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Abstract (for dissemination)
This report examines how real-time data currently provided by a number of digital ionospheric sounders operated by institutes in the DIAS consortium, can be efficiently used for regional area services and recommends added value products of particular interest for a variety of users. It concentrates on the design and development of competitive added value products, better adapted to the needs of the world market than those currently existing, and based on the raw digital ionospheric data. The DIAS added value products and services are fully specified taking as input: (a) The state of the art report, analysing the operation and the products delivered by systems similar to DIAS operated worldwide and (b) A preliminary user needs assessment, defining the types of data and added value products of maximum value to the potential DIAS users.

European Digital
Upper Atmosphere Server

DIAS

DIAS D3.1
Report on the specification of added value products

by

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1. Introduction

The physical parameters of the near-Earth space plasma affect the way radio waves reflect from or pass through the ionosphere. The temporal (sunspot cycle, season and time of day) and spatial (polar and auroral zones, mid-latitudes and equatorial regions) variation in terrestrial ionospheric structures additionally aggravates the efforts of communications, navigations and radar system operators who base their frequency planning decisions on long-term predictions and frequency management decisions on short-term forecasting of radio propagation conditions. These conditions allow waves with frequencies in the high-frequency (HF) band and below to propagate from ground-to-ground over very long distances, and influence quite significantly the ground-to-space and space-to-ground propagation of radio waves of higher frequencies. Having in mind that one of the main applications for the real-time data currently provided by a number of digital ionospheric sounders around the world is to manage the operation of radio channels and networks, this report examines how they can be efficiently used for regional area services and recommends added value products of particular interest for a variety of users (Belehaki et al., 2005a).

It concentrates on the design and development of competitive added value products, better adapted to the needs of the world market than those currently existing, and based on the raw digital ionospheric data provided by the European digital ionosondes operated by institutes in the DIAS consortium. Digital content as well as the required methods for the production of competitive added value products are fully specified here taking as input: (a) The state of the art report, analysing the operation and the products delivered by systems similar to DIAS operated worldwide (Belehaki et al., 2005b) and (b) A preliminary user needs assessment, defining the types of data and added value products of maximum value to the potential DIAS users.

There are two classes of basic data product of value to most users of DIAS:

- Ionograms: the raw outputs from the ionosondes that can be interpreted and analysed by scientific and expert commercial users. Making them available gives a degree of transparency to the DIAS system, since all the additional modelling and forecasting products depend ultimately on this raw data.
- Scaled parameters: since ionospheric sounding began it has been customary to scale off specific numbers from ionograms to summarise the features of interest. These are of continuing value and are often fed into models and prediction systems.

There are also three classes of added value product that are essential for DIAS ionospheric propagation predictions users:

- Long term ionospheric predictions: these supply information about the ionosphere for a particular epoch of solar activity and can be used for planning radio systems operations. Ultimately, their success depends on improvements in forecasting long term solar activity.
- Ionospheric specification in real-time: these are used for management of radio services in near real-time. This ionospheric now-casting makes use of the real time observations to show the geographical and temporal variations of the ionospheric parameters.
- Short term ionospheric forecasting: forecasting of ionospheric conditions over periods from hours to a few days ahead, for the purpose of management of radio services. These forecasts can be based on extrapolation of past data sets, forecasting of a short-term disturbance index on which the ionosphere critically depends and monitoring of solar-terrestrial parameters.

This report discusses each of these DIAS products in detail.

2. Ionospheric data

The ionosphere is that part of the upper atmosphere where ions and electrons of thermal energy are present in sufficient quantity to have a considerable influence on the propagation of radio waves. The ionization of the neutral atmospheric constituents is caused by the solar electromagnetic and corpuscular radiations and its structures vary greatly not only with time and location but also with certain solar-terrestrial related ionospheric perturbations. The most important technique for monitoring the ionospheric regions, ionospheric sounding, makes use of the propagation of radio waves by measuring all of these observable parameters at a number of discrete heights and discrete frequencies to map out and characterize the structure of the plasma in the ionosphere. The principle of ionospheric sounding is to transmit pulses of radio waves vertically from lower to higher frequencies (up to 20 MHz) and to measure the time which elapses before the echo is received. The resulting measurement is called an ionogram with sounding frequency as the abscissa and virtual reflection height (working out on the assumption of a constant velocity throughout) as the ordinate. An example is given in Figure 1. These echoes form characteristic patterns of "traces" that are scaled, manually or automatically (URSI Handbook, 1972).

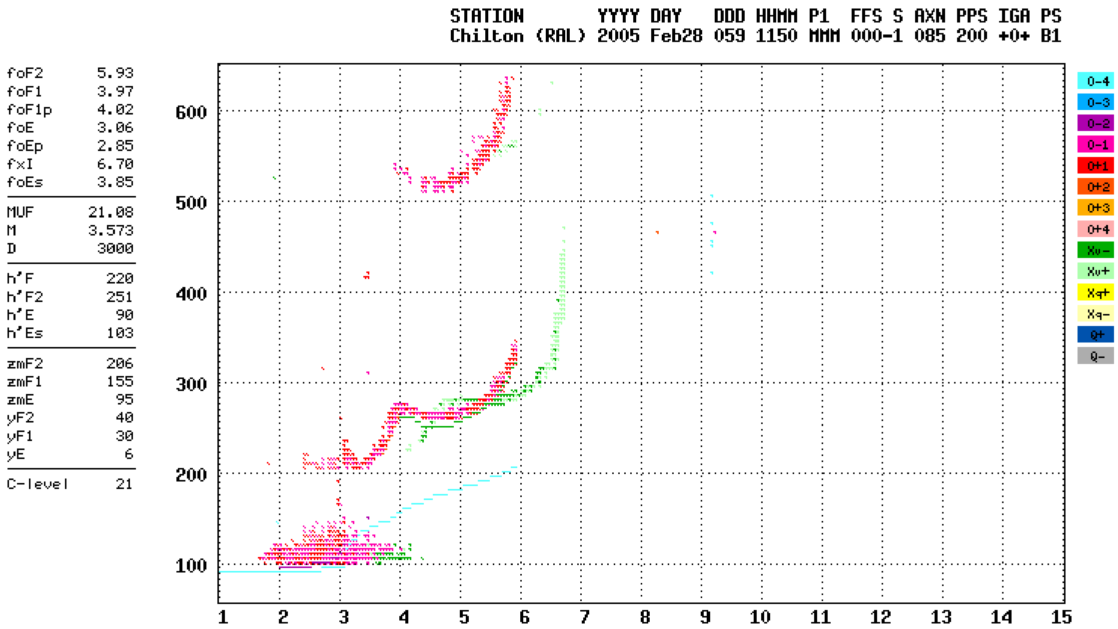


Figure 1. Typical day time ionogram with automatically scaled ionospheric data (from http://www.wdc.rl.ac.uk/cgi-bin/digisondes/cost_database.pl).

The resulting structure is traditionally divided into four broad regions called D, E, F, and topside. These regions may be further divided into several regularly occurring layers, such as Es, F1 or F2. The D region covers altitudes between about 75 and 95km where relatively weak ionization is mainly responsible for absorption of high-frequency radio waves. The E region is a solar-controlled ionospheric region between about 95 and 150km altitude that marks the height of the regular daytime E-layer. Other subdivisions, isolating separate layers of irregular occurrence within this region, are also labeled with an E prefix, such as a highly variable thin layer, the sporadic E layer Es. Ions in this region are mainly O_2^+ and NO^+. The F region is the region above about 150km in which the important reflecting layer, F2, is found. Other layers in this region are also described using the prefix F, such as a temperate-latitude regular stratification, F1. Ions in the lower part of the F-layer are mainly NO^+ and are predominantly O^+ in the upper part. The F-layer is the region of primary interest to radio communications.

The topside part of the ionosphere starts at the height of the maximum density of the F2 layer and extends upward with decreasing density to a transition height where O^+ ions become less numerous than H^+ and He^+. The transition height varies but seldom drops below 500km at night or 800km in the daytime, although it may lie as high as 1100km. Above the transition height, the weak ionization has little influence on radio signals. Note that the topside cannot be explored by ground-based ionosondes because it is effectively hidden by the F2 layer peak. Consequently, all of the DIAS products concentrate on the bottomside ionosphere extending up to the F2 layer but not higher.

2.1 Ionograms

Automatic scaling of ionogram enables direct transfer ionosonde data using the Internet. Starting in 1987 IIWG of the International Union of Radio Science (URSI) Commission G has developed recommendations for the data formats to be used for dissemination and archiving of scaled ionogram data and for the monthly ionospheric characteristics in terms of the Standard Archiving Output (SAO) format. Each SAO (text) file contains the scaled data for one ionogram including the echo traces h'(f), echo amplitudes, frequency and range spread, etc. and the electron density profile. Making the SAO files available to users, together with plots such as that shown in Figure 1, would give users the ability to interpret the raw data directly.

2.2 Ionospheric characteristics

Most ionograms contain an immense amount of information about the conditions in the ionosphere. Ionospheric characteristics usually scaled from ionograms include, among others, critical frequencies (foE, foF1 and foF2), virtual heights (h’E, h'F, and h'F2) and propagation factors (M(3000)F2 and MUF (3000)F2) of each layer as shown in Figure 2.

