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THE SOLAR FLARE IMPACT ON THE LOWER IONOSPHERE AND GEOMAGNETIC FIELD

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Abstract

The geophysical testing ground at Kamchatka provides wide possibilities to monitor the electromagnetic and ionospheric phenomena at the Far East. Here we demonstrate the facilities of this multi-instrument observational complex for the study of the solar flare impact on the lower ionosphere and geomagnetic field. We have used data of the VLF amplitude/phase monitoring along several radio paths, augmented by the geomagnetic observations. A typical VLF amplitude/phase response "replicates" the X-ray flux variations, however the magnitude of the response depends on a preexisting ionization level. The geomagnetic field, besides long-lasting (~30-40 min) magnetic bay, sometimes demonstrates the oscillatory (with quasi-periods ~ 4 mins) response to an impulsive X-ray/UV emission burst, whereas these oscillations are absent in the VLF data. We suggest that some ionospheric heavily damped acoustic-gravity or MHD modes may be responsible for this quasi-periodic response. Solar flare was found to enhance the intensity of magnetospheric Pc3 (~ 50 s) pulsations.

Introduction

Solar flares are giant explosions on the surface of the Sun when a huge amount of electromagnetic energy is released over the whole electromagnetic spectrum. A complex of associated geophysical phenomena is coined the solar flare effect (SFE). The UV radiation is absorbed at higher altitudes ionizing the F-region, the ionosphere E-layer is vulnerable to soft X-ray bursts, hard X-rays penetrate more deeply into the ionosphere reaching the D-region, and γ-rays transmit through the ionosphere into the stratosphere.

In this study we combine observational data from two techniques. The first one is the monitoring of Very Low Frequency (VLF, 3–30 kHz) radio signal propagation from transmitters within the waveguide created by the low ionosphere and Earth's surface [*Rozhnoi et al.*, 2019]. VLF radio waves normally reflect at altitudes of D-layer: 70-75 km during daytime and 80-90 km during nighttime. Sudden X-ray irradiance (flares of class X, M) affect the subionospheric VLF radio signal propagation as a deviation in amplitude and phase.

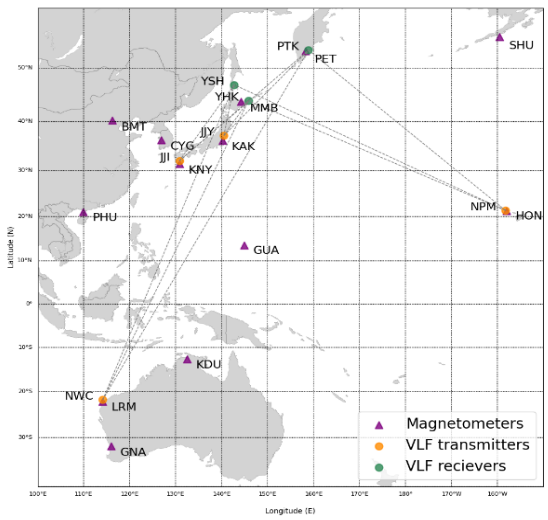

Figure 1. Location of VLF transmitters/receivers in the Far East region, and magnetometers.

Another technique we have used is the array of ground magnetometers. Burst of the electromagnetic emission flux during solar flares is accompanied by a sudden disturbance of the geomagnetic field. This disturbance can be understood as a geomagnetic response to a current intensification in the global ionosphere system due to the conductivity enhancement in the E-layer (100-120 km). Besides long-term effects (~1 h in duration), a quasi-periodic response is sometimes observed by ground magnetometers in various frequency range (periods from tens of secs to tens of mins), named Pc_{SFE} pulsations [*Dovbnya et al.*, 1995]. These periodic responses were attributed to resonant features of the magnetospheric [*Rosenberg et al.*, 1981] or atmospheric-ionospheric [*Parkhomov et al.*, 2006] systems. However, these suggestions have not been supported yet by detailed data analysis or theoretical modeling, and the relevant physical mechanisms have remained poorly studied.

The VLF radio wave method has been suggested for remote control of the earthquake preparation. Ionospheric effects 1-5 days before earthquakes were found by investigating the amplitude/phase of VLF radio waves in the Earth-ionosphere guide [*Rozhnoi et al.*, 2009]. The impulsive flare impact may be considered as a testing signal to reveal possible resonant features of the atmosphere-ionosphere-magnetosphere system, and to validate the sensitivity of the VLF technique for the detection of earthquakes. Here we use the facilities of the multi-instrument observational complex at Kamchatka for the study of the solar flare impact on the lower ionosphere and geomagnetic field using data of the VLF amplitude/phase monitoring and data from geomagnetic observatories.

