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 (-87.5°:2.5°:87.5°N in latitude, -180°:5°:180°E 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 ($W=\pm 1$) to intense storm ($W=\pm 4$) 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.

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

32

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

53 M3000F2 (Jones and Gallett, 1962) and URSI foF2 maps (Rush et al., 1989) are available, in
54 particular, in the International Reference Ionosphere (IRI) system (Bilitza, 2001). Each map allows for
55 a dependence on position, time, and solar epoch as given by spherical harmonic functions of
56 geographic latitude, geographic longitude and Universal Time (UT) for selected level of solar activity.
57 The associated numerical coefficients are chosen to match a data set of measurements from the world
58 network of vertical-incidence ionosondes for the years of 1954, 1955 and 1964 for solar minimum and
59 1956-1958 for solar maximum.

60 The temporal and spatial sparsity of data (e.g. the measurements of the ground-based
61 ionosondes located mainly on the land but rare over the oceans as shown in Figure 6) that have been
62 included in the development of IRI model can be compensated either by assimilation of new ionosonde
63 measurements, or by upgrading the IRI model to include situations like space weather storms (Araujo-
64 Pradere et al., 2002; Gulyaeva, 2012). When the first option is not feasible, it is better to approach the
65 problem with a cost-effective improvement in the IRI model. The International Reference Ionosphere
66 extended to the plasmasphere (IRI-Plas) (Gulyaeva et al., 2011) is the recent version of IRI where the
67 region of interest can include plasmasphere up to the height of 20,200 km (GPS orbit) so that the GPS-
68 derived Total Electron Content (GPS-TEC) can be ingested into IRI-Plas for better representation of
69 the temporal variations in the ionosphere and plasmasphere. As it is envisaged by IRI and IRI-Plas
70 algorithms, the model electron density height profile, $N_e(h)$, is parameterized using a relative layer
71 shape formula depending on vertical coordinate adapting the absolute values to those at the peak: the
72 peak electron density, N_mF2 , proportional to the critical frequency, foF2, and the corresponding peak
73 height, hmF2 (Gulyaeva and Bilitza, 2012). Daily-hourly implementation of plasmasphere part of IRI-
74 Plas code requires knowledge and prediction of 3-hrs geomagnetic kp-index. The daily data for the
75 past are provided online by Geomagnetic Data Service at Potsdam, and forecast for the forthcoming
76 hours of the day is produced in IWAF system with technique presented by De Franceschi et al. (2001).

77 The advantage of IRI-Plas code is the span of model electron density profile in the altitude range
78 from the bottom of the ionosphere (65-80 km) to 20,200 km (GPS orbit) relevant for automatic

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

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

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

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

123

124   **2. GIM-TEC Data Selection**

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

131 The slant TEC is transformed to vertical TEC at the sub-ionospheric piercing point (Smith et al., 2008)
132 from which the global ionospheric maps, GIM-TEC, are generated in a continuous operational way by
133 several Data Analysis Centers since 1998, covering the period more than the entire solar cycle
134 (Manucci et al., 1998; Dow et al., 2009; Hernandez-Pajares et al., 2011). Typically, GIM-TEC is
135 provided with two hour time resolution. The hourly files, JPLR and JPLG, are provided by Jet
136 Propulsion Laboratory since December, 2008, and hourly UHRG files are provided by Universitat
137 Politècnica de Catalunya since October, 2010. which are chosen as the source input in IWAF system.
138 The JPLR and JPLG are generated in the denser map grids ($-90:2:90^\circ$ in latitude, $-180:2:180^\circ$ in
139 longitude), and time specified for 0.5:1.0:23.5 hrs UT so these maps are preprocessed by linear
140 interpolation into standard IONEX format for 0:1:23 hrs UT. The vertical TEC is modeled by JPL in a
141 solar-geomagnetic reference frame using bi-cubic splines on a spherical grid; a Kalman filter is used to
142 solve simultaneously for instrumental biases and VTEC on the grid as stochastic parameters (Manucci
143 et al., 1998). The UHRG is produced by UPC software TOMION (TOmographic Model of the
144 IONosphere) using a Kriging based interpolation scheme (Orus et al, 2005) to get global coverage.
145 Both the input and output IWAF maps are provided in IONEX format collected in a daily set of the
146 hourly maps with 1 h UT resolution. The IONEX map consists of 5112 grid values binned in 87.5°S to
147 87.5°N in step of 2.5° in latitude, 180°W to 180°E in step of 5° in longitude. If the input data file is
148 missed for a certain day, it is substituted by another GIM-TEC product. When an input IONEX file is
149 available only with 2 h UT resolution, the linear interpolation in time is applied to bring GIM-TEC for
150 1 h UT resolution.

