SPACE WEATHER IMPACT ON SATELLITE NAVIGATION AND POSITIONING

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Keywords

Space weather, ionosphere, Total Electron Content (TEC), Global Navigation Satellite System (GNSS), Ionospheric perturbations, ionospheric models, monitoring, positioning

Abstract

Space weather can adversely affect accuracy, reliability and availability of global navigation satellite systems (GNSS) in different ways. GNSS satellites can be direct subject to damage by high energetic particles or radiation. Furthermore, enhanced solar radio emission can interfere with GNSS signals and solar wind enhancements can considerably disturb the propagation of navigation signals in the ionosphere. Single frequency GNSS measurements require a correction of the ionospheric range error. Modeling and monitoring of related errors contribute to mitigate the ionospheric impact on GNSS

In dual frequency GNSS systems space weather related ionospheric perturbations must be taken into account on a broad range in magnitude at quite different scales reaching from small scale plasma turbulences in the meter domain up to large scale ionization fronts in the 1000 km range. Thus, ionospheric perturbations can considerably reduce the achievable accuracy in precise positioning applications, whereas in safety of life applications such as aircraft landing in aviation, the protection level might be violated.

To reduce the space weather impact on those applications and to enable correction or mitigation of ionospheric effects, continuous monitoring of the ionospheric behavior is required e.g. by measuring the Total Electron Content (TEC). Thus, augmentation systems such as WAAS in US and EGNOS in Europe and ionospheric services such as SWACI provide correction information and messages concerning the current and predicted perturbation degree of the ionosphere. Much work has still to be done to fulfill customers' requirements on accuracy and reliability of forecast quality.

Introduction

Space weather can adversely affect accuracy, reliability and availability of global navigation satellite systems (GNSS) in different ways. High energetic particles or radiation may damage the functionality of GNSS satellites, solar radio emission may interfere with GNSS signals and finally GNSS signals may be significantly perturbed due to the ionospheric plasma. In single frequency applications ionospheric refraction is the biggest error source. Ionospheric range errors at slant ray paths may reach up to 100 m and therefore must be corrected even for mass market applications. Considerable efforts are undertaken to correct this error in a proper way. Problems arise due to the fact that the ionosphere is strongly impacted by electromagnetic and corpuscular radiation of the sun. Thus, the ionospheric key parameters such as electron density, ion composition and plasma temperature are highly variable during a solar cycle, the seasons, and the daytime and with geographic location due to changing solar

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irradiation conditions. Due to complex conversion of solar energy and related coupling processes in the magnetosphere-thermosphere-ionosphere systems the ionosphere itself is integral part of space weather. Electromagnetic GNSS signals traversing the ionosphere are mainly impacted by the electron density and its distribution along the ray path. Therefore, ionospheric refraction of radio waves is considered in the first section.

Ionospheric Impact due to Refraction of Radio Waves

The refraction of radio waves traversing the ionosphere is described by the refractive index n which can be approximated for GNSS signal frequency f by [1] :

$$n = 1 - \frac{f_p^2}{2f^2} \pm \frac{f_p^2 f_g}{2f^3}\cos\Theta - \frac{f_p^4}{8f^4} \qquad (1)$$

Here f_p denotes the plasma frequency ($f_p < 25$ MHz) which is defined by the formula

$$f_p^2 = \frac{e^2 n_e}{4\pi^2 m_e \varepsilon_0} \qquad (2)$$

and f_g is the gyro frequency ($f_g \approx 1.4$ MHz), ε_0 is the free space permittivity, B is the geomagnetic induction, Θ is the angle between the ray path and the geomagnetic field and e, n_e and m_e are electron charge, density and mass, respectively.

When travelling through the ionosphere, radio waves follow Fermat's law, i.e. the phase integral or Eikonal $L = \int n \cdot ds$

becomes a minimum. Following this rule, the ray path s prefers to go through regions of high electron density because the phase speed v=c/n is greater than the velocity of light c at high electron density according to Eq. (1). Thus, the ray path deviates from a straight line due to bending effects (Figure 1). Ray path bending and consideration of higher order effects may reach up to 20 centimeters and have to be considered in precise GNSS applications.

