MAPPING OF SPATIAL DISTRIBUTION OF IONOSPHERE SMALL-SCALE STRUCTURE, PHASE SLIPS AND POSITIONING ACCURACY AS DEDUCED FROM TWO-FREQUENCY MEASUREMENTS OF GPS SIGNALS

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ABSTRACT

Degradation of transionospheric radio signals and operation failures during geospace disturbances constitute a crucial factor of space weather influence on radio engineering satellite systems performance. The objective of this report is to investigate interaction of spatio-temporal characteristics of auroral activity, total electron content (TEC) variations, amplitude and phase fluctuations of GPS signals and positioning accuracy during strong magnetic storms on October 29-31, 2003. The method of mapping of spatial distribution of ionosphere small-scale structure as deduced from two-frequency measurements of GPS signals is offered. It is based on the technology of ionospheric disturbances global detecting used GPS receivers network data processing, developed in ISTP SB RAS. For positioning errors estimating software package “Navigator” developed by authors [6] on basis of the existing standard RINEX-files processing software TEQC was used.

INTRODUCTION

Satellite-related techniques are currently being actively developed for the purposes of optical monitoring the processes in the upper atmosphere with high spatial resolution, enabling some geophysical processes (especially those in the auroral region) to be visualized. Despite ample experimental research, an analogous technology for the global monitoring of ionospheric irregularities (IIs) is still lacking. The major obstacle to mapping the spatio-temporal distribution of the irregular structure intensity in the ionosphere by means of earlier known methods is the absence of global continuous simultaneous measurements with high spatio-temporal resolution.

A number of papers [1, 3, 5, 7, 8, 9] have reported that during strong magnetic storms at mid-latitudes the relative failure density in range measurements, particularly in L1-L2 phase difference measurements at two coherently related GPS frequencies f_1=1575.42 MHz and f_2=1227.60 MHz, is one to two orders higher than the corresponding index for magnetically quiet days. It can reach units per cent of the total observation density [3]. This entails a considerable decline in positioning accuracy which is the major indicator of the GPS system operation quality. The research has shown that the cause of phase slips lies in GPS signal being scattered on ionospheric irregularities with a characteristic size of the order of the first Fresnel zone radius (150-300 m). As a result, the signal amplitude may temporarily drop down to below noise level, leading to lost signal lock and failures in range measurements.

It was shown in [3, 4] that ionospheric irregularities causing GPS signal scattering form during a magnetic storm's main phase within the auroral oval, as well as in areas of enhanced electron concentration gradient outside the oval. Moreover, areas with intense small-scale irregularities can travel in space in the wake of large-scale high-amplitude wave disturbances forming in the auroral zone and traveling long distances equator-ward. Thus, a vital issue is the problem of visualizing the spatio-temporal distribution of the intensity of ionospheric irregularities and failure density in range measurements by the GPS system.

The method we have developed for visualizing the spatial distribution (mapping) of the ionosphere's irregular structure is demonstrated on the example of intensity measurements of total electron content variations and the GPS system phase measurements failure density during the 29-31 October 2003 magnetic storm.

The method is based on the notion that the TEC variation spectrum as measured from phase differences between the signals in two GPS frequencies is a power dependency and differs from the spectrum of electron concentration irregularities in spectral slope only. This enables the estimation of intensity variations of irregularities 100-1000 m in size based on changes in TEC variation intensities in the intermediate scale range (over 10-100 km, periods 1 to 10 min), i.e. in the longwave portion of the spectrum. During a geomagnetic disturbance the amplitude of irregularities of the entire scale range - from the meter to the kilometer scale and above - grows proportionally, as does the TEC variation amplitude, with the spectral slope of ionospheric irregularities and TEC variations remaining constant.

THE GLOBAL NETWORK OF GPS RECEIVERS. FORMING A REFERENCE GRID OF SPATIAL DISTRIBUTION.

The global GPS network, numbering over 2500 GPS stations by 2005, densely covers North America and Europe. There are much fewer GPS stations across the Asian and African regions, in the Pacific and Atlantic oceans. Nevertheless, the thus fitted Earth surface provides for solving the problem of the global detection of disturbances with a significantly higher spatio-temporal resolution as compared to earlier methods.

To obtain the spatio-temporal distribution of TEC variation intensity, this paper relied on data from the global network of GPS receivers located within North America (20º-60ºN, 60º-140º W). A particular region is subdivided into equal areas (cells) along the ΔB latitude and ΔL longitude. The black square in Fig. 1 denotes an (m, n)-cell, where m = 1, 2, ..., M; n = 1, 2, ..., N; M and N are, respectively, the number of columns and rows in the reference grid. Maximum values of the region's latitude and longitude are $L_m = M\Delta L; B_n = N\Delta B$.

