"Physics of Auroral Phenomena", Proc. XXXVI Annual Seminar, Apatity, pp. 77 - 80, 2013
© Kola Science Centre, Russian Academy of Science, 2013

Polar
Geophysical
Institute

MODULATION OF TEC/GPS BY ULF Pc5 WAVES

V. Pilipenko[1], V. Belakhovsky[2], D. Murr[3], E. Fedorov[4], M. Engebretson[3]

[1]*Space Research Institute, Moscow*
[2]*Polar Geophysical Institute, Apatity*
[3]*Augsburg College, Minneapolis*
[4]*Institute of Physics of the Earth, Moscow*

Introduction

The terrestrial ionosphere represents an inner boundary of the space environment where the transition from the neutral atmosphere to the ionized gas of space occurs, and where the transfer of energy through the coupled magnetosphere-ionosphere system takes place. The interaction between the solar wind and magnetosphere provides a rich source for various types of ULF waves, which are always present in the magnetosphere and ionosphere. Historically, ULF wave properties have been deduced from ground-based magnetometer arrays, supplemented by magnetic measurements from various spacecraft. Nowadays local variations of electron density caused by long-period ULF waves can be detected by ionosphere sounding techniques: Doppler sounders, SuperDARN radars, riometers, etc. The ever-growing facilities of GPS monitoring systems provide information on variations of a radiopath-integrated ionospheric parameter - the total electron content (TEC). GPS/TEC observations are becoming a global technique to monitor the propagation of waves and transients along the ionosphere. Early results reported related geomagnetic variations in the ULF band with TEC fluctuations. *Davies and Hartman* [1976] reported two cases where the change in TEC was associated variations in the ULF Pc4 range. A more comprehensive analysis by *Okuzawa and Davies* [1981] showed that variations in TEC with similar periods as in ground magnetometer records. However, the mechanism of TEC modulation by geomagnetic pulsations has not been established. In this paper, we demonstrate that TEC/GPS technique is sensitive enough to detect intense Pc5 pulsations at high latitudes.

Observational data

We use the slant TEC data with 30-s resolution from the array of GPS receivers in Scandinavia (Fig. 1). As a measure of path-integrated plasma density N_T the TEC units (1 TECU=1×10^{16} e/m2) are used, and TEC variations are given in the percentage $\Delta N_T / N_T \times 100\%$. Magnetometer data from the IMAGE array, covering the range of geographic latitudes from ~79° to ~58°, are used.

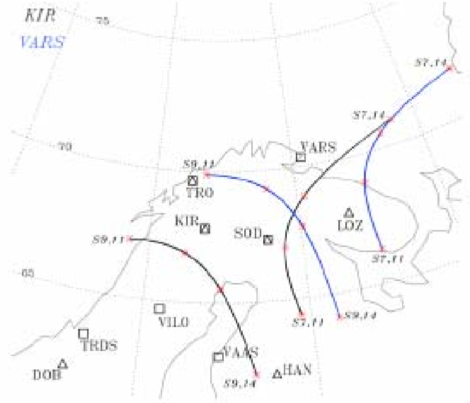

Fig. 1 Intersections of radio paths from GPS satellites S07 and S09 to ground receivers KIR and VARS in Scandinavia with the ionosphere at altitude 250 km. Magnetometers are denoted with triangles, GPS receivers are denoted with squares. Red stars along orbit projections denote time moments 11.00, 12.00, 13.00, and 14.00 UT.

31 October event

During the 2003 "Halloween storm" the superposition of 3 extremely large magnetic storms occurred on Oct. 29-31, caused by an extremely fast coronal mass ejection. During the recovery phases of these storms very intense global Pc5 waves were observed. In this study we concentrate on the Oct. 31, 2003 (day 304) event. During this event the global character of Pc5 waves is most pronounced: coherent quasi-monochromatic variations are observed over a wide range of CGM latitudes, from ~70° to ~50° during morning and post-noon hours in Scandinavia.

