IRI-Plas Optimization Based Ionospheric Tomography

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Abstract—Ionosphere plays an important role in High Frequency (HF) communications. In this paper, Global Ionospheric Maps (GIM) of Total Electron Content (TEC), maximum ionization height (hmF2) and critical frequency (foF2) of F2-layer are presented. These maps are obtained from the Nonlinear Least Squares (NLSQ) optimization of the International Reference Ionosphere (IRI) model extended to the Plasmasphere (IRI-Plas) using the one-hour resolution GIM-TEC (UHR) maps provided by the Polytechnical University of Catalonia (UPC) as the reference input.

I. INTRODUCTION

Ionosphere plays an important role in coupling space weather events into the atmosphere due to its time varying, inhomogeneous, conductive plasma structure. Ionosphere is the main channel in High Frequency (HF) communications. The electromagnetic signals in uplink or downlink to communications, broadcast, navigation, positioning, guidance and remote sensing satellites all traverse ionosphere [1]. As weather events such as ionosphere storm and solar flares can cause interruption of communications systems, it is important to investigate the effects of weather events around ionosphere. The structure of the ionosphere and its content of the electron depend on many factors, such as weather events, day/night, the effect of the magnetic storm occurring in the sun and geographical location [2]. Therefore, it is necessary to monitor the variability in ionosphere. Ionosphere can be defined with its electron density distribution. Yet, Global Ionospheric Maps (GIM) of Total Electron Content (TEC) in the ionosphere are provided by the International Global Navigation Satellite Systems Service (IGS) analysis centers, e.g., Jet Propulsion Laboratory (JPL), Center for Orbit Determination in Europe (CODE) and Polytechnical University of Catalonia (UPC). TEC is defined as the line integral of electron density profile along a ray path and it corresponds to the total number electrons in cylinder of 1 m² base area. The unit of TEC is TECU and 1 TECU = 10¹⁶ el/m². Provided GIM TEC maps are estimated using the data obtained from the globally distributed Global Positioning System (GPS) receivers. Since GPS satellites are in orbit at 20,200 km, TEC estimated from GPS (GPS-TEC) characterizes the variability in both ionosphere and plasmasphere [3]. As the atoms and molecules in ionosphere vary depending on the height and as their absorption rates are different, ionosphere is divided into four layers, namely, D, E, F1 and F2 layers [4].

F layer is defined as the layer in the atmosphere higher than 150 km. F layer is formed by the sun’s ultraviolet rays. F layer is the most important part of ionosphere for HF communications. F layer is not regular, so short time-scale approximation of F-layer characteristics is necessary. F region of ionosphere is divided into two layers called F1 and F2. F1 layer is at a height of approximately 150-180 km, F2 region is at a height of approximately 180-450 km. Ionization density of F1 layer depends on the angle of the sun. The main effect of F1 is absorbing HF waves passing through the F2 layer. F1 layer has not been so well defined as F2 layer in terms of its characteristics. F2 layer is the closest layer to the sun, so maximum ionization occurs there. F2 layer is the most important layer of long distance HF communications. It is a very variable layer and its height and density change with time of day, season, and sunspot activity [5]. Its critical parameters are defined as the critical frequency (foF2) and maximum ionization height (hmF2), respectively.

The most complete and widely used ionosphere models is the International Reference Ionosphere (IRI) model [6]. For a given location, time and date, IRI is an empirical model which provides the estimates of the electron density, electron temperature, ion temperature, and ion composition of the ionosphere. IRI model is extended to include plasmasphere (IRI-Plas) up to 20,000 km corresponding to the height of Global Positioning System (GPS) satellites [7]. IRI-Plas would produce TEC output for a given date and time (hour), location (latitude and longitude) and peak height of F2 layer (hmF2) and critical frequency of F2 layer (foF2). In IRI-Plas, TEC estimates can be also provided externally as input for the proper scaling of topside and plasmasphere extensions.

