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GEOMAGNETIC AND IONOSPHERE TEC RESPONSE TO THE ABRUPT INCREASE OF SOLAR WIND DENSITY

V.B. Belakhovsky[1], V.A. Pilipenko[2], Ya.A. Sakharov[3], S.N. Samsonov[4]

[1]*Institute of Physics of the Earth, Moscow*
[2]*Geophysical Center, Moscow*
[3]*Polar Geophysical Institute, Apatity*
[4]*Institute of Cosmophysical Research and Aeronomy, Yakutsk*

Abstract. We have examined multi-instrument observations of the geomagnetic and ionospheric response to the interplanetary shock on 24 January 2012. World-wide ground magnetometer array detected shock-induced sudden commencement (SC) with preliminary and main impulses throughout dayside sector, and substorm triggering in the nighttime hours. Clear resonant transient Psc5 oscillations are independently generated on the morning and evening flanks, no signatures of theoretically predicted cavity mode excitation is found. A new effect found was a 30-40 % positive pulse of the ionospheric total electron content caused by SC as determined from GPS receivers in the dawn sector and 10% pulse in the dusk sector. The VHF radar EISCAT in Tromso observed SC-associated increase of electron density in the bottom ionosphere (100-180 km). SC was accompanied by a burst of cosmic noise absorption recorded along a latitudinal network of riometers in Scandinavia. A responsible mechanism of TEC modulation may be related to field-aligned plasma transport by Alfven pulse, which provides an additional plasma flow in the bottom ionosphere.

1. Introduction. An impact of interplanetary (IP) shock onto the magnetosphere, observed by ground magnetometers as storm sudden commencement (SC), is a convenient probing signal for the experimental study of the near-Earth space. During a relatively short time period (<10 min) a significant energy and momentum is pumped into the magnetosphere from the solar wind. Despite a seemingly simplicity of such impact, a complex of impulsive and quasi-periodic phenomena stimulated by IP shock in the ultra-low-frequency (ULF) band (time scales from few sec to tens of min.) turns out to be surprisingly large. An observed response to an IP shock or discontinuity may be rather complicated due to the nearly-simultaneous excitation of several transient processes. The IP shock is known to stimulate a global compression of the magnetosphere [*Araki,* 1994], excitation of transient field-aligned current systems [*Fujita et al.,* 2005], generation of transient ULF waves in a wide band from Pc1 to Pc5-6 [*Saito and Matsushita,* 1967], triggering of VLF wave activity and enhancement of energetic electron precipitation [*Gail et al.*, 1990], dayside aurora activation – "shock aurora" [*Vorobiev et al.*, 2008]. Besides that, a SC pulse serves as an indicator of the onset of a more intense solar wind driving and buffeting the magnetosphere.

Though the basic physics of the related phenomena are qualitatively understood, some aspects of IP shock impact on the magnetosphere – ionosphere system has not been sufficiently established yet. Basing on the analysis of ground magnetometer data, *Araki* (1994) suggested the phenomenological model of SC, in which an observed disturbance is interpreted as the superposition of a stepwise compression of geomagnetic field (DL component) and bi-polar impulse, composed from a short preliminary impulse (PI) and following main impulse (MI). The nature of a stepwise increase of the geomagnetic field (DL) is now clearly identified as a result of global compression of the magnetosphere. The MI and PI are supposedly associated with transient magnetospheric field-aligned current (FAC) systems, but driven by different mechanisms.

Magnetometers, riometers, optical images, satellite particle detectors, and ionospheric radars have become a standard tool for the monitoring the solar wind - magnetosphere - ionosphere coupling. For an examination of ionospheric response to solar wind pressure pulses *Jayachandran et al.* (2011) suggested to use the GPS global navigation satellite system. This technique providing information on total electron content (TEC) along a radiopath satellite – ground receiver has turned out to be sensitive enough to detect ionospheric response to transient and periodic disturbances in ULF band [*Belakhovsky et al.*, 2016]. However, a possible mechanism of the ionosphere modification by magnetospheric ULF disturbance has not been firmly established yet. Therefore, examination of the impact on the ionosphere by disturbances of different physical nature with simultaneous data from magnetometers, riometers, ionospheric radars, and GPS/TEC receivers may provide an insight into the mechanism of magnetosphere-ionosphere coupling.

