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Ionospheric W Index Based on GNSS TEC in the Operational Use for Navigation Systems

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<http://dx.doi.org/10.5772/59902>

1. Introduction

The ionosphere can vary appreciably from day to day and from hour to hour at any location. The behaviour of the Earth's ionosphere is characterized by phenomena of different time and space scales, which is affected by not only Sun, solar wind and magnetosphere but also atmospheric weather and climate. Unusual behaviour is mostly related to space weather hazard. The ionospheric observing techniques are mostly based on radio waves affected by different phenomena disturbing their propagation.

The ionosphere behaviour is well recognized with ionosonde observations of the maximum electron density ($NmF2$), proportional to square of the F2 layer critical frequency ($foF2$), or satellite radio beacon measures of total electron content (TEC). TEC represents a measure of integrated electron density in a 1 m^2 column along a ray path through the ionosphere and plasmasphere up to three Earth's radii (e.g., Global Positioning Satellites, GPS, orbit, 20 200 km). Total Electron Content (TEC) observations are necessary for navigation, trans-ionospheric telecommunication and positioning applications. Radio propagation is affected by ionospheric, iono-plasmaspheric and slightly by tropospheric factors. Measurements of TEC are highly disturbed by varying ionospheric electron density. Ionospheric storms are by far the most important disturbances from the point of view of their societal impacts because of their durations (several days), their adverse effects on the radio spectrum, and their global effects. The small-scale ionospheric irregularities cause intense effects like scintillations with lifetimes of 2-3 hours in a localized area. Scintillation phenomena that have an impact on quality of the radio signal and related applications are particularly important at high and low latitudes. Descriptions of such effects are important for technical and technological systems management applications.

Ionospheric scintillation provides information that is necessary for warning about possible degradation of the signal and loss signal lock with the consequence of drastically decreased precision for positioning. Ionospheric scintillation refers to the scattering of radio waves interacting with a small scale irregular structures of plasma density in the upper atmosphere and is necessary information for warning about possible degradation of the signal and loss signal lock with the consequence of drastically decreased precision for positioning, for instance. This information is needed for the successful operation of GPS, radar, and other communication signals. Both amplitude and phase scintillation should be observed. Scintillation intensity indices for the two types of scintillations, which are S_4 and σ_ϕ , respectively, are necessary. Unfortunately, such information is rather rare in the global scales. Traveling Ionospheric Disturbances (TID) often detected as large-scale or medium scale phenomena by the two-dimensional GNSS-TEC observations have usually so small amplitude (generally up to 10% to the background) and their influence for telecommunications and navigations could be negligible. However TIDs may have impact on carrier-phase-based precise positioning or space-based Satellite Application Radar, SAR.

Availability of such information is currently relatively limited for both ground based and satellite observations. In-situ observations in the space are excellent source of measurements, but still give rather small complementary contribution to permanent monitoring. Ground-based GNSS receiver networks make it possible to monitor two-dimensional ionospheric structures with relatively high temporal and spatial resolutions. The knowledge of current state of the ionosphere at global scale is crucial for determination which GNSS observations, which GPS, Galileo or other satellite system might give accurate and reliable information [1-2]. An increased knowledge of effects imposed by the ionosphere on operational radio systems could be earned by the service providing online estimate of the degree of TEC perturbation at each grid point of the global map expressed by the ionospheric W index [3].

Space weather is characterized by “solar indices” as a measure of activity of the Sun, “geomagnetic indices” for estimate of behaviour of the magnetosphere, and the “ionospheric indices” as a measure of changes of plasma ionization. The spatial and temporal variations of plasma parameters such as the F2 layer peak electron density, N_mF_2 , and TEC, are of particular interest in applications, such as space-based navigation and positioning [2]. Operators of space telecommunications need to know whether the ionospheric parameters indicate the normal quiet conditions in the ionosphere and plasmasphere or the short-term perturbations of the ionospheric plasma related to disturbances on the Sun and in the magnetosphere of the Earth. Investigations of the ionospheric disturbances and storms have gained attention in the numerous publications [3-21]. Variance of TEC is proposed as a new ionospheric perturbation index to describe ionospheric disturbances [12-13]. An ionospheric activity index, AI, is introduced which correlates with geomagnetic activity [9, 20]. The difference between storm-induced and the quiet time occurrence of disturbances is discussed in [21]. Ionospheric specification and forecasting based on observations from European ionosondes is proposed [11]. A global empirical model of TEC response to geomagnetic activity is developed based on TEC deviation from the 15-days forerunning median [19]. The ionospheric weather W index allows distinguishing the state of the ionosphere and plasmasphere from quiet conditions to

the intense storms ranging the plasma depletions (negative phase) or plasma density enhancements (positive phase) regarding the quiet reference normal state [14-18].

The W index reveals TEC behaviour varying from quiet state ($W=\pm 1$) to intense storm ($W=\pm 4$) providing a useful proxy index driving space weather than geomagnetic indices alone. Analysis how the disturbance is developed in space and time provides information concerning the situation in the future under different scenarios. And that creates the very useful tool for operational applications for regional service.

Mapping methods, radio propagation and a study of ionospheric variability need information to extend measurements made at one station. The study of correlation distances of foF2 [22-25] leads to an understanding of what the correlation distances in the real ionosphere are. Investigation of correlation coefficients of foF2 values measured at different stations in the European area is presented below under the conditions defined by catalogues of ionospheric quietness and disturbances [26-27] and a magnetic catalogue based on the AE indices [28]. These catalogues are used to divide analyzed data set into three subsets: for quiet conditions, for disturbed conditions and for all conditions. Two options are used in specifying the data subsets: (1) all days per month, or 5 ionospheric disturbed days or 10 ionospheric quiet days as defined by ionospheric catalogues; (2) all days per month, or 5 geomagnetic disturbed days or 10 quiet days as defined by the Auroral Electrojet, AE-catalogue.

The ionosphere experiences variability over a whole range of scales, from years to seconds [29-30]. The main problem in estimating the variability and also in quantitative investigations of different ionospheric phenomena is in establishing the quiet level [31]. The quiet level automatically defines the disturbed conditions and hence gives a tool for diagnostics, modeling and predictions. The thermospheric and ionospheric responses to magnetic disturbances need some time. That is why although the ionospheric and magnetic disturbances have a common origin, their evolution is rather different: there is no simple relation between the ionosphere and magnetic disturbances defined by magnetic indices. The correlations distances during quiet and disturbed conditions defined by different categories with different catalogues are presented below in the analysis of ionospheric variability [25].

