Ionospheric Impact on GNSS Signals

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ABSTRACT:
Space weather can adversely affect accuracy, reliability and availability of global navigation satellite systems (GNSS). To be aware of the space weather impact on navigation signals in the L- band, a permanent monitoring of the ionospheric behavior is required in precise and safety of life applications. Enhanced ionization level of the ionosphere increases also ionospheric range errors. Whereas dual frequency GNSS measurements enable mitigating first order errors, higher order errors do not cancel out by combining the signals at both frequencies.
Space weather events affecting the ionospheric plasma distribution may degrade the navigation information or even the electromagnetic signal itself.
We discuss several space weather effects in the ionosphere such as strong perturbations in plasma density and distribution using ground and space based GNSS measurements.
The temporal variation of high latitude TEC data extracted from polar TEC maps indicate a close correlation of TEC fluctuations not only with geomagnetic activity indices but also with particle flux data.
Key words: ionosphere, GNSS, total electron content, radio wave propagation

RESUMEN:
El tiempo espacial puede afectar adversamente la precisión, fiabilidad y disponibilidad de los sistemas de navegación global por satélites (GNSS). Para tomar conciencia del impacto de la meteorología espacial en las señales de navegación en la banda L en aplicaciones de precisión y seguridad, es necesario disponer de un control permanente del comportamiento de la ionosfera.
El aumento del nivel de ionización de la ionosfera incrementa también el rango de los errores. Mientras las medidas de GNSS en frecuencia dual permiten mitigar los errores de primer orden, no es posible cancelar los de mayor orden mediante la combinación de señales a ambas frecuencias.
Los fenómenos de la meteorología espacial que afectan la distribución del plasma ionosférico pueden degradar la información para navegación o incluso la señal electromagnética en sí misma.
En este artículo se discuten varios efectos del tiempo espacial en la ionosfera, como las variaciones intensas en la densidad de plasma y su distribución, mediante el empleo de medidas de GNSS tomadas en el suelo y el espacio.
La variación temporal de datos de TEC de alta latitud, obtenidos a partir de mapas polares de este parámetro, indica una estrecha relación de las fluctuaciones de TEC no sólo con índices de actividad geomagnética sino también con datos de flujo de partículas.
Palabras clave: ionosfera, GNSS, contenido total de electrones, propagación de ondas de radio.

1. INTRODUCTION

Ionospheric effects have a measurable impact on radio signals up to frequencies of about 10 GHz. In Global Navigation Satellite Systems (GNSS) the interaction of trans-ionospheric radio waves with the plasma causes a first-order propagation delay which is proportional to the inverse of the squared radio frequency ($1/f^2$) and the integrated electron density (Total Electron Content - TEC) along the ray path (Davies and Hartmann, 1997). In addition to the first-order effect also secondary effects due to higher order terms in the ionospheric refractive index have to be taken into account in precise positioning applications (Brunner and Gu, 1991, Bassiri and Hajj, 1993, Hoque and Jakowski, 2006).

In addition to such regular propagation errors, ionospheric plasma irregularities may cause a significant degradation of navigation signals. On the other hand, measurable changes in phase, amplitude and polarization of transmitted radio waves can effectively be used to obtain essential information on space weather effects traced in the ionosphere (Jakowski et al., 2002a).

2. IONOSPHERIC RANGE ERRORS

2.1. REGULAR RANGE ERRORS

The refraction of radio waves traversing the ionosphere is described by the refractive index n which in case of GNSS frequencies can be approximated by:

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

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

$$f_p^2 = \frac{e^2 n_e}{4\pi^2 m_e \varepsilon_0} \tag{2}$$

and f_g is the gyro frequency of the electron ($f_g \approx 1.4$ MHz) defined by:

$$f_g = \frac{eB}{2\pi m_e} \tag{3}$$

The parameter 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 along the ray path s, the ray fulfils Fermats law, i.e. the phase integral or Eikonal $L = \int n \cdot ds$ becomes a minimum.

Considering eq. (1), the Eikonal can be rewritten in terms of ray path s according to:

$$s = \int ds_0 + \int (n-1)\, ds + \int ds - \int ds_0 \tag{4}$$

$$s = \rho_0 - \Delta s + \Delta s_B \tag{5}$$

Here ρ_0 is the true range between the transmitting satellite and the ground receiver along the vacuum ray path, Δs represents the range error terms of eq. 1 and Δs_B is the optical ray path excess due to bending. In positioning the true range ρ_0 shall be determined by phase measurements according to eq. (5). Computing Δs defined in eq. (5) by using the first two terms in eq. (1) and neglecting the excess ray path length Δs_B due to bending, the ionospheric range error d_I can be written as:

$$d_I = \frac{K}{f^2} \int_S^R n_e\, ds \tag{4}$$

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

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.

