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GIM-TEC adaptive ionospheric weather assessment and forecast system.

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Abstract

The Ionospheric Weather Assessment and Forecast (IWAF) system is a computer software package designed to assess and predict the world-wide representation of 3-D electron density profiles from the Global Ionospheric Maps of Total Electron Content (GIM-TEC). The unique system products include daily-hourly numerical global maps of the F2 layer critical frequency (foF2) and the peak height (hmF2) generated with the International Reference Ionosphere extended to the plasmasphere, IRI-Plas, upgraded importing the daily-hourly GIM-TEC as a new model driving parameter. Since GIM-TEC maps are provided with one- or two-days latency, the global maps forecast for one day and two days ahead is envisaged using the harmonic analysis applied to the temporal changes of TEC, foF2 and hmF2 at 5112 grid points of a map encapsulated in IONEX format (-87.5º:2.5º:87.5ºN in latitude, -180º:5º:180ºE in longitude). The system provides online the ionospheric disturbance warnings in the global W-index map establishing categories of the ionospheric weather from the quiet state (W=±1) to intense storm (W=±4) according to the thresholds sets for instant TEC perturbations regarding quiet reference median for the preceding 7 days. The accuracy of IWAF system predictions of TEC, foF2 and hmF2 maps is superior than the standard persistence model with prediction equal to the most recent ‘true’ map. The paper presents outcome of the new service expressed by the global ionospheric

foF2, hmF2 and W-index maps demonstrating process of origin and propagation of positive and negative ionosphere disturbances in space and time and their forecast under different scenarios.

Key words: Ionospheric weather, Global ionospheric map, Total electron content, Crirical frequency, Peak height, IRI-Plas

1. Introduction.

The requirement for near real-time products based upon current ionospheric specification has led to an increased importance of the real-time ionospheric models. These products are required for reliable HF communications along short-, medium- and long-range paths, satellite communication, navigation, guidance, control and positioning systems. With Global Positioning System, GPS, (acronyms are listed in Table 1) providing instantaneous time delay, or equivalently, the total electron content (TEC), the GPS-TEC values are estimated for the Earth based reference stations, and further processed by the International GNSS Service (IGS) ionospheric working group (Iono-WG) to produce the Global Ionospheric Maps (GIM), available online since 1998 (Manucci et al., 1998; Dow et al., 2009; Hernandez-Pajares et al., 2009). Among a variety of techniques applied to probe the ionosphere, the GPS monitoring and the vertical sounding with ground-based and satellite-based ionosondes are the most recognized sources of information on the ionosphere. Though the ionosonde network of sounding stations is operating for more than 70 years, its products are not used for the real-time global ionospheric mapping so far due to data sparsity in time and position over the globe. Instead, the efforts are focused on regional mapping of the ionosphere parameters for the areas of the denser set of the ionosonde observatories (Zolesi and Cander, 2000). Also the particular interest has centered on long-term global maps for radio-circuit design, service planning and frequency-band selection (Bradley et al., 2009).

Up to now, the reference global maps of monthly median of the F2 layer peak parameters, e.g. ITU-R (CCIR, 1976; 1991) maps of the critical frequency foF2 and the radio wave propagation factor

M3000F2 (Jones and Gallett, 1962) and URSI foF2 maps (Rush et al., 1989) are available, in particular, in the International Reference Ionosphere (IRI) system (Bilitza, 2001). Each map allows for a dependence on position, time, and solar epoch as given by spherical harmonic functions of geographic latitude, geographic longitude and Universal Time (UT) for selected level of solar activity. The associated numerical coefficients are chosen to match a data set of measurements from the world network of vertical-incidence ionosondes for the years of 1954, 1955 and 1964 for solar minimum and 1956-1958 for solar maximum.

The temporal and spatial sparsity of data (e.g. the measurements of the ground-based ionosondes located mainly on the land but rare over the oceans as shown in Figure 6) that have been included in the development of IRI model can be compensated either by assimilation of new ionosonde measurements, or by upgrading the IRI model to include situations like space weather storms (Araujo-Pradere et al., 2002; Gulyaeva, 2012). When the first option is not feasible, it is better to approach the problem with a cost-effective improvement in the IRI model. The International Reference Ionosphere extended to the plasmasphere (IRI-Plas) (Gulyaeva et al., 2011) is the recent version of IRI where the region of interest can include plasmasphere up to the height of 20,200 km (GPS orbit) so that the GPS-derived Total Electron Content (GPS-TEC) can be ingested into IRI-Plas for better representation of the temporal variations in the ionosphere and plasmasphere. As it is envisaged by IRI and IRI-Plas algorithms, the model electron density height profile, Ne(h), is parameterized using a relative layer shape formula depending on vertical coordinate adapting the absolute values to those at the peak: the peak electron density, NmF2, proportional to the critical frequency, foF2, and the corresponding peak height, hmF2 (Gulyaeva and Bilitza, 2012). Daily-hourly implementation of plasmasphere part of IRI-Plas code requires knowledge and prediction of 3-hrs geomagnetic kp-index. The daily data for the past are provided online by Geomagnetic Data Service at Potsdam, and forecast for the forthcoming hours of the day is produced in IWAF system with technique presented by De Franceschi et al. (2001).

The advantage of IRI-Plas code is the span of model electron density profile in the altitude range from the bottom of the ionosphere (65-80 km) to 20,200 km (GPS orbit) relevant for automatic conversion of the integral TEC into 3-D electron density profile (versus latitude, longitude and height). Going from an integral TEC to a height profile allows a reliable assessment of one key profile parameter, namely, the foF2 critical frequency (or the equivalent peak electron density, NmF2), accompanied by update of the topside scale height in terms of foF2 (Gulyaeva et al., 2011). Using deviation of TEC-adapted foF2 from its quiet reference one can produce the related change of the peak height, hmF2 (Gulyaeva, 2012). When the both ionosphere peak parameters and the topside scale height are specified, the process of TEC conversion to the vertical electron density profile Ne(h) passing through the ionization peak, is accomplished with the IRI-Plas model. This procedure has been successfully applied in evaluating the global electron content in the spherical segment of the interplanetary space from the Earth's surface to altitude of 20,200 km (GPS orbit) in the the plasmasphere (Gulyaeva and Veselovsky, 2012).