Previously, IRI-Plas model has been exposed to optimization with Non-linear Least Squares (NLSQ) method using GPS-TEC [8], [9], [10]. As a result of optimization, it is observed that valid foF2 and hmF2 estimates are produced for a single GPS receiver location. Thus, IRI-Plas optimization is effectively acting like a virtual ionosonde for single GPS receiver location.
In this paper, first NLSQ optimization of IRI-Plas using TEC measurements (observations or estimates) will be explained. Then, TEC, hmF2 and foF2 GIM maps obtained via IRI-Plas optimization using the one-hour resolution UPC GIM TEC (UHR) maps as the reference input will be presented.

II. OPTIMIZATION OF IRI-PLAS MODEL

Optimization method shown in Fig. 1, needs reference TEC values in order to compare the IRI-Plas model TEC output in the optimization loop. In this paper, we are going to use daily GIM TEC maps produced by the IGS analysis centers as the reference TEC values in order to produce IRI-Plas model based TEC, foF2 and hmF2 GIM maps. These daily TEC estimations are given with one or two hours resolution in time, 2.5 degrees resolution in latitude between −87.5°N and 87.5°N, and 5 degrees resolution in longitude between −180°E and 180°E around the world. This data can be obtained from ftp://cddis.gsfc.nasa.gov/gps/products/ionex/ website as a IONosphere Map Exchange Format (IONEX) file. Therefore, cyclic optimization model can produce a TEC estimation error for the IRI-Plas TEC output. Hence, in the scope of this study, main estimation error to be performed is TEC estimation error which is the difference between the observational data and the model estimation. Reference TEC observation data \( z \) which is taken from the IGS center is defined in (3). The obtained TEC estimation \( \hat{z} \) from the optimization of IRI-Plas model is defined in (4).

Let \( \theta \) denote latitude, \( \phi \) denote longitude and \( z(x,t) \) denote electron density at time \( t \), respectively, where \( x = [\theta \phi]^T \) is defined as the location vector. The subscript \( T \) is the transpose operator. Furthermore, ionosphere F2 layer maximum ionization height hmF2 and critical frequency foF2 are represented by \( h(x) \) and \( f(x,t) \), respectively. Also, \( N_\theta \) and \( N_\phi \) denote the number of latitude and longitude resolutions given in a GIM TEC map at a certain epoch, respectively. UHR and JPL GIM TEC maps are produced for one-hour or two-hours resolution, respectively. So, number of epoch per day is \( N_t = 24 \) for UHR, and \( N_t = 12 \) for JPL. In this study, since UHR GIM TEC maps are used, length of the observation vector will be as \( N_\theta \times N_\phi \times N_t = 124392 \).

Defined points (i.e. locations) in a two-dimensional \((\theta, \phi)\) space, can be expressed in a one dimension vector. The vector index \( l_e \) can be given as follows,

\[
l_e = n_\theta + (n_\phi - 1)N_\theta, \quad 1 \leq l_e \leq N_\theta N_\phi
\]

where subscript indices \( n_\theta \) and \( n_\phi \) represent the two-dimensional indices with \( 1 \leq n_\theta \leq N_\theta \) and \( 1 \leq n_\phi \leq N_\phi \), respectively. Thus, the predictive value of TEC in two dimensions can be written in one dimension as follows,

\[
z(l_e) = z(\theta_{n_\theta}, \phi_{n_\phi})
\]

where \( \theta_{n_\theta} \) and \( \phi_{n_\phi} \) indicate the latitude and longitude of the point (i.e. location), respectively.

According to (3) and (4), daily optimization error vector \( \mathbf{e}_z \) can be expressed as below,

\[
\mathbf{e}_z = \mathbf{z} - \mathbf{z}_o = [e_z(1), \ldots, e_z(N_\theta N_\phi N_t)]^T_{1 \times N_\theta N_\phi N_t}
\]

Optimization output of IRI-Plas model can be obtained for any \( \theta \) latitude \( \phi \) longitude and time. So, IRI-Plas optimization TEC output at time \( t \) can be defined as \( z_o(\theta, \phi, t) \). Furthermore, IRI-Plas optimization hmF2 and foF2 outputs can also be defined as \( h_o(\theta, \phi, t) \) and \( f_o(\theta, \phi, t) \), respectively. Error at a point \((\theta, \phi)\) for a given time \( t \) is defined in (6),

\[
e_{\text{point}}(\theta, \phi, t) = z(x) - z_o(x, t), \quad 1 \leq \theta \leq N_\theta, 1 \leq \phi \leq N_\phi, 1 \leq t \leq N_t
\]

Error function described in (6) is defined as the basic error signal.