The ionospheric ionization is produced by electromagnetic and particle radiation originating from the sun. The photoionization is most effective at wavelengths of less than 130 nm. Since the radiation intensity at this wave length range varies up to 100% of the average level during a 11 years solar activity cycle, it appears that the ionospheric ionization depends strongly on solar activity as it is clearly shown in Figure 1 by the close correlation of solar activity and TEC.

Since the photo ionization of the Earth's atmosphere depends on the incidence angle of the irradiation, diurnal, seasonal and latitudinal variation of the total ionization can easily be explained. TEC variation related to these different forces can be seen in Figure 2. Hourly maps of vertical TEC over Europe are generated in DLR Neustrelitz since 1995 (Jakowski, 1996) using GPS measurements provided by the ground based GPS receiver network of the International GNSS Service (IGS).

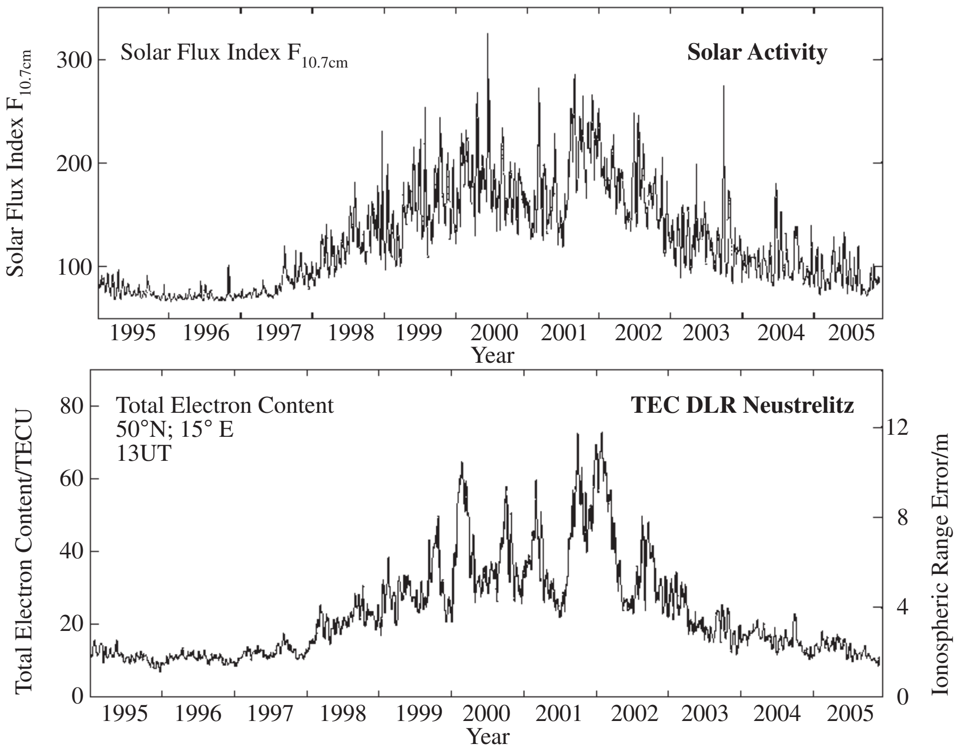


Figure 1.- TEC computed for 50°N; 15°E at 13:00 UT (bottom panel) in comparison with the solar radio flux index F10.7 (upper panel), showing a close correlation with the solar flux.

Vertical TEC (TEC_v) is free from the slant ray path geometry which is different for each satellite-receiver link. Vertical TEC is converted from the TEC measurements along slant ray paths (TEC_s) by applying a mapping function. Assuming a single layer ionosphere at height h_{sp}, the conversion can be performed according to:

$$TEC_V = \sqrt{1 - \left(\frac{R_E \cos\varepsilon}{R_E + h_{sp}} \right)^2} \, TEC_s \tag{5}$$

where ε denotes the elevation angle of the ray path and R_E is the Earth radius. Thus, knowing the vertical TEC map, a single frequency user can correct the first-order ionospheric range error d_I by converting TEC_v to TEC_s using eq. (7) and then inserting TEC_s in eq. (6) for each satellite link. This technique is applied when using satellite based augmentation systems such as WAAS and EGNOS.

