SPACE WEATHER EFFECTS ON COMMUNICATIONS

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Keywords

Ionosphere; Ionospheric monitoring; Ionospheric nowcasting; Ionospheric forecasting; Ionospheric mapping; Total Electron Content; Electron Density Profile; satellite operations; GNSS systems; topside ionosphere; plasmasphere; HF communications; trans-ionospheric propagation; space weather

Abstract

Knowledge of the state of the upper atmosphere, and in particular its ionized part, is very important in several applications affected by space weather, especially the communications and navigation systems that rely on radio transmission. To better classify the ionosphere and forecast its disturbances over Europe, a data and model infrastructure platform called the European Digital Upper Atmosphere Server (DIAS) has been established in the National Observatory of Athens by a European consortium formed around eight ionospheric stations, and funded by the European Commission.

The DIAS system operates since 2006 and the basic products that are delivered are real-time and historical ionograms from all DIAS ionospheric stations, frequency plots and maps of the ionosphere over Europe based on the foF2, M(3000)F2, MUF and electron density parameters, as well as long term and short term forecasting up to 24 hour ahead. The DIAS system supports more than 500 subscribed users from all over the world, including NOAA and ESA (SWENET). The system is currently under major upgrade in the frames to make available also maps of the electron density at user-defined heights up to GNSS orbits, and TEC and partial TEC maps over Europe updated in real-time.

The report presents the current status of DIAS, and summarizes the upgrades that are under implementation to release additional products and services aimed at supporting HF users, satellite operators, space agencies, research organizations and the space weather scientific community.

Introduction

Communications at all frequencies are affected by space weather. During periods of high solar activity, the ionosphere is strongly affected by flares which cause disruptions to radio signals, including the Global Positioning System, GLONASS and Galileo (GNSS). In some cases, solar radio bursts directly interfere with GNSS signals; in other cases, ionospheric irregularities cause strong scintillations disrupting radio signals from satellites.

Operational systems that characterize ionospheric conditions over Europe and predict space weather effects on communications, support mainly HF communication users making available parameters of the bottomside ionosphere, and trans-ionospheric propagation users with maps of Total Electron Content (TEC). The later represents height-integrated electron density from the surface to the GNSS satellites around 20000 km altitude. However, the successful operation of many space activities relying on trans-ionospheric propagation requires accurate estimates of the total electron content between the spacecraft and some location on the surface of the Earth – and in some cases between two spacecraft. For many space activities we must partition GNSS TEC above and below the spacecraft in order to derive the TEC applicable to a particular activity.

Therefore, there is a clear need to enhance current nowcasting and prediction capabilities and make available, in addition to what exists today, the whole range of information for the electron density distribution from the bottomside of the ionosphere up to the plasmapause.

The DIAS system

The European Digital Upper Atmosphere Server (DIAS) [1] is one of the few operating systems developed by European teams that characterise the ionosphere over Europe. The system collects data files from ionosondes, homogenise and analyse the data in real time and based on empirical models calculates and releases products and services for nowcasting and forecasting ionospheric conditions over Europe (Belehaki et al., 2005; 2006a; 2007). The system operates by the National Observatory of Athens continuously since 2006 and has registered more than 500 users, among them, telecommunication companies, broadcasting organizations, space agencies, radio amateurs, academic and research institutions, and civil protection agencies. Among them, ESA and NOAA are systematic users of the system.

Currently DIAS services are based on data acquired from 8 European Digisondes: Athens, Rome, Ebre, Arenosillo, Chilton, Juliusruh, Pruhonice, Moscow, with a transmission rate of 15 min.