Fig. 2 shows the detailed optimization method. Here, \( f_o(x,t) \) and \( h_o(x,t) \) are the foF2 and hmF2 parameters determined by the optimization loop, respectively, and and \( z_o(x,t) \) is the IRI-Plas TEC output for these two critical parameters. Then, in order to preserve the physical relationship between foF2 and hmF2 parameters, IRI-Plas is called using the \( f_i(x,t) \) only (i.e. by setting hmF2 input as zero), then IRI-Plas returns output with a corresponding maximum ionization height \( h_i(x,t) \), as represented in (7)

\[
h_i(x,t) = \text{IRI-Plas}(f_i(x,t), 0, \ldots).
\]

The corresponding IRI-Plas TEC output for the \( f_i(x,t) \) and \( h_i(x,t) \) is represented by \( z_{\text{irif}}(x,t) \) as given in (8),

\[
z_{\text{irif}}(x,t) = \text{IRI-Plas}(f_i(x,t), h_i(x,t), \ldots).
\]
A second error parameter $e_{teif}(x,t)$ is defined according to TEC difference with respect to the measured TEC estimates $z(x,t)$ as expressed in (9). Then $1 \times 2$ dimensional error vector $e(x,t)$ is obtained from (6) and (9) as shown in (10). Then, the $L^2$-norm square of this error vector, i.e., $e(x,t)e^T(x,t)$ is minimized by the optimization algorithm. In the optimization process, no external TEC input is supplied to IRI-Plas model [8].

$$e_{teif}(x,t) = z(x,t) - z_{irif}(x,t)$$ \hspace{1cm} (9)

$$e(x,t) = [e_{point}(x,t), \ e_{teif}(x,t)]$$ \hspace{1cm} (10)

The normalized difference between UHR TEC values and TEC outputs of IRI-Plas optimization is shown in (11).

$$e_{zopt}(t) = 100 \times \frac{\|e - e_{z0}\|}{\|e_{z0}\|}, \hspace{1cm} 1 \leq t \leq N_t$$ \hspace{1cm} (11)

Daily mean difference is described similarly in equation 12.

$$e = \frac{1}{N_t} \sum_{t=1}^{N_t} e_{zopt}(t)$$ \hspace{1cm} (12)

Firstly, input ranges for the hmF2 and foF2 optimization parameters are defined as 150-550 km and 2-9 MHz, respectively. When unchanged UHR TEC values is supplied to the optimization model, obtained results are presented in Fig. 3. Note that, 25 April 2011 is a quiet day and there are geomagnetic disturbances on the other days. Although, TEC normalized errors are small at some coordinates, they are much higher for some parts of the world, mostly because foF2 range is fixed to a 2-9 MHz range. For example, foF2 values are supposed to be higher at the equatorial zone. Therefore, hmF2 and foF2 ranges are modified to 150-550 km and 2-35 MHz respectively, in order to model all parts of the earth. Also, negative or very small TEC values (lower than 0.4 TECU) are corrected by averaging of up to eight neighbours as (starting from the nearest four) $z(\theta + 1, \phi + 1)$, $z(\theta + 1, \phi)$, $z(\theta + 1, \phi - 1)$, $z(\theta, \phi + 1)$, $z(\theta, \phi - 1)$, $z(\theta - 1, \phi - 1)$ and $z(\theta - 1, \phi + 1)$ points. Threshold error value is determined 0.01 TECU with non-linear least squares method.

In the NLSQ optimization initial values foF2 and hmF2 parameters are chosen as the hmF2 and foF2 outputs of IRI-Plas model when called for the given location and time without any other inputs. At the points where normalized error higher than 0.01%, the initial point of optimization is changed randomly within the range $h_{int}(x,t) = h_i(x,t) \pm 100$ km and $f_{int}(x,t) = f_i(x,t) \pm 2$ MHz and optimization loop is restarted again. This process is repeated at most 10 times. The result of this optimization, i.e., obtained TEC values, are given in Fig. 4.
are obtained lower than 0.01% and the maximum error point is also lower than 0.01%. The region exhibiting the highest errors is shown in Fig. 5. This area is between in latitude [22.5°N, 32.5°N] and in longitude [−180°E, −140°E] ranges in the Pacific Ocean. The obtained TEC error values are high in this area, because there are no GPS stations available in this area. So IGS centers can make extrapolation errors in their calculations.