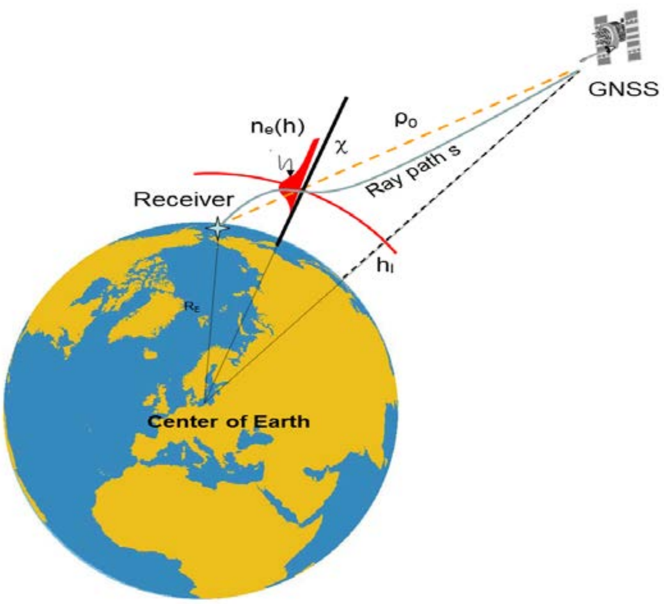


Figure 1: Illustration of transionospheric radio wave propagation.

$n_e(h)$: electron density, ρ_0: Line of sight, s: true ray path, h_I: ionospheric height for mapping function

Neglecting higher order terms in the refractive index in Eq. (1), the clearly dominating first order ionospheric range error d_I can be written as:

$$d_I = \frac{K}{f^2}\int_S^R n_e ds = \frac{K}{f^2}\cdot TEC \tag{3}$$

with K= 40.3 m^3s^{-2}.

Since the ionospheric range error in GNSS applications is proportional to the total electron content of the ionosphere (TEC), the range error follows all changes of the ionospheric ionization (1 TECu corresponds with 16.2 cm at L1 GPS frequency).
The close relationship between TEC or ionospheric range error with space weather or solar activity is shown in Figure 2.

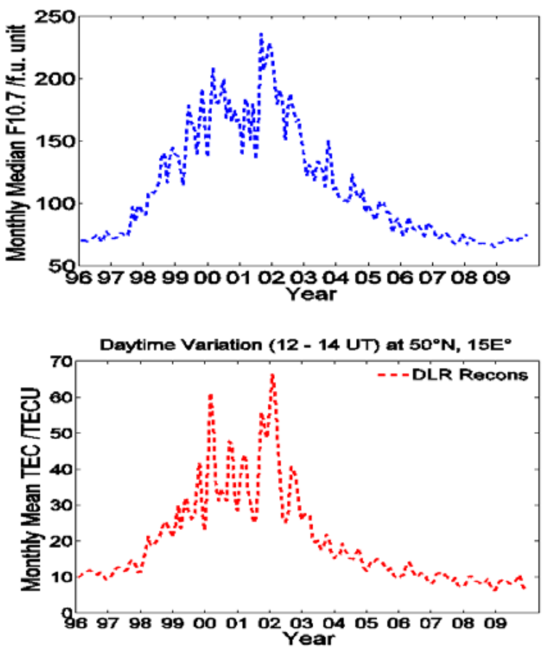


Figure 2: Comparison of solar activity index F10.7 with TEC at 50°N; 15°E during solar cycle 23. F10.7 is a proxy of ionizing EUV radiation of the sun.