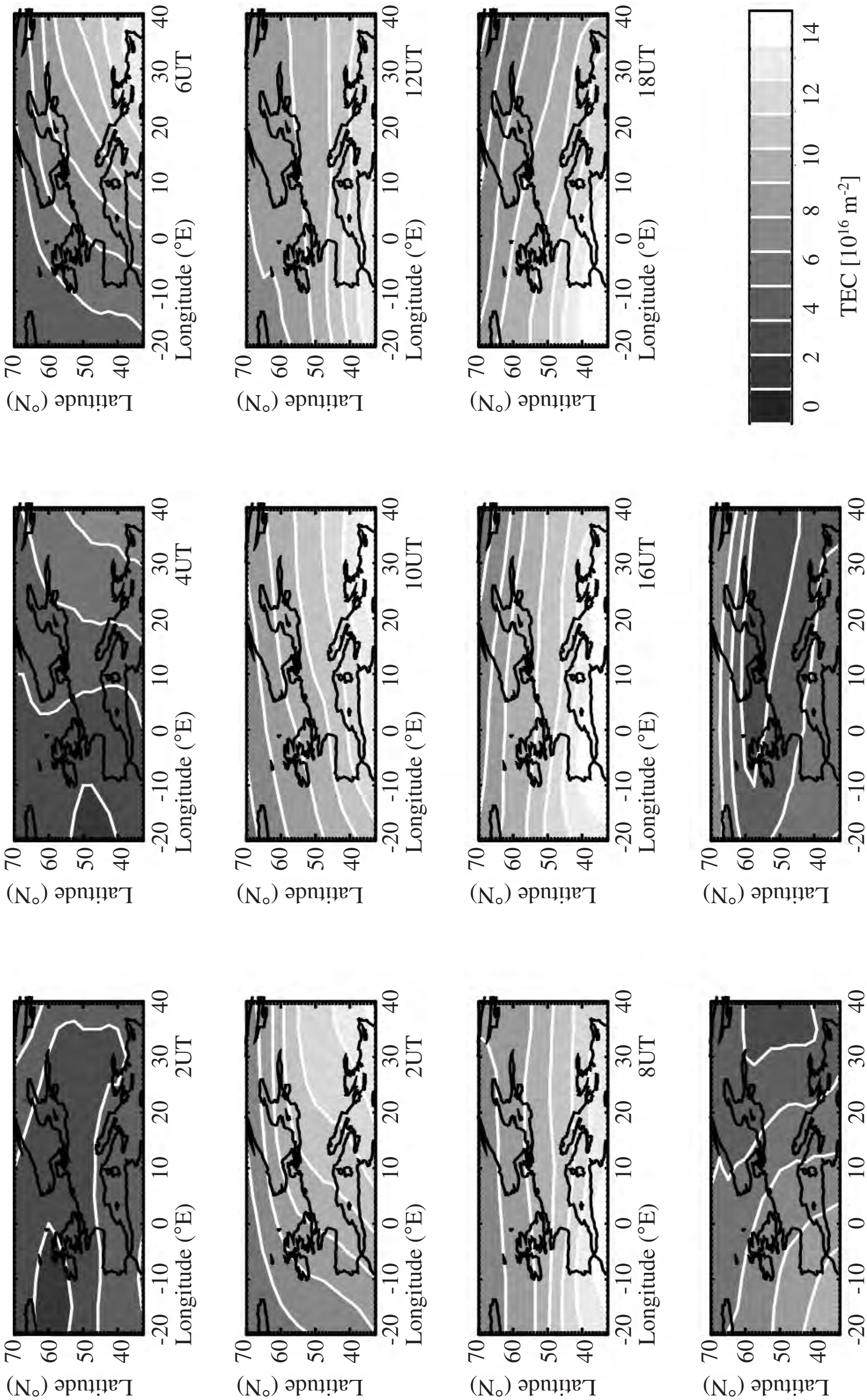


Figure 2.- TEC maps over Europe on a sample day (11 February 2000) indicating in particular latitudinal and LT variation of TEC which corresponds with the first-order range error according to eq. (6).

2.2. HIGHER ORDER RANGE ERRORS

Whereas the first-order range error defined in eq. (6) can be completely eliminated by a linear combination of dual frequency measurements at the two frequencies L1 and L2, higher order terms of the refractive index given in eq. (1) cannot be mitigated in a linear approach.

Several attempts have been made to mitigate second order effects (e.g. Brunner and Gu, 1991; Bassiri and Hajj, 1993, Jakowski et al., 1994, Hoque and Jakowski, 2006, 2007) applying different approaches. Depending on information about the ray path geometry, the electron density distribution and the shape of the geomagnetic field, it is possible to correct the higher order effects with an accuracy of about 1 mm. A rough estimate of the size of various higher order effects is shown in Fig. 3.

