Imaging the topside ionosphere and plasmasphere with ionospheric tomography using COSMIC GPS TEC

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Abstract GPS-based ionospheric tomography is a well-known technique for imaging the total electron content (TEC) between GPS satellites and receivers. However, as an integral measurement of electron concentration, TEC typically encompasses both the ionosphere and plasmasphere, masking signatures from the topside ionosphere-plasmasphere due to the dominant ionosphere. Imaging these regions requires a technique that isolates TEC in the topside ionosphere-plasmasphere. Multi-Instrument Data Analysis System (MIDAS) employs tomography to image the electron distribution in the ionosphere. Its implementation for regions beyond is yet to be seen due to the different dynamics present above the ionosphere. This paper discusses the extension of MIDAS to image these altitudes using GPS phase-based TEC measurements and follows the work by Spencer and Mitchell (2011). Plasma is constrained to dipole field lines described by Euler potentials, resulting in a distribution symmetrical about the geomagnetic equator. A simulation of an empirical plasmaspheric model by Gallagher et al. (1988) is used to verify the technique by comparing reconstructions of the simulation with the empirical model. The Constellation Observing System for Meteorology, Ionosfer, and Climate (COSMIC) is used as GPS receiver locations. The verification is followed by a validation of the modified MIDAS algorithm, where the regions’ TEC is reconstructed from COSMIC GPS phase measurements and qualitatively compared with previous studies using Jason-1 and COSMIC data. Results show that MIDAS can successfully image features/trends of the topside ionosphere-plasmasphere observed in other studies, with deviations in absolute TEC attributed to differences in data set properties and the resolution of the images.

1. Introduction

The topside ionosphere and plasmasphere extend from approximately 600 km altitude up to 4–5 Earth radii (Rₑ). This region is strongly coupled with the underlying ionosphere as it is populated by the outward diffusion of ionospheric plasma along magnetic flux tubes. Studies have shown that electron density structures and storm responses in the topside ionosphere (between ~600 km and ~1500 km) are influenced by plasma dynamics below the F₂ peak [Yizengaw et al., 2006; Kakinami et al., 2011]. The plasmasphere—characterized by the cold dense plasma torus extending up to midlatitudes—acts as a daytime sink for the ionosphere and as a source to maintain the nighttime F region [Lemaire and Gringauz, 1998]. The midlatitude trough found in the ionosphere shows a close association with the light ion trough in the topside and the plasmapause [Yizengaw and Moldwin, 2005; Yizengaw et al., 2005b], while evidence of plasmaspheric tails have been observed in the ionosphere [Foster et al., 2002]. Nevertheless, little effort has been extended to studying these higher altitudes relative to the ionosphere, as the bulk of the plasma (and thus its effect on radio signals) lies in the lower regions. Consequently, the dynamics of the topside ionosphere and plasmasphere and their interaction with the underlying ionosphere are yet to be fully realized.

First proposed by Austen et al. [1988], tomography has been instrumental in imaging the ionospheric electron concentration and understanding plasma dynamics of the region. Ionospheric tomography involves measuring the total electron content (TEC) along a signal path, which is then inverted to produce maps of electron concentration of the region of interest. TEC is an integral quantity defined as the number of free electrons along a column of unit cross-sectional area and has the unit TECU (total electron content unit, 1 TECU = 10¹⁶ el m⁻²). When measured along a radio signal passing through the ionosphere between a transmitting satellite and receiver, the measurement is known as slant TEC (sTEC). Ionospheric tomography falls under ray tomography, where the signal paths are approximated to straight lines, effectively rendering ray
bending effects negligible and simplifying the inverse problem. sTEC can be extracted from the differential phase of dual frequency transmissions [Davies, 1990] where the electron concentration is related to sTEC as

\[ s\text{TEC} = \int S N ds + c \]  

where \( S \) and \( R \) are satellite and receiver locations, respectively, \( N \) is the electron concentration to be derived, \( ds \) is the distance along the path from satellite to receiver, and \( c \) is an unknown constant equivalent to the number of differential phase cycles in the measurement.

Historically, low Earth orbit (LEO) systems such as Navy Navigation Satellite System, Cicada, and the Coherent Electromagnetic Radio Tomography (CERTO) beacons were used to derive TEC along LEO satellite-ground receiver paths using differential phase measurements, which were used for 2-D tomographic imaging of the ionosphere. The emergence of multifrequency Global Navigation Satellite Systems such as the Global Positioning System (GPS), however, enabled a new data set for tomographic imaging with near-global and continuous coverage of the ionosphere. In 1994, Hajj et al. introduced the concept of using ground- and space-based (radio occultation) dual frequency L1/L2 GPS receivers for ionospheric imaging and discussed their potential for detailed studies of the region [Hajj et al., 1994]. Extensive research has since been carried out on the ionosphere using ground-based receiver networks and LEO satellite receivers [e.g., Hernández-Pajares et al., 1998; Yin et al., 2004; Pedatella et al., 2009]. A comprehensive review of ionospheric imaging using GPS and its evolution to four-dimensional (3-D space and time evolving) imaging can be found in Bust and Mitchell [2008].