In this paper we consider the ionospheric response to the IP shock as observed by ground magnetometers, riometers, aurora imagers, GPS receivers, and EISCAT radar. We discuss what features of the SC-related phenomena are well understood, and what still require a further consideration and modeling.

2. Interplanetary shock on Jan. 12, 2012. The arrival of IP shock at ~1500 UT is revealed according to the OMNI database as a rapid jump of the solar wind velocity V from ~400 km/s up to ~700 km/s, the interplanetary magnetic field (IMF) magnitude B increase from ~3 nT up to ~30 nT, and the solar wind density N jump up to 15 cm^{-3} (Fig. 1). The shock impact occurs at the background of northward IMF Bz. This shock causes a jump of Dst index and a short impulsive increase of AE index up to ~800 nT. After that AE index has remained at elevated level.

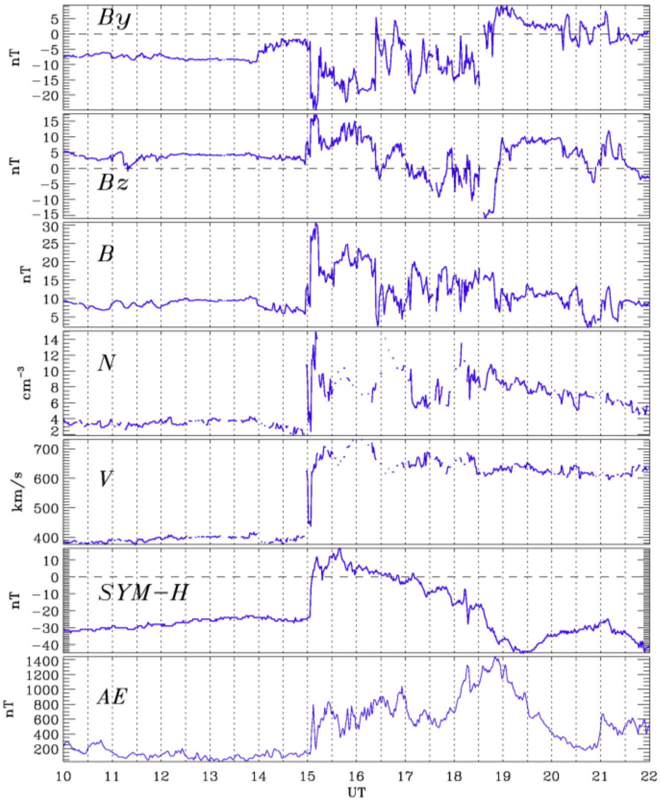

Figure 1. The interplanetary shock detected on Jan. 24, 2012 during time interval 1400-1900 UT: the OMNI solar wind velocity (Vx component), solar wind density *N*, IMF magnetic field magnitude *B* and component *Bz*, SYM-H index, and AE index.

3. Geomagnetic response on the ground to SC. We analyze data from latitudinal and longitudinal networks of magnetic stations. During SC the noon meridian is near the Eastern coast of Canada, and CARISMA array is in the morning sector. In morning hours (8.5 MLT) negative PI preceding positive MI is observed at very high geomagnetic latitudes only, Φ>72º (Fig. 2). At lower latitudes (below ~68º) only positive MI is recorded. In this LT sector MI triggers quasi-monochromatic slowly decaying Psc4-5 pulsations at various latitudes, with periods from *T*~5 min at Φ~72º (RANK) to *T*~1.5 min at Φ~58º-60º (PINA, THRF). The lack of oscillatory response at Φ~66º (GILL) probably corresponds to the plasmapause position.

