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Identification of travelling ionospheric disturbances in the ionosphere using GPS with independent verification

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ABSTRACT

The MIDAS (multi-instrument-data-analysis-system) and IDA (ionospheric-data-assimilation) algorithms are two mathematically different approaches to assimilating multiple ionospheric data sources into a coherent picture of the 3D time dependent ionospheric electron density. Currently, the vast majority of available observations of the ionosphere come from global positioning satellite systems such as GPS. However the long integration paths through the ionosphere, the movement of the satellites and the use of simplistic filtering techniques brings into question the reliable identification of fast moving structures such as medium- and large-scale TIDs.

This paper takes a comprehensive approach to determining the capability and limitations of using GPS signals for studying TIDs. In the first instance, a computer simulation of a TID-rich ionosphere is generated and used to formulate a set of fictitious satellite-to-ground observations using a realistic geometry of actual GPS observations for a given day over USA. The data are then used to show the strengths, limitations, blurring and artifacts associated with simplistic time-series filtering techniques. As a second stage, geostationary satellite observational geometry is investigated and the improvements in determining TID parameters are evaluated. In the final step, actual data taken over Europe through a TID rich ionosphere during disturbed geomagnetic conditions are analyzed to investigate the applicability of the study to real-world observations.

The results show promise for the identification of some TIDs using GPS and show the key importance of backing up the observations with computer modeling to test the techniques being used. The implications for the resolution of ionospheric data assimilation algorithms and in particular the use of different observations to infer the presence of TIDs are discussed.

1. INTRODUCTION

Over the past two decades GPS has become the most widely distributed and easily available source of observations of the ionosphere on a global scale.

There has recently been increased interest in TIDs. Even though they have been studied for over 70 years (e.g. Hargreaves, 1992; Hines, 1960; Hocke and Schleigel, 1996; Hooke, 1968 and references contained within), they are difficult to represent in deterministic ionospheric models. This is because they are averaged out in statistical models and the upward coupling is difficult to specify in physics-based models.

TIDs are well known to be identified in HF observations, and have been studied widely in this context since the 1950s. The identification of TIDs in GPS signals (Afraimovich, 1998) could potentially add new knowledge about the physics of TIDs, but there has been a problem in this progressing. To put it simply – there are several papers that report waves in line-of-sight GPS TEC, but exactly how these waves relate to the spatial and temporal field of TIDs in the ionosphere is unclear.

The first approach to this analysis is to limit the time-step to much shorter than a TID period, say 2 minutes. The problem is that the GPS signals used to create the line-of-sight TEC use both L1 and L2 GPS signals and these have inter-frequency biases that are associated with the transmission and the reception of the signal. So, each TEC observation between a specific satellite and a specific receiver is biased, and these biases are of the order of several TEC units. The biases are not thought to known to better than an error of +/- 1-5 TECu. Unfortunately the amplitude of a TID is usually of the order of or often a lot less than this. Across a continental-scale region such as the USA there are perhaps a hundred GPS receivers each viewing maybe ten satellites in an period of an hour, so there are around a thousand individual biases – *which are not the all the same but do correlate across common satellites and receivers*. This in itself can create a pattern that may look like a wave and will evolve with time. It is only in the case that the real TIDs have a much greater amplitude than the biases that a real TID field would emerge from this approach to the analysis. This may be the case for some large-scale TIDs.

The second approach is widely used and is to make use of an individual satellite observation from an individual receiver, and hence even though the bias is there it in common to the entire time series, known as a phase arc. This creates a subtler problem that is demonstrated here in this paper. The explanation is that the GPS satellites are in motion relative to the Earth and the velocity of the TEC path through the ionosphere is similar to that of a TID. So to take extreme cases, if the observation geometry were such that the path travelled with the TID at the same velocity it would travel at the TID velocity and the wave would not appear in the TEC. The opposite case would also be problematic because in a given time window of the wave period the observation velocity would add to the period and the wave period measured would be double that of the real TID period. There are of course all cases in between this and indeed some worse as is demonstrated in the next Section.

