

Chapter 10

The Effects of Space Weather on Radio Systems

with a focus on HF systems

P. S. Cannon^{*}, M. J. Angling, J. A. T. Heaton, N. C. Rogers, A. K. Shukla
*Centre for RF Propagation and Atmospheric Research, QinetiQ
Worcs, WR14 3PS, UK*

^{}Also at Dept of Electronic and Electrical Engineering, University of Bath, Bath, BA2 7AY, UK*

Abstract If the environment were isotropic and stable in time, it would be relatively easy to determine its effects on the propagation of RF waves. Unfortunately, this is not the case. The spatial scales of inhomogeneities vary from thousands of kilometres to turbulence with scale sizes of a less than a metre. Likewise the temporal scales vary over many orders of magnitude from many years (solar cycle effects on ionospheric propagation) to hours or even minutes (the scale of weather phenomena). As a consequence of this variability, timely and reliable strategies are required to both specify and accurately forecast the environment and to assess the attendant impact on the operational performance of the RF systems. These strategies can be used to automatically apply corrections to the system operating parameters or advise the user on a course of action that will improve the system functionality. This paper will review these phenomena and describe their impact on a number of systems. The effect that space weather has on high frequency (HF) systems will be addressed in some detail and strategies for mitigating its effects will be described.

Keywords Radio propagation, total electron content, HF communications, ionosphere, space weather

1. INTRODUCTION

The ionosphere, an area of the atmosphere which extends from ~80 to ~1000 km, can significantly affect the propagation of radio frequency (RF) signals which pass through it or are reflected by it [Cannon, 1994a; Cannon, 1994b]. The effects are varied but include absorption, refraction, retardation and scintillation. At frequencies above ~1 MHz, the lower *D* region causes absorption and the higher *E* and *F* regions cause a variety of other effects. These effects, which include refraction, signal group delay, signal phase advance, pulse broadening and Faraday rotation of the polarisation vector, all follow an inverse power law and are generally only significant up to a frequency of ~2 GHz. Below ~1 MHz radio systems bounce their signals from the tenuous *D* region; consequently although the height of the layer is important for system operation, absorption is not an issue.

The diverse set of affected systems (Figure 1) include ground-ground high frequency (HF) communications, ground-space communications, GNSS (Global Navigation Satellite Systems), such as GPS (Global Positioning System) and Galileo – particularly single-frequency systems, HF over-the-horizon radars, satellite altimeters and space-based radars [Goodman and Aarons, 1990]. HF communications and radar systems rely on the ionosphere for their operation but also have to contend with its effects. Most other systems are degraded by the ionosphere and its variability but for certain specialist applications this variability can be exploited. Loss of phase lock and range errors in GNSS are examples of such deleterious effects.

If the ionospheric environment were isotropic and stable in time, it would be relatively easy to determine its effects on the propagation of RF waves. Unfortunately, this is not the case. The spatial scales of inhomogeneities vary from thousands of kilometres to turbulence with scale sizes of a less than a metre. Likewise, the temporal scales vary over many orders of magnitude from many years (solar cycle effects on ionospheric propagation) to hours or even minutes (the scale of weather phenomena). As a consequence of this variability, timely and reliable strategies are required to both specify and accurately forecast the environment and to assess the attendant impact on the operational performance of the RF systems. These strategies can be used to automatically apply corrections to a systems operating parameters or, via a decision aid, advise the user on a course of action that will improve a systems functionality [Cannon *et al.*, 1997].

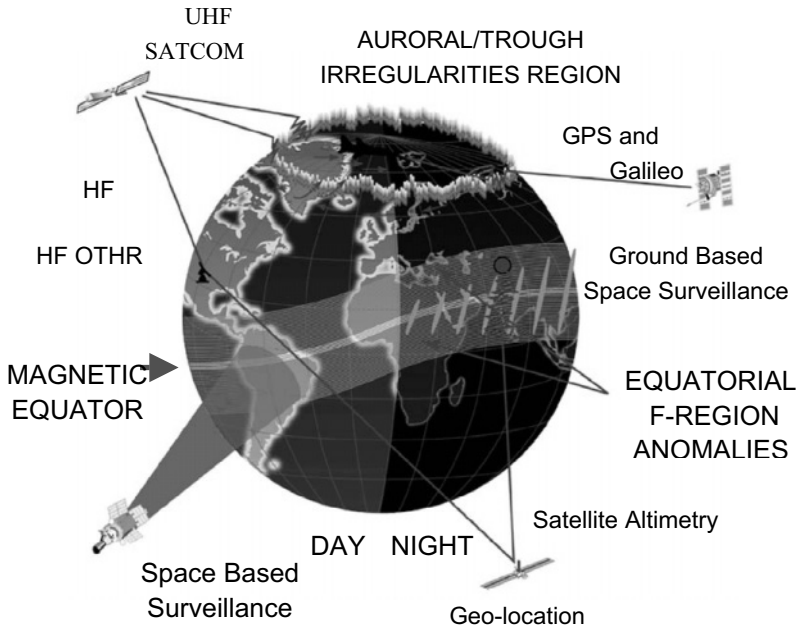


Figure 1. Systems affected by the ionosphere

2. IONOSPHERIC VARIABILITY

2.1 Naturally occurring variability

Natural variability can be categorized into that due to bulk (average) effects and that due to small-scale irregularities with sizes less than a Fresnel radius. The bulk effects, including variations in the refraction and time delay of signals propagating through the ionosphere, can cause varying areas of coverage in HF systems. At UHF they introduce errors in radar, altimetry, geolocation and space-based navigation systems ($\sim 30\text{m}$). Single frequency GNSS transmits model coefficients to mitigate these errors but it is unable to fully compensate for the day-to-day and hour-to-hour variations. Dual frequency GNSS can use the different delays of the two transmitted frequencies to calculate the total electron content (TEC) and make an almost exact correction. Irregularities in the plasma density cause signal scintillation [Aarons, 1982]; i.e. random variations in amplitude and phase. These are generally quantified in terms of the standard deviation of phase, σ_ϕ , and the standard deviation of the signal power, normalised to the average received

