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A method to determine exact wave parameters of tid

Abstract. Total electron content measurements by using dual-frequency signals of global navigation satellite systems (GNSS) makes it possible to obtain the global distribution of electron density of ionosphere with high spatial and temporal resolution. Such high spatial and temporal resolution allows to explore of small-scale traveling ionospheric disturbances generated by terrestrial geophysical events, including seismic activity, solar terminator passage, and atmospheric cyclones. One of the features of measuring the total electron content of the ionosphere with GNSS is that the measurements are made at the line of intersection of the satellite-receiver beam with the layer of maximum ionization of the ionosphere at height of ≈ 300 km. At the same time, due to the orbital motion of the satellites and the Earth rotation, the ionospheric points at which the measurements are providing carrying out a movement relative to each other, relative to the Earth and relative to the traveling ionospheric disturbances. Such a relative motion of the measurement points causes the occurrence of the Doppler effect and leads to a distortion of the wave parameters of the total electron content variations. In particular, the determination of the period of traveling ionospheric wave disturbances on the basis of time series leads to large distortions depending on the used satellite, the time and coordinates of the receiver. This paper describes a method for determining the exact wave parameters –frequency, wavelength, and propagation velocity of traveling ionospheric wave disturbances, based on the use of godochrones to analyze TEC variations. The difference between the wave parameters measured by the proposed method and from the time series of TEC data is shown on an example of wave disturbances generated by the passage of solar terminator.
Keywords: GPS TEC, ionosphere, data analysis, traveling ionospheric disturbances.

Introduction

The method of measuring the total electron content (TEC) of the ionosphere using navigation satellite systems, also known as the GPS TEC method, has been widely used in recent decades to monitor the influence of various sources of space and terrestrial origin on the Earth's ionosphere. Using this method, the global behavior of the electron density [1,2], the nature of the change in the electron density due to changes in solar activity [3] and other factors have been studied so far, the influence of ground-based sources of disturbances, such as earthquakes [4], powerful explosions, meteorological phenomena, has been discovered [5,6]. A number of anomalous ionospheric disturbances associated with the preparation of powerful earthquakes have been registered [7-9]. All the above sources are presented in TEC data in the form of periodic oscillations of the electron content level, which have a small amplitude relative to the daily TEC change and propagate in horizontal direction, called traveling ionospheric disturbances (TID) [5,10].

The problem of determining the wave characteristics of TID lies in the fact that the ionospheric points at which the TEC is measured move in the horizontal plane during the orbital movement of the satellites and the rotation of the Earth. The ionospheric points for which the TEC is calculated are located at the intersection of the layer of maximum electron density of the ionospheric F2 layer (altitude about 300 km) and the radio beam line from the satellite to the stationary GPS receiver are not fixed relative to the Earth, and their position depends on the orbital motion of satellites and Earth rotation. (Figure 1). The orbits of GPS satellites are located at altitude of about 20000 km, and the orbital period of satellites is about 12 hours [5]. Given this factor, the horizontal speed of the ionospheric points in which the measurement is made can reach 500 km/h, which, due to the Doppler effect, makes it difficult to determine the true period and wavelength of ionospheric disturbances based on data from individual GPS receivers, since the ionospheric point can move along the moving wave disturbance of the ionosphere, in the same or reverse direction, more than doubling the values of its period and wavelength. This effect is determined by the geometry of satellite orbits, geographic latitude and measurement time, i.e. depends on the specific satellite used, time and receiver coordinates [11].