During the 11-14 UT period with elevated Pc5 activity, TEC fluctuations detected by receivers at KIR and VARS from GPS satellites S07 and S09 have been compared with ground geomagnetic variations. The raw TEC data show gradual variations around N_T~30-40 TECU with superposed small-scale fluctuations. To highlight these fluctuations the TEC data have been detrended by high-pass filtering with a cut-off frequency of 1 mHz. The comparison of TEC fluctuations with magnetic variations at KIR shows the occurrence of persistent TEC periodicity nearly on the same time scale as geomagnetic pulsations (Fig. 2). The peak-to-peak amplitudes of oscillations of the ionospheric plasma are ΔN_T ~0.6 (S07/KIR), ~2.0 (S14/KIR), and ~1.0 (S09/KIR), and magnetic pulsations ~400 nT at KIR. TEC quasi-periodic pulsations are observed over a wide latitudinal range. The typical frequency of TEC pulsations at different latitudes is nearly the same, ~2.4 mHz. The cosmic radio noise absorption, measured by the multi-beam IRIS riometer at KIL, does not demonstrate the periodicity evident in magnetometer and TEC data.

Cross-spectral analysis confirms the good correspondence of both TEC and B variations. During the 1130-1300 UT time interval the coherency between TEC (S-09/KIR path) and X-component magnetic fluctuations at f~2.5 mHz is rather high, γ~0.8. The ratio between the spectral densities of TEC ΔN_T and magnetic ΔB variations at this frequency is $\Delta N_T/\Delta B \sim 2\times10^{-3}$ TECU/nT. This ratio is in accord with typical amplitude of TEC oscillations, ~1 TECU, and magnetic pulsations, ~400 nT.

The superposition of TEC data from different satellites shows a good coherency between these fluctuations. We tried to estimate the azimuthal propagation characteristics of TEC variations using different radio paths for the same GPS station. Fig. 3 shows the superposed TEC fluctuations from S7 and S9 satellites for KIR. The same figure shows the superposed magnetic variations at stations KIR-LOZ, longitudinally separated by ΔΛ~11.9°. Cross-correlation analysis reveals between KIR-LOZ a time shift Δτ~20 s. For the wave frequency *f*~3 mHz, this time shift corresponds to the azimuthal wave number m ≈ 1.8. However, a similar analysis did not reveal a time shift for the TEC variations Δτ ~ 0 s. Probably, this result is related to the low cadence of TEC data (30 s). Therefore, comparison of longitudinally separated TEC data provides only the upper limit on a m-value: for Δτ<30 s *m*<2.7.

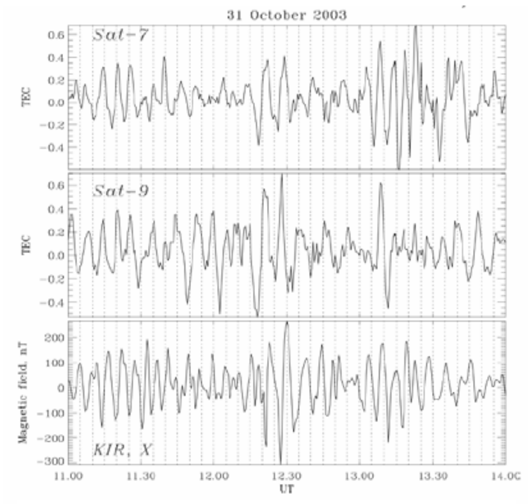

Fig. 2 Panels a and b: detrended TEC data with a high-pass filter (1 mHz cut-off frequency) along radio paths between S07 and S09 and KIR. TEC variations are measured in TEC units. Panel c: X-component (in nT) geomagnetic pulsations at KIR.

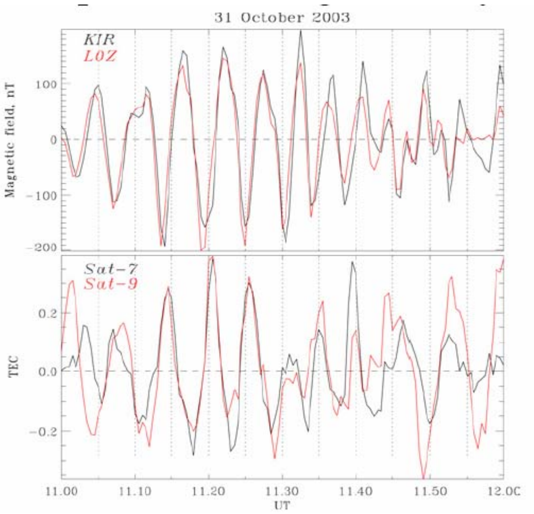

Fig. 3 Upper panel: Superposed magnetic variations (X-component) with 30-s cadence at longitudinally separated stations KIR (red) - LOZ (red); **Bottom panel**: Superposed TEC variations with 30 s cadence along longitudinally separated radio paths from S7 (black) and S9 (red) to GPS receiver at KIR.

