Modelling the effects of ionospheric disturbances on quasi-vertically incident ionograms using 3D magneto-ionic raytracing

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1 Introduction

Ionospheric disturbances are manifest over a large range of spatial and temporal scales. Currently DSTO has a good understanding of these disturbances at the largest scales (> 1000 km and > 15 min) through its network of vertical incident (VI) sounders. However, we are interested in investigating these disturbances at much smaller scale sizes. To this end DSTO has initiated an experimental programme, SpICE (Spatial Ionospheric Correlation Experiment), utilising state-of-the-art DSTO designed high frequency (HF) digital receivers. This programme seeks to understand ionospheric disturbances at scales < 150 km and temporal resolutions under 1 minute through the simultaneous observation and recording of quasi-vertical ionograms (QVI) with closely spaced ionospheric control points. The first experimental campaign was conducted in February 2008. A detailed description of and early results from this campaign were presented by [1] and [2]. Since then there have been a further 2 campaigns which are described by [3]. In this paper we show how 3D magneto-ionic Hamiltonian raytracing techniques can be used to model and understand the various ionospheric disturbances seen in the data.

2 Method

Hamilton's variational principle (see standard texts on mechanics) may be used to study the propagation of radio waves through an ionized medium in addition to dynamical systems to which it is usually applied. Haselgrove [4,5] first set down the Hamiltonian raytracing equations for the case of HF radio waves propagating through the Earth's ionosphere. These equations, now commonly know as Haselgrove's equations, have been extensively used to study HF radio wave propagation.

DSTO has developed a HF radio-wave raytracing toolbox (PHaRLAP) in order to study the propagation of radio wave waves through the ionosphere. PHaRLAP provides a variety of raytracing engines of various sophistication from 2D raytracing to full 3D magneto-ionic raytracing. Figure 1 shows a fan of rays calculated with the 2D raytracing engine while Figure 2 shows an example of ray paths for the ordinary (O) and extraordinary (X) polarization modes calculated using the 3D magneto-ionic raytracing engine. The green ray path in this figure is the case for no geomagnetic field. The ionosphere used in this example is spherically symmetric thus there are no ray deviations due to ionospheric tilts. The deviation of the O and X mode rays in this case is due to the magnetic field alone. Previous researchers (e.g. [6]) have used 2D ryatracing to model ionospheric disturbances. In the remainder of this paper we employ the 3D magneto-ionic raytracing engine to model our observed QVIs.

The method we use to model the ionospheric disturbances is first to model the undisturbed QVI immediately prior to the presence of a disturbance. This requires the specification of a model ionosphere through which the raytracing is performed. The model ionosphere is based on quasi-parabolic (QP) layers with the layer parameters tuned so as to allow us to model a QVI which matches our observed undisturbed QVI within some threshold . Once the undisturbed ionogram has been modelled we introduce a disturbance. The features of the disturbance are varied until we are able to reproduce the observed features in the ionogram. The form that the disturbance takes is an additional QP layer above the F2 layer. The above procedure is