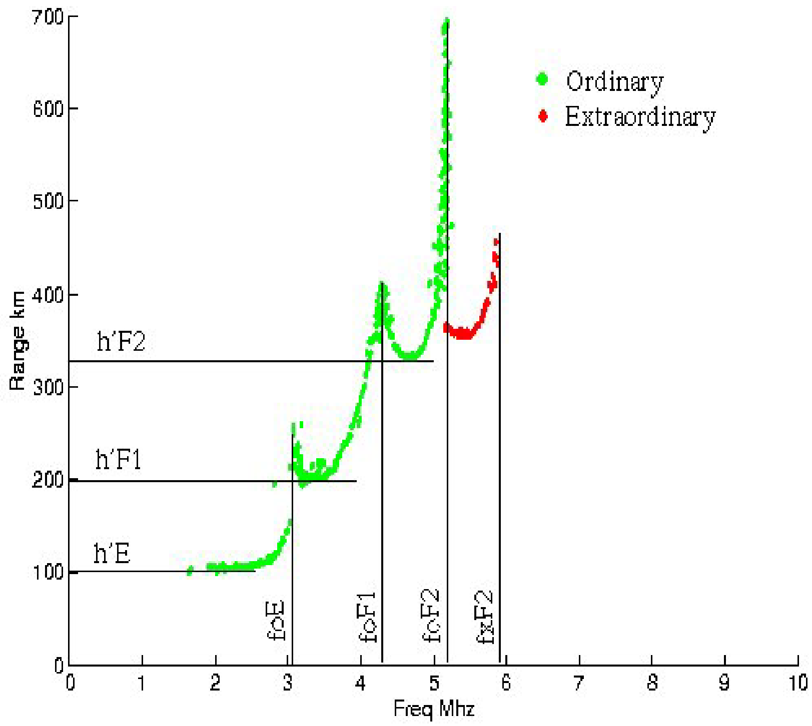


Figure 2. Critical frequencies and virtual heights as defined from ionograms (from http://www.eiscat.rl.ac.uk/dynasonde/ionogram.html).

The critical frequency of a layer is the highest frequency at which the layer reflects and transmits equally. The minimum virtual height is the height at which the trace is horizontal.

The Maximum Usable Frequency (MUF) is defined as the highest frequency for ionospheric transmission over an oblique path for a given radio system performance.

The f plot is a daily graph of the frequency characteristics of the traces of the ionograms as a function of time (Figure 3). In principle, any frequency characteristic can be indicated on an f plot. For particular DIAS project purposes the f plot enables transient phenomena to be recognized readily and thus aids in the identification of more stable phenomena in local or regional ionospheric response.

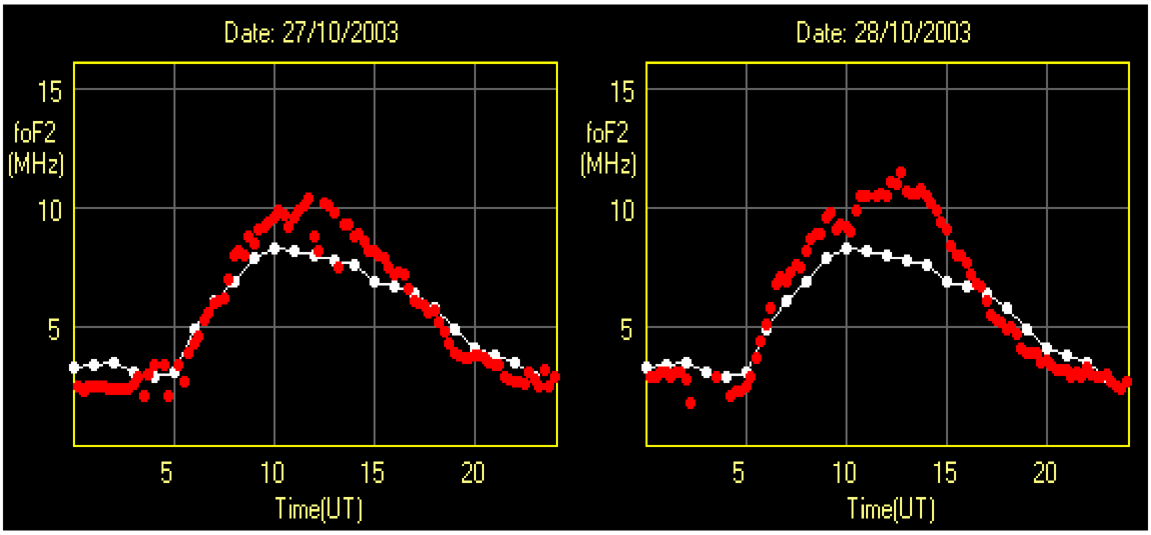


Figure 3. An example of f-plots from the ionosonde station at Juliusruh
(from ftp: ionos.ingv.it)

Modern ionosonde stations with computer-driven automatic scaling procedures routinely scale all the ionograms recorded every 15 minutes. Manually scaled ionospheric data are normally available only for the hourly recordings that are routinely reduced to numerical data. The resulting numerical values, sometimes along with the original ionograms, are archived at World Data Centers (WDCs) for Ionosphere as explained in the DIAS State of art report (Belehaki et al., 2005b). This gives DIAS project a significant role in complementing existing data provision and archiving facilities.

2.3 N(h) profiles

Physically as well as practically the most meaningful results from ionospheric soundings are the true heights of the maxima of the reflecting layers and the variation of electron density with height – the electron density profile N(h).The maximum electron densities are given with great accuracy by the critical frequencies. For example, in the case of the F region, maximum electron density is related to the critical frequency foF2 by

$$NmF2/m^{-3} = 1.24 * 10^{10} (foF2/MHz)^2$$

Generally it has to be said that in mathematical terms, the determination of the real ionospheric height requires the inversion of the integral equation which relates the virtual height with the group refractive index. The numerical inversion of the ionogram into an electron density profile requires that the virtual heights be known at all frequencies. The complete true height profile of electron density is given by modern ionosondes, including all layers and the valley between the E and F regions. The profile is reported with the true height as the argument of the N(h) function, i.e. all heights within the valid range are scanned with a fixed increment, say. The height increment and coverage for the profile specification is determined by the program which created the SAO file. Providing the derived N(h) profile from each sounding is therefore offering the minimum in terms of a physical interpretation of each sounding.

2.4 DIAS recommendations

The DIAS system should provide user access to:

- Real-time and archive ionograms and SAO files;

- Real-time f-plots of the standard ionospheric characteristics: the lowest frequency at which echo traces are observed on ionogram, fmin, the ordinary wave critical frequency of the highest stratification in the F region, foF2, and the propagation factor M(3000)F2;

- M(3000)F2 (= MUF(3000)/foF2) is a propagation factor closely related to the height of the F2 layer peak;

- Standard MUF(3000) is the highest frequency that, refracted in the ionosphere, can be received at a distance of 3000 km;

- MUF(D): Maximum usable frequency for ground distance D;

- M(D); M factor for distance D (= MUF(D)/foF2);

- N (h) profiles: the variation of electron density with height that will be provided though SAO files up to the F2 layer peak.

3. Ionospheric models for propagation prediction

A first requirement for accurate ionospheric propagation predictions is a model of the vertical distribution of electron density in the ionospheric regions. This needs to take account of the known large geographic and temporal variations in the ionosphere. The most extensive ionospheric database is that derived from the world network of ionosondes. Hence models of the vertical distributions are produced with the parameters of the models given by empirical equations in terms of the ionospheric characteristics which are scaled on a routine basis at all ionosonde stations. There are a number of ionospheric propagation prediction models based on an empirical fit to hourly monthly median values extracted from an archived ionosonde data base for past solar cycles. These climatological models very often provide ionospheric quiet-day reference conditions. The best-known ionospheric model is the IRI-International Reference Ionosphere (Bilitza, 2002). It provides monthly averages of ionospheric electron density, plasma temperature and ion composition as function of altitude for any location and time. Data set of this model contains the coefficients for the foF2 and M(3000)F2 models recommended by the Comité Consultatif International des Radiocommunications (CCIR) now known as the International Telecommunication Union (ITU).

The CCIR maps are based on monthly median values obtained by the worldwide network of ionosondes (about 150 stations) during the years 1954 to 1958, altogether about 10,000 station-months of data. Following a numerical mapping procedure developed by Jones and Gallet (1965) and Jones and Obitts (1970), each station data set is first represented by a Fourier time series (in UT), and then a worldwide development in a special form of Legendre functions (in geodetic latitude, longitude, and modified dip latitude) is applied for each Fourier coefficient. Coefficients sets are provided for high and low solar activity. For intermediate levels of solar activity, linear interpolation is suggested. The whole CCIR model consists of (988 + 441) * 2 * 12 = 34,296 coefficients.

Another data set of the IRI model contains the coefficients for the foF2 and M(3000)F2 models recommended by URSI Working Group G.5. The numerical mapping method is the same as for the CCIR foF2 model which has its shortcomings above the oceans and in the southern hemisphere, where ionosonde measurements do not exist or are sparse. Rush et al. (1984) used aeronomic theory to fill the data gaps before applying the spherical harmonics mapping procedure and Fox and McNamara (1988) established the final URSI coefficients for the combined data base of Rush's values and about 45,000 station-months of ionosonde data).

Previous studies have shown that global prediction and forecasting have limited meaning because of the regional nature of the ionosphere and real-time regional data availability (Wilkinson et al., 1997, Stamper et al., 2004a,b). Accordingly, DIAS recommends the use of regional maps and models.

3.1 Ionospheric long term prediction

The Improved SIRM (Simplified Ionospheric Regional Model) is a regional ionospheric model of the standard vertical incidence ionospheric characteristics, evolved from the original SIRM developed under the EU COST (Co-operation in the field of Scientific and Technical Research) 238 project (Bradley, 1995), and applied to a more extended area taking into account the consequences of high latitude regions (Zolesi et al., 1993, 1996). The model is based on the Fourier coefficients coming from the analysis of the median monthly values of the ionospheric characteristics measured at the stations in the European area and collected from the WDCs and contributing European ionospheric stations under the COST 251 project (Hanbaba, 1999). Throughout the remainder of this report, the term 'SIRM' should be understood as referring to this Improved SIRM rather than the more restricted original.

