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ScienceDirect
Advances in Space Research 38 (2006) 2596–2600
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

On developing a new ionospheric perturbation index for space weather operations

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Received 15 November 2004; received in revised form 7 July 2005; accepted 19 July 2005

Abstract

To better and faster quantify the strength and impact of the ionospheric perturbations, we propose a new index for operational use in communication/navigation systems. Presented here is the analysis of selected events of strong disturbances observed with techniques based on Global Navigation Satellite Systems (GNSS) in order to show some insufficiencies when using existing geomagnetic indices. We found that the GNSS Total Electron Content (TEC) measurements and/or derivatives are outstanding candidates for defining a new ionospheric perturbation index, more specialised and therefore more effective. It is believed that the standardization and usage of the proposed perturbation index, together with other indices of similar nature, can prove helpful in reducing the space weather impact on the GNSS-based navigation and positioning.

Keywords: GNSS; TEC; Ionospheric storms; Ionospheric disturbances; Storm indices

1. Introduction

It is well recognized that space weather induces severe ionospheric perturbations that can cause serious technological problems in applications based on Global Navigation Satellite Systems (GNSS) (Jakowski et al., 1999, 2001, 2004). Highly dynamic and strong deviations of the ionosphere electron density structure may cause unpredictable range errors by rapid phase and amplitude fluctuations of the satellite signals. For example, during the severe ionosphere storm period of 29–31 October 2003, reported were several significant malfunctions due to the adverse effects of the ionosphere perturbations: WAAS service was interrupted, high-latitude GPS receivers suffered by enhance signal outages, and military communications were impacted. Even in middle latitudes GPS reference services suffered because of strong ionospheric perturbations that propagated from the auroral region towards lower latitudes (Jakowski et al., 2001). To properly warn users of such commercial service, a quick evaluation of the current signal propagation conditions, effectively expressed in a suitable ionospheric perturbation index, would be of great benefit.

Space weather monitoring, modelling and forecasting, all refer to indices such as the Zurich sunspot number Rz and the 10.7 cm radio flux index F10.7 for the solar activity and the indices K_p, A_p, D_{st} for geomagnetic activity (Menvielle and Berthelier, 1991). There is a serious practical reason for using such indices because each index provides a quick and proxy measure of a complex and essential behaviour of the considered subject (Jakowski, 1996; Stankov, 2002; Stankov et al., 2002). The enhanced activity, i.e., the enhanced intensity level or enhanced variability of a given physical parameter, is simply given by the biggest index value.

The aim of this publication is to discuss the possibility of introducing ionospheric perturbation/disturbance

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doi:10.1016/j.asr.2005.07.043

indices for using them in practical applications, such as precise positioning and navigation by differential GPS techniques.

2. Perturbation indices and the ionosphere

Before introducing ionospheric indices let's have a brief review on the geomagnetic indices because they are often used for estimating the perturbation degree of the ionosphere. Geomagnetic indices are used to describe the disturbance levels of the Earth's magnetic field. Many geomagnetic activity indices have been developed during the years: the K_p and A_p planetary indices, the storm D_{st} index, the sub-storm index PC, etc. (Menvielle and Berthelier, 1991). Main reasons for developing geomagnetic indices are the needs to quantify variations representative of an isolated effect and to estimate global energy input into the magnetosphere. Most frequently used planetary indices are K_p and A_p based on 3-h measurements from 12 globally distributed ground stations. The daily planetary index A_p is obtained by averaging the 8 values of A_p for each day. K_p and A_p are probably the most suitable indices when carrying out preliminary correlative studies with other geophysical phenomena (Stankov, 2002; Stankov et al., 2002, 2004).

What is important to mention here is that, first, the majority of the above indices are so-called 'planetary' indices which are not always suitable for particular applications, and second, reliable estimates of these indices are not available in (near-) real time. A proper choice of indices describing the solar and geomagnetic activity is very important for analysis of the ionosphere–plasmasphere dynamics and successful prediction of its main parameters. The selection of any activity index depends on the purpose of using the index in a particular study and on other factors such as the degree of correlation with the predicted quantity and the index predictability and availability. The occurrence and behaviour of ionospheric perturbations do not fully correlate with the behaviour of the planetary geomagnetic indices. Due to their complex interaction with the thermosphere and magnetosphere, the ionospheric perturbations cannot be described sufficiently well by using geomagnetic activity indices only. To simplify the quantitative description of ionospheric perturbation processes we suggest the systematic introduction of ionospheric perturbation indices which describe essential features of the perturbation. Considering GNSS applications, the most important terms are the total vertical ionisation measurable by the Total Electron Content (TEC) and its spatial and temporal gradients.