The purpose of the present project is the development of the Ionospheric Weather Assessment and Forecast (IWAF) system using an assimilation of GIM-TEC by IRI-Plas code to make it capable to assess and predict the world-wide representation of 3-D electron density profiles, the daily-hourly global maps of the F2 layer critical frequency, peak height, and the ionospheric weather W-index maps. Since the daily-hourly GIM-TEC are available with a one day or two days latency due to insufficient stock of more recent GPS source information, the global maps forecast product for one day and two days ahead is provided with the harmonic analysis applied to the temporal changes of TEC, foF2 and hmF2 at each grid point of a map encapsulated in IONEX format (Shaer et al., 1998). The harmonic analysis is based on observations for four preceding days similar to foF2 forecasting (Vodjannikov and Gordienko, 2011) as described in Section 3. Adding the forecasting procedure, IWAF system products include daily-hourly results for the current day (with 1-day ahead forecast), and forecast for the next day (2-days ahead forecast). The results of IWAF maps prediction are compared with other GIM-TEC products (Hernandez-Pajares et al., 2009; Garcia-Rigo et al., 2011) and the standard persistence model which assumes that prediction is equal to the most recent 'true' data. Validation of IWAF Forecast Procedure is provided in Section 4.

An increased knowledge of effects imposed by the ionosphere on operational radio systems could be earned by the new service providing online estimate of the degree of TEC perturbation at each grid point of the map expressed by the ionospheric W index. The W index reveals TEC behavior varying from quiet state (W=±1) to intense storm (W=±4) providing a useful proxy index driving the space weather in the ionosphere-plasmasphere environment rather than the geomagnetic indices alone (Gulyaeva and Stanislawska, 2008; 2010). We have applied W indexing to the GIM-TEC products provided by the Universitat Politecnica de Catalunya (UPC) and Jet Propulson Laboratory (JPL) for generating online the hourly W index maps for a period from January 1999 up-to-date. The planetary Wp index representing span between the greatest positive storm magnitude occurrence (W = 3 or 4) and the least negative storm magnitude (W = -3 or -4) at each latitude weighted by the occurrence of the both signs stormy indices on a map is used for generating the "Catalogue of the planetary ionosphere storms". Although the planetary Wp-storms comprise approximately 10% of time in a long-term perspective, their impact on the technological devices is increasing, creating a high risk for their mulfunction. An increasing number of space weather storms may cause serious threat to various technological systems due to their increased dependency on satellite and power systems.

Analysis of the W-index variation in space and time provides information on the ionosphere state under the different scenarios. Appendix A introduces the formulae for the W-index derivation from GIM-TEC maps. Results and discussion are given in Section 5, followed by Conclusions in Section 6.

2. GIM-TEC Data Selection

The Global Positioning System (GPS) presents a global network of satellites which ensures a global coverage for monitoring the satellite-emitted dual-frequency signals yielding information on the ionospheric parameters along the propagation path. The GPS-derived information on the integrated ionospheric parameters along the trans-ionospheric path of the signals, i.e. the time delay measurements of the satellite-emitted signal is converted into Total Electron Content (TEC), which is the total number of electrons in a cylinder with a cross section of 1 m^2 with its axis along a ray path.

The slant TEC is transformed to vertical TEC at the sub-ionospheric piercing point (Smith et al., 2008) from which the global ionospheric maps, GIM-TEC, are generated in a continuous operational way by several Data Analysis Centers since 1998, covering the period more than the entire solar cycle (Manucci et al., 1998; Dow et al., 2009; Hernandez-Pajares et al., 2011). Typically, GIM-TEC is provided with two hour time resolution. The hourly files, JPLR and JPLG, are provided by Jet Propulson Laboratory since December, 2008, and hourly UHRG files are provided by Universitat Politècnica de Catalunya since October, 2010. which are chosen as the source input in IWAF system. The JPLR and JPLG are generated in the denser map grids (-90:2:90º in latitude, -180:2:180º in longitude), and time specified for 0.5:1.0:23.5 hrs UT so these maps are preprocessed by linear interpolation into standard IONEX format for 0:1:23 hrs UT. The vertical TEC is modeled by JPL in a solar-geomagnetic reference frame using bi-cubic splines on a spherical grid; a Kalman filter is used to solve simultaneously for instrumental biases and VTEC on the grid as stochastic parameters (Manucci et al., 1998). The UHRG is produced by UPC software TOMION (TOmographic Model of the IONosphere) using a Kriging based interpolation scheme (Orus et al, 2005) to get global coverage. Both the input and output IWAF maps are provided in IONEX format collected in a daily set of the hourly maps with 1 h UT resolution. The IONEX map consists of 5112 grid values binned in 87.5ºS to 87.5ºN in step of 2.5º in latitude, 180ºW to 180ºE in step of 5º in longitude. If the input data file is missed for a certain day, it is substituted by another GIM-TEC product. When an input IONEX file is available only with 2 h UT resolution, the linear interpolation in time is applied to bring GIM-TEC for 1 h UT resolution.

A recent assessment of the performance of UHRG VTEC global maps corresponding to the last available 170 days (May to October 2012) is provided in Figure 1. It is remarkable to notice that the UHRG performance is typically better than the combined rapid and final IGS VTEC maps, especially during the last 120 days (right after the last software update), with daily standard deviations systematically 0.5 to 1 TECU lower (in a range of 2 to 5 TECU), and relative RMS percentage of 15-25%, instead of 20-25% for the combined IGS products.

3. The Forecasting Procedure incorporated in IWAF system

Since the daily-hourly GIM-TEC are available with a one day or two days latency due to insufficient stock of more recent GPS-related information in RINEX format (Hernandez-Pajares et al., 2009), the global maps forecast product in the framework of IWAF system is envisaged for one day and two days ahead. There are different techniques applied for forecasting of the different ionospheric parameters (Rose, 1993; Jakowski et al., 2002; Garcia-Rigo et al., 2011; Gulyaeva, 2012; Blanch and Altadill, 2013; and references therein). In particular, the Disturbance Impact Assessment System (DIAS) is designed by Rose (1993) as an expert system to assess and predict the influence of the solar flares on high-latitude HF radio communications covering rules and warnings on the sudden ionospheric disturbances, polar cap absorption, ionospheric critical frequency storm, auroral zone absorption and auroral sporadic E and auroral E layers appearance. Review of the different techniques of GIM-TEC forecast designed in the frame of the International GNSS Service and the UPC prediction performance are summarized by Garcia-Rigo et al. (2011). Magnetosphere-ionosphere interactions used for forecasting the F2 layer peak parameters are discussed by Blanch and Altadill (2013). Empirical model of storm-time update of the F2 layer peak height hmF2 in terms of the foF2 changes deduced from the topside sounding data base (Gulyaeva, 2012) is employed by IWAF system as mentioned in the Introduction.