2. Ionospheric W index

An increased knowledge of effects imposed by the ionosphere on operational radio systems could be earned by the service providing online estimate of the degree of TEC perturbation at each grid point of the map expressed by the ionospheric W index. For any specified location on the Earth, a segmented logarithmic scale of the ionospheric weather W index is introduced with the different thresholds of change in $NmF2$ or TEC according to Eq. (1) for quantifying the ionosphere variability [3, 14]:

$$D \log = \log(Y / Y_{med}) \tag{1}$$

where Y stands for the F2 layer peak plasma density $NmF2$ or TEC , and Y_{med} means quiet median for the same parameter estimated during a specified time period (e.g., 27-days running median).

Similar to the magnetic indices, ionospheric state description is provided by 4 levels of W -index of the ionospheric quiet state, moderate disturbance, moderate storm or an intense storm assigned for a specified thresholds of $Dlog$ according to the categories given in Table 1.

W-index	The ionosphere state
± 1	quiet state
± 2	minor activity
± 3	moderate activity (ionospheric storm)
± 4	major activity (intensive ionospheric storm)

Table 1. Specification of W -index magnitude and relevant ionosphere state with the sign '+' for $NmF2$ or TEC enhancement or '-' for $NmF2$ or TEC depletion [15].

3. Source EGNOS database for W index derivation

In this chapter we show application of W index for European area based on EGNOS. The European Geostationary Navigation Overlay Service, EGNOS, provides online the regional maps of the vertical total electron content in timely, continuous regime. EGNOS, as an augmentation system helps to improve the navigation position from about 5 meters to less than two meters. It provides the information to the users containing the errors in the position measurements and informs about disruptions of satellite signal. The system consists of three segments: Ranging and Integrity Monitoring Stations (RIMS) segment is designed for observing and collecting GPS signal and sending it to the Master Control Centers (MCC) which determine the accuracy of GPS and GLONASS signals and determine position inaccuracies due to disturbances in the ionosphere. Then the computed corrections are Up-Linked to the geostationary satellites, which then transmit it for reception by GPS users with an EGNOS enabled receiver.

The EGNOS signal is encoded according to the Radio Technical Commission for Aeronautics (RTCA) in DO-229D document. All EGNOS messages are stored and accessible free-of-charge, using standard means (specifically, the FTP protocol). EMS stores the augmentation messages broadcast by EGNOS in hourly text files. The EGNOS messages can be used to other applications. In the project the data for further analysis was taken from EMS and decoded to the simpler form containing only most important information.

For our purpose, the EGNOS messages number 18 and 26 are used. First of them contains the ionospheric grid point marks – the encoded position of grid point for which the ionospheric corrections are sent. The grid points are located in different degree-distance according to the

latitude. For the mid-latitude it is 5 degrees and for high-latitude it is from 10 to 30 degrees. Message number 26 contains the ionospheric delay corrections together with their errors. The data are presented in increments of 0.125 of unit.

The output file contains the information about the time of correction, grid point co-ordinates and value of ionospheric delay together with its error and TEC value.

The ionospheric delay and TEC combines the simple dependence:

$$Id = \frac{40.3}{f^2} TEC \quad (2)$$

where:

Id – ionospheric delay

f – frequency of signal

TEC – total electron content

We have applied W indexing to the EGNOS-TEC map output for producing online the hourly ionosphere-plasmasphere W index maps. The regional distribution of W index is produced at 66 grid points of a map (latitudes 35°N to 60°N in step of 5°, longitude-10°E to 40°E in step of 5°). The W index maps characterizing quiet or stormy state of the ionosphere-plasmasphere plasma are provided online at <http://www.cbk.waw.pl/> and archived for comparison with W index maps derived from the global ionospheric maps, GIM [3].

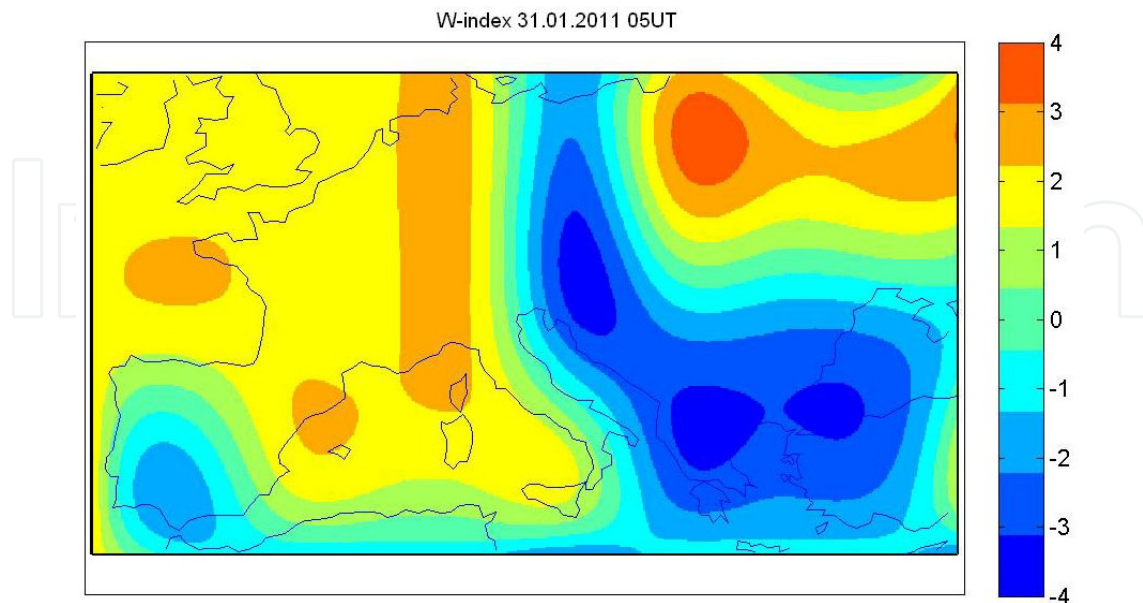


Figure 1. European regional W-index map during the substorm on 31 January, 2011, 5 UT, observed at latitudes from 35°N to 60°N and longitudes from 10°W to 40°E (EGNOS-TEC area).

