Ionospheric specification services delivered by the National Observatory of Athens for the European Space Agency

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ABSTRACT

The European Ionosonde Service (EIS) is a federated service belonging to the Expert Service Center Ionospheric Weather (I-ESC) of the Space Situational Awareness (SSA) Programme - Space Weather segment of ESA. EIS is operated by the National Observatory of Athens since 2013 and releases a set of products to characterize the bottomside and topside ionosphere over Europe for nowcasting, forecasting and long-term planning purposes. The EIS products meet the requirements of various SSA service domains, especially the trans-ionospheric radio link and the spacecraft operations. In this contribution we present an assessment of the EIS performance and an outlook for improving existing products and developing new ones.

1. OVERVIEW OF THE PRODUCTS

The European Ionosonde Service (EIS) is based mainly on the exploitation of real time measurements from ground based DPS4 and DPS4D ionosondes operating in Europe. The service monitors the critical frequency foF2 and the bottomside electron density and extrapolates the electron density profile up to the height of the Global Navigation Satellite System (GNSS) at European middle and high latitudes. It also provides estimates for forthcoming disturbances mainly triggered by geo-effective Coronal Mass Ejections (CMEs).

The development of the service was based on the implementation of a number of models that are able to provide updated information in real time at least hourly. The models are implemented in the DIAS system (http:\\dias.space.noa.gr) and apart from the ionosonde data they exploit a variety of additional datasets, such as TEC parameters from the Regional Reference Frame Sub-Commission for Europe (EUREF), as well as solar wind parameters from the Advanced Composition Explorer (ACE) satellite and solar (R12 and F10.7) and geomagnetic indices (predicted Kp) from the National Oceanic and Atmospheric Administration (NOAA). The performance of the models implemented by EIS has been validated and based on these results it was possible to issue together with the products, quality metrics characterizing the product's reliability. A comprehensive overview of the EIS products is provided in Table 1.

The access to the EIS service is provided by the ESA SWE portal. The EIS portal communicates with the ESA SWE portal using the single sign-on (SSO) protocol. The EIS portal provides the Graphical User Interface (GUI) where all products are available in real-time. Historical values are also kept and provided to the user through the archive interface. Access is given for free from ESA upon registration (http://swe.ssa.esa.int/web/guest/dias-federated).