power, *S4*. Scintillation can cause data errors in communications, loss of coherence in radar applications and loss of signal lock in GNSS navigation. At the peak of the sunspot cycle fade depths of 30 dB are possible at 400 MHz and 20 dB fades are possible at 1 GHz. Phase changes also limit the ability of synthetic aperture radar (SAR) systems to form a phase coherent aperture and so reduce resolution.

2.2 Artificially induced variability

The ionosphere is a naturally occurring plasma environment, which can be artificially modified by a number of techniques. Modification of the ionosphere by the release of large volumes of chemically reactive gases is one such technique. This possibility was first recognised by the discovery that rocket exhausts deplete the local charged particle density. A second technique makes use of charged particle accelerators both to modify ionospheric properties and create artificial auroras. A third technique uses VLF radiation generated on the ground to stimulate instabilities in the magnetospheric plasma that in turn generate hydromagnetic emissions and cause particle precipitation. This technique arose from the discovery that ground based power transmission lines could affect the particle distribution in the magnetosphere. A fourth technique uses high power ground based transmitters at LF or higher frequencies both to modify the ionosphere and to generate secondary radio emissions. For purpose built facilities the effective isotropic radiated power (EIRP) can be as high as 80-90 dBW. An example of unintended artificial modification of the ionosphere is reported in [*Cannon, 1982*].

3. SCOPE OF PAPER

The previous sections have discussed the impact that the ionosphere has on a broad range of systems. A discussion of the relevant space weather research and development being undertaken to support all of these systems is outside of the scope of this paper. The remainder of this paper will consequently address in more detail the effect that space weather has on high frequency (HF) systems - with an emphasis on work being undertaken in our own laboratory.

4. HF SYSTEMS

4.1 Median models

To ensure circuit reliability, an HF communications operator or provider is assigned a number of frequencies to counter the effects of the day-to-day variability of the ionosphere. The choice of the correct frequency is fundamental to maintaining acceptable communications. The successful selection of the most appropriate frequency depends upon the ability to predict and respond to the prevailing ionospheric conditions.

Space weather affects the operation of HF systems in many ways and to a first approximation this can be dealt with using climatological (monthly median) models of the electron density height profile, such as that described by [Bradley and Dudeney, 1973], coupled with a propagation model. In these climatological approaches a simple virtual mirror propagation model is assumed. These concepts are formalized in the secant law, Breit and Tuve's theorem and Martyn's equivalent path theorem, e.g [McNamara, 1991]. There are a number of such HF propagation tools available to aid the system manager (or operator). They require as input the geographic co-ordinates of the transmitter and receiver, the level of solar activity, the month and time, and the background noise level at the receiver. Additional inputs may consist of the planetary magnetic index (k_p), the transmitter power, the bandwidth, and the required circuit reliability. Example monthly median propagation tools are: ICEPAC [Stewart and Hand, 1994], IONCAP [Teters *et al.*, 1983], VOACAP [Lane *et al.*, 1993], MINIMUMF [Rose *et al.*, 1978] and REC533 [ITU-R, 1999].

Monthly median models to predict the performance of HF systems were first introduced over 40 years ago and there has been steady progress improving the core ionospheric models [Bilitza, 2002]. Examples include NeQuick [Radicella and Leitinger, 2001], PIM [Daniell *et al.*, 1995], and various upgrades to the International Reference Ionosphere, IRI [Bilitza, 2000].

4.2 Ionospheric variability in the context of HF propagation

Figure 2 shows the maximum usable frequency (MUF) measured by an IRIS oblique ionosonde [Arthur *et al.*, 1997] on a 400 km path from Inskip (53.9°N, 2.8°W) to Malvern (52.1°N, 2.3°W), in the UK, over a period of 13 days in October 2002. This period coincided with a period of variable geomagnetic activity. The selected oblique ionograms from the data sets were examined and the MUF of the F layer trace was extracted using IRIS

analysis software [Heaton, 1999]. Figure 3 shows the minimum and maximum measured MUF alongside the predicted value from REC 533. This period was moderately disturbed geomagnetically with k_p lying between three and five. Both figures illustrate the day-to-day variability in the MUF with values changing by several megahertz. There is a notable drop in the MUF on the 2nd and 3rd of November, corresponding to increased geomagnetic activity.