151 A recent assessment of the performance of UHRG VTEC global maps corresponding to the last
152 available 170 days (May to October 2012) is provided in Figure 1. It is remarkable to notice that the
153 UHRG performance is typically better than the combined rapid and final IGS VTEC maps, especially
154 during the last 120 days (right after the last software update), with daily standard deviations
155 systematically 0.5 to 1 TECU lower (in a range of 2 to 5 TECU), and relative RMS percentage of 15-
156 25%, instead of 20-25% for the combined IGS products.

157

158 **3. The Forecasting Procedure incorporated in IWAF system**

159   Since the daily-hourly GIM-TEC are available with a one day or two days latency due to
160 insufficient stock of more recent GPS-related information in RINEX format (Hernandez-Pajares et al.,
161 2009), the global maps forecast product in the framework of IWAF system is envisaged for one day
162 and two days ahead. There are different techniques applied for forecasting of the different ionospheric
163 parameters (Rose, 1993; Jakowski et al., 2002; Garcia-Rigo et al., 2011; Gulyaeva, 2012; Blanch and
164 Altadill, 2013; and references therein). In particular, the Disturbance Impact Assessment System
165 (DIAS) is designed by Rose (1993) as an expert system to assess and predict the influence of the solar
166 flares on high-latitude HF radio communications covering rules and warnings on the sudden
167 ionospheric disturbances, polar cap absorption, ionospheric critical frequency storm, auroral zone
168 absorption and auroral sporadic E and auroral E layers appearance. Review of the different techniques
169 of GIM-TEC forecast designed in the frame of the International GNSS Service and the UPC prediction
170 performance are summarized by Garcia-Rigo et al. (2011). Magnetosphere-ionosphere interactions
171 used for forecasting the F2 layer peak parameters are discussed by Blanch and Altadill (2013).
172 Empirical model of storm-time update of the F2 layer peak height hmF2 in terms of the foF2 changes
173 deduced from the topside sounding data base (Gulyaeva, 2012) is employed by IWAF system as
174 mentioned in the Introduction.

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

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

186

$$187 \quad X = \bar{X} + \sum_{i=1}^5 [A_i \sin(2\pi i t / 24) + B_i \cos(2\pi i t / 24)] \quad (1)$$

188

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

190

$$191 \quad A_i = \frac{2}{N} \sum_{k=1}^{96} X_k \sin(2\pi i t / 24) \quad (2)$$

192

$$193 \quad B_i = \frac{2}{N} \sum_{k=1}^{96} X_k \cos(2\pi i t / 24)$$

194

195 The Eqns. (1-2) reproduce the diurnal variation of X parameter one day ahead taking into
 196 account the diurnal (24 h), semi-diurnal (12 h), 8 h, 6 h, and 4 h tidal components. Though the
 197 harmonics are given in terms of the universal time, t , the period of 24 local hours around the world is
 198 fully represented by the global UT map (Maruyama, 2010). Each harmonic based on the relevant maps
 199 for four recent days can be treated as a separate object of a particular physical meaning, for example,
 200 the first harmonic of the diurnal variation of foF2, hmF2 and TEC depicts the results of feeding the
 201 ionosphere and plasmasphere by the solar ionizing radiation; the second harmonic is related with half-
 202 diurnal variations of the plasma density separated on the Earth by the solar terminator (Somsikov,
 203 2011). The higher order harmonics may be due to the solar wind energy input captured by the
 204 magnetosphere (Gulyaeva and Veselovsky, 2012), transformed and dissipated in the polar upper
 205 atmosphere (Rose, 1993) that triggers and drives the ionospheric storm effects along the magnetic field
 206 lines between the conjugate hemispheres (Gulyaeva et al., 2011, 2012). The harmonic analysis is

207 applied for the prediction one day ahead and the first prediction results serve as an input combined
 208 with the source GIM-TEC maps for three preceding days in order to forecast an ionospheric map two
 209 days in advance.