2. SIMULATION

A computer simulation of GPS observations through an ionosphere TID model was performed. The IRI model Bilitza et al., (2014) was used as a background and the Hooke (1968) model of TIDs was used to create the dynamic (time-dependent) perturbations.

A set of models were generated with TID horizontal wavelength 1000 km; propagation angle south east 110 degrees or south west 135 degrees azimuth from geographic north; amplitude at peak perturbation resulting a 10% change in electron density. The period of the wave was varied between 10 minutes and 2 hours, resulting in horizontal speeds of between 140 and 1600 m/s.

An example of cross section through a model at 105 W is shown in Figure 1, with the corresponding profile of electron density through the F-layer peak in the lower portion of the figure. Each of the models used in this simulation had this spatial structure but varied in period and angular propagation direction.

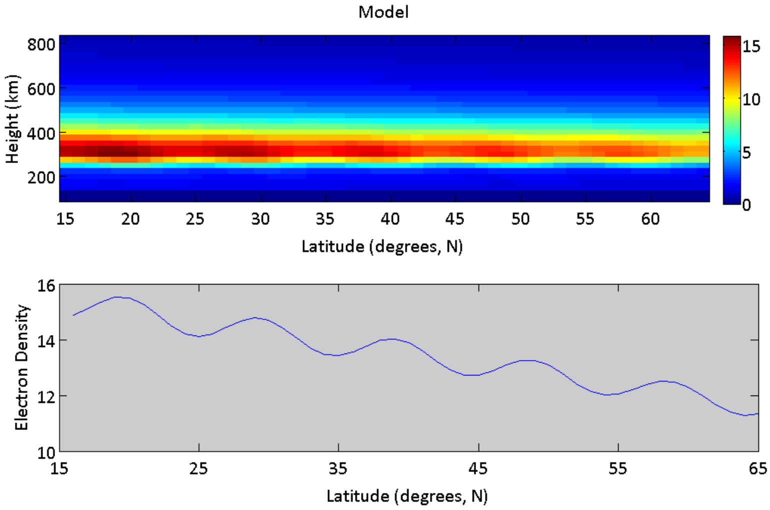

Figure 1. Cross section and profile through a TID model, with a wavelength of around 1000 km.

GPS computer-simulated observations were generated from actual satellite and receiver geometry during a 2-hour period of time using the network of ground-based receivers shown in Figure 2. Then these TEC observations are examined to investigate whether the correct TID parameters could be determined.

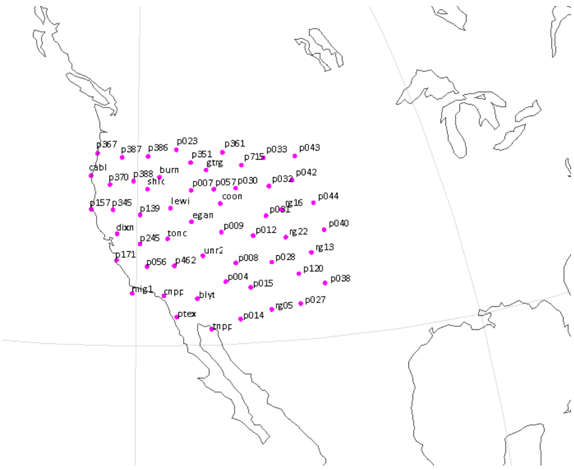

Figure 2. Network of ground-based GPS receivers used in the study.

3. RESULTS OF SIMILATIONS

3.1 LINE OF SIGHT

Figure 3 shows the simulated TEC observations from a receiver in the center-south of the map of Figure 1 (P004) through a TID with the 2-hour period, that is a wave period of 120 minutes. The simulation is for a GPS satellite and for geostationary satellite (polar plots of the azimuth and elevation of the satellites are also given). It can be seen immediately that the geostationary satellite reveals the wave period correctly at 120 minutes but the GPS traces out a complicated path that shortens the apparent period it to around 20 minutes!