The basic products already available are listed below:

- Real-time ionograms from the contributing DIAS stations in a common format
- Daily values and plots of scaled ionospheric parameters, e.g. the critical frequency of the F2 layer (foF2), the lowest frequency reflected by the ionosphere which appears on the ionogram (fmin), the ratio of the maximum reflected frequency from the F2 layer over a 3000km range to the critical frequency of the layer (M(3000)F2), etc.
- Profiles of the electron density versus height up to hmF2, over each contributing DIAS ionospheric station
- Nowcasting regional maps showing the variation of relevant ionospheric parameters over the European area middle latitudes (i.e. maps of foF2, M3000F2, Maximum Usable Frequency (MUF), based on SIRMUP model (Zolesi et al., 2004)
- Nowcasting regional maps of the electron density (Ne) for the European middle latitudes at pre-selected heights up to 450 km

[1] The DIAS portal is currently functioning in the address http://hertz2.space.noa.gr:8080/LatestDias2/homePageMin.jsp. After the completion of the upgrades, normal operation will be resumed in the portal http://dias.space.noa.gr

- Daily plots of the Effective Sunspot Number, Reff (Houminer et al., 1993), which give estimates of the best fit between the Simplified Ionospheric Regional Model – SIRM (Zolesi et al., 1993) and the foF2 measurements from the DIAS sounder grid
- Forecasted foF2 values for the next 24 hours over each DIAS station. These values are based on the SWIF (Tsagouri and Belehaki, 2008) and on the GCAM (Muhtarov et al., 2002) models
- Maps of the forecasted foF2 parameter over Europe for the next 24 hours, based on SWIF and GCAM models, for the European middle latitudes
- Point to point calculation of the MUF for user-defined coordinates
- Activity Index for foF2 providing specifying current ionospheric conditions over European middle latitudes
- Alert for the forthcoming ionospheric disturbances in the European sector based on the Alert Algorithm of the SWIF model, which processes in real-time the ACE interplanetary magnetic field data at L1 point.

Some samples of DIAS products are presented in Figures 1 to 5.

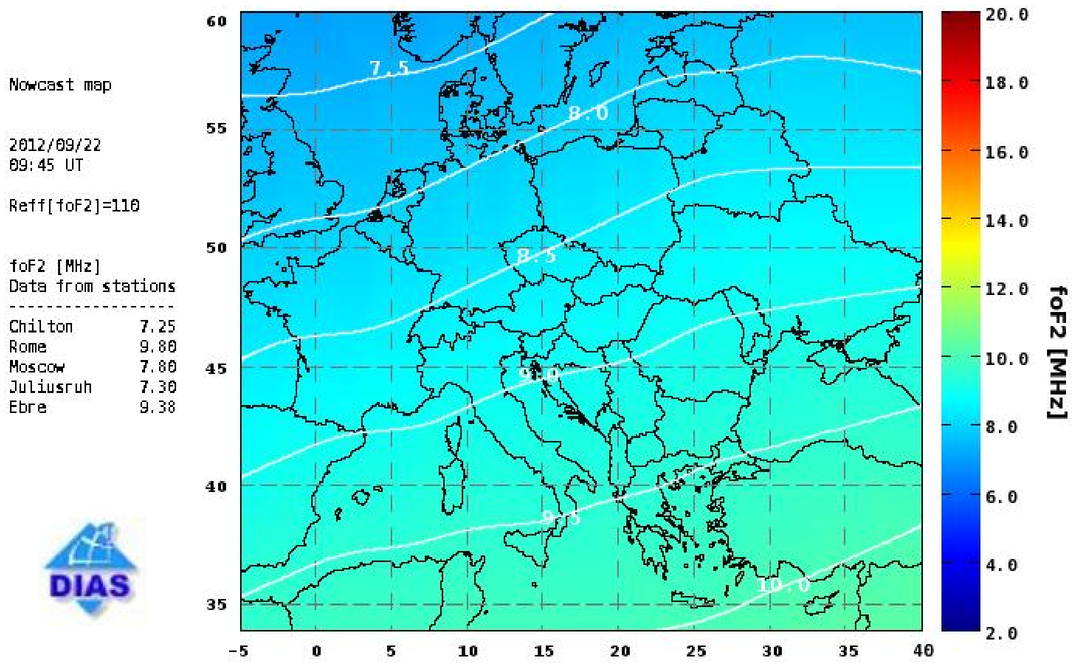

Figure 1: An example of a regional foF2 nowcasting map on 22/9/2012 at 09:45 UT which has been generated using the ionospheric data from the DIAS sounders, based on the SIRMUP model. The estimated value of the effective sunspot number as well as the real-time values of the foF2 parameter observed from the DIAS stations are given on the left hand side.

