PROGRESS TOWARDS A PROPAGATION PREDICTION SERVICE FOR HF COMMUNICATIONS WITH AIRCRAFT ON TRANS-POLAR ROUTES

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SUMMARY

Commercial airlines began operations over polar routes in 1999 with a small number of proving flights. By 2014 the number had increased to in excess of 12,000 flights per year, and further increases are expected. For safe operations, the aircraft have to be able to communicate with air traffic control centres at all times. This is achieved by VHF links whilst within range of the widespread network of ground stations, and is by HF radio in remote areas such as the Polar regions, the North Atlantic and Pacific where VHF ground infrastructure does not exist. Furthermore, the Russian side of the pole only has HF capability.

Researchers at the University of Leicester and at Lancaster University have developed various models (outlined below) that can be employed in HF radio propagation predictions. It is anticipated that these models will form the basis of an HF forecasting and nowcasting service for the airline industry.

Propagation coverage predictions make use of numerical ray tracing to estimate the ray paths through a model ionosphere. Initially, a background ionospheric model is produced, which is then perturbed to include the various ionospheric features prevalent at high latitudes (in particular patches, arcs, auroral zone irregularities and the mid-latitude trough) that significantly affect the propagation of the radio signals. The approach that we are currently adopting is to start with the IRI and to perturb this based on measurements made near to the time and area of interest to form the basis of the background ionospheric model. This is then further perturbed to include features such as the convecting patches, the parameters of which may also be informed by measurements. A significant problem is the high variability of the high latitude ionosphere, and the relative scarcity of real-time measurements over the region. Real time measurements that we will use as the basis for perturbing the IRI include ionosonde soundings from, e.g. the GIRO database, and TEC measurements from the IGS network.

Real-time modelling of HF radiowave absorption in the D-region ionosphere is also included. The geostationary GOES satellites provide real-time information on X-ray flux (causing shortwave fadeout during solar flares) and the flux of precipitating energetic protons which correlates strongly with Polar Cap Absorption (PCA). Real-time 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 (on a probabilistic basis) and the proton rigidity cutoff boundary that defines the latitudinal extent of PCA during solar proton events (SPE). Empirical climatological models have been uniquely adapted to

assimilate recent measurements of cosmic noise absorption (at 30 MHz) from a large array of riometers in Canada and Scandinavia. The model parameters are continuously optimised and updated to account for regional and temporal variations in ionospheric composition (and hence HF absorption rate (dB/km)) that can change significantly during the course of an SPE, for example. Real-time optimisation during SPE can also improve estimates of the proton rigidity cutoff and improve the modelled ionospheric response function (absorption vs. zenith angle) at twilight.

1 INTRODUCTION

Communications within the high latitude region is of growing importance for civil airlines operating trans-polar routes (see Figure 1) as these may form the shortest path between significant destinations (e.g. New York to Hong Kong), reducing travel time, cost and carbon emissions. Operation over polar routes began with a small number of flights in 1999, and by 2014, polar routes were operated by more than 10 major airlines, with over 12,000 cross-polar flights (see Figure 2). 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.