1.1. Topside Ionosphere-Plasmasphere Imaging With GPS

GPS satellites broadcast at L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies from an orbiting altitude of 20,200 km. Ground and LEO dual frequency L1/L2 receivers used for ionospheric imaging are placed such that the received signals propagate through the ionosphere. However, before entering the region, GPS signals must travel through the overlying plasmasphere. This means that the TEC derived from the signal phase and/or time delays recorded at the receivers represent the integrated electron concentration through both regions. Since TEC at ionospheric altitudes significantly exceeds that of the topside and the plasmasphere, any signatures present in the higher altitudes are effectively masked by the TEC present in the ionosphere. Imaging the topside ionosphere and plasmasphere thus requires LEO GPS receivers installed at altitudes that allow the upper ionized regions to be isolated from the ionosphere, with their antennas oriented such that there is a direct line of sight between transmitter and receiver (e.g., zenith oriented). Since GPS is widely used for precise orbit determination (POD) of satellites, navigation data received by POD antennas can be used for topside ionosphere-plasmasphere imaging, provided that the LEO orbit altitude is above 600 km.

To date, POD data from several missions (e.g., CHAMP, SAC-C, FedSat, Jason-1, and TerraSAR-X) housing dual frequency GPS receivers have been used to quantify and study plasmaspheric TEC [Heise et al., 2002; Yizengaw et al., 2005a, 2008; Lee et al., 2013; Zakharenkova and Cherniak, 2015]. However, these are single
satellite missions not sufficient for imaging the topside ionosphere-plasmasphere in a global scale. To overcome this, \textit{Hajj et al.} [2000] proposed the use of Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)—a constellation of six microsatellites in Sun-synchronized circular orbits at an altitude of \(-800\) km. With the orbital planes evenly spaced in longitude and having an inclination of \(72^\circ\), COSMIC satellites travel approximately \(14.6\) revolutions \textit{Hajj et al.}, [2000] with a precession of \(-12\) min per day \textit{Pedatella and Larson}, [2010], thus providing near-global coverage. COSMIC GPS receivers have two antennas for POD and occultation in the \(xy\) plane, where \(+x\) is defined in the direction of travel, \(+y\) is directed eastward, and \(+z\) is oriented toward the zenith (Figure 1). Since the installation into its final orbit, COSMIC has been a key source for global topside ionosphere and plasmasphere research as shown by \textit{Pedatella and Larson} [2010] and \textit{Pedatella et al.} [2011].

2. Tomographic Imaging With MIDAS

\textit{MIDAS} (Multi-Instrument Data Analysis System) was first introduced by \textit{Mitchell and Spencer} [2003] as a new three-dimensional space and time-evolving imaging algorithm for the ionosphere using GPS. The problem is defined within a 3-D grid of voxels (volumetric pixels) of latitude, longitude, and altitude. Each voxel considers the GPS transmitter-receiver ray path elements passing through it individually, assuming a constant electron concentration within a given voxel. The approach enables the inverse problem described by equation \(1\) to be discretized and represented in a matrix form as

\[
\mathbf{b}_{(i)} = \mathbf{A}_{(i,j)} \mathbf{x}_{(j)} + \mathbf{c}_{(i)}
\]

where \(\mathbf{b}\) is a vector of \(i\) TEC observations, \(j\) is the number of voxels, \(\mathbf{A}\) is a \((i \times j)\) matrix of ray path geometry, \(\mathbf{x}\) is a column vector of \(j\) components holding the unknown electron concentration in each voxel, and \(\mathbf{c}\) holds the unknown cycle offset for each observation and other components such as receiver biases. The unknown quantity \(c\) is removed from the problem by differencing between successive observations (i.e., observations taken from the same satellite-receiver pairs at different times), which effectively derives relative observations of differential phase of L1/L2 signals along the same ray path geometry. As explained in \textit{Mitchell and Spencer} [2003], for ionospheric tomography, the changes of TEC across a continuous satellite-receiver arc are the input data to the inversion process. The calibration constant for each continuous satellite-to-receiver observation is evaluated within the matrix inversion itself. This allows relative differential phase observations to be used directly within the inversion algorithm. As such, equation \(2\) in \textit{MIDAS} is now reduced to

\[
\mathbf{b} = \mathbf{A} \mathbf{x}
\]

While matrix equation \(3\) represents a set of simultaneous equations, the limited ray paths over the entire grid result in an under-constrained problem that does not contain a unique solution for each voxel without a priori knowledge. \textit{MIDAS} addresses this by using a mapping matrix \(\mathbf{X}\) containing a set of empirical orthogonal functions (EOFs) in the radial dimension and spherical harmonics-generated basis functions for horizontal variations. As the approach is not based on models derived from long-term statistical data, only a minimum of a priori assumptions are required on the electron density distribution of the upper atmosphere \textit{Mitchell et al.}, [2002]. The use of EOFs is expressed in matrix form as

\[
\mathbf{b} = \mathbf{AXw}
\]

where \(\mathbf{AX}\) is the basis set of line integral electron concentrations and \(\mathbf{w}\) is the unknown relative contribution of the basis functions realized by

\[
\mathbf{w} = (\mathbf{AX})^{-1} \mathbf{b}
\]

where the solution to \(\mathbf{w}\) is obtained using singular value decomposition or minimal residual method—the latter an iterative numerical approach. The unknown electron concentration \(\mathbf{x}\) for each voxel is recovered by

\[
\mathbf{x} = \mathbf{Xw}
\]

Since the orbital period of GPS satellites is \(-12\) h, a fixed ground receiver will track satellites at high elevation for several hours between rise and set times. TEC measurements taken throughout this time thus contains information on the temporal evolution of the ionosphere. In order to account for these time variations, \textit{Mitchell and Spencer} [2003] further extended the algorithm to produce time-dependent inversions. Thus, \textit{MIDAS} now includes a priori knowledge of the change in electron concentration during a given time period, with the
assumption that changes are linear within a voxel. The change in TEC observed at consecutive time intervals within a given voxel is related to the changes in the ray path geometry and electron concentration such that

$$\Delta \text{TEC} = \Delta y$$

(7)

where $\Delta \text{TEC}$ is the observed change in TEC within the voxel, $D$ is the difference in ray path geometry at consecutive time intervals, and $y$ is the unknown change in electron concentration with time. The evolution of the electron concentration per voxel ($y$) is recovered by adopting the same process used for the spatial reconstruction described by equations (3)–(6). For the ionosphere, linear variations while having sufficient data are ensured by collecting TEC measurements for a typical period of 1 h with sampling at 30 s intervals.