Theoretical estimates

The determination of an apparent impedance of global Pc5 waves, using the combined SuperDARN and magnetometer data, demonstrated that these waves are predominantly composed of Alfven waves [*Pilipenko et al.*, 2012]. Therefore, it is necessary to consider possible mechanisms of Alfven wave impact on the ionosphere-magnetosphere plasma. Nearly 90% of TEC is provided by the ionospheric plasma at altitudes less than 10^3 km. The temporal variations in the TEC evaluated along the line between a source (S) and receiver (R) is given by $\partial_t N_T = \int_S^R \partial_t N dz$. Variations of local plasma density N are described by the continuity equation

$$\frac{\partial N}{\partial t} = -\mathbf{V}\nabla N - N\nabla\mathbf{V} + Q - L \qquad (1)$$

where Q and L are the electron production and loss rates respectively and $\mathbf{V}$ is the plasma velocity from the ULF perturbation. Variations in TEC along the signal path introduce time/phase delays for high frequency radio wave propagation through the ionosphere. For the order of magnitude estimate we suppose that $N_T \simeq N\Delta z$, where Δz is the characteristic thickness of F-layer.

Possible mechanisms

Wave modulation. Among possible MHD waves in a cold plasma, the Alfven mode does not perturb the plasma density. The plasma oscillations in a fast mode are of the same relative amplitude as oscillations of the magnetic field, that is $\Delta N/N \leq \Delta B/B$. Thus, it seems that toroidal Pc5 waves cannot directly modulate the magnetospheric plasma density.

Periodic particle precipitation. In our event no noticeable riometer variations were observed. Though riometer data can detect the precipitation of energetic electrons with E>10 keV, therefore the possibility of periodic low-energy electron precipitation remains unclear.

Plasma compression by fast mode. Upon the interaction with the ionosphere the wave properties are expected to be modified considerably, and the problem of TEC modulation needs a special consideration of Alfven wave interaction with the ionosphere. TEC modulation may be related to the plasma/magnetic compression in a wave. An evanescent fast compressional mode can be excited by incident Alfven wave in the upper ionosphere owing to the ionospheric Hall conductance. The mechanism of TEC modulation by an evanescent compressional mode arising during the interaction of an Alfven wave with the anisotropic E-layer was considered by *Pilipenko and Fedorov* [1995]. According to their estimates, for a large-scale wave with transverse scale larger than the height *h* of the E-layer (*kh*<1) the modulation depth is as follows

$$\left|\frac{\Delta N}{N}\right| \simeq \left|\frac{B_x^{(g)}}{B_0}\right| kh \tag{2}$$

Therefore, relative TEC variations could be comparable with relative magnetic variations only for small-scale poloidal Alfven waves with *kh*~1. However, such small-scale Alfvenic structures are to be screened by the ionosphere from ground magnetometers.

Lateral plasma gradient. Another possible TEC modulation mechanism may comprise an advection of lateral gradient of the ionospheric plasma [*Waters and Cox*, 2009]. *Shagimuratov et al.* [2008] found strong TEC fluctuations with periodicity ~10 min and associated them with polar patches - large-scale (~100-1000 km) regions of enhanced (by a factor of 2 and more) F-region plasma density travelling through the polar caps due to ionospheric convection. The periodic modulation of polar patch plasma by ULF wave electric field may produce noticeable TEC modulation. However, the feasibility of this effect is hard to evaluate because of the lack of information on lateral F-layer structure.