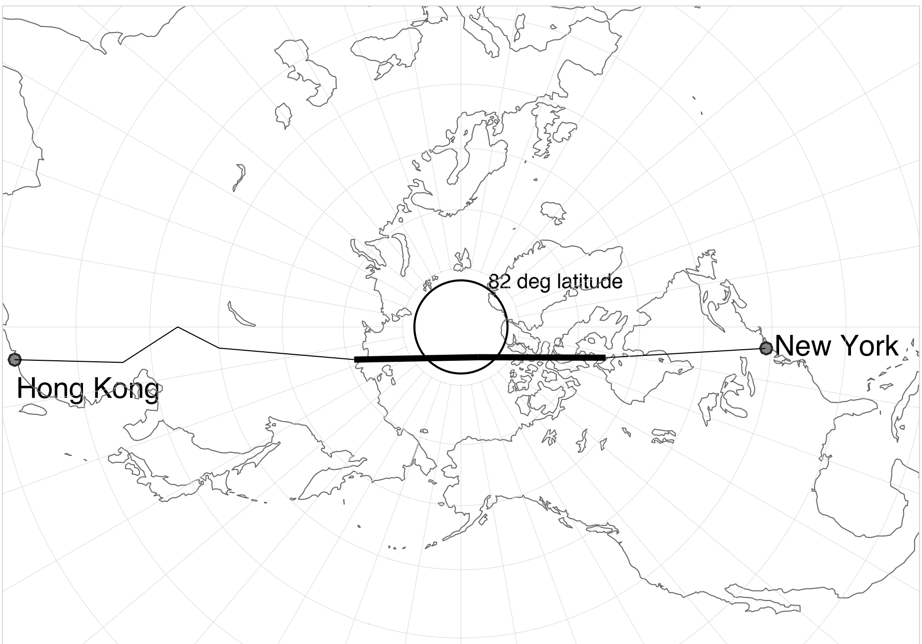

Figure 1. Example trans-polar route from New York to Hong Kong via Polar 3. The bold line indicates where communication is out of range of the VHF infrastructure and is only possible via HF links.

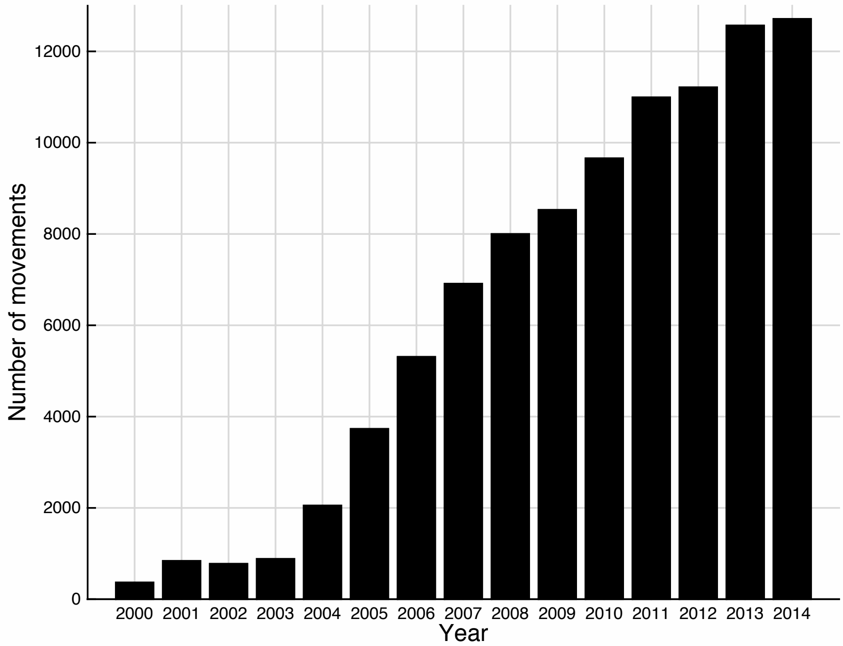

Figure 2. Number of trans-polar flights from 2000 until 2014.

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.

In addition to absorption, it is also necessary to take into account the presence of various features that are prevalent in the high latitude regions (in particular patches, arcs, auroral zone irregularities and the mid-latitude trough) that significantly affect the propagation of the radio signals. Propagation coverage predictions make use of numerical ray tracing to estimate the ray paths through a model ionosphere. Initially, a background ionospheric model is produced, which is then perturbed to include the various ionospheric features. The results of the ray tracing predictions may then be combined with absorption predictions to provide an overall estimate of signal strength and coverage over the region of interest.

2 PROPAGATION MODEL

Extensive HF propagation measurements have been made by the University of Leicester and colleagues at northerly latitudes over a number of years (see, e.g. *Warrington et al* [1997], *Zaalov et al* [2003], *Rogers et al* [1997; 2003], *Siddle et al* [2004]). Of particular relevance to this paper, measurements undertaken in the polar cap found that the presence of convecting patches and sun-aligned arcs of enhanced electron density can lead to signals arriving in directions displaced from the great circle path by up to 100° [*Warrington et al*, 1997; *Zaalov et al*, 2003]. Patches are formed in the dayside auroral oval [see, e.g. *MacDougall and Jayachandran,* 2007] during periods of southward directed Interplanetary Magnetic Field (IMF) ($Bz < 0$) and the associated high levels of geomagnetic activity and generally convect in an anti-sunward direction across the polar cap into the nightside auroral oval, whereas arcs occur when geomagnetic activity is low and the IMF is directed northward (Bz > 0) and drift in a duskwards direction [*Buchau et al.*, 1983]. Our early work was based on goniometric measurements of azimuthal direction of arrival obtained in the 1990s. More recently, we have undertaken further measurements of signals received over a number of paths (see Figure 3), including direction of arrival, time of flight (TOF) and signal strength with the specific aim of validating and developing our modelling procedures.