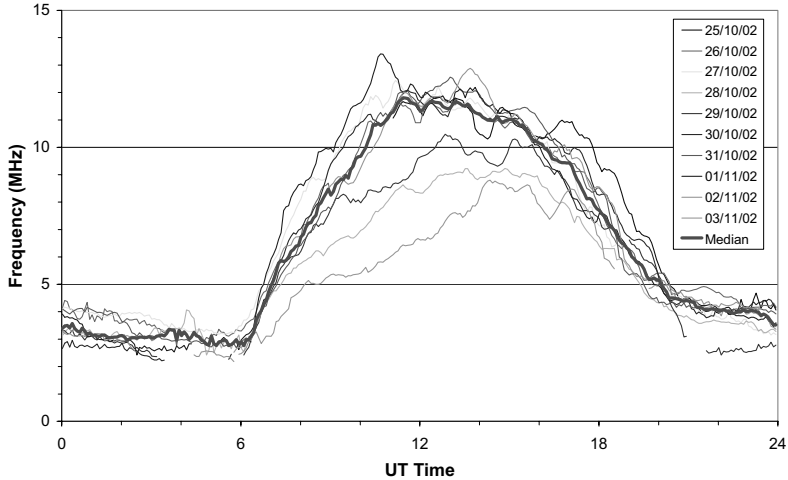


Figure 2: Maximum Usable Frequency as a function of time measured by the IRIS sounder for the Inskip to Malvern path for 25 October to 3 November 2002.

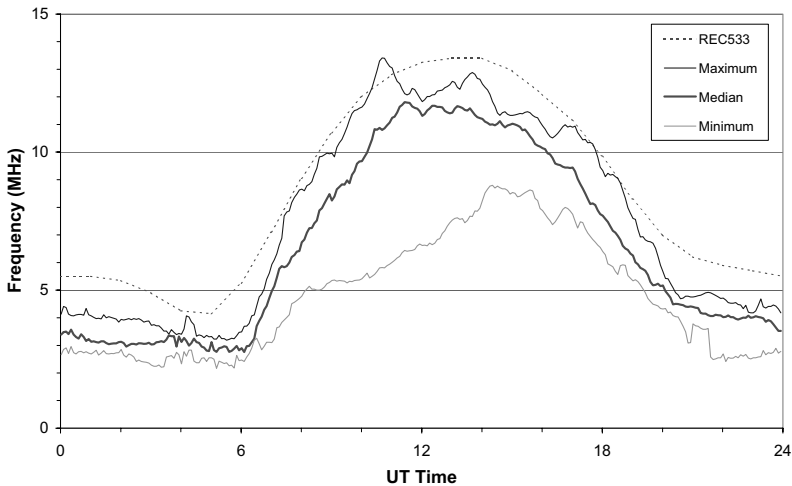


Figure 3. Minimum, median and maximum measured MUF (solid lines) determined from Figure 2, along with the median MUF determined by REC533 (dotted line).

4.3 A simple strategy for ionospheric model updating

We have seen that the MUF of a BLOS HF communications link can be predicted using HF communications prediction programs such as VOACAP and REC533. However, we have also seen that values of the predicted MUF may depart considerably (e.g. up to 50%) from the measured MUF.

A number of simple strategies have also been developed for dealing with the short-term variability in the context of HF propagation. Examples can be found in such propagation tools as: HF-EEMS [Shukla *et al.*, 1997], OPSEND [Bishop *et al.*, 2002], the Teleplan HF frequency management tool (Norwegian Army) and WinHF. Varying levels of sophistication are embodied in these techniques and others are still in development.

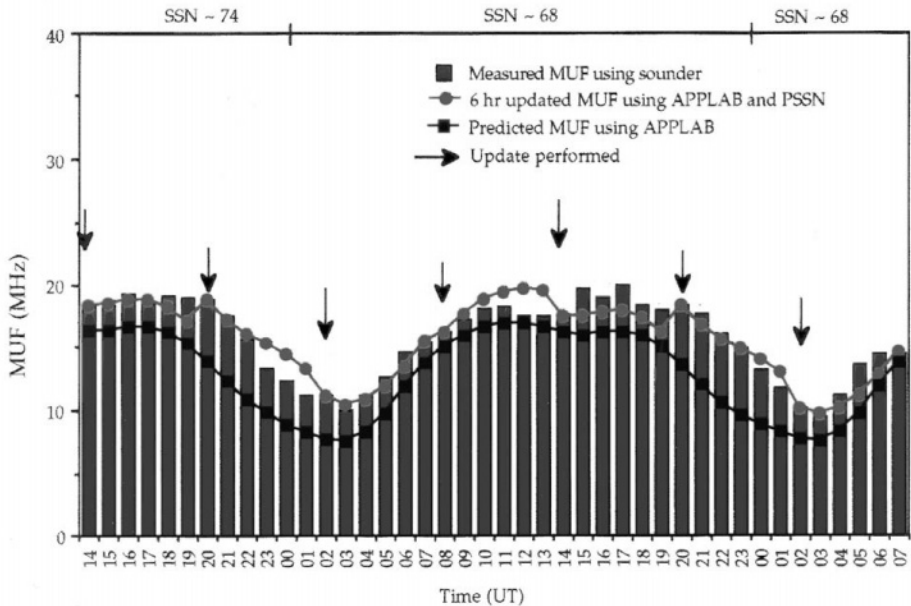


Figure 4: Six hourly updates of the Andoya (Norway) to Cobbett Hill path using PSSNs for 27 to 29 April 1993.

A simple and effective approach to dealing with space weather variability in the context of HF involves comparing measured (e.g. using sounders) and predicted (e.g. using REC533) MUF values. The prediction program input parameters (e.g. sunspot number) are then varied until the predicted MUF agrees with the measured MUF value. The prediction program then uses these best-fit input parameters, termed pseudo-parameters, until the next update is performed. Whilst this technique has been successfully applied to

the mid-latitude (and often benign) ionosphere, the technique is of limited use when applied to high latitude paths.