Figure 1 illustrates W index map for positive and negative ionospheric disturbances over Europe created in real time by means of EGNOS-TEC data at the Regional Warning Centre RWC-Warsaw of the International Space Environment Service web page (<http://www.rwc.cbk.waw.pl>). Clear distinction of negative storm (blue) and positive storm (orange) signatures are seen in the map.

4. Discussion

Fig. 2 presents an example of the ionosonde observations of f_oF2 (left panel) and relevant TEC extracted from JPL-provided Global Ionosphere Map, GIM-TEC, (right panel) during the storm on 27-28 August, 2014, at Tomsk (56.5°N, 84.9°E). Hourly instantaneous data and quiet median (med) are plotted in Fig. 2a, b, relevant logarithmic deviations $Dlog$ are given in Fig. 2c,d, and W-index bars for f_oF2 and TEC are shown in Fig. 1e,f, respectively (Eq. 1). Relevant global magnetosphere ring current storm recorded with Dst index is plotted in Figure 3. Clear two-phase development of the ionosphere-plasmasphere storm is demonstrated with positive phase (plasma density and total electron content enhancement) during daytime on 27 August followed by the negative phase (plasma depletion) during the night and the following day on 28 August, 2014. The variations of two sets of parameters slightly differ one from another depicting the different level heights in the ionosphere, namely, f_oF2 near the peak of the F2 layer (300-400 km) while TEC represents the integral electron content over the altitude range from 65 to 20 200 km (GPS orbit).

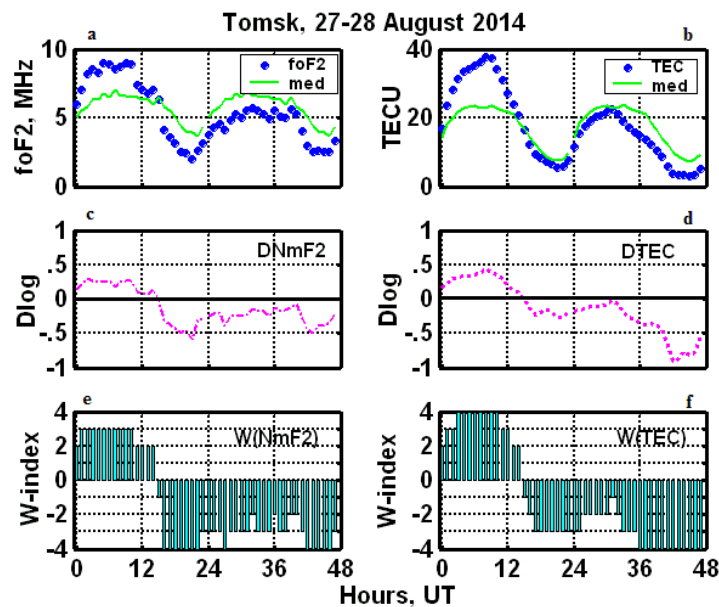


Figure 2. Source data and quiet median of the F2 layer critical frequency and TEC, the logarithmic deviation of the instantaneous values from the quiet reference, and local W-index at Tomsk during the ionospheric storm on 27-28 August, 2014.

The ionospheric storm may appear even under quiet geomagnetic conditions [17, 21]. This underlines the necessity of a specific ionospheric weather index complementing geomagnetic indices for the assessment and forecast of the space weather storms [9, 12-13, 15] for improving accuracy and safety of operational radio systems that are sensitive to an ionospheric impact.



Figure 3. Dst index from WDC Kyoto in August 2014.

