IONOSPHERIC ELECTRON CONCENTRATION MAPPING USING GPS OVER EUROPE AND USA DURING THE STORM OF JULY 2000

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ABSTRACT

A new method has been devised for two, three and four-dimensional inversion of satellite and ground-based measurements taken from diverse instrumentation. The time-dependent algorithm is applied to multi-directional ground-based GPS data. The output of the inversion is a three-dimensional movie of electron concentration. This technique is demonstrated by showing a series of images of the ionosphere during the storm of July 2000, from the auroral to the northern equatorial regions. The images reveal the large-scale dynamics of the ionosphere during disturbed conditions and show the great potential of GPS data for such geophysical studies.

INTRODUCTION

Dual-frequency GPS signals are now received at a network of ground-based receivers and are also increasingly available from space-based receivers. These ray paths yield a complex and constantly changing geometry of total electron content (TEC) measurements. Such an experimental system can use a tomographic approach, but in this case it has introduced the need to extend conventional two-dimensional ionospheric tomography. Tomographic reconstructions in two dimensions have been used to image the electron-density distribution in the ionosphere for a number of years. A review of this topic has been given [1]. Since both ground- and space-based GPS observations are becoming more widely available the possibility of extending these techniques has arisen, [2; 3; 4]. In this paper inversion algorithms are used to image the ionosphere during the major storm of July 2000. During the most disturbed conditions severe storms have a global impact on the ionisation, manifested as dramatic changes in latitudinal morphology and abrupt changes in layer height. While the main phase of a storm may last less than a day the entire recovery time, accounting for the dynamical, thermal and compositional changes, can last for many days. Consequently it is advantageous to study these physical processes with measurements that are near continuous in latitude, longitude and time, as can be done using GPS.

METHOD

GPS observations from a world-wide network of receivers have been made available to the scientific community by the International GPS Service (IGS) and these data have been used in this study. The GPS phase observations provide a highly accurate measure of the TEC to within an unknown number of cycles. The majority of receivers also provide P-code observations, which enable an absolute estimate of TEC along a ray path. However in this case differential satellite and receiver biases and multipath effects also have to be taken into account.

The GPS data have been analysed using the MIDAS[1] (Multi-Instrument Data analysis System) software [4]. This type of inversion provides a consistent method to invert ionospheric observations from various ground and space-based instrumentation. Ground-based GPS data were recorded at a large number of locations throughout the storm period of July 2000. Examples over the USA are shown in Fig. 1. The first stage of the analysis consisted of a calibration procedure, using both the differential time and differential phase properties of the GPS signals. The data were then partitioned into one-hour sets and a three-dimensional inversion with a linear time evolution was performed, resulting in a series of hour-long movies of the electron concentration.

The peak F-layer density in those voxels from the MIDAS inversions at the same latitude and longitude and time as ionosonde soundings were plotted against the corresponding ionosonde values. These values were then compared to evaluate the results.

RESULTS

Fig. 2 shows observations of NmF2 from two US ionosondes (points) and the corresponding values from the MIDAS inversions (circles). The upper plot is from an ionosonde at 30.4° N, the lower one at 40.0° N. The

[1] MIDAS software (© University of Bath) was developed by a grant from the UK Engineering and Physical Sciences Research Council.

ionosonde at 30.4° N shows a large amount of variability in observations of peak density during the afternoon (UT) of 15th July. Later in the day the peak density at 40.0° N shows a systematic increase and decrease, maximising at around 1800 LT (midnight, UT),. The very high-density ionosonde soundings could be from off-vertical returns, rather than directly overhead and hence the discrepancy with the inversion values of NmF2 in the voxels above the ionosondes. This event coincides with the steep wall of ionisation seen in the cross-sectional images of Fig. 3. The series of images are taken from the centre frame of each one-hour movie, at a longitude of 98° W. Increasing electron concentrations can be seen in the four images between 2030 to 2330 UT. Around this time the positive storm effects evolved into extreme steep electron-density and TEC gradients to the south of Florida. This event was associated with the upwelling of the entire ionization, evidenced by hugely enhanced peak heights and topside content. This is likely to result from changes in the electric field, as discussed for previous storm events by [5].