210

211 **4. Validation of IWAF Forecast Procedure**

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

217

$$218 \quad \delta X = \frac{1}{n} \sum_{i=1}^n \sqrt{\frac{(X_{obi} - X_i)^2}{(\overline{X_{obi}} - \overline{X_{ob}})^2}} \quad (3)$$

219

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

224 An example of the comparison is plotted in Figure 2 for a quiet day on April 25, 2011 (left
 225 panel), and a storm day on September 17, 2011 (right panel). Results for 1 day forecast by IWAF
 226 system Z1PG shows minimum δTEC error for the quiet day as compared with other GIM-TEC
 227 products. This means that a departure of the IWAF prediction of TEC map from the true UHRG map is
 228 less than the difference between the different Iono-WG maps for the quiet day. This advantage,
 229 however, is not so evident for the sunlit hours of the storm day (right panel) when the IWAF 1-day
 230 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 W_p index (Gulyaeva and Stanislawska, 2008; 2010) varies between $W_p=3.5$ and the peak $W_p = 6.7$ i.u. (index units) during the day (see W_p 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 W_p index (Gulyaeva and Stanislawska, 2008) plotted in Figure 3a demonstrates the

257 transition from quiet to storm period during 17 to 24 January, 2012. The percentage root mean square
 258 RMS deviation is plotted in Figure 3b. Figure 3c illustrates the standard deviation of GIM-TEC from
 259 the reference Topex/Jason data. Figure 3d shows the bias of GIM-TEC and the Topex/Jason daily
 260 averages. The bias (defined as averaged difference of JASON-2 VTEC minus global VTEC value) of
 261 URTG map is positive, higher than the negative bias obtained in the most of other results (Figure 3d).
 262 In principle, from the physical point of view, due to the difference in the orbits of two systems of TEC
 263 products (the GPS constellation orbits the Earth at 20,200 km against 1,336 km of Topex/Jason), this
 264 bias should be positive, containing the averaged electron content between the altimeter and the GPS
 265 constellation (Lee et al., 2013). However, and due to the well known positive bias in the altimeters
 266 calibration (of few TECUs affecting the TOPEX and JASON VTEC values see, for instance, (Brunini
 267 et al. 2005), it is not an issue to have a slightly negative bias. **On the other hand**, the GPS-TEC
 268 measurements are rare over the oceans with measurements made on the islands so that GIM-TEC
 269 become less reliable in these areas dependent on a method of mapping functions used for filling gaps
 270 in missing GPS receiving data (Hernandez-Pajares et al., 2009). The standard deviation and RMS, in
 271 percent, (Figure 3b, c) illustrate the results of the preliminary RT URTG map which are of the same
 272 order of accuracy as a GIM-TEC forecast by IWAF system, Z1PG. The RMS deviation can amount up
 273 to 30% against the reference Topex/Jason data during the storm the both Z1PG and URTG errors
 274 exceeding the errors of other GIM-TEC maps computed with much more available observations in
 275 post-processing mode.