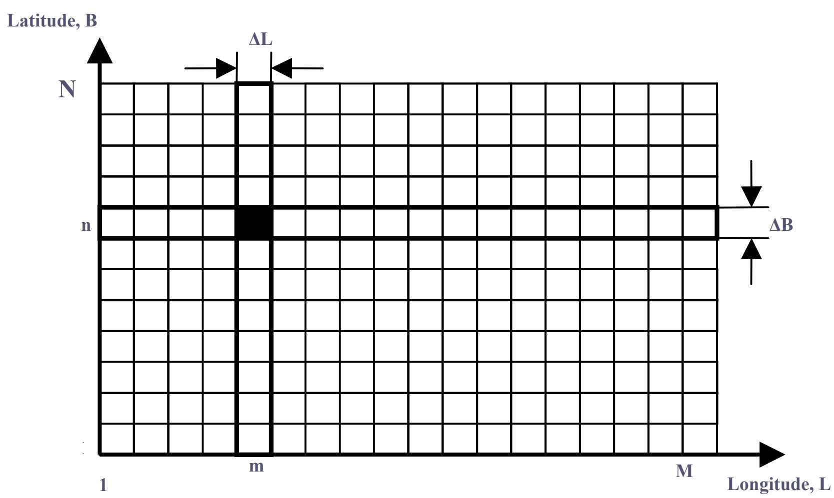


Fig. 1. Grid of the spatial distribution

ESTIMATING THE VARIATION AMPLITUDE OF THE TOTAL ELECTRON CONTENT A AND GPS PHASE SLIP DENSITY *P*

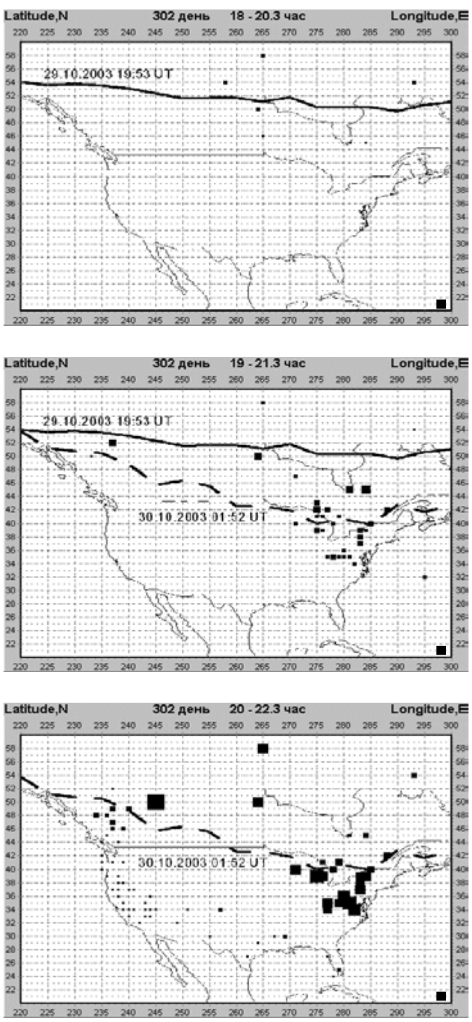
A methodology for the data preprocessing has been detailed in [3, 5] and will not be dwelt upon in this paper. The software complex GLOBDET developed at the ISTP SB RAS [2] allows, for each data series with about 2.3h duration, an estimate to be made of the relative failure density P of L1-L2 phase difference measurements, as well as TEC data series I(t) containing no phase slips to be selected. L1-L2 phase difference measurement failures are registered in the case when TEC increment for a time interval of 30 s (the standard for the majority of GPS data available over the Internet) exceeds a set threshold of the order of, e.g. 100-200 TECU (TECU=10^{16} el/m^{-2}). For a given i-receiving GPS station and for each observed j-AES, the value of P_{ij} is defined as the ratio of the number of phase slips to the total number of observations.

Series I(t) not containing L1-L2 phase difference slips or absent counts are used to estimate values of A_{ij} and C_{ij}, equal to the RMSD of TEC variations dI(t) in the period range of 20-60 min and 1-10 min, respectively, for the same stations and time intervals as were used in estimating P_{ij}. Variations with such periods correspond to ionospheric irregularities of the medium (100-300 km) and kilometer (1-10 km) scales.

