# VERY LOW AND LOW FREQUENCY SIGNALS METHOD TO STUDY THE LOWER IONOSPHERE RESPONSE TO THE LITHOSPHERE AND ATMOSPHERE EVENTS

*Rozhnoi A.A.[1], Solovieva M.S.[1], Kopylova G.N.[2], Chebrov D.V.[2], Korkina G.M.[2], Budilova E.A.[2], Levin B.W.[3], Shevchenko G.V.[3], Loskutov A.V.[3], Hayakawa M.[4, 5], Fedun V.[6]*

[1] Schmidt Institute of Physics of the Earth of RAS, Moscow, Russia, rozhnoi@ifz.ru; [2] Kamchatka Branch of Geophysical Survey, RAS, Petropavlovsk-Kamchatsky, Russia; [3] Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia; [4] Advanced Wireless Communications Research Center, [5]Research Station on Seismo Electromagnetics, Tokyo, Japan; [6] University of Sheffield, Sheffield, United Kingdom

Measurements from a network of Very Low and Low Frequency (VLF/LF) receivers were used for investigation of such natural hazard events as earthquakes, volcanic eruptions, tsunamis propagation, cyclones and tropical cyclones. Our network consists from 11 receivers that give us possibility to control high seismic active regions of the Far East, Alpine - Himalayan belt and Central America.

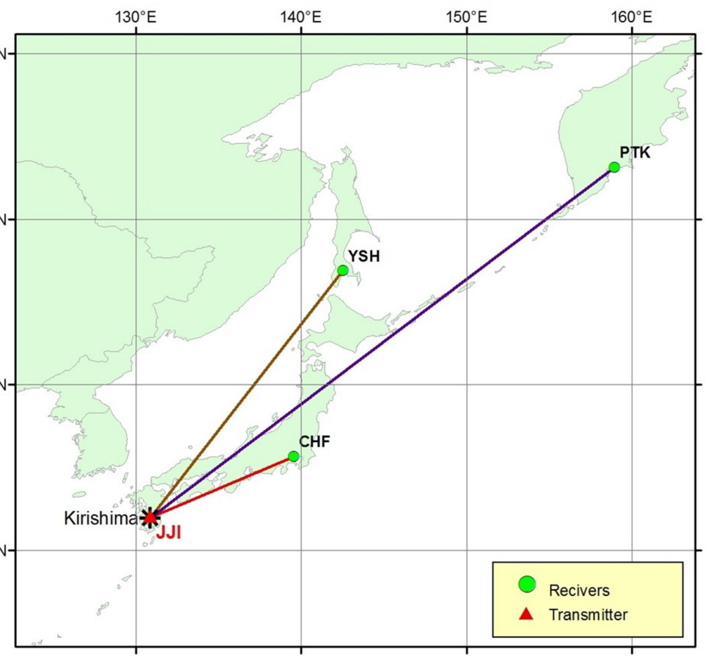
As a case in point we consider the anomalies in the amplitude of VLF signals in connection with two strong earthquakes in Nepal in 2015 (**Fig. 1**). It was found that the two crossing paths have shown the anomalous signal behavior during several days before the first lager earthquake. The crossing of the paths has shown good coincidence with the epicenter of earthquake.

Data from four VLF receivers have been used to study the response of the lower ionosphere to the January 2011 Mt. Kirishima (South Japan) volcanic eruption (**Fig. 2**). A major explosive eruption was preceded by several small eruptions. Perturbations of nighttime subionospheric VLF signals have been detected in all paths on the day of the first small eruption. The nighttime signal remained disturbed during the subsequent pre-eruptive and eruptive activity of Mt. Kirishima. The frequency of the maximum spectral amplitude was found to be in the range of periods of 6-30 min, which corresponds to the periods of internal gravity waves.

We investigated the lower ionosphere response driven by tsunamis caused by 2004 Sumatra, 2006 Kuril, 2011 Tohoku and 2010 Chile earthquakes. In this work we consider the tsunami triggered by the 2011 Tohoku earthquake based on data from two receiving stations (**Fig. 3**). We compare our VLF data with the measurements from the Deep-ocean Assessments and Reporting of Tsunamis (DART) bottom pressure stations. In both stations during tsunami propagation signal exhibits a significant decrease in amplitude (about 10-15 db) together with phase variations of up to 40 degrees relative to the monthly averaged signal. The frequency of the maximum spectral amplitude was in the range of 8-60 min for the amplitude of the signal and in the range 10-40 min for the phase. These periods correspond to the range of periods for internal gravity waves and they are also in compliance with the periods of sea level oscillations.