Unfortunately, the knowledge of the actual electron density distribution and the geomagnetic field structure is rather poor in operational GNSS applications. Thus, correction formulas taking into account the ionosphere and geomagnetic field structures could be of practical importance. Following this approach, empirical formulas depending only on ray path geometry (azimuth and elevation) and TEC have been developed to compute higher order effects for selected regions

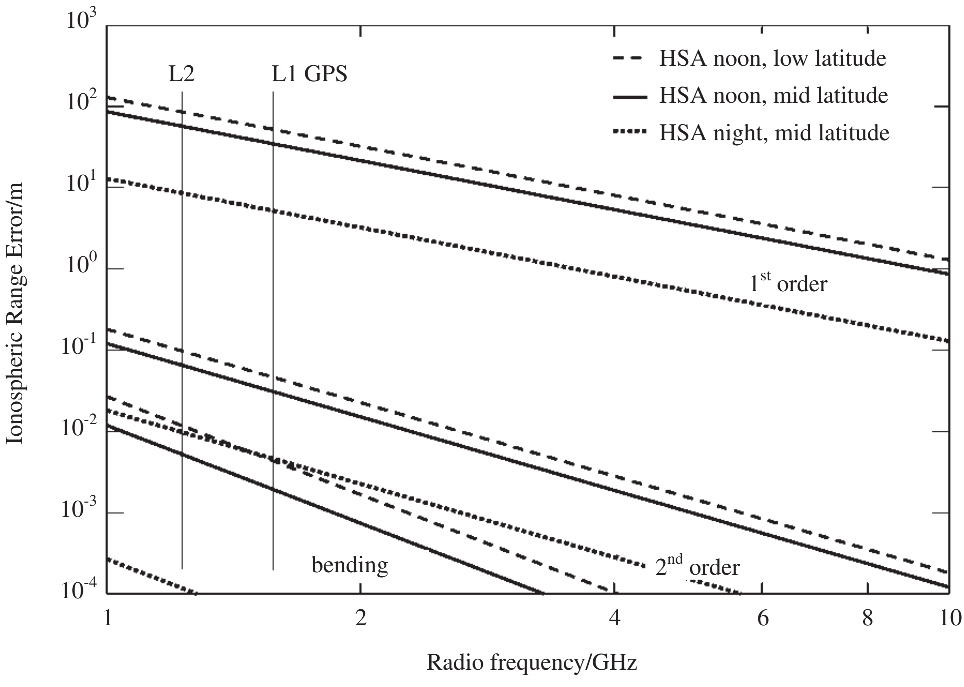


Figure 3.- Review of ionospheric range errors as a function of the frequency of radio waves up to 10 GHz for typical ionisation levels at high solar activity (HSA) and low solar activity (LSA) conditions. The 2nd order error corresponds to the magneto-ionic term in the refractive index whereas the bending error refers to the excess ray path due to ray path bending.

with accuracy in the mm level (Hoque and Jakowski, 2006, 2007). Due to the anisotropy in the refraction index, introduced by geomagnetic field dependent terms in eq. (1), the second order effect depends on the direction of the ray path as it is shown in Fig. 4. Systematic range errors of this type will not cancel out in measurement statistics.

Taking into account that the error in the sample shown in Fig. 4 can reach up to 60 mm, precise applications require a correction of higher order effects. If more than two frequencies are available as planned in modernized GPS or GALILEO systems, higher order effects can be mitigated better by using more frequency combinations.

3. IONOSPHERIC PERTURBATIONS

Ionospheric disturbances can cause additional range errors in GNSS applications due to rapid phase and amplitude fluctuations of satellite signals leading to

