STUDY OF THE LOWER IONOSPHERE EFFECTS CAUSED BY SPACE WEATHER EVENTS AND PHENOMENA

Solovieva M.S.[1], Rozhnoi A.A.[1], Kopylova G.N.[2], Chebrov D.V.[2], Korkina G.M.[2], Budilova E.A.[2], Fedun V.[3], Boudjada M.Y.[4], Schwingenschuh K.[4], Eichelberger H.U.[4]

[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] University of Sheffield, Sheffield, United Kingdom; [4] Space Research Institute of AAS, Graz, Austria

We present a short review of studies of the lower ionosphere effects caused by Space weather events and phenomena. The analysis is based on measurements from a network of Very Low and Low Frequency (VLF/LF) receivers. We analyse the electromagnetic narrow-band signals from ground-based navigational transmitters and transmitters of time service (in range 10-50 kHz) which are deployed all over the world. The propagation of subionospheric VLF/LF signals over distances of thousands of kilometers enables remote sensing over large regions of the lower ionosphere (D region) in which ionospheric modifications lead to changes in the received amplitude and phase.

Presented here are the results of effects of solar eclipses, solar flares, geomagnetic storms, proton bursts and relativistic electron fluxes. The solar flares are one of the main Space weather events. As an example of solar X-ray flares influence on the lower ionosphere we consider here X9.3 flare occurred on 6 September 2017 (**Fig. 1**). Sudden Phase Anomalies (SPAs) were observed in all middle-latitudes paths under consideration with length from 350 km to 7000 km and different orientation in 2-3 min after their registration on geostationary satellite the GOES. The change in effective height of reflection due to the lowering of reflecting layer during a flare was found to be about 12 km. Spectral analysis of the filtered in the range 5 sec-16 min X-ray and LF data was shown that spectra of the LF signal are very similar to spectra of X-ray. Maximum both X-ray and LF spectra was in interval 2-16 min.

Super strong magnetic storms influence is very significant, especially in the northern paths (**Fig. 2a,b**). Effects in the lower middle-latitude ionosphere caused by magnetic storms with -150 <Dst<-100 nT were investigated for 24 wave paths in Europe and in the Far East. It was found that such magnetic do not influence considerably on variations of the VLF/LF signals (**Fig. 3**). In middle latitude are most important effects in VLF/LF signals during the recovery stage of magnetic storms ("post storm effect"). The anomalies can be observed during several days, up to week or more (**Fig. 4**).

To examine the sensitivity of VLF/LF signals in the middle-latitude paths to the relativistic electron fluxes (> 2MeV) and proton bursts (0.6-2.4 MeV) the correlation method was applied to the period of 2012. Data series of daily maximum characteristics recorded by satellite the GOES were used for cross-covariance functions calculation. Correlation with outer-zone particles fluxes was found for almost half of the paths under analysis. Correlation with particle fluxes was about 40% in the vicinity of the events (**Fig. 5**).

As an example of the response of the lower ionosphere during the total solar eclipse we consider here the case of eclipse on 20 March 2015 in North Europe. In total 22 paths have been investigated. The paths crossed areas of obscuration from 40 to 100 %. The area of 90-100 % of obscuration was crossed by four long paths. The anomalies both in the amplitude and phase of signals have been found out for all four paths. The negative phase anomalies were from -75° to -90°.The amplitude's anomalies were both positive and negative and did not exceed 5 dB. Estimations of change of the effective reflection height of the ionosphere during an eclipse have shown that the increase in effective height of an ionosphere was about 6.5 - 11 km (**Fig. 6,7**).