The Fourier Series Expansion is applied in the forecasting procedure of IWAF system based on the temporal changes of TEC, foF2 and hmF2 at each grid point of a map encapsulated in IONEX format. Historical source GIM-TEC and the output foF2 and hmF2 maps during four latest days (the latest ‘true’ 96 hourly maps) are used to produce five spherical harmonic coefficients similar to the ionosonde foF2 forecast (Vodyannikov and Gordienko, 2011). The Fourier analysis limited by five harmonics is aimed to represent mainly the general features of map variations based on the data for four preceding days which provides a reasonable compromise between the reliability of results and the low cost of data processing.

Forecast of parameter X (which denotes TEC, foF2, or hmF2 for the current time t, in hours of Universal Time, UT) is based on synthesis of mean $\bar{x}$ (average of data for the preceding 96 hourly values at the times *t-96*, *t-95, ..., t-1* for a given grid point) and the sum of 5 harmonic terms of, t:

$$X = \overline{X} + \sum_{i=1}^{5} \left[A_i \sin(2\pi it/24) + B_i \cos(2\pi it/24) \right] \tag{1}$$

Coefficients A_i and B_i are derived from N source values of X_k :

$$A_i = \frac{2}{N} \sum_{k=1}^{96} X_k \sin(2\pi it/24)$$

(2)

$$B_i = \frac{2}{N} \sum_{k=1}^{96} X_k \cos(2\pi it/24)$$

The Eqns. (1-2) reproduce the diurnal variation of X parameter one day ahead taking into account the diurnal (24 h), semi-diurnal (12 h), 8 h, 6 h, and 4 h tidal components. Though the harmonics are given in terms of the universal time, t, the period of 24 local hours around the world is fully represented by the global UT map (Maruyama, 2010). Each harmonic based on the relevant maps for four recent days can be treated as a separate object of a particular physical meaning, for example, the first harmonic of the diurnal variation of foF2, hmF2 and TEC depicts the results of feeding the ionosphere and plasmasphere by the solar ionizing radiation; the second harmonic is related with half-diurnal variations of the plasma density separated on the Earth by the solar terminator (Somsikov, 2011). The higher order harmonics may be due to the solar wind energy input captured by the magnetosphere (Gulyaeva and Veselovsky, 2012), transformed and dissipated in the polar upper atmosphere (Rose, 1993) that triggers and drives the ionospheric storm effects along the magnetic field lines between the conjugate hemispheres (Gulyaeva et al., 2011, 2012). The harmonic analysis is applied for the prediction one day ahead and the first prediction results serve as an input combined with the source GIM-TEC maps for three preceding days in order to forecast an ionospheric map two days in advance.

4. Validation of IWAF Forecast Procedure

The validation of the forecasting technique is made comparing one day forecast and two days forecast of TEC maps with ‘true’ UHRG which is available later on for the particular day. The normalized relative error δX for IWAF forecast is compared with different GIM-TEC maps (both real maps and forecast) available from Iono-WG. The δX error with X assigned for foF2, hmF2 or TEC value is calculated as

$$\delta X = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{(X_{ob\,i} - X_i)^2}{(X_{obi} - \overline{X}_{ob})^2}} \tag{3}$$

where X_i presents a grid value of the one day (or two days) IWAF forecast, Z1PG, (or Z2PG) or other Iono-WG IONEX maps. The UHRG map provides a reference ‘true’ value X_{obi} at a grid point and the global mean $\overline{X}_{ob}$ averaged for the total 5112 grid points of the UHRG map, *n*, which is the total number of *X* grid values in an IONEX daily collection of maps.

An example of the comparison is plotted in Figure 2 for a quiet day on April 25, 2011 (left panel), and a storm day on September 17, 2011 (right panel). Results for 1 day forecast by IWAF system Z1PG shows minimum δTEC error for the quiet day as compared with other GIM-TEC products. This means that a departure of the IWAF prediction of TEC map from the true UHRG map is less than the difference between the different Iono-WG maps for the quiet day. This advantage, however, is not so evident for the sunlit hours of the storm day (right panel) when the IWAF 1-day ahead forecast for the storm day remains more accurate than the 2-days ahead forecast U2PG (Garcia-

Rigo et al., 2011) and more consistent with the UHRG true data than the mean Iono-WG IGRG map which smoothes the extreme storm signatures during averaging of the few source GIM-TEC maps.

The one day forecast and two days forecast by the IWAF system are compared in Table 2 for the worst case storm day on October 1, 2012, when the extreme ring current index Dst = -143 nT, and the GIM-TEC derived planetary Wp index (Gulyaeva and Stanislawska, 2008; 2010) varies between Wp=3.5 and the peak Wp = 6.7 i.u. (index units) during the day (see Wp and Dst variation in Figure 7). The comparisons in Table 2 are made using the relative error δX (Eqn. 3). The total number of the grid values used for the comparison amounts to n=122,688 for the 24 daily-hourly set of the maps, for each type of a map (foF2, hmF2, TEC) and two types of forecast products (1-day and 2-days ahead). The IWAF forecast is based on UHRG maps for 27-30 September, 2012, in producing the one day forecast for October 1, and on UHRG maps for 27-29 September, 2012, and also 1-day forecast for September 30, 2012, in producing the 2-days forecast for October, 1. Results are given in Table 2 in terms of local time, hours, compiled and averaged from 0 to 23 h UT maps. Results presented in Table 2 appear to be very promising. The δX error is less during the night than during the daytime, slightly growing towards noon. The 2-day forecast is slightly less accurate than the 1-day forecast as should be expected. The forecast product maps of foF2 and hmF2 (being based on IRI-Plas products of the relevant maps) show a better accuracy than the TEC forecast which is compared with the 'true' reference UHRG map for the October, 1.

