SPACE WEATHER EFFECTS IN THE IONOSPHERE AND THEIR IMPACT ON POSITIONING

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ABSTRACT/RESUME

The ionosphere region plays an active role in the complex space weather relationships. So a permanent monitoring of the ionospheric state on global scale is required. The world-wide use of Global Navigation Satellite Systems (GNSS) such as GPS and GLONASS offer the unique chance for a permanent monitoring of the total ionization (Total Electron Content - TEC) of the global ionosphere/plasmasphere up to about 20000 km height. On the other hand, accuracy and reliability of GNSS suffer from the ionospheric impact on navigation signals.

The talk discusses several space weather effects in the ionosphere detected by 30s- measurements in the GPS tracking network of the International GPS Service (IGS).

A direct correlation between space weather events and phase degradation of GNSS signals for positioning has been found. The ionosphere impact on GNSS navigation signals is demonstrated by analyzing 1 Hz sample rate data of GPS and GLONASS measured on 6 August 2000. The derived signal phase irregularities that degrade navigation and positioning applications indicate highly variable horizontal structures. The discussion of ionospheric irregularities is completed by several simulation scenarios showing their influence on positioning.

A close correlation of TEC fluctuations with geostationary satellite particle flux data was detected too.

1. INTRODUCTION

It has been shown by a number of authors that Global Navigation Satellite Systems (GNSS) such as GPS and GLONASS offer a unique chance for a permanent monitoring of the total electron content (TEC) of the ionosphere on regional and global scale [1], [2], [3].

The measurements take advantage of regional and global networks of ground receivers. So the International GPS Service (IGS) operates more than 200 GPS ground receivers worldwide. IGS provides essential support to use their data also for non-geodetic applications of GPS technique. For instance IGS has hosted a HIgh RAte measuring Campaign (HIRAC) to monitor the ionosphere at more than 100 globally distributed GPS and GLONASS stations at high solar activity during 23-29 April 2001 [4].

The electromagnetic interaction of radio waves with charged particles of the ionospheric plasma may cause on the one hand 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 about the ionospheric state. This has been shown in numerous publications since more than three decades.

In the following sections we will discuss at first the monitoring capabilities of GNSS techniques to contribute essentially to space weather information. Secondly, because technical systems that use transionospheric radio signals, are subjected to ionospheric space weather conditions, we discuss also some aspects of ionospheric impact on navigation and positioning.

2. IONOSPHERE MONITORING

Due to the dispersive nature of the ionosphere dual frequency GPS measurements may provide integral information about the ionosphere by computing differential phases of code and carrier phase measurements. In a first order approximation this differential phase is proportional to the integral of the electron density along the ray path between the transmitting GNSS satellite and the receiver.

After the total electron content along a number of ray paths has been determined by using a special calibration technique for the ionospheric delay of GPS signals [5], the slant TEC is mapped to the vertical by using a single layer approximation for the ionosphere at h_{sp} = 400 km height. The GPS ground stations of the European IGS network are used to compute about 60-120 TEC data points covering the area 20 °W $\leq \lambda \leq$ 40 °E; 32.5 °N $\leq \varphi \leq$ 70 °N and the polar cap at geographic latitudes φ > 50 °N. Then the measured data are combined with the empirical TEC models NTCM2 and NTCMP-1 for the European and polar area, respectively [6].

For each grid point value a weighting process between nearest measured values and model values is carried out. A typical data coverage for the polar area is illustrated in Fig. 1 by a coverage snapshot at 18:00 UT.