Effects from solar flares

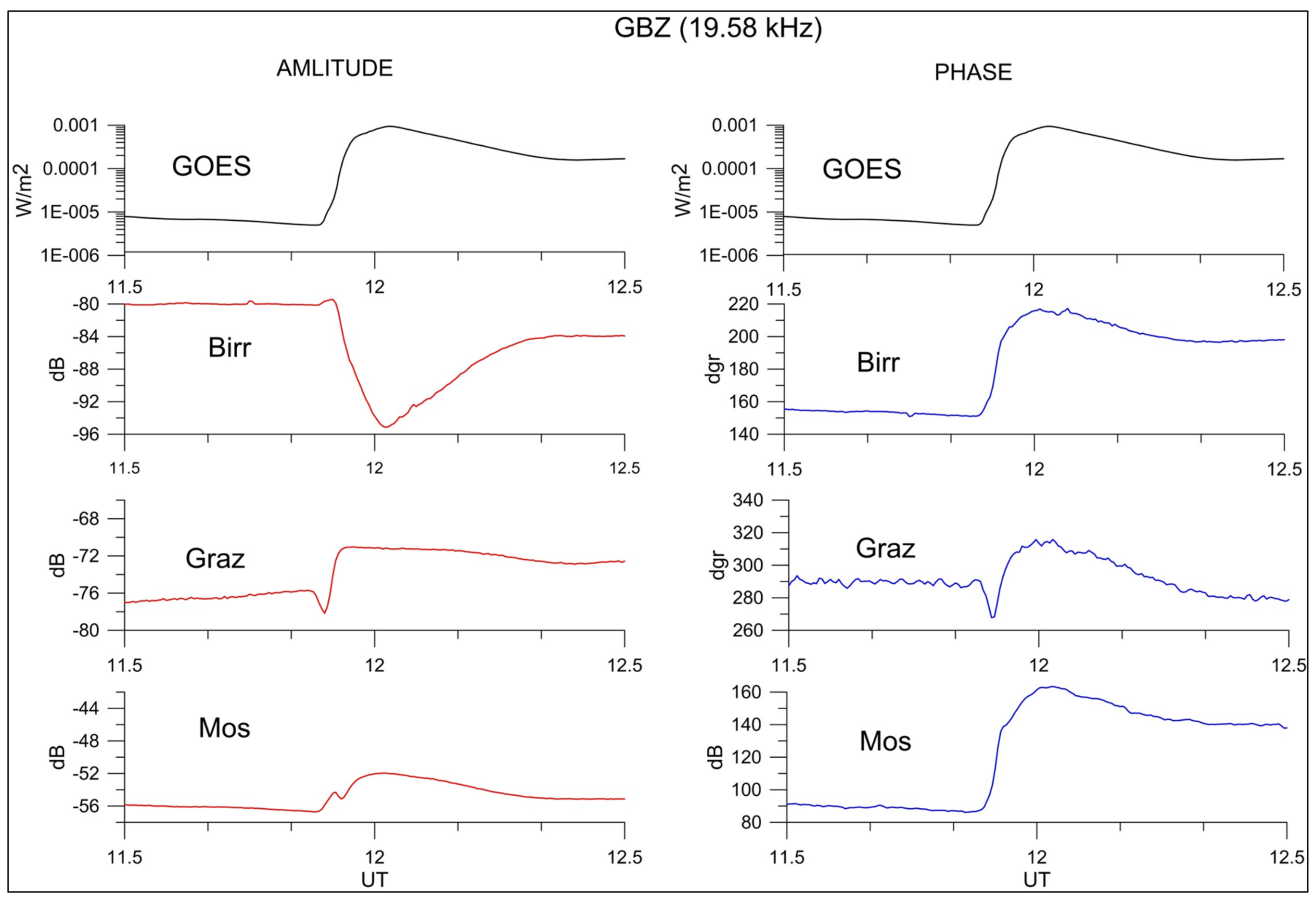

Fig. 1. *Amplitude (left) and phase (right) anomalies recorded in the GBZ signal in Birr, Graz and Moscow receiving stations during X-Ray burst on September 6, 2017 (class X9.3). Top panel shows X-ray observed in satellite the GOES (0.05-0.4 nm).*