The limitations of temporal updating have been investigated [*Shukla and Cannon, 1994*]. An oblique sounder was used to make MUF measurements on a path from Andoya (in northern Norway) to Cobbett Hill (south of London, UK) from 27 to 29 April 1993. These measurements were used to update the APPLAB (similar to REC 533) propagation mode every six hours and every 12 hours, Figure 4. The predictions compare more favourably with the measurements when the model is updated more frequently, ie every six hours. Calculations show that 12 hourly updated MUF predictions indicate an improvement of ~38% compared with ~63% MUF prediction improvement observed using 6 hourly updates.

4.4 Adaptive techniques

Another strategy to cope with ionospheric variability due to space weather is to use adaptive systems, such as automatic link establishment (ALE) or automatic radio control systems (ARCS), that can automatically select and change frequency as appropriate. [*Jodalen et al., 2001*] has used oblique data from the Doppler And Multipath Sounding Network (DAMSON) sounder and modem performance characterizations [*ITU, 2000*], coupled with the ICEPAC HF prediction code [*Stewart and Hand, 1994*], to determine the optimal number of allocated frequencies required by an adaptive HF system. Optimal was considered to be the minimum number of frequencies to achieve maximum reliability. On a 2000 km path it was shown that 5-6 frequencies were sufficient whereas on a short 200 km path 3-4 frequencies were sufficient. Figure 5 shows an example from this study.

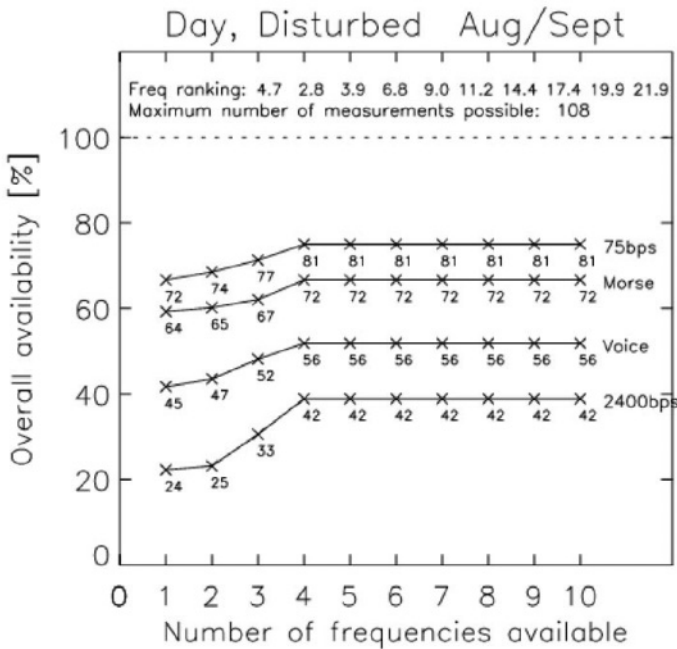


Figure 5. Overall availability of modems when the frequency set consists of 1,2,...,10 frequencies a propagation path from Harstad (Norway) to Kiruna (Sweden).

4.5 Data Assimilation

Climatological models are not sufficiently accurate to support new HF applications where it is important to adapt to the changing ionosphere. For these HF applications, and many of the others described in Section 2, it is necessary to have a much more accurate real-time ionospheric map in order to be able to better predict the propagation of the radio signals. Local area and wide area forecasts have been developed using predictive filtering and heuristic techniques, e.g. [Francis *et al.*, 2000] but more recently data assimilation approaches have been addressed. PRISM [Daniell *et al.*, 1995], was an early attempt to deal with the problem of fusing data from various sources into the model.

Although many ground and spaced based techniques have been developed to characterise the ionosphere, the measurements are generally sparsely distributed. Furthermore the measurements often do not measure ionospheric electron density directly; rather they may measure critical frequencies, integrated total electron contents (TEC) or airglow. Such measurements must be inverted to yield electron density. Often the inversions are underdetermined and it is therefore necessary to apply

constraints to the inversions. This may be done by making assumptions about the ionosphere (i.e. it is spherically symmetric), by using a limited number of functions to represent the ionosphere (e.g. empirical, spherical harmonics), or by assimilating the data into a background model of the atmosphere.

The output of a data assimilation process aims to combine measurement data with a background model in an optimal way [Rodgers, 2000]. It is necessary to include a background model because the information that can be extracted from many ionospheric measurements is low compared to the required resolution of the electron density field under investigation (i.e. the problem is mathematically under-determined). Since both the observations and the background model contain errors it is not possible to find the true state of the environment – instead the best statistical estimate of the state must be found. Such techniques are also well suited to sparse data sets. Best Linear Unbiased Estimator (BLUE) and related variational (one, three and four dimensional) data assimilation techniques have been used in meteorology for a number of years and have recently been applied to ionospheric inversion [Wang *et al.*, 1999], [Pi *et al.*, 2003], [Hajj *et al.*, 2003].

Angling and Cannon, [2003] describe the application of data assimilation techniques for combining radio occultation data with background ionospheric models. In simulations where tomographic images provide the truth data and PIM provides the background, a fourfold decrease in the electron density error at 300 km altitude was achieved. A global assimilation simulation has also been conducted using IRI as the truth data. For a constellation of eight RO satellites, a factor of four decrease in the vertical TEC RMS error has also been demonstrated (Figure 6). The same simulation also results in a factor of three decrease in the NmF2 RMS error, and a halving of the hmF2 RMS error.