Solar radiation may rapidly increase during solar flares if the solar emission spectrum contains also a strong enhancement of the ionizing extreme ultraviolet radiation (EUV). In such cases the range error may increase by several meters within a minute. This may lead to problems in monitoring systems to derive reliable corrections and at receiver level due to rapid phase changes.
Another effect, strongly related to the coupling of Coronal Mass Ejections (CMEs) into the magnetosphere is the generation of the dynamic convection electric field which drives the ionospheric plasma from the day- to the night side across the poles and forms the so called ‘tongue of ionization’. This can nicely be seen in Figure 3 over the North Pole area around 20:00 and 21:00 UT during the Halloween storm on 30 October 2003.
Seen is strong enhancement of ionospheric ionization (TEC) over the polar area forming a large tongue of ionization. The related spatial and temporal changes, may cause severe impact on GNSS which is considered in the subsequent section. During storms, the strong enhancements of the solar wind energy due to CMEs generate large perturbations in the high-latitude ionosphere and thermosphere. This results in a significant variability of the plasma density and/or the formation of ionization fronts which commonly propagate towards lower latitudes. The high latitude electric field, precipitation of energetic particles, perturbation induced winds are probably the most powerful driving forces for highly dynamic and complex processes at high latitudes.

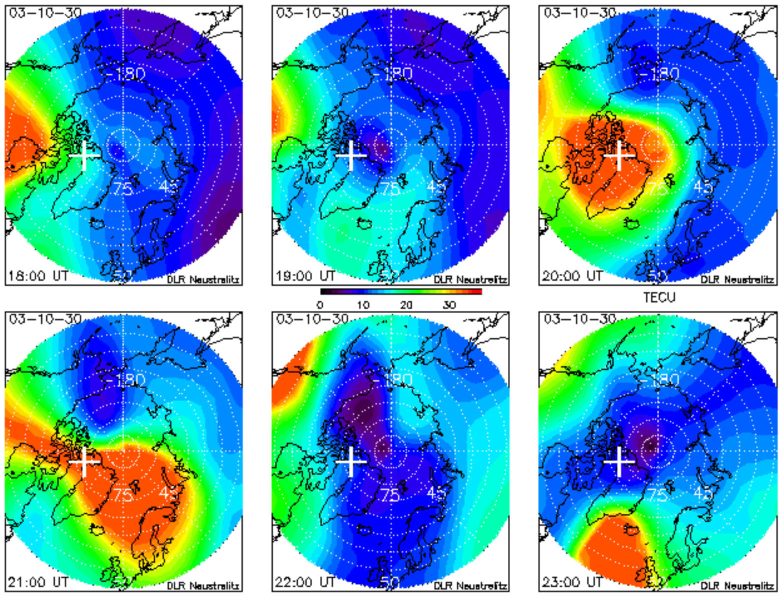


Figure 3: Polar TEC maps during the Halloween storm from 18:00 - 23:00 UT on 30 October 2003

Ionospheric perturbations and their impact on GNSS

Mid- and large scale perturbations

Whereas first order ionospheric range error can be eliminated in dual (multi) frequency GNSS applications, single frequency applications at mass market and in aviation require external ionospheric range error corrections. This can be realized either by modeling the ionospheric behavior (TEC) or by monitoring TEC with sufficient accuracy. Both methods suffer from ionospheric perturbations. Current correction models such as the GPS or the Klobuchar model [2] and the NeQuick model [3] planned to be used as single frequency correction model for Galileo are climatological, i.e. they are not able to describe highly variable ionospheric perturbations. The accuracy of the alternative correction method based on ionospheric monitoring is limited due to ionospheric gradients and perturbations which are not properly considered in the mapping technique. The problem of ionospheric gradients in aviation is illustrated in Figure 3.

