DATA ASSIMILATION OF IONOSPHERIC RADIO OCCULTATION MEASURMENTS

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ABSTRACT

The standard technique for inverting Radio occultation (RO) measurements (i.e. the Abel Transform) has three limitations: spherical symmetry must be assumed, and both transmitter and receiver should be in free space, and in the same orbital plane. These limitations can be overcome by employing data assimilation techniques to incorporate RO data into background models of the environment. Such techniques are also well suited to sparse data sets. This paper will describe the use of such data assimilation techniques for the inversion of ionospheric RO measurements. Results will be presented from simulated measurements produced by ray tracing through ionospheric models.

INTRODUCTION

Comprehensive, global and timely specifications of the earth's atmosphere (particularly refractivity profiles of the troposphere and ionosphere) are required to ensure the effective operation, planning and management of many radio frequency systems. Although many ground based techniques have been developed to measure atmospheric refractivity, radio occultation (RO) methods are being increasingly investigated [1]. RO involves monitoring transmissions from Global Positioning System (GPS) satellites using receivers on Low Earth Orbiting (LEO) satellites and provides the potential of measuring refractivity profiles in regions where ground based sensors cannot easily be located, such as deep sea waters.

Unfortunately, the measurements are generally both underdetermined and sparsely distributed and consequently it is necessary to constrain inversions of RO data. This may be done by making assumptions about the atmosphere (i.e. it is spherically symmetric), by using a limited number of functions to represent the atmosphere (i.e. empirical, spherical harmonics, etc), or by assimilating the data into a background model of the atmosphere. This paper will describe the application of data assimilation techniques to ionospheric RO measurements. The emphasis will be on a practical approach which enables RO measurements from an eight satellite LEO constellation to be assimilated in an efficient manner on a single processor PC.

STANDARD TECHNIQUES

The standard technique for inverting RO measurements to provide vertical profiles of refractivity relies on the Abel Transform [2]. Using this technique, bending angle (derived from the excess Doppler shift observed on the GPS signals) can be inverted to provide vertical refractivity profiles with very high vertical resolution (of the order of the width of the first Fresnel zone), but with poor horizontal resolution. The geometry of the measurement results in the measured bending angles containing information from a large region of the atmosphere, because the near horizontal rays from the GPS to the LEO may remain in the atmosphere for many hundreds of kilometres. Therefore, in the presence of atmospheric structures, the assumption of spherical symmetry required for the Abel transform will not hold, and the calculated vertical profile may contain errors. Furthermore, in order to apply the Abel transform the measurement must lie close to the orbital plane of the LEO and ideally, both the transmitter and receiver should be in free space.

DATA ASSIMILATION

The limitations inherent in the Abel transform can be overcome by employing techniques to incorporate RO data into a background model of the environment. Data assimilation aims to combine measurement data with a background model in an optimal way [3]. It is necessary to include a background model because the amount of information that can be extracted from RO 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 neutral atmosphere RO measurements [4, 5]. Work has also been conducted on applying such techniques to ionospheric inversion [6, 7].

A Best Linear Unbiased Estimation (BLUE) technique has been implemented to directly modify the electron density grid produced by the PIM ionospheric model [8]. PIM was chosen because, being derived from parameterised physical models, it provides a better representation of ionospheric structures. PIM is also well suited to RO applications as it contains the Gallagher Plasmasphere model. As an initial test, seventy tomographic images [9] have been used to simulate RO measurements. In each case the difference between the tomography derived slant TEC along each ray and both the PIM electron density grid and the output of the BLUE have been calculated. The results show the an order of magnitude increase in accuracy provided by the BLUE. Similarly, the vertical electron density errors have been calculated. In this case the BLUE produces an approximately fourfold reduction in the errors at an altitude of 300 km [10].

GLOBAL ASSIMILATION

To further test the performance of the BLUE technique, global data assimilation simulations have been conducted. The International Reference Ionosphere (IRI) is used to provide the truth ionosphere, but now measurements are generated for a radio occultation satellite constellation. The constellation consists of eight LEOs in four orbital planes. The orbits are circular, have an altitude of 750 km and have an inclination of 70° (similar to GPS/MET). The Satellite Tool Kit (STK) has been used to provide ephemerides for both the LEO constellation and for the currently operational GPS network. Occultation periods are then found by searching for rays from a GPS satellite to a LEO that have a minimum altitude between 50 and 650 km.