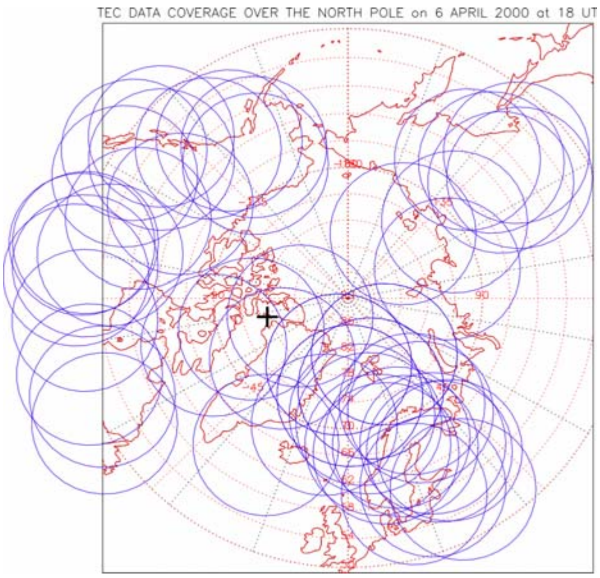


Fig. 1 Data coverage of ground based GPS measurements (IGS sations) over the polar cap on 6 April 2001, 18:00 UT.

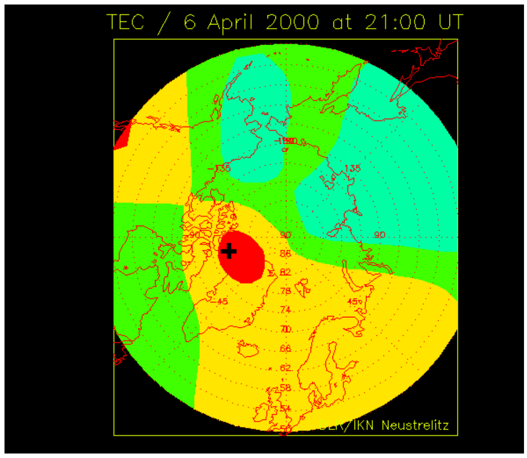
The circles indicate the half width of the distance depending weighting function for each data point. As it has been shown earlier [5], the achieved accuracy is high enough to monitor large scale perturbation processes due to Space Weather effects. TEC data are processed on a regular basis in Neustrelitz since February 1995 for Europe (http://www.kn.nz.dlr.de/daily/tec-eu) and for the northern polar cap since mid of 2001 (http://www.kn.nz.dlr.de/daily/tec-np).

3. SOLAR RADIATION CONTROL

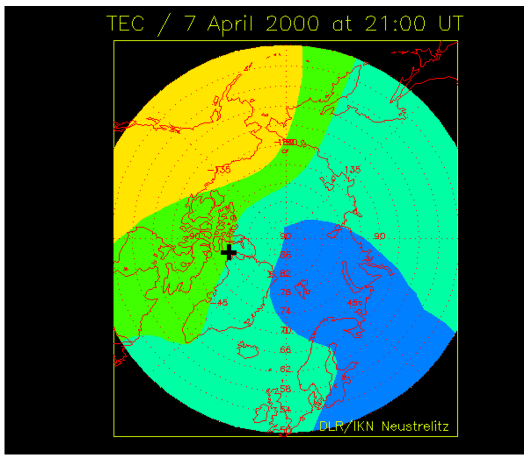
It has been shown that TEC is very sensitive to variations in the solar radiation on long [8], medium [9], and short term [10] scales. Therefore there is a close relationship between solar space weather information and the corresponding ionospheric response.
An impressive example how the solar radiation controls the ionospheric ionization is the solar eclipse on 11 August 1999 [11] (see also http://www.kn.nz.dlr.de -> Space Weather -> Special Events -> Eclipse 99). It is interesting to note that ionospheric changes of the total ionization are slightly delayed against the variation of the 10.7 cm solar radio flux [9]. This knowledge should be helpful for developing forecast models of the ionspheric ionization on global scale.