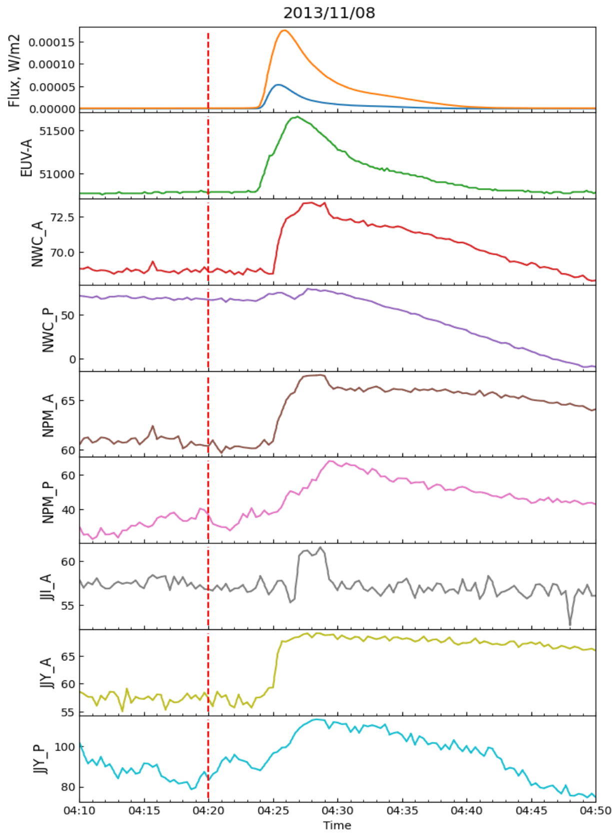

Figure 2. Effects of the solar X-ray flare on 2013/11/08: upper panel – GOES observations of soft X-ray (red line) and hard X-ray (blue line) fluxes; second panel – EUV counts at GOES; next panels - VLF signals from NWC (amplitude and phase), NPM (amplitude and phase), JJI (amplitude), and JJY (amplitude and phase) transmitters.

Observational facilities

The X-ray 2-sec data in two energy bands soft (0.05-0.4 nm) and hard (0.1-0.8 nm) X-ray fluxes from the geosynchronous GOES-14, -15 satellites have been used to record bursts of the solar flare emission. We also have used data on extreme ultra-violet (EUV) emission in the band 5-20 nm from the geostationary GOES-13 satellite.

We have used data from VLF receiver, sited at Petropavlovsk-Kamchatsky (PTK, 158.92°E, 53.15°N). It receives signals from the transmitters JJY (40.0 kHz, Fukushima) path length=2271 km, JJI (22.2 kHz, Miyazaki), path length=3247 km, NWC (19.8 kHz, Australia), path length=9420 km, and NPM (21.4 kHz, Hawaii), path length=4852 km. The radio paths are shown in Fig. 1. The VLF receiver records with 20 sec sampling period the amplitude (in dB) and phase (in degrees).

These observations are augmented by 1 sec data from INTERMAGNET magnetometers. The location of selected magnetic stations in South-East Asia is shown in Fig. 1.

Typical events

We provide the observational results for selected typical events. The reported solar flare onset is marked by the vertical dotted red line. During all events under study the soft and hard X-ray fluxes varied by 2-4 times from event to event, whereas EUV count rates varied not more that by ~2%.

Solar X-ray flare occurs on **2013/11/08**, around 0420UT (Fig. 2). Stepwise response can be seen in the VLF data. Magnetic response is composed from two elements: gradual long-term (~30 min) magnetic bay (KAK, MMB) and short-period (~10 min) impulse during flare onset (Fig. 3) evident at GUA, KAK.

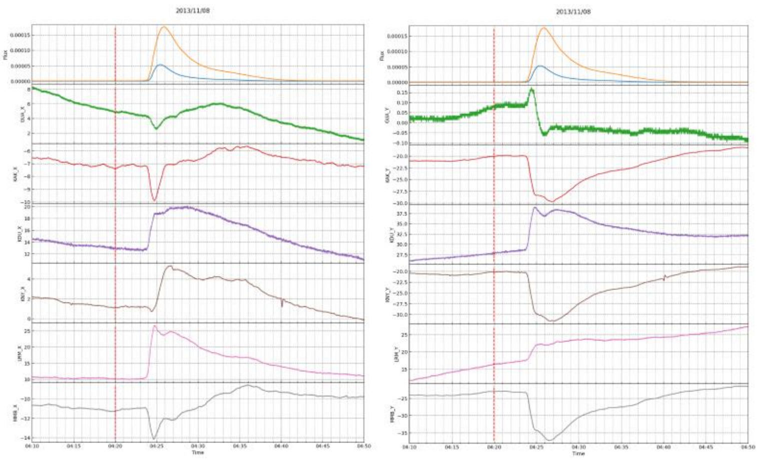

Figure 3. Geomagnetic response to the solar flare on 2013/11/08 in X (left-hand panels) and Y (right-hand panels) components. Upper panels show X-ray fluxes as measured by GOES.