PIM is run to provide the initial background model. Then occultations are assimilated in 20 minute time periods, during which time the ionosphere is assumed to remain unchanged. For each period IRI is run to provide the truth ionosphere and slant TEC measurements are simulated by integrating along straight lines rays between occulting satellites. Each occultation in turn is then assimilated into the background model. Consequently the analysis ($\mathbf{x_a}$) generated by assimilating the first measurement becomes the background model for the next. It should be noted that the error covariance matrix of the analysis is not calculated and, therefore, the background model error covariance matrix for each occultation is calculated from the background model as described in [10].

After all the occultations from one 20 minute period have been assimilated it is necessary to evolve the analysis in time to provide the background model for the next period of occultations. In principle a physical model of the ionosphere should be used to predict the future state of the electron density grid from the current data assimilation analysis. However, such an approach would require both a sophisticated model and, probably, large computing resources. Therefore a highly simplified approach to the time evolution has been adopted – it is assumed that, in geomagnetic coordinates, the ionosphere remains invariant in space while the earth rotates beneath it. In practice the time evolution is performed by randomly sampling the electron density at each altitude and converting the geographic coordinates of each sample to geomagnetic (at present a simple dipole magnetic field is used). The change in longitude corresponding to the required amount of time evolution is then subtracted from each coordinate. Each sample is then converted back to geographic coordinates and a regular latitude-longitude grid is generated by interpolation. This process is repeated for each altitude in the electron density grid.

The global assimilation simulation has been run for a period of 24 hours and for two scenarios. In the first, only occultations that lie close to (within 30°) the orbital plane of the LEO have been assimilated. This corresponds to the typical limitation of current RO missions that restrict the data to be along the fore or aft boresite of the satellite motion to facilitate the use of the Abel transform. The second scenario assimilates all available RO measurements. In each case the RMS errors in the vertical TEC, NmF2, and HmF2 have been calculated for each 20 minute period (Figures 1, 2 and 3). For comparison PIM has also been run for each 20 minute period and the RMS errors between it and IRI have been calculated. It can be seen that in the first scenario the vertical TEC error is halved, whilst in the second the error is reduced by a factor of four. Similarly, the second scenario (all RO measurements assimilated) reduces the RMS error in NmF2 by a factor of three and the RMS error in HmF2 by a factor of two.

Figures 4 and 5 show the difference in vertical TEC between the truth data and PIM and the BLUE output respectively for the second scenario. It can be seen that the TEC differences have been reduced.

CONCLUSIONS AND FUTURE WORK

Data assimilation techniques have been investigated and applied to ionospheric RO measurements. These techniques show the potential to overcome the limitations of the Abel transform: i.e. the assumption of spherical symmetry; measurements in the orbital plane; and transmitter and receiver in free space. A global assimilation simulation has been run using a constellation of eight LEO RO satellites and IRI has been used to provide the truth ionosphere. A factor of four decrease in the vertical TEC RMS error has been demonstrated.

The effectiveness of data assimilation is highly dependent on the accuracy of the relevant error covariance matrices (both observation errors and background errors). Further work is required on the specification of the error covariance matrices used in the BLUE technique described in this paper. In particular, different values for the latitudinal and longitudinal horizontal scale lengths should developed that can be varied for different locations. Furthermore, a very simple approach to the problem of ionospheric time evolution has been adopted – the benefits of a more sophisticated technique should be assessed.