4. IONOSPHERIC STORMS

Geomagnetic/ionospheric storms generate significant large scale signatures in the TEC maps [12], [13].
In particular differential TEC maps generated by subtracting monthly averages from actual TEC maps are helpful to draw conclusions concerning the nature of ionospheric storm processes. So the corresponding analyses of the storm on 10 January 1997 indicate both the action of an eastward directed electric field as well as the action of perturbation induced meridional winds in the thermosphere [3], [12].
Furthermore, statistical studies showed characteristic storm pattern of percentage TEC deviations from monthly medians for winter and summer storms [13]. The storm pattern provide a deeper insight into storm mechanisms and may be useful for an adequate modeling of ionospheric storm behavior in space weather forecast models.



a)



b)

Fig. 2 Vertical TEC over the North pole at 21:00 UT on 6 April (top) and on 7 April 2001 (bottom)

The geomagnetic storm on 6 April 2000 is characterized by a strong geomagnetic activity (Kp up to 9) and an intensive and long lasting hemisphere power index. After the shock wave has been detected by particle detectors onboard NASA's Advanced Composition Explorer spacecraft (ACE) around 16:00 UT, various space weather effects were detected at different spheres down to the Earth surface. So geomagnetic induced voltages on Ruhrgas pipelines were detected in Germany starting on 6 April at about 18:00 UT with amplitudes of up to 12 V. These voltage differences are the result of a long chain of interaction processes of solar wind particles with the Earth's magnetosphere, ionosphere and thermosphere thus generating strongly varying ionospheric currents, magnetic and electric fields that induce so-called Geomagnetically Induced Currents (GIC's) on the Earth surface. Such GIC's may disturb or even destroy electrical power transmission systems [14].

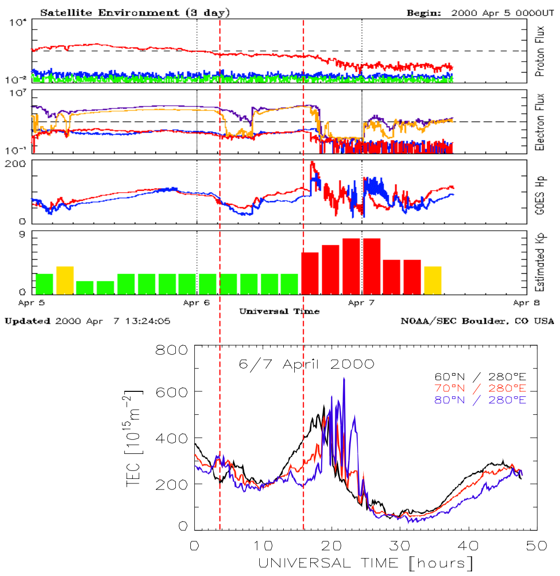


Fig. 3 Comparison of polar TEC (bottom) with space environment data from SEC, Boulder

In the ionosphere the space weather event is accompanied by strong enhancements of nighttime ionization in the polar region. This is probably due to particle precipitation through the cusp region. As Fig. 2a shows, there is a strong ionization enhancement near the geomagnetic pole (marked by a black cross) around 21:00 UT that is even bigger than the ionization at latitudes ϕ > 50 °N at the American longitude sector on the day-side.

For comparison Fig. 2b shows the same area 24 hours later indicating a reduced ionization level in general that is well known as the negative storm phase [15].

We suppose that the strong impact on the magnetosphere/ ionosphere systems in the evening hours of 6 April is due to the southward direction of the interplanetary magnetic field (Bz < 0) that has been measured from about 17:00 until 24:00 UT with a short break around 22:00 UT. Principally, the polar ionization is strongly irregular between 17:00 and 24:00 UT. This can be seen at the bottom of Fig. 3 where the temporal variation of TEC at three different latitudes is plotted against satellite environment data published by the NOAA Space Environmental Center in Boulder, USA. It is interesting to see that the unusual high irregular behavior of TEC is closely correlated with space environment parameters measured onboard the GOES satellite. This is not only visible at the evening perturbation but also during a precursor starting around 02:00 UT on 6 April.

The 10 min TEC data have been extracted from the corresponding polar maps. The temporal variation indicates a strong irregular structure starting at about 17:00 UT at λ = 280 °E which is close to the magnetic zero longitude.