Being a robust integral characteristic of the ionosphere–plasmasphere system, the TEC has been successfully used in various investigations of the ionospheric and plasmaspheric behaviour under both quiet and disturbed conditions. Due to the availability of the dual frequency signals of GNSS, TEC can effectively be monitored over large areas such as Europe (Jakowski, 1996) or even on global scale (Ho et al., 1996). Thus, due to the importance of TEC for GNSS applications and the capability of using dual frequency GNSS signals for deriving TEC maps, this parameter (and/or its derivatives) is an outstanding candidate for defining ionospheric perturbation indices. TEC based indices may be used as input parameters in reliable TEC forecasting models and can directly be utilized to improve various aspects of the communications, navigation, and geodetic surveying practices.

In the following section we describe some TEC-based perturbation parameters which may provide the basis for the definition of widely acceptable ionospheric perturbation indices.

3. GNSS-based TEC measurements-candidates for ionosphere perturbation indices

Since 1995, the German Aerospace Centre (DLR) operates a system for regularly processing ground based GPS data and producing maps of the integrated ionospheric electron content over the European region. For the purpose, used are mainly measurements of the ground station network of the International GPS Service (IGS). To produce regional TEC maps over Europe, the measured and calibrated TEC data are assimilated into the regional TEC model Neustrelitz TEC Model (NTCM) (Jakowski, 1996). Both, the TEC and the differential TEC (the absolute or percentage deviation of the actual TEC measurements from their monthly medians) are very helpful when analysing ionospheric storm phenomena (Jakowski et al., 1999; Foerster and Jakowski, 2000). In particular, the differential TEC maps provide an excellent measure of the spatial and temporal development of a space weather induced perturbation pattern. To construct a perturbation index from these maps, the grid values might be averaged over selected regions. Another perturbation index may be derived from horizontal TEC gradients over a selected area. Three types of gradients can be considered – latitudinal (GLAT), longitudinal (GLON), and temporal (time) gradients (GTIM). A rectangular grid in the (x, y) – plane (Fig. 1) with grid spacing Δx in the x (longitude) direction and Δy in the y (latitude) direction, respectively, consists of points $(x_i = x_0 + \mathrm{i}\Delta x,\ \ y_j = y_0 + \mathrm{j}\Delta y)$. Thus, gradients with respect to longitude, GLON_{ij}, and latitude, GLAT_{ij}, are defined at an arbitrary grid point (x_i, y_j) in the following way:

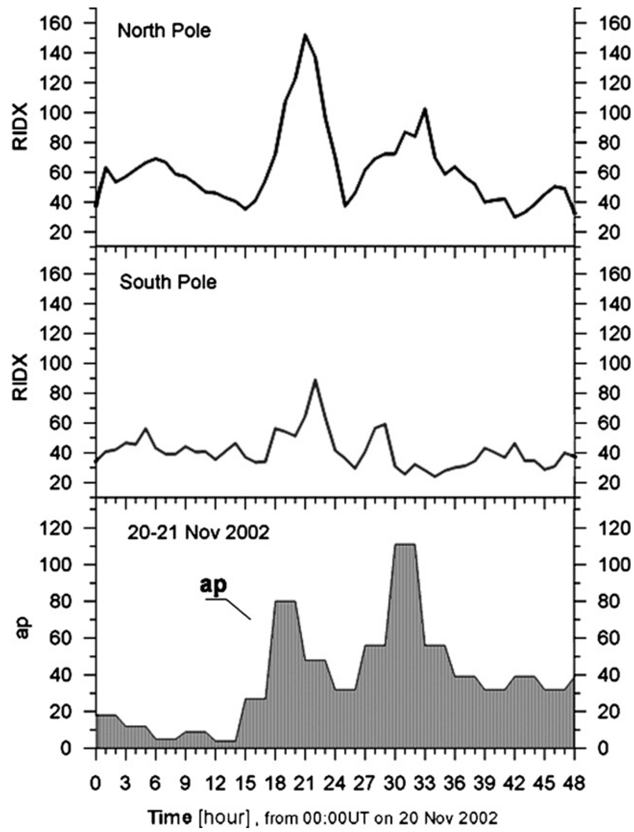

Fig. 1. Comparison of horizontal TEC perturbation parameters derived from high-latitude TEC maps (lat > 50°) on 20/21 November 2002 with the corresponding geomagnetic A_p index.

$$\mathrm{GLON}_{ij} = \frac{\partial u}{\partial x} = \frac{u_{i+1,j} - u_{i-1,j}}{2\Delta x},$$
$$\mathrm{GLAT}_{ij} = \frac{\partial u}{\partial y} = \frac{u_{i,j+1} - u_{i,j-1}}{2\Delta y}. \quad (1)$$

The formulae use a 5-node (cross) computational molecule. If higher precision is sought, then the gradients should be calculated on a 'broader' molecule with more nodes. The observance of strong ionospheric gradients indicates the development of highly dynamic processes in the Earth's ionosphere–plasmasphere system with the potential of having degrading effect on positioning/navigation by inducing large biases. Recently, the TEC monitoring system at DLR has been upgraded and now TEC maps of both the northern and southern polar ionosphere are also produced. Such maps clearly show the coupling processes between the magnetosphere and the solar wind (Jakowski et al., 2002). Here defined is a new perturbation index, (provisionally) named Regional Ionosphere Disturbances IndeX (RIDX), which has a few formulations in order to better address the nature of perturbation phenomena.