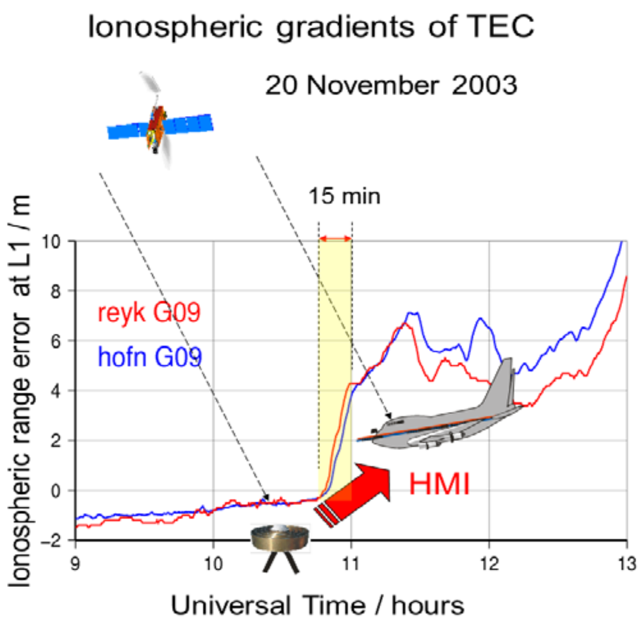


Figure 3: Illustration of ionospheric threats caused by ionospheric fronts during GNSS guided aircraft landing.

If the ground based augmentation system measures significantly different range errors as they should be applied to the landing aircraft, the assisting ground system provides a Hazarding Misleading Information (HMI).

The measurements were made on 20 November 2003 at IGS stations Reykjavik and Hofn.

It becomes evident that severe ionospheric gradients may cause threat in Safety of Life (SoL) applications. Therefore, estimations of the occurrence probability function of horizontal gradients of ionization and monitoring of the actual ionospheric state contribute to fulfill SoL requirements e.g. in aviation. Reported are horizontal gradients in the order of 300mm/km over US whereas over Europe gradients of up to about 117mm/km have been reported [4] (TEC is converted via Eq. (3) to range error at L1 in mm). During maximum solar activity conditions and severe storms, gradients up to 500mm/km might occur. To support the certification of the aircraft CAT I landing system at airport Bremen, DLR has developed an ionospheric threat model. Satellite Based Augmentation Systems (SBAS) like the European Geostationary Navigation Overlay Service (EGNOS) or the Wide Area Augmentation Service (WAAS) of US provide correction information to aircrafts for flight and landing operations. During ionospheric perturbations the gridded information at grid sizes of 5° x 5° in latitude and longitude is insufficient to map local ionospheric fronts within the grid mesh. Thus, during strong ionospheric perturbations the required protection level might be violated, i.e. the availability of the augmentation service is reduced. This was the case for WAAS at Alaska area during a moderate storm on 24 September 2011 when the availability dropped down to about 60% around 21:00 UT. The related ionospheric perturbation is shown in Figure 4 as a strong enhancement over the North American - Pacific Ocean area compared with median reference values.

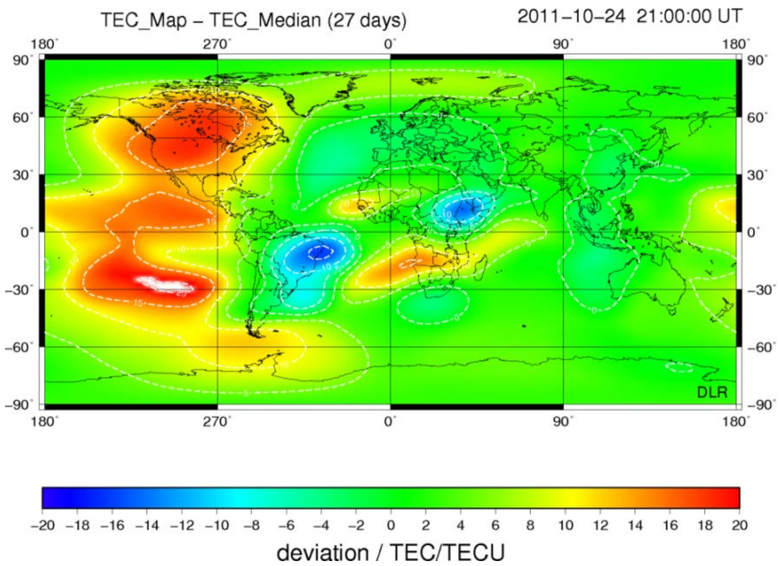


Figure 4: Deviations of global TEC from previous 27 day medians at 21:00 UT on 24/10/ 2011. Actual TEC and related median maps are created every 5 minutes in DLR Neustrelitz at SWACI (http://swaciweb.dlr.de).