2.1. MIDAS for the Topside Ionosphere-Plasmasphere

The first results from the extension of MIDAS to include the topside ionosphere and plasmasphere were produced by Spencer and Mitchell [2011]. TEC was measured by POD antennas of the COSMIC GPS receivers, thus enabling reconstruction of the global electron concentration from an altitude of ~800 km to 20,200 km, effectively isolating the region.

The original version of MIDAS developed for the ionosphere contains basis functions that describe the electron concentration morphology specific to the local region, which is based on plasma properties. In contrast, particle motion in the topside ionosphere and plasmasphere is influenced largely by the geomagnetic field. Thus, to image these higher altitudes correctly, MIDAS requires basis functions that incorporate the physics governing the regions. Spencer and Mitchell [2011] achieved this by substituting the original basis functions with a description of a dipole magnetic field in terms of Euler potentials $\alpha$ and $\beta$

$$\alpha = \frac{\sin \theta}{r}$$

(8)

$$\beta = \phi$$

(9)

where $\theta$ and $\phi$ are magnetic latitude and longitude and $r$ is the radius. The magnetic field $B$ is described through Euler potentials as [Stern, 1970]

$$B = \nabla \alpha \wedge \nabla \beta$$

(10)

The mapping matrix $X$ defined in equation (4) thus linearly transforms the spatial grid of $\theta$, $\phi$, and $r$ to a two-dimensional quantized Euler space through interpolation with a reconstruction resolution of $\delta \alpha$ and $\delta \beta$ at each time step.

In addition to the process described by equations (3)–(7), quadratic smoothing in space and time is introduced to minimize any artifacts produced during the inversion. This is expressed in matrix form as

$$[(AX)^{-1}(AX) + \lambda(RX)^{-1}(RX))w = (AX)^{-1}b$$

(11)

where $R$ is the regularization (Hessian) matrix and $\lambda$ specifies the relative weighting between observations and regularization [Spencer and Mitchell, 2011].

Since only a maximum of six receivers are available at any given time, a longer time duration is needed to collect sufficient data for the inversion, which needs to be considered against the temporal evolution of the topside ionosphere-plasmasphere. In contrast to time-dependent ionospheric reconstructions in Mitchell and Spencer [2003], Spencer and Mitchell [2011] used data averaged over 3 h with the time window extending for 33 h to provide evolutionary a priori information.

3. Method

The results presented in this paper are the extension of work carried out by Spencer and Mitchell [2011], where MIDAS is validated for the use of topside ionospheric/plasmaspheric imaging. Yearlong data of 2009 are used in this validation as the year lies in a solar minimum, when solar and geomagnetic activities are lowest. Consequently, the plasmasphere exists in a “quiet” state with minimal or no storm-induced structures, which is optimal to investigate and understand the performance of the new algorithm.

In the first phase, ray path geometry between GPS satellites and COSMIC receivers during the year is used to undertake a computer simulation using an empirical topside ionosphere-plasmasphere model by

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Gallagher et al. [1988, hereafter “Gallagher model”]. This allows the new technique to be tested and benchmarked against a case where the plasmasphere is modeled, ensuring the correct answer is known. The algorithm is then used with true differential phase from COSMIC GPS POD antennas of the receivers for the same year (2009). Validation is achieved by qualitatively comparing the reconstructions against features previously observed by Pedatella et al. [2011] and Lee et al. [2013].

The COSMIC GPS data used in the validation are obtained in receiver-independent exchange (RINEX) format from the UCAR (University Corporation for Atmospheric Research) COSMIC database, available from http://cdaac-www.cosmic.ucar.edu/cdaac/products.html. Quality control of data for use in the second phase (the validation process) is implemented by preprocessing data before being ingested by the algorithm. Cycle slips are removed by filtering out data where there is >5 TECU difference in differential phase TEC, and the data set is rejected if >5% of the data has cycle slips. The choice of the threshold of 5 TECU for the detection of cycle slips is a standard for GPS processing used previously in both ground-based and LEO-based GPS data processing [Mitchell et al., 2005]. Noteworthy is that, although six satellites are available in the constellation, their operation during the year 2009 was observed to be intermittent. Particularly, some orbit data providing receiver positions appear to be compromised, although dual frequency phase measurements are available when the orbit data are missing. The orbits are recovered by substituting the position data from a future complete orbit. Drift and perturbations are accounted for by minimizing differences between the ground tracks of the two orbits.