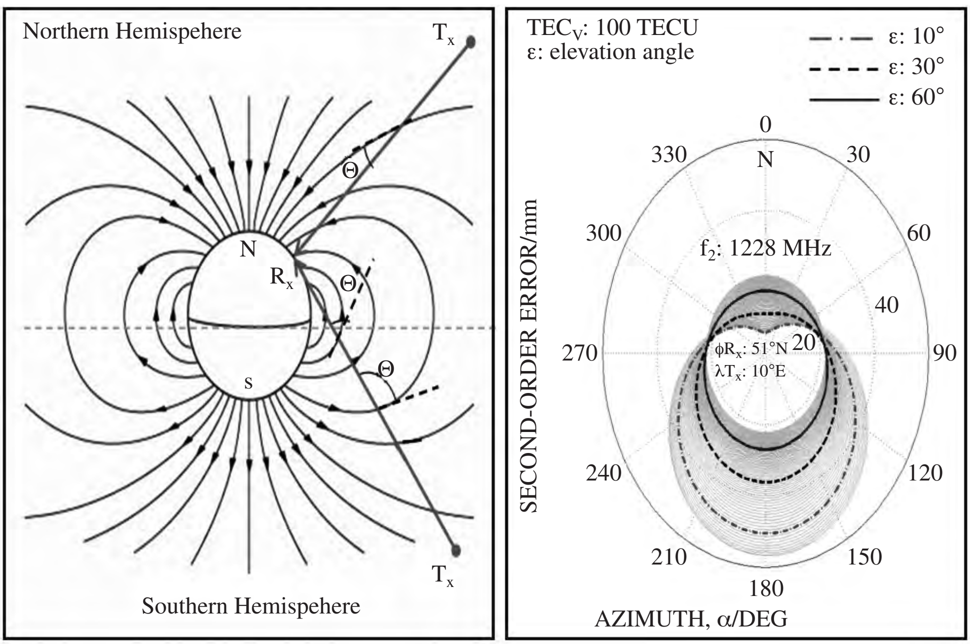


Figure 4.- Left panel: Illustration of the effect of the ray path-magnetic field geometry causing an asymmetry in the refraction. Right panel: Second order ionospheric range error for the GPS L2 frequency assuming a vertical TEC of 100 x 1016 electrons /m^2 for a mid-European station as a function of azimuth at different elevation angles. The error scale in radial direction ranges up to 60 mm at the outer circle. The closed curves related to the elevation angles 10, 30 and 60 degrees show the 2nd order error as a function of azimuth direction. The computation made for a receiver position at 51°N and 10°E, clearly indicates a maximum error in southward direction.

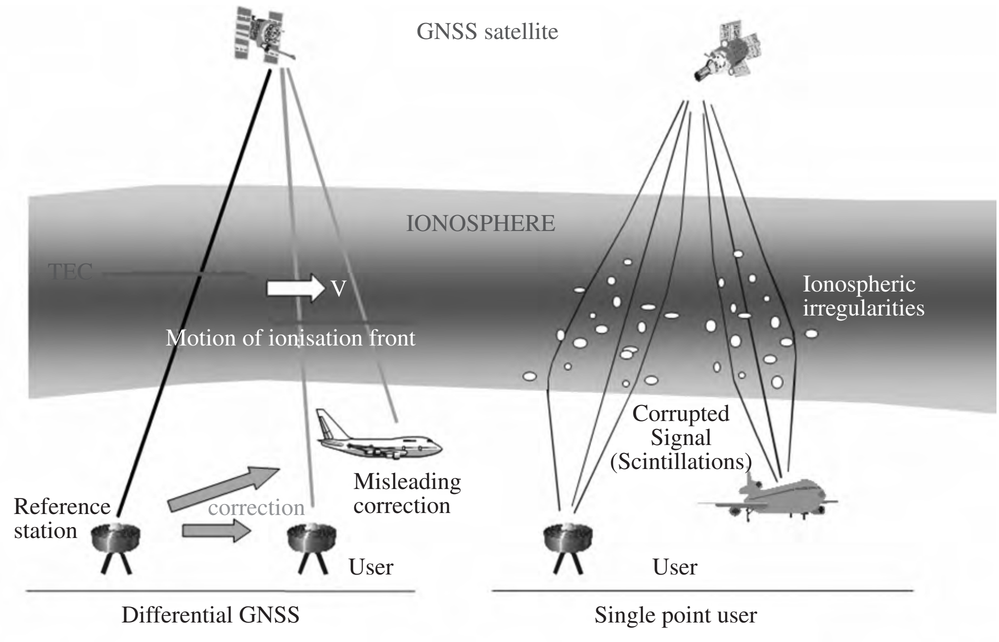


Figure 5.- Illustration of ionospheric impact on GNSS users due to ionospheric perturbations. Left side: moving ionization front may cause hazardous misleading information in a ground based augmentation system. Right side: small scale ionospheric irregularities may cause severe ionospheric scintillations of the signal strength which may cause loss of lock.

degradation of the system performance, its accuracy and reliability. Some of these effects are illustrated in Fig. 5. GNSS errors may occur due to strong horizontal gradients of the ionospheric ionization as illustrated on the left side of Fig. 5. Here a ground based augmentation system can give misleading corrections to an aircraft which might be dangerous in particular during landing. The right side illustrates diffraction of GNSS signals due to small scale ionospheric perturbations. This may lead to loss of lock of the receiver.

3.1. LARGE SCALE PERTURBATIONS

As the left side of Fig. 5 illustrates, a moving ionization or TEC front may lead to misleading correction information in GNSS reference systems. Severe ionization fronts are often generated in the course of ionospheric storms which are driven by space weather conditions (Ho et al., 1996, Jakowski et al. 1999, 2001).

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 plasma convection, are probably the most powerful driving forces for the highly dynamic and complex processes. During storms, the 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 (Prölss, 1995, Foerster and Jakowski, 2000).

In the course of the storm on 7 November 2004 large ionization gradients were generated in the high latitude ionosphere shown in the upper panel of Fig. 6. It is worth mentioning that the enhanced gradients peak about 1.5 hours earlier than the performance degradation of the GPS reference network operated by Allsat GmbH Hannover. Thus, the enhanced TEC gradient observed at 60°N (not at 40°N) can be considered as a precursor of ionospheric perturbations reaching mid-latitudes 1-2 hours later. More systematic studies may reveal whether high-latitude TEC monitoring has the capability of forecasting performance degradation of GNSS networks due to ionospheric storms (Jakowski et al. 2005).