The amplitude of TEC can reach extreme high values of up to 60 $\times 10^{16}$ m^{-2}. It has to be noticed that both the high absolute TEC level as well as the high temporal dynamics may cause serious problems in navigation satellite system applications. This will be discussed in the following section.

5. IMPACT ON NAVIGATION SIGNALS

The ionosphere propagation medium acts on transionospheric communication and navigation signals via the interaction of electromagnetic waves with the charged electrons and ions of the ionospheric plasma that is penetrated by the geomagnetic field. The resulting complex refractivity is proportional to $1/f^2$ meaning that the ionospheric impact can practically ignored at frequencies f > 10 GHz. At L- band frequencies of about 1.5 GHz, as they are used by operational and planned Global Navigation Satellite Systems, the ionosphere may cause signal delays that correspond with range errors of up to 60 meters. In a first order approximation the range error is proportional to the integral of the electron density (TEC) along the ray path.

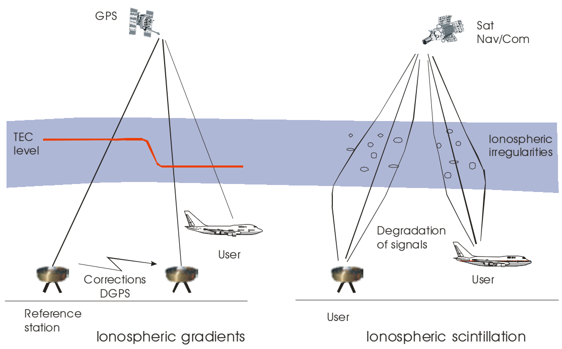


Fig. 4 Ionospheric impact on GNSS signals

The frequency dispersion can therefore effectively be used to derive the total electron content of the ionosphere or to cancel out the ionospheric delay in navigation and positioning by a simple linear combination of L1 and L2 phases.
Beside the already mentioned delay also horizontal gradients in the ionospheric ionization (TEC) and ionospheric irregularities producing phase fluctuations and radio scintillations may cause a significant degradation of navigation signals up to loss of lock [16] . These effects are schematically illustrated in Fig. 4. Strong TEC gradients, Traveling Ionospheric Disturbances (TID's) and phase fluctuations are often correlated with the development of geomagnetic/ionospheric storms as it is indicated for high latitudes in Fig. 3.

5.1 Observations on 6 April 2000

As it can be seen in Fig. 2a, the strong ionospheric perturbation observed in the evening hours on 6 April 2000 has distributed over the high latitude European area ($\phi > 50$ °N) causing beautiful polar lights. In agreement with this figure, the storm caused unusual variations of TEC at corresponding European GPS and GLONASS stations as it is shown in Fig. 5 for the German GLONASS receiving stations in Hannover and Neustrelitz.

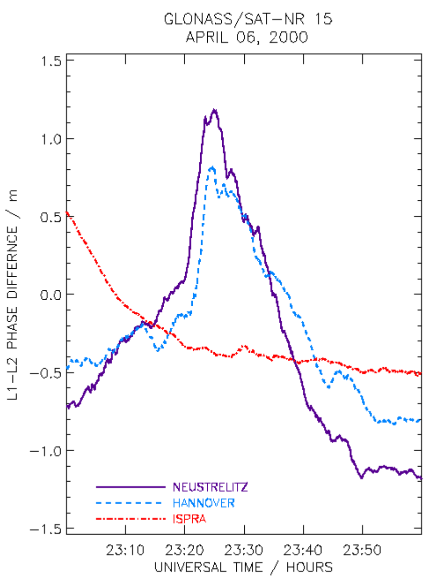


Fig. 5 Differential phases of GLONASS carrier frequencies measured at sites in Neustrelitz, Hannover and Ispra on 6 April from 23 - 24:00 UT.