Following the acquisition of phase and orbit data, a three-dimensional spatial grid is defined in geomagnetic coordinates for the topside ionosphere-plasmasphere. The radial aspect extends from 600 km to 20,200 km altitude with a step size of 1000 km, while the geomagnetic latitude and longitude dimensions have a step size of 10° and 20°, respectively. Pole-to-pole latitudes are used in the inversion, although the plasmasphere only extends to regions of closed magnetic field lines — ±50° geomagnetic latitude. This is to ensure that ray path geometries toward the edge of the plasmasphere are not discarded during reconstructions. Following the reconstruction, the analysis considers a limited latitude range of ±40° for the simulation (due to model limitations) and ±50° for real data. An elevation cutoff of 40° is also imposed to maximize the contribution from the plasmasphere in the inversion while minimizing the contribution from ray paths that travel through the main ionosphere.

Although applying the same 3 h temporal resolution used by Spencer and Mitchell [2011] ensures sufficient data coverage for the inversion, the longer window means that any fast evolving (<3 h) structures will not be faithfully reconstructed. To determine the effects of this, the inversion process of the model simulation is conducted with both 1 h and 3 h time resolutions. Considering both coverage and quality of reconstruction, a suitable time resolution is then selected to proceed with the validation using true COSMIC GPS data.

### 3.1. Simulating Observations of the Gallagher Model

The empirical model by Gallagher et al. [1988] is used to simulate the procedure of imaging the electron concentration in the topside ionosphere and plasmasphere. The model was based on the data from the Retarding Ion Mass Spectrometer (RIMS) onboard Dynamics Explorer 1 (DE 1). It describes the steady state low-energy proton distribution in the plasmasphere, while the topside ionosphere is modeled using a modified chapman layer. The model was developed by Gallagher et al. using RIMS data collected for a magnetic latitude range of ±40° between 0000 h and 1200 h magnetic local time, obtained during moderate geomagnetic activity immediately following a solar maximum.

The proton concentration described by the Gallagher model is translated to an electron concentration in MIDAS by assuming quasi-neutrality of the medium. The electron concentration is simulated within each voxel of the spatial and temporal grids defined earlier. Ray path geometries through the simulation (a) required by the algorithm are generated between GPS and COSMIC satellites, the latter providing receiver positions at the time of signal reception sampled every 60 s. The simulated TEC “observations” (b) at the receiver are then inverted to reconstruct the topside ionosphere-plasmasphere model. Figure 2 shows the Gallagher model for the topside ionosphere-plasmasphere simulated by MIDAS with a 3 h resolution (averaged data) at two time steps: 0300–0600 h UT and 0600–0900 h UT. Although the model is applied to simulate the topside ionosphere-plasmasphere globally, only the latitude range ±40° is considered when evaluating the quality of reconstruction. This is because the model is only valid for the limited latitude range. The model only incorporates diurnal variations.
3.2. Validation of MIDAS for the Topside Ionosphere/Plasmasphere

Once the quality of the reconstruction process and technique is verified by simulation, the study progresses to real observations from COSMIC GPS receivers to qualitatively validate the algorithm against previous observations by Pedatella et al. [2011] and Lee et al. [2013]. In contrast to the verification process (by simulation), here the latitudinal dimension extends between ±50° to ensure that the entire plasmasphere is considered. Measured differential phase data, sampled every 60 s, are processed by MIDAS together with the ray path geometries produced at each point of sampling (b and A, respectively). The reconstructed electron density is evaluated in terms of diurnal and seasonal variations and specific features observed by previous studies.

4. Results

4.1. Reconstruction of the Gallagher Model

The reconstruction of the Gallagher simulation is carried out using both 3 h and 1 h time resolutions. This is to identify the optimum resolution for imaging plasmaspheric structures that would also provide good ray path coverage across the spatial grid. The 3 h (averaged data) time resolution uses a 33 h window containing 11 3 h time frames, centered on the time of interest. Observations from all time frames contribute to the central time through a regularization process, which linearly constrains the evolution of dynamics and prevents any large or abrupt changes in electron density through successive frames. The contribution of multiple frames (i.e., windows) also provides better ray path coverage, which may otherwise not be available if only the 3 h of interest (i.e., frame of interest) was considered. In contrast to the 3 h time frames, the 1 h time resolution uses 11 1 h frames, effectively increasing the time resolution but reducing the coverage contributing to the time of interest.

Reconstructions of the simulation using the two time resolutions and respective ray path coverage are shown in Figures 3 and 4 in geomagnetic coordinates. Two time windows for 22 May 2009—0300–0600 h UT for 3 h resolution and 0600–0900 h UT for 1 h resolution—are considered to demonstrate the evolution of the simulated plasmasphere and its effect on the reconstructions. Although the simulation only represents diurnal variations, it is important to consider the day of year for reconstructions as the ray path coverage is not consistent and has a significant bearing on the quality of the reconstruction.

Figures 5 and 6 give the absolute error and percentage error (respectively) between the simulations and reconstructions at each time step to quantify the quality of reconstruction for both time resolutions. The maps are in geomagnetic coordinates. Results show that the inversion using a 1 h time frame with an 11 h time window (Figure 4) represents the simulation better than that performed with a 3 h time frame using a 33 h time window (Figure 3). This is because the structures of the Gallagher model evolve significantly over 3 h, resulting in considerable discontinuation between two consecutive time windows. Therefore, given the limited observations from only six receivers, the window of 33 h has a stronger influence on the solution than the observed data itself. This can be seen in Figure 5, where the errors appear on the edges of the structure (compared with Figure 4), which are indicative of smoothing across the image region. Considering inversions with an 11 h time window, although the solutions appear to represent the simulation more faithfully,
two factors need to be considered: (1) the evolution of structures in the model through two consecutive time steps is more continuous and thus less realistic, making the solution easier to compute, and 2) the number of observations compared to the number of unknowns (i.e., electron density along field lines) per inversion for 1 h is very small, resulting in the problem being further under-constrained. The latter is particularly important.