4.6 Ionospheric channel effects

Because of the detrimental effects of the ionospheric radio channel it was common, until about 10 years ago, for HF users to expect both data rates of little more than 75 bit.s^{-1} and low availabilities. However, with the advent of cheap digital signal processing in the last few years, data rates have increased significantly to 2.4 kbit.s^{-1} , 4.8 kbit.s^{-1} , and beyond in a 3kHz channel. Data rates on benign skywave channels and on ground wave paths can now reach 64 kbit.s^{-1} , albeit sometimes using wider channel bandwidths, and there is an increasing desire to achieve 16 kbit.s^{-1} reliably.

In considering the impact that space weather has on HF systems it is easy to lose sight of the fact that the Doppler and multipath characteristics of the signal are critically important issues [Cannon and Bradley, 2003]; [Cannon

et al., 2002]. Indeed it is these issues that have driven the standardization and imminent introduction of digital HF transmissions for broadcasting.

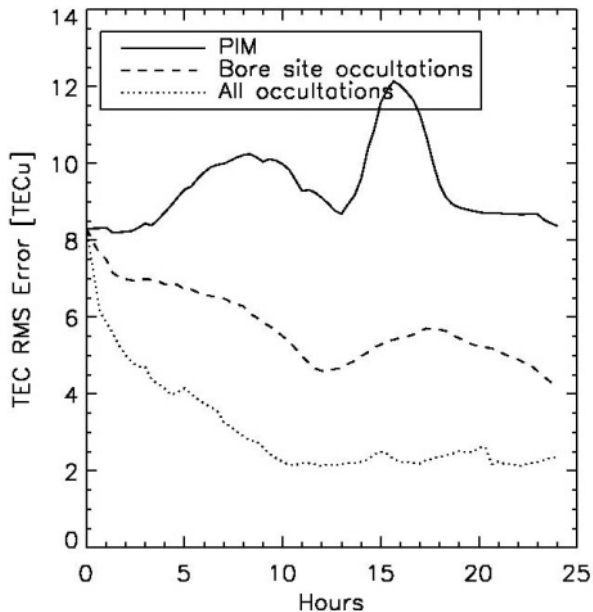


Figure 6. Vertical TEC RMS errors between IRI and PIM (solid line), IRI and a data assimilation process using bore site ($\pm 30^\circ$) radio occultation measurements (dashed line) and IRI and the same process using all available radio occultation measurements (dotted line).

The design of modern HF systems is a considerable technical challenge, the success of which critically depends on good understanding and modelling of the radio channel that is in turn controlled by space weather.

Multipath propagation may arise because replicas of the transmitted signal arrive at the receiver after reflection from more than one ionospheric layer. Additionally, the transmitted signal may undergo multiple reflections between the ionosphere and the ground, and all of these signals may be received. Each signal (or propagation mode) generally arrives with a different time delay and to complicate the situation further each may exhibit time spreading. Viewed in the frequency domain, multipath distortion dictates the coherency bandwidth of the channel.

Frequency shifts and frequency spread distortion can also be imposed on the transmitted signal by the temporal variability of the ionospheric channel, e.g. [Basler *et al.*, 1988], and this defines the coherency time of the channel. Such effects are particularly prevalent at high and equatorial latitudes where Doppler spreads of many hertz are common. However, slow fading at mid-

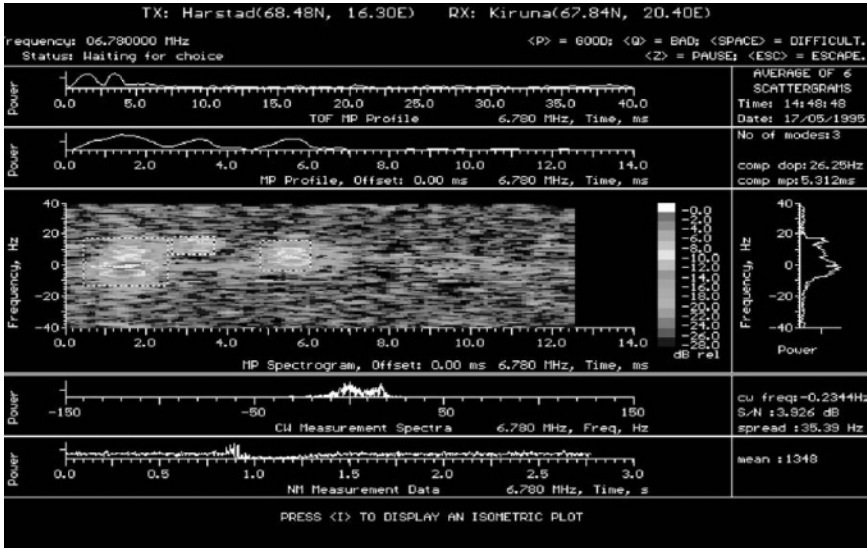


Figure 7. Doppler and multipath measurement for a high latitude path from Harstad (Norway) to Kiruna (Sweden).

latitudes is equally challenging since it can result in long periods of low signal strength.

DAMSON (Doppler And Multipath SOunding Network) [Davies and Cannon, 1993] is a relatively low power pulse compression ionospheric sounder. It uses pulse compression sequences, on pre-selected frequencies between remote transmit and receive sites to provide real-time HF channel measurements of the channel scattering function. It therefore provides measurements of absolute time of flight (typically up to 40 ms), multipath (typically up to 12.5 ms with 600 μ s resolution in a 3 kHz bandwidth), Doppler shift and spread (typically up to ± 40 Hz with 0.6 Hz resolution), signal to noise ratio (SNR) and absolute signal strength (Figure 7).

