Assessing the degree of ionospheric perturbation from radio tomographic data

Ivan A. Nesterov(1), Elena S. Andreeva(1), Marina O. Nazarenko(1), Yulia A. Tumanova(1) and Artem M. Padokhin* (1)
(1) Lomonosov Moscow State University, Moscow, Russia

Abstract

The methods are suggested for constructing the ionospheric perturbation indices (IPIs) from the empirical electron density distributions retrieved by the ionospheric radio tomography (RT). The indices take into account the specificity of the low- and high-orbiting (LO and HO) RT data, their spatio-temporal resolution and coverage. We consider and analyze various schemes of IPIs construction, calculate the correlation between the IPIs and geomagnetic Kp index, identify the indices that are most sensitive to the geomagnetic activity factor.

1. Introduction

As of now, many indices describing ionospheric perturbations based directly on ionospheric parameters (electron density distribution and TEC) and highly sensitive to the geomagnetic disturbance factors have been suggested by the different authors. These indices primarily differ by the types of the initial data. To date, three data types have been used.

The first data type is the ionosonde measurements. These data are used e.g. for constructing the AI ionospheric perturbation indices [1] and Js, Jp indices [2]. The main limitations of this data type are due to the locality of the measurements and low reliable performance of the ionosondes during the disturbed conditions up to the complete failure and data absence during the strong ionospheric disturbances.

The second type comprises the slant total electron content (TEC) data estimated from phase and code measuremets of GNSS signals recorded by the ground receivers [3]. The analysis of the rate of change of slant TEC provided the basis for introducing the I_{ROT} [4], ROTI [5], f_P and F_p [6], G_{RMS}, RIDX [7], DIX [3] and other indices. The main difficulty of using the rate of change of slant TEC as a proxy for the perturbations of the ionosphere is associated with the necessity to take into account the changes in the directions (the slope angle) of the satellite–receiver rays in the course of satellite motion.

The global ionospheric maps (GIM) of vertical TEC are the third type of the data. These maps can also be understood as a certain result of processing the initial data of GNSS [8]. For instance, as the indices reflecting the variability of the ionosphere in response to the geomagnetic impacts, Gulyaeva et al. suggested the W and Wp indices constructed based on the GPS-IONEX maps [9]. The GIM data are calculated at several data centers and currently contain the bihourly vertical TEC values with the spatial resolution of 2.5° in latitude and 5° in longitude. The capabilities of IGS network provides the possibility to increase spatial and time resolutions of GIM product in nearest future. As of now, the extremely low spatial and time resolution of GIMs is the key limitation of these data.

In the present work, we intended to construct a set of indices of ionospheric perturbations which rely on a different data type, not previously used, --- the RT data (both LO and HO), while RT is one of the most efficient present methods for retrieving the information about the structure and dynamics of the ionosphere [10].

RT-based indices can help to overcome some limitations inherent in the IPIs that are based on the data types described above and, at the same time, preserve the benefits of these indices. In contrast to the ionosonde measurements, the frequencies of radio signals used in the RT methods are sufficiently high to allow imaging the ionosphere even under highly disturbed conditions. In contrast to the “raw” slant TEC data, our approach bypasses the difficulties associated with the allowance for the slope angle of the satellite-to-receiver rays. In contrast to GIM, the fairly detailed spatial and time resolution of the RT reconstructions makes it possible to take into account local ionospheric features, which are important manifestations of the disturbances.

2. Constructing the IPIs Based on LORT data (LORT Indices)

LORT instruments are efficient for reconstructing different types of electron density irregularities that are present in the disturbed ionosphere. These irregularities broadly vary by their structure and scales in space and time. Together with the regional and global features, also the distinct local structures are typically present in the disturbed ionosphere. The enhancement of heterogeneity in the distribution of electron density can be tracked by the growth of the gradients of the latter, therefore when considering the design of the IPIs we will place special emphasis on the gradients.