The data from three stations, sited in the Russian Far East was used to study the disturbances in the lower ionosphere caused by cyclones and by tropical cyclones (typhoons in Pacific). VLF/LF signal variations during 8 typhoons have been analysed (**Fig. 4**). Negative nighttime anomalies in the signal amplitude were found for 6 events. Those anomalies are observed during 1-2 days when typhoons moved inside the sensitivity zones of the subionospheric paths. Perturbations of the VLF signal observed during 2 typhoons could be caused by both the typhoons influence and seismic activity.

## Effects from volcanic eruption




*A map showing the position of the volcano Kirishima together with the position of the VLF/LF receivers in Petropavlovsk-Kamchatsky (PTK), Yuzhno-Sakhalinsk (YSH) and Chofu (CHF) and the position of the Japanese VLF transmitter JJI (22.2 kHz).*

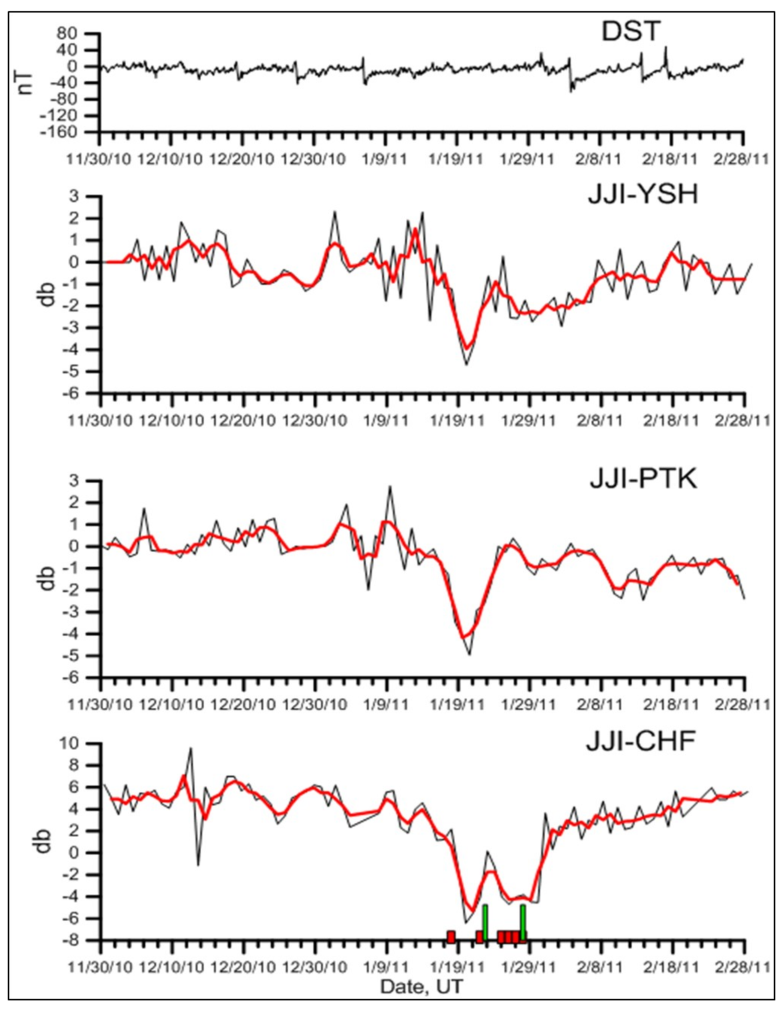



***Fig. 2.** Top panel shows the Dst index of magnetic activity. Next three panels show the residual amplitude (averaged over nighttime) of the JJI signal recorded at Yuzhno-Sakhalinsk (YSH), Petropavlovsk-Kamchatsky (PTK) and Chofu (CHF) stations during the period from December 1, 2010 to February 28, 2011. Black lines and red lines are the real and smoothed signals, respectively. The red bars on the bottom panel show the occurrence times of the volcano eruptions in January 2011, the green bars show the peaks in the thermal anomalies.*