The first step of the procedure is the linear regression analysis of the monthly median values of a given ionospheric characteristic $\Gamma_{h,m}$ taken at local or universal time against the solar index R_{12}

$$\Gamma_{h,m} = \alpha_{h,m} R_{12} + \beta_{h,m}$$

The parameters $\alpha_{h,m}$ and $\beta_{h,m}$ are two matrices of 24 x 12 = 288 coefficients for each hour of the day, h, and for each month of the year, m. Once they are defined following the procedure explained below, foF2 and M(3000)F2 can be predict for any solar epoch providing that long-term prediction of the 12-monthly smoothed sunspot number R_{12} is available.

The second step is a Fourier analysis of these data for two fixed values of solar activity R_{12} = 0 and R_{12} = 100

$$\Gamma_{h,m} = A_0 + \sum A_n \sin(n\,\omega\, t + Y_n)$$

where n is the harmonic number, ω is the fundamental pulsation and t the time in hours. In order to reproduce the monthly behaviour more accurately the Fourier analyses were performed month by month. Then considering that the 12 pairs of Fourier coefficients A_n and Y_n for every different month show a linear dependence on the solar activity and on the geographic latitude it can be written:

$$An = (a^1_n \varphi + a^2_n) R_{12} + a^3_n\varphi + a^4_n$$
$$Yn = (b^1_n \varphi + b^2_n) R_{12} + b^3_n\varphi + b^4_n$$

where the a^j_n and b^j_n can be easily calculated using a linear regression analysis versus the latitude φ (Zolesi et al., 1993).

The application of SIRM to the extended COST 251 area (Figures 4 and 5) showed better performances than the ITU-R global model (see Table 1). Comparisons of measurements and predictions for the testing stations were carried out, using all the valid monthly median data available in the COST 251 vertical incidence sounding database. The models were ranked according to the global rms error, given by

$$\sigma = \left(\frac{1}{N} \sum_{i=1}^{N} \left(p_i - m_i \right)^2 \right)^{1/2}$$

where *N* is the total number of samples, p_i is the value predicted by the model for sample *i*. and m_i is the measured value for sample *i*.

Table 1. Test results for long-term mapping of foF2 and M(3000)F2.

Models	σ (foF2)	σ M(3000)F2
ITU-R	0.635 MHz	0.116
SIRM	0.610 MHz	0.114

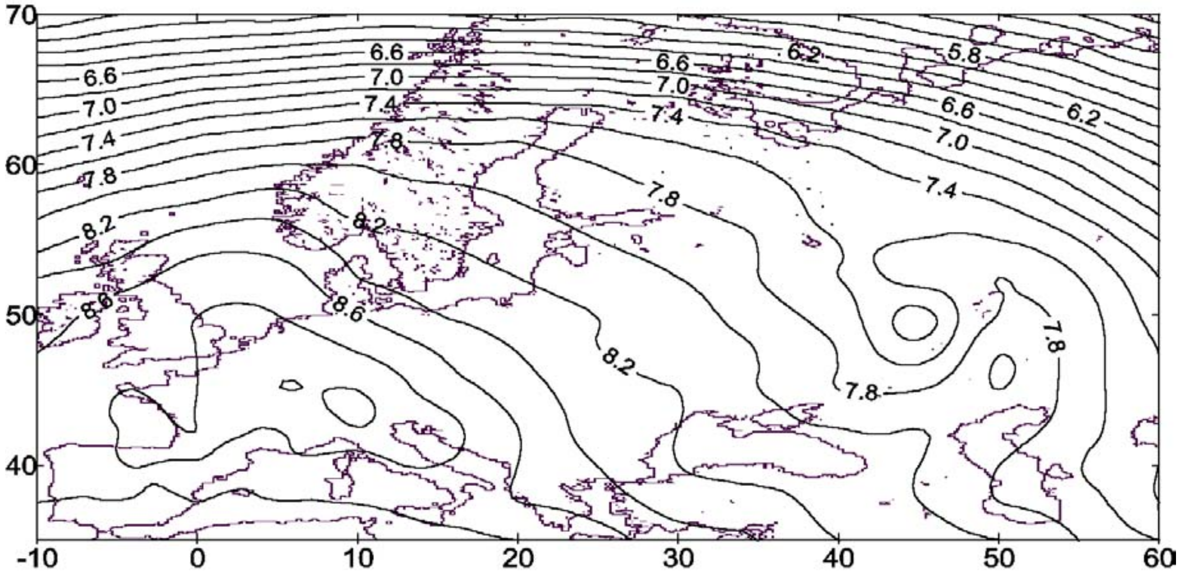


Figure 4. Map of the ionospheric F region critical frequency foF2 over European area at 1200 UT in March 1992 derived from SIRM.

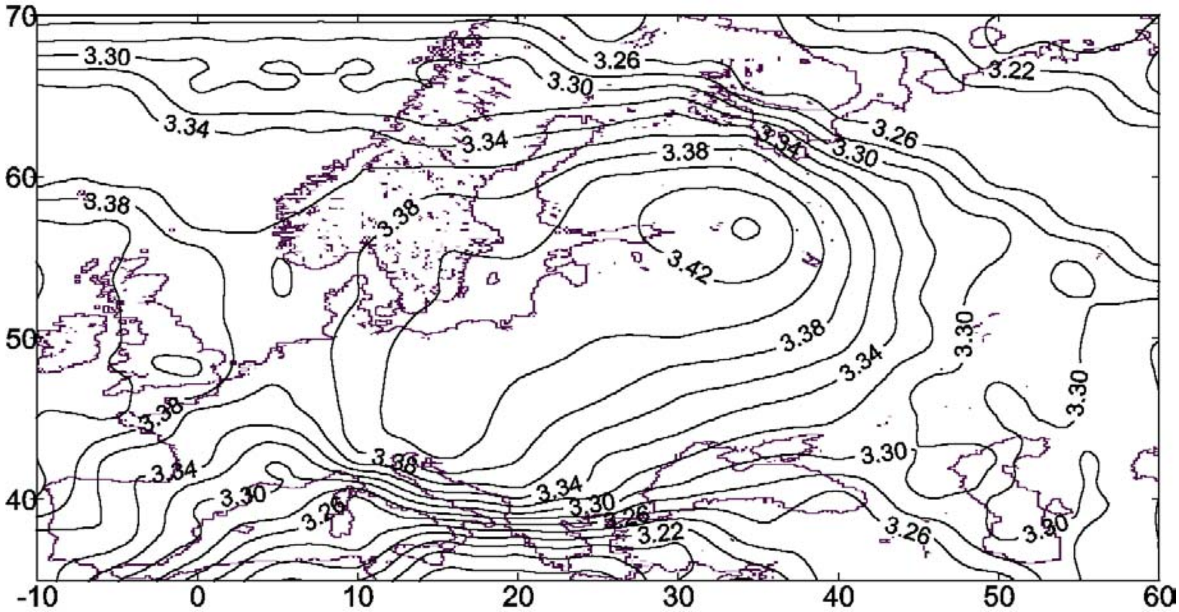


Figure 5. Map of the ionospheric propagation factor for a 3000 km range M(3000)F2 over European area at 1200 UT in March 1992 derived from SIRM.

Running the SIRM model is a very simple procedure, not only for its easy mathematical formulation and for the reduced number of numerical coefficients, but above all for the short software program, less than one fourth of the ITU model, that can be easily used and linked with other software procedures. Starting from a simple model for each station given by a linear regression analysis of the ionospheric characteristic versus solar activity index R_{12}, it is shown that 12 dominant Fourier coefficients are sufficient to reproduce the main features of the combined diurnal, seasonal and solar-cycle behaviour of the mid-latitude ionosphere under median conditions

3.2 Ionospheric specification

3.2.1 Now-cast maps of foF2 and M(3000)F2

It is well known that instantaneous ionospheric maps are those for specific epochs on a given day, whereas now-casting ionospheric maps use the real time measured data to show the geographical and temporal variations of foF2 and M(3000)F2. These are valuable to users because they provide a coherent near-real time view of the ionosphere over the whole European area, driven by the raw data (also made available by DIAS) but using this in conjunction with models of the ionosphere. To give consistence across the DIAS products, the same SIRM model used for the long-term predictions is also used as the underlying model when extrapolating from observations to give a coherent Europe-wide view of the ionosphere. This applies to retrospective studies using instantaneous maps as well as operational use of now-casting maps.

SIRM updating method (SIRMUP) is based on the idea that real time values of foF2 at one location can be determined from the SIRM model by using an effective sunspot number, R_{eff}, instead of the 12-month smoothed sunspot number, R_{12},. The main steps of the methodology can be summarized here as follows: R_{eff} is chosen to give the best fit between model calculation and actual measurements obtained from a grid of ionosondes located in the mapping area, refer to hereafter as reference stations. To initiate the procedure, a starting value of foF2 is used calculated by the SIRM model. Then, an iterative procedure is applied to adjust the sunspot number used by SIRM until the mean square error between the SIRM calculation and the real observations is minimised. The sunspot number, giving the minimum mean square error, is called the effective sunspot number. The mean square error is given by:

$$\Delta = \frac{1}{n}\sum_{i=1}^{n}(\Omega_{obsi} - \Omega_{calci})^2$$

where Ω stands for the foF2 or the M(3000)F2, n is the number of reference stations, Ω_{obsi} is the observed value of the Ω characteristic at the reference station i, and Ω_{calci} is the corresponding calculated value at station i by SIRM. After the calculation of R_{eff}, the new grid based on SIRMUP calculations is generated. The final output from this 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.