Fig. 4 shows a series of vertical TEC maps. Each has been obtained by vertical integration through the voxels of the centre frame of each one-hour movie, over the USA. The maps show the steep wall of TEC building up to the south of the region. Although the TEC scale in this Figure is limited to 140 TECU, values of equivalent vertical TEC along individual ray paths extending off the southeast coast were well in excess of 200 TECUs. Simultaneous images over Europe revealed the expansion of the auroral oval and the rapid equatorial movement of the main trough, eventually at an extreme southerly position over northern Italy. During these very disturbed conditions the geomagnetic index Kp reached 9. The extreme southerly location of the trough was confirmed using independent TRANSIT data from IROE, Firenze. Finally, the images for the 16th have shown the collapse of the ionization levels in the characteristic recovery phase.

SUMMARY

Two-dimensional tomographic methods originally applied to the reconstruction of TRANSIT satellite observations have been extended to four-dimensions and applied to ground based GPS observations. GPS observations are generally continuous in space and time, enabling the evolution of large-scale ionospheric features to be studied. The time-dependent inversion applied here is important because of temporal changes in the ionosphere during the data collection period.

The imaging technique has been demonstrated for a highly disturbed storm period during July 2000. The images showed very steep gradients in electron-concentration and TEC over the USA. Comparisons with ionosonde peak densities diverged during the evening of 15th July, when extreme TEC values and gradients were observed. This event was associated with a sudden upwelling of the ionization. Simultaneous events over Europe have revealed the main trough at the extreme equatorward position of 45° N geographic. The results demonstrate the potential of a new analysis technique allowing GPS data to be used for large-scale studies of the ionosphere under very disturbed geomagnetic conditions.

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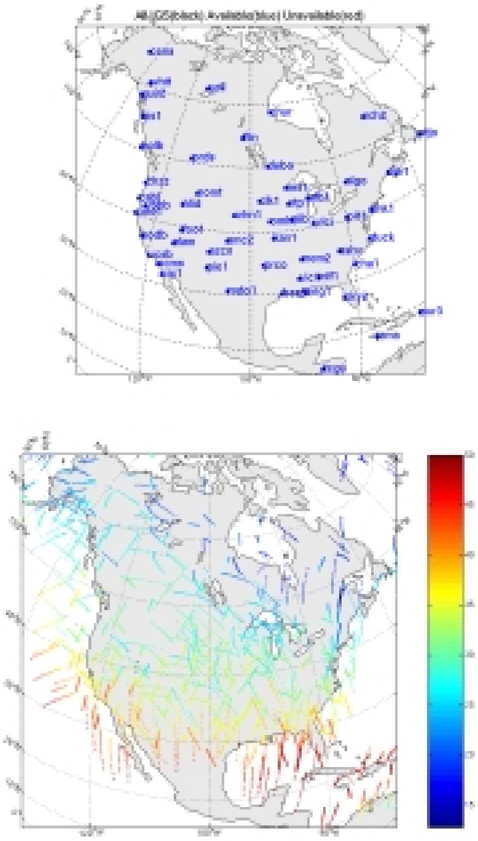

Fig. 1. IGS receivers and typical shell intersection points for 00UT on 14th July 2000. Intersection points are coloured according to their vertical TEC through an infinitesimal shell