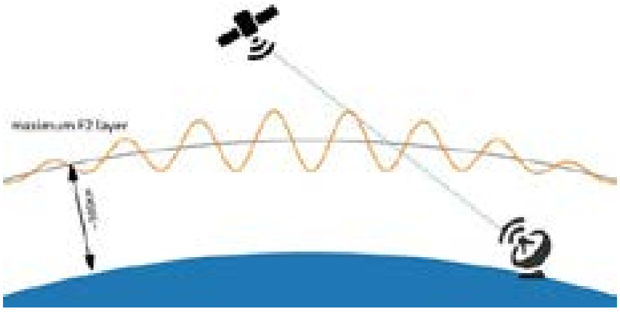


Figure 1 – Illustration of the occurrence of the Doppler effect during TEC measurements

Materials and Methods

The technique proposed in the present study makes it possible to measure the true values of the wave parameters of traveling ionospheric disturbances, its frequency (periods), wavelength, and horizontal velocity. The methods is based on the use of range-time diagrams, also known as hodochrones. Hodochrones are plots on which time is plotted along the abscissa axis, distance is plotted along the ordinate axis. In this case, the range is calculated as the distance between the ionospheric point at a given time and a given point on the Earth's surface. The time series of TEC variations, after removing the regular trend associated with the daily variation of TEC, are plotted with the color of the line, in accordance with the selected color scale. These diagrams are built for all tracks observed for the studied period of time, time series of TEC variations for each pair of satellite-receiver. The distance is plotted along the abscissa axis and calculated by different methods, depending on the type of the studied disturbance source. For quasi point sources (earthquakes, local meteorological phenomena, explosions, etc.), the distance from the point of the epicenter of the earthquake, explosion, cyclone center, etc. to the ionospheric point is calculating. In the case of a point source and in the approximation of spherical wave propagation, the synchronous phases of the wave disturbance will move along the radius vector constructed from the source center, forming a coherent wave pattern on the hodochrone. For extended sources (passage of the solar terminator, global atmospheric phenomena), the "Range" coordinate is calculated as the distance from the ionospheric point to the horizontal line passing through the center of the study area in the direction of propagation of the ionospheric disturbance. In this case, in the case of approaching the propagation of an ionospheric disturbance by a flat wave, a coherent wave pattern will be observed on the hodochrone (Figure 2). In this case, the horizontal cut of the hodochrone gives a temporal sweep of TEC variations, the vertical cut gives a spatial sweep of TEC variations, i.e. wavelength, and the TID velocity is equal to the tangent of the slope angle α of the coherent lines of the TEC variation maxima (Figure 2).

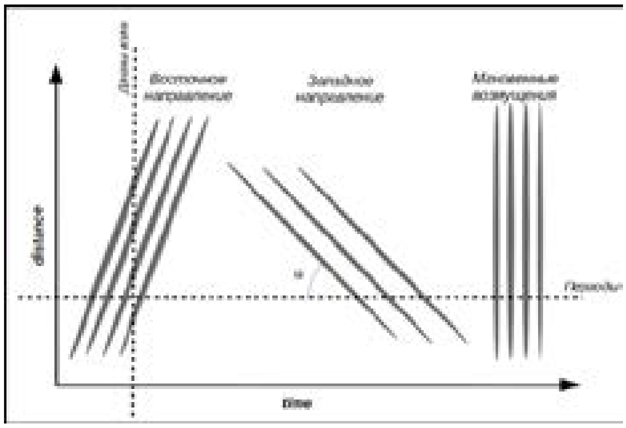


Figure 2 – Information available in the analysis of TEC variations hodochrons

The data used in this work is the data of permanent dual-frequency GNSS receivers (CORS – Continuously Operating Reference Stations), organized into global and regional networks of IGS, UNAVCO, GEONET, etc.

Results and discussion

The following is an example of time series of TEC variations calculated for individual satellites at a given moment and at a given point, and a time series of TEC variations along the horizontal cut of the hodochrone.

Figure 3 shows an example of a hodochrone, which allows illustrating the problem of determining the parameters of wave disturbances. This hodochrone is drawn according to data for April

17, 2018, based on data from GNSS receivers on the US West Coast, and contains a coherent wave pattern of TIDs that arose after the passage of the evening solar terminator. This hodochrone was built for the azimuthal direction 55°, i.e. the distance axis corresponds to the distance along the azimuth of 55°, which coincides with the direction of motion of the considered TIDs. This day is characterized by very low geomagnetic activity, the maximum daily value of the Ap-index was 5, and for the previous day – 4. Low geomagnetic activity causes the absence of irregular disturbances in the data. The disturbance from the solar terminator is directly observed in the interval of 700-800 minutes UT, after which, for nine hours, a coherent TID wave pattern is observed [12]. This hodochron is constructed from the data of all observed GPS satellites.