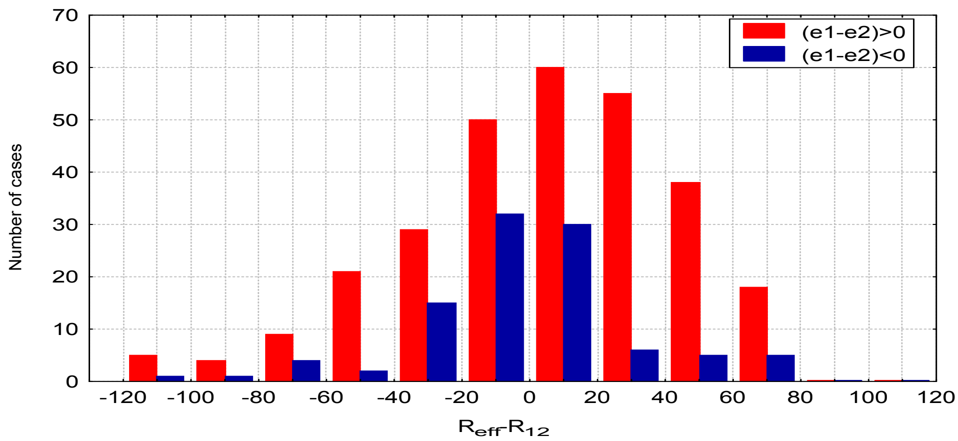
To test the reliability of the proposed methodology the model predicted foF2 and/or M(3000)F2 values were compared with the observed values resulted from the manual validation of the ionograms recorded at some test stations in the mapping area different from those used in calculating R_{eff}. At the location of each test station, foF2 and/or (M(3000)F2 was calculated by the SIRM model, using first the observed sunspot number R_{12}, and then the calculated R_{eff}. The relative errors between the observed (manually validated) and the calculated foF2 values were determined using the following equations:

$$e_1 = \frac{|\Omega_{obs} - \Omega_{SIRM}|}{\Omega_{obs}}$$

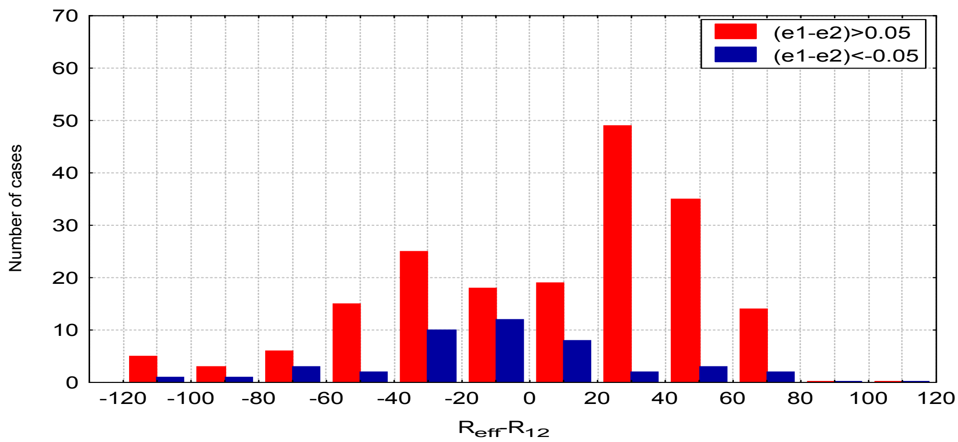
$$e_2 = \frac{|\Omega_{obs} - \Omega_{SIRMUP}|}{\Omega_{obs}}$$

where Ω_{obsi} is the observed foF2 or M(3000)F2 at the test station, Ω_{SIRM} is the SIRM calculated foF2 or M(3000)F2 at the test station using the observed R_{12} sunspot number, and Ω_{SIRMUP} is the SIRMUP calculated foF2 or M(3000)F2 at the test station using R_{eff}. When the criterion e2<e1 is met, the method of real time updating is successful in the sense that the resulting map in the specific area is more representative of the real ionosphere than the corresponding map resulting from the use of monthly median values. Accordingly the R_{eff}-R_{12} should be considered as a regional index of the ionospheric activity for the European region.

To further establish this idea in case of foF2, the distribution of the ($R_{ef\ f}$- R_{12}) parameter for positive and negative cases of the (e1-e2) is presented in Figure 6(a). It is statistically verified that the performance of SIRMUP is better than SIRM since the number of cases for which e1-e2>0 are always greater than the number of cases for which e1-e2<0, for all values of R_{eff}- R_{12}. There is also an indication that the relative performance of the two models depends on the level of ionospheric disturbance as this is expressed by R_{eff}-R_{12}. To further investigate this point, the distribution of R_{eff}-R_{12} is examined only for cases with (e1-e2)>0.05 and (e1-e2)<-0.05 (Figure 6b). This will eliminate from the statistical sample cases for which the performance of the two models differs marginally and therefore the results of the distribution should be more important statistically. In Figure 6(b) it is shown that SIRMUP performance is strongly improved for cases for which the ionospheric activity is moderate to intense, although even during quiet intervals SIRMUP performance is still better than SIRM. In cases of very intense geomagnetic activity, SIRMUP performance is still improved but this result is not statistically significant.



(a)



(b)

Figure 6. The distribution of the (R_{eff}-R_{12}) quantity for the cases: (a) (e1-e2)>0, marked with red and (e1-e2)<0, marked with blue, and (b) (e1-e2)>0.05, marked with read and (e1-e2)<-0.05 marked, with blue.

The final output from the SIRMUP now-casting method are maps of foF2 and M(3000)F2 covering the European area from 5°W to 40°E in longitude and 34°N to 60°N in latitude (Zolesi et al., 2004). A comparison between the ionospheric maps of foF2 using SIRM and the updated SIRM (SIRMUP) on 6 December 2001 at 0900UT is presented in Figure 7. During this time the ionosphere over Europe was affected by large-scale effects caused by changes in the global wind circulation. SIRMUP performance according to the e2<e1 criterion was particularly successful. Indeed the foF2 values in the SIRMUP generated map are greater than those appeared in the SIRM map. In addition, the topology of the ionosphere is much better determined, especially in the southeast region, where a latitudinal dependence of foF2 is well described by SIRMUP.

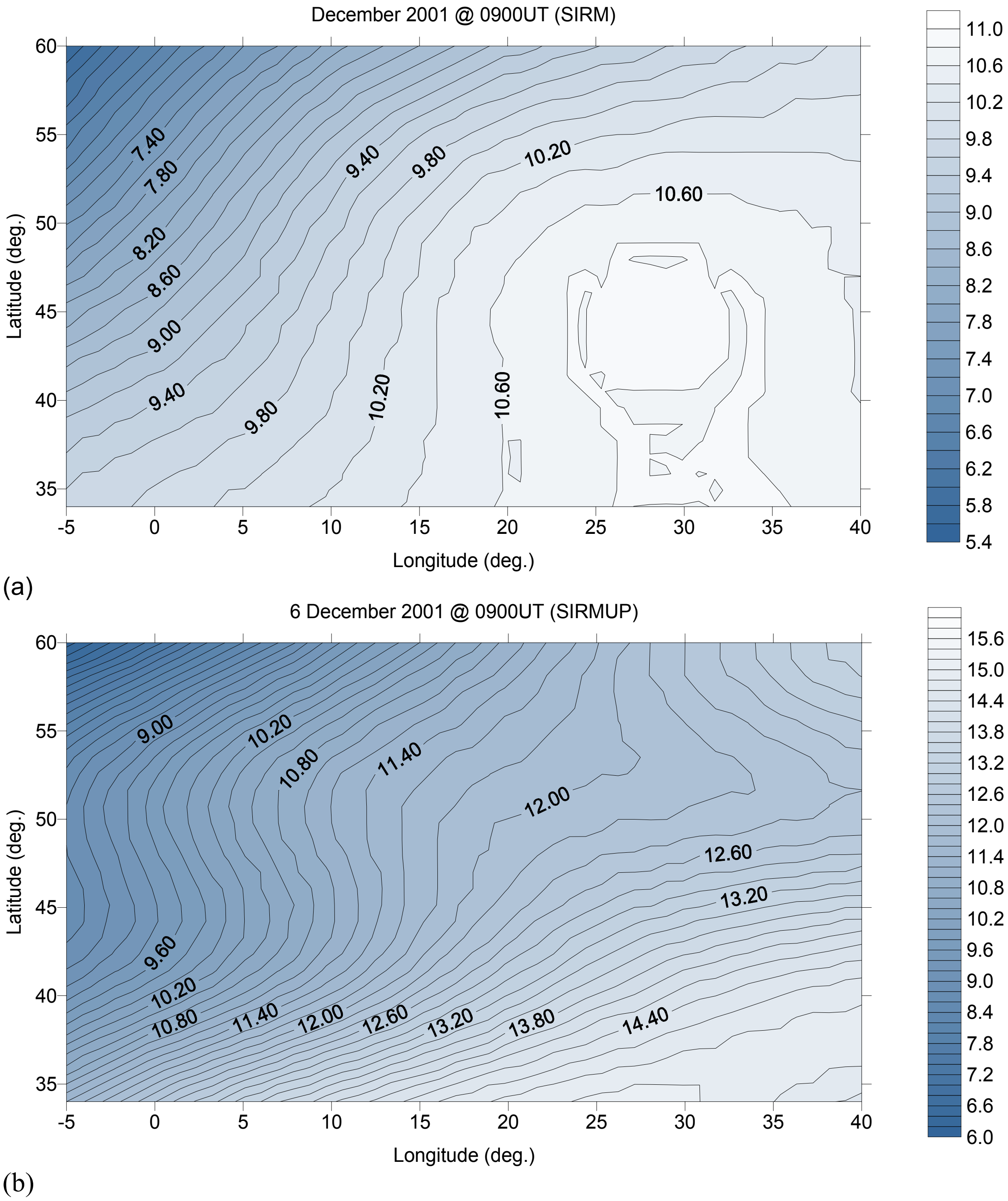
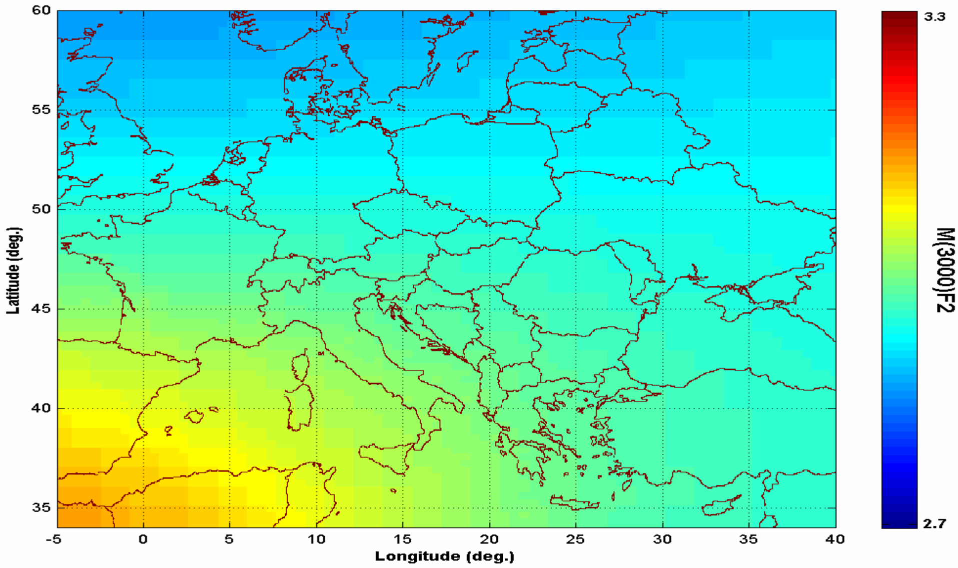
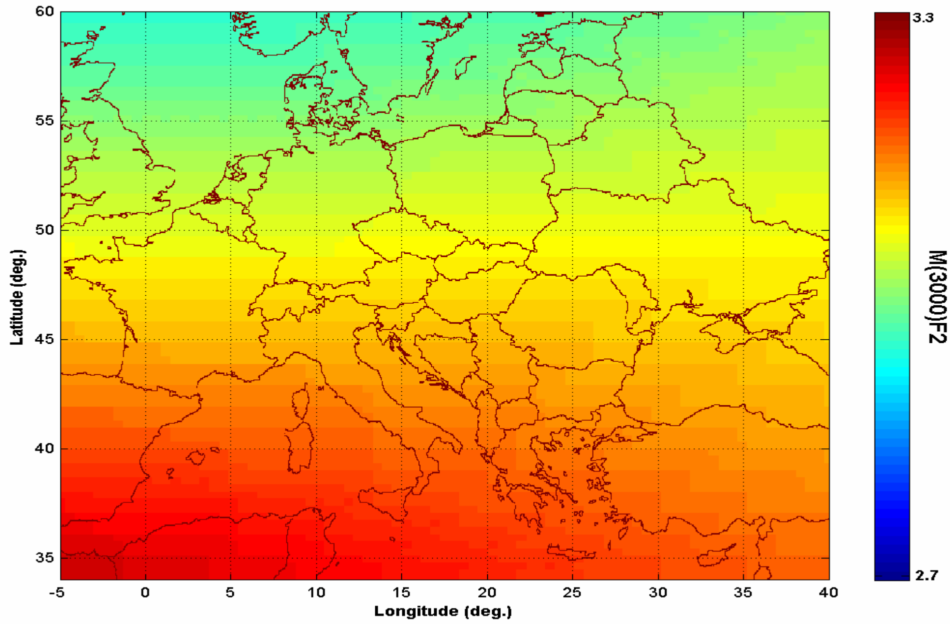