Field-aligned plasma transport. A possible mechanism may be related to field-aligned plasma transport by Alfven waves [*Cran-McGreehin et al.,* 2007]. The field-aligned current transported by an Alfven wave provides an additional in/out periodic plasma flow into the E-layer. An Alfven wave with magnetic disturbance ~400 nT should carry a considerable field-aligned current. For example, Pc5 pulsations carrying ~2μA/m^2 current will cause fluctuations in the E-layer with $N_e=10^{11}$ m^{-3} and Δh=20 km of $\Delta N_e \sim 6.10^{10}$ m^{-3}. Thus, the field-aligned current during an intense Pc5 event is sufficient to cause a significant pumping of electron density in the E-layer. However, the relative contribution of the E-layer to the TEC is much smaller than the contribution from the F-layer.

Periodic shift of plasma vertical profile. The finite East-West electric component of the incident Alfven wave E_y causes a vertical plasma drift $V_z = E_y \cos I / B_0$. Although the vertical gradient may be severe, there will be no temporal TEC changes provided *N*=0 at the end points of integration. However, owing to the strong dependence of ionization and recombination rates on altitude, the vertical shift causes a plasma modification due to the changes of ionization-recombination balance. In the F-layer the recombination rate in (1) is $L=\beta N$. The maximum of the vertical profile is formed at the altitude where $Q \sim \beta N$. Let us assume that the recombination coefficient depends exponentially on z, $\beta = \beta \exp[-(z-z_m)/H]$. An order of magnitude estimate [*Poole and Sutcliffe,* 1987] gives

$$\frac{\Delta N}{N} = \frac{2\beta V_z}{\omega^2 H} \tag{3}$$

For Pc5 with $\omega \sim 10^{-2}$ s^{-1}, $\beta \sim 10^{-4}$, $V_z \sim 20E$, cos*I*~0.5, *E*~20 mV/m, this estimate gives Δ*N*/*N* ~1.2%.

Ion heating. The heating of the ionospheric ions during the plasma dragging through neutrals (having velocity V_n and temperature T_n) can be estimated using the classical relation for the frictional heating [*Lathuillere et al.,* 1986]

$$\Delta T_i - T_n = \frac{M_n}{3k}(\mathbf{V}_i - \mathbf{V}_n)^2 \tag{4}$$

For a typical F-layer plasma the coefficient $M_n/3k \sim 7.4 \cdot 10^{-4}$. The background plasma velocity is produced by ion dragging by neutrals $|V_i^{(0)}| \sim |V_n|$. During time intervals when $\mathbf{V}_i$ is anti-parallel to $\mathbf{V}_n$ a noticeable ion heating occurs. During the Pc5 event considered here, the oscillatory E-field component ~20 mV/m imposed on the background field $E^{(0)} \sim 30$ mV/m corresponds to a convection velocity disturbances $V_i \sim 400$ m/s. Assuming that $V_i - V_n = 300$ m/s, $T_n = 10^3$ K, it follows from (4) that the ion Joule heating can cause $\Delta T_i \sim 250^o$. The additional plasma heating shifts the ionization-recombination balance due to the temperature-dependent recombination coefficient β and causes plasma density variations. The coefficient β(*T*) of the dominant F-layer ion O^+ with O_2 and N_2 grows rapidly with temperature *T*, starting from $T \sim 10^3$ K. Thus, periodic ion heating of F-layer plasma *T*+Δ*T* will cause the decrease of the recombination coefficient β+Δβ, and consequently, the periodic plasma density variations *N*=*N*+Δ*N*. Linearization of the balance equation (1) yields

$$\frac{\Delta N}{N} = -\frac{\Delta\beta}{-i\omega+\beta} \simeq -i\frac{\Delta\beta}{\omega} \tag{5}$$

According to (5), for $\omega\sim 2*10^{-2}$ s^{-1}, $T\sim 10^3$ K, $\Delta T\sim 250$ K, $\Delta\beta\sim 10^{-4}$ s^{-1}, the expected effect is to be $\Delta N/N\sim 0.5\%$.

Discussion

ULF pulsations are the most powerful wave process in the terrestrial environment and they can significantly modulate the magnetospheric and ionospheric plasma. The radar community has demonstrated that Pc5 waves can modulate the ionospheric electric field and plasma convection velocity; field-aligned current; E-layer electron density and the ionosphere conductance; and electron T_e and ion T_i temperatures in F- and E-layers. Our observations demonstrate that these waves are capable to modulate TEC as well. Moreover, our observations, as well as other reports, reveal that the relative disturbance of TEC is even larger than that of magnetic field.