The SC triggers the development of moderate substorm, e.g. magnetic bay at PBK with amplitude up to ~500 nT (not shown), though IMF Bz remains northward before and after the shock.

In a greatest detail we analyze the multi-instrument data from the dusk sector (Scandinavia) (Fig. 3). The IMAGE magnetometers (LT~17) record "classical" SC: positive MI and preceding it negative PI at 1504 UT (Fig. 3). At a latitude about 67º PI changes its polarity from negative (TRO) to positive (NOR), whereas MI changes polarity between 68º-74º. This polarity reversal of geomagnetic disturbance is commonly interpreted as an evidence of vortex-like structure of the ionospheric currents associated with PI and MI.

At latitudes ~65º-67º (NOR, IVA, TRO, SOD) fast-decaying transient Psc5 pulsations with *T*~5-6 min are excited (Fig. 3). A quasi-period of these pulsations is latitude dependent, so they cannot be associated with cavity oscillations. Their waveforms differ considerably from the Psc4-5 pulsations on the morning flank (Fig. 2). Thus, oscillatory responses of the magnetosphere on the IP shock at the morning and evening flanks are independent.

Detailed examination of PI at stations IVA – SOD – OUL – HAN, covering latitudes from ~59º to ~65º (Fig. 3), reveals its apparent poleward propagation. This effect may be interpreted as a delay of the Alfven pulse propagation time from an excitation region in the equatorial magnetosphere towards the ionosphere along different field lines with latitude-dependent Alfven period $T_A(\Phi)$. A peak of MI also demonstrates poleward propagation, but with an apparent velocity even larger than that of PI.

4. Ionospheric TEC response to SC as observed by GPS system. We have examined the TEC response from GPS 30-s data downloaded from the IGS website. The TEC data have been converted into the vertical vTEC. The TEC response in the morning hours (Canadian sector) is shown in Fig. 4. The TEC data derived from signals from different GPS satellites received at station CHUR demonstrate a gradual vTEC growth started after SC. These variations are possibly the result of prompt electric field penetration during the main phase of the storm. This TEC growth during SC in the morning sector (Canada) is observed at latitudes above 60º only. The ΔTEC/TEC reaches the value 30-40%.

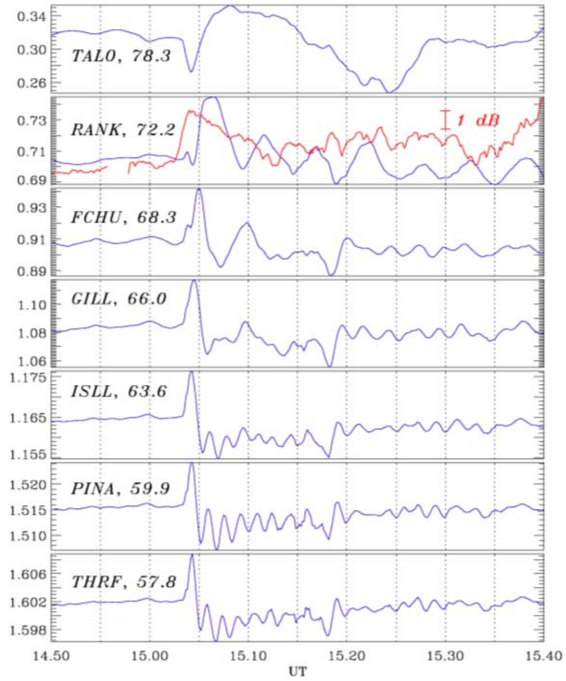

Figure 2. The magnetograms (X-component in 10^4 nT) of the latitudinal profile of stations TALO-RANK-FCHU-GILL-ISLL-PINA-THRF from the CARISMA array, red line shows variations of riometric absorption at RANK.