Figure 7. The ionospheric map of the foF2 over Europe from 5°W to 40°E in longitude and from 34°N to 60°N in latitude on 6 December 2001 at 0900UT, computed with (a) SIRM and (b) SIRMUP.

A comparison between the ionospheric maps of the M(3000)F2 characteristic using SIRM and SIRMUP on 18 August 2001 at 0900UT is shown in Figure 8. It is an example when the SIRMUP performance was particularly good, giving more realistic M(3000)F2 values in the SIRMUP generated map than those in the SIRM map (Tsagouri et al., 2005).



(a)



(b)

Figure 8. The ionospheric map of the M(3000)F2 characteristic over Europe from 5^{o}W to 40^{o}E in longitude and from 34^{o}N to 60^{o}N in latitude on 18 August 2001 at 0900UT, generated by (a) SIRM and (b) SIRMUP.

3.2.2 Electron density height profiles

As European ionosonde data are now available in real time, it is now possible to construct instantaneous 3-dimensional maps of electron density at any chosen height. The mapping scheme applied uses a specific technique that fits the background model to the set of measurements (Stanislawska et al., 2000, 2001). To avoid numerical instabilities and ensure a higher accuracy additional data from a background NeQuITUR model (Leitinger et al., 2002) are added during the interpolation procedure, using moments of the probability distribution function. In the simplest approach, weight functions depend on the distance of the chosen point from all sites of observation. This dependency is anisotropic. The anisotropy is specified by the ratio of the correlation radii in the longitudinal and latitudinal directions (*CRX* / *CRY*). The weight function adopted has the form:

$$W = exp\ [-(dx/CRX)^2 - (dy/CRY)^2]$$

where *dx* and *dy* are the longitudinal and latitudinal distances from the chosen point to the one where observations were made. It can be specified by the scaling factor (SF). The scaling factor is specified in geographical latitude and longitude and is applied before the interpolation procedure is completed. The SF is the ratio of the length of the E-W and S-N axes of the spatial correlation ellipse. In principle the SF is not uniform across the entire area of the map and depends also on solar and geomagnetic activity. As a simplifying assumption, however, an averaged SF value is used throughout the studied area and the selected period. For foF2 the axes ratio of the correlation ellipse for mid-latitudes is approximately 2. The interpolation method with the background model has been applied to the plasma frequencies at parallel-stratified heights determined from the ionosonde-derived electron concentration height profiles at selected ionospheric stations (Stanislawska et al., 2004).

The maps created by means of this fitting technique with an empirical background model were tested against the measurements with 5 km steps in height. Tests were made with an n-1 error-calculation cycle, where n is the number of considered observational sites. There are n calculation stages that make up one error-calculation cycle. In each stage one point is omitted and the map is constructed on n-1 points. Tests were repeated over a range of heights, hours and days. Ionosonde and model profiles (NeQuITUR) were compared and percentage deviations determined. Test results are shown in Table 2. Note that the differences are much higher than those for maps of ionospheric characteristics. Three-dimensional profiles were calculated for quiet samples using the fitting technique and NeQuITUR as the background model. Results in the height range 100 to 300 km are presented as plasma frequency maps in Figure 9. Two quiet days are shown: 12 November 1998 and 17 July 2000. Observed data fit well with the background model (NeQuITUR).

Table 2. Average percentage deviation for the whole set of data, and for selected stations and periods separately.

	Total	JR 055	MZ 152	RLC 52	PQ 052	RO 041	EB 040	EA 036	1998	2000
Fitting	27.1	27.0	26.3	23.6	21.8	33.7	29.1	27.7	30.4	24.3
NeQ ITU-R	32.8	37.6	36.6	26.7	30.3	37.5	31.1	29.2	34.0	31.9
N. data	23760	3683	3408	2349	3564	2990	3846	3920	10707	13053

The described plasma frequency mapping procedure is proposed to construct electron density images at any moment, both retrospectively and in real time. Preliminary samples of maps and tests show a fair agreement of measurements and mapping. Therefore, this configuration of the procedures has been implemented in DIAS project software.

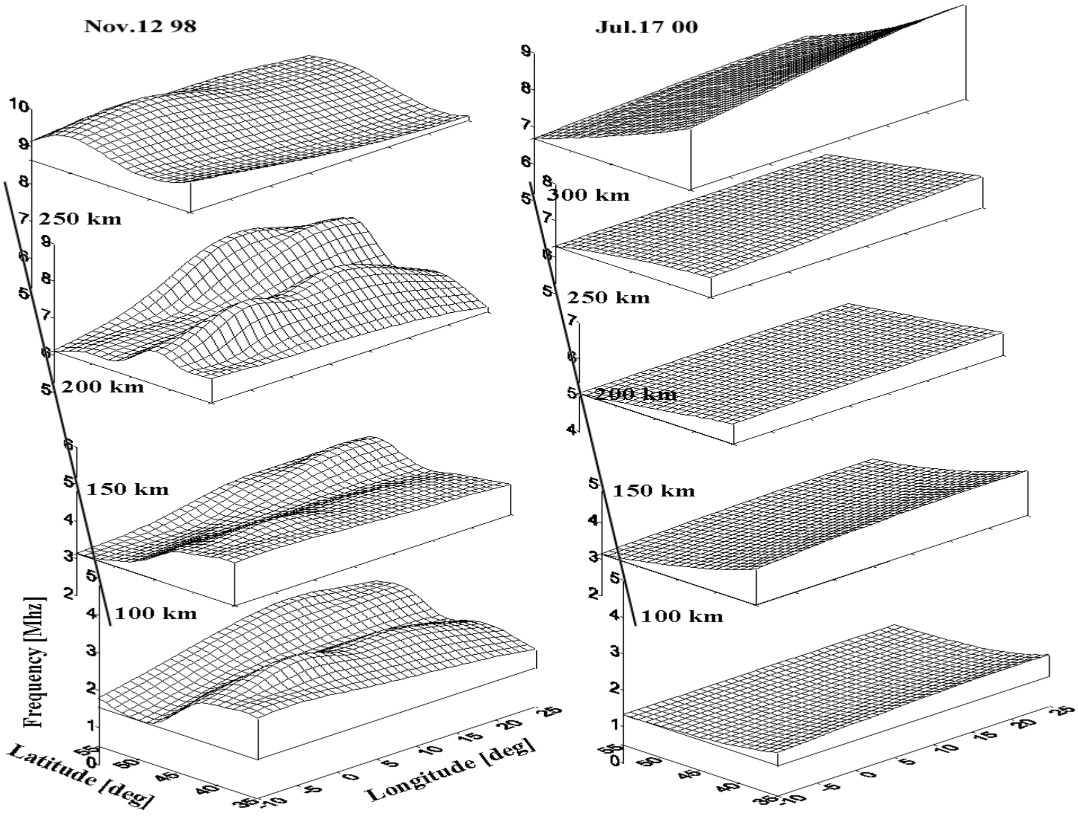


Figure 9. Maps for 12 November 1998 (left panel) and 17 July2000 at 12 UT (right panel) obtained for different height levels by fitting technique with background NeQuITUR model.

