Imaging the Earth's Ionosphere with Multi-Satellite Observations

Cathryn Mitchell and Paul Spencer, University of Bath

Department of Electronic and Electrical Engineering, University of Bath, BATH BA27AY, UK.
c.n.mitchell@bath.ac.uk*;* p.s.spencer@bath.ac.uk

ABSTRACT

Ionospheric imaging is now well established with over 20 years of research having proven the techniques for both scientific studies and radio system planning tools. Many algorithms now use data from the Global Positioning System (GPS). GPS has revolutionised our ability to monitor the entire ionosphere simultaneously on a global scale. However, the vertical resolution of the images and in particular the separation of the topside ionosphere with the plasmasphere remains a challenge. A further issue is the uneven coverage of ground-based receivers across the Earth. After a general introduction to the science, this paper focuses on two issues; first is the determination of the vertical profile in ionospheric imaging and the ionosphere/plasmasphere separation. A new approach to the determination of the basis functions is discussed that takes into account the plasma behaviour along the magnetic field. Secondly the sparsity of data over certain regions of the Earth and the challenges of producing images with a consistent and reliable resolution standard is considered. Future improvements in both of these areas and the science expected with new low-Earth orbit satellites are discussed.

INTRODUCTION

Ionospheric imaging has been used for both physical studies and for operational radio communications systems for a number of years. A number of authors have shown that the routine monitoring of the ionsphere is possible using dual-frequency signals from the Global Positioning System (GPS) but it is widely acknowledged that additional information from either other instruments on the ground or from space-based instruments in Low-Earth-Orbit is helpful for achieving an accurate representation of the electron density. A review of ionospheric imaging and the closely-related technique of data assimilation is found in Bust and Mitchell (2008).

This paper explores the achievements and limitations of ionospheric imaging applied to major storms of the last solar maximum and looks toward future enhancements that SWARM will offer to understanding the physics of the magnetosphere-ionosphere-theremosphere system. A review of ionospheric storms can be found in Mendillo (2006).

REVIEW OF PREVIOUS RESULTS

Changes in the solar wind velocity and pressure together with the appropriate magnetic field configurations result in sudden inputs of solar-wind energy into the ionosphere. This energy dissipates as heating initially in the auroral regions and changes the configuration of the thermospheric winds. It is well known that the thermospheric winds can move the plasma preferentially along the magnetic field and due to the tilt this will alter the recombination rates and complicate the effects. Recent research, stimulated by ionospheric imaging using the Global Positioning System (GPS), has shown that the equatorial and mid-latitude ionosphere experiences extreme disturbances in layer height and plasma density gradients during the positive phase of major storms (see for example Spencer and Mitchell, 2001; Basu et al., 2001; Yin et al., 2004). Chi et al (2005) state that mid-latitude observations of the great storm of October 2003 '*challenge our conventional wisdom,'* indicating that a better understanding of magnetosphere-ionosphere coupling processes is needed. Clearly it is not possible to isolate our thinking about the mid-latitude ionosphere from the polar and equatorial regions. Indeed there is considerable evidence building that the origins of extreme mid-latitude structures eventually convecting in the polar cap could be equatorial (Kelley, 2004). A 'daytime super fountain effect' has been hypothesised (Manucci et al., 1995) to transport plasma poleward from the equatorial regions. The exact mechanism to convect it into the mid-latitude remains unproven although recently some theories have been put forward, notably by Kelley (2004). Foster and Rideout (2005) state the storm enhanced densities (SED) relate to the dusk plasmasphere and low latitude ionosphere and are transported by the sub-auroral polarisation stream (SAPS) electric field. Nevertheless, the reason why the SED is so intense over the USA in comparison to other regions elsewhere remains unproven. The great storm of

October 2003 was selected for a dedicated special section of Geophysical Research Letters (Vol 32 2005) emphasising the importance of storms in current solar-terrestrial physics and also demonstrating the extensive use of GPS observations in this research area.