DIAS upgrades

The system is keeping analytical statistics for the usage of the various products. Statistical results show a systematic shifting of users' preference from the ionograms to the electron density maps. Based on this, and in an effort to support more efficiently our users, we have planned a major upgrade of the system in order to release products that best meet their needs, i.e. 3D maps of the electron density up to the plasmaspheric heights and the corresponding TEC maps over Europe.

It was a fortunate coincidence that at the same period, the DIAS system was selected as one of the federated services to support the pilot phase of the Space Situational Programme of the European Space Agency, and this facilitate our plans and systematize our efforts. The DIAS upgrade consists on the ingestion of data from additional ionosonde sounders in Europe (including non-Digisonde stations) and from other types of instruments, like RINEX files from GNSS receivers co-located with the sounders. In addition the following algorithms are implemented into the system for the calculation of the new products:

a) The upgraded algorithm for foF2 mapping to cover higher European latitudes

b) The TaD algorithm that produces the 3D electron density distribution and the TEC maps over Europe.

The following methodology is adopted:

Upgraded foF2 mapping algorithm for nowcasting ionospheric conditions over Europe

The Simplified Ionospheric Regional Model Updated in real-time (SIRMUP) provides immediately updated nowcast maps of the ionosphere over Europe (Zolesi et al., 2004).

The SIRMUP is based on the Simplified Ionospheric Regional Model (SIRM), which is then updated with real-time ionospheric observations to produce now-casting maps over Europe. SIRMUP operates by using real-time automatic scaled foF2 and M(3000)F2 data from the DIAS ionosondes to generate new driving parameter of the SIRM, the effective sunspot number (Reff), calculated by a method described by Houminer et al. (1993). The new Reff is chosen as the value that gives the best fit between the SIRM model output and the actual measurements obtained from the ionosondes located in the mapping area. The final outputs from the SIRMUP now-casting method are maps of foF2 and M(3000)F2 covering the European area from -5^{o}W to 40^{o}E in longitude and 34^{o}N to 60^{o}N in latitude.

For this upgrade, the maps of the foF2 will be extended to the high latitudes based on the following methodology:

- The climatological model SIRM will be applied to the northern extended regions to obtain extended long term prediction maps. To extend SIRM, we will use CCIR coefficients.
- Considering that the hourly foF2 conditions at high latitudes may be affected by the so called trough behavior, the performances of SIRMUP in this area must be tested. Maps drawn by using Reff calculated from mid latitudes stations are not so sensitive to this behavior. Therefore as a first approach the real-time update SIRMUP technique will be applied only to the high latitude zone.
- Tests should be done by using different sets of ionospheric stations to verify if it is necessary to introduce two R12eff, one for northern and another one for central and southern Europe.