3.3 Ionospheric forecasting

Short-term forecasting models for frequency management are directed towards assessing the best frequency to use with an existing system in the light of the prevailing ionospheric conditions. Therefore, the requirement is to use system-performance predictions of the form already described, but with the forecast ionosphere replaced by a more accurate representation. The greatest fractional variations in the E and F regions arise in foF2. Hence a useful improvement in modelling capability could be achieved by using two short-term forecasting methods under development by NOA in the DIAS project.

The first method under development is based on the model developed by Muhtarov et al. (2002) that has been applied at the six different locations where DIAS ionospheric stations operate (Athens, Rome, Juliusruh, Warsaw, Lycksele and Chilton). The DIAS partners, who operate the ionospheric stations, have provided long time series of historical data required by this application. The first results demonstrating the operation of this computer code were presented during the Working Package 3 meeting held in Rome, February 2005.

Muhtarov et al. (2002) is a method for short-term prediction of ionospheric parameters developed by incorporating the cross-correlation between the ionospheric characteristic of interest and the Ap index into the autocorrelation analysis. It considers the hourly time series of an ionospheric characteristic as composed of a periodic component and a random component. The periodic component containing the average diurnal variation could be removed by using its relative deviations from the median values (Φ), which in the case of the critical frequency of the F2 layer, foF2, takes the form: $\Phi=(foF2-foF2_{med})/foF2_{med}$. The GCAM (Geomagnetically Correlated Autoregression Model) is an extrapolation model based on the weighted past data. The new term in the regression equation expresses linear dependence of $\underline{\Phi}$ on magnetic activity by introducing a synthetic geomagnetic index G, which approximates the average dependence of $\underline{\Phi}$ on hourly-interpolated Kp. Using parametric expressions of the auto- and cross-correlation functions ensures statistical sufficiency in GCAM; the parameters are then obtained by data fitting. Data from two years of high solar activity (1981-82) and two years of low solar activity (1985-86) were used to evaluate the prediction accuracy of GCAM. The mean square error in percent of the one-day prediction of foF2 relative to the median shows a large gain of accuracy of GCAM in the first 8-10 hours of prediction relative to the median based prediction, a diurnal variation of errors and a steady offset of the GCAM prediction error from the median based prediction error. The GCAM error at the first hour is lowest, but gradually approaches the median error with a time scale of 8-10 hours.

The second method is the prediction of the foF2 parameter using Auto Regression (*AR*) models (Koutroumbas and Belehaki, 2005). The problem considered is the estimation of the value of the foF2 parameter *s* time-steps ahead, based on its current and its previous *M* observations. The observations for the foF2 parameter were extracted from ionograms obtained by the Athens Digisonde, every 15 minutes. More specifically, denoting by {x(n)} the time series of the foF2 observations, the problem is to estimate the value x(n+s) based on the values x(n), x(n-1),…,x(n-M). Assuming that foF2 parameter is modelled by an *AR* model, the estimate of x(n+s), $\hat{x}(n+s)$, is given by

$$\hat{x}(n+s) = w_0\, x(n) + w_1\, x(n-1) + \cdots + w_M\, x(n-M)$$

where *M* is the order of the model and w_i are its parameters. In order to determine the *AR* model that best describes the data (that is the appropriate *M* and w_i's), the available data set was split into a training set and a test set. Then, several values of *M* have been considered and, based on the training set, estimated for each one the corresponding w_i's, using the Yule-Walker equations, extended to the case where *s>1*. The model that exhibits the minimum mean square error on the test set is selected as the best one. Taking into account the variation of foF2 over a year (seasonal variation), the above procedure is used to re-estimate the *AR* model at the beginning of each month, taking as training set the observations obtained during the first half of the previous month and as test set the observations obtained during the second half of the previous month. Finally, it should be noted that if predictions for different values of *s* are required, an *AR* model for each different value of *s* must be adopted. The method is to be applied at all the locations where DIAS ionospheric stations operate (Athens, Rome, Juliusruh, Warsaw, Lycksele and Chilton).
Some of the results are shown in Figures 10 and 11.

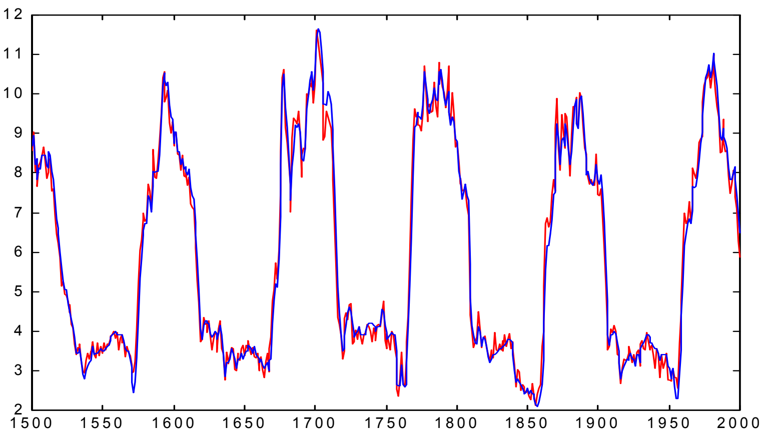


Figure 10. Results of the second model for 1 step (15 min) ahead prediction (blue are the actual and red the predicted values) for the interval 15/12/2003 – 15/2/2004.

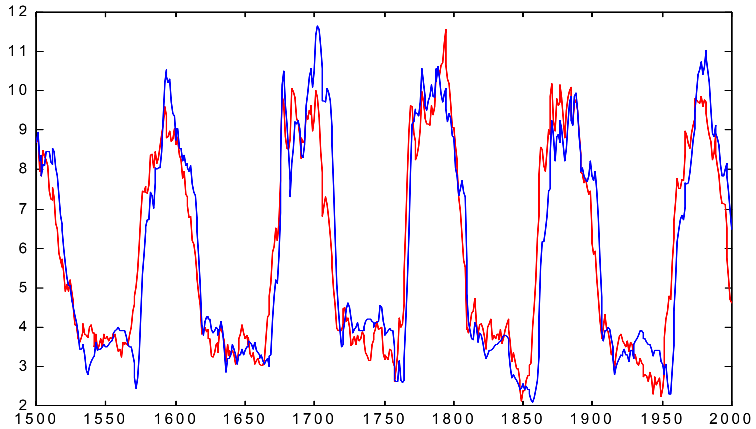


Figure 11. Results of the second model for 4 steps (1 hour) ahead prediction (blue are the actual and red the predicted values) for the interval 15/12/2003 – 15/2/2004.

Using either method, the forecast foF2 values for the stations at each time step can be used to generate forecasting maps of foF2 using the SIRMUP method. For any given time step, the forecast foF2 values for the set of stations would be used to generate the corresponding R_{eff} value, and a map created just as with the now-casting maps described previously.

3.4 DIAS recommendations

- Ionospheric maps over the European area of monthly median foF2 and M(3000)F2 for different solar epochs in hourly time resolution for the long-term prediction of frequency planning services. They are based on the improved Simplified Ionospheric Regional Model (SIRM), a model developed specifically for European ionospheric area;

- Ionospheric maps over the European area of instantaneous foF2 and M(3000)F2 values at a time specified by the user. They will be based on SIRM Updating model (SIRMUP);

- Ionospheric maps over the European area of the real-time foF2 and M(3000)F2 for individual epochs for the now-casting frequency management. They will be based on SIRM Updating model (SIRMUP);

- Ionospheric forecast maps over the European area representative of foF2 conditions up to 24-hours ahead of the present for use in spectrum management;

- Instantaneous and real-time ionospheric electron density, available both as profiles and as maps over the European area at user-specified heights;

Based on foF2 and M(3000)F2 input values given by SIRM, SIRMUP and the chosen forecasting algorithm, the additional product is recommended:

3.4.1. Maps of the basic Maximum Usable Frequency

Concerning isoline maps of the MUF for a given transmission point in the European Area, it is proposed to test a simplified procedure summarized below:

1. to calculate the coordinates of the mid-points of the radio paths for every distance between the given point of transmission and all the points of the grid over the European area;
2. for these points to obtain the predicted values of foF2 and M(3000)F2 by using the grid map given by SIRM for the long term prediction and by SIRMUP for now-casting;
3. to calculate the M(d)F2, where d is the distance between each grid point and the given transmission point, using an algorithm that applies a geometrical transformation of the

value of M(3000)F2 plus an empirical correction or, as a second option, by using the formula proposed in paragraph 2.5 of the P.533 (ITU-R, 1994);

4. to apply a similar procedure to calculate M(d) for the E layer, taking into account that the predicted values of the critical frequencies of the lower ionospheric layers F1 and E may be obtained by regional Chapman models as given by the literature (Dominici and Zolesi, 1987; Davies, 1990);

5. to consider only one hop on the ionospheric layer F, for distances less than 3500km and only one hop on the E layer for distances less than 2000km and to take into account the eventual cutoff frequencies;

6. to calculate for every point of the grid the MUF and design the isolines.