NORMALIZATION AND VISUALIZATION OF THE SPATIAL DISTRIBUTIONS OF THE FAILURE DENSITY IN PHASE MEASUREMENTS AND TEC VARIATION INTENSITIES

The need for a spatial averaging of failure density values in phase measurements of P and RMSD of TEC variations *A* and C results from the non-uniform distribution of receiving GPS stations on the Earth's surface. For all stations located in each (m, n)-cell of the reference grid of the spatial distribution (Fig.1), mean failure densities in phase measurements *P*, and TEC variation intensities *A* and *C* are computed. Thereby, the reference grid is used to produce spatio-temporal distributions of the phase measurements failure density *P(L, B)*, and TEC variation intensities *A(L, B)* and *C(L, B)*.

Figs. 2, 3 display maps of the North American region, where the sizes of black squares *S* are proportional to the RMSD of TEC variations *S=kA*, or to the phase slip density *S=kP*, where k is the normalization coefficient, equal to the inverse maximum value of the RMSD of dI(t) variations, or of maximum failure density *P*.

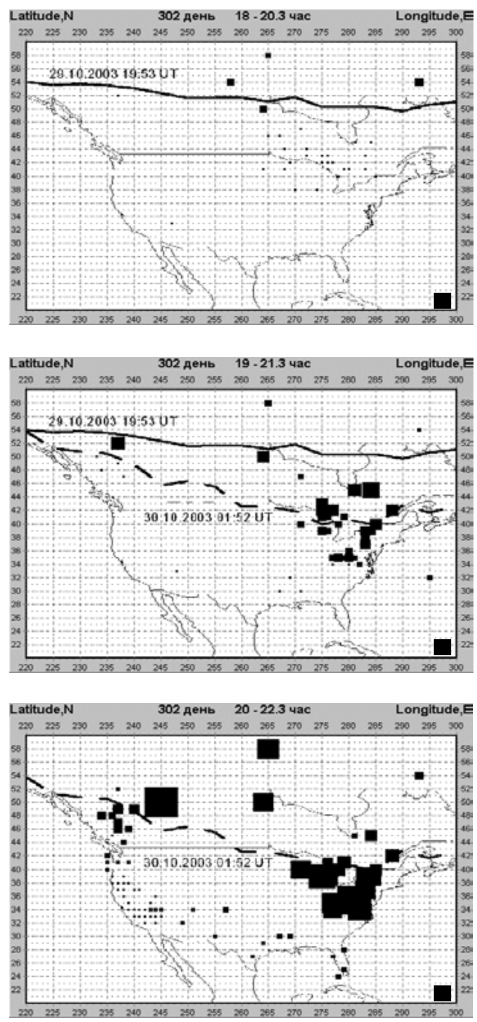


a

b

c

Fig.2. Spatial distribution of RMSD TEC variations ***C(L, B)***.



a

b

c

Fig.3. Spatial distribution of phase slip densities ***P(L, B)***.

Fig.2 displays for the time intervals 18-20.3 UT (a), 19-21.3 UT (b), 20-22.3 UT (c) on 29 October 2003 maps of the spatial distribution of the RMSD of TEC variations *C(L, B)* with 1-degree steps on both latitude ΔB and longitude ΔL, within the period range of 1-10 minutes. The size of the bottom-right black square corresponds to the maximum value of the RMSD of dI(t) equal to 1 TECU. The map marks the position of the southern boundary of the auroral oval for these time intervals. The distribution of *C(L, B)* corresponds to the distribution of the intensity of ionospheric irregularities causing GPS signal degradation. One can see in Fig.2 the emergence of intense small-scale structures in the north-eastern USA and their south-westward propagation with ever increasing intensity, the emergence and increase of II intensity not always determined by the auroral effects. Thus, Fig.2 exhibits an extensive enough area with IIs at 30-40º N.

Fig.3 displays, for the same region and time intervals, spatial distribution maps of phase slip density *P(L, B)*. The size of the bottom-right black square corresponds to the maximum value of phase measurements failure density of 40%.

One can see from Figs. 2 and 3 that the spatio-temporal distributions of the RMSD of TEC variations and phase slip densities are well correlated, which is consistent with earlier findings and offers new possibilities for researching the development dynamics of the ionosphere's irregular structure as well as the dynamics of the GPS operation efficiency indices during geomagnetic disturbances.

The above described mapping technique can be applied to visualizing the spatio-temporal distributions of any characteristics of the ionospheric structure, obtained when processing the data from the global GPS receiver network, as well as from the Russian GLONASS and the European GALILEO systems.

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