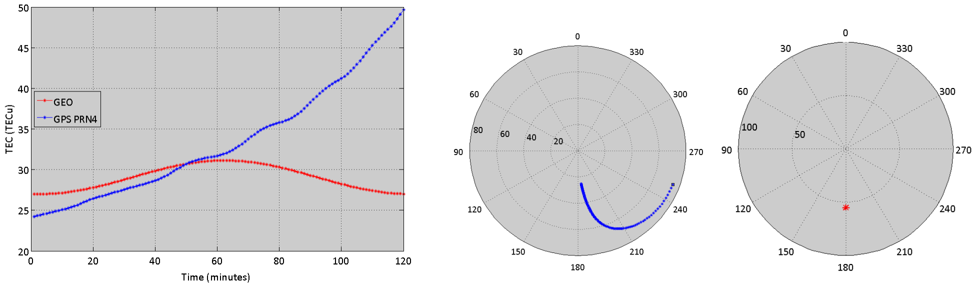

Figure 3. Integrated electron density (TEC) through the model for a GPS and a geostationary satellite.

Table 1 shows the actual wave, the apparent wave period using the geostationary satellite and the apparent wave period using this particular GPS satellite.

Table 1. Actual and apparent wave periods in the simulation tests.

Actual wave velocity (m/s)	140	280	560	830	1600
Actual wave period (minutes)	120	60	30	20	10
Apparent wave period GEO	120	60	30	20	10
Apparent wave period PRN 4	20	22	33	20	10

But this is just an example PRN. Another PRN to the west shows an apparent period of around 60 minutes for the 120-minute case. So there will be a distortion of the period by varying amounts until the wave velocity significantly exceeds that of the GPS to ground ray-paths.

3.2. IONOSPHERIC IMAGING

A model was set up with TID horizontal wavelength 1000 km; propagation angle south-west 225 degrees clockwise azimuth from geographic north; amplitude at peak perturbation 10% and period 40 minutes. The MIDAS algorithm (See Bust and Mitchell, 2008) was run at a time-step of 2 minutes. The resulting image from a single time-step is shown in Figure 4.

It can be seen that the reconstruction is able to accommodate the time-varying property of the wave and to show the spatial structure. There is a loss of definition to the edges of the grid away from the receivers, where the viewing directions are limited. Time-varying images in the movie show that the period is correctly determined at 40 minutes.

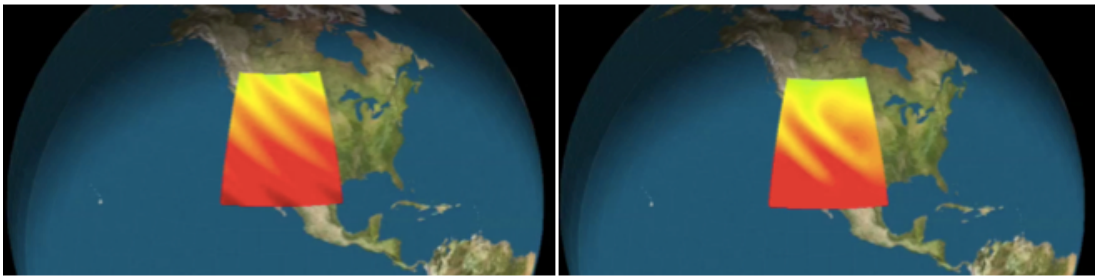

Figure 4. Model (left) and reconstruction (right) for the simulation. Some distortion can be seen away from the receiver sites which were shown in Figure 2. The distortion is due to the limited viewing geometry caused by the localized sites chosen for this study.

4. EXPERIMENTAL OBSERVATIONS

An example from the ionospheric storm (sustained Kp of 6) of 20 December 2015 is presented from Europe. Europe is chosen because of the good distribution of GNSS receivers monitoring GEO satellites and also the number of ionosondes (Reinisch and Huang, 1983) that all provide independent verification for the GPS assimilation in MIDAS.

Figure 5 shows GPS receivers (denoted by their four letter name) and ionosonde locations in Europe (denoted by a two letter name in capitals). Helg, Karl and Heug lie in an approximate longitude line with the direction of the geostationary satellite transmitting GPS PRN 136 (SES5 a.k.a. Astra 4B, at 5 degrees East).

Figure 5. Map showing GPS receivers observing GEOs and ionosondes in Europe.