However, the Italian station in Ispra was practically not perturbed by this storm. This observation indicates the existence of significant horizontal structures producing strong TEC and in conjunction with this also strong phase irregularities as Fig. 6 demonstrates.

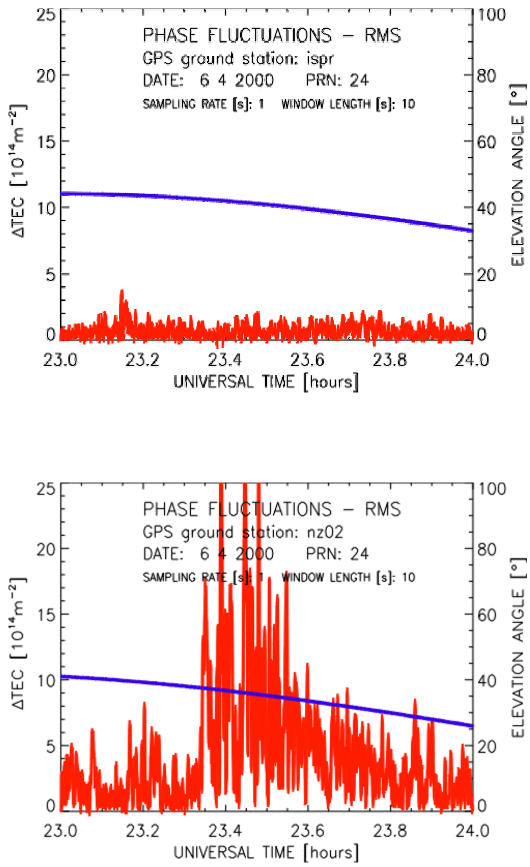


Fig. 6 Differential phase fluctuations (red line) within 10 s windows at sites Ispra/Italy (top) and Neustrelitz / Germany (bottom) on 6 April from 23 - 24:00 UT. The blue line marks the satellite elevation.

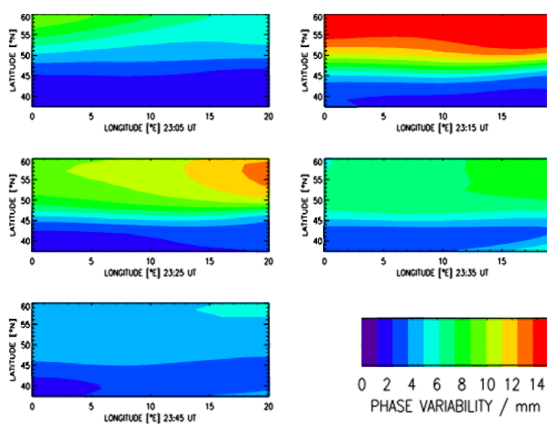


Fig. 7 Differential carrier phase fluctuation maps over Mid-Europe on 6 April from 23:05-23:45 UT.

A more concrete impression about the horizontal extension of these phase irregularities is given in Fig. 7. Here the TEC variability derived from 1 Hz sampled differential carrier phases of GPS and GLONASS signals received at several stations in Germany and Italy is plotted in differential carrier phase fluctuation maps over the observation area. Fig. 7 demonstrates the high dynamics of GPS phase fluctuations by presenting a few sequential maps that have been generated every 10 minutes starting at 23:05 UT.

Of particular interest is the sharp border between the high latitude region of space weather induced ionospheric irregularities and the quiet area southward of about 45°N. If GNSS users are provided with such an information, they can exclude radio links going through the irregularity zone in their positioning algorithms to save higher accuracy and reliability of the measurements. So space weather monitoring and the operational derivation of relevant information concerning the horizontal structure of the ionosphere and its dynamics should be helpful for users in navigation, positioning and surveying.

5.2 Simulation studies

In order to understand more carefully the ionospheric impact on navigation signals we present some results obtained with the navigation simulation tool NAVSIM that has been developed in DLR recently to simulate the overall performance of satellite navigation systems [17].