Data from a high latitude DAMSON network were analysed by [Willink, 1997] to determine the diurnal distribution of Doppler spread, multipath spread and SNR on each high latitude path. An important result of this work was the specification of the operating envelope for the low data rate NATO HF modem, STANAG 4415 [NATO, 1998].

In analysis by [Angling *et al.*, 1998] the data were broken down into seasons, two time periods and four frequency bands. The times used were all day (0000-2400 UT) and 1900-0100 UT; the latter period approximately corresponded to 2100-0300 CGMLT (Corrected GeoMagnetic Local Time) when the auroral oval was expected to be in its southernmost position and, consequently, when the largest disturbances were expected. A summary of the 95th percentile multipath, Doppler spreads and SNRs were presented for

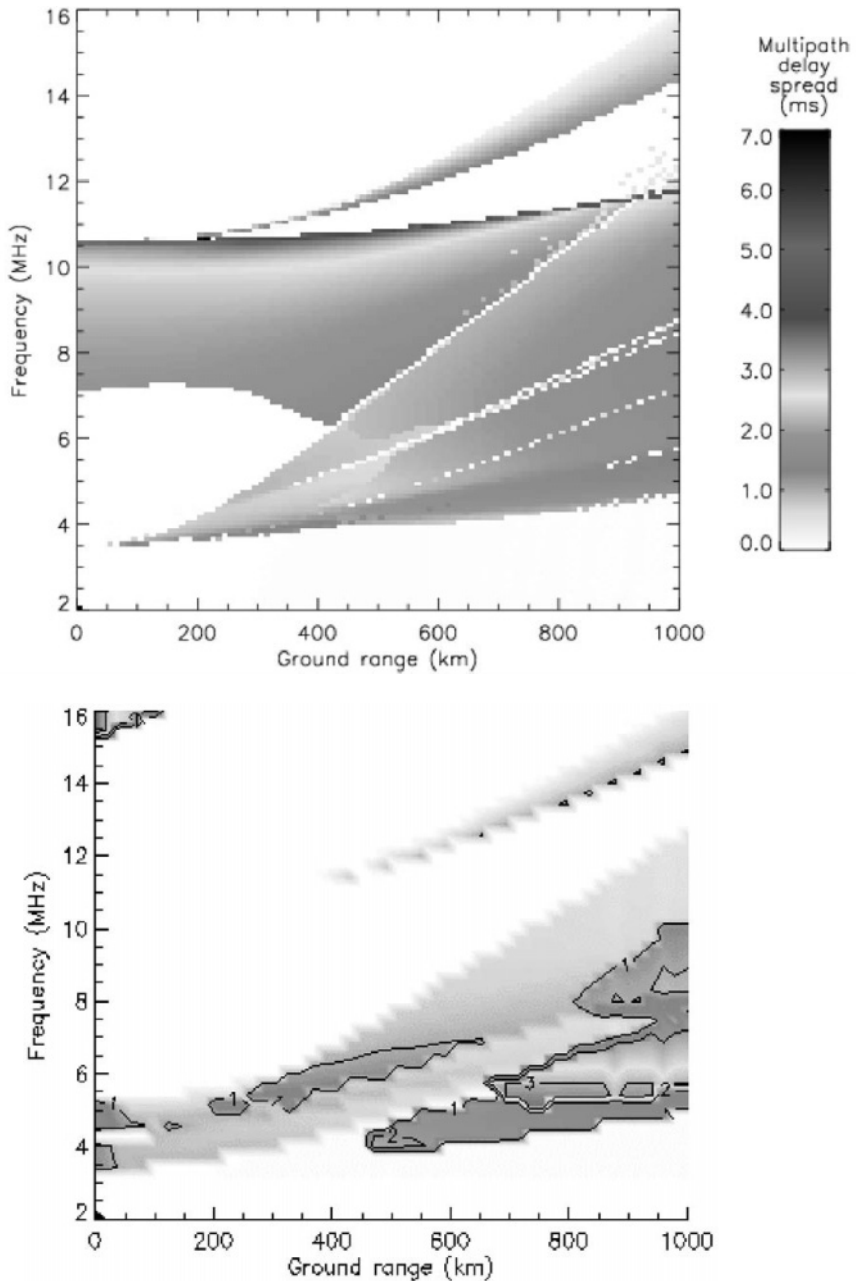


Figure 8. Multipath delay spread determined (upper panel) with SMART ray tracing through a FAIM model ionosphere and compared with (lower panel) “virtual mirror” median model predictions. Propagation is due south of 55°N, 15°E at 11UT on a March equinox day with sunspot number = 122. Modes of propagation with signal strength less than 15 dB below the strongest mode are excluded.

each path. For certain time/frequency/path combinations the 95th percentile Doppler spreads exceeded 73 Hz, while 95th percentile multipath spreads exceeded 11 ms.

4.7 Ray tracing

Ray tracing may be used in HF Over-The-Horizon Radar and HF Direction Finding systems for both frequency planning and the accurate co-ordinate registration of targets or transmitters. Importantly however, with the increasing use of digital HF broadcasting, ray tracing finds another application in as a tool for determining multipath delays, since these are not adequately determined, theoretically, using virtual mirror techniques.

A propagation model based on mirror reflection geometry is well matched to monthly median models but with improved electron density mapping of the effects of space weather improved propagation modeling will also be required. Numerical ray tracing [Jones and Stephenson, 1975] will provide the highest accuracy but analytic techniques have been developed which provide comparable accuracy with much shorter computer run times [Bennett *et al.*, 1991; Norman and Cannon, 1997; Norman and Cannon, 1999].