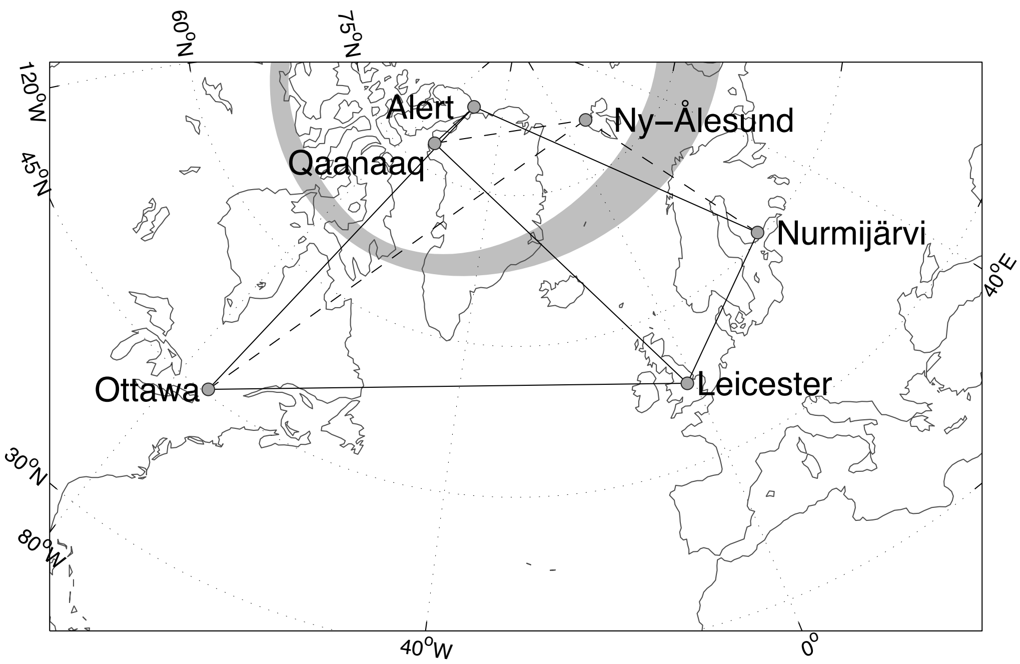

Figure 3. Map indicating our experimental configuration. Transmitters are located at Nurmijärvi, Qaanaaq and Ottawa, direction finding receivers at Alert and Leicester, and a single channel receiver at Ny-Ålesund. The solid lines indicate the paths for which directional measurements are available, and the dashed lines those paths where only signal strength measurements are made.

To estimate ray paths, and hence signal coverage, we use an ionospheric ray-tracing model, in conjunction with HF soundings, GPS TEC measurements and other geophysical data as inputs to define a model ionosphere suitable for use with the ray tracing code. A realistic background ionosphere based on the observations is combined with localised ionospheric features (e.g. polar patches and arcs), D-region absorption (see Section 3) and HF-transmitter/receiver antenna gain patterns in order to predict radio propagation behaviour.

The ionospheric ray-tracing model employed has been described elsewhere [*Zaalov et al.*, 2005], and the reader is directed to this sources for a detailed description. However, the main aspects of the model are summarised as follows:

- The simulations make use of a numerical ray tracing code [*Jones and Stephenson*, 1975] to estimate the ray paths through a model ionosphere. The background ionosphere comprises two Chapman layers, the main parameters of which (critical frequency, critical height, vertical scale height of each layer) are determined from vertical ionospheric soundings.

- The background model is then perturbed to include the various ionospheric features of interest (i.e. patches, arcs, the trough, etc). Note that the perturbations are formed from a number of Gaussian features, thus ensuring that the functions describing the electron density (and hence the refractive index) and its first derivative are continuous as required by the ray tracing code [*Jones and Stephenson*, 1975].
- Patches of enhanced electron density associated with high geomagnetic activity are modelled 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.
- 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 centre of the arc.