III. IRI-Plas Maps

In this section, example TEC, foF2 and hmF2 maps will be provided for both quiet and geomagnetically disturbed days of ionosphere. In Figure 4a, GIM-TEC map from UHR is presented for April 25, 2011 which is a quiet day of ionosphere. The TEC map is obtained at 1200 UT, at the peak ionization time for longitude 0. The IRI-Plas TEC map without any external TEC input or optimization is given in Figure 4b. It can be observed that IRI-Plas can not represent the global TEC distribution. When UHR-TEC map is given as input to IRI-Plas, the TEC map in Figure 4c is obtained. This time IRI-Plas scaled the internal parameters and the TEC map is similar to original GIM-TEC. The optimized IRI-Plas TEC map is provided in Figure 4d, and the optimized IRI-Plas TEC map is able to duplicate the GIM-TEC successfully for all regions of the world.

In Figure 5a, GIM-TEC map from UHR is presented for March 26, 2001, which is a disturbed day of ionosphere. The TEC map is again obtained at 1200 UT. The effect of the geomagnetic storm is highly visible when the TEC distribution is compared with that of Figure 4a. The IRI-Plas TEC map in Figure 5b fails to represent the geomagnetic disturbance in the ionosphere when no external TEC map is input. The IRI-Plas map with TEC input in Figure 5c slightly improves the model TEC distribution but the best fit with GIM-TEC is obtained when the IRI-Plas is run with the optimization routine as given in Figure 5d. The normalized errors without TEC input for IRI-Plas model typically varies in the range of 20%-30%. With TEC input, IRI-Plas model TEC global normalized error reduces to 5% - 10%. With optimization the normalized global error is less than 1% as discussed in previous section.

In Figure 6, the IRI-Plas foF2 maps with and without optimization are provided for April 25, 2011, a quiet day, at 1200 UT. The optimization routine has modified the foF2 distribution globally. In Figure 7, the IRI-Plas foF2 maps with and without optimization are provided for March 26, 2001, a disturbed day, at 1200 UT. When Figures 6a and 7a are compared, the effect of the geomagnetic storm can be easily observed. The optimization changes the distribution of foF2 and the global normalized error is within the range of %10 and %50.

The hmF2 maps are provided in Figures 10 and 11 for a quiet day and a disturbed day, respectively, do not reflect the effect of optimization. The normalized global error is within the range of 1% to 4% for hmF2. It is known that IRI-Plas is more sensitive to the modifications in foF2 compared to those in hmF2. As a result, the difference between the optimized IRI-Plas foF2 and non-optimized IRI-Plas foF2 is significantly greater than those in hmF2.
Fig. 8. April 25, 2011 quiet day and at 1200 UT, a) IRI-Plas foF2 map with optimization, b) IRI-Plas foF2 map without optimization.

Fig. 9. March 26, 2001 disturbed day and at 1200 UT, a) IRI-Plas foF2 map with optimization, b) IRI-Plas foF2 map without optimization.

Fig. 10. April 25, 2011 quiet day and at 1200 UT, a) IRI-Plas hmF2 map with optimization, b) IRI-Plas hmF2 map without optimization.

Fig. 11. March 26, 2001 disturbed day and at 1200 UT, a) IRI-Plas hmF2 map with optimization, b) IRI-Plas hmF2 map without optimization.

IV. CONCLUSION

In this study, global ionospheric TEC maps are used as a reference in an optimization algorithm to modify the TEC, foF2 and hmF2 outputs of IRI-Plas model. The fusion of GPS based TEC maps into the best known model of ionosphere extended to plasmasphere provides the scaling of critical parameters. With the help of optimization algorithm, IRI-Plas, the empirical and deterministic algorithm is modified to represent the variability in the ionosphere during a geomagnetic storm. The results indicate that IRI-Plas is a reliable model for ionosphere. Optimized IRI-Plas model can work as a virtual ionosonde to produce critical ionospheric parameters.

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