Figure 3 presents the comparison of the preliminary real-time (RT) UPC TEC maps, URTG, computed with a limited number of 70 to 80 GPS receivers during 17-24 January, 2012, with IWAF 1-day predicted TEC maps, Z1PG, against Topex/Jason daily mean TEC. The Topex/Jason altimeter provides the ionospheric TEC measurements over the oceans at altitudes below 1,336 km (Topex/Jason orbit) which do not include the plasmasphere contribution present in GPS-TEC, so an allowance for GPS-TEC exceeding Topex/Jason TEC should be kept in mind when comparing these two data sources (Azpilicueta and Brunini, 2008; Gulyaeva et al., 2009; Lee et al., 2013). The planetary Wp index (Gulyaeva and Stanislawska, 2008) plotted in Figure 3a demonstrates the transition from quiet to storm period during 17 to 24 January, 2012. The percentage root mean square RMS deviation is plotted in Figure 3b. Figure 3c illustrates the standard deviation of GIM-TEC from the reference Topex/Jason data. Figure 3d shows the bias of GIM-TEC and the Topex/Jason daily averages. The bias (defined as averaged difference of JASON-2 VTEC minus global VTEC value) of URTG map is positive, higher than the negative bias obtained in the most of other results (Figure 3d). In principle, from the physical point of view, due to the difference in the orbits of two systems of TEC products (the GPS constellation orbits the Earth at 20,200 km against 1,336 km of Topex/Jason), this bias should be positive, containing the averaged electron content between the altimeter and the GPS constellation (Lee et al., 2013). However, and due to the well known positive bias in the altimeters calibration (of few TECUs affecting the TOPEX and JASON VTEC values see, for instance, (Brunini et al. 2005), it is not an issue to have a slightly negative bias. On the other hand, the GPS-TEC measurements are rare over the oceans with measurements made on the islands so that GIM-TEC become less reliable in these areas dependent on a method of mapping functions used for filling gaps in missing GPS receiving data (Hernandez-Pajares et al., 2009). The standard deviation and RMS, in percent, (Figure 3b, c) illustrate the results of the preliminary RT URTG map which are of the same order of accuracy as a GIM-TEC forecast by IWAF system, Z1PG. The RMS deviation can amount up to 30% against the reference Topex/Jason data during the storm the both Z1PG and URTG errors exceeding the errors of other GIM-TEC maps computed with much more available observations in post-processing mode.

The W-index of the ionospheric quiet state, moderate disturbance, moderate storm or an intense storm is assigned according to the categories given in Table 3. The derivation of the W-index map from GIM-TEC maps is specified in Appendix A. The W-index can also be computed using foF2, instead of TEC in the equations A1-A9 (Gulyaeva et al., 2008). In IWAF system the W-index is computed using the source JPLR and UHRG maps and forecast of GIM-TEC with Eqns. (1-2).

Figure 4 illustrates usage of the W-index map for specification of ‘quiet’ day, ‘positive’ storm day (with dominant occurrence of storm-time index W = 3 and 4 on the map for a specific UT) and ‘negative’ storm day (with reduced TEC regarding its quiet reference for majority of GIM-TEC cells corresponding to index W = -3 and -4). Here the occurrence (in percent of total number of 5,112 map cells) of W-index of the said magnitudes is calculated hour-by-hour from UHRG (marked by W-u and W+u) and JPLR (marked by W-j and W+j) maps for three periods selected from the Catalogue of the planetary Wp storms deduced and permanently upgraded in the framework of IWAF system (Gulyaeva and Stanislawska, 2010). The first period for 21-23 January, 2012, refers to part of the days shown in Figure 3 the maps representing winter in the North hemisphere and summer in the South hemisphere. The second period for 22-24 April, 2012, belongs to the equinox. The third period for 14-16 July, 2012, represents the summer/winter seasons in North/South hemisphere. Results of two GIM-TEC sources display consistent results starting from the quiet day with low occurrence of stormy W-index followed by an enhahced occurrence of positive storm indices with gradual developments of the negative storm afterwards. These are the typical two-phase ionosphere storm patterns (Mendillo, 2006) which imply injection of plasma by the solar wind into the ionosphere-plasmasphere system (positive phase of the ionospheric storm) followed by the plasma ejection (plasma depletion during the negative phase of the storm) towards the magnetosphere tail (Gulyaeva and Veselovsky, 2012).

We have computed the Root Mean Square Error, RMSE, for the residuals between predicted maps of TEC, foF2 and hmF2, and ‘true’ UHRG-based and JPLR-based maps for the periods shown in Figure 4 and listed in Table 4. For each UT hour of day two vectors of grids were selected referring to the local time, LT, noon and midnight longitudes. In total we combined 24 individual sets of data (from maps for 0, 1,…, 23 h UT) each set for 71 latitude grids at -87.5:2.5:87.5º N in a daily vector of length n consisting of 1,704 elements denoted by $\vec{Y}$ for the ‘true’ maps and $\vec{X}$ for the prediction maps. The RMSE in a vector form is equal to

$$RMSE = \sqrt{(\vec{X} - \vec{Y})^2 / n} \qquad (4)$$

The IWAF system forecast with Eqns.1-2 for 1-day prediction (RMS1) and 2-day ahead prediction (RMS2) are compared with standard persistence model (RMS0) which assumes that prediction is equal to the true value for the preceding day. Table 4 contains the results (a) for TEC maps, (b) foF2 maps, (c) hmF2 maps. It follows from Table 4 that the RMSE is lower for the quiet (q) day as should be expected because the harmonic analysis limited by 5 harmonic terms reproduces more common (quiet) features of the four preceding days. The RMSE is growing at transition from quiet day to the positive storm day (s+) because no assumption is put so far on an expected plasma injection into the ionosphere-plasmasphere space. The RMSE is largest for the negative storm day (s-) because the harmonic analysis for the preceding four days includes the day of the positive ionosphere storm hence the residuals are growing at transition from the day of plasma input to the day of plasma loss. The JPL maps errors are less than the UPC maps errors but the general trends are similar for the both sets of the data. The IWAF results in total provide higher accuracy with less RMSE than the persistence model.

4. Results

One of the objectives of this project is to provide the daily-hourly global foF2, hmF2 and W-index maps congruent with GIM-TEC product. An example of these maps along with the source UHRG map is provided in Figure 5 for 1200 UT of the storm day on October 1, 2012, which is analyzed in Table 2. The maps in Figure 5 are placed on the topographic map for longitudes from 0º to 360º E so that for 1200 UT, the noon is shown at 0º E, the midnight at 180º E, and sunrise-sunset in between.