The area coverage expected from a transmitter at a given location is then estimated by ray-tracing through model ionospheres containing patches and arcs of enhanced ionisation. 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. Example coverage maps produced by this process for an 8.0 MHz transmitter located at Qaanaaq, Greenland are presented in Figure 4. The effect of introducing patches into the model is particularly marked in this instance.

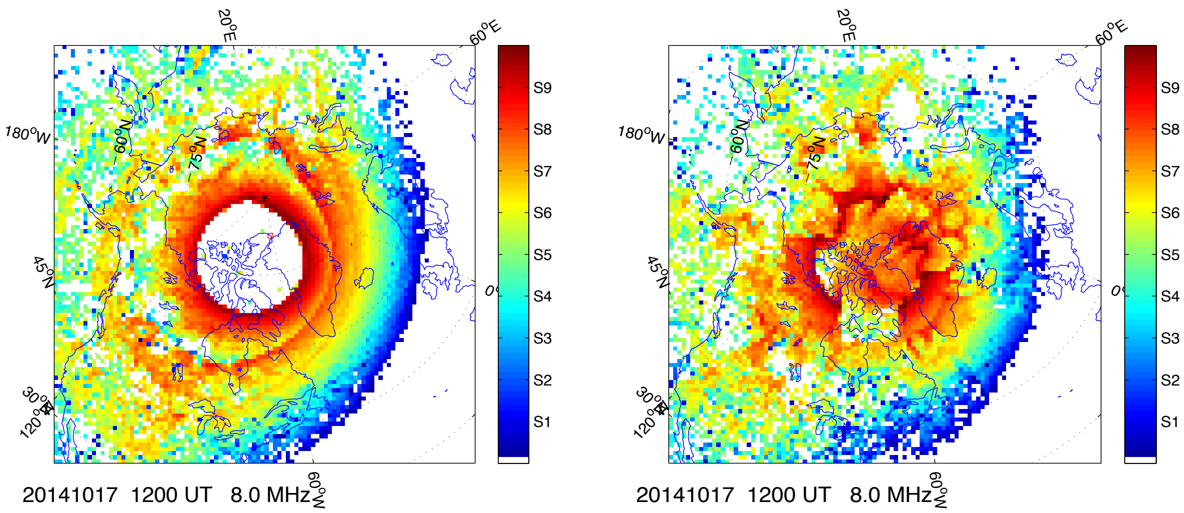

Figure 4. Coverage predicted for the Qaanaaq transmitter at 8.0 MHz using the ray-tracing model for a 1 kW transmitter and monopole antennas at both transmitter and receiver. 12:00 UT, 17 October 2014. The left hand frame is for the background ionosphere, and the right hand frame has patches included in the simulation.

3 ABSORPTION MODEL

HF absorption enhancements result from D-region ionisation by three main sources: (i) solar X-rays (from short-lived solar flares); (ii) energetic (> 20 keV) electrons precipitating from the magnetosphere into the auroral zones; and (iii) energetic (> 1MeV) solar protons. The latter source dominates absorption across the polar caps in the hours and days following large solar flares and coronal mass ejections. During a Solar Proton Event (SPE) a high flux of energetic protons enter the Earth environment and cause up to several decibels of Polar Cap Absorption (PCA) at 30MHz, with absorption at lower frequencies increasing as a power law with exponent of approximately 1.5 to 2. PCA is several times greater (in dB) during the day than during the night, mainly due to higher effective electron recombination rates in the night-time D-region. At lower latitudes, most protons have insufficient rigidity (momentum per unit charge) to overcome geomagnetic forces and access the D-region. The rigidity cutoff boundary latitude decreases with strengthening magnetospheric ring currents and has been modelled by *Smart et al.* [1999] as a function of geomagnetic indices K_p and D_{st}, and more recently by *Dmitriev et al.* [2010] and *Nesse* Tyssøy *et al.* [2013] who included a magnetic local time (MLT) dependence.