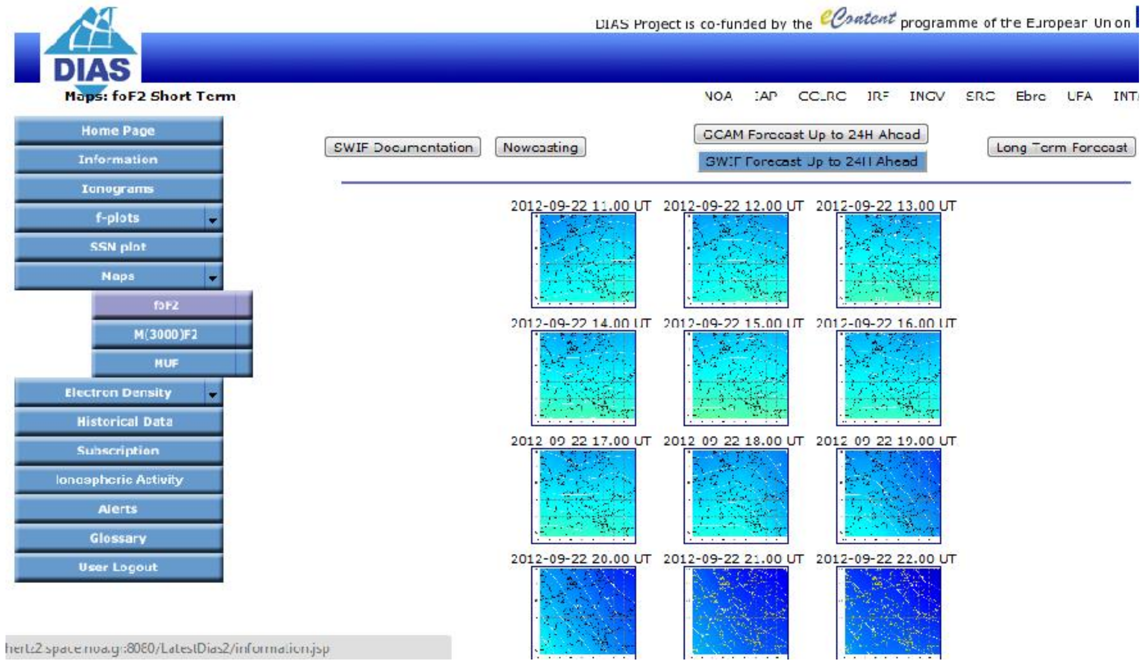

Figure 2: A screen shot from the DIAS portal, showing the calculated maps of foF2 forecasts for the next 24 hours. Predictions are calculated with the SWIF model (Solar Wind Driven Ionospheric Forecast) and for the mapping the SIRMUP model is applied. SWIF forecasts are updated hourly.

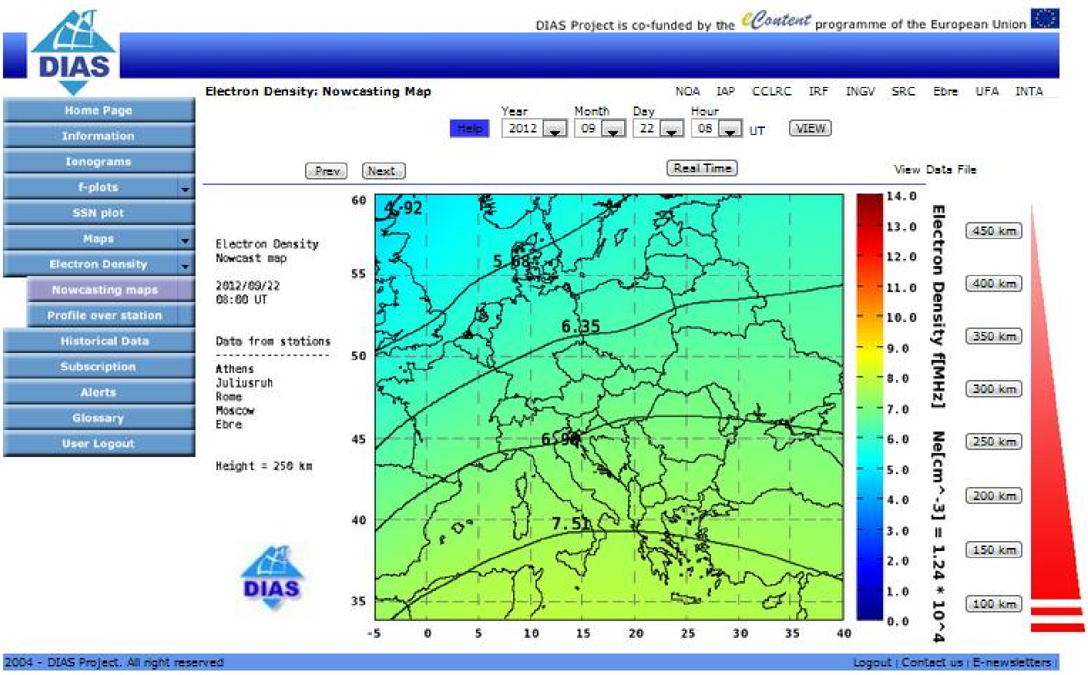

Figure 3: A screen shot showing the map of the electron density at the height of 250 km is given in the figure above.