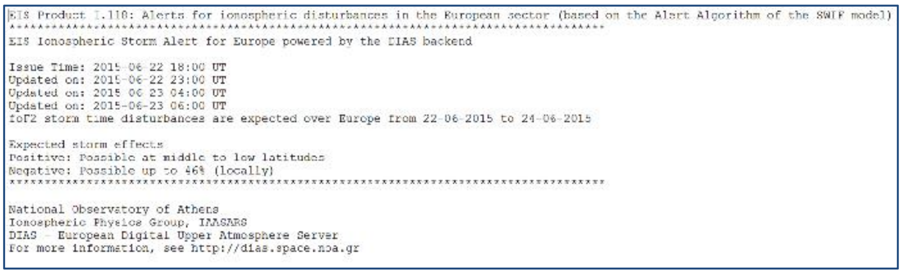
Table 1: Overview of the EIS products

Product	**Update rate**	**Spatial Coverage**	**Background model**	**Quality Indicator**
Long-term predictions of the foF2 in map format	Monthly	Europe: Regional Longitude: -10°W – 40°E Latitude: 34°N – 80°N	Combination of the Simplified Ionospheric Regional Model (SIRM) and the Comité Consultatif International pour la Radio (CCIR) model [*Zolesi et al.*, 1993; *Belehaki et al.*, 2015]. Input: Predicted R12 Validation results: *Belehaki et al.*, 2015.	Not applicable for operational availability
Nowcasting regional maps of the foF2 critical frequency	Hourly	Europe: Regional Longitude: -10°W – 40°E Latitude: 34°N – 80°N	The enhanced version of the Simplified Ionospheric Regional Model Updated in Real-Time (SIRMUP) [*Zolesi et al.*, 2004; *Belehaki et al.*, 2015] Input: Real time foF2 autoscaled values from DIAS network Validation results: *Belehaki et al.*, 2015.	Number and distribution of stations contributing data for the generation of the maps Relative deviation of the nowcasts from observed values over DIAS stations
Maps of the forecasted foF2 over Europe for the next 24 hours	Hourly	Europe: Regional Longitude: -10°W – 40°E Latitude: 34°N – 80°N	The enhanced version of the Solar Wind Driven Autoregression Model for Ionospheric Short-term forecast (SWIF) [*Tsagouri et al.*, 2009; *Tsagouri and Belehaki*, 2015; *Belehaki et al.*, 2015] in collaboration with the SIRMUP mapping technique. Input: Real-time and recent past foF2 autoscaled values from DIAS network; real-time Interplanetary Magnetic Field (IMF) parameters (IMF-B and IMF-Bz) from ACE. Validation results: *Tsagouri*, 2011; *Tsagouri and Belehaki*, 2015; *Belehaki et al.*, 2015.	Relative deviation of the mapped foF2 values from the foF2 forecasted values over each station. This quality indicator refers to the mapping procedure and not to the forecasted routine

Near real-time TEC maps for the European region	15 min	Europe: Regional	The Topside Sounders Model – assisted by Digisondes (TaD) [*Kutiev et al.*, 2012; *Belehaki et al.*, 2015]. Input: Real time automatic scaled SAO files from DIAS stations; TEC values from EUREF (provided by GNSS Group of the Royal Observatory of Belgium); daily F10.7 solar flux; three-hourly Kp indices (forecasted values). Validation results: *Belehaki et al.*, 2012; *Belehaki et al.*, 2015; *Kutiev et al.*, 2016.	Number and distribution of stations contributing data for the generation of the maps. The TEC maps are characterised by a quality index which is a measure of the deviation between the model and the GNSS-derived TEC parameters. The smallest the quality index is, the best is the fit between the model-derived maps and the GNSS-derived TEC maps.
Alerts for the forthcoming ionospheric disturbances in the European sector	Whenever an event occurs	Europe: Regional	The enhanced version of the SWIF model [*Tsagouri et al.*, 2009; *Tsagouri and Belehaki*, 2015; *Belehaki et al.*, 2015]. Input: Real-time IMF-B and IMF-Bz from ACE. Validation results: *Tsagouri and Belehaki*, 2015; *Belehaki et al.*, 2015.	Not applicable for operational availability
Maps of current ionospheric conditions at each station location	15 min	Europe: Local	Real time activity index Input: Real time and past (30 days) foF2 values from DIAS network of stations	foF2 observed values foF2 running median values Number of days in the estimation of the median
Forecasted foF2 values for the next 24 hours over each station.	Hourly	Europe: Local/Single stations	The enhanced SWIF model [*Tsagouri et al.*, 2009; *Tsagouri and Belehaki*, 2015; *Belehaki et al.*, 2015]. Input: Real-time and recent past foF2 autoscaled values from DIAS stations; real-time IMF-B and IMF-Bz from ACE. Validation results: *Tsagouri*, 2011; *Tsagouri and Belehaki*, 2015; *Belehaki et al.*, 2015.	Mean Relative Error and Running Median are available at the main nodes of the network.

2. EIS MONITORING AND PREDICTION CAPABILITIES

In the following, we attempt a demonstration of the EIS capabilities in monitoring and forecasting the ionospheric conditions over Europe during space weather disturbances. In particular, we follow the ionosphere-plasmasphere response to the storm event occurred in the time interval 21 - 25 June 2015 as it was "seen" by the system services. This was an intense storm event with multiple onsets (see the variation of the Dst index available in http://wdc.kugi.kyoto-u.ac.jp/dstdir/) that was driven by ICME-associated solar wind structures (http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm). In Figure 1, we present the EIS alert report issued on 22 June 2015 at 18:00 UT. This was the last one of a series of alerts that were issued by the system during the specific storm event and summarizes all previous alert activity (see the list of updates in the report). Figures 2 - 5 depict the ionospheric response of the foF2 critical frequency over Europe during the storm onset and main day (22 June 2015 and 23 June 2015, respectively).


