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Modulation of total electron content by global Pc5 waves at low latitudes

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Abstract

Earlier studies have successfully demonstrated that the GPS–TEC technique is a powerful method to study the propagation pattern of transient disturbances in the ionosphere. This technique has turned out to be sensitive enough to detect ionospheric signatures of ULF waves as well, particularly at high latitudes. It has already been reported earlier that during the recovery phase of the strong magnetic storm on Oct. 31, 2003, intense Pc5 geomagnetic activity was accompanied with distinct pulsations of the same periodicity in the TEC data from high-latitude GPS receiving stations. The present study reveals the identical features in geomagnetic and TEC data at low-latitude stations in the Indian sector as well. However, the presented observational results on TEC modulation by global Pc5 waves at low latitudes cannot be interpreted on the basis of the Alfven mode concept. The most promising mechanism that can explain the present observations is the plasma compression by fast magnetosonic mode. Theoretical order-of-magnitude estimates of the ratio between pulsation amplitudes in TEC and geomagnetic field based on the proposed mechanism is found to be about the same as the observed values.

Keywords: ULF waves; GPS/TEC; Low latitude; Ionosphere

1. Introduction

The terrestrial ionosphere represents an inner boundary of the space environment where the transfer of energy through the coupled magnetosphere–ionosphere–atmosphere system takes place. The ionosphere can be imagined as a thin film of the ionized gas stretched over the globe, and this film is very sensitive to impacts from above and below. The ever-growing facilities of navigation global satellite system (GPS) provide information on variations of a radiopath-integrated ionospheric parameter – the total electron content (TEC). GPS/TEC observations have emerged as a global technique to monitor the propagation of waves and transients in the ionosphere (Komjathy et al., 2012). This is the reason for wide interest to use ionospheric observations with the use of the global positioning system (GPS) to monitor tsunami propagation (Galvan et al., 2011), to detect distant explosions (Fitzerald, 1997), to reveal the earthquake precursory (Liu et al., 2004; Zakharenkova et al., 2008) and post-seismic signatures (Tsai et al., 2011), etc. The ionosphere is also under the permanent impact from various space weather

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disturbances. Using the technique introduced by Saito et al. (1998), GPS-derived TEC has been extensively used to characterize traveling ionospheric disturbances (TIDs) of different nature, including space weather related disturbances, at middle (Tsugawa et al., 2007) and high (Van de Kamp et al., 2014) latitudes. The interaction between the solar wind and the magnetosphere provides a rich source for various types of ultra-low-frequency (ULF) waves, which are always present in the magnetosphere and perturb its inner boundary, the ionosphere. Local variations of ionospheric electron density caused by long-period ULF waves (Pc3–5, Pi2–3) can be detected by modern ground-based sounding techniques: HF Doppler sounders (Menk et al., 2007), SuperDARN radars (Teramoto et al., 2014), transionospheric radiowave propagation (Sinha et al., 2001), riometers (Spanswick et al., 2005), etc. The TEC technique is sensitive enough to detect at least some types of ULF waves in the ionosphere: Pc5 waves at high latitudes (Pilipenko et al., 2014a,b; Watson et al., 2015) and Pc3–4/Pi2 waves at middle (Davies and Hartman, 1976; Hamada et al., 2015) latitudes.

So far, the effect of TEC modulation by ULF waves is not well understood and is still a challenge for the MHD wave theory. Observations have revealed that the relative disturbance of TEC by Pc3 waves is about the same or even larger than that of geomagnetic field (Skone and Nicholson, 2006). Also, in the high-latitude Pc5 event of Oct. 31, 2003 analyzed by Pilipenko et al. (2014a,b) the relative amplitude of TEC variations, $\Delta N_T/N_T \sim 2.5\%$, was larger than that of geomagnetic pulsations, $\Delta B/B \sim 1\%$. Various proposed TEC modulation mechanisms (Poole and Sutcliffe, 1987; Waters et al., 2007; Pilipenko et al., 2014a,b), were based on different aspects of the Alfven wave interaction with the high-latitude ionosphere. In general, Pc5 pulsations are localized at auroral latitudes, and are the eigenmodes of Alfven field line oscillations between the conjugate ionospheres.