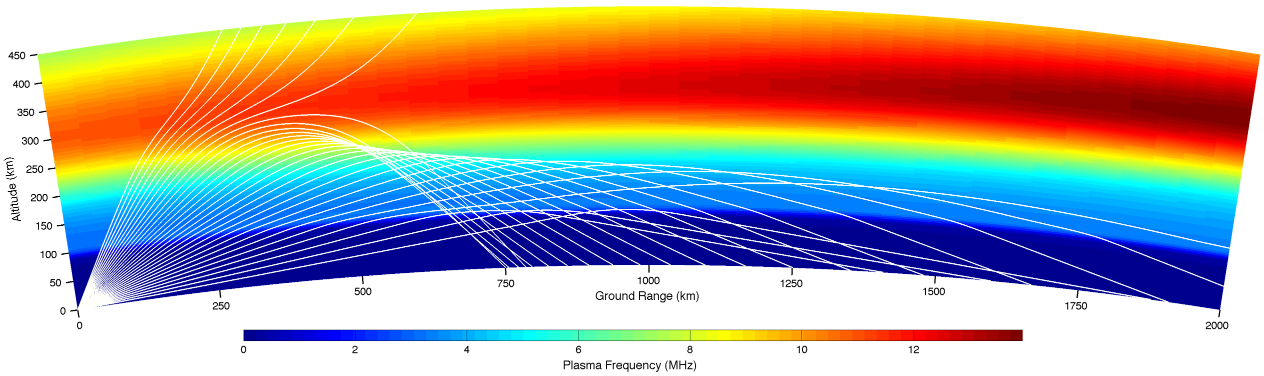

Figure 1: Example of 2D raytracing with PHaRLAP for a fan of rays originating at lat. -23.5°, lon. 133.7°, bearing 325°. The ionosphere was generated using IRI2007 at 07:00UT on 15 March with an R12 index of 100. Rays refracted by the E-layer ($\sim 100\,$km) and F-layer ($\sim 200\,$km) are evident together with high-mode F rays and penetrating rays.

repeated at various time intervals in order to model the temporal evolution of the ionospheric disturbance as shown in the time sequence of ionograms.

We now describe the procedure for modelling an individual ionogram. First the launch directions of a filled cone of rays from an origin (the transmitter) are defined. The rays are evenly distributed in solid angle and their points of intersection with the surface of a sphere of unit radius centred at the transmitter and taken in triplets define identical equilateral triangles (see Fig. 3). Each of the ray triplets is tagged. Next, rays at a particular frequency are launched and their endpoints on the ground defined by the raytracing are recorded. We then loop over all of the ray triplets and note which of the triplets "surround" the receiver. This is achieved via Delaunay triangulation. These ray triplets then represent a propagation mode from the transmitter to receiver. The Delaunay triangulation process is also used to interpolate the group range and launch direction of the actual ray which would land at the receiver. This process is repeated at various frequencies and a model ionogram constructed. We use a much greater density of rays than that shown in Figure 3. In total 6051 rays which yield 11846 triplets are launched at each frequency.

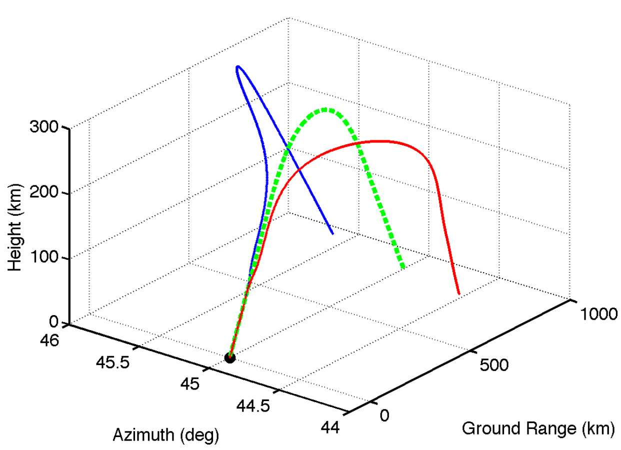

Figure 2: Example of 3D raytracing with PHaRLAP showing O (blue) and X (red) polarization modes and the case for no geomagnetic field (green). Azimuth is with respect to the origin of the rays (black dot).

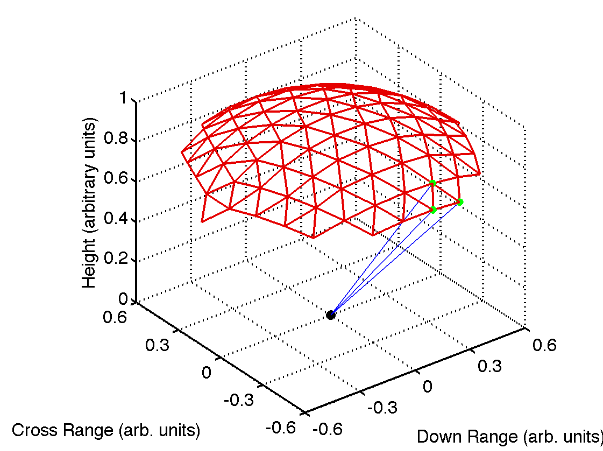

Figure 3: Schematic depicting how the ray launch directions are defined. Each ray from the transmitter (black dot) passes through a triangle vertex. The blue lines indicate three such rays which form a triplet (see text).The triangles are equilateral and identical ensuring that the ray launch directions are evenly distributed.