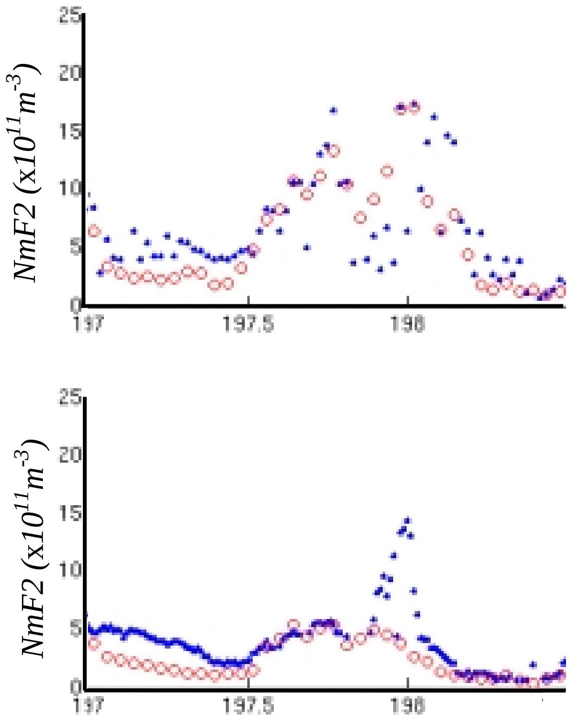

Fig. 2. Comparison of NmF2 from ionosondes (points) and inversions (circles) using ground -based GPS data from 00 UT on 15th July 2000 to 12 UT on 16th July 2000. The upper plot is for the ionosonde at 30.4°N, 86.7°W, the lower plot for 40°N, 105.3°W.

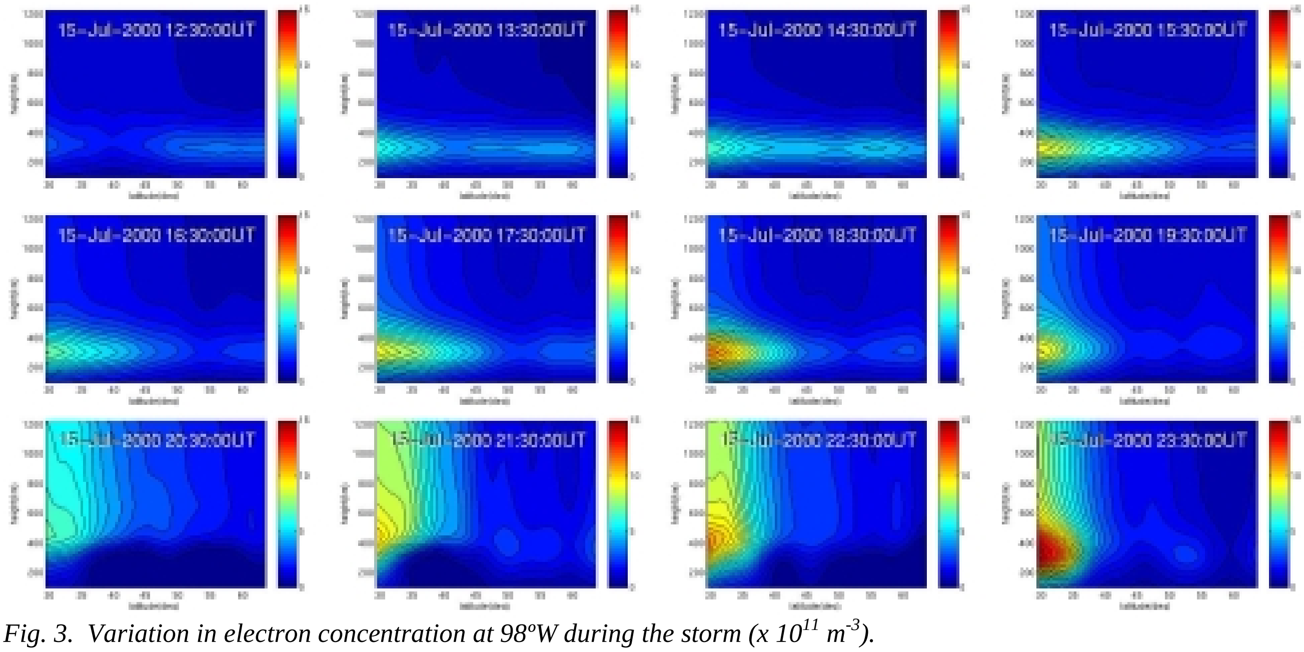

Fig. 3. Variation in electron concentration at 98°W during the storm (x 10^{11} m^{-3}).

