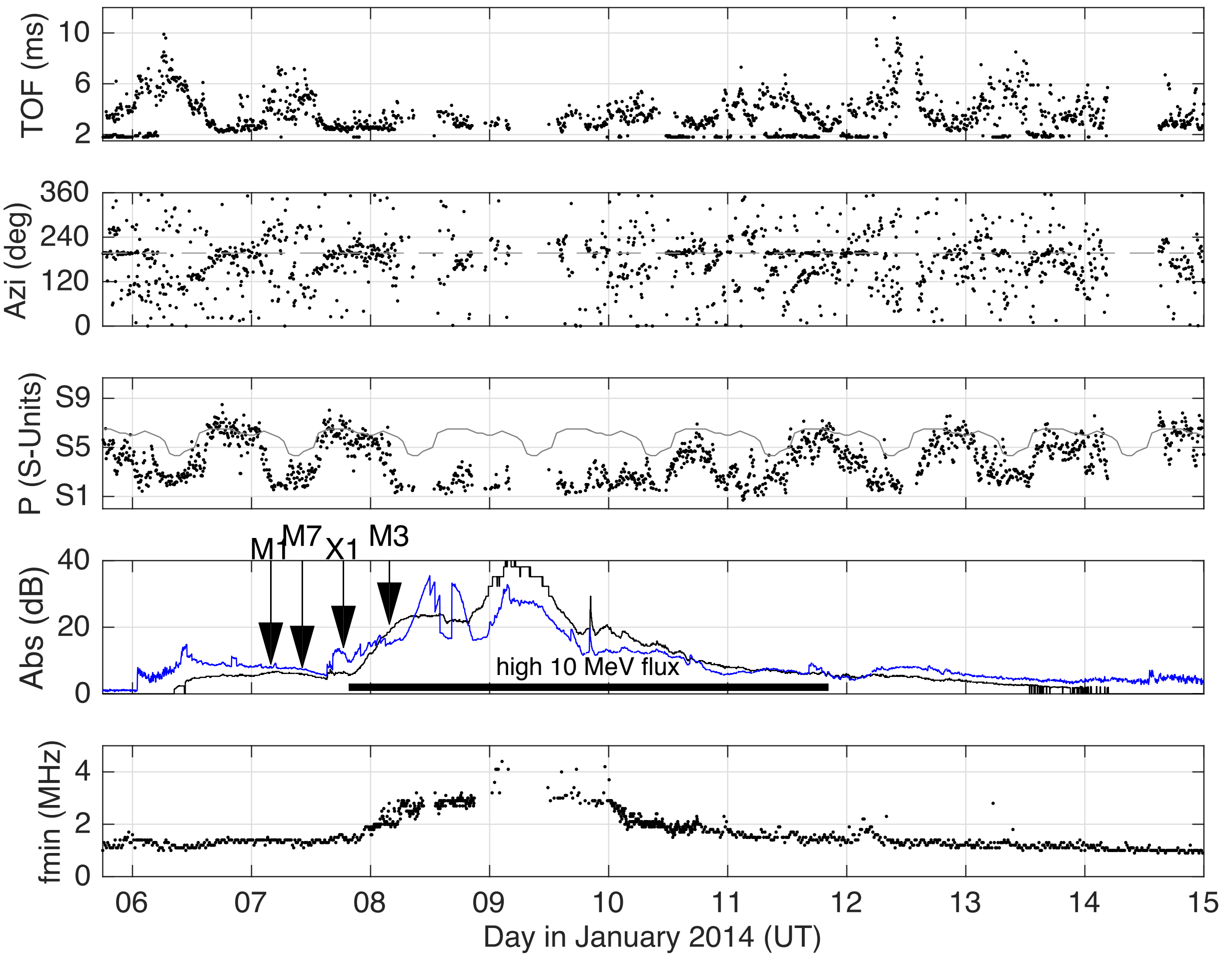

Figure 2. Measurements for the Qaanaaq to Alert path at 7.0 MHz for the period 6-15 January 2014 of (upper frame to lower frame): (a) signal time of flight, (b) the azimuthal angle of arrival, (c) signal strength (dots) and predicted signal strength using VOACAP (grey line), (d) absorption predicted by PCAM (blue line) and DRAP (black line) corrected for the oblique path, and (e) lowest observed frequency on the Qaanaaq ionosonde.

An increase in the minimum observed frequency on the Qaanaaq ionosonde (Figure 2(e)) corresponding to the period of increased absorption is evident. This corresponds to an increase in the system dependent lowest usable frequency (LUF) for the ionosonde. *Zaalov et al* [2015] considered the effect of absorption on both vertical and oblique ionograms, and latterly *Zaalov and Moskaleva* [2016] have considered employing vertical ionogram structure to optimize polar cap absorption models.