To demonstrate the potential influence of ionospheric scintillations on GPS positioning, NAVSIM was initialised with a 2 GPS-station scenario. One station was located at Neustrelitz representing a typical mid-latitude site, the other was located at Ascension Island representing a typical equatorial site. The reproduction of the ionospheric propagation effects inside the simulator are based on the International Reference Ionosphere (IRI 95) and a specific scintillation model. Further technical parameters of the simulation scenario are listed in Tab. 1.

Tab.1 Simulation parameters

Satellite System	GPS CA on L1 & L2
Sampling Frequency	50 Hz
Elevation Mask	10°
Antenna	GPS choke ring antenna
Navigation Algorithm	Least squares algorithm, both code and phase measurements used, dual frequency ionospheric corrections and tropospheric model corrections applied.

Figs. 8-11 show a sub-sample of the positioning data obtained by the simulation. The data cover a time span from 21:00 UT to 21:15 UT (45000 samples), with a strong amplitude scintillation activity in the equatorial region and a calm ionosphere in mid-latitudes. Strong amplitude scintillation can lead to intermittent tracking-loss of the affected satellite-receiver radio link.

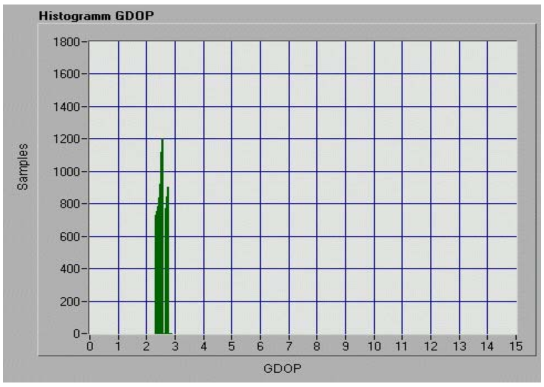


Fig. 8 GDOP at the mid-latitude site Neustrelitz

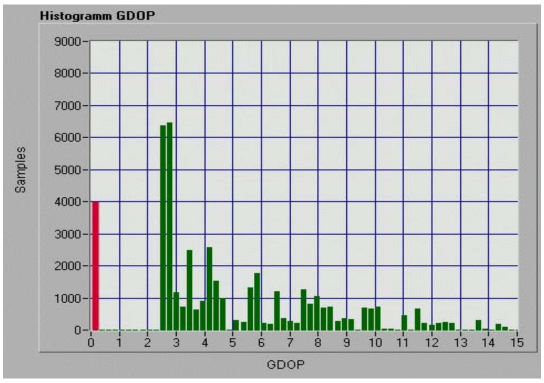


Fig. 9 GDOP at the low latitude site Acsencion Island

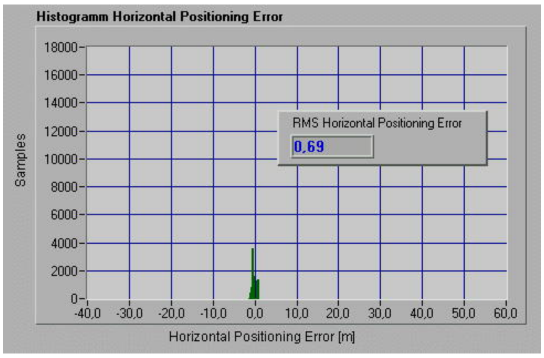


Fig. 10 Horizontal positioning error (RMS) at the mid-latitude site Neustrelitz

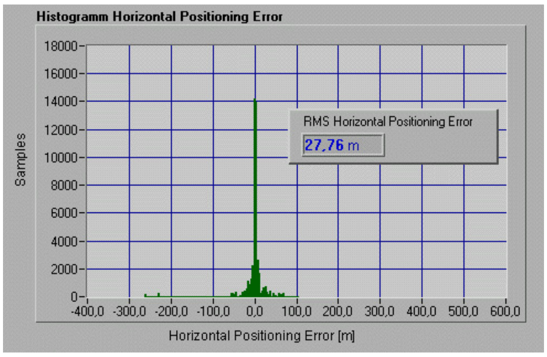


Fig. 11 Horizontal positioning error (RMS) at the low latitude site Ascension Island