EIS Product I.118: Alerts for ionospheric disturbances in the European sector (based on the Alert Algorithm of the SWIF model)

EIS Ionospheric Storm Alert for Europe powered by the DIAS backend

Issue Time: 2015-06-22 18:00 UT
Updated on: 2015-06-22 23:00 UT
Updated on: 2015-06-23 04:00 UT
Updated on: 2015-06-23 06:00 UT
foF2 storm time disturbances are expected over Europe from 22-06-2015 to 24-06-2015

Expected storm effects
Positive: Possible at middle to low latitudes
Negative: Possible up to 46% (locally)

National Observatory of Athens
Ionospheric Physics Group, IAASARS
DIAS - European Digital Upper Atmosphere Server
For more information, see http://dias.space.noa.gr

Figure 1: The EIS alert issued on 22 June 2015 at 18:00 UT. The alerts are provided with an average probability of detection 80% (*Tsagouri and Belehaki*, 2015).

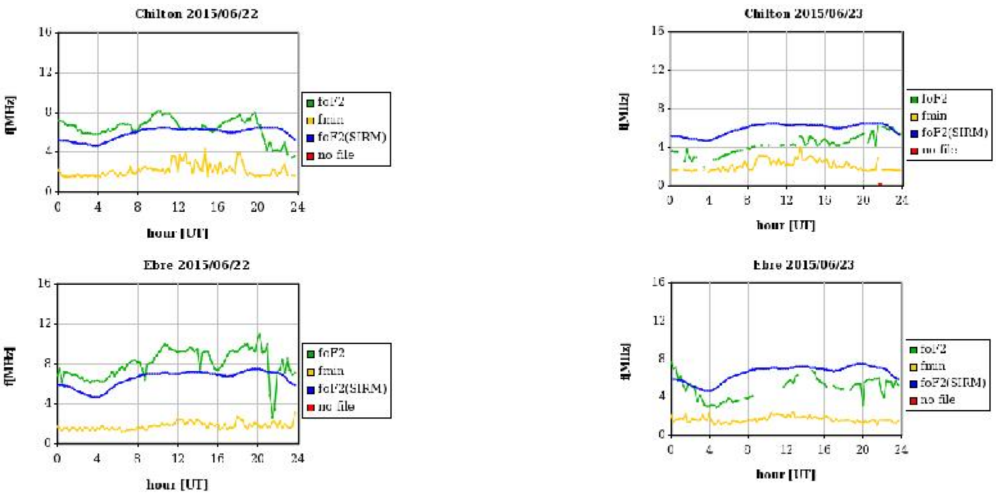


Figure 2: The daily plots of the foF2 critical frequency provided by the DIAS system for Chilton (UK) and Ebre (Spain) locations. Ionization increases (positive storm effects) and decreases (negative storm effects) are apparent over Europe during the storm onset and main day, respectively. The predictions of the SIRM model are also provided as representative of the ionospheric reference level. SIRM is used in EIS for the generation of the foF2 long-term prediction maps. The comparison between actual or forecasted conditions and SIRM predictions provides an estimate of the magnitude of the ongoing or expected ionospheric disturbances.