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

281 Figure 4 illustrates usage of the W-index map for specification of ‘quiet’ day, ‘positive’ storm
 282 day (with dominant occurrence of storm-time index $W = 3$ and 4 on the map for a specific UT) and

283 ‘negative’ storm day (with reduced TEC regarding its quiet reference for majority of GIM-TEC cells
 284 corresponding to index $W = -3$ and -4). Here the occurrence (in percent of total number of 5,112 map
 285 cells) of W -index of the said magnitudes is calculated hour-by-hour from UHRG (marked by $W-u$ and
 286 $W+u$) and JPLR (marked by $W-j$ and $W+j$) maps for three periods selected from the Catalogue of the
 287 planetary W_p storms deduced and permanently upgraded in the framework of IWAF system (Gulyaeva
 288 and Stanislawska, 2010). The first period for 21-23 January, 2012, refers to part of the days shown in
 289 Figure 3 the maps representing winter in the North hemisphere and summer in the South hemisphere.
 290 The second period for 22-24 April, 2012, belongs to the equinox. The third period for 14-16 July,
 291 2012, represents the summer/winter seasons in North/South hemisphere. Results of two GIM-TEC
 292 sources display consistent results starting from the quiet day with low occurrence of stormy W -index
 293 followed by an enhanced occurrence of positive storm indices with gradual developments of the
 294 negative storm afterwards. These are the typical two-phase ionosphere storm patterns (Mendillo, 2006)
 295 which imply injection of plasma by the solar wind into the ionosphere-plasmasphere system (positive
 296 phase of the ionospheric storm) followed by the plasma ejection (plasma depletion during the negative
 297 phase of the storm) towards the magnetosphere tail (Gulyaeva and Veselovsky, 2012).

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

305

$$306 \quad RMSE = \sqrt{(\vec{X} - \vec{Y})^2 / n} \quad (4)$$

307

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

321

322 **4. Results**

323 One of the objectives of this project is to provide the daily-hourly global foF2, hmF2 and W-
 324 index maps congruent with GIM-TEC product. An example of these maps along with the source
 325 UHRG map is provided in Figure 5 for 1200 UT of the storm day on October 1, 2012, which is
 326 analyzed in Table 2. The maps in Figure 5 are placed on the topographic map for longitudes from 0° to
 327 360° E so that for 1200 UT, the noon is shown at 0° E, the midnight at 180° E, and sunrise-sunset in
 328 between.

329 Figure 5a demonstrates the diurnal variation of TEC around the globe with enhanced TEC and
 330 foF2 around noon which is gradually decreased towards the nighttime. Minimum TEC equal to 2.4
 331 TECU occurs around 0200 LT at 60° S, the maximum TEC equal to 102.1 TECU is reached at the
 332 crest of the Equatorial Anomaly (EA) region. The specification of the ionospheric weather is provided
 333 by the W-index map in Figure 5b. where the positive storm signatures (W=3 and W=4) are

334 concentrated at low latitudes the most of those in the evening sector. The decreased plasma density and
335 electron content at the negative phase of the storm ($W = -3$ and $W = -4$) are observed in the auroral and
336 sub-auroral latitudes, and also near the equator around midnight. The foF2 map (Figure 5c) mirrors
337 TEC features (Figure 5a) though the EA region is shifted to the afternoon, 1400 LT, and foF2 by night
338 is remarkably decreased towards the poles. The map of the peak height (Figure 5d) is obtained using
339 the empirical model of changes of hmF2 opposite to the foF2 changes (Gulyaeva, 2012) when the
340 quiet reference is taken from the IRI-CCIR predictions. As a result, the higher hmF2 are seen along the
341 midnight meridian. Near the noon equator, the lower hmF2 are obtained near the crests of EA.
342 Another case for lower hmF2 occurred near the latitudes of the crests of EA but in the evening sector
343 around 2000 LT. Remarkably mirrored (opposite) features can be captured in the hmF2 and W-index
344 maps. These are due to hmF2 model (Gulyaeva, 2012) which is constructed by analysis of foF2 with
345 W-index evaluation. Hence, while proper TEC and foF2 maps indicate neither the degree of a storm
346 development nor its positive or negative signatures until relevant W-index map is produced, the peak
347 height hmF2 map can provide a picture for the expected features of a storm opposite to the pattern on
348 W-index map prior to its generation.