The ionization over US and the Pacific Ocean region is enhanced by more than 20 TECU (3.2 m at L1) in the vertical direction, i.e. the range error may rapidly change up to more than 9 m during the storm at low elevation angles. Due to the dispersive refractive index shown in Eq (1), dual frequency measurements enable the mitigation of the first order effect defined in Eq (3) by using the so-called L3 combination of two phases. Nevertheless, Differential GNSS Systems such as Real Time Kinematic (RTK) systems are sensitive to horizontal inhomogeneities of ionospheric plasma due to ambiguous solutions when determining the integer number of carrier wavelengths between satellite and receiver. The rate of successful ambiguity resolution may considerably drop down during severe ionospheric storms. Besides gradients of ionization fronts as indicated in Figure 5, also Mid-Scale Travelling Ionospheric Disturbances (MSTIDs) may already cause problems in precise geodetic systems [5].

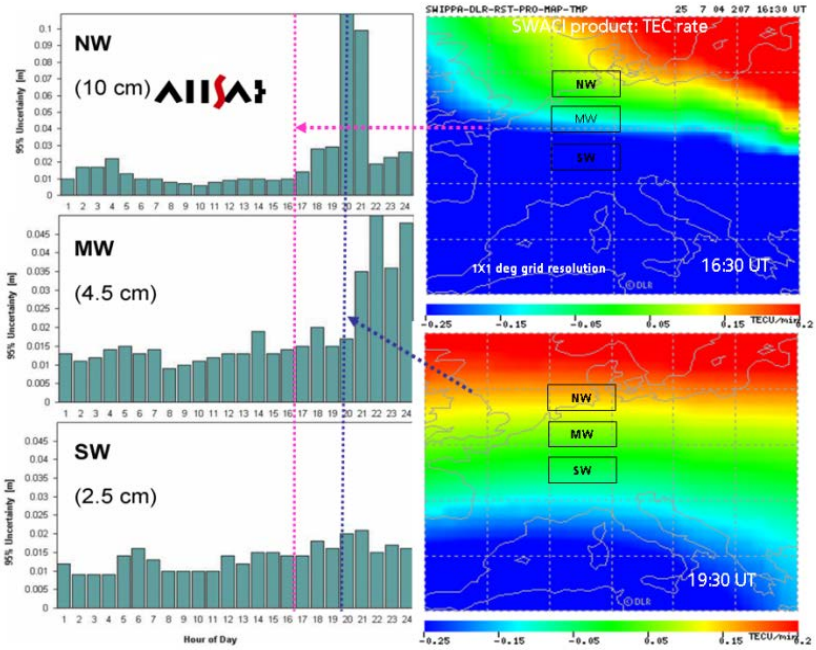


Figure 5: Performance of the DGPS network of Allsat (left panel) compared with TEC rate maps from SWACI over Europe at 16:30 and 19:30 UT on 25 July 2004.

Although dual frequency measurements are used in precise surveying networks, ionospheric perturbations may significantly degrade their performance

Small scale perturbations

Besides regular refraction of GNSS signals as considered in the previous section, other propagation effects such as diffraction and forward scattering have a significant impact on GNSS signal propagation at small perturbation scales of the ionospheric plasma. These propagation effects result in rapid fluctuations of signal phases and amplitudes. At high latitudes the plasma irregularities are often caused by particle precipitation and related to ionization patches [6]. At low latitudes plasma turbulences due to Rayleigh Taylor instability and so-called “plasma bubbles” along magnetic field lines may occur. Under the influence of an electric field the latter my drift across geomagnetic field lines.
The most commonly used parameter to characterize the intensity of signal strength fluctuations is the scintillation index S_4, defined by the equation:

$$S_4 = \sqrt{\frac{< I^2 > - < I >^2}{< I >^2}} \qquad (4)$$

where I is the signal intensity.
Carrier phase scintillations are commonly defined by the phase noise σ_φ over a time interval of 1 minute.
As Figure 6 shows, strong amplitude fluctuations (S_4> 0.6) may cause loss of lock of signals dependent on the robustness of the receiver. In GNSS applications loss of lock means a reduced availability of GNSS signals which reduces the accuracy of the positioning solution because the achievable accuracy depends also on the geometry of ray paths. The wider the angle between used ray paths the better the achievable accuracy. If the number of signals is reduced to less than four, practically no solution is possible. Thus, ionospheric scintillations may have an impact on continuity, accuracy and availability of GNSS services.