Figure 3. 3 h reconstructions of the Gallagher simulation (of plasmaspheric TEC) for 22 May 2009 from 0300 to 0900 h UT with ray path coverage. (a and b) Plasmaspheric TEC from the Gallagher simulation for 0300–0600 h UT and 0600–0900 h UT, respectively. (c and d) Reconstruction of the simulation through MIDAS for the same time durations. (e and f) Ray path coverage at each time duration.

Figure 4. 1 h reconstructions of the Gallagher simulation (of plasmaspheric TEC) for 22 May 2009 from 0300 to 0400 h and 0600 to 0700 h UT, with ray path coverage. (a and b) Plasmaspheric TEC from the Gallagher simulation for 0300–0400 h UT and 0600–0700 h UT, respectively. (c and d) Reconstruction of the simulation through MIDAS for the same time durations. (e and f) Ray path coverage at each time duration.
when reconstructing the true plasmasphere, which has more structures than a model simulation. Both these factors mean that, when imaging the plasmasphere using observed differential phase measurements, the 3 h time resolution will be more reliable due to the higher number of observations per voxel. Indeed, this means that the algorithm is only suitable for the quiet time plasmasphere which has slower evolving structures (>3 h). Reconstruction of a more active (storm time) plasmasphere will be possible in the future, provided there is a better availability of observations due to a higher number of either satellites or receivers, thus allowing for an increase in the algorithm’s time resolution (e.g., 1 h time frames) to image more dynamic structures.

4.2. Reconstruction of the Topside Ionosphere-Plasmasphere
Validation of MIDAS for the topside ionosphere-plasmasphere is carried out by qualitatively comparing reconstructed features against previous results. Given the results from the simulation, 3 h time frames are used to provide a 33 h window for the inversions. Diurnal, seasonal, and longitudinal variations are analyzed...
against independent sources to confirm the integrity of MIDAS inversions. GPS-derived TEC from Jason-1 by Lee et al. [2013] is used as the primary source since it shows global characteristics of the plasmasphere above 1336 km. Results from COSMIC GPS TEC by Pedatella et al. [2011] are used as they provide observations of the underlying topside ionosphere, thus enabling the validation of MIDAS for both regions.

4.2.1. Seasonal and Local Time Variations
Seasonal variations are observed by evaluating TEC during the solstices and equinoxes of the year. The distribution over ±2 weeks around the solstice (or equinox) is studied to identify seasonal evolution of the topside ionospheric-plasmaspheric TEC. General trends over the year are observed by imaging the annual TEC distribution. Variations in local time (LT) are analyzed by sorting the data into 1 h bins. Daytime is defined from dawn to dusk (0600–1800 LT), while dusk to dawn (1800–0600 LT) is considered as nighttime.

Figure 6. Comparison of the percentage error between the simulation and reconstruction for 3 h and 1 h mean TEC at two instances on 22 May 2009. (a) Percentage error for 0300–0600 h UT (3 h) and 0300–0400 h UT (1 h). (b) Percentage error for 0600–0900 h UT (3 h) and 0600–0700 h UT (1 h).
Figure 7. Seasonal TEC maps showing variation with local time. (a) TEC distribution for June. (b) TEC distribution for December. (c) Mean TEC distribution for March and September equinoxes. (d) Average TEC for each solstice and equinox season against local time. The TEC maps of Figures 7a–7c are plotted against the geomagnetic latitude.
Figure 7 shows the mean TEC distribution during the solstice and equinox seasons and their variation with local time. The annual trend for 2009 is shown in Figure 8. TEC in the topside ionosphere-plasmasphere rises during daytime to a peak in the afternoon (1200–1800 h LT) and falls during the night with an average day-night TEC difference of 1–2 TECU. June is noted to have the lowest TEC across the globe and December the highest. The semiannual anomaly, prevalent in the ionosphere, is nearly nonexistent in the upper regions, having only an approximately 7% difference between equinox and solstice TEC. These features from MIDAS-based COSMIC TEC reconstructions agree well with characteristics observed by Lee et al. [2013] using Jason-1 TEC, as well as a more recent study by Zakharenkova and Cherniak [2015] with TerraSAR-X TEC, although higher TEC is seen with the COSMIC data. Both Lee et al. [2013] and Zakharenkova and Cherniak [2015] saw a maximum in the afternoon, with Lee et al. [2013] reporting an approximate 1 TECU diurnal difference and an absence of the semiannual anomaly.

The small differences observed between results presented here from COSMIC and those from Jason-1 may be attributed to the contribution from the topside ionosphere, which is not present in Jason-1 measurements due to its higher orbit altitude of ~1336 km. It must be noted that the periodic variation seen with local time (Figures 7 and 8) is an artifact arising from the binning of averaged 3 h reconstructions to 1 h local time bins. The artifact is observed most prominently in the month of December (Figure 7b) due to the strong gradients caused by the annual anomaly within 3 h. This is in contrast to other seasons, where no strong gradients are present in the electron density within a 3 h period; thus, the artifact is nearly nonexistent. The results support the outcome of the verification process discussed in section 4.1 (the reconstruction of the simulated Gallagher model), which shows that the algorithm can be successfully implemented for the topside ionosphere-plasmasphere, provided that the evolution of structures extend over >3 h.