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

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

366 The results of extracting the foF2 and hmF2 values at the magnetic conjugate counterparts from
367 the IWAF products are demonstrated in Figure 7a, and 7b for three days of the space weather storm on
368 September 30, 1-2 October, 2012. The geographic and magnetic coordinates of five ionosondes,
369 namely, Tromso (TR), Novosibirsk (NS), Boulder (BC), Port Stanley (PS), and Mawson (MW), and
370 geographic/magnetic coordinates of their magnetic conjugate points (C.P.) are given in Table 5.
371 Projection of the magnetic field lines passing through the selected observatory and its corresponding
372 magnetic conjugate point are plotted in Figure 6 in white lines. The relevant F2 layer peak parameters
373 of foF2 and hmF2 are analyzed during the three days of storm which occurred at the origin of a
374 cascade of the series of the space weather storms at the beginning of October, 2012. The foF2 and
375 hmF2 measured at five observatories and predicted in their conjugate counterparts are presented in
376 Figure 7. The planetary Wp index and the ring current Dst index are shown for a comparison (bottom
377 sections). Both the ‘true’ values and the IWAF system prediction of foF2 and hmF2 at the conjugate
378 points clearly demonstrate the space weather storm signatures. Thus, foF2 values are decreased during
379 October 1 when the peak of the ring current, Dst, index is decreased and planetary Wp index
380 increased. The data for this day are also analyzed in Table 2 and illustrated by the global maps in
381 Figure 5. The hmF2 behavior has become more irregular on October 1, particularly, at Port Stanley.
382 The small-scale variability of the F2 layer peak parameters at the magnetic conjugate low latitude
383 stations was discussed in more details by McNamara et al. (2008). The results of IWAF reconstruction
384 of foF2 at the source observatories (crosses) are nearly coincident with the observations (circles). The

385 shift of the diurnal profile of foF2 and hmF2 at the origin observatory and their conjugate point closely
386 follows the difference in local time (longitude) at each pair of the ends of the magnetic field line. More
387 results of analysis of the ionosphere and plasmasphere storms with outcome of IWAF system are given
388 by Gulyaeva et al. (2011; 2012).

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

400

401 **5. Conclusions**

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

410 to be an excellent proxy for storm classification and analysis in terms of coupling of solar wind into
411 the Earth's ionosphere and plasmasphere.

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

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

422

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425 <ftp://cddis.gsfc.nasa.gov/gps/products/ionex/>. The TOPEX/Jason data are provided by JPL at
426 <ftp://podaac-ftp.jpl.nasa.gov/>. The ionosonde data are provided at <http://spidr.ngdc.noaa.gov/spidr/>.
427 The kp-index is provided at http://www-app3.gfz-potsdam.de/kp_index/. The IWAF system is
428 mirrored at IZMIRAN web site <http://www.izmiran.ru/services/iweather/> and IONOLAB web site
429 <http://www.ionolab.org/> to guarantee the proposed service for a potential user. The assistance of Umut
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435

436 **References**

- 437 Araujo-Pradere, E.A., Fuller-Rowell, T.J., Codrescu, M.V., 2002. STORM: An empirical storm-time
438 ionospheric correction model. 1. Model description, *Radio Sci.*, 37(5), 1070,
439 doi:10.1029/2001RS002467.
- 440 Azpilicueta, F., and Brunini, C., 2008. Analysis of the bias between TOPEX and GPS vTEC
441 determinations, *Journal of Geodesy*, 83(2), 121–127, 2008.
- 442 Bilitza, D., 2001. International Reference Ionosphere 2000, *Radio Science*. 36, 261–275,
443 doi:10.1029/2000RS002432.
- 444 Blanch, E., and Altadill, D., 2013. Midlatitude F region peak height changes in response to
445 interplanetary magnetic field conditions and modeling results. *J. Geophys. Res.*, 117, A12311,
446 doi:10.1029/2012JA018009.
- 447 Bradley, P. A., Stanislawska, I., Juchnikowski, G., 2009. Options for mapping foF2, *Adv. Space Res.*,
448 43, 1776–1779.
- 449 Brunini, C., Meza, A., Bosch, W., 2005. Temporal and spatial variability of the bias between TOPEX-
450 and GPS-derived total electron content, *Journal of Geodesy*, 79(4-5), 175-188,
451 doi:10.1007/s00190-005-0448-z.
- 452 Bust, G.S., Mitchell, C.N., 2008. History, current state, and future directions of ionospheric imaging,
453 *Rev. Geophys.*, 46, RG1003, doi:10.1029/2006RG000212.
- 454 CCIR Atlas of Ionospheric Characteristics, 1966, 1991. Comité Consultatif International des
455 Radiocommunications, Report 340-1, 340-6, ISBN 92-61-04417-4, International
456 Telecommunication Union, Genève, Switzerland.
- 457 De Franceschi G., Gulyaeva, T.L., and Perrone, L., 2001. Forecasting geomagnetic activity 3 hours in
458 advance for ionospheric applications. *Annali di Geofisica*, 44, No.5/6, 1067-1074.
- 459 Dow, J.M., Neilan, R.E., Rizos, C., 2009. The International GNSS Service in a changing landscape of
460 Global Navigation Satellite Systems, *Journal of Geodesy*, 83, 191-198.