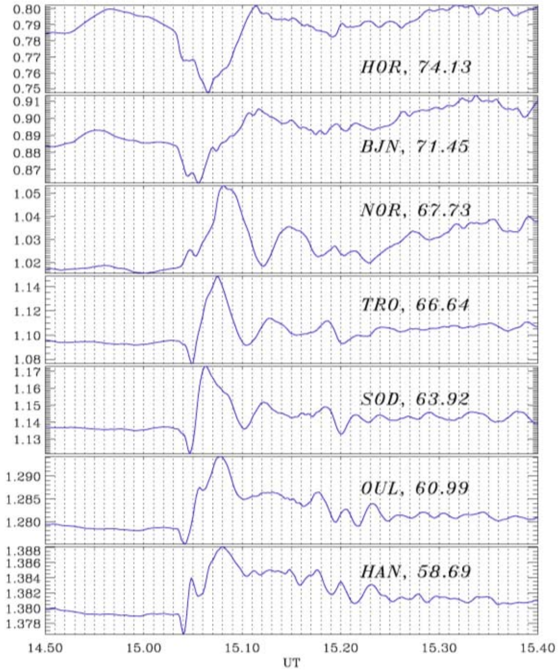

Figure 3. The magnetometer data (X-component in 10^4 nT) along the latitudinal profile HOR-BJN-NOR-TRO-SOD-OUL-HAN from the IMAGE array.

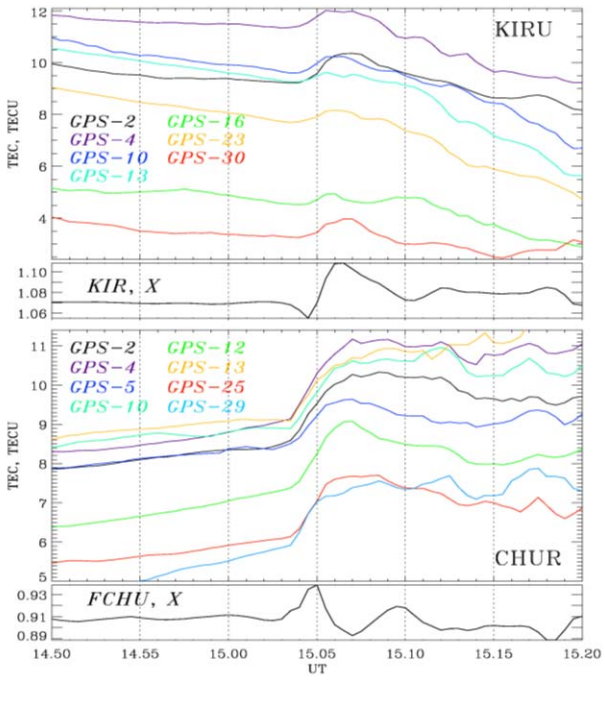

Figure 4. vTEC data from GPS satellites with α>45° in Scandinavian sector from the KIRU GPS receiver, bottom panel shows magnetic variations from station KIR (X-component). vTEC data from GPS satellites with α>45° in Canadian sector from the CHUR GPS receiver, bottom panel shows magnetic variations from station FCHU (X-component).