4.2.2. Longitudinal and L Shell Variations

Longitudinal and L shell variations are studied in terms of seasonal and diurnal TEC distributions in the equatorial plasmasphere (±20° geomagnetic latitude). Day and night are defined as 1000–1600 LT and 2200–0400 LT, respectively, while variations with altitude are characterized in terms of small ($L < 2.5$) and large ($L > 2.5$) L shells.
MIDAS reconstructions of the plasmasphere show the presence of the annual anomaly in the American sector (30°W to 60°E geomagnetic longitudes)—a feature identified in a number of past studies (e.g., Clilverd et al., 1991; Guiter et al., 1995; Richards et al., 2000) and observed by both COSMIC (Pedatella et al., 2011) and Jason-1 (Lee et al., 2013) GPS TEC. The average annual TEC distribution for 2009, given in Figure 9, shows a maximum in December and a minimum in June over American longitudes. The results, imaged for ±20° geomagnetic latitude between 1200 and 1800 LT, agree well with the analysis carried out by Pedatella et al. (2011) for the previous year (2008) also using COSMIC data, although the absolute TEC from MIDAS is 2–4 TECU higher for 2009, particularly during the December maximum. The ratio of December TEC to June TEC is found to be between 1 and 3, which also conforms to previous findings.

Figure 10 shows the distribution of TEC with the L shell parameter. The annual anomaly is consistently present regardless of the altitude, as is the ratio between December TEC and June TEC. Additionally, for small
L shells, a peak is seen in June at 120°W geomagnetic longitude, while December holds the lowest TEC (i.e., reversed from the annual anomaly). This is notably absent at L > 2.5. The result was also observed by Lee et al. [2013] using Jason-1 data.

Diurnal variations with longitude for different seasons are given in Figure 11. Both the annual anomaly in the American sector and reversal of this feature (i.e., June > December) at ~120°W geomagnetic longitude seen by Pedatella et al. [2011], Lee et al. [2013], and Zakharenkova and Cherniak [2015] can be clearly observed regardless of the time of day. Corroborating with results by Lee et al. [2013], the December to June TEC ratio over American longitudes is greater during the night relative to daytime. However, the nighttime difference between December and June TEC is higher for COSMIC data, with a maximum of 6–7 TECU, compared to 3–4 TECU observed by Jason-1. This is due to the contribution from the topside ionosphere, which is strongly coupled to the higher density lower altitude ionosphere.

5. Discussion

Reconstructions of the quiet time topside ionosphere-plasmasphere by MIDAS show strong agreement with characteristics and features seen in previous studies, excluding hemispheric variations. Notwithstanding the enforced hemispherical symmetry of TEC distribution (due to Euler potentials representing a dipole geomagnetic field), comparison of results with Jason-1 [Lee et al., 2013] and COSMIC [Pedatella et al., 2011] GPS TEC has enabled the validation of the algorithm for the region. However, notable differences can be seen in the absolute TEC, particularly against Jason-1 data, which may be attributed to several factors. The orbital altitude of Jason-1 is ~1336 km, which effectively isolates the plasmasphere. COSMIC satellites are at an altitude of 750–850 km and thus include the higher density topside ionosphere. The use of Euler potentials of a dipole geomagnetic field as a constraint results in MIDAS assuming a constant electron density along field lines for the entire region. Since the physics of the topside ionosphere is influenced by both the lower ionosphere and the plasmasphere, the variations in the TEC distribution may also account for the deviations observed between Lee et al.’s [2013] results and MIDAS reconstructions. Differences in data processing also have an effect on the final analysis. Lee et al. [2013] used averaged data over a period of 8 years (2002–2009), thus observing the plasmasphere over decreasing solar activity during solar cycle 23. The majority of the data were collected from 2003 to 2006, enabling the study to be performed during moderate solar activity. Furthermore, the analysis with Jason-1 TEC by Lee et al. [2013] was done by classifying the data into low and high solar ($F_{10.7} < 100$ and $F_{10.7} > 100$, respectively) and geomagnetic ($Kp < 2.5$ and $Kp > 2.5$, respectively) activities. In contrast, the validation of MIDAS was carried out using COSMIC data for the year 2009 only—i.e., during the solar minimum of cycle 24—for which no solar/geomagnetic classification of data was applied.

Figure 11. Diurnal and seasonal variations in TEC with longitude. The first two panels show the average TEC distribution during day and night for the solstices and equinox. The December to June ratio is also given which shows the annual anomaly over American longitudes. The last panel compares the December to June ratio between day and night.
The rationale for the differences between Lee et al. [2013] and MIDAS results is further supported by Pedatella et al. [2011]. The absolute TEC derived from the 2008 COSMIC data in the study is comparable to the MIDAS reconstructions of the topside ionosphere-plasmasphere using the same data source. The differences observed here can be attributed to three factors. Validation of MIDAS was performed using the 2009 COSMIC data and thus contained inherent variations in data coverage and the region’s dynamics relative to the previous year. Second, MIDAS constrains the electron density to be constant along field lines for altitudes of the topside ionosphere measured by COSMIC (i.e., from the orbit altitude of 750 km upward). Finally, the spatial, temporal, and data resolutions are different in the two studies. The MIDAS algorithm discussed here uses considerably large spatial voxels, where the electron density is assumed constant, to compromise on computational resources. The data are also averaged over 3 hr per inversion, providing a smaller data resolution and binning, which has a significant effect on the images as highlighted by the 3 hr and 1 hr reconstructions of the Gallagher model simulation.