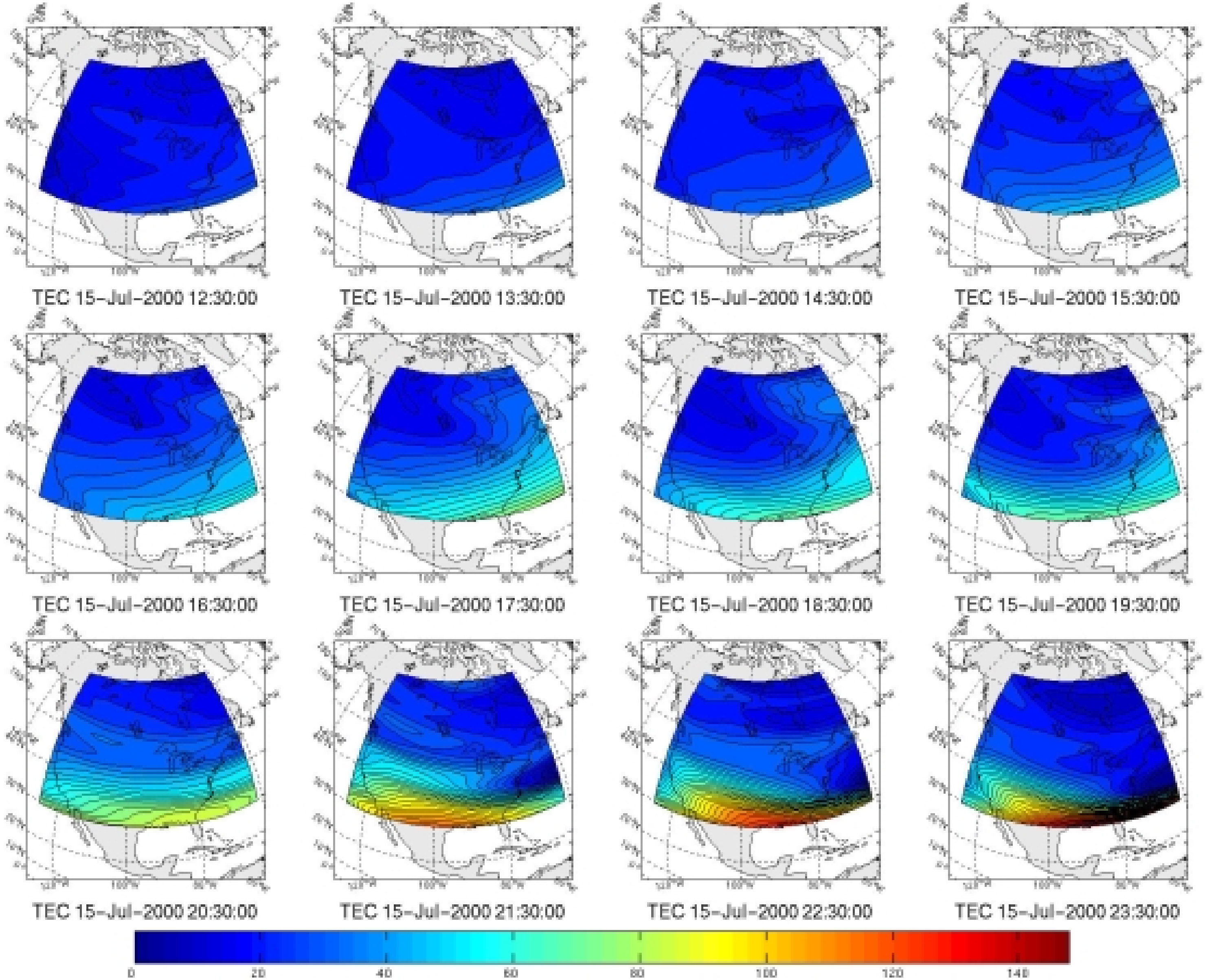

Fig. 4. Variation in vertical total electron content over the USA during the storm (in TEC units).