## Effects from typhoons

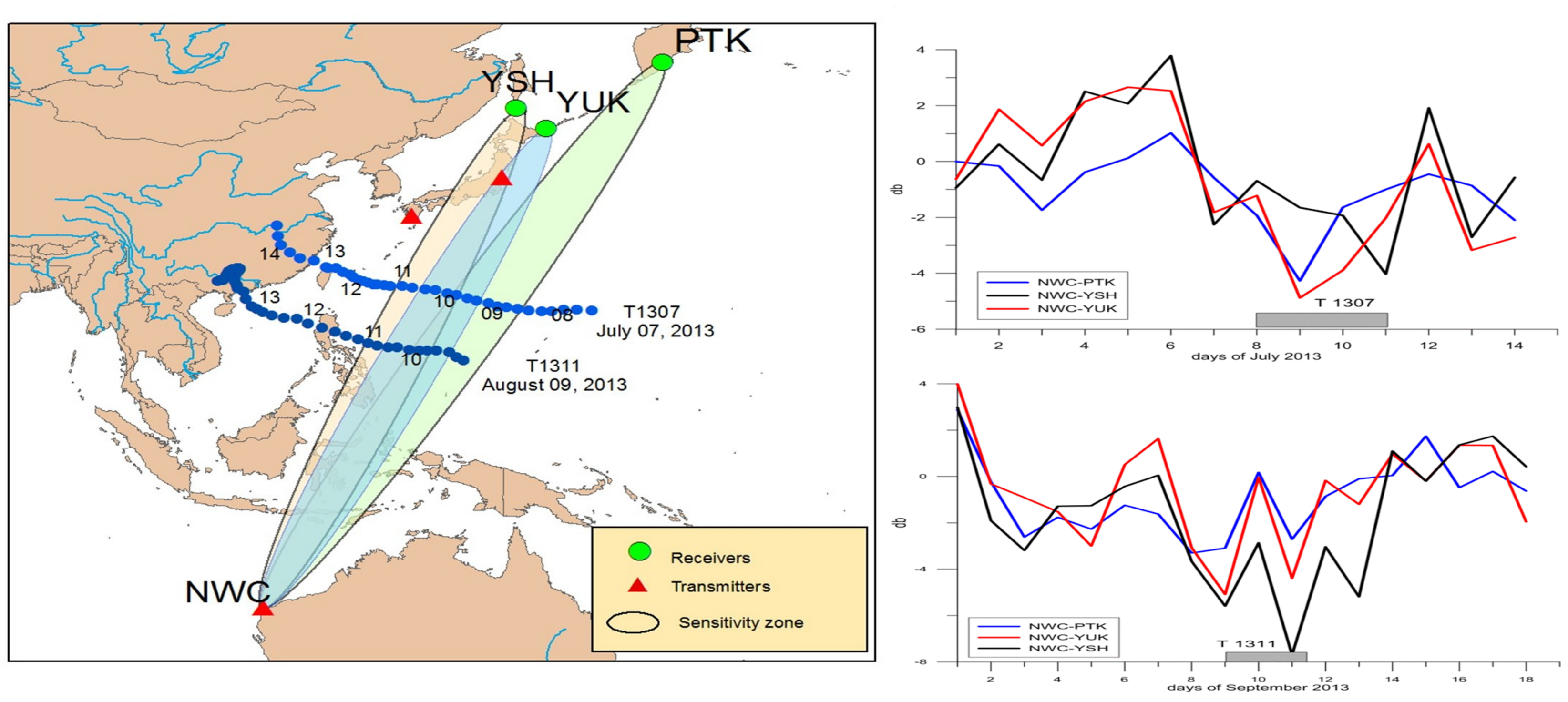
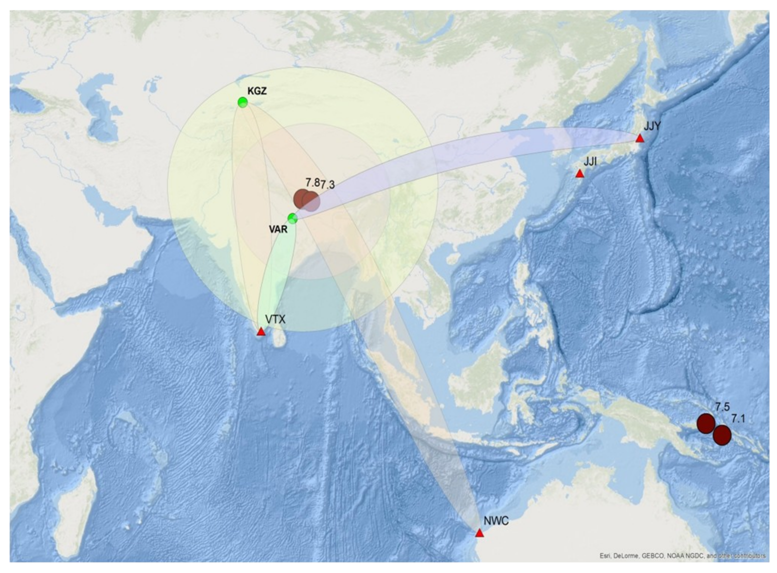