3.2. SMALL SCALE IONOSPHERIC IRREGULARITIES

Satellite navigation in the L-band is sensitive to rapid and severe fluctuations of the signal amplitude called scintillations. Principally, scintillation phenomena are caused by small-scale irregular structures in the ionization density via forward scattering and diffraction of the GNSS signal.

The most commonly used parameter characterizing the intensity fluctuations is the scintillation index S_4, defined by equation:

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \tag{6}$$

The S4 index depends strongly on geophysical conditions, such as local time, season, latitude, and solar activity level (Aarons et al., 1988, Basu et al., 1996). As typically is seen in Fig. 7, strong scintillation activity is observed at low latitudes in Bandung /Indonesia (107°”35’ E; 06°53’ S) after sunset in the evening/early night hours. Although the solar activity was very low in 2006, scintillations have been observed in Bandung at an occurrence probability of about $6x10^{-3}$ for severe scintillations with S4 ≥0.8. Subsequent studies in the upcoming years with growing solar activity and resulting enhanced scintillation activity shall further validate this conclusion. The seasonal dependence shows usually maxima around the equinoxes. High S4 index level may lead to a loss of lock of the GNSS signals as it is shown in Fig. 7. To avoid problems in accurate and safety critical applications, the ionospheric behaviour must permanently be monitored.

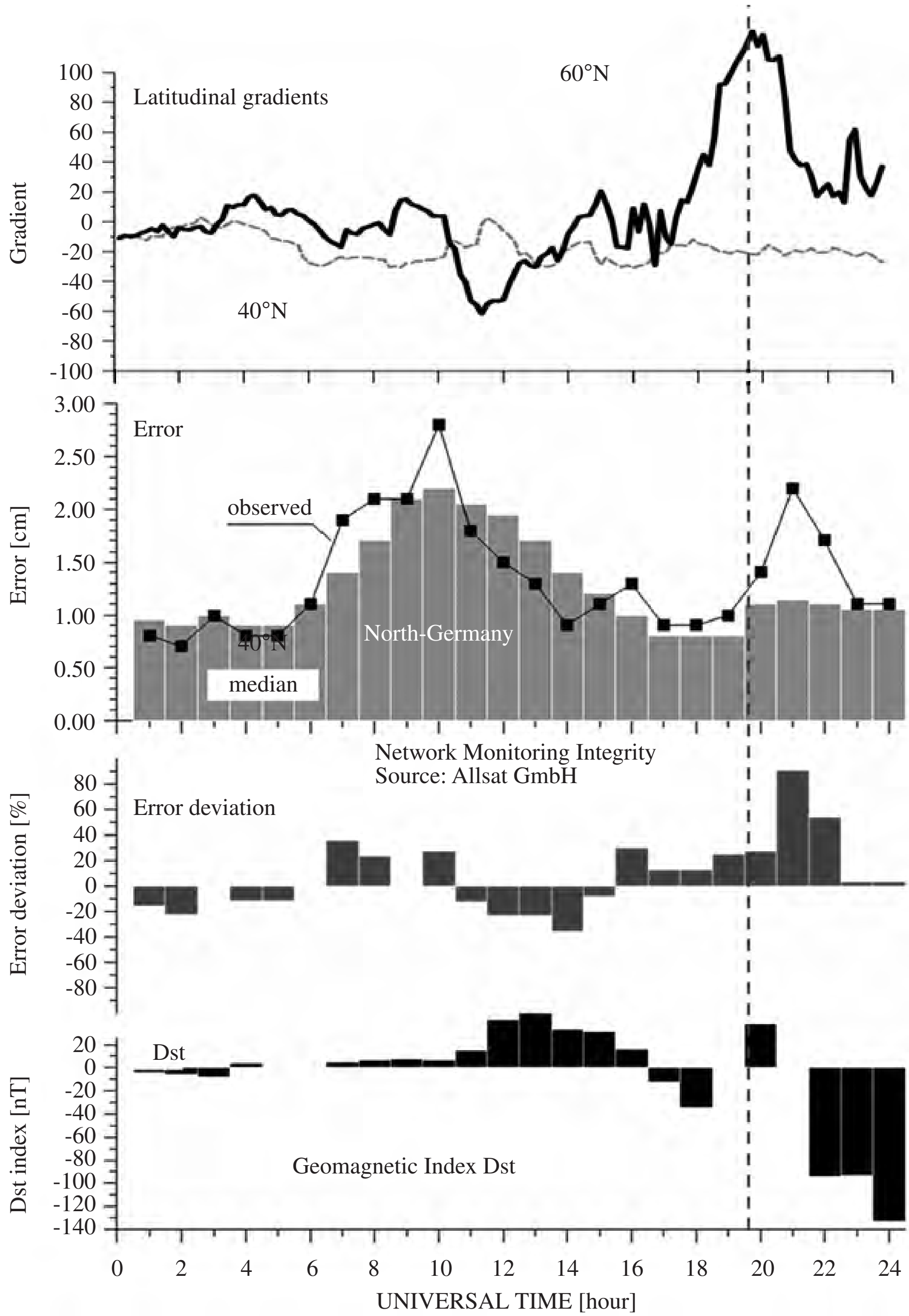
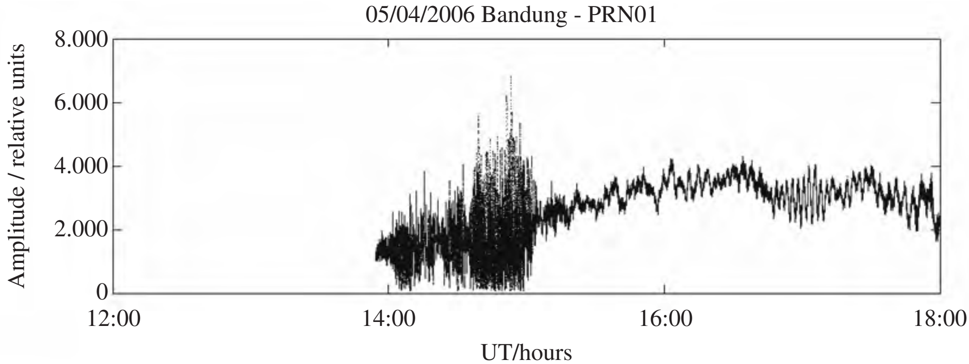