Figure 5a demonstrates the diurnal variation of TEC around the globe with enhanced TEC and foF2 around noon which is gradually decreased towards the nighttime. Minimum TEC equal to 2.4 TECU occurs around 0200 LT at 60º S, the maximum TEC equal to 102.1 TECU is reached at the crest of the Equatorial Anomaly (EA) region. The specification of the ionospheric weather is provided by the W-index map in Figure 5b.where the positive storm signatures (W=3 and W=4) are concentrated at low latitudes the most of those in the evening sector. The decreased plasma density and electron content at the negative phase of the storm (W = -3 and W = -4) are observed in the auroral and sub-auroral latitudes, and also near the equator around midnight. The foF2 map (Figure 5c) mirrors TEC features (Figure 5a) though the EA region is shifted to the afternoon, 1400 LT, and foF2 by night is remarkably decreased towards the poles. The map of the peak height (Figure 5d) is obtained using the empirical model of changes of hmF2 opposite to the foF2 changes (Gulyaeva, 2012) when the quiet reference is taken from the IRI-CCIR predictions. As a result, the higher hmF2 are seen along the midnight meridian. Near the noon equator, the lower hmF2 are obtained near the crests of EA. Another case for lower hmF2 occurred near the latitudes of the crests of EA but in the evening sector around 2000 LT. Remarkably mirrored (opposite) features can be captured in the hmF2 and W-index maps. These are due to hmF2 model (Gulyaeva, 2012) which is constructed by analysis of foF2 with W-index evaluation. Hence, while proper TEC and foF2 maps indicate neither the degree of a storm development nor its positive or negative signatures until relevant W-index map is produced, the peak height hmF2 map can provide a picture for the expected features of a storm opposite to the pattern on W-index map prior to its generation.

Numerical representation of the maps in IONEX format makes it possible to incorporate results in other operational communication and navigation systems (Goodman, 2005). In particular, the numerical maps of foF2 and hmF2 deduced with IRI-Plas code from GIM-TEC, could further serve as the IRI driving parameters for the IRI-Real Time implementation. Though the formal IRI code is limited by the ionosphere altitudes (below 1,500 km) excluding the plasmasphere part (Bilitza, 2001; Gulyaeva and Bilitza, 2012), the formal IRI is often used as the ionosphere background model with the Computerized Ionosphere Tomography, CIT (Bust and Mitchell, 2008). In such capacity the input of GIM-TEC adapted maps of foF2 and hmF2 (instead of CCIR or URSI maps) into the IRI code would speed up process of CIT convergence to 3-D ionosphere reconstruction from the navigation satellites signal measurements.

Another implementation of the foF2 and hmF2 product maps (adapted to 'true' GIM-TEC or predicted by IWAF system) is made for reconstruction of missed foF2 and hmF2 ionosonde observation and their forecast at the magnetic conjugate locations for the global network of ionosonde stations. Relevant procedures are included in the algorithm and applied online for more than 60 ionospheric observatories and their conjugate counterparts worldwide (Figure 6). The titles of the ionosonde stations, their geographic coordinates and geographic coordinates for their magnetic counterparts are provided at the "Ionospheric Weather' site (http://www.izmiran.ru/services/iweather/).

The results of extracting the foF2 and hmF2 values at the magnetic conjugate counterparts from the IWAF products are demonstrated in Figure 7a, and 7b for three days of the space weather storm on September 30, 1-2 October, 2012. The geographic and magnetic coordinates of five ionosondes, namely, Tromso (TR), Novosibirsk (NS), Boulder (BC), Port Stanley (PS), and Mawson (MW), and geographic/magnetic coordinates of their magnetic conjugate points (C.P.) are given in Table 5. Projection of the magnetic field lines passing through the selected observatory and its corresponding magnetic conjugate point are plotted in Figure 6 in white lines. The relevant F2 layer peak parameters of foF2 and hmF2 are analyzed during the three days of storm which occurred at the origin of a cascade of the series of the space weather storms at the beginning of October, 2012. The foF2 and hmF2 measured at five observatories and predicted in their conjugate counterparts are presented in Figure 7. The planetary Wp index and the ring current Dst index are shown for a comparison (bottom sections). Both the 'true' values and the IWAF system prediction of foF2 and hmF2 at the conjugate points clearly demonstrate the space weather storm signatures. Thus, foF2 values are decreased during October 1 when the peak of the ring current, Dst, index is decreased and planetary Wp index increased. The data for this day are also analyzed in Table 2 and illustrated by the global maps in Figure 5. The hmF2 behavior has become more irregular on October 1, particularly, at Port Stanley. The small-scale variability of the F2 layer peak parameters at the magnetic conjugate low latitude stations was discussed in more details by McNamara et al. (2008). The results of IWAF reconstruction of foF2 at the source observatories (crosses) are nearly coincident with the observations (circles). The shift of the diurnal profile of foF2 and hmF2 at the origin observatory and their conjugate point closely follows the difference in local time (longitude) at each pair of the ends of the magnetic field line. More results of analysis of the ionosphere and plasmasphere storms with outcome of IWAF system are given by Gulyaeva et al. (2011; 2012).

The percentage occurrence of the W-index characteristics of the global ionosphere/plasmasphere storms is plotted in Figure 8 for the period of 1999 to 2012, which covers more than the total solar cycle shown by the monthly mean 10.7 cm solar radio flux, F10.7 (dashed curve). The daily peak occurrence of stormy W-index (W = ±3 and W = ±4), in percent, relative to the total number of cells (5112) on a map, is plotted (black line) for each day of observations, and their monthly average is provided (circles). Typical W-storm occurrence is about 10% of a globe surface but it can reach as much as 70% of the globe at the peak of the intense space weather storm. This type of W-index occurrence follows the variation of the solar activity demonstrating the global storm effects reduced from the solar maximum to solar minimum. The annual and seasonal components with equinoctial maxima, particularly pronounced at the high solar activity (Figure 8) deserve a special investigation and modeling for a reliable prediction of global ionospheric storms.

5. Conclusions

The variability of space weather and its potential impact on HF and satellite systems are important study areas with approaching the forthcoming solar maximum of the 24th solar cycle expected in 2013. In this study, two important space weather products are introduced by the Ionospheric Weather Assessment and Forecast (IWAF) system. The first product is the daily-hourly global foF2, hmF2 and TEC maps that are based on IRI-Plas empirical climatic model adjusted to GIM-TEC data. Hourly GIM maps from JPL, JPLR, and UPC, UHRG, serve as an input to IRI-Plas to scale the coefficient set for actual space weather. In IWAF, W-index maps are produced from 1999 up-to-date to represent the intensity and distribution of an ionospheric disturbance. W-index proved itself to be an excellent proxy for storm classification and analysis in terms of coupling of solar wind into the Earth's ionosphere and plasmasphere.