Ionospheric Storm		2012	05	Issue Time: 2012-04-23 14:00:00 (UT)
DIAS Location	Forecasted Onset (UT)	Forecasted Duration (hours)	Forecasted Maximum Deviation from Median (%)	Ionospheric Storm Effect
Athens	2012-04-23 19:00:00	23	-50	negative
Chilton	2012-04-23 19:00:00	38	-46	negative
Juliusruh	2012-04-23 18:00:00	38	-46	negative
Moscow	2012-04-23 18:00:00	38	-46	negative
Rome	2012-04-23 20:00:00	23	-50	negative
Ionospheric Storm		**2012**	**04**	**Issue Time: 2012-03-09 02:00:00 (UT)**
DIAS Location	Forecasted Onset (UT)	Forecasted Duration (hours)	Forecasted Maximum Deviation from Median (%)	Ionospheric Storm Effect
Athens	2012-03-09 04:00:00	17	26	positive
Chilton	2012-03-09 07:00:00	27	-41	negative
Juliusruh	2012-03-09 10:00:00	25	-36	negative
Moscow	2012-03-09 14:00:00	25	-36	negative
Rome	2012-03-09 04:00:00	17	26	positive

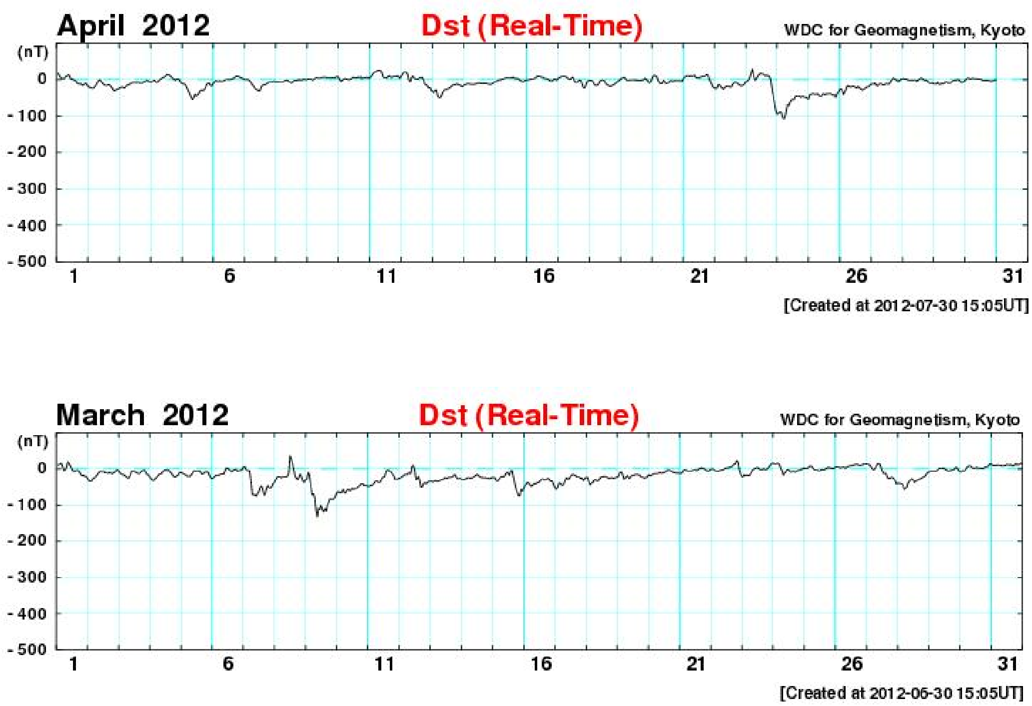

Figure 4: An example from two alerts reports released from DIAS in 2012, with the corresponding recordings of the Dst index.