In Figure 2(d), the black curve represents the absorption of 7.0 MHz radiowaves predicted by the DRAP model corrected for slant propagation using the secant of the ray incidence angle. The DRAP model incorporates contemporary ('real-time') geomagnetic indices and satellite measurements of the solar X-ray and energetic proton fluxes. However, the ionospheric response parameters of the DRAP model (which can vary with D-region chemistry, electron temperature and layer structure) are constants based on climatological average values. The PCAM predictions

(Figure 2(d), blue curve) optimised these parameters by assimilating real-time absorption measurements from the polar cap riometer at Taloyoak (69.5°N, 93.6°W geodetic), which measures ionospheric absorption of 30 MHz cosmic noise and forms part of the Canadian Riometer Array [*Danskin et al*., 2008]. This model updated the day- and night-time values of the parameter $m = A/J(> E_t)$, where A is the cosmic noise absorption (dB) and $J(> E_t)$ is the equivalent isotropic flux (cm^{-2} sr^{-1} s^{-1}) of solar protons with energies exceeding thresholds E_t (MeV), which were determined following the procedure in [*Sauer and Wilkinson*, 2008]. The modified parameters (updated every 1 hour) were determined by regression to riometer measurements, which were weighted according to their age, T, using the exponential weighting, $w = \exp(-T/\tau)$, with τ = 24 h. PCAM also allowed the solar zenith angle (χ) thresholds defining the twilight transition region to be similarly determined by regression, as discussed in [*Rogers et al*., 2015], whereas in DRAP these thresholds are fixed at χ = 80° and 100°.

Figures 3(a) and (b) illustrate the expected coverage of the 7 MHz Qaanaaq transmitter at 1800 UT on 9 and 13 January 2014 respectively, corresponding to a time of increased absorption and a time where the absorption has almost returned to normal background levels.

The propagation mechanisms during this period are not straightforward. Swings in the direction of arrival with a period of 24 hours, coupled with periods of on-great circle propagation, are evident (Figure 2(b)). Associated with the swings, significant increases in the time of flight (Figure 2(a)) occur corresponding to excess path lengths of up to around 1500 km. These swings (intuitively) appear to be consistent with the behaviour expected by reflection from a tongue of ionisation extending from the dayside to over the pole. Simulations for this 9 day period have been undertaken using the model outlined earlier, and the resulting times of flight, azimuthal direction of arrival and signal strength presented in Figure 4. Many of the features in the measurements are reproduced in the simulations.

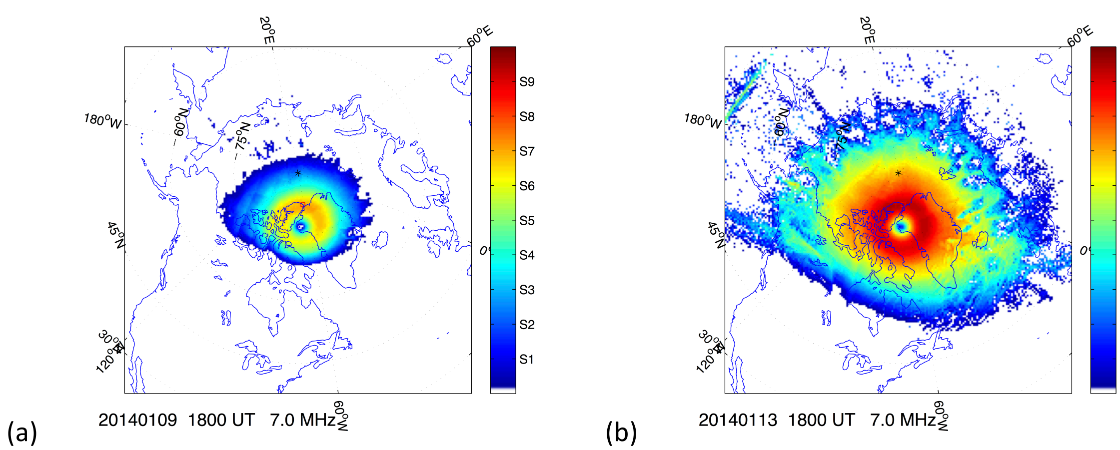

Figure 3. Coverage predicted for 7.0 MHz using the ray-tracing model for a 100 W transmitter and monopole antennas at both transmitter and receiver. (a) 18:00 UT, 9 January 2014, during the absorption peak. (b) 18:00 UT, 13 January 2014, absorption decayed to background levels.

