The Response of the Ionosphere to the Earthquake in Japan on March 11, 2011 as Estimated by Different GPS-Based Methods

Yu. V. Yasyukevich, V. I. Zakharov, V. E. Kunitsyn, and S. V. Voeikov

1. INTRODUCTION

The mega-earthquake in Japan occurred on March 11, 2011 at 0546:24 UT. Its magnitude was $M_w = 9.0$ and the epicenter was located at 38.322° N, 142.369° E. The significant power of this event attracted the strong interest of geophysicists (Gokhberg et al., 2011; Astafyeva et al., 2011; Liu et al., 2011; Rolland et al., 2011; Tsugawa et al., 2011) as favorable for gaining more detailed insight into the interactions between different geospheres. The main shock of this temblor was preceded by a few foreshocks having lower magnitudes ($M_w > 6.0$). The main shock was followed by strong aftershock activity, which included 60 quakes with $M_w > 6.0$ and three quakes with $M_w > 7.0$. The rupture originated at a depth of about 24.4 km (www.iris.edu/news/events/japan2011). According to the estimates, the length of the rupture was 380–400 km and the field of the aftershocks covered about 450 km. It was calculated that the earthquake was a low-angle thrust event on a gently dipping fault plane (http://www.tectonics.caltech.edu/slip_history/2011_tohoku-oki-tele/index.html; www.gsi.go.jp/cais/topic110422-index-e.html) and the amplitude of the thrust was 25–30 m; moreover, an analysis involving the entire complex of the data upgraded this value to 35 m (Yokota et al., 2011). The block of the islands of Japan has moved eastwards relative to the Pacific Plate in a direction that is nearly perpendicular to the plate contact. In Figs. 1a and 1b, this region is shown by the thick black line.

For analyzing the responses of the ionosphere to different geophysical events, it is quite common to use estimates of the total electron content (TEC) $I$ derived from the dual-frequency phase measurements of GPS signal (Hofmann-Wellenhof, 1998):

$$ I = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \left[ (L_1 \lambda_1 - L_2 \lambda_2) + K + nL \right], $$

(1)

where $f_1$ and $f_2$ are carrier frequencies of GPS signals; $L_1 \lambda_1, L_2 \lambda_2$ are the additional paths of radio signals due to the phase delay in the ionosphere, m; $L_1$ and $L_2$ are the numbers of the full cycles of GPS carrier phases $\lambda_1$ and $\lambda_2$ are the wavelengths, m; $K$ is a constant due to the phase ambiguity and mistiming between the frequency channels; and $nL$ are the phase-path errors.

Applied to data from the GEONET network (Japan), which includes ~1200 stations, this method provides sufficiently high spatial resolution. The time resolution of the free-access data is 30 s.

2. SPATIAL STRUCTURE OF THE WAVE DISTURBANCES IN TEC BASED ON MAPPING THE TEC VARIATIONS

Saito et al. (1998) suggested the algorithm for visualizing the spatial distribution (mapping) of the intensity of TEC variations reflecting the irregular structure of the ionosphere, which is based on the use of data from dense networks of GPS receivers, such as the GPS receiving networks in Japan and California. For
After 0556 UT, the reconstructions reveal an intense fast LS perturbation. This perturbation was moving to the southwest, more or less parallel to the plate contact. As the perturbation moved farther away from the epicenter, its intensity rather rapidly decreased. The less intense and faster perturbations propagating in the southwest direction were observed south of the epicentral area up to 0700 UT.

Significantly later after the main shocks of the earthquake, the southeastern part of Japan was in the area of turbulentized ionosphere, which was marked with a highly heterogeneous spatial structure of TEC variations (indicated by the oval in Fig. 3). This area slowly drifted to the north and existed from 0800 to 0945 UT. It again appeared after 1030 and persisted up to 12 UT.

3. DISTANCE–TIME DIAGRAMS

It has recently become quite a widespread practice to estimate the velocity of the ionospheric perturbations with the use of the distance–time diagrams suggested in (Calais et al., 2003). The idea of this approach is to correlate the intensity of TEC variations to the time and distance to the source of the ionospheric perturbations (epicenter of the earthquake). The resulting time series of TEC are filtered in the selected interval of periods, after which the satellite elevations, line-of-sight azimuths, and coordinates of IPPs are computed for each time instant and each measurement based on the data on the positions of the satellite. For each IPP, the great-circle distance to the selected source of the perturbations is computed. This yields a two-dimensional (2D) map of TEC variations in the distance–time coordinates, where the color (or