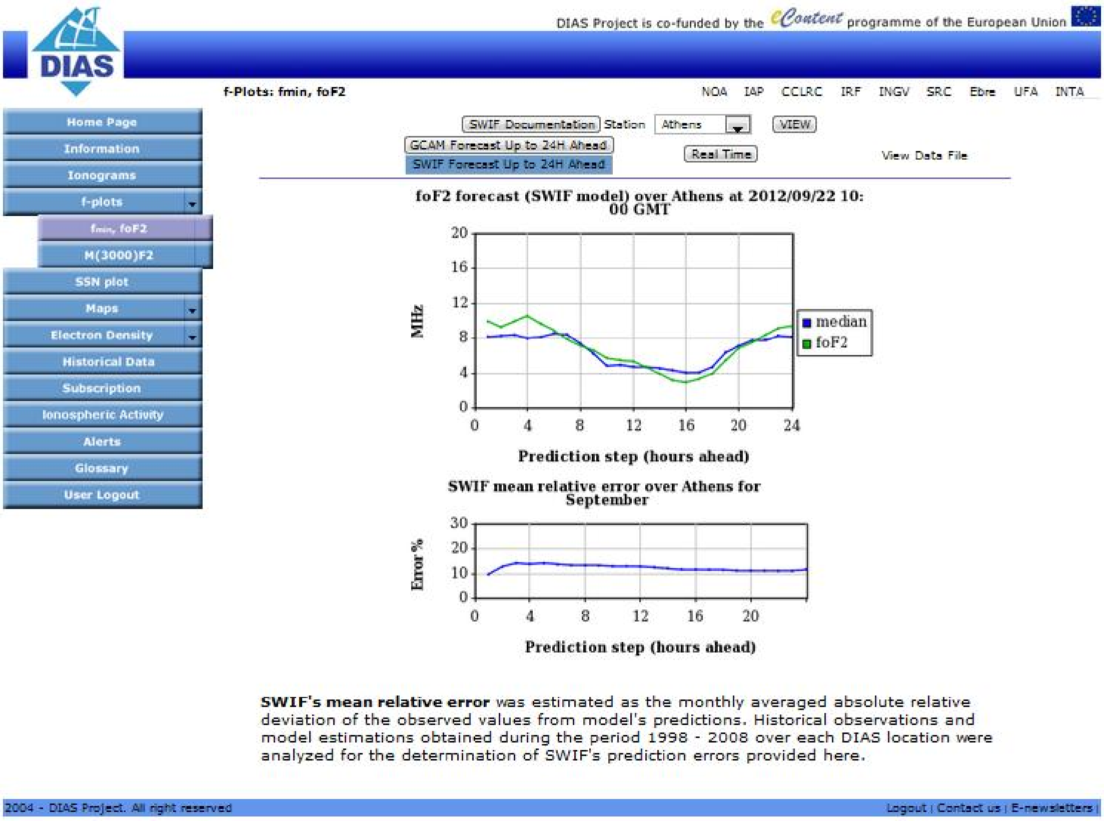

Figure 5: In the screenshot above we present an indicative example of the foF2 forecasts for the next 24 hours over Athens based on the SWIF model with the mean relative error for each prediction step.

TaD algorithm for the development of near real-time TEC maps

The TaD algorithm is based on the empirical model for the O^+- H^+ transition height (h_T), the topside electron density scale height (H_T) and their ratio $Rt=H_T/h_T$, named Topside Sounder Model (TSM) based on the Alouette/ISIS database, that has been developed few years ago by Kutiev et al. (2006). A first verification has been completed through the comparison with the CHAMP scale height (Belehaki et al., 2006b). To further increase the TSM accuracy, Kutiev et al. (2009a;b) offered analytical formulas for obtaining the shape of the vertical plasma distribution in the topside ionosphere and plasmasphere based on TSM parameters. This profiler models separately the O^+ and H^+ density profiles. To obtain the density distribution, the profiler needs specification of the F layer maximum density (NmF2), its height (hmF2) and its scale height (Hm) at its lower boundary. Therefore, to improve the operational capabilities of this profiler, Kutiev et al. (2009b) and Belehaki et al. (2009a) adjusted the algorithm to ingest Digisonde measurements for the reconstruction of the electron density profile from the F layer peak to GNSS orbits (TaD model). A new expression of H^+ scale height in the plasmasphere was extracted from ISIS-1 topside sounder data, as a function of geomagnetic latitude.