The second important product of IWAF is the prediction of TEC on a global scale one day or two days ahead through a forecast model which is represented in spherical harmonics functions. The accuracy of forecasted TEC maps are of the same order as IGS forecast products from various data analysis centers. With production of the IWAF forecast of TEC, foF2 and hmF2 maps, the near real-time assessment and forecast of these parameters are provided for any location on the globe including the missed observations at the global ionosonde network and their magnetic conjugate locations.

IWAF services can be reached at Ionospheric Weather Service of IZMIRAN at http://www.izmiran.ru/services/iweather/ or at IONOLAB website at www.ionolab.org. The foF2, hmF2, TEC and Wp movies for selected collection of the severe ionospheric and plasmaspheric storms since 2001 are provided in youtube under IONOLAB or at IONOLAB website under 'videos'.

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Appendix A. Computation of W-index for a TEC Map

The W-index computation for a rectangular region defined by (θ_i, ϕ_i) to (θ_s, ϕ_s) is provided for the increments in θ and in ϕ given as $\Delta\theta$ and $\Delta\phi$, respectively. The grid structure is arranged such that (θ_i, ϕ_i) forms the initial grid point (lower left corner of the rectangular region) and the rectangular region extends towards north and east. The grid ends at (θ_s, ϕ_s) as the upper right corner of the rectangular region. The number of grid points in θ and in ϕ can be obtained as

$$N_\theta = |\theta_s - \theta_i| / \Delta\theta + 1$$

(A1)

$$N_\phi = |\phi_s - \phi_i| / \Delta\phi + 1$$

Similarly,

$$\Delta\theta = |\theta_s - \theta_i| / (N_\theta - 1)$$

(A2)

$$\Delta\phi = |\phi_s - \phi_i| / (N_\phi - 1)$$

Any point defined by (θ,ϕ) in the given region can also be indexed in the grid as a point (n_θ, n_ϕ), as

$$\theta = \theta_i + \Delta\theta\,(n_\theta - 1)$$

(A3)

$$\phi = \phi_i + \Delta\phi\,(n_\phi - 1)$$

where $1 \le n_\theta \le N_\theta$ and $1 \le n_\phi \le N_\phi$. If, for a given day d, TEC values on such a rectangular grid are updated for a total of N_T times with incremental steps of time index, n_T (where $1 \le n_T \le N_T$), then the TEC value at any point (θ, ϕ) and time index n_T can be represented using a lexicographical index notation as

$$X_d = [x_d(1) \; ... \; x_d(l) \; ... \; x_d(N_\theta \, N_\phi \, N_T)]^T \tag{A4}$$

where the superscript T is the transpose operator and the index *l* is defined as

$$l = n_\theta + (n_\phi - 1)\, N_\theta + (n_T - 1)\, N_\theta \, N_\phi \tag{A5}$$

and $1 \le l \le N_\theta \, N_\phi \, N_T$. For the total number of days $N_{d_s - d_i}$ from day d_i to day d_s prior to the day d, the TEC values can be arranged in a matrix as

$$X_{d_s - d_i} = \left[x_{d_i} \; ... \; x_{d_s} \right]_{(N_\theta N_\phi N_T) \times (N_{d_s - d_i})} \tag{A6}$$

Let the vector

$$x_{m;d_s - d_i} = \left[x_{m;d_s - d_i}(1) ... \; x_{m;d_s - d_i}(l) ... \; x_{m;d_s - d_i}(N_\theta \, N_\phi \, N_T) \right]^T \tag{A7}$$

denote the median of $X_{d_s - d_i}$ across each row as

$$x_{m;d_s - d_i}(l) = median \; (x_{d_i}(l) ... \; x_{d_s}(l)) \tag{A8}$$

The deviation TEC value from the median TEC of $N_{d_s - d_i}$ number of days prior to day d is expressed as

$$D_d(l) = \log\left(\frac{x_d(l)}{x_{m;d_s - d_i}(l)}\right) \quad \text{(A9)}$$

The W-index derivation is applied to produce W-index map in IONEX format from the source Global Ionospheric Map, GIM-TEC.

Table 1. Acronyms used in the paper and their meaning

Acronym	Content
CCIR	Comité Consultatif International des Radiocommunications
CDDIS	Crustal Dynamics Data Information System
CIT	Computerized Ionospheric Tomography
CODE	Center for Orbit Determination in Europe, University of Bern
C.P.	Magnetic Conjugate Points
EHRG	ESA-ESTEC generated GIM-TEC
HF	High Frequency from 30 MHz to 3 MHz
gAGE/UPC	Technical University of Catalonia, Spain
GIM-TEC	Global Ionospheric Map of Total Electron Content
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IGS	International Geodynamic Service
IGRG	**IONEX file containing the combined IGS Ionosphere maps**
IONEX	IONosphere map EXchange format
Iono-WG	Ionospheric Working Group of GNSS service
IRI-Plas	International Reference Ionosphere extended to Plasmasphere
ITU-R	International Telecommunication Union, Radio Division
IWAF	Ionospheric Weather Assessment and Forecast system
JPLR	Jet Propulsion Laboratory Rapid (preliminary) GIM-TEC
JPLG	Jet Propulsion Laboratory final GIM-TEC
M3000F2	Radio wave Propagation Factor at a distance of 3,000 km
RT	Real Time
TEC	Total Electron Content
TECU	TEC Unit; 1TECU = 1×10^{16} el/m^2
UHRG	Hourly Rapid UPC product of GIM-TEC
URTG	Preliminary UPC product of GIM-TEC
U2PG	2-day forecast of UPC GIM-TEC
URSI	International Union of Radio Science
VTEC	Vertical Total Electron Content

Table 2. Relative error of 1-day forecast (δ_1) and 2-days ahead forecast (δ_2) of TEC, foF2 and hmF2 maps regarding to the reference UHRG 'true' maps for the worst case storm conditions on October 1, 2012.