A comparison between ray-traced multipath spreads with those predicted using a popular 'virtual mirror' type of HF median model is presented in Figure 8. Clear differences in the distribution of multipath spread as a function of frequency and ground range between the analytic ray trace through the FAIM model [Anderson *et al.*, 1989.] (Figure 8a, upper panel) and the "virtual mirror" median model predictions (Figure 8b, lower panel) are evident. For example, the highest multipath spreads of Figure 8a are associated with one-hop and two-hop ionospheric F-layer reflections and these are not evident in the median model predictions (Figure 8b, lower panel). Ray tracing has the potential to considerably improve multipath delay predictions, particularly where group retardation due to underlying layers of the ionosphere is significant, and where high and low angle rays or o and x polarisations are present with similar signal strength.

However, the accuracy of ray tracing is always limited by the the veracity of the electron density model used. This fact emphasises the importance of space weather studies leading to ionospheric models which can be updated using real-time measurements.

5 SUMMARY

In this paper we have sought to provide some understanding of why space weather is important to so many radio systems and then to illustrate this by reference to the mitigation of space weather especially in the context of HF systems.

6. ACKNOWLEDGEMENTS

The results presented herein cover work conducted by a number of people – past and present – in the Centre for RF Propagation and Atmospheric Research at QinetiQ – formerly DERA. We acknowledge their input with gratitude.

7. REFERENCES

- Aarons, J., Global morphology of ionospheric scintillation, *Proc. IEEE*, 70 (4), 360-377, 1982.
- Anderson, D.N., J.M.Forbes, and M. Codrescu, A Fully Analytical, Low- and Middle-Latitude Ionospheric Model, *Journal of Geophysical Research*, 94, 1520, 1989.
- Angling, M.J., and P.S. Cannon, Assimilation of Radio Occultation Measurements into Background Ionospheric Models, *Submitted to Radio Science*, 2003.
- Angling, M.J., P.S. Cannon, N.C. Davies, T.J. Willink, V. Jodalen, and B. Lundborg, Measurements of Doppler and Multipath Spread on Oblique High-Latitude HF Paths and their use in Characterising Data Modem Performance, *Radio Science*, 33 (1), 97-107, 1998.
- Arthur, P.C., M. Lissimore, P.S. Cannon, and N.C. Davies, Application of a high quality ionosonde to ionospheric research, in *HF Radio Systems and techniques*, pp. 135-139, IEE, Nottingham, UK, 1997.
- Basler, R.P., P.B. Bentley, R.T. Price, R.T. Tsunoda, and T.L. Wong, Ionospheric Distortion of HF Signals, *Radio Science*, 23 (4), 569-579, 1988.
- Bennett, J.A., J. Chen, and P.L. Dyson, Analytic Ray Tracing for the Study of HF Magnetoionic Radio Propagation in the Ionosphere,, *App. Computational Electromagnetics J.*, 6, 192-210, 1991.
- Bilitza, D., International Reference Ionosphere 2000, *Radio Science*, 36 (2), 261-275, 2000.
- Bilitza, D., Ionospheric Models for Radio Propagation Studies, in *Review Of Radio Science 1999-2002*, edited by W.R. Stone, pp. 625-679, IEEE and Wiley, 2002.
- Bishop, G., T. Bullett, K. Groves, S. Quigley, P. Doherty, E. Sexton, K. Scro, R. Wilkes, and P. Citrone, Operational Space Environment Network Display (OpSEND), in *10th International Ionospheric Effects Symposium*, Alexandria, Virginia, USA, 2002.
- Bradley, P.A., and J.R. Dudeney, A simplified model of the vertical distribution of electron concentration in the ionosphere, *J. Atmos. Terr. Phys.*, 35, 2131-2146, 1973.
- Cannon, P.S., Ionospheric ELF radio signal generation due to LF and/or MF radio transmissions: Part I Experimental results, *J. Atmos Terr Phys*, 44, 819-829, 1982.