Figure 6.- Latitudinal gradients of TEC during the space weather event on 7 November 2004 in comparison with the geomagnetic Dst index and GPS reference network errors monitored by Allsat GmbH Hannover.



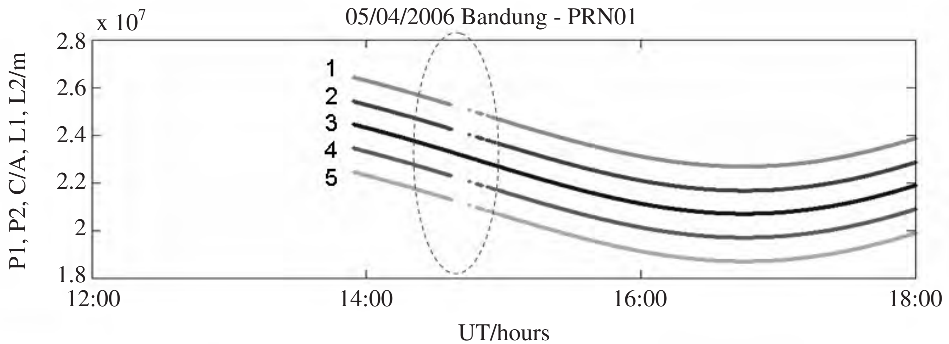


Figure 7.- Amplitude scintillation event in the evening hours of 5 April 2006 at Bandung / Indonesia. Numbers 1 – 5 correspond with phase measurements P1, P2, C/A, L1, L2, respectively. The phase values are shifted for plotting by adding proper constant values.

4. IONOSPHERIC MONITORING AND FORECAST

The permanent monitoring of the structure and dynamics of the ionosphere is a key to successfully overcome problems associated with the ionospheric impact on GNSS applications including both regular effects as well as perturbation induced signal degradation.

Dual frequency GPS measurements can effectively provide integral information on the electron density along the ray path by computing differential phases of code and carrier phase measurements. Neglecting higher order terms in the refractive index, the differential phase is proportional to the integral of the electron density along the ray path (TEC) between the transmitting GNSS satellite and the receiver.

Considering the increasing availability of dense GPS networks and the fact that one receiver may track up to more 10 satellites simultaneously, a large number of measurements can be obtained by ground based measurements.

Before the TEC measurements can really be used, the hardware biases of individual satellite-receiver pairs have to be removed by careful calibration procedures.

In DLR Neustrelitz the ionospheric TEC is continuously monitored since 1995 over Europe using the permanent operating GPS ground stations of the European International GNSS Service (IGS) network (Jakowski, 1996, Jakowski et al, 2005).

Thus, the European ionosphere (20°W ≤ λ ≤ 40°E; 32.5°N ≤ φ ≤ 70°N) is continuously monitored over more than one solar cycle. The polar cap is monitored at geographic latitudes φ > 50°N. In both areas the measured data are combined with the empirical European and Polar TEC models NTCM-2 and NTCMP-1 for the European and polar area, respectively (over Europe (http://www.kn.nz.dlr.de/daily/tec-eu/), over the Northern Polar area (http://www.kn.nz.dlr.de/daily/tec-np/).