6. Conclusion

The work presented here validated MIDAS—a toolkit of algorithms for ionospheric tomography and data assimilation—for quiet time topside ionospheric-plasmaspheric imaging using LEO GPS TEC. The COSMIC constellation during the year 2009 (solar minimum), orbiting at an altitude of 750–850 km, was used as the data source. Extension of MIDAS was achieved by incorporating the geomagnetic field’s influence on the electron density distribution of the topside ionosphere-plasmasphere by means of Euler potentials. The validation process was performed in two stages. A simulation of the empirical model by Gallagher et al. [1988] was first sampled from COSMIC GPS receiver positions and inverted by MIDAS to verify the quality of reconstruction. The verification process was also used to identify the optimal time resolution, found to be averaged 3 hr data, given the limited coverage of COSMIC for continuous global imaging. The algorithm was then validated by reconstructing the (quiet) topside ionosphere-plasmasphere for the year 2009. This was achieved by using COSMIC satellites’ GPS POD observations and comparing the results with previous independent studies on global plasmaspheric TEC [Pedatella et al., 2011; Lee et al., 2013].

Reconstructions of the topside ionosphere-plasmasphere TEC by MIDAS successfully showed the various characteristics and features seen in previous studies. The annual variation of TEC for 2009 with local time saw an increase during daytime with a peak in the afternoon (1200–1800 h LT). A seasonal trend was observed with MIDAS which was also seen by Lee et al. [2013], where the lowest global TEC was found in June with a maximum in December. The presence of the annual anomaly only across the American longitudes, confirmed by a number of studies, was clearly visible in the reconstructions. Variation of TEC with L shells also corroborated with Jason-1 observations [Lee et al. [2013]], where a peak was seen in June at 120°W geomagnetic longitude for L < 2.5. A similar feature was observed by Zakharenkova and Cherniak [2015], particularly in the topside ionosphere.

In addition to the trends and patterns of TEC distribution, the paper also analyzed the absolute TEC reconstructed, which notably saw some deviations relative to previous studies. MIDAS showed a maximum of 6–7 TECU in the nighttime difference between December and June TEC over American longitudes, while Jason-1 observed a maximum of 3–4 TECU. The former also showed a small variation (~7%) between the average equinox and solstice TEC, thus showing a weak presence of the semiannual anomaly, reported by Jason-1 TEC to be nonexistent. Comparisons with the analysis by Pedatella et al. [2011] on COSMIC GPS TEC for the year 2008 showed that the absolute TEC of MIDAS reconstructions was higher by 2–4 TECU. The deviations were attributed to a number of factors: Jason-1’s orbit altitude effectively eliminates the topside ionosphere, thus showing a lower absolute TEC and no signatures from the topside of a weak semiannual anomaly. The period of observation also has an effect on the TEC values. This was evident in the comparison between the study by Pedatella et al. [2011] for the year 2008 and the MIDAS reconstructions for 2009.

While the validation of MIDAS was successful for the quiet topside ionosphere-plasmasphere, some limitations still need to be addressed. The algorithm’s application of Euler potentials of a dipole to represent the geomagnetic field leads to an enforced hemispherical symmetry, resulting in the masking of any hemispherical variations. Furthermore, the assumption of constant electron density along a geomagnetic field line is less valid at lower altitudes and hence will mask topside features that are influenced by dynamics from the lower ionosphere. These factors could be improved upon in the future by incorporating a more realistic...
geomagnetic field, and with better data coverage from more LEO satellites at multiple altitudes, it may be possible to improve on the vertical resolution. In addition, the current time resolution of 3 h averaged data (frames) is not sufficient to image the storm time or active time topside ionosphere-plasmasphere due to the presence of more dynamic structures. Increasing this resolution, however, requires better ray path coverage of the region to maintain the quality of reconstructions which may be achieved in the future through an improved network of LEO GPS receivers.