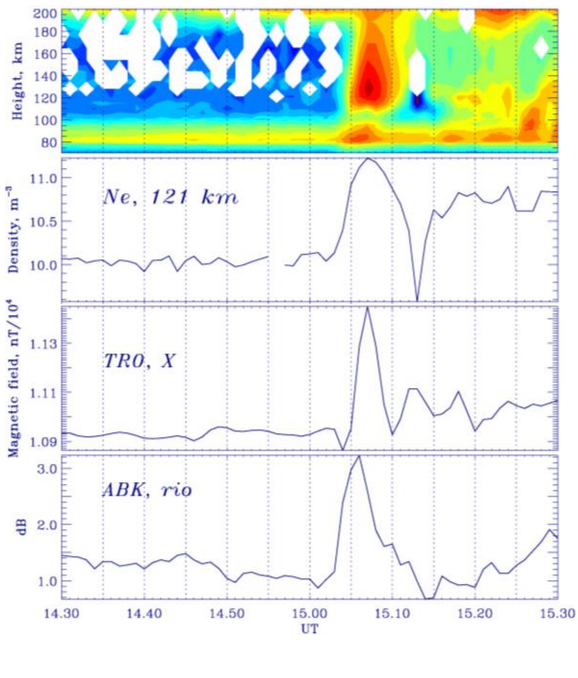

Figure 5. Ionospheric and geomagnetic observations during Jan. 24, 2012, 1430-1530 UT (from top to bottom): altitude distribution of electron density Ne variations measured by EISCAT; variations of Ne at altitude z=121 km; magnetic field variations (X-component) at TRO and riometer variations at IVA.

In the evening sector (Scandinavia), vTEC variations have been constructed for different radiopaths between available GPS satellites and KIRU receiver. At a background of gradual increase of vTEC, a superposed positive pulse of vTEC is observed with amplitude up to $\Delta N_T \sim 1$ TECu (Fig. 4). The ΔTEC/TEC in the dusk sector is less than the 10%. Onset of TEC growth coincides with PI at station KIR, but no PI signatures can be seen in TEC. The impulsive TEC enhancements coincide with the geomagnetic MI at KIR. The observed ionospheric response may be caused by plasma compression, additional ionization due to the electron precipitation, or ionospheric plasma redistribution owing to the wave electric field. The vertical structure of the ionospheric disturbance can be determined with incoherent radar.

5. EISCAT radar response to SC. Incoherent radar EISCAT in Tromso provides a vertical profile up to 200 km of main ionospheric parameters with cadence 1 min. The EISCAT-measured electron density Ne evidently shows an impulsive response to SC (Fig. 5). At the same time, no clear signatures in ionospheric E-field coherent with magnetic disturbance are observed. EISCAT reveals an irregular increases of Ti and Te at altitudes >150 km. Most evident response in electron density Ne can be seen at altitudes 110-170 km (Fig. 5). A growth of Ne in the E-layer (120 km) starts simultaneously with riometer increase and PI. The increase of Ne from $10^{10}m^{-3}$ to $1.7 \cdot 10^{11}m^{-3}$ reaches maximum simultaneously with MI peak, but decays during the period ~2 min that is longer that the duration of MI ~ 1 min.

6. Discussion and conclusions. The analysis of SC event recorded simultaneously by various instruments on the ground and in space has shown a surprisingly large variety of associated effects. Only latitudinally localized transient Pc5 pulsations at the dawn and dusk flanks have been observed, which correspond to the independent response of resonant field lines in the morning and evening sectors [*Samsonov et al.*, 2011]. The lack of oscillatory response at $\Phi \sim 66^o$ is probably caused by the plasmapause, because in its vicinity the radial gradient of Alfven period $T_A(\Phi)$ becomes smooth. Therefore, a mode conversion into Alfven oscillations of geomagnetic shell is weak in this region. Clear resonant transient Psc5 oscillations are independently generated on the morning and evening flanks, no signatures of theoretically predicted cavity mode excitation is found.

In this study, for the first time (to the best of our knowledge) a TEC response to SC was found. A responsible mechanism of TEC modulation may be related to field-aligned plasma transport by Alfven pulse, which provides an additional plasma flow in the bottom ionosphere. During the SC event under examination, the path-integrated electron density TEC, $N_T(t)$, response to MI only has been detected. The modulation of the ionospheric plasma density may be caused by the interaction of an incident MHD pulse with the ionosphere - atmosphere - ground system. Shear Alfven wave does not produce plasma/magnetic field compression, so any compressional effects arise upon interaction of this mode with the anisotropic inhomogeneous ionosphere. A precipitation of energetic electrons and ionization of the lower ionosphere during SC recorded by riometers can influence bottom E-layer and D-layer which contribution into TEC is small. Nearly simultaneous response in riometer, TEC, and EISCAT Ne may be interpreted as a stimulated by SC precipitation of electrons with a wide energy range, from soft (≤keV) to energetic (tens of keV).

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