The simultaneous Pc3 waves and TEC periodic fluctuations presented in [Skone et al., 2008] had peak-to-peak amplitudes $\Delta N_T \sim 0.02$ TECU, and $\Delta B \sim 2$ nT, so assuming that typical NT ~ 40 TECU, the relative TEC fluctuations $\Delta N_T/N_T \sim 0.05\%$, whereas the relative magnetic fluctuations $\Delta B/B \sim 0.004\%$ only. *Davies and Hartman* [1976] reported the percentage change in TEC ~0.03% and ~0.006% with associated magnetic variations in the range 30–50 s. *Okuzawa and Davies* [1981] reported that variations in TEC over the 10–50 s band ranged from 0.005% up to 0.1%. Assuming that typical Pc4 wave amplitude is $\Delta B\sim 10$ nT, for background $B\sim 3*10^4$ nT, these pulsations had the relative amplitude in the ionosphere ~0.03%. Thus, the reported TEC fluctuations are to be caused by magnetic pulsations with much weaker relative amplitudes.

In the analyzed Pc5 event of Oct. 31, 2003 $N_T \sim 40$ TECU, $\Delta N_T \sim 1$ TECU, hence $\Delta N_T / N_T \sim 2.5\%$. At the same time, the ground magnetic pulsations $\Delta B \sim 400$ nT, so $\Delta B/B \sim 1\%$. Thus, during this event, the relative amplitude of TEC variations is about the same or even ~2-3 times larger than that of magnetic pulsations. Comparison of possible mechanisms of TEC modulation by Alfven waves indicate that the mechanisms of periodic plasma heating and vertical plasma drift might be the most promising. However, any conclusive judgments can be stated only after more detailed studies with the use of other ionospheric instruments and more advance theoretical modeling.

Conclusion

GPS TEC technique has turned out to be unexpectedly sensitive to ULF waves. Combined usage of magnetometers and GPS/TEC is a very promising way to reveal the physical mechanism of disturbances. Both earlier observations and the current study have revealed that relative TEC disturbance is about or even larger than that of the magnetic field. The most promising mechanisms are the periodic ion heating and vertical plasma drift. However, the effect of TEC modulation by Pc5 waves is a challenge for the MHD wave theory, because the responsible mechanism of such modulation has not been firmly established yet.

Acknowledgements. This study was supported by NSF grant ATM-0827903 (DM, ME), RFBR grants 12-05-98522 (EF), 13-05-90436 (VP), 12-05-00273 (VB), and Program №4 of the RAS Presidium.

References

Cran-McGreehin A.P., et al., Ionospheric depletion in downward currents, J. Geophys. Res., 112, A10309, 2007.

Davies K., Hartman G.K., Short-period fluctuations in TEC, J. Geophys. Res., 81, 3431, 1976.

Lathuillere C., et al., Ionospheric ion heating by ULF Pc 5 magnetic pulsations, J. Geophys. Res., 91, 1619, 1986.

Okuzawa T., Davies K., Pulsations in the total columnar electron content, J. Geophys. Res., 86, 1355, 1981.

Pilipenko V.A. Fedorov E.N., Modulation of TEC by geomagnetic pulsations, Geomagn. Aeron., 34, 516, 1995.

Pilipenko V., et al., Determination of the wave mode contribution into the ULF pulsations from combined radar and magnetometer data: Method of apparent impedance, J. Atmosph. Solar-Terr. Phys., 77, 85–95, 2012.

Poole A.W.V., Sutcliffe P.R., Mechanisms for observed TEC pulsations, J. Atmos. Terr. Phys., 49, 231, 1987.

Skone C., Mitigating geomagnetic noise in airborne magnetic surveys using GPS, in: ION GNSS 2008, Savannah, USA, 2008.

Shagimuratov I.I., et al., Observations of GPS TEC fluctuations in Antarctic and Arctic ionosphere during 28 October 2003 storm, "Physics of Auroral Phenomena", Proc. 31 Annual Seminar, Apatity, 167, 2008.

Waters C.L., S.P. Cox, ULF wave effects on high frequency signal propagation through the ionosphere, Ann. Geophys., 27, 2779, 2009.