The S_4 index depends strongly on geophysical conditions, such as local time, season, latitude, and solar activity level. Although the solar activity was very low in 2006 (F10.7 = 80), scintillations have been observed in Bandung/Indonesia at an occurrence probability of about $6x10^{-3}$ for severe scintillations with $S_4 \geq 0.8$. The seasonal dependence shows typical maxima around the equinoxes.

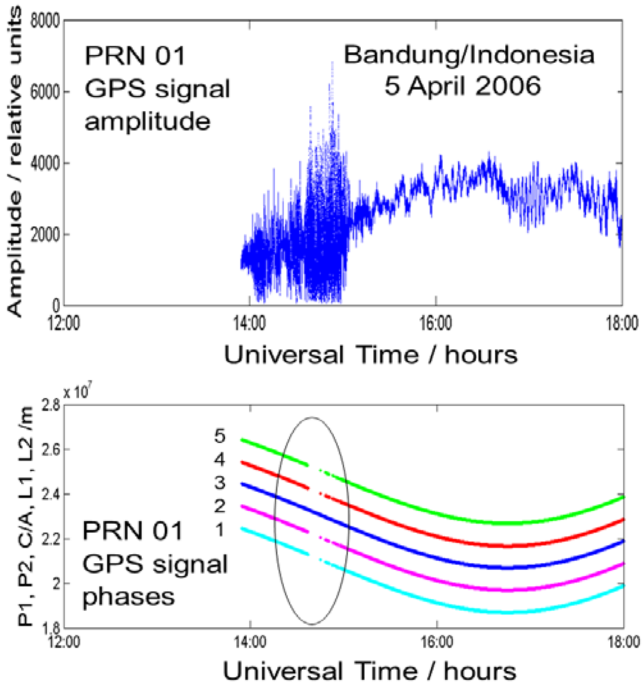


Figure 6: Amplitude scintillation event in the evening hours of 5 April 2006 at Bandung/Indonesia (06°53'S; 107°35' E) at signal path of satellite PRN01.

Numbers 1 – 5 correspond with GPS phase measurements P1, P2, C/A, L1, L2, respectively. The phase values are shifted for plotting by adding proper constant values.

Mitigation of ionospheric impact

There are several possibilities to reduce the space weather or ionospheric impact on GNSS systems. It is possible to correct regular refraction errors by direct measurements (dual frequency techniques), by using external monitoring information or by modelling results. The impact of severe space weather induced perturbations may be reduced by estimating the current perturbation degree of the ionosphere and to take into space weather warnings and forecasts. Ionosphere related monitoring services, warning messages and forecasts based on original information from the sun are under development in Europe [7]. A few mitigation techniques are briefly reviewed in this chapter.

Modelling

GPS uses the so-called Klobuchar model [2] from the beginning to correct ionospheric range errors to a certain degree (about 60%). The permanently actualized 8 coefficients of this internal TEC model are provided to GPS users via the navigation message. So the user can perform these corrections very easily. The European Galileo system plans to use the NeQuick model [3] or correcting single frequency measurements. Single frequency measurements are commonly used in mass market devices and in aviation. Therefore, there is a big potential for using this type of corrections. DLR has developed a family of small and fast TEC models for range error corrections (NTCM-GL) [8], TEC monitoring assistance and forecasting [9]. In addition to such first order correction models DLR has developed model approaches to correct higher order ionospheric range errors in the order of up to about 20 cm [1]. Such models can be used in precise GNSS applications.