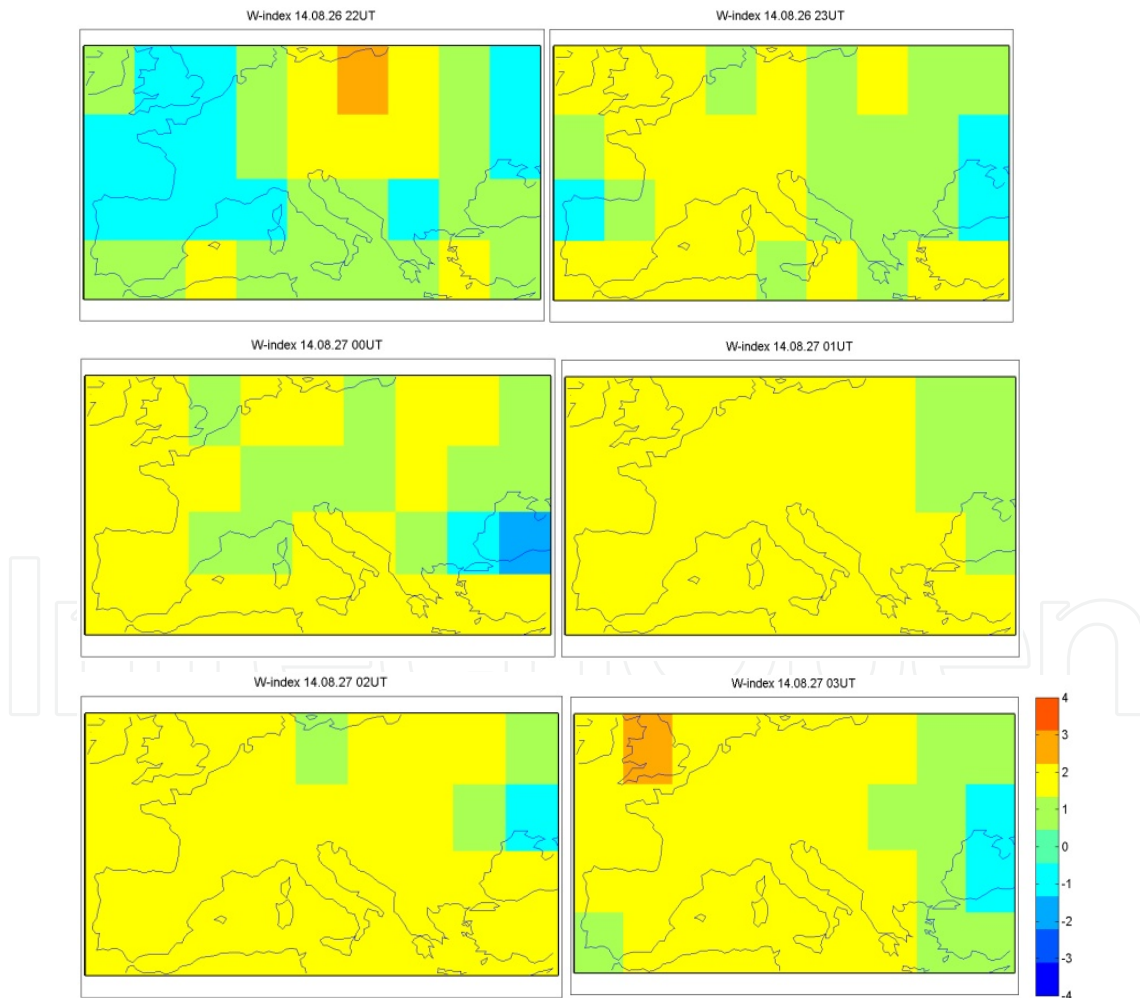


Figure 4. W index maps for the quiet period from 26.08.2014 22 UT to 27.08.2014 03 UT preceding start of magnetic storm on 27 August 2014.

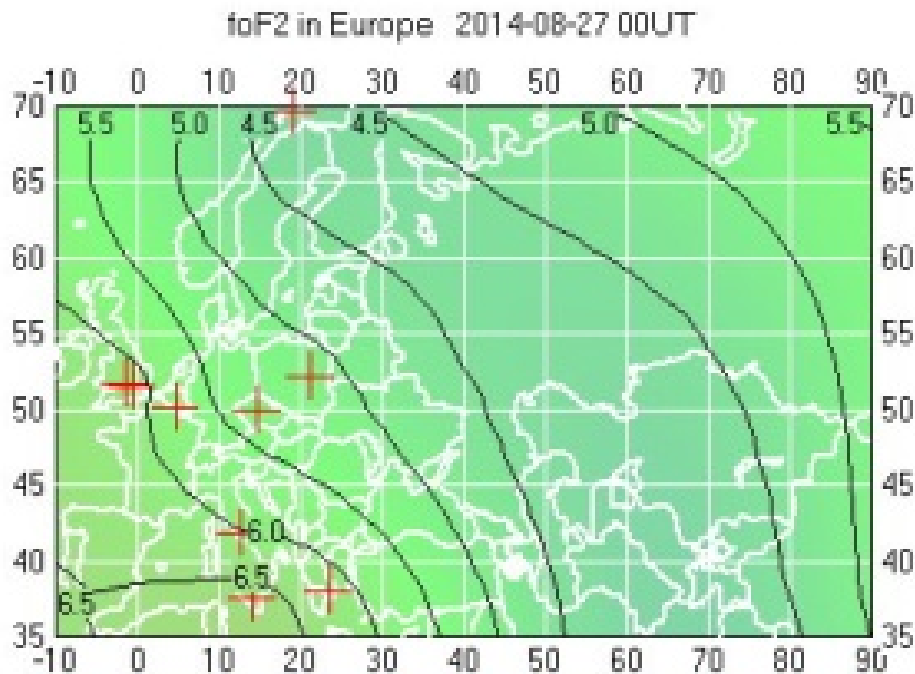


Figure 5. Near-real-time European map of foF2 at 27.08.2014 00 UT based on ionosonde measurements. Crosses show the ionosones sites.

Proposed W index scheme is based on the knowledge gained from the history of ionospheric estimate of the positive and negative plasma deviation regarding the quiet reference (e.g. [4-10]). As distinct from these publications, the TEC-based DIX index [13] does not distinguish between signs, i.e. the parameter pronounces only rapid changes of GNSS carrier phase ignoring increasing and decreasing behaviour of TEC which may be confusing for an index application when operator should take opposite steps in mitigating the positive or negative storm effects. While a need for introducing of the ionospheric indices is stressed out by majority of the authors, consensus on the best approach is a subject of more studies.

Further analysis has been performed based on data available in real-time RWC-Warsaw service. It reflects the situation of services working on-line where operational decisions have to be made automatically due to current situation.

The performance of W index for the quiet period that precedes start of the magnetic storm at 27 of August 2014 (Fig.3) is presented in Fig. 4.. Magnetic storm selected as gradual has been recognized only by high latitude stations Murmansk (68N, 33E) and Dixon (74N, 81E) as low intense storm. For comparison European map of foF2 at 27.082014 00 UT is presented in Fig. 5.. Superiority of light colours shows quiet behaviour of the ionosphere and plasmasphere. Current state of the F2 layer presented in Fig. 5. confirms quiet night within European area. Insignificant differences marked by green colour do not change the overall indication of low degree of perturbation for this period over Europe and is related more to irregular data coverage for this region.

