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IONOSPHERE RESPONSE TO THE INTENSE ULF WAVES AS OBSERVED BY GPS/TEC AND EISCAT INSTRUMENTS

V. Pilipenko [1], V. Belakhovsky[1], D. Murr[2], E. Fedorov[1], A. Kozlovsky[3]

[1]*Institute of Physics of the Earth, Moscow*
[2]*Augsburg College, Minneapolis*
[3]*Sodankyla Geophysical Observatory of the University of Oulu*

Abstract. Earlier studies demonstrated that the monitoring of the ionospheric total electron content (TEC) by global satellite navigation systems is a powerful method to study the propagation of transient disturbances in the ionosphere, induced by internal gravity waves. This technique has turned out to be sensitive enough to detect ionospheric signatures of magnetohydrodynamic (MHD) waves as well. However, the effect of TEC modulation by ULF waves is not well examined a responsible mechanism has not been firmly identified. During periods with intense Pc5 waves distinct pulsations with the same periodicity were found in the TEC data from high-latitude GPS receivers in Scandinavia. We analyze jointly responses in TEC variations and EISCAT ionospheric parameters to global Pc5 pulsations during the recovery phase of the strong magnetic storms on Oct. 31, 2003. Comparison of periodic fluctuations of the electron density at different altitudes from EISCAT data shows that main contribution into TEC pulsations is provided by the lower ionosphere, up to ~150 km, that is the E-layer and lower F-layer. This observational fact favors the TEC modulation mechanism by field-aligned plasma transport induced by Alfven wave. Analytical estimates and numerical modeling support this conjecture.

1. Introduction

The ionosphere represents an inner boundary of the near-Earth environment where the energy exchange occurs between the neutral atmosphere and the plasma of outer space. MHD waves provide an effective channel of the energy transfer from the outer magnetosphere to the bottom of the ionosphere. The interaction between the solar wind and magnetosphere acts as a permanent source of various types of MHD waves in the ultra-low-frequency (ULF) band, which fill the entire magnetosphere and reach its inner boundary, the ionosphere. While ground magnetometers and magnetospheric satellites provided tremendous amount of information about ULF wave properties in the magnetosphere and on the ground, the wave properties in the ionosphere remained unavailable to in-situ observations. The ever-growing array of global satellite navigation systems (GPS, GLONASS, etc) provide information on variations of a radiopath-integrated ionospheric parameter - the total electron content (TEC).

The GPS/TEC technique turned out to be sensitive enough to detect ionospheric signatures of ULF waves. The TEC modulation by intense Pc5 pulsations was found by [*Pilipenko et al., 2014a; Watson et al., 2015*]. Thus, the standard TEC/GPS technique is sufficiently sensitive to detect ULF waves in some cases. However, a physical mechanism of TEC periodic modulation associated with ULF waves has not been established yet.

Here we analyze a unique event when the same global Pc5 waves were detected in the ionosphere by the GPS/TEC technique [*Pilipenko et al., 2014a*] and EISCAT radar [*Pilipenko et al., 2014b*]. We analyze these observations simultaneously which has provided an additional information on the relationship between geomagnetic and ionospheric variations.

2. Observational data

We use the standard TEC data with 30-sec resolution from an array of GPS receivers in Scandinavia. The slant TEC along a radiopath can be converted into the vertical vTEC, denoted here as N_T, by assuming the altitude of pierce points to be 250 km. As a measure of columnar density N_T the TEC unit (1 TECu=10^{16} m^{-2}) is used.

Magnetometer 10-s data from the IMAGE array, covering the range of geographic latitudes from ~79° to ~58°, are used (Fig. 1). The magnetometer observations are augmented with the multi-beam IRIS riometer data from Kilpisjarvi (KIL), that monitors a cosmic noise absorption caused by the energetic (>30 keV) electron precipitation into the ionosphere. The magnetometer data have been decimated to a common 30-s step with TEC data.

We use the data with 30-s cadence from the UHF radar EISCAT, comprising the receivers at Sodankyla (SOD) and Kiruna (KIR), and receiver-transmitter at Tromso (TRO) (Fig. 1). EISCAT radar beam was directed along the geomagnetic field line. Intersection of receiving paths from SOD and KIR is located nearly above the magnetic station TRO (68.0° N, 19.1° E) at altitude ~290 km. This radar system enables one to determine the vector of the ionospheric plasma drift velocity **V** and corresponding electric field **E**. The EISCAT radar system also measures the altitude profile of electron density $N_e(z)$, ion temperature $T_i(z)$, and electron temperature $T_e(z)$ along the beam up to ~400 km.