Figure 6 shows the electron density reconstruction from MIDAS, integrated vertically to show TEC. A complex distribution of the electron density is apparent in this storm period. Figure 7 shows the uncalibrated (relative) TEC derived from geostationary satellites picked up by the GPS receivers. The diurnal variation is clear, as are several wave-like peaks. The northerly site is generally seeing the peaks slightly before the other two. These observations were not used in MIDAS, so are independent verification to be compared with vertical TEC at heug, shown in Figure 8.

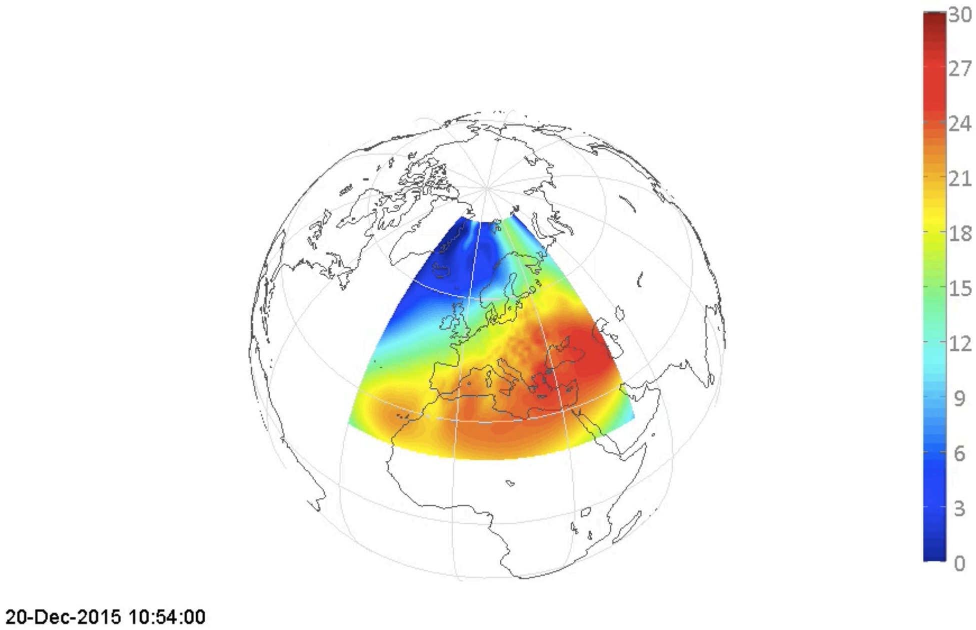

Figure 6. Single frame showing TEC from MIDAS using only GPS data an input to the assimilation (no ionosonde or geostationary data input).

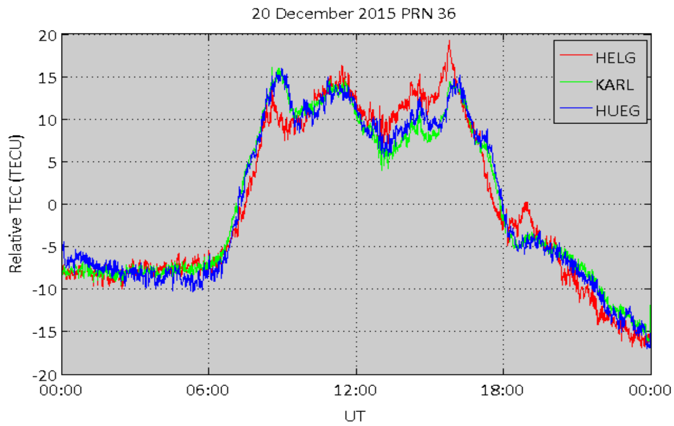

Figure 7. Relative slant TEC from the geostationary satellite to three sites indicated in the map of Figure 5. Note that one TECu is equivalent to10^{16} electrons /m^2.