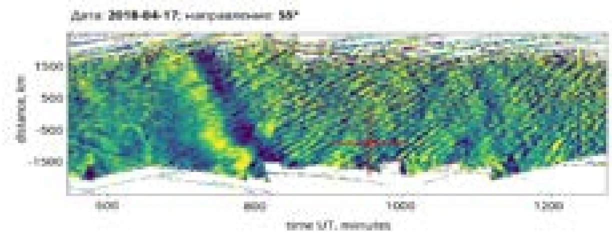
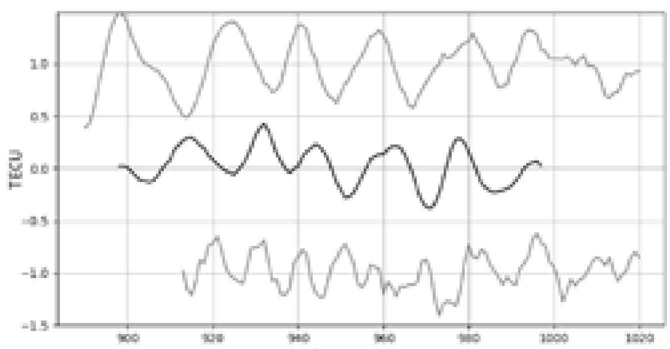


Figure 3 – Fragment of the TEC variations for April 17, 2018

In Figure 3, the red cross indicates the position and time at which the tracks of two GPS prn-26 and GPS prn-7 satellites intersect. The trajectories of these satellites at a given moment of time are such that the ionospheric point for the sounding beam to the prn-26 satellite moves in the same direction as the direction of the TID propagation, and the ionospheric point for the sounding beam to the prn-7 satellite moves in the opposite direction to the direction of the TID propagation direction. Thus, if we consider the ionospheric point at which TEC is calculated as the measurement point, then we have moving receivers, and we observe the Doppler effect. This effect leads to the fact that the time series of TEC variations for these satellites have different observed oscillation periods [13]. Figure 4 shows fragments of the time series for the satellite prn – 26 (upper graph), for the satellite prn – 7 (lower graph), and a slice of the hodochrone along the horizontal line of the red cross in Figure 3. Figure 4 also shows the values of the periods of the first harmonics for all three graphs. It can be seen from the figure that the periods of oscillations of TEC variations for the prn–7 satellite are two times less than the periods for the prn–26 satellite, and are 10.4 and 20.5 minutes, respectively. The oscillation period obtained from the horizontal cut of the hodochrone is 15.7 minutes, and since the Doppler effect is excluded when it is obtained, this period value can be considered true for a given time and place.



№ GPS satelite	Period (minutes)
26	20.5
26, 7, 9 hodochrone	15.7
7	10.4

Figure 4 – Time series and time slice according to the hodochrone of TEC variations for April 17, 2018

A similar result is observed for any satellites, since the trajectories of the movement of ionospheric points in which the TEC is calculated depend on the complex orbital motion of the satellites and the Earth's rotation (Figure 5).

The TID wavelength is determined in a similar way. To determine it, a vertical (along the distance axis) slice of the hodochrone is taken. So, for the area indicated in Figure 3, the horizontal wavelength of the TID is 170 kilometers.

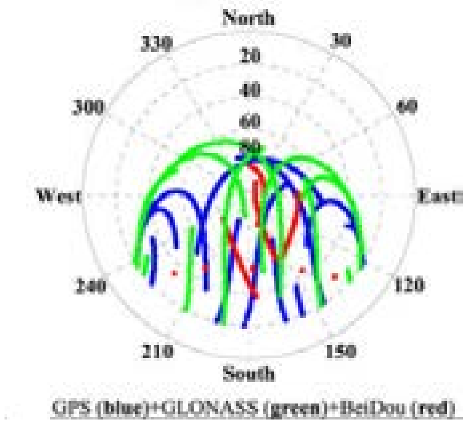


Figure 5 – Trajectories of ionospheric points for various satellites of GPS navigation system.