In the first formulation, the ionospheric perturbation parameter is defined as the standard deviation of the measurements from the vertical TEC model (used as a background model for the assimilation procedure), i.e.

$$\mathrm{RIDX}_{\mathrm{a}}^{\mathrm{mod}} = \sqrt{\left(\frac{1}{N_{\mathrm{obs}}-1}\right)\sum_{n=1}^{N_{\mathrm{obs}}}(\mathrm{TEC}_n - \mathrm{TEC}_n^{\mathrm{mod}})^2}, \quad (2)$$

where TEC_n is the vertical TEC deduced from the nth measurement, $\mathrm{TEC}^{\mathrm{mod}}$ is the corresponding TEC model value, and N_{obs} is the number of simultaneous measurements (observations). Calculated for 20/21 November 2002 (Fig. 1), the perturbation indicator shows a good correlation with the geomagnetic index A_{p}, particularly over the North Pole. It should be underlined that the northern and southern high-latitude ionospheres are controlled by different energy inputs leading to a different behaviour which cannot be reflected in a planetary index. Obviously, the ionospheric perturbation degree is stronger on 20 November than on 21 November although the A_{p} peaks on the second day. This is due to storm-induced processes leading to ionospheric exhaustion (Foerster and Jakowski, 2000).

Seeking better definitions of the perturbation index, various formulae and procedures were applied. For example, it is also possible to define the perturbation index via the deviation of TEC from non-perturbed reference values such as monthly medians. Thus, the index is defined by the following formula:

$$\mathrm{RIDX}_{\mathrm{r}}^{\mathrm{med}} = \sqrt{\left(\frac{1}{N_{\mathrm{grp}}-1}\right)\sum_{k=1}^{N_{\mathrm{grp}}}((\mathrm{TEC}_k - \mathrm{TEC}_k^{\mathrm{med}})/\mathrm{TEC}_k^{\mathrm{med}})^2}, \quad (3)$$

where TEC_k is the vertical TEC derived for a grid point $k = (i,j)$, $\mathrm{TEC}_k^{\mathrm{med}}$ is the corresponding TEC monthly median, and N_{grp} is the number of grid points in a given regional map. Here, in contrast to the previous definition, the index is based on all vertical TEC values at the grid points of a given regional map. Also, it has to be pointed out that these values are obtained after the assimilation process. To demonstrate the possibility of studying subregional (zonal) differences, RIDX was calculated separately over two important zones, the "auroral zone" (57.5°N < lat < 70°N) providing $\mathrm{RIDX}_{\mathrm{r}}^{\mathrm{mod}}$ (AUR), and the "polar cap" zone (75°N < lat < 87.5°N) providing $\mathrm{RIDX}_{\mathrm{r}}^{\mathrm{mod}}$ (CAP). These are 'first-order' approximations only and are shown here to simply illustrate the procedure; to analyse specific phenomena taking place in the auroral zone and/or the polar cap ionosphere, more refined definitions must be applied. Nevertheless, in both cases, a good correlation of the different TEC based perturbation parameters with the geomagnetic index A_{p} was demonstrated. Interestingly, on some occasions there were strong deviations indicated by RIDX due to ionospheric disturbances that were not clearly 'captured' by the A_{p} index, e.g., during the night of 26/27 October 2004 (around the 144 h in Fig. 2, left panels). The fact underlines again the necessity of regional monitoring and developing regional indices.