3 Results

Figure 4 shows an ionogram recorded at 22:07 UT on 26 Feb 2008 during our first SpICE campaign. The transmitter was located at Woodside, South Australia in the Adelaide hills, and the receiver at DSTO Edinburgh $\sim$ 40km away. Superposed on the ionogram are black dots and crosses indicating the modelled ionogram for the O and X polarizarion modes. The plasma frequency profile of the model ionosphere we used to generate the model ionogram is shown in Figure 5. The layer parameters describing this profile are foE = 2.61 MHz, hmE = 116.41 km, ymE = 25.0 km, foF1 = 4.0 MHz, hmF1 = 175.0 km, ymF1 = 45.0 km, foF2 = 5.08 MHz, hmF2 = 224.0 km, and ymF2 = 68.0 km. Whilst the agreement between the observed and model ionograms is generally good, there are some minor differences. This is due to the model ionosphere being only a parametric model; there is a limited number of parameters to tune. In subsequent work we intend to use POLAN [7] to invert our ionograms to obtain an ionospheric profile which more accurately represents the real ionosphere than the QP parametric model.

Figure 6 shows an ionogram recorded 4 minutes later than that shown in Figure 4. Note the disturbance feature near the top of the trace which is typical of the disturbances we observe in our data. The black dots/crosses are again the modelled ionogram. The blue curve is the ionospheric plasma frequency profile used to generate the model ionogram. For the blue curve the Y axis label should read as true height. This profile consists of the profile in Figure 5 with an imposed disturbance. This disturbance takes the form of an additional QP layer above the F2 peak. This additional layer has a critical frequency some 0.2 MHz greater than the background foF2, and a peak height and width of 245 km and 40 km. The model iongram matches the real ionogram quite well.

Finally, to examine the temporal evolution of the disturbance, we show in Figure 7 an ionogram recorded 2 minutes later than that in Figure 6. This figure shows the disturbance feature having “moved” down the ionogram and again we are able to model this feature. The critical frequency and layer width parameters of the ionospheric disturbance in this case are unchanged with the layer peak height descending by 15 km to an altitude of 230 km (6 km above the F2 layer peak).

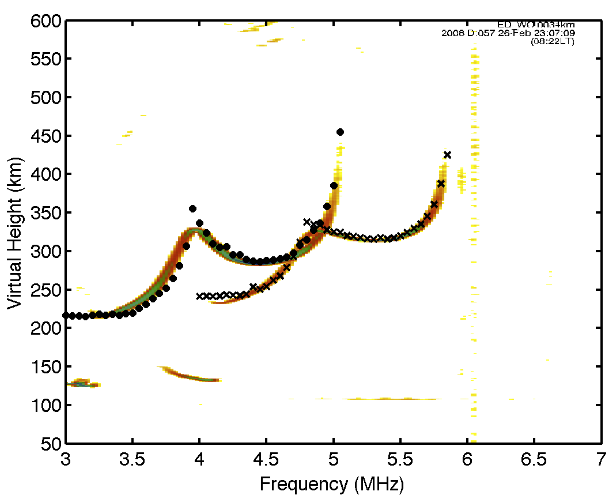

Figure 4: Ionogram observed at 22:07 UT on 26 Feb 2008 immediately prior to the passage of an ionospheric disturbance with superposed modelled ionogram (O mode - black dots, X mode - black crosses)