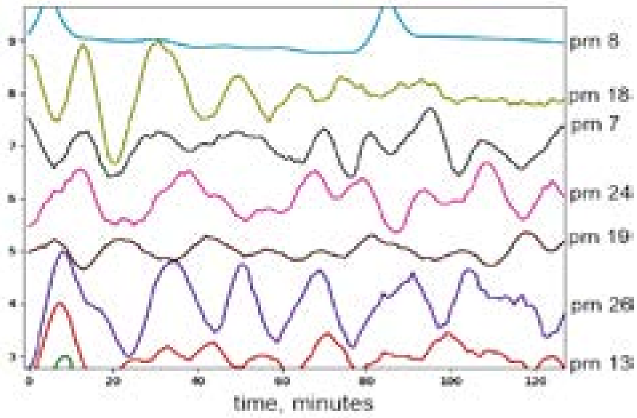


Figure 6 – TEC variations for seven simultaneously visible GPS satellites

The horizontal TID velocity is defined as the tangent of the slope angle α of the coherent lines of the TEC variation maxima. Figure 7 shows the dependence of the signal-to-noise ratio of TEC variations depending on the speed and direction of TID propagation for April 17, 2018 for 15-16 hours UT, which corresponds to the time specified in Figure 3. The maximum signal-to-noise value corresponds to the horizontal velocity of TID propagation ≈ 300 km/h, and direction of propagation 50-60°.

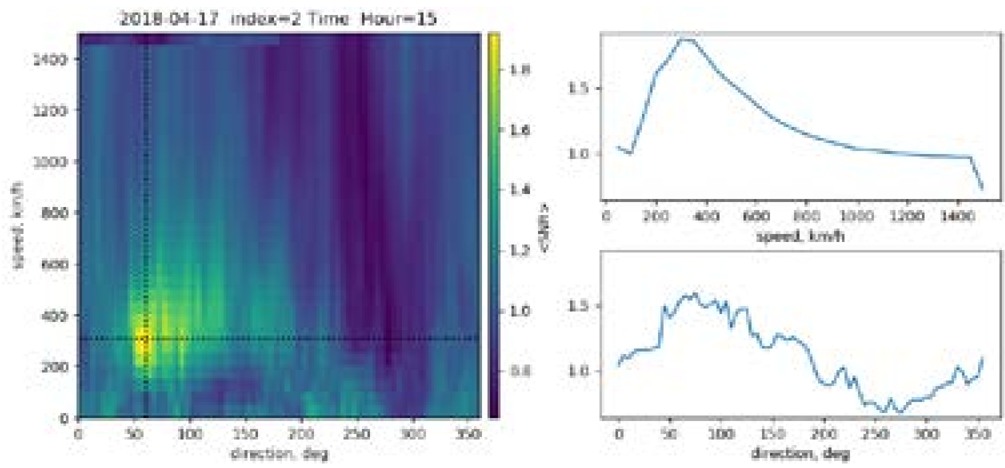


Figure 7 – Distributions of the signal-to-noise ratio of TEC variations depending on the speed and direction of TID propagation for April 17, 2018 for 15-16 hours UT

This signal-to-noise ratio distribution was constructed using the developed system for collecting and analyzing data from GNSS stations [14].

Conclusions

Thus, the applicability of the proposed method for determining the exact wave parameters of moving ionospheric wave disturbances based on the construction of hodochrons – range-time diagrams of TEC variations is shown. It is demonstrated that the direct time series of TEC variations have strong phase and frequency distortions caused by the Doppler effect and are unsuitable for analyzing the frequency characteristics of traveling ionospheric wave disturbances. The proposed method for determining the exact wave parameters of traveling ionospheric wave disturbances is applied in the developing GNSS TEC monitoring system to analyze wave disturbances of the ionosphere from the passage of the solar terminator and other sources.

Acknowledgments

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