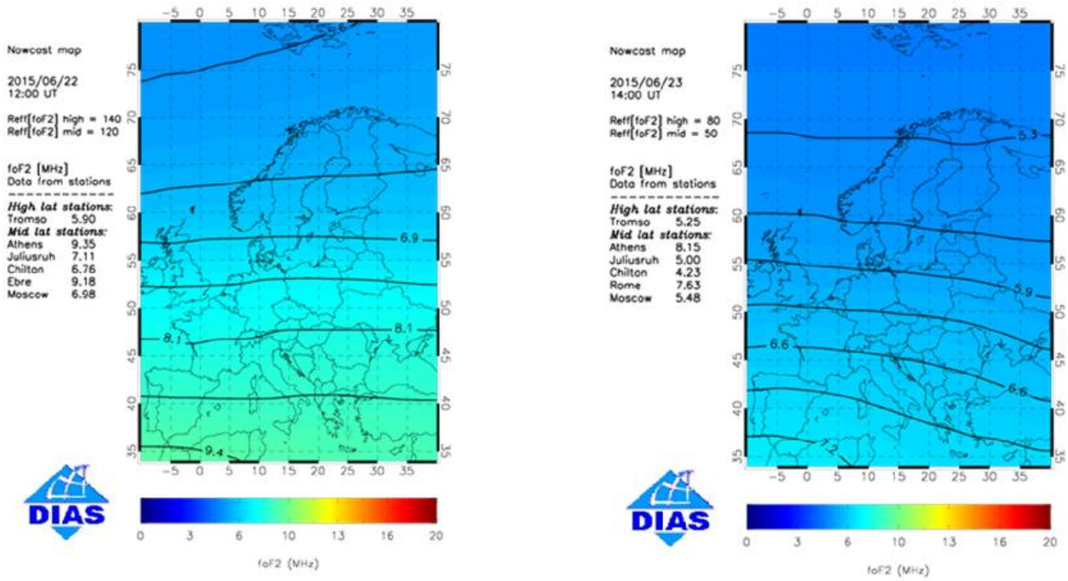


Figure 3: EIS nowcasting regional maps of the foF2 critical frequency generated on 22 June 2015, 12:00 UT (left) and 23 June 2015, 14:00 UT (right). Positive and negative storm effects are also apparent here on June 22 and June 23, respectively. The legend on the left of each map informs the users that the generation of the maps is based on data from 5 stations in the mid-latitudes (Athens, Juliusruh, Chilton, Ebre, Moscow) and from one station in the high latitudes (Tromso), indicating nowcasting estimates of significant reliability (*Belehaki et al.*, 2015).

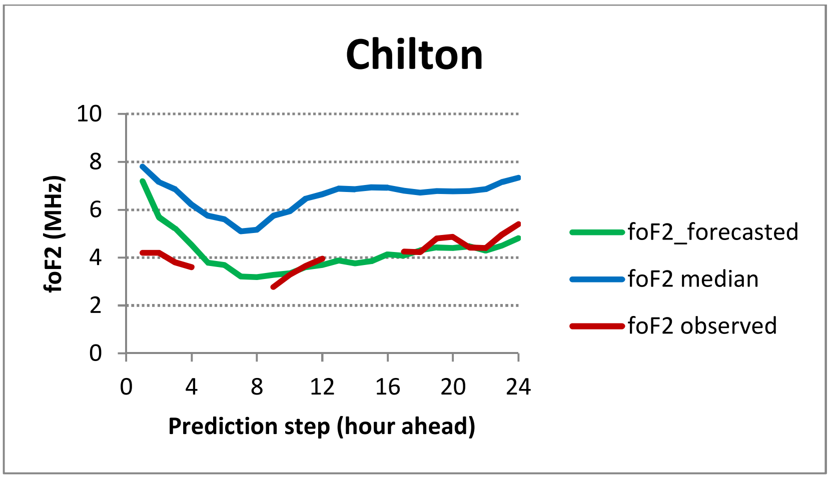


Figure 4: The single site 24-hour forecasts of the foF2 issued by EIS for Chilton location on 22 June 2015, 20:00 UT. The plot was reproduced here to include actual measurements of the foF2 for comparison purposes.