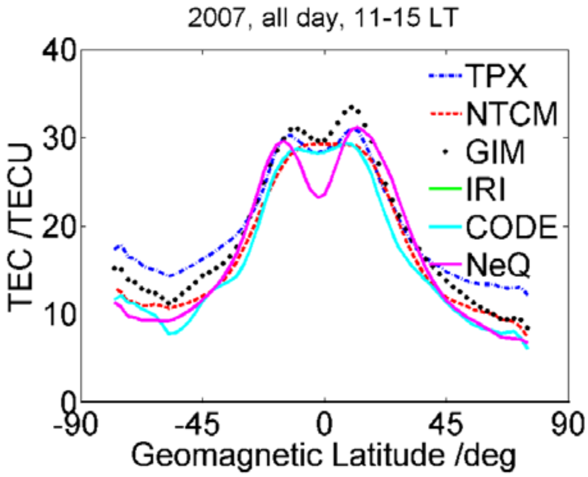
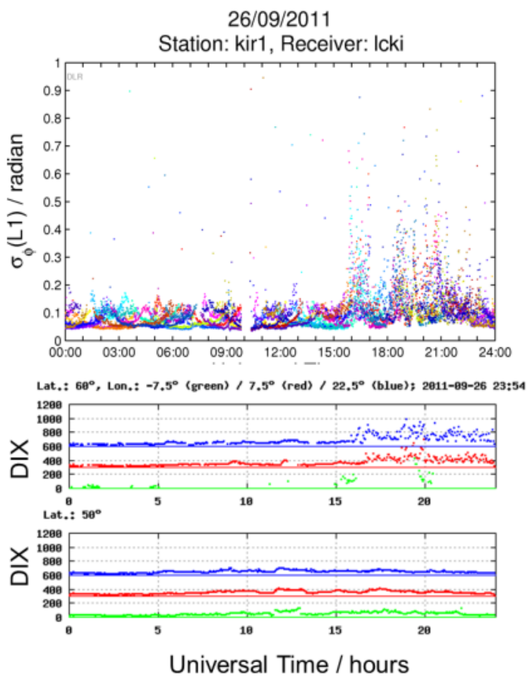


Figure 7: Comparison of TEC data from ionospheric models IRI, NeQuick (NeQ) and NTCM-GL with TEC reconstructions and measurements from TOPEX, GIM and CODE

Although the global NTCM-GL model uses only 12 coefficients, it provides a similar performance as other much more complex models such as NeQuick and the International Reference Ionosphere (IRI). Principally, such empirical models can correct ionospheric range errors in average, i.e. climatological sense. During ionospheric perturbations they may fail by more than 200%. Therefore, ionospheric monitoring is a better solution for deriving correction information.

Monitoring services

To provide a single frequency aviation aircraft landing system with ionospheric corrections, special augmentation systems have been established. Ground based Augmentation Systems (GBAS) as illustrated in Figure 2 or Satellite Based Augmentation Systems (SBAS) such as EGNOS and WAAS have been established during the last years. Although these augmentation systems provide more accurate correction information to users, they are still sensitive to space weather storms as discussed in the previous section. Therefore, it is essential to provide information on the reliability of the provided corrections to the user. In severe cases, if well-defined protection levels are violated, the service is not available. This may happen over Europe especially at high latitudes in Scandinavian countries and at low latitudes over North Africa.



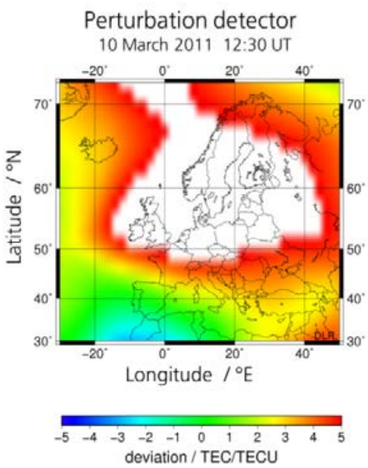


Figure 8: Perturbation detection in DLR Neustrelitz via scintillation monitoring Upper left panel), DIX monitoring and a perturbation detector (right panel).