Solar X-ray flare occurs on **2011/09/06**, around 2213 UT. The X-ray intensity variation shows a sudden burst and gradual decay (Fig. 4). However, geomagnetic field, besides gradual variations, demonstrates oscillatory response (Fig. 5). In detail these magnetic variations are examined in Fig. 6. The figure shows Y-component only because the properties of X-component variations are very similar. The data have been detrended by subtraction of running average in 10-min window. The dynamic spectra (see sonograms in the right-hand part of Fig. 6) reveal that the periodicity of transient geomagnetic response is ~4 min. These oscillatory variations are absent in the VLF data. Probably, the geomagnetic oscillatory response is caused by excitation of some resonant ionospheric system by the solar flare. During this event, another interesting feature is observed. After the solar flare, quasi-monochromatic (period ~50 s) geomagnetic pulsations start and last for about one hour (Fig. 6).

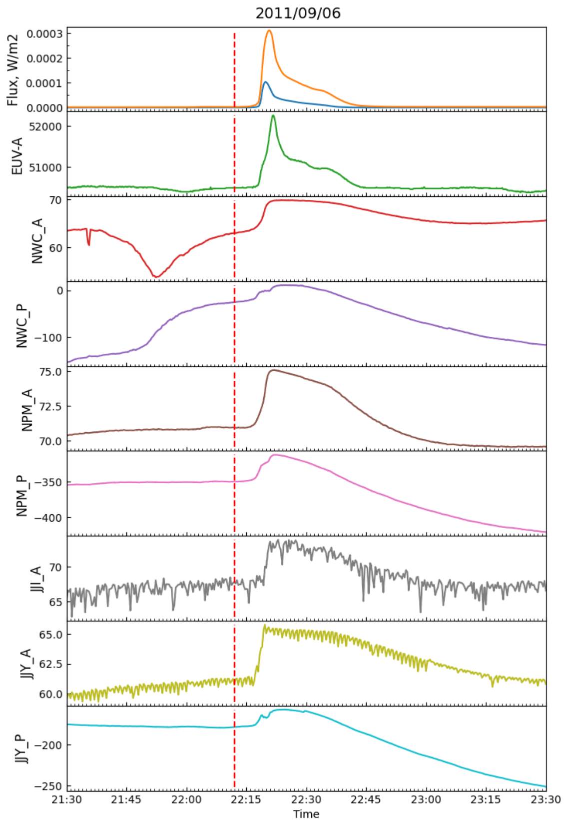

Figure 4. Solar X-ray flare on 2011/09/06 as observed by various instruments: upper panel – GOES observations of soft X-ray (red line) and hard X-ray (blue line) fluxes; second panel – EUV counts at GOES; next panels - VLF signals from NWC (amplitude and phase), NPM (amplitude and phase), JJI (amplitude), and JJY (amplitude and phase) transmitters.

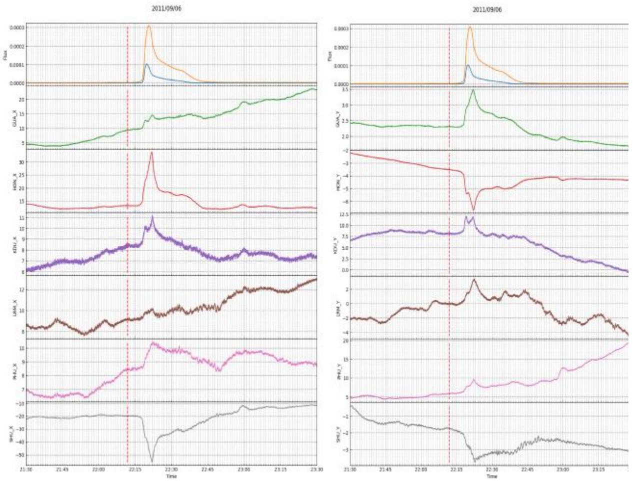

Figure 5. Geomagnetic response in X (left-hand panels) and Y (right-hand panels) components at Far-East stations to solar flare on 2011/09/06.

Discussion

A received signal is a sum of ground wave from VLF transmitter and sky multi-hop waves. An ionization of the bottom ionosphere modifies the reflection/absorption of the sky wave, which results in the modification of the interference pattern and change of the wave amplitude/phase. Solar photons of different energies ionize ionospheric plasma at different altitudes: UV radiation ionizes the F-region, soft X-ray (0.1-1 nm) – the E-layer, hard X-rays (1-10 nm) reach the D-region, and γ-rays penetrate through the ionosphere into the upper atmosphere. Thus, a solar flare may provide the largest response in different layers depending on its energy spectrum. However, electrodynamic coupling between layers may results in a more complicated response of an entire ionosphere to a solar flare.