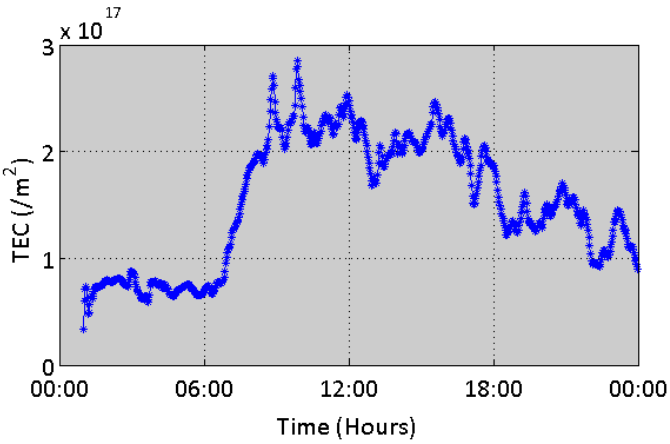

Figure 8. Vertical TEC from MIDAS at the location of the heug site. Note that one TECu is equivalent to10^{16} electrons /m^2.

Figure 9 shows the fof2 from the four ionosondes as denoted in the legend: Chilton, Dourbes, Roquetes and El Arensillo.

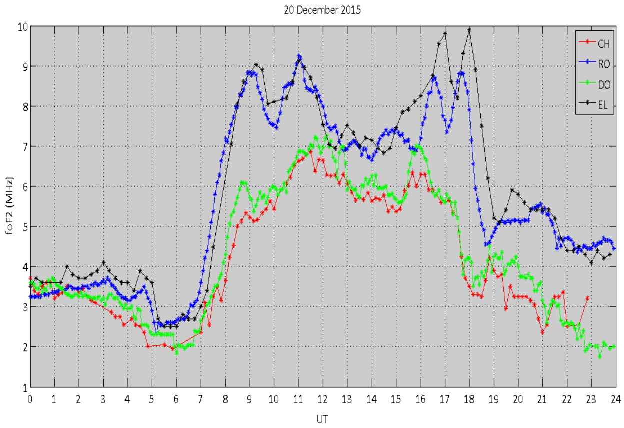

Figure 9. foF2 from four European ionosondes.

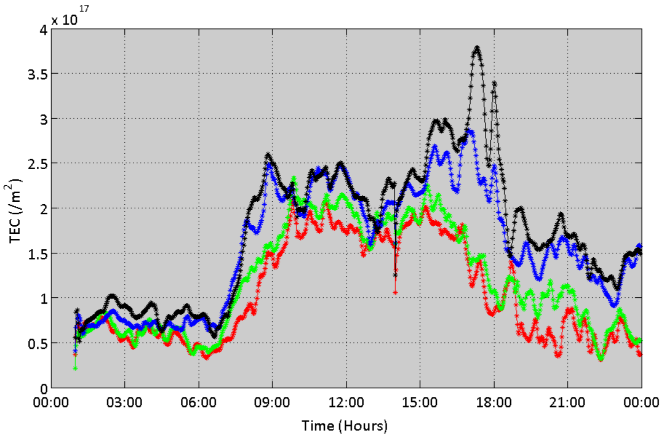

Figure 10. TEC vertically through the ionosphere from MIDAS over the ionosonde sites of Figure 8. The line colors correspond to the same sites as in Figure 10. A good correlation can be seen, indicating that the MIDAS GPS assimilation is performing well.

5. CONCLUSIONS

This is the first study that performs a 4D computer simulation of TIDs in the ionosphere in order to investigate the use of GPS signals in the study of their properties.

There are several recommendations that arise from this study.

1. The simulation of TIDs in the ionosphere is a very valuable tool to verify the validity of GPS observations and to study any distortions.
2. TIDS in the ionosphere can be seen in GPS TEC but the properties can be distorted by the satellite geometry and the satellite movement.
3. Spaced ionosonde observations are reliable and well understood but in isolation they are limited in their resolution of TID motion and spatial structure.
4. Observations of TEC to geostationary satellites are very useful because they do not distort the wave period.

5. 4D imaging algorithms like MIDAS can use the moving GPS relative slant TEC observations to reveal the spatial/temporal TID field across a region of ground-based receivers, providing a useful view of the spatial field of TIDs.
6. The combination of multiple ionospheric instrumentations reveals a more complete picture of the complex field of TIDs in the ionosphere during storms and will be a useful technique to study future ionospheric events.

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