3. Oct. 31, 2003 ULF event

During the recovery phase of large magnetic storm on Oct. 31, 2003 very intense (up to a few hundred nT) global quasi-monochromatic Pc5 waves were observed [*Kleimenova, Kozyreva, 2005*].

During the periods 11.00-12.00 UT and 12.00-13.00 UT with elevated Pc5 activity, TEC fluctuations have been compared with ground geomagnetic variations at station KIR (geographic latitude 67.8°) and ionospheric parameters determined by EISCAT radar. The TEC data show gradual variations around 30-40 TECu with superposed small-scale fluctuations. To highlight these fluctuations the TEC data have been detrended with a cut-off frequency of 1 mHz. Quasi-periodic TEC pulsations have been revealed over a wide latitudinal range.

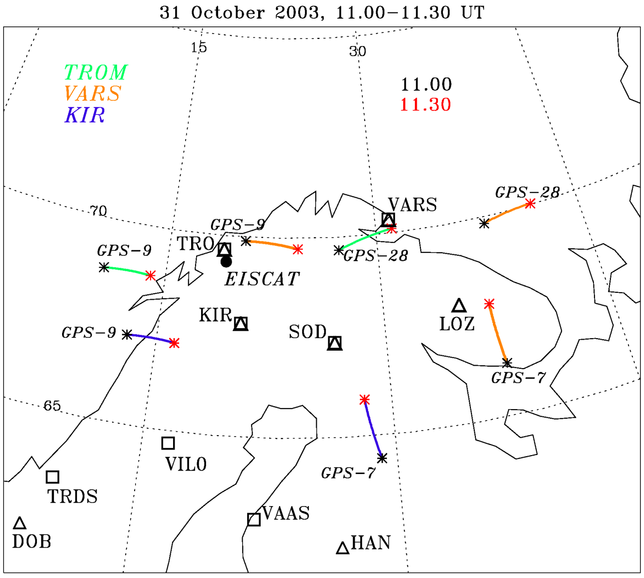

Figure 1. Pierce points at 250 km altitude of radio paths from GPS satellites GPS7, GPS9, and GPS28 to ground receivers KIRU (violet line), VARS (orange line), and TROM (green line) in Scandinavia during Oct. 31, 2003, 11.00-11.30 UT. Magnetometers are denoted with triangles, GPS receivers are denoted with squares, riometer KIL is marked with asterisk, and EISCAT is shown by dark circle.

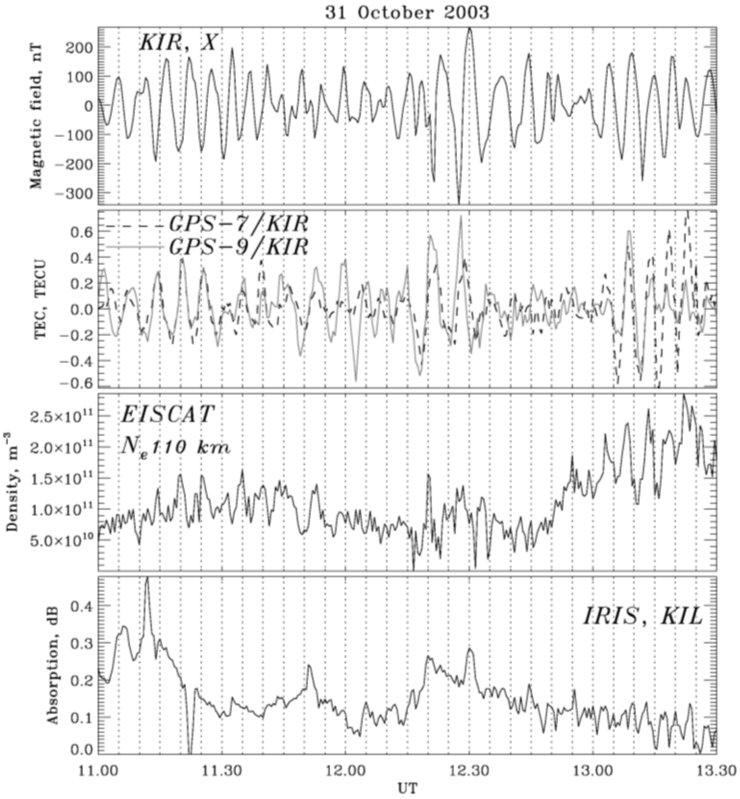

Figure 2. Multi-instrument observations of Pc5 waves during Oct. 31, 1100-1330 UT. From top to bottom: X-component (in nT) of geomagnetic pulsations at KIR; detrended (with a 1 mHz cut-off frequency) TEC fluctuations (in TECu) along radio paths GPS07/KIRU (dotted line) and GPS09/KIRU (solid line); EISCAT N_e fluctuations at h=110 km; and cosmic noise absorption from KIL riometer.