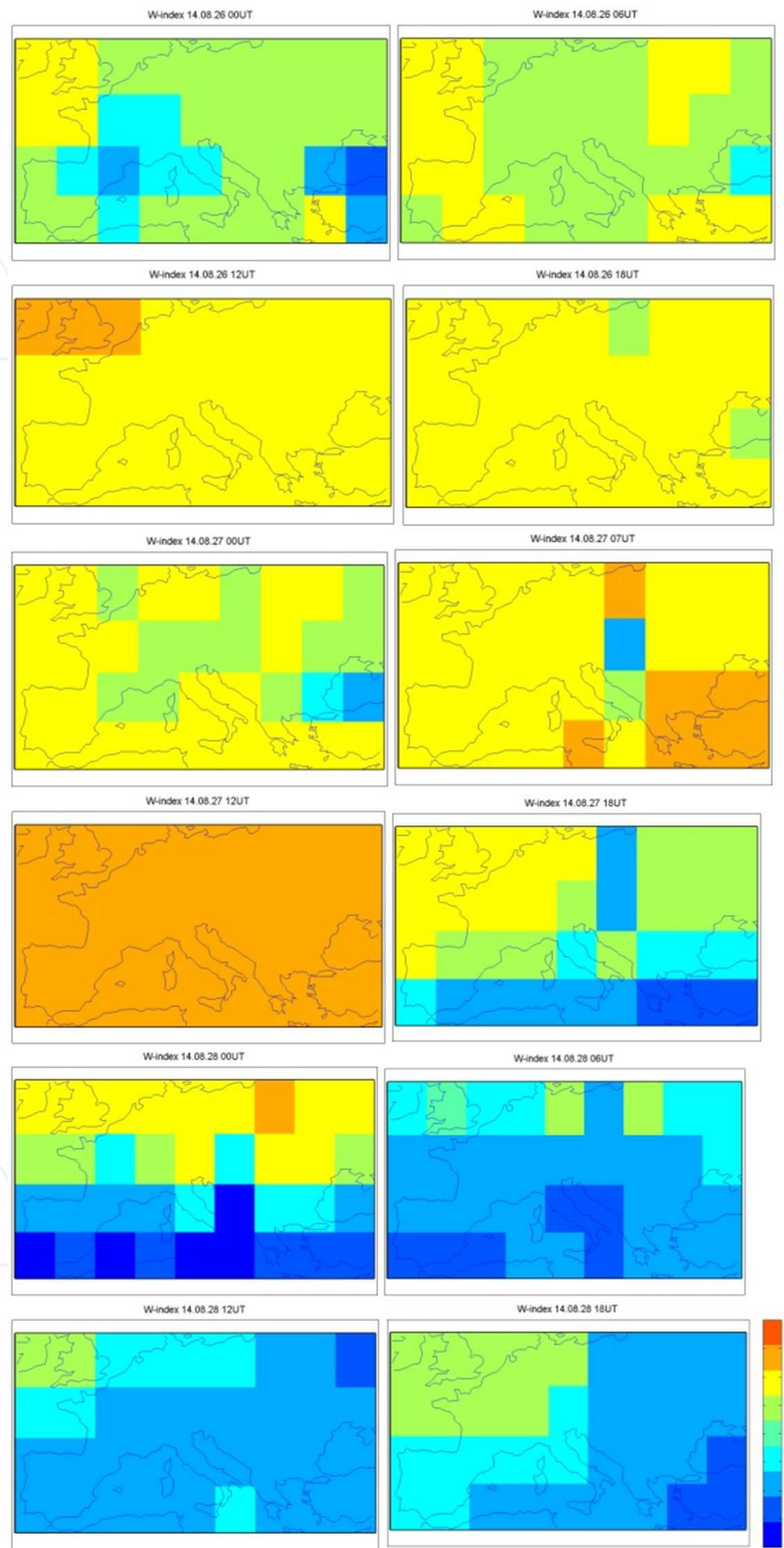


Figure 6. W index for European area at 00, 6, 12 and 18 UT, 26-28 August 2014.

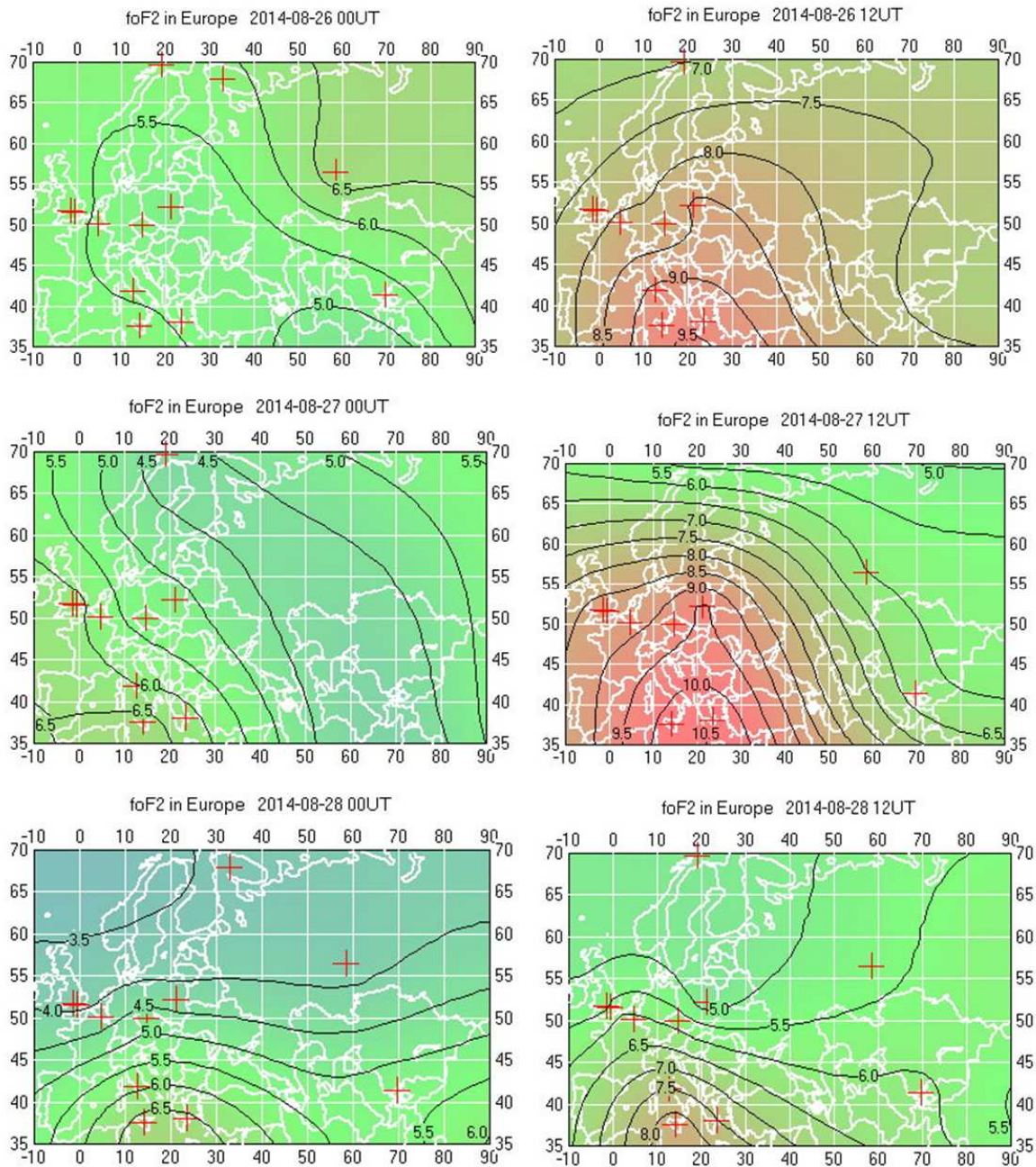


Figure 7. The foF2 maps for European area at 00 and 12 UT, 26-28 August 2014.