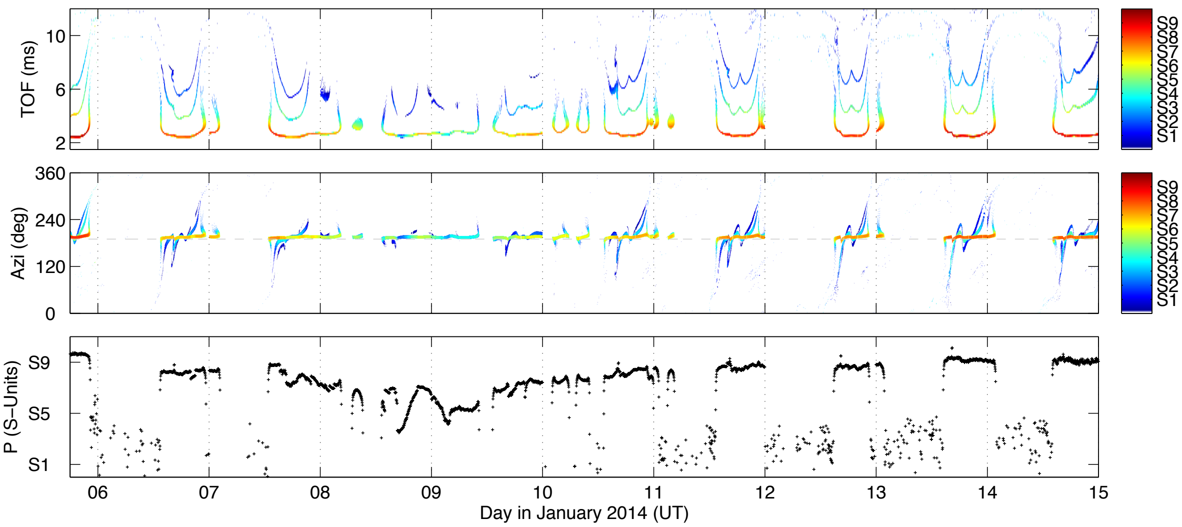

Figure 4. Time of flight, direction of arrival, and signal strength for 7.0 MHz predicted by the ray-tracing model combined with DRAP absorption using one specific patch scenario for the period 6-15 January 2014.

4 CONCLUDING REMARKS

The aim of this work is to be able to provide an operational service to the airline industry with sufficient information to guide them on whether communications are likely to be maintained on a polar route for the duration of the flight (forecasting) and to provide frequency management information during a flight (nowcasting). Currently the modelling is able to use a range of real-time data sources (e.g. ionosondes, GPS TEC, particle fluxes, etc.) to provide nowcasts of HF ionospheric propagation and absorption conditions that are consistent with measurements made on a number of oblique HF paths.

A single period has been presented in this paper as a case study. Further studies will be presented in the full version of this paper.

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REFERENCES

Akmaev, R. A., Newman, A., M. Codrescu, C. Schulz and E. Nerney (2010), DRAP Model Validation: I. Scientific Report. Available online: www.ngdc.noaa.gov/stp/drap/DRAP-V-Report1.pdf, 2010.

Danskin, D. W., D. Boteler, E. Donovan, and E. Spanswick (2008), The Canadian riometer array. Proc. 12th International Ionospheric Effects Symposium (IES 2008), Alexandria, VA, USA, 13-15 May 2008, 80–86. (Available online http://www.ntis.gov, PB2008112709).

Reinisch, B. W., and I. A. Galkin (2011). Global ionospheric radio observatory (GIRO). *Earth, Planets, and Space*, 63, 377-381, doi:10.5047/eps.2011.03.001.

Rogers, N.C. and F. Honary (2015), Assimilation of realtime riometer measurements into models of 30 MHz polar cap absorption, *J. Space Weather Space Clim.*, 5 A8. doi:10.1051/swsc/2015009.

Rogers, N.C., F. Honary, E.M. Warrington, A.J. Stocker, J. Hallam, D.R. Siddle, D.W. Danskin, and B. Jones (2015), Assimilative Real-time Models of HF absorption at High Latitudes, *Proc. 14th International Ionospheric Effects Symposium (IES 2015)*, Alexandria, VA, USA. 12-14 May 2015, paper 048, 1-8 (Available online http://ies2015.bc.edu/wp-content/uploads/2015/05/048-Rogers-Paper.pdf).

Sauer, H.H. and D.C. Wilkinson (2008), Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons. *Space Weather, 6,* S12002, doi:10.1029/2008SW000399.

Sweeney N.M., F.J. Rhoads and L.M. DeBlasio (1993), *Voice of America coverage analysis program (VOACAP) user's manual*, VOA B/ESA/TR-02-93, USIA/SW/CK-93/001A, PB93-155174INZ.

Zaalov, N.Y., E.V. Moskaleva, D.D. Rogov and N.N. Zernov (2015), Influence of X-ray and polar cap absorptions on vertical and oblique sounding ionograms on different latitudes, *Advances in Space Research, 56(11),* 2527-2541, doi:10.1016/j.asr.2015.09.008.

Zaalov, N.Y., E.M. Warrington and A.J. Stocker (2003), The 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, *Radio Science*, *38(3)*, 1052, doi:10.1029/2002RS002798.

Zaalov, N.Y., E.M. Warrington and A.J. Stocker (2005), A ray-tracing model to account for off-great circle HF propagation over northerly paths, *Radio Science, 40*, RS4006, doi: 10.1029/2004RS003183.

Zaalov, N.Y. and E.V. Moskaleva (2016), A polar cap absorption model optimization based on the vertical ionograms analysis, *Advances in Space Research, 58(9),* 1763-1777, doi: 10.1016/j.asr.2016.07.024.