Hours LT	***foF2***		***hmF2***		***TEC***	
	δ_1	δ_2	δ_1	δ_2	δ_1	δ_2
0000	0.0185	0.0174	0.0218	0.0203	0.0199	0.0221
0100	0.0207	0.0192	0.0231	0.0221	0.0144	0.0191
0200	0.0117	0.0130	0.0260	0.0263	0.0103	0.0113
0300	0.0085	0.0086	0.0252	0.0261	0.0078	0.0076
0400	0.0077	0.0076	0.0273	0.0268	0.0076	0.0072
0500	0.0080	0.0078	0.0336	0.0310	0.0088	0.0076
0600	0.0108	0.0101	0.0208	0.0192	0.0106	0.0097
0700	0.0287	0.0327	0.0120	0.0150	0.0207	0.0194
0800	0.0296	0.0294	0.0111	0.0119	0.0358	0.0349
0900	0.0300	0.0333	0.0120	0.0132	0.0316	0.0340
1000	0.0305	0.0302	0.0176	0.0167	0.0301	0.0303
1100	0.0259	0.0292	0.0187	0.0190	0.0288	0.0327
1200	0.0253	0.0265	0.0214	0.0224	0.0265	0.0350
1300	0.0251	0.0241	0.0243	0.0242	0.0261	0.0338
1400	0.0254	0.0244	0.0242	0.0224	0.0258	0.0339
1500	0.0251	0.0260	0.0222	0.0201	0.0263	0.0277
1600	0.0259	0.0243	0.0186	0.0218	0.0286	0.0328
1700	0.0265	0.0296	0.0178	0.0191	0.0298	0.0306
1800	0.0287	0.0295	0.0203	0.0221	0.0308	0.0361
1900	0.0250	0.0300	0.0272	0.0350	0.0224	0.0249
2000	0.0229	0.0248	0.0261	0.0268	0.0219	0.0208
2100	0.0194	0.0204	0.0238	0.0246	0.0199	0.0233
2200	0.0162	0.0161	0.0213	0.0244	0.0178	0.0266
2300	0.0155	0.0141	0.0193	0.0194	0.0178	0.0159
Average	0.0213	0.0220	0.0215	0.0221	0.0217	0.0241

Table 3. Categories of the ionospheric weather W-index corresponding to the logarithmic deviation from the median.

$D_d(l)$	**W**	**Categories of the Ionospheric State**
$D_d(l) > 0.301$	4	Intense positive W^+ storm
$0.155 < D_d(l) \leq 0.301$	3	Moderate W^+ storm or W^+ substorm
$0.046 < D_d(l) \leq 0.155$	2	Weak W^+ disturbance
$0.0 < D_d(l) \leq 0.46$	1	Quiet W^+ state
$D_d(l)=0$	0	Reference Quiet state
$-0.046 \leq D_d(l) < 0.0$	-1	Quiet W^- state
$-0.155 \leq D_d(l) < -0.046$	-2	Weak W^- disturbance
$-0.301 \leq D_d(l) < -0.155$	-3	Moderate W^- storm or W^- substorm
$D_d(l) < -0.301$	-4	Intense negative W^- storm

Table 4. Validation of IWAF system prediction of GIM-TEC (a), foF2 (b), and hmF2 (c) maps 1-day ahead (1) and 2-days ahead (2) along with the standard persistence model (0) which assumes that prediction is equal to data of numerical map for the preceding day. Daily averaged noon and midnight data are selected from 24 hourly UT maps, for quiet (q) day, dominant positive storm day (s+), and dominant negative storm day (s−) for three months of 2012 (January, April, and July) representing different seasons.

(a) Mean TEC, RMS [TECU].

Date, 2012	Midnight				Noon			
	UPC							
	Mean	RMS0	RMS1	RMS2	Mean	RMS0	RMS1	RMS2
Jan 21q	15.0	3.00	2.95	3.16	30.9	4.26	3.70	3.82
22s+	16.4	3.52	3.50	3.76	33.4	5.61	5.34	5.58
23s–	15.0	4.65	4.34	4.60	31.9	7.45	5.73	5.86
Apr 22q	15.7	4.94	3.92	4.06	36.5	6.95	5.32	5.41
23s+	16.3	6.85	4.90	4.85	38.0	7.68	5.43	5.44
24s–	14.7	7.21	5.54	5.39	34.7	8.62	7.09	7.10
Jul 14q	10.5	2.22	2.13	2.39	21.7	3.87	4.52	5.02
15s+	11.6	4.23	3.61	3.49	23.6	6.89	6.10	6.01
16s–	8.6	4.82	4.02	4.29	19.2	8.36	6.73	6.93
Average	13.8	4.60	3.88	4.00	30.0	6.63	5.55	5.69
Date, 2012	JPL							
	Mean	RMS0	RMS1	RMS2	Mean	RMS0	RMS1	RMS2
Jan 21q	14.9	2.68	2.03	2.22	32.2	3.72	3.09	3.20
22s+	15.4	3.33	3.35	3.52	34.7	6.64	6.24	6.25

23s–	13.6	4.17	4.15	4.43	32.7	7.98	6.33	6.70
Apr 22q	17.1	4.01	2.87	2.79	38.9	6.16	4.96	5.15
23s+	16.2	3.85	3.65	3.87	39.9	5.43	3.86	4.18
24s–	15.3	5.50	4.58	4.54	36.9	8.68	7.55	7.44
Jul 14q	12.5	2.34	2.31	2.62	24.7	4.03	4.71	5.28
15s+	12.9	4.41	3.61	3.44	26.6	6.75	6.08	6.00
16s–	10.5	4.66	3.92	4.20	21.9	8.12	6.51	6.80
Average	14.3	3.88	3.39	3.51	32.1	6.39	50.48	5.67

(b) Mean foF2, RMSE [MHz].

Date, 2012	Midnight				Noon			
	UPC							
	Mean	RMS0	RMS1	RMS2	Mean	RMS0	RMS1	RMS2
Jan 21q	4.9	0.48	0.48	.52	7.6	0.51	0.44	0.46
22s+	5.2	0.60	0.60	0.64	7.9	0.70	0.68	0.71
23s–	4.9	0.80	0.60	0.79	7.6	0.95	0.70	0.72
Apr 22q	5.4	0.84	0.64	0.65	8.3	0.78	0.60	0.63
23s+	5.5	1.19	0.86	0.84	8.5	1.02	0.73	0.71
24s–	5.1	1.22	0.93	0.90	8.0	0.96	0.78	0.80
Jul 14q	4.2	0.95	0.95	0.94	6.6	0.57	0.66	0.73
15s+	4.5	0.92	0.80	0.77	6.9	1.04	0.93	0.92
16s–	3.9	0.98	0.92	0.99	6.1	1.19	0.94	0.98
Average	4.8	0.89	0.77	0.78	7.5	0.86	0.72	0.74
Date, 2012	JPL							
	Mean	RMS0	RMS1	RMS2	Mean	RMS0	RMS1	RMS2
Jan 21q	5.0	0.41	0.35	0.38	7.7	0.44	0.38	0.40
22s+	5.1	0.58	0.60	0.64	8.0	0.77	0.60	0.77
23s–	4.7	0.73	0.71	0.76	7.7	0.95	0.74	0.78
Apr 22q	5.5	0.61	0.45	0.44	8.6	0.70	0.56	0.59
23s+	5.4	0.62	0.56	0.59	8.6	0.65	0.46	0.49
24s–	5.2	0.83	0.71	0.71	8.2	0.98	0.88	0.88
Jul 14q	4.7	0.46	0.46	0.51	7.1	0.59	0.68	0.77
15s+	4.7	0.89	0.76	0.73	7.3	0.89	0.85	0.86
16s–	4.2	0.88	0.79	0.86	6.6	1.10	0.82	0.86
Average	4.9	0.67	0.60	0.62	7.8	0.79	0.68	0.71

(c) Mean hmF2, RMSE [km].