As a result the receiver has to estimate the position with a reduced number of available satellites. The effect of such a scenario can be clearly seen in Figs. 8 and 9, showing the Geometric Dilution Of Precision (GDOP) of the station Neustrelitz, practically unaffected by scintillations, and Ascension Island, strongly affected. It can be seen that the GDOP values in Ascension Islands are partially 5 times more worse than in Neustrelitz which leads to a different positioning accuracy at both stations.
Additionally, the receiver at Ascension Island was unable to estimate a position in about 8.9% of the time anyway (see the extra red bar in Fig. 9 at the left hand side of the plot).
The influence of scintillation induced tracking losses on positioning accuracy can be exemplary estimated from the results shown in Figs. 10 and 11. While the positioning error at Neustrelitz site has a RMS value below 1 m, mainly resulting from small multipath effects, the RMS error at Ascension Island is getting up to about 28 m.
Knowledge of the occurrence of ionospheric perturbations and irregularities in space and time should be very helpful to make navigation applications more save and reliable.

6. SUMMARY AND CONCLUSIONS

It has been shown that complex space weather events such as the event from 6 April 2000 modify the ionosphere in a complex and up to now unpredictable manner. Space based technical and science systems such as satellite communication, GNSS or satellite altimetry using transionospheric radio waves below 10 GHz, are principally affected by ionosphere induced propagation errors.
In navigation and positioning inosphere induced range errors, ambiguities in phase resolution due to phase fluctuations and loss of lock due to radio scintillations cannot be ignored.
To achieve high precision, maximum availability and highest reliability of satellite navigation, ionospheric space weather components have to be monitored to provide an adequate now- and forecast service for numerous users of space based

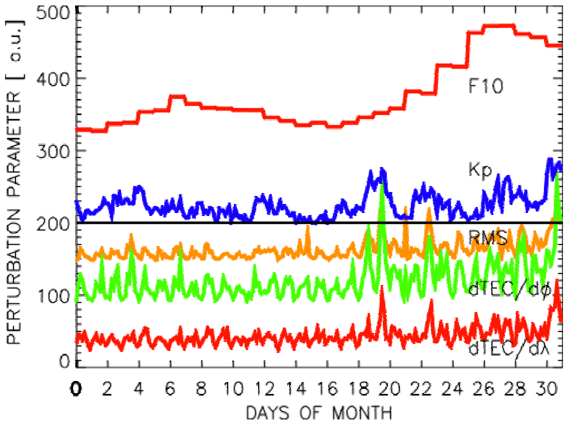


Fig. 12 Comparison of solar radio flux index F10, geomagnetic index Kp with TEC derived indices that should be of interest for GNSS users.

navigation, positioning and surveying.
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 quantify type and strength of ionospheric perturbations, we propose to derive new indices or parameters that provide specific information to GNSS users, enabling them to respond to ionospheric perturbations in an adequate manner [18]. An example for such new indices is given in Fig. 12 where TEC variability and spatial gradients taken from European TEC maps are shown. As discussed earlier, strong horizontal TEC gradients and TID's may seriously degrade differential surveying systems (DGPS).
Ground based GNSS monitoring systems can effectively be supported by GNSS measurements onboard Low Earth Orbiting (LEO) satellites.
In particular operational and future satellite missions such as SAC-C, CHAMP and METOP will essentially contribute to monitor the 3-dimensional electron density distribution over the globe.
A permanent space weather monitoring including the main space weather contributors such as the sun and solar wind, the magnetosphere, ionosphere and thermosphere enables a permanent and effective control of the ionospheric impact on global navigation satellite systems.

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