Further development of the disturbance is presented in Fig. 6. for W index and is illustrated by behaviour of F2 layer critical frequency in Fig. 7.. The magnetic storm that happened in the beginning of 27 of August 2014 has been indicated by W index as a moderate ionospheric storm manifested by increase of electron concentration during the day of 27 of August (orange colour). Usual behaviour of the storm with the decrease of electron concentration during the next phase is indicated by dynamic changes of W index from relative quietness during the second part of the day 27 of August and increase of intensity of negative disturbance shifted to middle latitudes (dominant blue segments).

5. Ionosonde data for correlation distances

Only one ionospheric characteristic, foF2, was considered for the correlation studies. Measurements are limited to the middle latitudes of European area for the years 1984-1987. All daily values of foF2 in digital form in COST238 PRIME Data Base in CNET, Lannion, France, were used. The stations used were: Uppsala (59.8°N, 17.6°E), South Uist (57.4°N, 7.3°W), Kaliningrad (54.7°N, 20.6°E), St. Peter Ording (54.3°N, 8.6°E), Miedzeszyn (52.1°N, 21.1°E), Slough (51.5°N, 0.6°W), Kiev (50.5°N, 30.5°E), Dourbes (50.1°N, 4.6°E), Pruhonice (50.0°N, 14.6°E), Lannion (48.8°N, 3.5°W), Poitiers (46.6°N, 0.4°E), Sofia (42.7°N, 23.4°E), Rome (41.9°N, 12.5°NE), Lisbonne (38.8°N, 9.2°W), Athens (38.0°N, 23.6°E), Gibilmanna (37.6°N, 14.0°E). All stations are located within the European area at middle latitudes. The differences between measured daily-hourly foF2 values and medians were determined for each station to eliminate the daily trend and the cross-correlation was calculated for the resulting differences for each pair of the stations to determine which ionospheric changes at one location are linearly related to changes at another. The overall 0.9-correlation distance was found to be around 500 km E-W and slightly less N-S. This anisotropy is systematically growing for correlation distances 0.8, 0.7 and becomes the greatest for 0.5, however in this last case it does not exceed 1300 km N-S and 2000 km E-W. Considerably stronger correlation can be seen under quiet and disturbed conditions.

6. Correlation distances under quiet and disturbed conditions

Criteria for the definition of ionospheric disturbances and quietness have been discussed in several papers [25-27, 29]. Generally, a poor correlation has been found for the deviations of daily foF2 from the median values and magnetic indices. Here we consider two categories: ionospheric and magnetic (defined by AE index) quiet and disturbed periods. Three catalogues were used; two for the definition of ionospheric conditions [26-27] and one for the definition of magnetic conditions [28]. The catalogue [27] is based on the visual analysis of daily foF2 measurements from 16 stations compared with the median. The catalogue [26] is based on the analysis of a number of the stations ranked each day as disturbed or quiet with deviations exceeding a diurnally varying reference level. The magnetic catalogue [28] defines disturbances and quietness using the magnetic AE index.

Correlation distances at middle latitudes are usually less in latitude than in longitude. This fact produces the elliptical shape of the curves on a plane described in degrees. One could expect this because of the distance difference between 1 degree in latitude and 1 degree in longitude. However elliptical shapes can also be seen when the distance between the stations is described in kilometers. In Fig. 8. the distances are shown for correlations equal to 0.9, 0.8, 0.7 and 0.5 for 1984-1987. All available ionosonde measurements of foF2 have been used in the calculations. In almost all cases, the ellipses are less flattened when constructed for higher correlation coefficients. Ellipses obtained for disturbed or quiet conditions are flattened out more than those for average conditions. Fig. 9. presents the ellipses obtained for correlation

coefficient $R=0.8$ for quiet and disturbed conditions defined by ionospheric and magnetic catalogues for 1984 and 1987. In all cases these specified conditions show that measurements are better correlated in longitude than in latitude. One could expect this for disturbed conditions; the disturbances usually propagate from higher to lower latitudes, however the correlation is not so strong as is seen during quiet conditions. High solar activity, Fig. 10., is added for a comparison.