Date, 2012	Midnight				Noon			
	UPC							
	Mean	RMS0	RMS1	RMS2	Mean	RMS0	RMS1	RMS2
Jan 21q	351	10.3	10.2	10.8	322	7.9	6.1	6.2
22s+	347	13.7	13.2	13.7	319	9.8	9.9	10.3
23s–	351	19.2	19.5	20.2	321	13.3	12.5	13.3
Apr 22q	364	18.5	14.6	14.7	333	11.4	8.8	9.4
23s+	371	22.0	17.3	17.4	333	14.1	9.9	9.7
24s–	367	27.7	21.5	20.4	335	19.9	16.8	16.5

Jul 14q	351	11.5	11.7	12.8	318	8.0	9.0	10.0
15s+	344	23.2	21.4	21.3	315	18.4	14.6	13.9
16s–	359	27.2	25.0	26.2	324	22.8	17.7	17.6
Average	356	19.3	17.2	17.5	324	14.0	11.7	11.9
Date, 2012	JPL							
	Mean	RMS0	RMS1	RMS2	Mean	RMS0	RMS1	RMS2
Jan 21q	345	8.2	7.6	8.4	317	6.1	4.8	5.0
22s+	343	12.4	12.9	13.5	314	10.6	10.2	10.3
23s–	349	15.0	15.8	17.0	316	13.3	12.7	13.6
Apr 22q	358	13.3	10.4	10.5	328	10.6	8.0	8.2
23s+	362	12.1	11.7	12.6	327	9.0	6.7	7.3
24s–	363	17.2	14.9	15.2	331	15.7	15.5	16.0
Jul 14q	341	11.1	11.1	12.1	314	8.9	9.8	10.7
15s+	339	19.5	17.6	17.7	310	15.3	11.9	11.5
16s–	348	23.0	17.2	17.9	318	20.8	16.6	16.3
Average	350	14.6	13.2	13.9	319	12.3	10.7	11.0

Table 5. Geographic coordinates of five ionosondes and geographic coordinates of their magnetic conjugate counterparts and the magnetic coordinates of the both.

Station	**Geographic Coordinates**		**Magnetic Coordinates**		**C.P. Geographic Coordinates**	
	Glati (^{0}N)	**Glongi (^{0}E)**	**Mlati (^{0}N)**	**Mlongi (^{0}E)**	**Glati (^{0}N)**	**Glongi (^{0}E)**
Tromso, Norway (TR)	69.9	19.2	67.4 -67.4	116.5 116.5	-61.5	61.5
Novosibirsk, Russia (NS)	54.6	83.2	45.4 -45.4	159.9 159.9	-35.9	90.4
Boulder, USA (BC)	40.0	254.7	48.1 -48.1	321.2 321.2	-55.4	240.3
Port Stanley, UK (PS)	-51.6	302.1	-41.9 41.9	12.0 12.0	32.1	298.2
Mawson, Australia (MW)	-67.6	62.9	-73.2 73.2	111.4 111.4	74.0	4.8

Figure captions.

Fig.1. The UHRG VTEC (continuous line), compared with the performance of rapid and final combined IGS global VTEC maps (long-dashed and short-dashed lines), in terms of Standard Deviation (a) and relative RMS percentage (b) regarding to the daily mean reference VTEC value, taking as reference the actual JASON-2 VTEC measurements gathered over the oceans (days 119 to 292, 2012).

Fig.2 Example of the normalized relative error δTEC for the daily set of GIM-TEC maps for April 25, 2011 (a - quiet day) and September 17, 2011 (b - storm) regarding source UHRG map. Here Z1PG is 1-day ahead forecast by IWAF system; EHRG – true hourly ESTEC map; JPLG – true 2-h JPL map; CODG – true 2-h CODE map; IGSG –true 2-h map averaged by UWM from other true IonoWG 2-h maps; U2PG – two days ahead forecast by UPC.

Fig.3. Comparison of the preliminary real-time (RT) UPC TEC maps *urtg* computed with a limited number of about 70 to 80 GPS receivers 17-24 January, 2012, with 1-day predicted TEC maps, *z1pg* (among the hourly *uhrg*, final *upcg* UPC maps and the final combined IGS one *igsg*) against JASON-2 direct VTEC measurements over the oceans. (a) Planetary Wp-index; (b) Root-mean square deviation, in percents; (c) Standard deviation; (d) Bias, in TECU.

Fig. 4. Specification of ionospheric ‘quiet’ day, ‘positive’ storm day (dominant index W = 3 and 4) and ‘negative’ storm day (dominant index W = -3 and -4) in terms of occurrence (in percent) of W-index of the storm magnitudes calculated from UHRG maps (marked by W-u and W+u) and JPLR maps (marked by W-j and W+j) for three periods during 2012.

Fig.5. The global maps for the storm day on October 1, 2012, 1200 UT: (a) the source *uhrg* TEC, and the IWAF system products: (b) W-index map, (c) foF2 map, and (d) hmF2 map.

Fig.6. The world-wide distribution of more than 60 ionospheric observatories (circles) and their magnetic conjugate counterpart locations (triangles) used for online analysis at the Ionospheric Weather site. Projection of the magnetic field line on the Earth’s surface is shown by white lines for five pairs of the conjugate locations used for the subsequent analysis (Table 5 and Figure 7).

Fig.7. The hour-to-hour variation of foF2 and hmF2 observed at five ionosonde stations (circles), the IWAF products at the source stations (crosses) and at the magnetic conjugate counterpart locations (dashed line) for the space weather storm on September 30, 1 and 2 October, 2012. The ring current Dst index and the planetary Wp index are given in the lower sections.

Fig.8. The percentage daily peak occurrence of the W-index storm characteristics (total number of cells of W = ±3 and W = ±4 on a map), their monthly average and the monthly mean solar radio flux, F10.7, i.u., during 1999-2012.