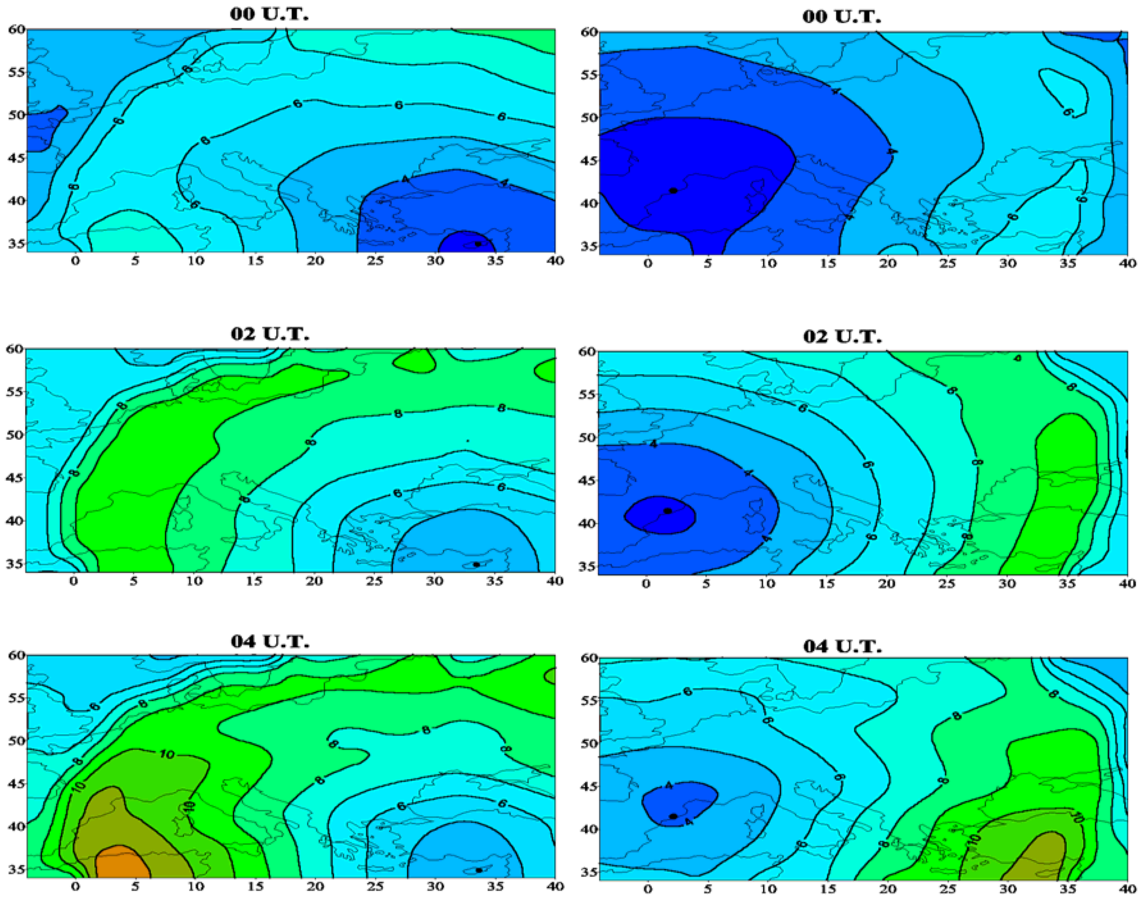


Figure 12. Examples of MUF(MHz) calculated for different hours in November 2003 and for two different points of transmission: right at 42.1N, 02.1E and left at 35.1N, 33.2E.

4. Warnings and Alerts

There are different centres for the identification of precursors of solar disturbances responsible for changes in the ionosphere and in the Earth’s magnetic field. Optical, X-ray and radio emissions from the Sun are observed daily at a number of ground-based sites and also aboard satellites. Ionospheric disturbances following solar flares occur either in close time succession and last for several hours, or begin 24-36 hours later and last for several days. The former arise from enhanced X-ray, ultra-violet and -high-energy particle radiation, while the latter are associated with lower-energy particles. Various attempts have been made to correlate daily foF2 values with indices of solar and geomagnetic activity. Ionospheric disturbance forecasts and short-term forecasting services are currently offered by a few organizations as described in the State of Art report (Belehaki et al., 2005b).

4.1 Solar-terrestrial warnings and alerts

The wide range of time scales over which the Sun is evolving is reflected by the large number of warnings, reports and data products that are issued by the Solar Influences Data analysis Center (SIDC) at Royal Observatory of Belgium. The SIDC is collocated with the World Data Center for the Sunspot Index, which belongs to the World Data Center network. Outgoing messages can be either in plain text format or encoded in the ISES message codes (http://www.sec.noaa.gov/ises/ises_code_pages/index_page.html). The products are freely available to both the scientific community as well as to the wide public, at the anonymous ftp site ftp://omaftp.oma.be (directory dist/astro/sidcdata), and at the Web address: http://sidc.oma.be.The information on the web site and on the ftp server is updated as soon as new data become available. Table 3 lists messages that can give information required for DIAS added value products. In case of SIRM, the required input is predictions of the monthly smoothed sunspot number R12 based on the last provisional value circulated for the particular month. Presto is an alert issued by a Regional Warning Center to give rapid notification of significant solar and geomagnetic activity in progress or just concluded that influence ionospheric structure and dynamic. URSIGRAMS and geomagnetic indexes are highly relevant for short-term forecasting under development

Table 3. Products provided by the SIDC.

Frequency	Message	Type	Source	Description of data
ASAP	Presto	text	SIDC	Solar events alerts
Daily	URSIGRAMS	text	SIDC	ISES message
Daily	Indices K Wingst	ISES	Relayed	from Wingst (Germany)

For the convenience of DIAS users, links to these selected solar-terrestrial warnings would be made available on the DIAS web server with proper acknowledgement of their origin**.**

4.2 Ionospheric alert

Ionospheric alert indexes for real-time monitoring ionospheric propagation conditions over Europe and customer's warning purposes are introduced by the following equations:

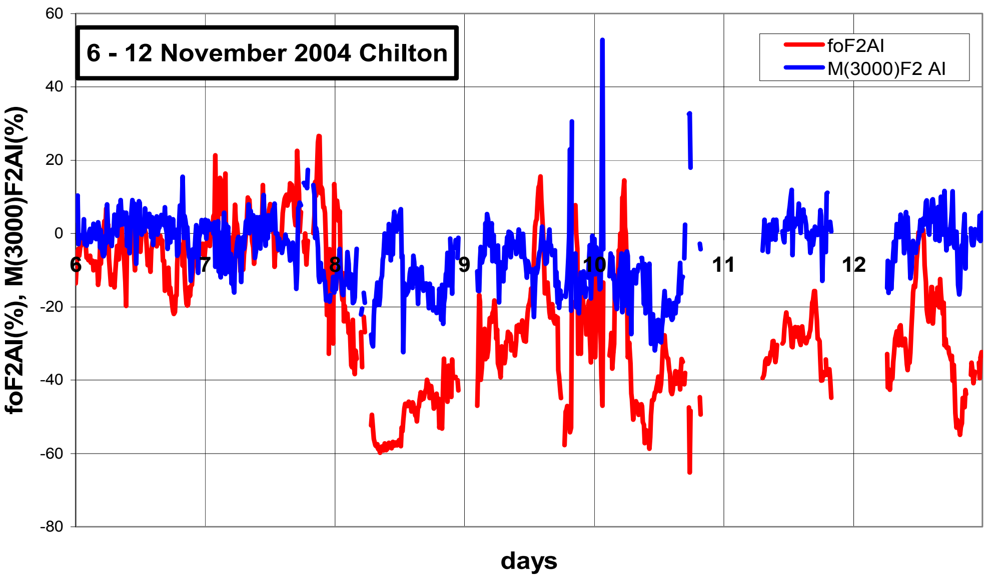
$$foF2AI\ (\%) = 100 \times (foF2^{SIRMUP} - foF2^{SIRM}) / foF2^{SIRM}$$

$$M(3000)F2AI\ (\%) = 100 \times [M(3000)F2^{SIRMUP} - M(3000)F2^{SIRM}] / M(3000)F2^{SIRM}$$

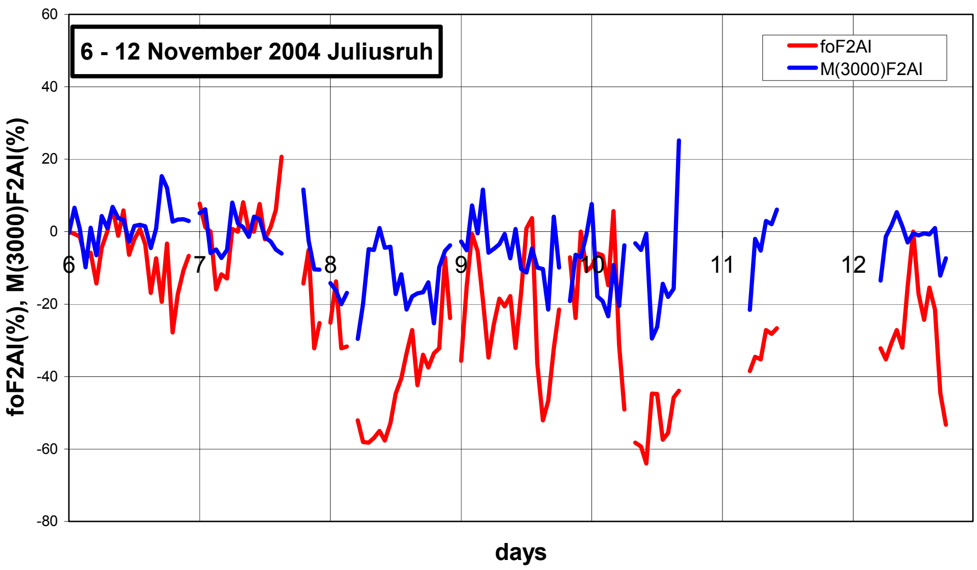
Criteria for ionospheric activity can be defined by the following relationship:

- foF2AI (%) and M(3000)F2AI (%) within ±20% - low
- foF2AI (%) and M(3000)F2AI (%) within ±20% to ±50% - disturbed
- foF2AI (%) and M(3000)F2AI (%) beyond ±50% - extremely disturbed

These ionospheric alert indexes for foF2 and M(30000)F2 have been calculated from October 2003 to the present for Juliusruh, Chilton and Rome ionosonde stations and the results obtained are currently under investigation. As prominent large-scale ionospheric disturbance was observed in European area during the recent extreme space weather event in November 2004, variations of foF2AI (%) and M(3000)F2AI (%) at Chilton and Juliusruh during the 6 - 12 November 2004 are used to describe the temporal and spatial storm evolution process. Figure 13 shows that the ionospheric F region storm morphology was dominated by overall negative disturbances during the main phase of the 7 -12 November 2004 storm and the usefulness of these indexes in their identification.