The comparison for the period 11.00-13.30 UT of TEC fluctuations along paths GPS7/KIRU, GPS9/KIRU with magnetic variations at KIR and EISCAT-derived ionospheric density N_e in the lower ionosphere, shows the occurrence of persistent periodicity in all these parameters (Fig. 2). The peak-to-peak amplitudes of oscillations of the TEC are ΔN_T ~0.6 TECU (GPS07/KIR), and ~1.0 TECU (GPS09/KIRU), and magnetic pulsations ΔB~400 nT

(X-component) at KIR. Visual inspection of Fig. 2 shows that magnetic (X-component) and TEC variations are approximately out-of-phase. At the same time, the riometer data do not demonstrate the periodicity evident in magnetometer data (bottom panel in Fig. 2).

Spectral analysis confirmed the occurrence of the same periodicity with f~2.4 mHz in variations of the geomagnetic field, TEC (GPS07, GPS09), and EISCAT N_e [*Pilipenko et al., 2014b*]. Cross-spectral analysis also showed a good correspondence between TEC and B variations. During the 11.30-13.00 UT time interval the spectral coherency of TEC fluctuations at GPS09/KIRU and magnetic pulsations at KIR around the frequency 2.5 mHz was high, $\gamma(f)$~0.8. The ratio between the spectral densities of TEC and X-component magnetic variations at this frequency was $\Delta N_T(f)/\Delta B(f) \sim 2{\cdot}10^{-3}$ TECu/nT. Magnetic pulsations (X-component, KIR) and EISCAT electric field E_x had coherency γ~0.8. The cross-correlation between TEC variations from GPS09/KIRU and EISCAT field E_x had a high coherency $\gamma(f)$~0.86. The ratio between spectral amplitudes at this frequency was $\Delta N_T(f)/E_x(f) \sim 4{\cdot}10^{-3}$ TECu/(mV/m).

An important parameter of ULF wave structure is its scale in the latitudinal (radial) and longitudinal (azimuthal) directions. The longitudinal propagation characteristics are characterized by the azimuthal wave number m, which can be determined from a cross-correlation time shift $\Delta\tau$ between two detrended time series with periodic variations with period T at sites separated in longitude by $\Delta\Lambda$, as follows $m=(\Delta\tau/T)(360^0/\Delta\Lambda)$. The cross-correlation function $R(\Delta\tau)$ for magnetic and TEC variations has been estimated using the magnetic stations KIR-LOZ at latitude ~67.8°, longitudinally separated in geographic coordinates by $\Delta\Lambda$~15.4°, and the longitudinally separated pierce points along receiver/satellite paths TROM/GPS9 and VARS/GPS28 at geographic latitude ~69.7^0 and separated in longitude by $\Delta\Lambda$=27.2°. For the wave frequency f~2.5 mHz the azimuthal wave number $m \approx 0.9$ for magnetic data, $m \approx 0.5$ for TEC data. Thus, though both magnetic and TEC data show a Pc5 wave propagation in the same direction, the m-values from ionospheric TEC data are somewhat lower than those from ground geomagnetic data.