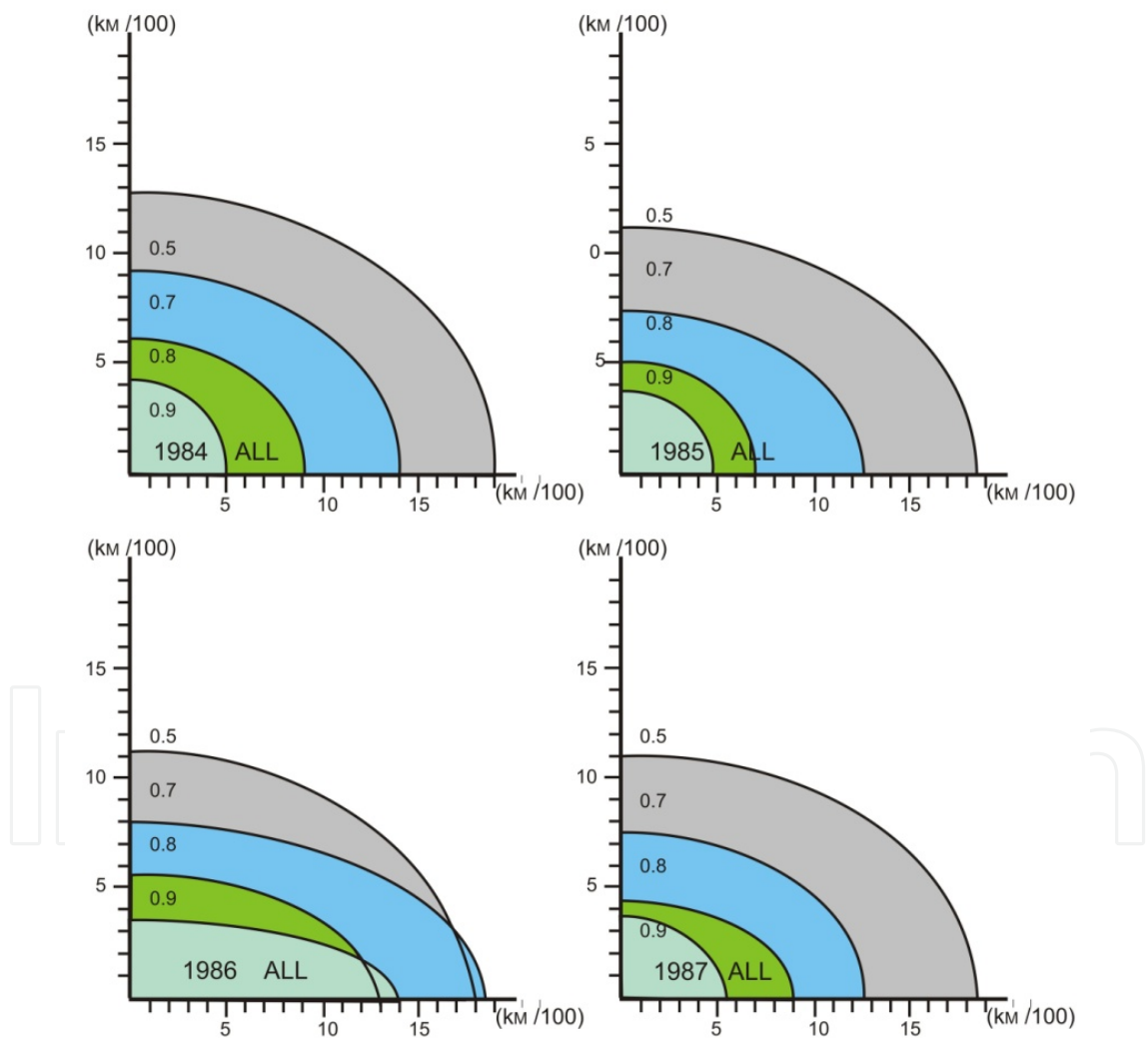


Figure 8. Correlation distances for correlation coefficients equal to 0.9, 0.8, 0.7, 0.5 for years 1984-1987.

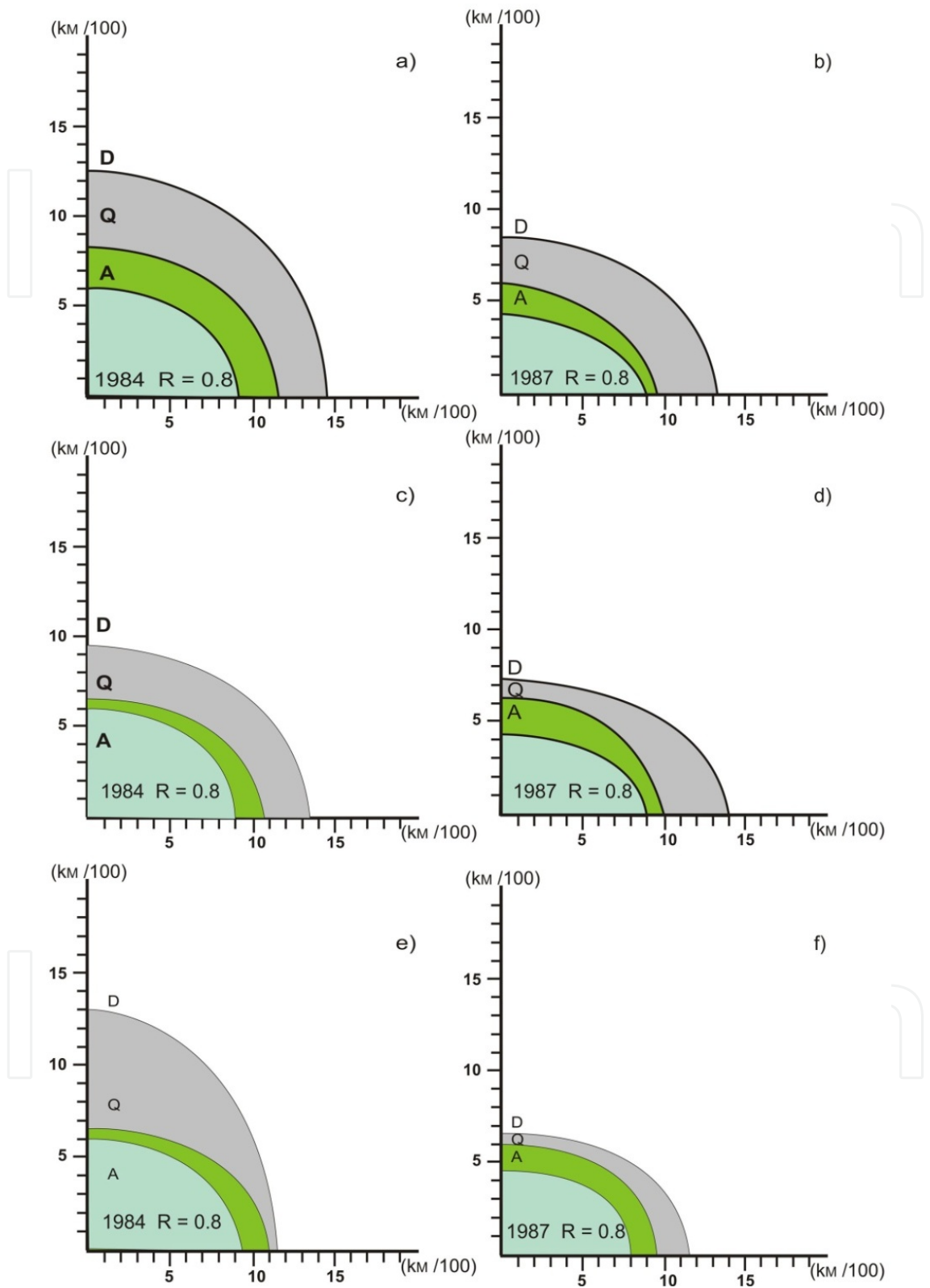


Figure 9. Ellipses for quiet and disturbed conditions in 1984 and 1987 for the first ionospheric catalogue (a,b), the ionospheric catalogue (c,d), magnetic catalogue (e,f).