We suggest the following set of basic indices for estimating the degree of ionospheric perturbation from the LORT data:

the spatially averaged horizontal gradient of electron density (hereinafter, averaging is understood in the sense of RMS values)

$$\sigma[N_x] = \sqrt{\left\langle \left(\frac{\partial N}{\partial x} \right)^2 \right\rangle} = \sqrt{\frac{\int \left(\frac{\partial N}{\partial x} \right)^2 dS}{S}}, \quad (1.1)$$

the spatially averaged vertical gradient of electron density

$$\sigma[N_y] = \sqrt{\left\langle \left(\frac{\partial N}{\partial y} \right)^2 \right\rangle} = \sqrt{\frac{\int \left(\frac{\partial N}{\partial y} \right)^2 dS}{S}}, \quad (1.2)$$

the spatially averaged total gradient of electron density

$$\sigma[\vec{\nabla} N] = \sqrt{\left\langle \left(\vec{\nabla} N \right)^2 \right\rangle} = \sqrt{\frac{\int \left(\vec{\nabla} N \right)^2 dS}{S}}, \quad (1.3)$$

and the spatially averaged value of electron density itself:

$$\sigma[N] = \sqrt{\left\langle N^2 \right\rangle} = \sqrt{\frac{\int N^2 dS}{S}}, \quad (1.4)$$

Here, *N(x,y)* is two-dimensional electron density distribution and *dS* is the element of integration over the area of LORT reconstruction. This area may slightly vary depending on the particular conditions of reception of the signals from the LORT satellites during the different satellite passages above the receiving chain. By normalizing the suggested indices by the area of the reconstruction (S) (i.e., by spatial averaging), we eliminate the effects associated with these variations.

These main indices can be used as the basis for constructing a number of the secondary (derivative) indices, including e.g. the relative (or scaled) indices which have a sense of the characteristic inverse scales of the ionospheric structures. These are the full inverse scale:

$$L^{-1} = \frac{\sigma[\vec{\nabla} N]}{\sigma[N]} = \sqrt{\frac{\int \left(\vec{\nabla} N \right)^2 dS}{\int N^2 dS}}, \quad (2.1)$$

the characteristic horizontal inverse scale:

$$L_x^{-1} = \frac{\sigma[N_x]}{\sigma[N]} = \sqrt{\frac{\int \left(\frac{\partial N}{\partial x} \right)^2 dS}{\int N^2 dS}} \quad (2.2)$$

and the characteristic vertical inverse scale of the ionospheric structures:

$$L_y^{-1} = \frac{\sigma[N_y]}{\sigma[N]} = \sqrt{\frac{\int \left(\frac{\partial N}{\partial y} \right)^2 dS}{\int N^2 dS}}. \quad (2.3)$$

3. Constructing the IPIs Based on HORT data (HORT Indices)

Let us consider the set of the HORT data (i.e., the HORT reconstructions of electron density distributions) for the time interval which is, on one hand, sufficiently long to allow statistical description and, on the other hand, reasonably short to neglect the seasonal variability within this interval. Among the considered dataset, we identify the days with relatively low geomagnetic activity (Kp≤3) and carry out data averaging for these days, which gives the average undisturbed characteristics---the means and the RMS deviations from the means for the distributions of electron concentration and vertical TEC.

Based on these characteristics, we now introduce the HORT indices of ionospheric perturbation. The first type of the IPIs incorporates:
the field of deviations from the mean:

$$\Delta f = f - \overline{f}, \quad (3.1)$$

the field of relative deviations from the mean:

$$\delta_\mu[f] = \frac{f - \overline{f}}{\overline{f}}, \quad (3.2)$$

the field of deviations from the mean normalized to RMS deviations:

$$\delta_\sigma[f] = \frac{f - \overline{f}}{\sigma[f]}, \quad (3.3)$$

where the field of RMS deviations over the ensemble is

$$\sigma[f] = \sqrt{\overline{\left(f - \overline{f} \right)^2}}. \quad (3.4)$$

Symbol f denotes the values of electron density (a function of three spatial coordinates and time) or vertical TEC (a function of two spatial coordinates and time). The horizontal bar above the symbol, $\overline{f}$, denotes averaging over the ensemble of relatively quiet days. The result of this averaging is a function that depends on the spatial variables and on the time from the beginning of the day (UT). The indices pertaining to the first group depend on the spatial variables and time. At a fixed time of the day, these indices are maps that provide the data for analyzing the zonal characteristics of the ionospheric perturbation.