461 Garcia-Rigo, A., Monte, E., Hernandez-Pajares, M., Juan, J.M., Sanz, J., Aragon-Angel, A., Salazar,
462 D., 2011. Global prediction of the vertical total electron content of the ionosphere based on GPS
463 data. *Radio Sci.*, 46, RS0D25, doi:10.1029/2010RS004643.

464 Goodman, J.M., 2005. Operational communication systems and relationships to the ionosphere and
465 space weather, *Adv. Space Res.*, 36, 2241-2252.

466 Gulyaeva, T.L., Stanislawska, I., Tomasik, M., 2008. Ionospheric weather: Cloning missed foF2
467 observations for derivation of variability index. *Annales Geophysicae*, 26(2), 315-321.

468 Gulyaeva, T.L., Stanislawska, I., 2008. Derivation of a planetary ionospheric storm index, *Annales*
469 *Geophysicae*, 26(9), 2645-2648.

470 Gulyaeva, T.L., Arikan, F., Delay, S., 2009. Scale factor mitigating non-compliance of double
471 frequency altimeter measurements of the ionospheric electron content over the oceans with GPS-
472 TEC maps, *Earth, Planets and Space*, 61, 1103-1109.

473 Gulyaeva, T.L., Stanislawska, I., 2010. Magnetosphere associated storms and autonomous storms in
474 the ionosphere-plasmasphere environment. *J. Atmos. Solar-Terr. Phys.*, 72, 90-96,
475 doi:10.1016/j.jastp.2009.100.012.

476 Gulyaeva, T.L., Arikan, F., Stanislawska, I., 2011. Inter-hemispheric Imaging of the Ionosphere with
477 the upgraded IRI-Plas model during the space weather storms, *Earth, Planets and Space*, 63(8),
478 929-939, doi: 10.5047/eps.20110.040.007.

479 Gulyaeva, T., 2012. Empirical model of ionospheric storm effects on the F2 layer peak height
480 associated with changes of peak electron density, *J. Geophys. Res.*, 117, A02302,
481 doi:10.1029/2011JA017158.

482 Gulyaeva, T., Veselovsky, I.S., 2012. Two-phase storm profile of global electron content in the
483 ionosphere and plasmasphere of the Earth, *J. Geophys. Res.*, 117, .A9, A09325,
484 doi:10.1029/2012JA018017.

485 Gulyaeva, T.L., Arikan, F., Stanislawska, I., Poustovalova, L.V., 2012. Symmetry and asymmetry of
 486 ionospheric weather at magnetic conjugate points for two midlatitude observatories, *Adv. Space*
 487 *Res.*, doi:10.1016/j.asr.20120.090.038.

488 Gulyaeva, T.L., Bilitza, D., 2012. Towards ISO standard earth ionosphere and plasmasphere model, in
 489 *New Developments in the Standard Model*, edited by R. J. Larsen, pp. 1-39, NOVA, Hauppauge,
 490 New York, https://www.novapublishers.com/catalog/product_info.php?products_id=35812.