The observed quasi-periodic responses were interpreted as a signature of the following resonators:

- Geomagnetic waves with periods ∼70–100 sec at low latitudes excited by rapid changes in the ionospheric conductivity may be eigenoscillations of the geomagnetic field lines [*Rosenberg et al.*, 1981]. At high latitudes irregular geomagnetic pulsations associated with hard X-rays flares revealed spectral peaks at periods of 40, 100, and 300 sec, corresponding to local magnetospheric resonances [*Lukovnikova and Parkhomov*, 1983].
- Pulsed heating of the lower ionosphere by ionizing radiation can excite an acoustic-gravity wave (AGW) [*Metelkin et al.*, 1982]. The ionization of the ionosphere in the conducting region changes the electric current in it, which leads to the fast release of heat responsible for the AGW generation [*Sorokin et al.*, 2022]. The propagation of an AGW through the ionosphere generates oscillations of the geomagnetic field.

In all daytime events we have examined the solar flare burst was unipolar, without a quasi-periodic structure. We suppose that the mechanism of magnetospheric oscillations cannot be responsible for the observed quasi-periodic geomagnetic response. At middle/low latitudes, periods of fundamental magnetospheric field line oscillations (Pc3 pulsations) are about few tens of secs, that is much less the periodicity of the observed geomagnetic response. Thus, the observed periodicity corresponds rather to AGW band. However, the excited AGW seemingly should modulate not only conducting E-layer, but D-layer as well. So, they must be detected by the VLF monitoring technique. However, we have not found any traces of the quasi-periodic signatures in the VLF data, whereas quasi-periodic variations have been observed in magnetic field. We suggest that besides AGW, a specific MHD mode may be excited in the E-layer. As a possible candidate the

MHD surface-type wave (named the gyrotropic mode) propagating along the gyrotropic E-layer may be indicated [*Gorbachev et al.*, 1995]. It may be speculated that heavily damped geomagnetic oscillations following some solar flares may be associated with the excitation of the ionospheric gyrotropic mode.

During the event on 2011/09/06 another interesting effect has been observed. After the solar flare quasi-monochromatic geomagnetic pulsations started and lasted for about one hour (Fig. 6). Their period corresponds to that of typical Pc3 pulsations. We suppose that these pulsations cannot be interpreted as a result of direct excitation by the solar flare. The driver of Pc3 pulsations is the turbulent region upstream the bow shock, which is not controlled by a solar flare. Probably, the enhanced UV/X-ray emission during solar flare produces an enhancement of the E-layer conductivity. This process increases the Q-factor of the magnetospheric field-line resonator, which leads to enhancement of eigenoscillations in this resonator – Pc3 pulsations.

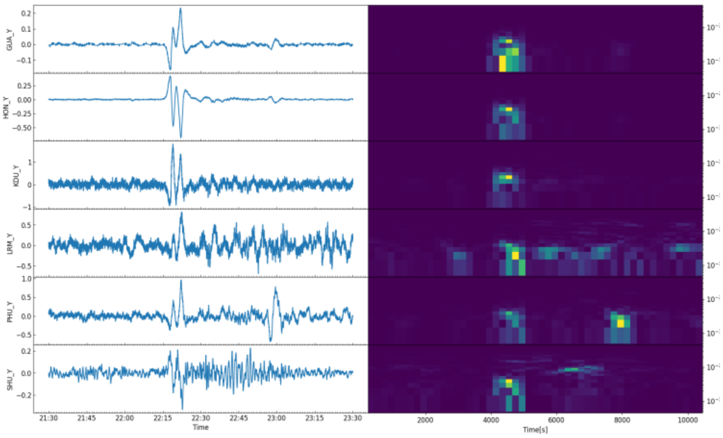

Figure 6. The detrended magnetograms of Y component during 2011/09/06 event (left-hand panels), and their sonograms (right-hand panels).

Summary and conclusions

We have examined the response of VLF amplitude/phase along the radio paths at Far East to X-ray solar flares. The VLF response "replicates" the X-ray flux variations. Geomagnetic observatories in this region sometimes demonstrate the oscillatory response to a pulse of UV/X-ray emission, whereas these oscillations are absent in the VLF data. We suggest that some ionospheric heavily damped MHD mode or acoustic mode in the E-layer may be responsible for a quasi-periodic response to the sudden ionization produced by an X-ray solar flare. Comparative analysis of the ionospheric response to the solar flare with known energy and to pre-earthquake activity may provide a clue to mechanism of seismo-ionospheric phenomena.

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Data Availability Statement

The X-ray and EUV data from the GOES-13, -15 satellites are provided by NOAA through https://satdat.ngdc.noaa.gov/sem/goes/data/avg/ and https://satdat.ngdc.noaa.gov/sem/goes/data/euvs/.

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