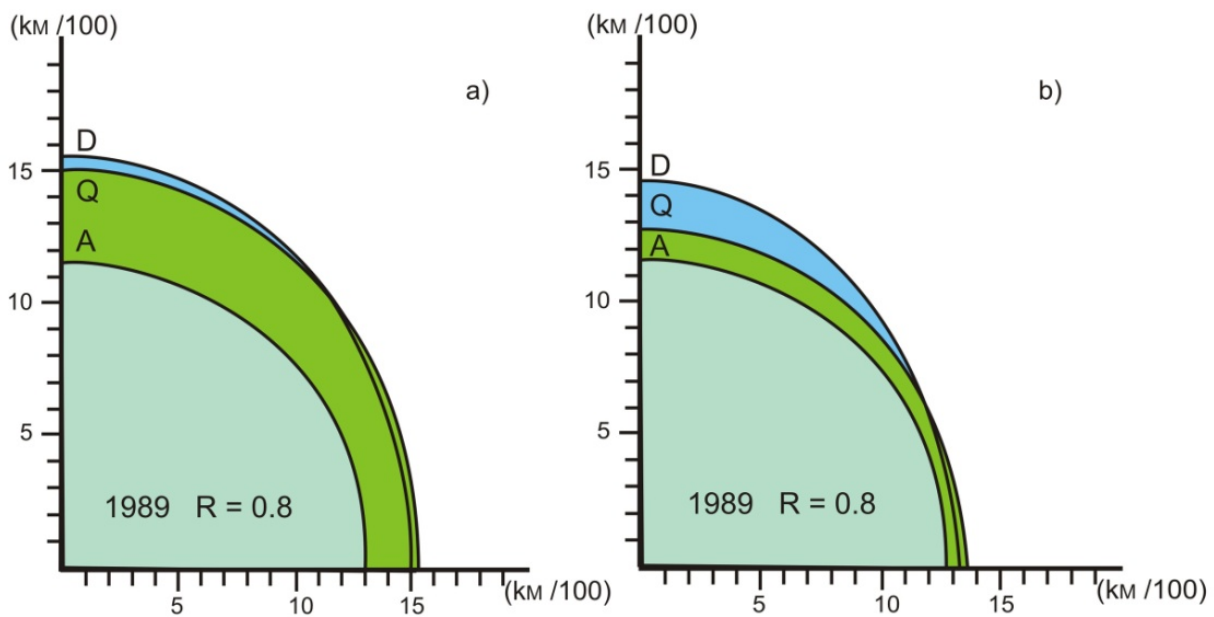


Figure 10. Ellipses for correlation coefficient 0.8 for quiet and disturbed conditions in 1989 year (a) for the first ionospheric catalogue and (b) for the second ionospheric catalogue.

7. Conclusions

It is clear that correlation distances during high solar activity are much larger. Measurements are also much better correlated in latitude than during lower solar activity. Correlation distances for disturbed conditions defined by magnetic AE catalogue are remarkable greater than for the second ionospheric catalogue, but less than for the first one. Thus, the magnetic catalogue chooses disturbed days which manifest only special ionospheric disturbances, while the ionospheric catalogue takes into account all disturbances, which are not always well connected to the global AE disturbances. Ionospheric variations at middle latitudes are better correlated in latitude when magnetic AE catalogue is used. It is evident that for this case latitudinal direction has equal footing and the flatness of the ellipse becomes smaller. Thus, the magnetic AE catalogue can give better correlations in longitude when analyzing ionospheric variability. However a large amount of ionospheric disturbances are not included in the analysis using the AE catalogue, so it cannot be treated as the only tool in an analysis of ionospheric variability. This presentation leads to the conclusions that the flatness of the ellipse in the most cases, during the disturbed and the quiet conditions, is smaller than for all available data. The average conditions represent the most 'chaotic' correlation, while foF2 during disturbed conditions are better correlated. The correlation is also stronger during quiet conditions than for average conditions. However the longest distances for better correlated data can be achieved using the first ionospheric catalogue.

This chapter presents scenario for new product of the ionospheric weather W-index in the space weather services first specified for any given location on the Earth and then applied to producing the regional and global W-index maps. The instantaneous W-index is scaled in metrics of four positive and negative index values of the ionospheric quiet state, moderate disturbance, moderate storm or an intense storm assigned for a specified thresholds of logarithmic deviation of the F2 layer peak plasma density NmF2 (critical frequency foF2) or total electron content TEC from their quiet reference. Implementation of the above technology using the EGNOS-TEC data is made for an online presentation of the ionosphere W-index maps over Europe characterizing the ionosphere from quiet state to an intense storm. Being product of the ionosonde measurements of the ionosphere peak electron density NmF2 or GNSS TEC observations, the W-index is capable to characterize the disturbance in the ionosphere which is not seen straightforward with NmF2 or TEC source data. W index gives quick information about disturbed area and so the reliability of GNSS signal from this direction. It allows for instance to exclude irrelevant satellite from TEC calculations, or confirms the reason of total lack of the signal. In this capacity W-index presents an important tool for improving the operational use of technological telecommunication and navigation systems.

Acknowledgements

The EGNOS data are provided at <http://egnos-portal.gsa.europa.eu/>. The foF2 values in digital form in COST238 PRIME Data Base in CNET, Lannion, France, were used. Tomsk ionosonde data are provided at <http://sosrff.tsu.ru/>. The equatorial Dst index and Auroral Electrojet AE index are provided by WDC for Geomagnetism at <http://wdc.kugi.kyoto-u.ac.jp/dst/dir/index.html>. The European regional foF2 maps W index maps are provided online at <http://www.cbk.waw.pl/>. W-index for the ionosonde stations network and global W-index maps are provided at <http://www.izmiran.ru/services/iweather/>. The assistance of Lukasz Tomasik of SRC and Ljubov Poustovalova of IZMIRAN in web products design is gratefully acknowledged. TLG acknowledges the support of joint grant of RFBR 13-02-91370-CT_a and TUBITAK 112E568 for this work. This work is partly supported by National Science Center Poland grant no 2011/01/B/ST9/06108.

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