491 Hernandez-Pajares, M., Juan, J.M., Sanz, J., Garcia-Rigo, A., Feltens, J., Komjathy, A., Schaer, S.C.,
 492 Krankowski, A., 2009. The IGS VTEC maps: A reliable source of ionospheric information since
 493 1998, *Journal of Geodesy*, 83(3-4), 263-275.

494 Jakowski, N., Heise, S., Wehrenpfennig, A., Schlüter, S., Reimer, R., 2002. GPS/GLONASS-based
 495 TEC measurements as a contributor for space weather forecast, *J. Atmos. Solar-Terrestrial Phys.*,
 496 64, 729-735.

497 Jones, W.B., Gallet, R.M., 1962. The representation of diurnal and geographic variations of
 498 ionospheric data by numerical methods, *Telecomm. J.*, 29, 129-149.

499 Lee, H.-B., Jee, G., Kim, Y.H., and Shim, J.S., 2013. Characteristics of global plasmaspheric TEC in
 500 comparison with the ionosphere simultaneously observed by Jason-1 satellite. *J. Geophys. Res.*
 501 *Space Physics*, 118, doi:10.1002/jgra.50130.

502 Manucci, A.J., Wilson, B.D., Yuan, D.N., Ho, C.M., Lindqwister, U.J., and Runge, T.F., 1998. A
 503 global mapping technique for GPS-derived ionospheric total electron content measurements.
 504 *Radio Sci.*, 33, 565-582.

505 Maruyama, T., 2010. Solar proxies pertaining to empirical ionospheric total electron content models, *J.*
 506 *Geophys. Res.*, 115, A04306, doi:10.1029/2009JA014890.

507 McNamara, L.F., Retterer, J.M., Abdu, M.A., Batista, I.S., Reinisch, B.W., 2008. F2 Peak parameters,
 508 drifts and spread F derived from digisonde ionograms for the COPEX campaign in Brazil, *J.*
 509 *Atmos. Solar-Terrestrial Phys.* 70, 1144-1158.

510 Mendillo, M., 2006. Storms in the ionosphere: Patterns and processes for total electron content.
511   Reviews of Geophys., 44, RG2001, doi:10.1029/2005RG000193.

512 Orus R., Hernandez-Pajares, M., Juan, J.M., Sanz, J., 2005. Improvement of global ionospheric VTEC
513   maps by using kriging interpolation technique, J. Atmos. Solar-Terrestrial Phys. 67, 1598-1609.

514 Rose, R.B., 1993. A high-latitude ionospheric disturbance impact assessment system, Radio Sci.,
515   28(1), 97-104.

516 Rush, C., Fox, M., Bilitza, D., Davies, K., McNamara, L., Stewart, F., PoKempner, M., 1989.
517   Ionospheric mapping - an update of foF2 coefficients, Telecomm J., 56, 179 – 182.

518 Schaer, S., Gurtner, W., and Feltens, J., 1998. IONEX: The IONosphere Map Exchange format
519   Version 1, in: Proc. of the IGS Analysis Center Workshop, ed. By Dow, J.M., Kouba, J., and
520   Springer, T., pp.233-247, Darmstadt, Germany.

521 Smith, D.A., Araujo-Pradere, E.A., Minter, C., Fuller-Rowell, T. A, 2008. Comprehensive evaluation
522   of the errors inherent in the use of a two-dimensional shell for modeling the ionosphere. Radio
523   Sci., 43, RS6008, doi:10.1029/2007RS003769.

524 Somsikov, V.M., 2011. Solar terminator and dynamic phenomena in the atmosphere: A review,
525   Geomagnetism and Aeronomy, 51(6), 707-719, doi: 2011.10.1134/S0016793211060168.

526 Vojannikov, V., Gordienko, G., 2011. A statistical method for reconstruction of missed observations
527   and foF2 short-term prediction, IEEE Xplore, General Assembly and Scientific Symposium, 2011
528   XXXth URSI, doi:10.1109/URSIGASS.2011.6051029, 1-4.