DLR has developed the Space Weather Application Center Ionosphere (SWACI – http://swaciweb.dlr.de) which provides regional and global TEC maps and additional local and regional information on ionospheric perturbation degree. Besides ionospheric scintillation information at selected sites information on mid- to large scale perturbations is provided via the Disturbance Ionosphere Index to registered users [10]. As Figure 8 shows, small scale induced scintillations at Kiruna and mid- to large scale perturbations are often coupled. In case of 26 September 2012 the perturbations appear only at higher latitudes ($\varphi > 55$ °N). In Figure 8 the DIX values are segmented into 9 sub regions which may presented also as instantaneous maps thus providing information on the regional distribution of perturbations. Such information is valuable for precise GNSS networks as the error distribution map of AxioNet shows. Since DIX is based on one hand on pure space weather –ionosphere relationships and on the other hand is closely related to the performance of precise GNSS networks, there is a chance to estimate the performance of GNSS applications in advance by developing space weather related warning and forecasting tools.
As for terrestrial weather there is a practical need for ionospheric forecasts. Since space weather is a natural phenomenon, basic features of the ionospheric behaviour can be forecasted when knowing the underlying physics of the coupled magnetosphere - thermosphere - ionosphere system, its current state and the driving space weather forces such as solar radiation and solar wind. Therefore, more detailed studies are needed to improve our understanding of space weather related ionospheric effects.
Enhanced space weather impact is expected first on the high-latitude ionosphere because of its stronger electro-dynamic coupling with the magnetosphere and the solar wind. The high latitude electric field, precipitation of energetic particles, and, are probably the most powerful driving forces for the highly dynamic and complex processes. During storms, strong enhancements of the solar wind energy generate large perturbations in the high-latitude ionosphere and thermosphere resulting in significant variability of the plasma density, which commonly propagate towards lower latitudes.

Summary and Conclusions

Space based radio systems such as those developed for satellite communication, GNSS navigation and positioning or remote sensing are affected by ionosphere induced propagation errors. Regular ionospheric propagation delay and perturbation induced range errors, ambiguities in phase resolution or loss of lock cannot be ignored in precise and SoL applications of GNSS. To reduce the ionospheric impact on GNSS navigation and positioning, several mitigation techniques are applied.
The GNSS technique provides a unique opportunity to monitor ionospheric key parameters on regional and/or global scale in near real time to provide corrections and/or warnings on ionospheric perturbation degree. Ionospheric perturbations cover a broad spectrum of spatial and temporal scales therefore causing different effects in various GNSS applications.
Range errors may be reduced in single frequency applications by using empirical models or monitoring data.
Customers of dual frequency GNSS networks are interested in warnings and forecasts of space weather events and related ionospheric perturbations and threats. Methods and techniques to characterize the perturbation degree of the ionosphere and to forecast the ionospheric behaviour during storms are under development. Intensive research is still needed to improve our understanding of physics of space weather induced processes in the Earth's environment.

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Biography

Norbert Jakowski received a Ph.D. degree in solid state physics in 1974 from the University of Rostock. After finishing the university he joined the Institute of Space Research in Neustrelitz, East Germany in the same year. Since German reunification in 1991 he has been working in the German Aerospace Center (DLR). Currently he heads the ionospheric research group in the Institute of Communications and Navigation of DLR.

Norbert Jakowski has long-term experience in ionospheric research, modelling and monitoring the ionosphere by using transionospheric radio sounding methods, in particular GNSS techniques. He has developed methods to estimate the Total Electron Content (TEC) of the ionosphere from ground and space based GPS measurements by using dual frequency code and phase measurements. Comprehensive GPS data sets have been used to develop robust empirical models of ionospheric key parameters such as TEC, peak electron density or F2 layer height. Research studies focused on ionospheric storm mechanism and propagation of perturbations. Besides first order ionospheric range errors also higher order refraction effects on navigation signals have been studied. He has published more than 100 papers in refereed journals. Due to participation in a number of projects of European Commission and ESA, he is well experienced in international collaboration.

Norbert Jakowski is national representative of the European action COST ES 0803 "Developing space weather products and services in Europe", member of the steering committee of the Space Weather Working Team and the 'Network of Experts on Electromagnetic Wave Propagation' at ESA, National delegate of the World Meteorological Organization Inter-Programme Coordination Team on Space weather, and is a member of the Space Weather Expert Team for the UN Committee on the Peaceful Use of Outer Space Working Group on the Long-Term Sustainability of Outer Space.