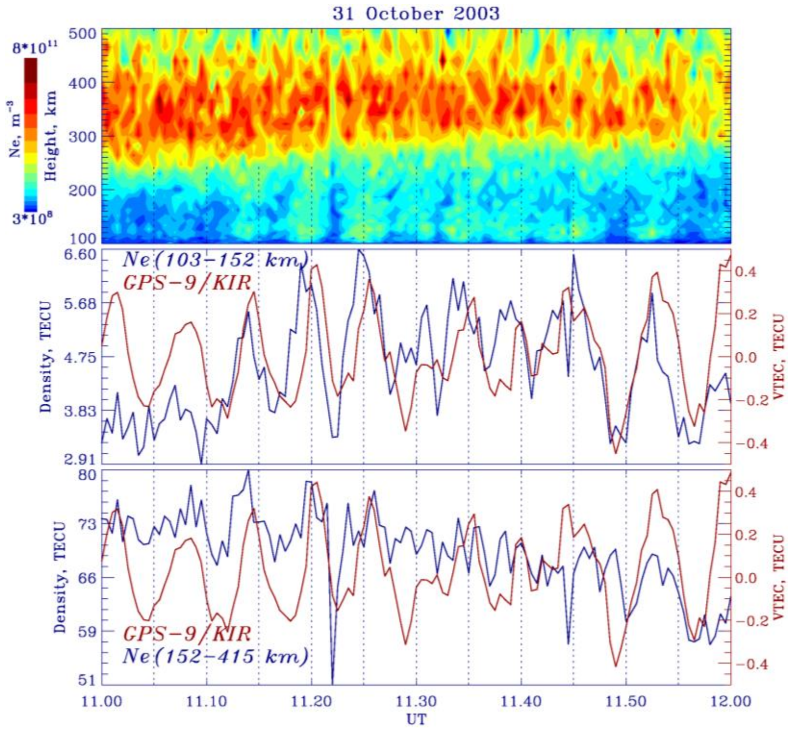

Figure 3. Time variations of the EISCAT electron density during 2003, Oct. 31, 11.00-12.00 UT: (upper panel) altitude-time plot; (middle panel) Ne variations altitude-integrated over altitude range 103 - 152 km (in TECu), and superposed TEC variations from GPS9/KIRU; (bottom panel) Ne variations altitude-integrated over altitude range 152 - 415 km (in TECu) and superposed vTEC variations GPS9/KIRU.

To find out which altitudes contributes most to the TEC variations, we have integrated ionospheric Ne(z) data from EISCAT over two different altitude range: the bottom ionosphere from 103 km to 152 km; and the F-layer from 152 km to 415 km. Comparison between height-time diagram of $N_e(t)$ variations, and altitude-integrated ionospheric densities $\langle N_e \rangle$ (in TECu) are compared with actual TEC variations for two time intervals: 11.00-12.00 UT (Fig. 3). Comparison of these fluctuations with periodic variations of TEC shows that main contribution is provided by lower ionosphere, up to ~150 km (that is the E-layer and lower F-layer).

4. Discussion

Long-period pulsations are the most powerful wave process in the near-Earth environment. The radar observations showed that Pc5 waves can noticeably modulate the ionospheric plasma: the electric field **E,** plasma convection velocity **V,** *E*-layer electron density *Ne* and the ionosphere conductance Σ, and electron T_e and ion T_i temperatures in both *F*- and *E*-layers (see references in [*Pilipenko et al., 2014a*]). Recent observations by [*Pilipenko et al., 2014a; Watson et al, 2015*] have demonstrated that Pc5 waves are capable to modulate TEC as well.

One may expect that all the Pc5 wave-induced fractional variations of plasma and magnetic field should be of the same magnitude, like in any linear wave. However, GPS observations have revealed that the depth of periodic TEC modulation is sometimes even somewhat larger (e.g., in the event of Oct. 31, 2003 $\Delta N_T / N_T \sim 2.5\%$) than the geomagnetic field modulation ($\Delta B/B_0 \sim 1\%$). In principle, ULF modulation of energetic electron precipitation, inducing an additional periodic ionization of the lower ionosphere, can cause periodic TEC variations with much higher depth than geomagnetic field variations [*Watson et al., 2007*]. However, during the event under consideration no periodic electron precipitation occurred as evidenced by simultaneous riometer observations. The mechanism of the field-aligned plasma transport by Alfven waves can produce relative amplitudes of TEC variations larger than that of geomagnetic pulsations.

Consideration of possible mechanisms of TEC modulation by magnetospheric Alfven waves has shown that in principle the plasma heating, vertical plasma drift, steep gradient, and field-aligned electron transport can provide a noticeable input into the observed TEC variations transport [*Cran-McGreehin et al., 2007*]. The field-aligned current transported by an Alfven wave, incident onto the ionosphere from the magnetosphere, provides an additional periodic plasma flow in/out the ionosphere. As a result, the plasma density in the bottom ionosphere periodically increases/decreases. A feature of the field-aligned plasma transport mechanism is that it contributes mainly into the bottom layers of the ionosphere, in accordance with the combined GPS/EISCAT/magnetometer observations. Surely, any conclusive judgments can be stated only after more detailed studies with the use of other ionospheric instruments that will provide more detailed information about ionospheric plasma parameters.

5. Conclusion

Long-period Pc5 pulsations being the most powerful wave process in the terrestrial environment can significantly modulate the local densities of the magnetospheric and ionospheric plasma. Even radiopath-integrated TEC has turned out to be sensitive enough to response to intense Pc5 waves. So far, the effect of TEC modulation by ULF waves is a challenge for the MHD wave theory, because responsible mechanisms of such modulation have not been firmly established yet. Analysis of the altitude profile of the electron density fluctuations derived from EISCAT data during the global Pc5 wave event has shown that main contribution into the periodic TEC variations is provided by lower ionosphere, up to ~150 km, that is the E-layer and lower F-layer. This observational fact favors the field-aligned plasma transfer induced by Alfven wave as a dominant modulation mechanism.

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