As has been found out in former studies, the achieved accuracy is high enough to monitor large scale perturbation processes due to space weather effects.

In addition to the ground based GPS measurements also measurements onboard Low Earth Orbiting (LEO) satellites may essentially contribute to detect space

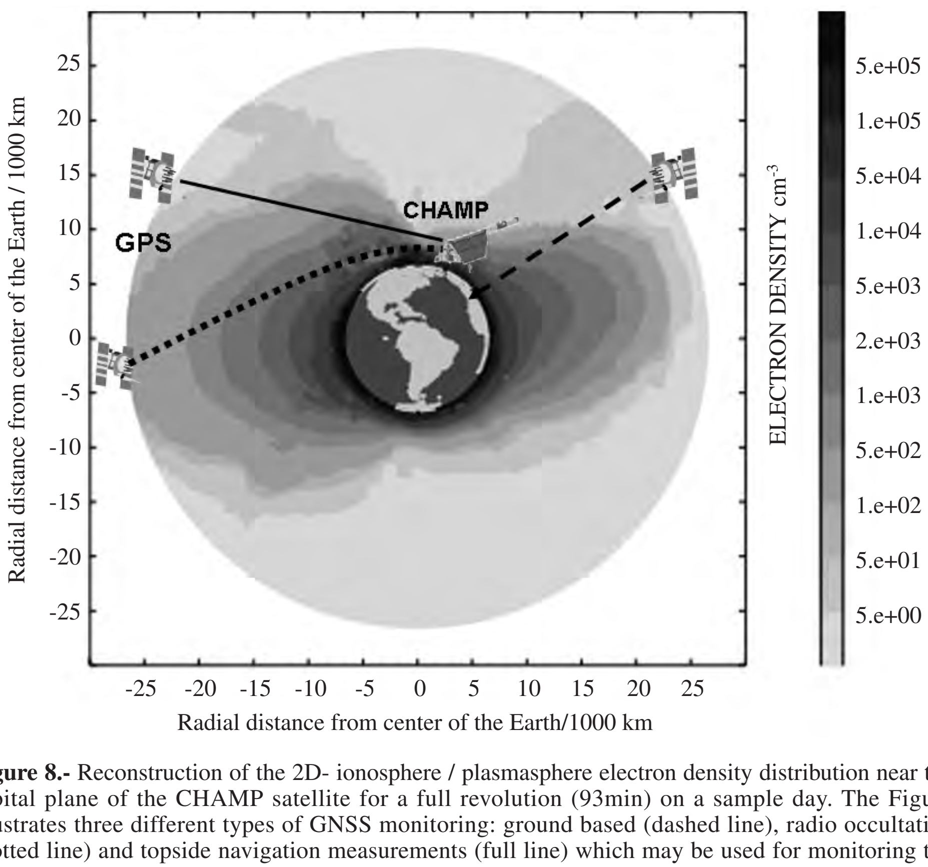


Figure 8.- Reconstruction of the 2D- ionosphere / plasmasphere electron density distribution near the orbital plane of the CHAMP satellite for a full revolution (93min) on a sample day. The Figure illustrates three different types of GNSS monitoring: ground based (dashed line), radio occultation (dotted line) and topside navigation measurements (full line) which may be used for monitoring the ionosphere in near real time.

weather effects in the Geo-plasma. Whereas GPS radio occultation measurements onboard a LEO satellite may provide up to about 200 vertical electron density profiles in velocity or anti-velocity direction near the orbit plane (e.g. Hajj and Romans, 1998, Jakowski et al., 2002b) topside tracking data for satellite positioning can effectively be used to monitor the 3D electron density distribution of the topside ionosphere/plasmasphere near the orbit plane (Heise et al., 2002) as shown in Fig. 8.

The electron density reconstructions may reveal strong plasma density enhancements in particular in the polar region (Jakowski et al., 2007).

DLR Neustrelitz has established a near real time ionospheric data service using all three types of GNSS measurements illustrated in Fig. 8. (http://w3swaci.dlr.de/http://w3swaci.dlr.de). The European TEC maps are updated every 5 minutes making them attractive for single frequency users to correct remaining ionospheric errors.

5. SUMMARY AND CONCLUSIONS

Space based technical and science systems such as satellite communication, GNSS positioning or remote sensing techniques using transionospheric radio waves below 10 GHz, are principally affected by ionosphere induced propagation errors. In navigation and positioning ionosphere induced range errors, ambiguities in phase resolution due to phase fluctuations and loss of lock due to radio scintillations cannot be ignored.

Fortunately, the GNSS technique itself provides a unique opportunity to monitor ionospheric key parameters continuously on regional and/or global scale in near real time to provide corrections and/or warnings on ionospheric perturbations.

Ground based GNSS monitoring systems can effectively be supported by GNSS measurements onboard Low Earth Orbiting (LEO) satellites.

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