The indices of the second type are introduced as a group of the characteristics that are obtained by the spatial averaging of the indices of the first type. Hence, this type of the indices only depends on time. These indices are most convenient for the comparison with the integral characteristics of the perturbing factors, in particular, with the geomagnetic indices. We consider two groups of the quantities: the means

$$\langle \Delta f \rangle = \langle f - \overline{f} \rangle \quad (4.1)$$

$$\langle \delta_\mu[f] \rangle = \left\langle \frac{f - \overline{f}}{\overline{f}} \right\rangle \quad (4.2)$$

$$\langle \delta_\sigma[f] \rangle = \left\langle \frac{f - \overline{f}}{\sigma[f]} \right\rangle \quad (4.3)$$

$$\delta_{\langle\,\rangle\sigma}[f] = \frac{\langle f - \overline{f} \rangle}{\sigma_{\langle\,\rangle}[f]} \quad (4.4)$$

and spatial deviation quantities:

$$\sigma_{\langle\,\rangle}[f] = \sqrt{\left\langle \left(f - \overline{f}\right)^2 \right\rangle} \quad (4.5)$$

$$\delta_\mu^{RMS1}[f] = \frac{\sqrt{\left\langle \left(f - \overline{f}\right)^2 \right\rangle}}{\sqrt{\left\langle \overline{f}^2 \right\rangle}} \quad (4.6)$$

$$\delta_\sigma^{RMS1}[f] = \frac{\sqrt{\left\langle \left(f - \overline{f}\right)^2 \right\rangle}}{\sigma_{\langle\,\rangle}[f]} \quad (4.7)$$

$$\delta_\mu^{RMS2}[f] = \sqrt{\left\langle \frac{\left(f - \overline{f}\right)^2}{\overline{f}^2} \right\rangle} \quad (4.8)$$

$$\delta_\sigma^{RMS2}[f] = \sqrt{\left\langle \frac{\left(f - \overline{f}\right)^2}{\sigma^2[f]} \right\rangle} \quad (4.9)$$

Angular brackets, $\langle f \rangle$, denote averaging over all the spatial variables at a fixed time. We consider the regional HORT reconstructions, therefore averaging is conducted over the region of the HORT reconstruction.

Generally speaking, the discussed technique is not limited to using exactly the HORT data as the initial spatial distributions to be analyzed. This technique is also applicable to the other data types, e.g., TEC maps obtained in the thin sheet approximation, etc. However, for each particular data type, among the variety of the possible IPIs it is necessary to identify the ones that are most sensitive to the perturbing factors.

4. Comparison of the LORT IPIs with the Kp and Dst Geomagnetic Indices

We studied the LORT images of electron density for the regions of Northwest Russia and Alaska under different conditions of geomagnetic activity. We used coherent 150/400 MHz transmissions of LO navigational Parus and Transit satellites recorded by the Svalbard-Kola Peninsula-Karelia-Moscow and Cordova-Gakona-Delta receiving chains. The phase measurements of LO satellites transmissions were used for reconstructing LORT images by the phase-difference tomographic approach [10].

Based on these LORT reconstructions of electron density, we have calculated and analyzed the LORT indices of the ionospheric perturbations described above for the period of the strongest Halloween geomagnetic storm at the end of October 2003.

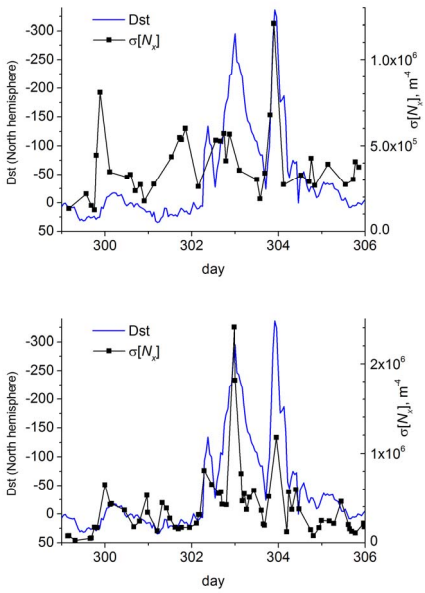

Figure 1. LORT IPI $\sigma[N_x]$ for Northwest Russia (top) and Alaska (bottom) regions during Halloween geomagnetic storm 2003.