***Fig. 4.** The anomalies in the NWC signal recorded at three stations during the passage of the TC Soulik (1307) (the top right panel), and the TC Utor (1311) (the bottom right panel). Horizontal grey bars on the abscissa show the periods when the TCs crossed the sensitivity zones of the paths under consideration. The position of the TCs centers are shown in the left panel.*

## Effects from earthquakes



*A map of the wave paths under analysis together with the epicenters of earthquakes with M>7 (solid brown circles) occurred in April-May 2015 (NEIC/USGS). KGZ stands for the station in Bishkek (Kirgizstan), VAR means the station in Varanasi (India). The areas of earthquake preparation where precursors can be found are shown by the yellow circle for the first earthquake on 25 April and pink circle for the second earthquake on 12 May 2015. The ellipses are projections of the third Fresnel sensitivity zone on the Earth's surface.*

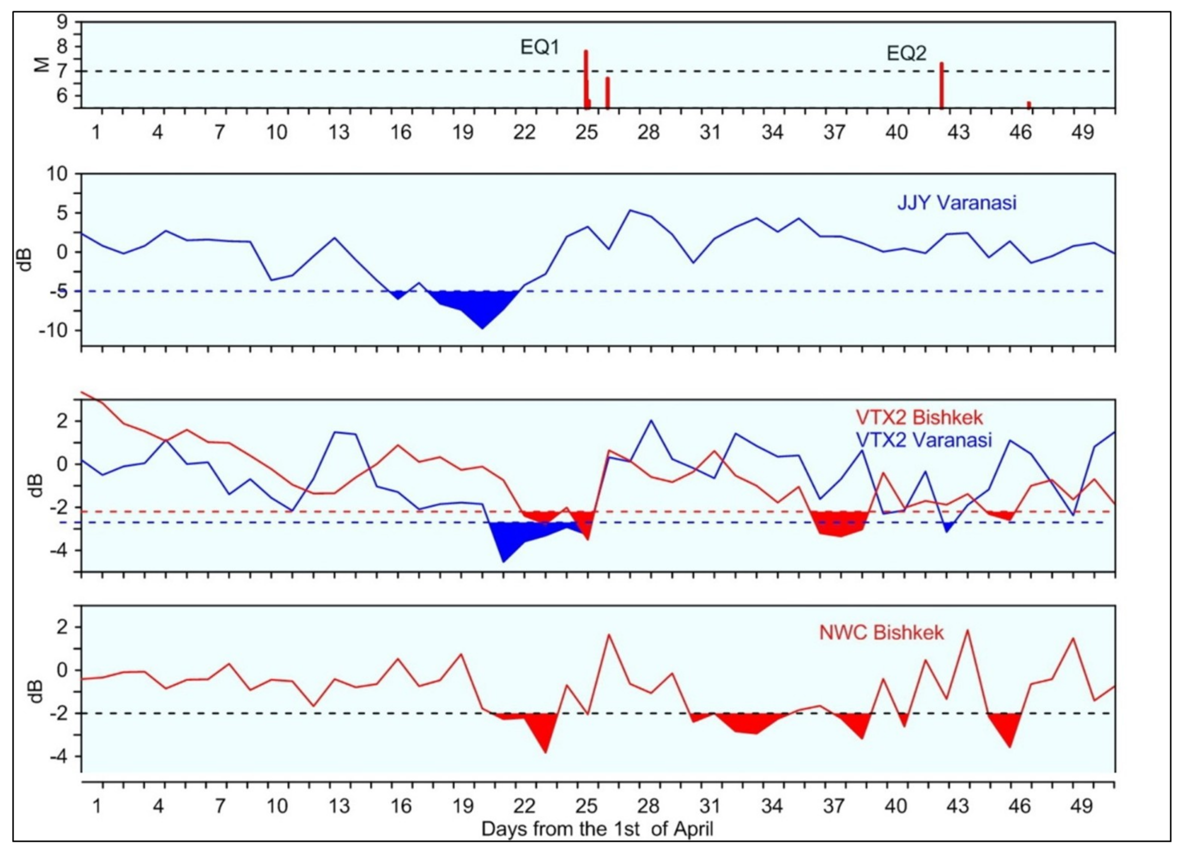
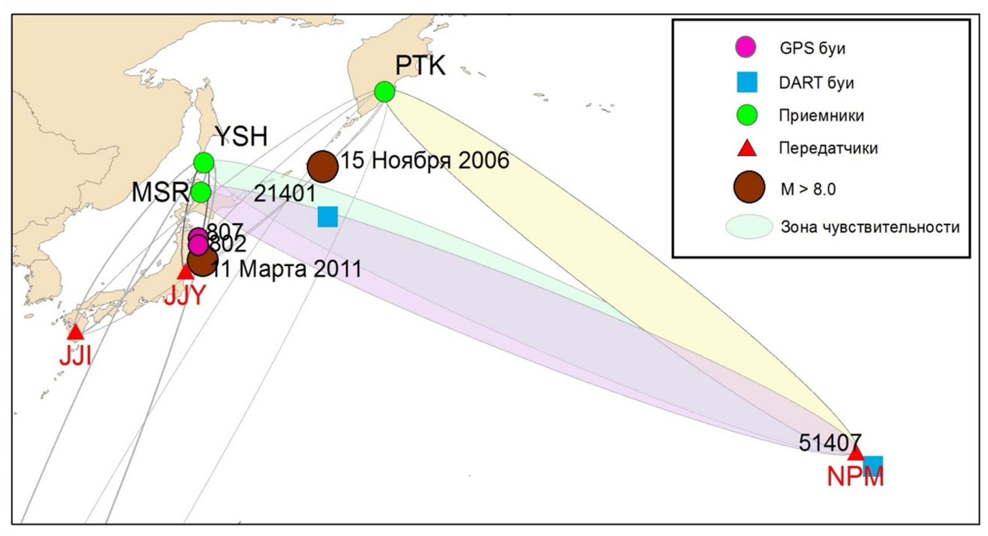



***Fig. 1.** The average residual amplitudes of the VLF/LF signals in nighttime are shown (top to down) for: JJY (40 kHz) transmitter signal recorded in Varanasi, VTX (17.0 kHz) transmitter signal recorded in Bishkek (red) and Varanasi (blue), NWC (19.8 kHz) transmitter recorded in Bishkek. The upper panel shows the occurrence time of the earthquakes. The color filled zones highlight values exceeding the -2σ (σ is the standard deviation) level, indicated by the horizontal dotted lines.*

## Effect from tsunami propagation




*A map showing the position of the VLF receivers in Yuzhno-Sakhalinsk (YSH), Petropavlovsk-Kamchatsky (PTK) and Moshiri (MSR) and the transmitters NPM (21.4 kHz)in Hawaii, JJY and JJI in Japan together with the position of the deep water DART stations and NOWPHAS GPS buoys in the region under analysis. The solid circles shows the position of the earthquake epicenter on March 11, 2011 and on November 15, 2006 (USGS/NEIC). The ellipses are projections of the fifth Fresnel sensitivity zone on the Earth's surface.*