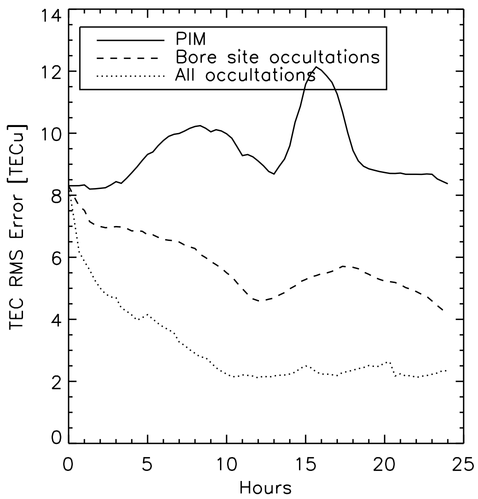

Figure 1. Vertical TEC RMS error

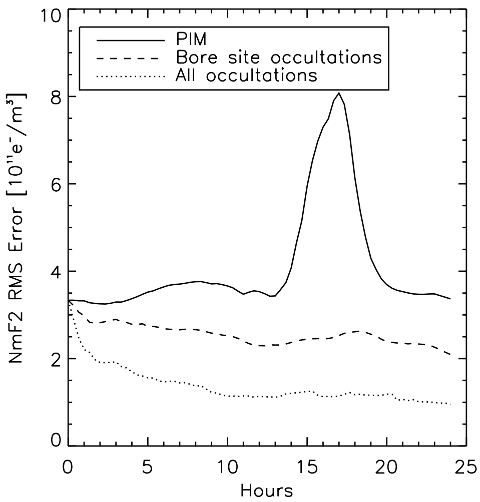

Figure 2. NmF2 RMS error

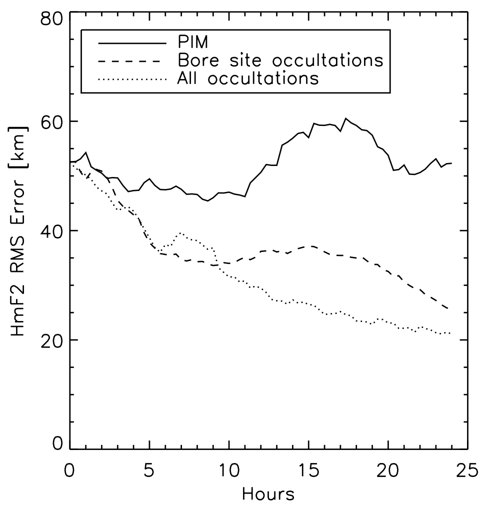

Figure 3. HmF2 RMS error

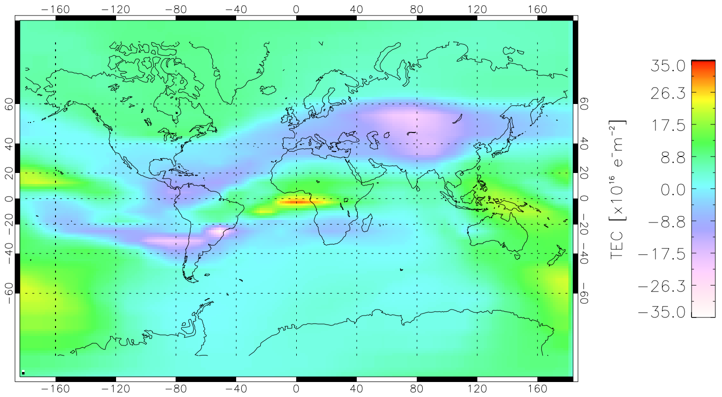

Figure 4. Vertical TEC difference between IRI (truth) and PIM (background model)

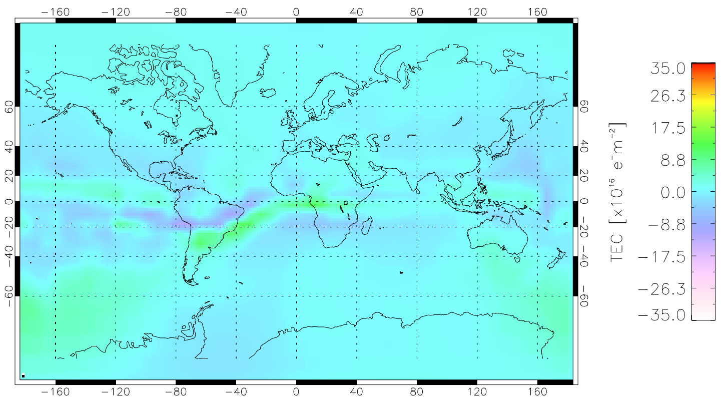

Figure 5. Vertical TEC difference between IRI (truth) and output of data assimilation after 24 hours

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