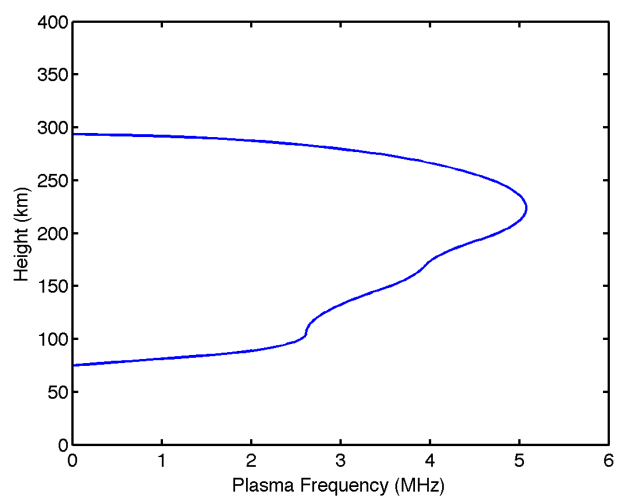

Figure 5: Plasma frequency profile of model ionosphere used to generate the undisturbed model ionogram shown in Figure 4. The QP layer parameters are listed in the text.

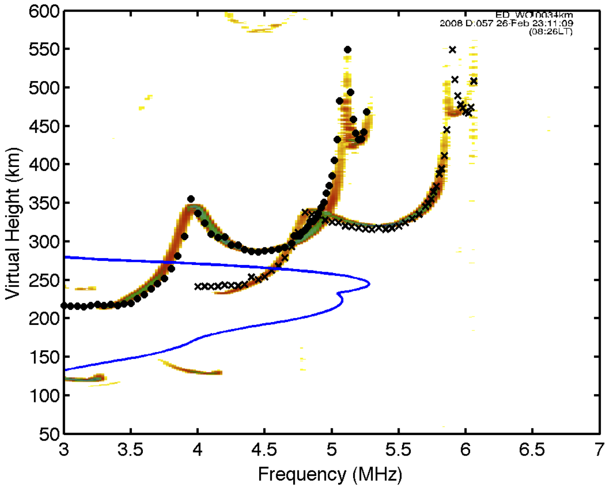

Figure 6: Ionogram recorded at 22:11 UT on 26 Feb 2008 showing a disturbance feature with superposed model ionogram (black dots/crosses). The plasma frequency of the disturbed ionosphere has been overlaid (blue curve).

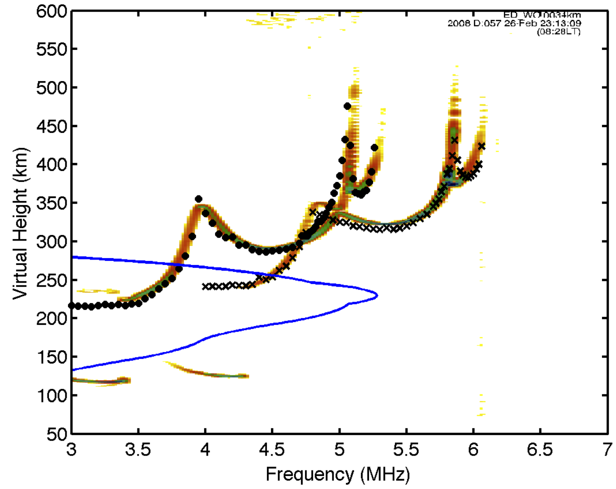

Figure 7: Ionogram recorded at 22:13 UT on 26 Feb 2008 showing a disturbance feature with superposed model ionogram (black dots/crosses). The plasma frequency of the disturbed ionosphere has been overlaid (blue curve).

4 Concluding remarks and future work

We have shown that Hamiltonian raytracing techniques may be used to model disturbance features observed in quasi-vertical ionograms and thus allow us to gain insight into the form of the disturbances in the ionosphere. The disturbance that we have modelled in this paper is typical of what we observe in our data and was relatively simple to model. We have observed many other much less common disturbances which are more difficult to interpret. Modelling these disturbances will be the subject of future work.

5 References

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