Further improvements of the TaD scaling technique were based on the calculation of O^+, H^+, and He^+ density distributions in transition region between topside F region and plasmasphere, extracted from the analysis of the electron density profiles from ISIS-1. This yield a more reliable determination of important scale height parameters (O^+, H^+, and He^+) and transition height. Finally improvements of the TSM profiler formulation yielded to achieve optimization of the TaD algorithm. The main model expressions were revised to include He^+ distribution as a function of geomagnetic latitude and local time (Belehaki et al., 2012). A systematic validation of the new profiler using Topside and ISR Electron Density Profiles (EDP), TEC and partial TEC parameters, demonstrated reduction of the model error 2.25 times in comparison to the previous version of the TaD model. Validation of the model results based on comparison with ISIS-1 EDP shows clearly the model's ability to reproduce with impressive accuracy the ISIS-1 EDP (98.8%). Systematic comparison between the O^+ distribution of TaD and measured EDP from the Malvern ISR gave a mean RMSE of 12%, including cases where the transition height was above 700 km and this forced the model to give artificial results (Belehaki et al., 2012). The comparison between the TaD-TEC with the corresponding GNSS-TEC gave a model error of 3TECU which is close to the measurement (GNSS) error. These results clearly demonstrate the ability of the TaD model to be implemented operationally to provide in real time the analytical function of the electron density distribution over specific locations. Lately TaD was further adjusted using TEC measurements from GNSS receivers co-located with Digisondes; comparison of modelled TEC extracted from the TaD model and from the TEC adjusted version shows significant improvement (Kutiev et al., 2012).

For the implementation of the TaD algorithm, the following methodology is adopted:

- Application of the TaD reconstruction algorithm over each DIAS ionospheric station location. This will provide the reconstructed electron density profile over the station. As an example we show in Figure 6 the application of TaD in Athens Digisonde location.
- Mapping of the basic parameters required to calculate TEC based on TaD. These parameters are Hp, hT, Hm, hmF2 and foF2.
- Based on the individual maps we can reproduce TEC maps over Europe applying the Kriging interpolation, or the Polynomial-weighted interpolation.

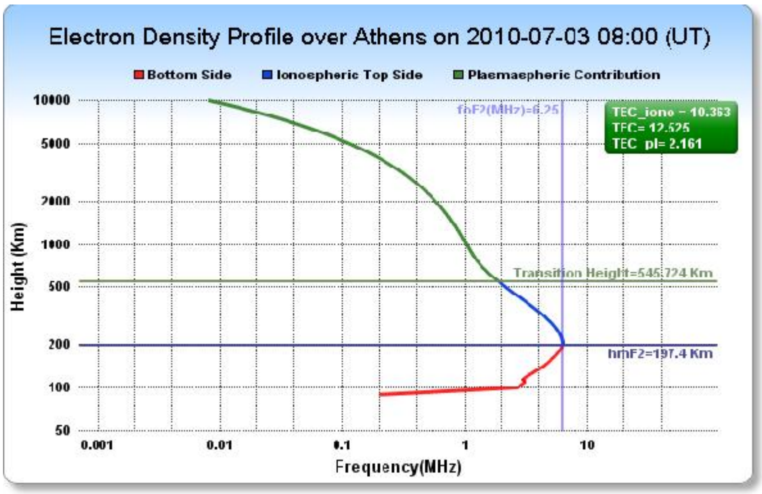

Figure 6: An example of reconstructed electron density profile over Athens Digisonde applying the TaD model. Red line corresponds to Digisonde bottomside reconstructed profile. The topside is extrapolated with TaD algorithm. The blue part corresponds to the topside and the green part to the plasmasphere. It is possible with this analytical approach to calculate partial TEC that corresponds to the topside and to the plasmaspheric part.