529 Zolesi, B., Cander, Lj R., 2000. Evolution of the ionospheric mapping and modelling during the last
530   four decades, Fisica de la Tierra, 12, 127–154.

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

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

542

$$543 \quad N_\theta = |\theta_s - \theta_i| / \Delta\theta + 1$$

$$544 \quad (A1)$$

$$545 \quad N_\phi = |\phi_s - \phi_i| / \Delta\phi + 1$$

546

547 Similarly,

548

$$549 \quad \Delta\theta = |\theta_s - \theta_i| / (N_\theta - 1)$$

$$550 \quad (A2)$$

$$551 \quad \Delta\phi = |\phi_s - \phi_i| / (N_\phi - 1)$$

552

553 Any point defined by (θ, ϕ) in the given region can also be indexed in the grid as a point $(n_\theta,$
554 $n_\phi)$, as

555

$$556 \quad \theta = \theta_i + \Delta\theta (n_\theta - 1)$$

$$557 \quad (A3)$$

$$558 \quad \phi = \phi_i + \Delta\phi (n_\phi - 1)$$

559

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

$$564 \quad \mathbf{X}_d = [x_d(1) \dots x_d(l) \dots x_d(N_\theta N_\phi N_T)]^T \quad (A4)$$

566
 567 where the superscript T is the transpose operator and the index l is defined as

$$568 \quad l = n_\theta + (n_\phi - 1) N_\theta + (n_T - 1) N_\theta N_\phi \quad (A5)$$

570
 571 and $1 \leq l \leq N_\theta N_\phi N_T$. 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
 572 TEC values can be arranged in a matrix as

$$573 \quad \mathbf{X}_{d_s - d_i} = \begin{bmatrix} x_{d_i} & \dots & x_{d_s} \end{bmatrix}_{(N_\theta N_\phi N_T) \times (N_{d_s - d_i})} \quad (A6)$$

575
 576 Let the vector

$$577 \quad x_{m; d_s - d_i} = \begin{bmatrix} x_{m; d_s - d_i}(1) \dots x_{m; d_s - d_i}(l) \dots x_{m; d_s - d_i}(N_\theta N_\phi N_T) \end{bmatrix}^T \quad (A7)$$

579
 580 denote the median of $x_{d_s - d_i}$ across each row as

$$581 \quad x_{m; d_s - d_i}(l) = \text{median} \quad (x_{d_i}(l) \dots x_{d_s}(l)) \quad (A8)$$

583

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

586
$$D_d(l) = \log \left(\frac{x_d(l)}{x_{m;d_s - d_i}(l)} \right) \quad (A9)$$

587

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

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607 **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

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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.

<i>Hours</i>	<i>foF2</i>		<i>hmF2</i>		<i>TEC</i>	
<i>LT</i>	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

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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
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

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640 (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

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642 (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,	JPL							
2012	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

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

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Station	Geographic Coordinates		Magnetic Coordinates		C.P. Geographic Coordinates	
	Glati (°N)	Glongi (°E)	Mlati (°N)	Mlongi (°E)	Glati (°N)	Glongi (°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

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654 **Figure captions.**

655 **Fig.1.** The UHRG VTEC (continuous line), compared with the performance of rapid and final
656 combined IGS global VTEC maps (long-dashed and short-dashed lines), in terms of Standard
657 Deviation (a) and relative RMS percentage (b) regarding to the daily mean reference VTEC value,
658 taking as reference the actual JASON-2 VTEC measurements gathered over the oceans (days 119 to
659 292, 2012).

660 **Fig.2** Example of the normalized relative error δTEC for the daily set of GIM-TEC maps for April 25,
661 2011 (a - quiet day) and September 17, 2011 (b - storm) regarding source UHRG map. Here Z1PG is
662 1-day ahead forecast by IWAF system; EHRG – true hourly ESTEC map; JPLG – true 2-h JPL map;
663 CODG – true 2-h CODE map; IGSG –true 2-h map averaged by UWM from other true IonoWG 2-h
664 maps; U2PG – two days ahead forecast by UPC.

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

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

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

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

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

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

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