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References
Austen, J. R., S. J. Franke, and C. H. Liu (1988), Ionospheric imaging using computerized tomography, Radio Sci., 23(3), 299–307, doi:10.1029/RS023i003p0299.
Bust, G. S., and C. N. Mitchell (2008), History, current state, and future directions of ionospheric imaging, Rev. Geophys., 46, RG1003, doi:10.1029/2006RG000212.
Cillverd, M. A., A. J. Smith, and N. R. Thomson (1991), The annual variation in quiet time plasmaspheric electron density, determined from whistler mode group delays, Planet. Space Sci., 39(7), 1059–1067, doi:10.1016/0032-0633(91)90113-O.
Davies, K. (1990), Ionospheric Radio, IET, Peter Peregrinus Ltd, London.
Foster, J. C., P. Erickson, J. Goldstein, and F. J. Rich (2002), Ionospheric signatures of plasmaspheric tails, Geophys. Res. Lett., 29(13), 1623, doi:10.1029/2002GL015067.
Gallagher, D. L., P. D. Craven, and R. H. Comfort (1998), An empirical model of the earth’s plasmasphere, Adv. Space Res., 8(8), 15–24, doi:10.1016/S0273-1177(88)90258-X.
Guler, S. M., C. E. Rasmussen, T. I. Gombosi, J. J. Söjka, and R. W. Schunk (1995), What is the source of observed annual variations in plasmaspheric density?, J. Geophys. Res., 100(A5), 8013–8020, doi:10.1029/94JA02866.
Hajj, G. A., R. Ibañez-Meier, E. E. Kurisinski, and L. J. Romans (1994), Imaging the ionosphere with the global positioning system, Int. J. Imaging Syst. Technol., 5(2), 174–187, doi:10.1002/ima.1850050214.
Heise, S., N. Jakowski, A. Wehrenfenning, C. Reigber, and H. Luhr (2002), Sounding of the topside ionosphere/plasmasphere based on GPS measurements from CHAMP: Initial results, Geophys. Res. Lett., 29(14), 1699, doi:10.1029/2002GL014738.
Hernández-Pajares, M., J. M. Juan, J. Sanz, and J. G. Solé (1998), Global observation of the ionospheric electronic response to solar events using ground and LEO GPS data, J. Geophys. Res., 103(A9), 20,789–20,796, doi:10.1029/98JA01272.
Kakinami, Y., C. H. Lin, J. Y. Liu, M. Kamogawa, S. Watanabe, and M. Parrot (2011), Daytime longitudinal structures of electron density and temperature in the topside ionosphere observed by the Hitonori and DEMETER satellites, J. Geophys. Res., 116, A05316, doi:10.1029/2010JA015632.
Lee, H.-B., G. Lee, Y. H. Kim, and J. S. Shim (2013), Characteristics of global plasmaspheric TEC in comparison with the ionosphere simultaneously observed by Jason-1 satellite, J. Geophys. Res. Space Physics, 118, 935–946, doi:10.1002/jgra.50130.
Lemaire, J. F., and K. I. Gringauz (1998), The Earth’s Plasmasphere, Cambridge Univ. Press, Cambridge, U. K.
Mitchell, C. N., and P. S. J. Spencer (2003), A three-dimensional time-dependent algorithm for ionospheric imaging using GPS, Ann. Geophys., 21(46), 687–696, doi:10.4401/ag-4373.
Mitchell, C. N., P. S. Cannon, and P. S. J. Spencer (2002), Multi-Instrument Data Analysis System (MIDAS) Imaging of the ionosphere, DTIC Document, U. K.
Mitchell, C. N., L. Alfonso, G. De Franceschi, M. Lester, Y. Romano, and A. W. Wemik (2005), GPS TEC and scintillation measurements from the polar ionosphere during the October 2003 storm, Geophys. Res. Lett., 32, L12503, doi:10.1029/2004GL021644.
Pedatella, N. M., and K. M. Larson (2010), Routine determination of the plasmasphere based on COSMIC GPS total electron content observations of the midlatitude trough, J. Geophys. Res., 115, A09301, doi:10.1029/2010JA015265.
Pedatella, N. M., J. Lee, K. M. Larson, and J. M. Forbes (2009), Observations of the ionospheric response to the 15 December 2006 geomagnetic storm: Long-duration positive storm effect, J. Geophys. Res., 114, A12131, doi:10.1029/2009JA014568.
Pedatella, N. M., J. M. Forbes, A. Maute, A. D. Richmond, T.-W. Fang, K. M. Larson, and G. Millward (2011), Longitudinal variations in the F region ionosphere and the topside ionosphere/plasmasphere: Observations and model simulations, J. Geophys. Res., 116, A12309, doi:10.1029/2011JA016600.
Richards, P. G., T. Chang, and R. H. Comfort (2000), On the causes of the annual variation in the plasmaspheric electron density, J. Atmos. Solar-Terrestrial Phys., 62(10), 935–946, doi:10.1016/S1364-6826(00)00393-0.
Spencer, P. S. J., and C. N. Mitchell (2011), Imaging of 3-D plasmaspheric electron density using GPS to LEO satellite differential phase observations, Radio Sci., 46, RS0004, doi:10.1029/2010RS004565.
Stern, D. P. (1970), Euler potentials, Am. J. Phys., 38(4), 494–501.
Yin, P., C. N. Mitchell, P. S. J. Spencer, and J. C. Foster (2004), Ionospheric electron concentration imaging using GPS over the USA during the storm of July 2000, Geophys. Res. Lett., 31, L12806, doi:10.1029/2004GL019899.
Yizengaw, E., and M. B. Moldwin (2005), The altitude extension of the mid-latitude trough and its correlation with plasmasphere position, Geophys. Res. Lett., 32, L09105, doi:10.1029/2005GL022854.
Yizengaw, E., M. B. Moldwin, P. L. Dyson, and T. J. Immel (2005a), Southern Hemispheric ionosphere and plasmasphere response to the interplanetary shock event of 29–31 October 2003, J. Geophys. Res., 110, A09301, doi:10.1029/2004JA010920.
Yizengaw, E., H. Wei, M. B. Moldwin, D. Galvan, L. Mandrake, A. Mannucci, and X. Pi (2005b), The correlation between mid-latitude trough and the plasmasphere, Geophys. Res. Lett., 32, L10102, doi:10.1029/2005GL022954.
Yizengaw, E. M. B. Moldwin, A. Komjathy, and A. J. Mannucci (2006), Unusual topside ionospheric density response to the November 2003 superstorm, J. Geophys. Res., 111, A02308, doi:10.1029/2005JA011433.
Yizengaw, E. M. B. Moldwin, D. Galvan, B. A. Ilijima, A. Komjathy, and A. J. Mannucci (2008), Global plasmaspheric TEC and its relative contribution to GPS TEC, J. Atmos. Sol. Terr. Phys., 70(11–12), 1541–1548, doi:10.1016/j.jastp.2008.04.022.
Zakharenkova, I., and L. Cherniak (2015), How can GOCE and TerraSAR-X contribute to the topside ionosphere and plasmasphere research?, Space Weather, 13, 271–285, doi:10.1002/2015SW001162.