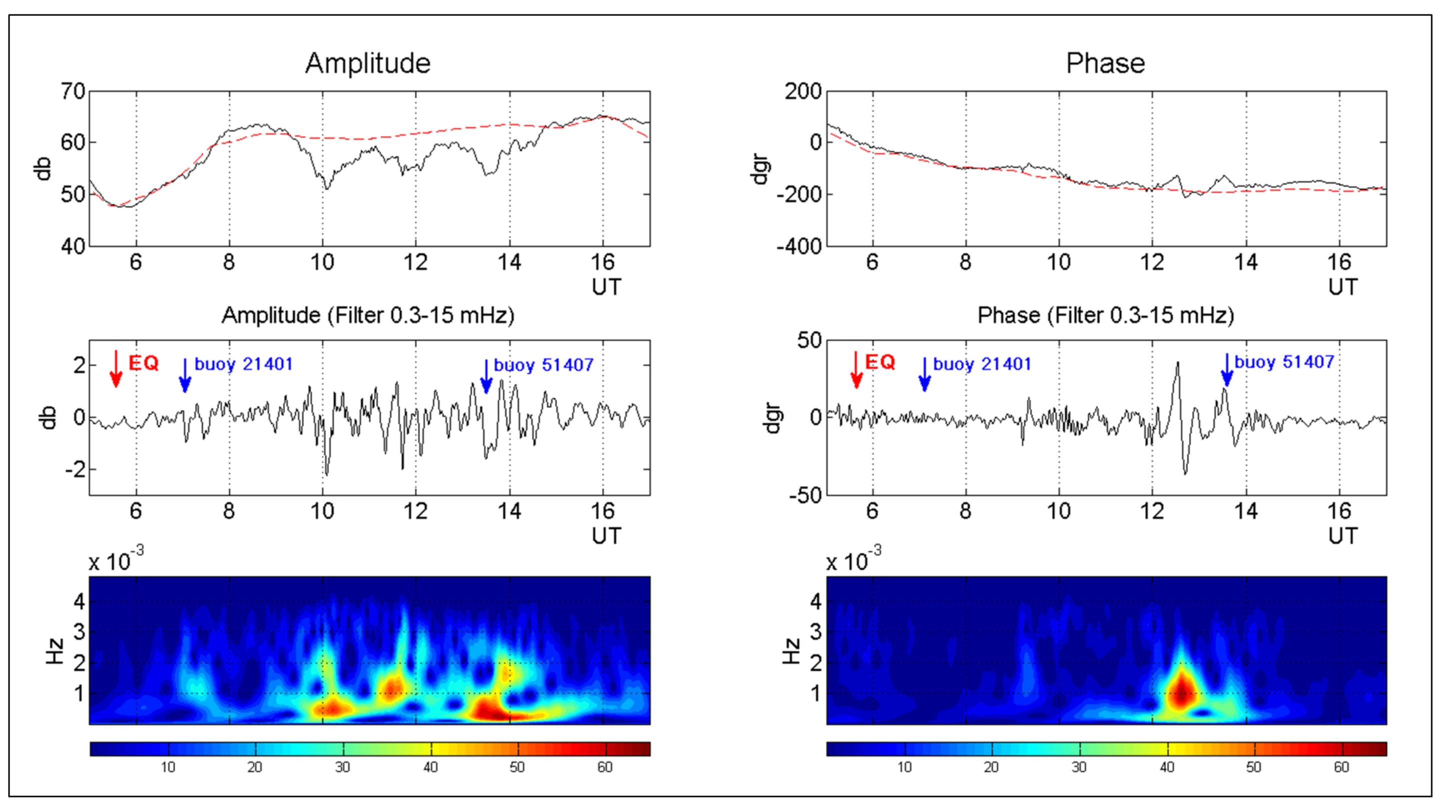



***Fig. 3.** Top panels show the amplitude (left) and the phase (right) of the signal from the NPM (21.4 kHz, the Hawaiian Islands) transmitter recorded on March 11, 2011 in Moshiri station (Japan). Dotted lines are the monthly averaged signals. The middle panels show the signals filtered in the range 0.3-15 mHz. The bottom panels show the wavelet spectra of the filtered signals. Arrows in the middle panels show the occurrence time of the earthquake and arrival time of the tsunami to the DART buoys 21401 (near Japan) and 51407 (near the Hawaiian Islands).*