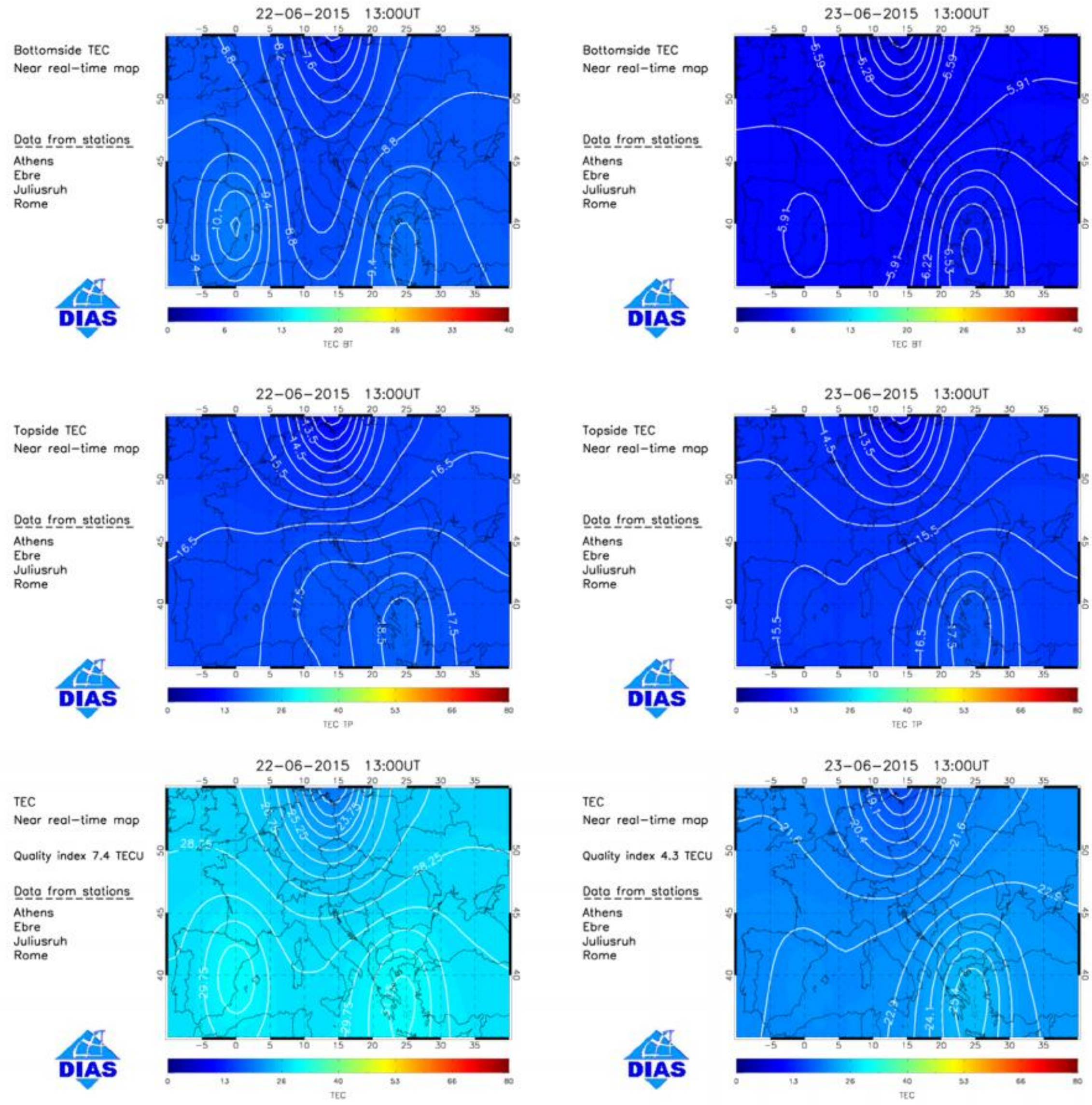


Figure 5: EIS near real-time TEC maps for the European region generated on 22 and 23 June 2015, at 1300 UT: bottomside TEC is the integrated electron density from 90 km to the hmF2 altitude; topside TEC is the integrated electron density from the hmF2 altitude up to the O+/H+ transition height; total TEC is the integrated electron density from 90 km up to 20,000 km. The generation of the maps is based on data from only 4 stations (Athens, Ebre, Juliusruh, Rome), which is the minimum number of stations required for the generation of the map. All other stations of the EIS network were not transmitting data at the specific time. As a result, the quality index ranges from 4.3 to 7.4TECu, indicating deviations between the modelled and the corresponding EUREF maps. However, the maps are still representative of the overall disturbance due the ongoing geomagnetic storm.