(a)



(b)

Figure 13. Examples of ionospheric alert indexes for foF2 and M(3000)F2 at (a) Chilton displaying 10 minutes data and (b) Juliusruh displaying hourly data during the space weather events in November 2004.

4.3 DIAS recommendations

It is proposed the DIAS makes available the following warning and alert products:

- There SIDC data products, forecasts and warnings that are vital significant in identifying and anticipating solar influences relevant for ionospheric propagation modelling and prediction;

- Maps of the ionospheric alert indexes foF2AI (%) and M(3000)F2AI (%) with the sections of the map coloured appropriately to show where the criteria hold.

5. Accuracy and reliability of added value products

The accuracy with which ionospheric characteristics can be measured depends on the inherent accuracy of the equipment, the accuracy of the method of calibration and the accuracy used in automatic scaling of ionograms. In general, DIAS ionosondes should be capable of giving ionograms and numerical data with the required accuracy established internationally. In case of F region it means the virtual height accuracy is limited to 5 km, the critical frequency accuracy is limited to 0.1 MHz and M(3000)F2 factor to 0.05. However, variability in the physical properties of the reflecting ionospheric layers may demand lower standards of accuracy in some areas so that a reasonable sample of ionospheric data can be obtained.

The accuracy of the long term ionospheric prediction based on the improved SIRM is given in Table 1. It strongly depends on long term prediction of the model input parameter: the 12-monthly smoothed sunspot number R_{12}. The accuracy of the electron density height profiles techniques is given in Table 2. Since there is no generally accepted measure of DIAS prediction accuracy, further work will be needed to determine the measures appropriate to each product. The overall recommendation is therefore to establish an on-going statistical assessment of the accuracy of prediction outputs.

For the now-cast products based on SIRMUP a measure of the degree of success of the fitting algorithm is given by a quantity analogous to the error value e2 calculated for the test stations when evaluating the effectiveness of the SIRMUP updating method. This quantity, eN is defined as

$$eN = \frac{\left|\Omega_{obs} - \Omega_{SIRMUP}\right|}{\Omega_{obs}}$$

and is calculated at each of the reference stations used in determining how to update the SIRM model to give the SIMRUP now-cast. For each station this quantity indicates how well the SIRMUP model was able to fit the observation; if eN = 0 then SIRMUP exactly fitted the data, and as the value increases the quality of the fit decreases. eN can therefore be used as a quality indicator, since the larger the value the less well was the model able to represent the observations. This might occur either because the model was genuinely unable to represent the state of the ionosphere, or because of an error in the auto-scaling process leading to a physical implausible “observation”. In either case, users would be well advised to treat the model output with more caution.

Each reference station will generate an eN value, and the most appropriate use of those values should be determined during the operation of the DIAS prototype, informed by statistical analysis of how the eN values behave. Decisions to be made include:

- Whether to present all the eN values for each of the reference stations, or to compute an average over the set of reference stations.

- Whether to present the eN value(s) directly as fractional errors, or to determine thresholds which trigger a series of warnings.

The index of reliability for DIAS data products and added value produces is to be developed during the DIAS implementation phase.

6. Conclusions

The current set of DIAS recommended data products and added value products are clearly explained in this report and summarised in Tabled 4. Looking further ahead, it should be remembered that DIAS is addressing two categories of potential users. The first category consists of end-user in non-scientific domains, such as private individuals, governmental entities, the military, space agencies and private companies. These will have varying levels of scientific understanding and will typically only want to receive data, information and services from DIAS; the second category consists of scientifically expert individuals and organisations, such as the WDCs, public scientific institutions, and scientific communities as COST 271/296, IRI and ITU-R. This second category, although having numerous potential applications for the products and services of DIAS, will also be providing data, models and indices to DIAS.

Table 4. List of the DIAS added value products and their producers.

Added value products	Main contributor	Other contributors
Ionograms	**NOA, CCLRC, INGV, IAP, IRF, SRC**	
f-plots	**NOA, CCLRC, INGV, IAP, IRF, SRC**	
Forecasts of foF2	**NOA**	
Maps of foF2 now-casting	**INGV, CCLRC and NOA**	
Maps of foF2 forecasting	**NOA**	**INGV, CCLRC**
Maps of foF2 long-term forecasts	**INGV and CCLRC**	**NOA**
Maps of M(3000)F2 now-casting	**INGV, CCLRC and NOA**	
Maps of M(3000)F2 long-term forecasts	**INGV and CCLRC**	**NOA**
Maps of MUF	**INGV and CCLRC**	
Maps of electron density	**SRC**	
Ionospheric alerts	**CCLRC and IAP**	

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Annex 2. Glossary of DIAS terms

ap index: a mean, 3-hourly "equivalent amplitude" of geomagnetic activity based on K index data.

Ap index: The planetary index for measuring the strength of a disturbance in the earth's magnetic field, defined over a period of one day from a set of standard geomagnetic observatories around the world. It is determined from the eight daily ap indexes.

Dst index: A geomagnetic index describing variations in the equatorial ring current.

Coordinated Universal Time (UTC): The local time at the prime meridian, which passes through Greenwich, England. It is also known as Greenwich mean time, or often simply universal time (UT).

foE: The critical frequency of the E layer. The maximum frequency which can be reflected from this layer.

foF2: The critical frequency of the F2 layer. The maximum ordinary mode radiowave frequency capable of vertical reflection from the F2 layer of the ionosphere.

Geomagnetic activity: Natural variations in the geomagnetic field classified into quiet, unsettled, active and storm conditions.

Geomagnetic storm: A worldwide disturbance of the Earth's magnetic field, distinct from regular diurnal variations that can be: (i) Minor: a storm for which the Ap index was greater than 29 and less than 50; (ii) Major: a storm for which the Ap index was greater than 49 and less than 100; (iii) Severe: a storm for which the Ap index was100 or more.

h'F2: The virtual height of the F2 layer. At night when the F2 and F1 layers merge to form the F layer, h'F is measured. Similar heights are obtained for the E and F1 layers.

hmF2: The height of maximum obtained by fitting a theoretical h'f curve for the parabola of best fit to the observed ordinary wave trace near foF2 without correcting for underlying ionization.

High latitudes: With specific reference to zones of geomagnetic activity, "high latitudes" refers to 50deg. to 80deg. geomagnetic latitude. The other zones are equatorial, polar and middle latitude.

High Frequency (HF): That portion of the radio frequency spectrum between 3 and 30 MHz.

Ionospheric storm: A disturbance in the F region of the ionosphere, which occurs in connection with geomagnetic storms.

Interplanetary Magnetic Field (IMF): The magnetic field carried with the solar wind.

K Index: A three hourly index of geomagnetic activity relative to an assumed quiet day curve for the recording site. K index values range from 0 (very quiet) up to 9 (extremely disturbed).

Kp index: A 3-hourly planetary geomagnetic index of activity generated in Gottingen, Germany, based on the K index from 12 or 13 geomagnetic observatories distributed around the world. Kp indexes are used to determine the ap indexes.

Lowest Usable Frequency (LUF): The lowest frequency which allows an acceptable grade of HF service.

M(3000)F2: The ratio of the maximum frequency reflected once from an ionospheric layer over a 3000-km range to the critical frequency of the layer.

Median: The middle value when all values are ordered.

Middle latitudes: With specific reference to zones of geomagnetic activity, "middle latitudes" refers to 20 deg. to 50 deg. geomagnetic latitude.

N (h) profiles: The variation of ionospheric electron density with height

Optimum Working Frequency (OWF): This is the lower decile MUF. It is the frequency which is usable for at least 90% of the days of the month.

Plasma: A gas in which there are approximately equal numbers of positive ions and negative particles. There may also be many neutral particles, as is the case for the ionosphere.

Plasma frequency: The maximum frequency of internal oscillation of plasma. The plasma frequency is proportional to the square root of the electron density.

Reflection: Although a radio wave is actually refracted in the ionosphere, it is often permissible to substitute a simple triangular ray path for the real ray path, as if the ray were reflected from a mirror. Thus radio waves are often referred to as being reflected from the ionosphere.

Refraction: The bending of a wave when it crosses a boundary between media due to a change in velocity of the wave. Until it reaches the ionosphere, a radio wave propagates in a straight line. Once in the ionosphere, it is refracted back towards the ground. The amount of refraction depends on the electron density of the ionosphere and the operating frequency.

Refractive index: An index to define the amount of refraction a wave will undergo when it enters a medium.

Retardation: The delay in propagation of a radio wave near the critical frequency caused by the slowing down of the wave by the ionosphere.

Smoothed Sunspot Number (SSN): An average of monthly sunspot numbers centred on the month of concern. There are various formulas; however, the aim is to smooth discrete data points.

Solar index R_{12}: The 12-monthly smoothed sunspot number R adopted following ITU-R Recommendations.

Solar index R_{eff}: The effective sunspot number calculated using real-time foF2 observations.

Sporadic E: A thin ionised layer in the E region that occurs irregularly.