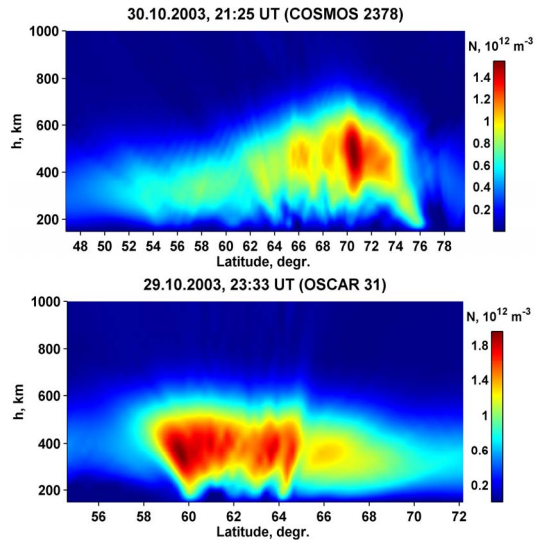

Figure 2. LORT reconstructions for Northwest Russia (top) and Alaska (bottom) regions during Halloween geomagnetic storm 2003.

Our study showed that among all suggested LORT IPIs the behavior of indices $\sigma[N_x]$, $\sigma[\vec{\nabla} N]$ and $\sigma[N]$ is closest to the time variations of the geomagnetic activity, and among these indices, $\sigma[N_x]$ has a highest sensitivity to this disturbing factor. Figure 1 shows the behavior of index $\sigma[N_x]$ and the time variations of Dst index during considered time interval for Northwest Russia (top) and Alaska (bottom) regions respectively, while Figure 2 presents LORT reconstructions for these regions for the most perturbed days.

5. Comparison of the HORT IPIs with the Kp and Dst Geomagnetic Indices

For this study we selected the American region (20-150°W, 20°S-90°N) and time interval - March 2015. HORT reconstructions were conducted using GPS/GLONASS L1 and L2 measurements from the IGS stations with the approaches and algorithms explicitly describeded in [11].

Our studies revealed $\delta_{\sigma}^{RMS2}[TEC]$ as one of the most sensitive indices to geomagnetic disturbances. Its behavior in comparison with Kp index for March 2015 is presented in Figure 3 (top). The correlation between Kp and $\delta_{\sigma}^{RMS2}[TEC]$ is higher than 0.75 and the maximum of the correlation function is lagged by a few hours, which means that the ionospheric perturbations are somewhat delayed with respect to geomagnetic disturbances. Figure 3 (bottom) presents the example map of $\delta_{\sigma}[TEC]$ which illustrates the position of the areas with the increased ionospheric perturbations, mainly located in the auroral and subauroral regions.

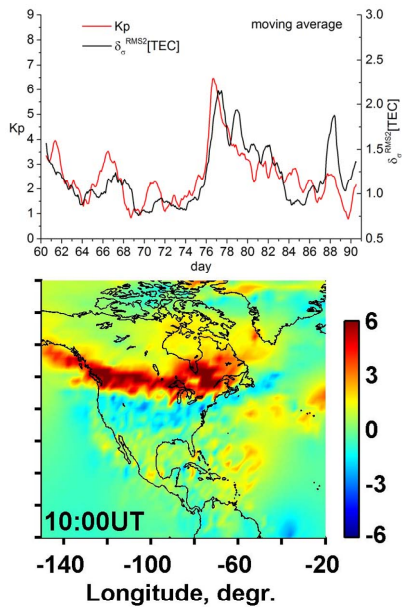

Figure 3 The results for HORT IPI $\delta_{\sigma}^{RMS2}[TEC]$ for March 2015 (top) and $\delta_{\sigma}[TEC]$ for March 17, 2015 10:00 UT (bottom)

6. Conclusions

In this work, we suggest the technique for constructing the IPIs, which takes into account the specificity of the LORT and HORT data. The analysis of the extensive LORT and HORT data shows that the suggested indices clearly reveal the influence of geomagnetic factor on the state of the ionospheric plasma. Among most sensitive to geomagnetic disturbances are suggested LORT IPI $\sigma[N_x]$ and HORT IPI $\delta_{\sigma}^{RMS2}[TEC]$.

7. Acknowledgements

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8. References

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