A PCA model must therefore predict the day- and night-time HF absorption as a function of the proton flux, the appropriate threshold (minimum) energies of the protons for day and night conditions, a model of the twilight transition, and a model of the rigidity cutoff boundary. A widely used PCA model is the NOAA D-Region Absorption Prediction (DRAP) model [*Sauer and Wilkinson*, 2008; *Akmaev et al.*, 2010] that incorporates real-time energetic proton flux measurements from the geostationary GOES satellite. For fully-developed day or night ionospheres, the model is expressed simply as $A = m\,(J(>E_t))^{0.5}$ where A is the absorption (in dB) of 30 MHz radio signals on a vertical one-way path through the ionosphere, m is a sensitivity parameter, $J(>E_t)$ is the flux of protons with energy greater than E_t (MeV). Since J varies approximately as a power law, $J(>E) = J(>E_t)\,(E / E_t)^{-\gamma}$, the threshold E_t is chosen to minimise the variability of m with changes in γ. Thus m and E_t are modelled as constants for fully-developed day or night-time atmospheric conditions, whilst for twilight conditions – between solar-zenith angles of $\chi_l = 80°$ and $\chi_u = 100°$ – absorption is modelled as a linear variation with zenith angle, χ.

The DRAP model framework has been developed into a new Polar Cap Absorption Model (PCAM) [*Rogers and Honary*, 2015; *Rogers et al.,* 2015] which assimilates measurements from the growing network of riometers in the Global Riometer Array (GloRiA) (Figure 5), many of which are providing real-time data online [*Danskin et al*., 2008]. Both DRAP and PCAM also incorporate real-time 0.1-0.8 nm X-ray flux measurements from GOES to improve nowcast absorption predictions during solar flare periods.

In PCAM, a set of model parameters is allowed to vary over a limited range of values. The optimal values are determined from a weighted non-linear regression to absorption measurements, where the weights, $w = \exp(-t/\tau)$, decrease with increasing age, t, over a characteristic time, τ (typically 24 h). PCAM therefore dynamically optimises the parameters m and E_t (each for day and night), the twilight zenith angle ranges χ_l and χ_u (independently for sunrise and sunset), and a parameter, $\Delta\lambda$, which corrects the *Smart et al.* [1999] model of the rigidity cutoff latitude. The twilight transition is modified slightly from the linear model in DRAP to a smoother error function transition. Figure 6 presents an example of a fitting such a model for sunset transitions during the SPE of April 2002 at the Ft Churchill riometer (labelled FCHU in Figure 5), illustrating the optimisation of m for day and night (labelled m_d and m_n respectively), and the zenith angle limits of the twilight region χ_l and χ_u.

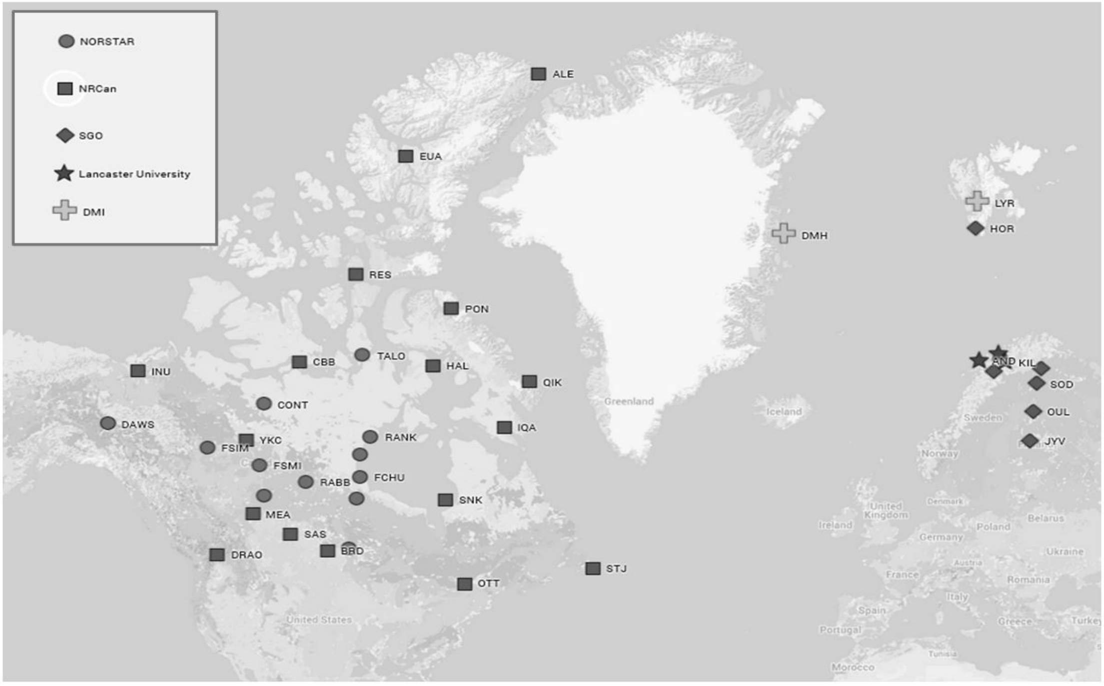

Figure 5. Selected riometers in the Global Riometer Array (GloRiA).