- Cannon, P.S., Propagation in the ionosphere (A), in *Propagation Modelling and Decision Aids For Communications, Radar and Navigation Systems*, pp. 1A1-1A10, NATO-AGARD, 1994a.
- Cannon, P.S., Propagation in the ionosphere (B), in *Propagation Modelling and Decision Aids For Communications, Radar and Navigation Systems*, pp. 1B1-1B17, NATO-AGARD, 1994b.
- Cannon, P.S., M.J. Angling, and B. Lundborg, Characterisation and Modelling of the HF Communications Channel, in *Review Of Radio Science 1999-2002*, edited by W.R. Stone, pp. 597-623, IEEE-Wiley, 2002.
- Cannon, P.S., and P. Bradley, Ionospheric Propagation, in *Propagation of Radio Waves (2nd Edition)*, edited by L.W. Barclay, pp. Chapter 16, IEE, London, 2003.
- Cannon, P.S., J.H. Richter, and P.A. Kossey, Real time specification of the battlespace environment and its effects on RF military systems, in *Future Aerospace Technology in Service of the Alliance*, AGARD multi-panel symposium, Paris, 1997.
- Daniell, R.E., L.D. Brown, D.N. Anderson, M.W. Fox, P.H. Doherty, D.T. Decker, J.J. Sojka, and R.W. Schunk, PRISM: A global ionospheric parameterisation based on first principles models, *Radio Science*, 30, 1499, 1995.
- Davies, N.C., and P.S. Cannon, DAMSON- A System to Measure Multipath Dispersion, Doppler Spread and Doppler Shift, in *AGARD Symposium on Multi-Mechanism Communication Systems*, pp. 36.1-36.6, NATO AGARD/RTO, 7 Rue Ancelle, 92200 Neuilly sur Seine, France, Rotterdam, Netherlands, 1993.
- Francis, N.M., P.S. Cannon, A.G. Brown, and D.S. Broomhead, Nonlinear prediction of the ionospheric parameter foF2 on hourly, daily and monthly timescales., *J. Geophys. Res.*, 105 (A6), 12839-12849, 2000.
- Goodman, J.M., and J. Aarons, Ionospheric effects on modern electronic systems, *Proc. IEEE*, 78 (3), 512-528, 1990.
- Hajj, G.A., B.D. Wilson, C. Wang, W. Pi, and I.G. Rosen, Ionospheric data assimilation of ground GPS TEC by use of the Kalman filter, *Submitted to Radio Science*, 2003.
- Heaton, J.A.T., IRIS Analysis Package Users Guide, DERA/CIS/CIS1/SUM990673, DERA, Malvern, Worcs, UK, 1999.
- ITU, Testing of HF Modems with Bandwidths of up to about 12 kHz using Ionospheric Channel Simulators, pp. 11, Rec. ITU-R F.1487, ITU, Geneva, Switzerland, 2000.
- ITU-R, HF Propagation Prediction Method, ITU-R P.533-7, International Telecommunications Union, Geneva, Switzerland, 1999.
- Jodalen, V., T. Bergsvik, P.S. Cannon, and P.C. Arthur, The performance of HF modems on high latitude paths and the number of frequencies necessary to achieve maximum connectivity, *Radio Science*, 36 (6), 1687, 2001.
- Jones, R.M., and J.J. Stephenson, A Three-Dimensional Ray Tracing Computer Program for Radio Waves in the Ionosphere, OT Report 75-76, US Dept. of Commerce, Office of Telecommunication, 1975.
- Lane, G., F.J. Rhoads, and L. DeBlasio, Voice of America coverage analysis program, (VOACAP). A guide to VOACAP, *B/ESA Technical Report 01-93*, US Information Agency, Bureau of Broadcasting, Washington, D. C. 20547-0001, 1993.
- McNamara, L.F., *The ionosphere: communications, surveillance and direction finding*, Krieger Publishing Company, Malabar, Florida, 1991.
- NATO, STANAG 4415: Characteristics of a Robust Non-Hopping Serial Tone Modulator/Demodulator for Severely Degraded HF Radio Links, NATO, Brussels, 1998.

- Norman, R.J., and P.S. Cannon, A Two-dimensional Analytic Ray Tracing Technique Accommodating Horizontal Gradients, *Radio Science*, 32 (2), 387-396, 1997.
- Norman, R.J., and P.S. Cannon, An evaluation of a new 2-D analytic ionospheric ray tracing technique - SMART, *Radio Science*, 34 (2), 489-499, 1999.
- Pi, X., C. Wang, G.A. Hajj, G. Rosen, B.D. Wilson, and G.J. Bailey, Estimation of $E \times B$ drift using a global assimilative ionospheric model: an observation system simulation experiment,, *J. Geophys. Res.*, 108(A2), doi:10.1029/2001JA009235, 1075, 2003.
- Radicella, S.M., and R. Leitinger, The evolution of the DGR approach to model electron density profiles, *Advances in Space Research*, 27 (1), 35-40, 2001.
- Rodgers, C.D., *Inverse methods for atmospheric sounding: theory and practice*, World Scientific Publishing, Singapore, 2000.
- Rose, R.B., J.N. Martin, and P.H. Levine, MINIMUF-3: A simplified HF MUF prediction algorithm, Tech. Rep. NOSC TR 186, Naval Ocean Systems Center,, San Diego, California, USA, 1978.
- Shukla, A.K., and P.S. Cannon, Prediction Model Updating Using the ROSE-200 Oblique Ionospheric Sounder at Mid and Higher Latitudes, in *HF, Radio Systems and Techniques Conf*, pp. 89-103, IEE, York, UK, 1994.
- Shukla, A.K., P.S. Cannon, S. Roberts, and D. Lynch, A tactical HF decision aid for inexperienced operators and automated HF systems, in *7th International Conference on HF Radio Systems and Techniques*, pp. 383, IEE, Nottingham, UK, 1997.
- Stewart, F.G., and G. Hand, Technical description of the ICEPAC Propagation prediction program, Private Communication, Institution of Telecommunications Sciences, Boulder, Colorado, USA, 1994.
- Teters, L.R., J.L. Lloyd, G.W. Haydon, and D.L. Lucus, Estimating the performance of telecommunications systems using the ionospheric transmission channel: Ionospheric Communications Analysis and Prediction Program (IONCAP) User's manual, *NTIA report 83-127, NTIS order no N70-24144*, NTIA, Springfield, VA, USA, 1983.
- Wang, C., G.A. Hajj, X. Pi, and L.J. Romans, The Development of an Ionospheric Data Assimilation Model, in *Ionospheric Effects Symposium*, edited by J. Goodman, Alexandria, Virginia, USA, 1999.
- Willink, T.J., Analysis of High-Latitude HF Propagation Characteristics and their Impact for Data Communications, CRC Report 97-001, Industry Canada, 1997.