While the TEC over Europe mapped at 13:00 UT on 23 June 2015 shows clear signs of ionization decrease over the area in respect to the same representation taken the previous day, inspecting the maps of the partial TEC along the bottomside and topside parts of the electron density profile, we conclude that the decrease is mainly due to ionization changes in the bottomside ionosphere.

3. CONCLUSIONS AND OUTLOOK

EIS offers unique services for ionospheric propagation and for nowcasting trans-ionospheric conditions which are useful for GNSS, radio applications and satellite operators and designers. Table 2 summarizes key concepts of the EIS products in comparison to the users' needs. Further developments are possible driven by the users' requirements. Preliminary considerations apply to:

- Improved forecasting algorithms for ionospheric disturbances: in its present form, the SWIF model predicts mainly ionospheric foF2 disturbances driven by CME-associated structures at L1 point. Improvements include the consideration of the effects of solar flares [*Kontogiannis et al.*, 2016] and high-speed solar wind streams [*Tsagouri and Belehaki,* 2015], but also the expansion of the models' capabilities in forecasting the TEC storm-time response [*Tsagouri et al.,* 2017].
- New algorithms for the identification of travelling ionospheric disturbances based on the measurement of angle-of-arrival, Doppler frequency, and time-of-flight of ionospherically reflected high-frequency (HF) radio pulses exploiting the capabilities of modern ionosondes DPS4D [*Reinisch et al.,* 2017].
- Improved 3D electron density distribution models to trace the variation of the electron density along any arbitrary orbit in space which is a specific request of satellite operators [*Kutiev et al.*, 2016].

Table 2: Discussion of the EIS products in comparison to the users' needs.

Users' needs	**EIS products**
Transionospheric radio link	
Estimation of ionospheric disturbance for ionospheric and trans-ionospheric propagations	Long-term predictions of foF2, which corresponds to background ionospheric conditions and short term forecasts.
Near-real time estimate of ionospheric and trans-ionospheric propagation conditions	*Bottomside:* maps of foF2 and maps of the integrated electron content at the bottomside (bottomside TEC). *Topside:* maps of the integrated electron content at the topside (topside TEC) and at the plasmasphere (plasmaspheric TEC).
Real-time TEC maps to estimate high level description of the state of the ionosphere	Maps of TEC in near-real time by EIS.
Spacecraft Operation	
Knowledge of the uncertainties caused by the ionosphere at least 1 hour in advance	foF2 forecasts for the next 24 hours and the mean relative error of the model for selected locations.
Forecast and near real-time assessment of the effects of ionospheric disturbances	EIS forecasting and nowcasting products for foF2, partial TEC and TEC.
Altitude dependent TEC maps for ionospheric correction for satellites with a single frequency GNSS receiver	Near real-time altitude dependent TEC maps for the bottomside, the topside ionosphere and the plasmasphere. Upon user request the altitude of the TEC maps can be modified depending on the specific application requirements.

Forecasts with estimates of probability of occurrence of space weather events and of "All quiet conditions"	EIS provides alerts for forthcoming ionospheric disturbances mainly triggered by geo-effective CMEs. As soon as an alert is issued, the user is able to know the expected magnitude of the ionospheric disturbance over Europe, while at the same time short term ionospheric forecasts can provide the local forecast for the next 24 hours with the model error.
Spacecraft Design	
Estimate of the environment and its effects actually experienced	Services upon request: statistical data regarding the foF2 variability, and the altitude dependent TEC data over the locations of the DIAS stations

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