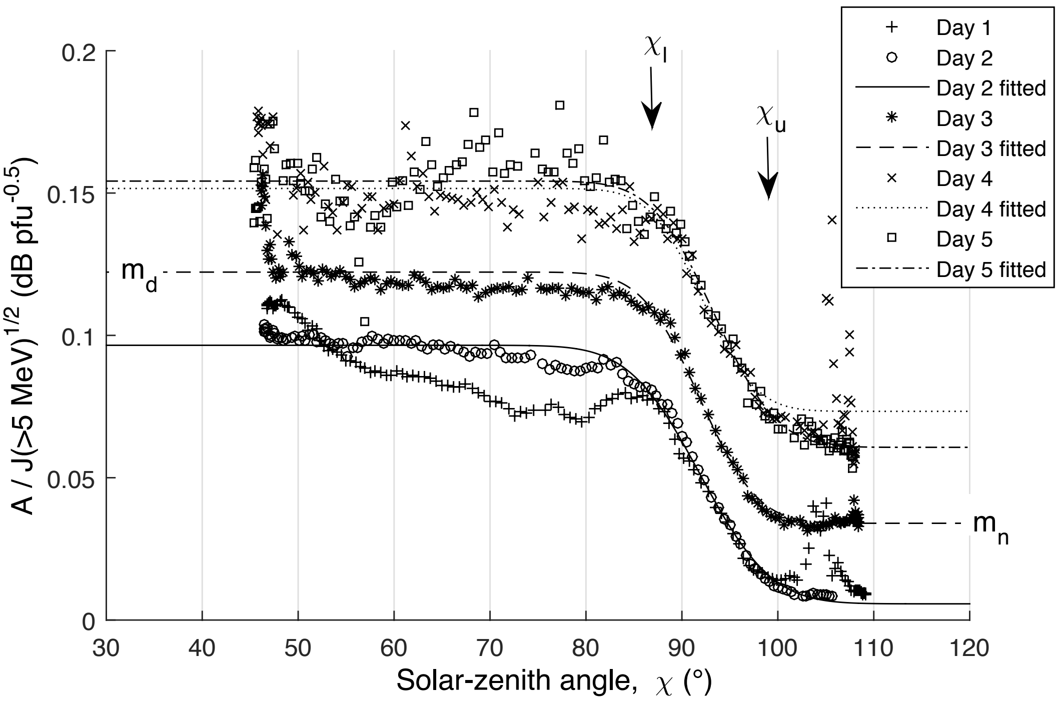

Figure 6. An example of fitting PCA model parameters m (day and night), χl and χu to Ft Churchill riometer measurements (points) of 30 MHz absorption and GOES measurements of proton flux. Model fits (lines) are optimised for sunset periods for 21-25 April 2002 (the plots cover the 12-24 local time period).

Further optimisation is possible by adding terms describing MLT and seasonal dependences. Based on an analysis from all SPEs in the period 1995-2010, assimilating data from 14 riometers reduced root-mean-square errors by 22-36% depending on the number of parameters chosen for optimisation [*Rogers and Honary*, 2015].

When there are no SPEs or solar flares in progress, HF absorption in the auroral zones is dominated by electron precipitation from the magnetosphere. This can be localised and sporadic in nature and so is modelled on a probabilistic basis, adopting the model of *Foppiano and Bradley* [1983], which is a function of K_p, MLT, season, and location. This model predicts the median absorption and the probability that $A > 1$ dB assuming a Normal probability distribution function of log(A(dB)). In nowcasting applications, the K_p index may be replaced by forecasts based on in-situ measurements of the solar wind and interplanetary magnetic field at the ACE or DSCOVR satellites [*Wing et al.*, 2005, and references therein].

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 a nowcast of HF ionospheric propagation and absorption conditions that is consistent with measurements made on a number of oblique HF paths. In order to provide forecasts, anticipated space weather conditions need to be incorporated into the model.

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