However, there are specific global Pc5 waves which are about an order of magnitude more intense than common Pc5 pulsations. They are observed in the recovery phases of geomagnetic storms during high solar wind streams (Rae et al., 2005; Potapov et al., 2006). The reason for such outstanding intensity has not been firmly established yet. Global Pc5 waves are not confined only to auroral latitudes, but they are extended deep into the magnetosphere and can be observed even at equatorial latitudes. The large latitudinal range of global Pc5 pulsations cannot be interpreted based on the theory of field line Alfven resonance excitation, because this mechanism provides a latitudinally localized wave structures. Moreover, global Pc5 waves do not show typical features of resonant structure: latitude-dependent spectral peaks and phase gradient. Marin et al. (2014) indicated that the observed Pc5 oscillations at low and equatorial latitudes are not due to evanescent surface-like mode at the magnetopause, but could be a result of different wave transmission mechanism, probably the MHD waveguide mode. Motoba et al. (2002) suggested that the penetration of global Pc5 waves towards the Earth's equator was caused by a nearly instant propagation of electromagnetic disturbance in the Earth-ionosphere waveguide with velocity about the light speed.

In this paper, we consider an example of global Pc5 waves excited during the recovery phase of Oct. 31, 2003 storm, and demonstrate that the standard TEC/GPS technique is sensitive enough to detect intense Pc5 geomagnetic pulsations at low latitudes. We also discuss possible physical mechanisms of TEC fluctuations associated with these waves.

2. Observational information and data processing

Magnetometer data from the meridional array along the geomagnetic longitude $\Lambda \sim 150°$ (local noon $\sim$7 UT) extending from mid-latitude station Bishkek (Kyrgyzstan) across India up to the dip equator are used (Fig. 1). Their coordinates are given in Table 1.

The GPS technique provides the means to estimate the slant TEC variations N_T on the basis of phase measurements of two-frequency, f_1 and f_2, GPS receivers using the widely-used relationships from (Hofmann-Wellenhof et al., 1992; Afraimovich et al., 2013). We have used these relationships without differential code biases. The slant TEC can be converted into vertical vTEC at the pierce point (intersection of radiopath with the ionosphere maximum) using the formula from Klobuchar (1986). To estimate absolute values of TEC the uncertainty of phase

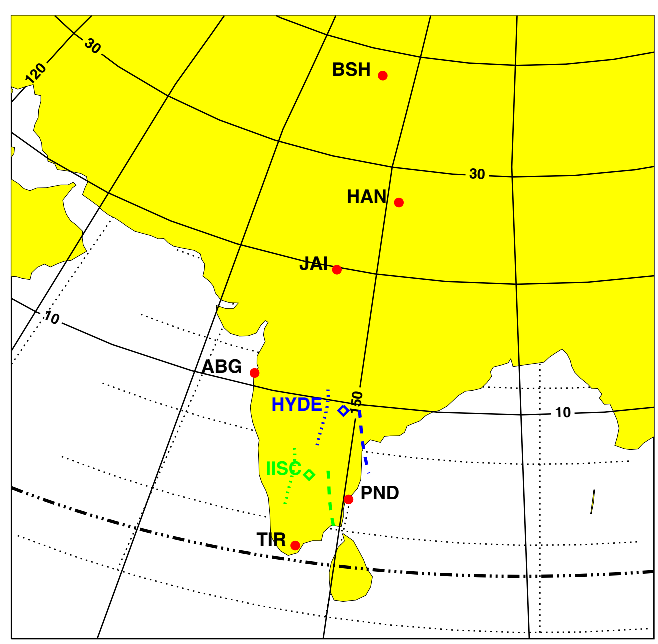

Fig. 1. Map of magnetic stations (red dots) and GPS receivers (empty squares) used in the study in geomagnetic (solid lines) and geographic (dotted lines) coordinates. Dotted-dashed line denotes the geomagnetic dip equator. The ionospheric traces of the pierce points at altitude 300 km are shown for GPS20 satellite during time interval A (0400–0630 UT) with dotted line, and for GPS27 satellite during interval B (1000–1200 UT) with dashed line, for the receivers at HYDE (blue) and IISC (green).