The University of Bath has developed a 4D ionospheric imaging system called MIDAS (Multi-instrument Data Analysis System) that uses any ionospheric measurement that relates in a near-linear manner to the electron density to produce 4D (space-time) maps of electron density (Mitchell and Spencer, 2003; Spencer and Mitchell, 2007). The technique has been applied to studies of the storms of the past solar maximum and results are reported in the following papers:

- Imaging of dramatic elevation of the F layer of the ionosphere over Europe and the USA (Spencer and Mitchell., 2001; Yin et al., 2005)
- Convection of the plasma from the dayside ionosphere over the USA towards the nightside in Europe within polar-cap patches associated with GPS phase and amplitude scintillation at mid and high latitudes in Europe (Mitchell et al., 2005)
- The F2 layer elevation propagates from high latitudes to lower latitudes for the Nov 2003 storm but for the October 2003 and July 2000 storms the elevation is simultaneous across all latitudes. (Yin et al., 2006)
- All three storms (Nov 2003, October 2003, July 2000) show an east-west time delay in the peak height elevation, that is, firstly, in the European sector, then the east coast of the USA, then later occurring in the west coast of the USA. (Yin et al., 2006)
- The uplifts in the USA sector are always accompanied by TEC/electron density enhancements, but those in the European sector are accompanied by decreasing electron densities/TEC (Yin et al., 2006)
- The coupling of the images to an ionospheric model indicates the importance of the electric field but does not uniquely determine the physics drivers (Smith et al., 2009)

An excellent review of the contributions of GPS to storm studies can be found in Mendillo (2006). He concludes that the foremost area for GPS to contribute now is in data assimilation models. Nevertheless we are still short of data and this is just what SWARM will provide. It will also add a vital new data set for plasmaspheric imaging.

PLASMASPHERIC IMAGING

The proposed method uses the geometry free phase linear combination which can be derived from dual frequency GPS observations. These measurements provide a very accurate estimate of the total electron content as a function of time from satellite to receiver to within an unknown constant. Within a four dimensional space/time volume the solution to the electron density distribution can be presented as an under-constrained linear inverse problem. In the ionospheric imaging case, the ambiguity of this problem can be reduced by using a mapping in the radial direction to a set of orthogonal functions. These functions are obtained from a singular value decomposition of a set of realistic electron density profiles.

In the case of plasmaspheric imaging from a limited number of LEO satellites a different mapping was developed. Above a certain altitude the electron density is constant along magnetic field lines. To the orbital altitude of the GPS satellites the Earth's magnetic field may be approximated as a dipole which can be represented parametrically in terms of Euler potentials. A linear mapping is constructed which transforms the coordinate system from three Cartesian spatial dimensions into two dimensions corresponding to the Euler potentials. This reduces the dimensionality of the inverse problem by one and provides solutions which are limited to be constant along magnetic field lines.

SUMMARY

In spite of these recent successes from the last solar maximum it is clear that there is still insufficient information on the physical parameters responsible for storm dynamics. Physical models alone are unable to resolve this issue and there is a need for new measurements. Figure 1 shows an ionospheric image showing the electron density distribution during a major storm from 30 October 2003 (22 UT). Superimposed onto the image is the possible track of the SWARM satellites if a similar event were to occur in the next solar maximum. Since the instrumentation planned for SWARM includes neutral density and electric field observations it will be possible to distinguish between the competing mechanisms and to answer some of the outstanding questions in mid-latitude ionospheric physics.

In summary SWARM will assist in ionospheric imaging by:

- Improving the images resolution temporally and spatially

- Assist with the model optimisation in data assimilation

i.e. once we have found a model run that matches the tomographic images how unique is that result? SWARM has more than just GPS – E field, neutral density, particle velocity can all be used to help to identify the underlying ionospheric physics

- Help to extend data assimilation into the plasmasphere

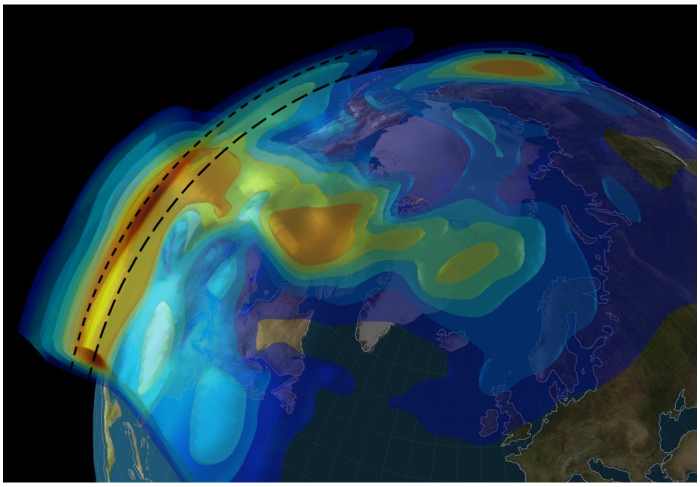

Figure 1. Ionospheric image of the electron density (contours at steps of $2x10^{11}$ m^{-3}) from the last solar maximum (30 October 2003 at 21 UT) with superimposed (hypothetical paths) of the SWARM satellites shown as dashed lines.

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