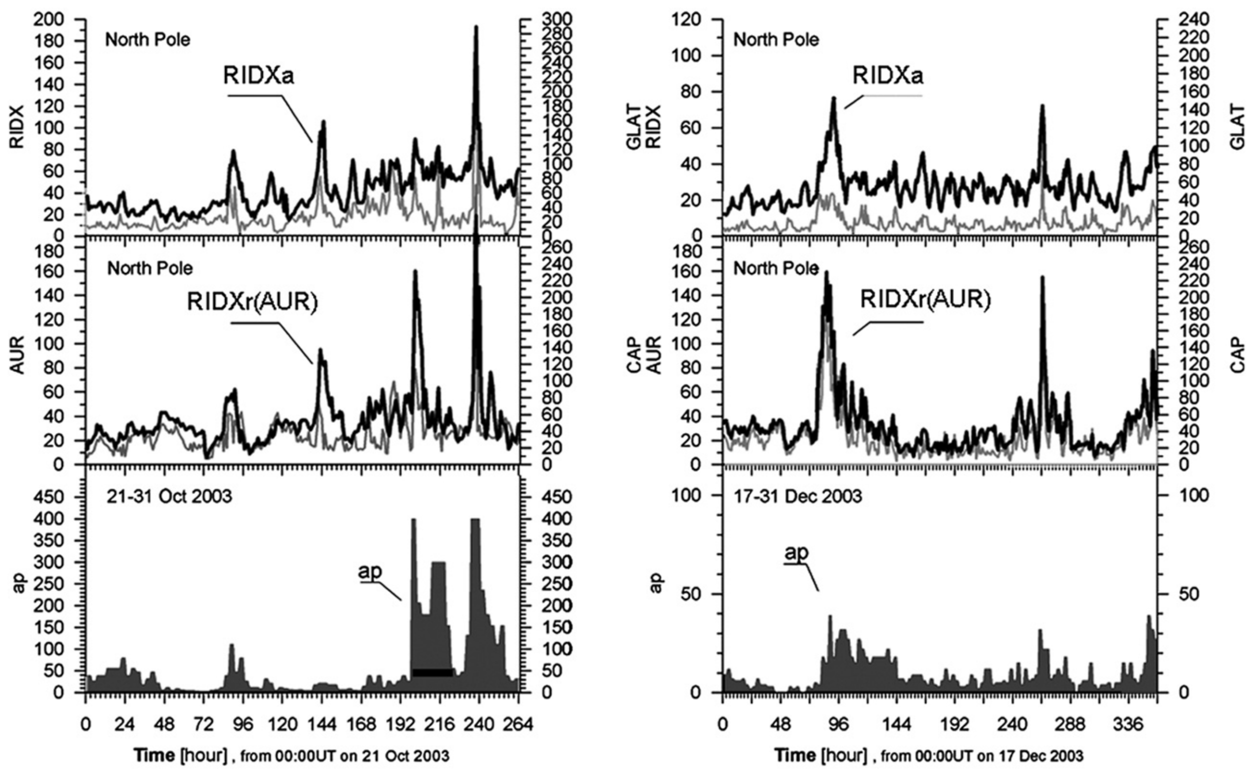

Fig. 2. Comparison of ionospheric perturbation indices for the North Pole region during the periods of 21–31 October 2003 (left panels) and 17–31 December 2003 (right panels). Top panel: comparison between $RIDX_a$ (black line) and GLAT (gray line). Middle panels: comparison between the auroral perturbation indices $RIDX_r^{mod}$ (AUR) (black line) and $RIDX_r^{mod}$ (CAP) (gray line). Bottom panels: the A_p index.

By comparing the absolute ($RIDX_a^{mod}$, upper panels) and the relative ($RIDX_r^{mod}$, middle panels) perturbation indicators, we can conclude that the percentage measure is better suited to identify/detect a perturbation event. This is probably due to the fact that the absolute TEC measure, by including the corresponding gradients, reflects not only the perturbation but also the regular ionospheric variations (diurnal, seasonal, or geographical). On the other hand, a GNSS user might be more interested in an absolute measure of the current ionospheric conditions that is independent from the current perturbations. Thus, the establishment of more specific indices may be justified in the future. For example, the temporal gradients of TEC, indicated by strong phase fluctuations, have a strong impact on the performance of GNSS systems (Jakowski et al., 2001). Severe radio scintillations may even cause a loss of lock of GPS receivers. However, these are complex topics of their own and deserve proper studies/discussions in follow-on publications.

4. Summary and outlook

Motivated by problems experienced by GNSS users, after analysing these problems and considering the research and operational monitoring experience, we propose a new type of ionospheric perturbation index which will more closely describe the ionospheric perturbations in a given region. The observations will allow for real-time monitoring of the ionosphere which ultimately will make such index suitable for operational services to GNSS users. Principally, the indices may have a local, regional or global character. Whereas planetary indices are well suited to represent global phenomena and to satisfy international needs and standards, regional indices are more helpful to users of local/regional services.

It has been found that the here defined perturbation indices are somewhat correlated with the geomagnetic activity indices (particularly A_p) but behave also differently, depending on the concrete solar weather conditions. Hence, the new ionospheric perturbation index is needed to provide an optimal ionospheric space weather service.

More detailed studies with various data sets will be needed to find out which of the index formulations have the potential to become a representative ionospheric perturbation index. Of course, the optimal definition of ionospheric perturbation indices need to be determined after evaluation by users of GNSS-based space weather services.

Acknowledgements

This research is funded by the German State Government of Mecklenburg-Vorpommern under grant SWACI – V230-630-08-TIFA-334.

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