Conclusions and future plans

DIAS system operates as a prototype since 2006 and the number of users is continuously increasing. Statistical results of the system usage are indicative of the needs of the users and show users' demands for adjustments, therefore could be used as a performance indicator. Other factors that should be considered are the reliability of the operation and the accuracy of the products.

Reliability basically relies on the continuous streaming of datafiles from the stations and this is the responsibility of the institutes that operate the monitoring stations. Of course reliability depends also on the functionality of the IT system that supports the operation of DIAS should be also monitored. Therefore we are planning to use the Nagios software to monitor all critical services running in DIAS back-end engine and restore any possible problems within the next working day, if possible.

The accuracy of the products is the third factor that should be considered. Accuracy should be tested through a systematic validation process which will concern:

i. determination of the accuracy of the algorithms under all possible conditions (quiet and disturbed);
ii. verification of the operational validity of the implemented algorithms;
iii. calculation of the necessary metrics to monitor the service outputs.

In summary, DIAS is a Europe-wide project aimed at the collection of ionospheric observations from European ionosondes and the development of added-value products for radio propagation services. The major strength of DIAS is that it can easily integrate new sets of observations from other areas around the world, it can be easily updated by newly developed models, and it can follow the latest technological advances. These are the elements that will enable the evolution of DIAS services over the next years and into the future. In the near future, DIAS could posibly expand its services through collaboration with existing ionospheric service providers on other continents, improving the accuracy for the worldwide specification of the ionosphere, and contribute to the development of more accurate products to support communications for all space weather conditions.

Acknowledgements: Thanks are due to the data providers Jens Mielich (Juliusruh Digisonde), Dalia Buresova and Jan Lastovicka (Pruhonice Digisonde), Bruno Zolesi (Rome Digisonde), David Altadill Felip (Ebre Digisonde), Mike Hapgood (Chilton Digisonde), Andrei Mikhailov (Moscow Digisonde) and Benito de la Morena (El Arenosillo Digisonde). Many thanks are due to Ivan Kutiev, Pencho Marinov, Bruno Zolesi and Ioanna Tsagouri for the long and successful collaboration that led to the development of the DIAS nowcasting and forecasting algorithms. The upgrade of the DIAS system is implemented with support received from EOARD Award FA8655-12-1-004 and from ESA SSA SN IV-3 project.

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Biographies

Anna Belehaki received a Ph.D. on Space Physics in 1992 from the National and Kapodistrian University of Athens and immediately after, she joined Prof. Gordon Rostoker's group in the Canadian Network for Space Research of the University of Alberta in Canada as post doctoral fellow. In 1995 she was elected in a research position in the National Observatory of Athens and since 2007 she is research director and head of the Ionospheric Group. Anna Belehaki has a long term experience on ionospheric experiments and monitoring techniques, on space weather prediction and forecast models for ionospheric effects, on the development of operational space weather services and on the study of solar wind-magnetospheric-ionospheric interactions for the modeling of the topside ionosphere and the plasmasphere. Anna Belehaki is the PI of the Athens Digisonde project, coordinator of the DIAS project (the European Digital Upper Atmosphere Server, funded by the EC, eContent Programme) and scientific manager of the ESPAS project (Near-Earth Space Data Infrastructure of e-Science, funded by the EC, FP7-eInfrastructures). She is the chair of the Management Committee of the COST Action ES0803 "Developing Space Weather Products and Services in Europe", a network among 26 countries where 85 experts from all over the world participate. From 2009 to 2012 she is co-chairing the European Space Weather Weeks. She has published more than 70 papers in peer review international scientific journals and participated to more than 120 scientific conferences. In 2010 together with the core group of COST Action ES0803 she established the Journal for Space Weather and Space Climate – SWSC, for which she is serving as Editor in Chief.