Effects from magnetic storms

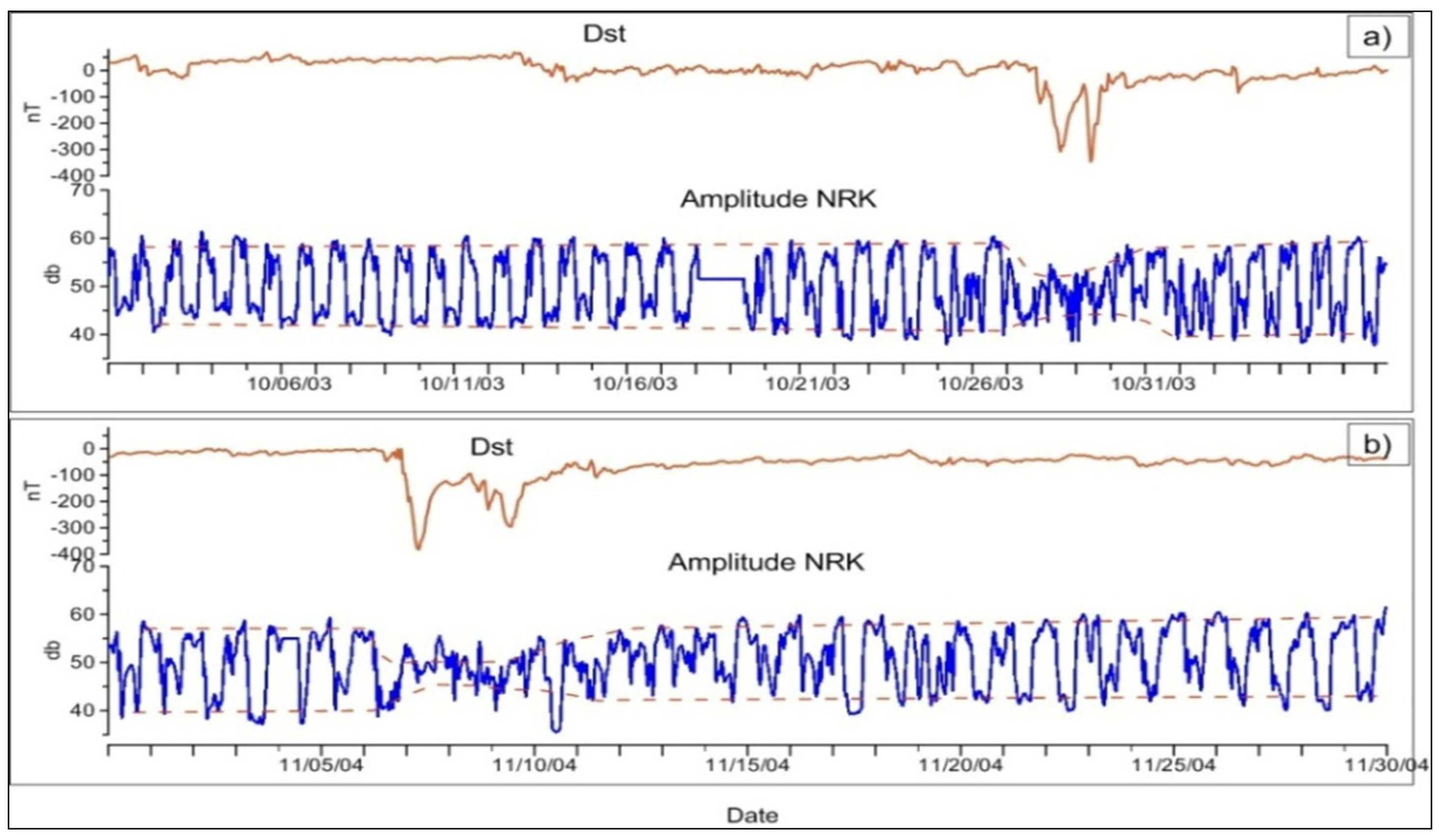

Fig. 2. *Examples of the influences of two super strong magnetic storms (Dst~-400 nT) on variations of the LF signal in the path Iceland-Bari (Italy).*

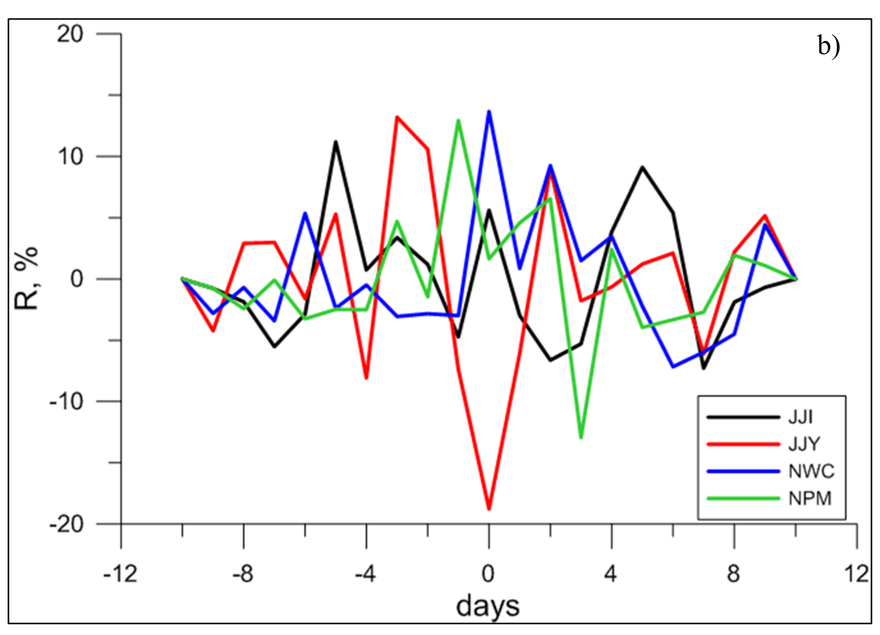

Fig. 3. *Cross-covariance functions for the average residual amplitude in nighttime of the signals received in Petropavlovsk-Kamchatsky and MaxDst indexes calculated in the interval ± 10 days. Axis Y is the correlation coefficient.*

Post storm effect

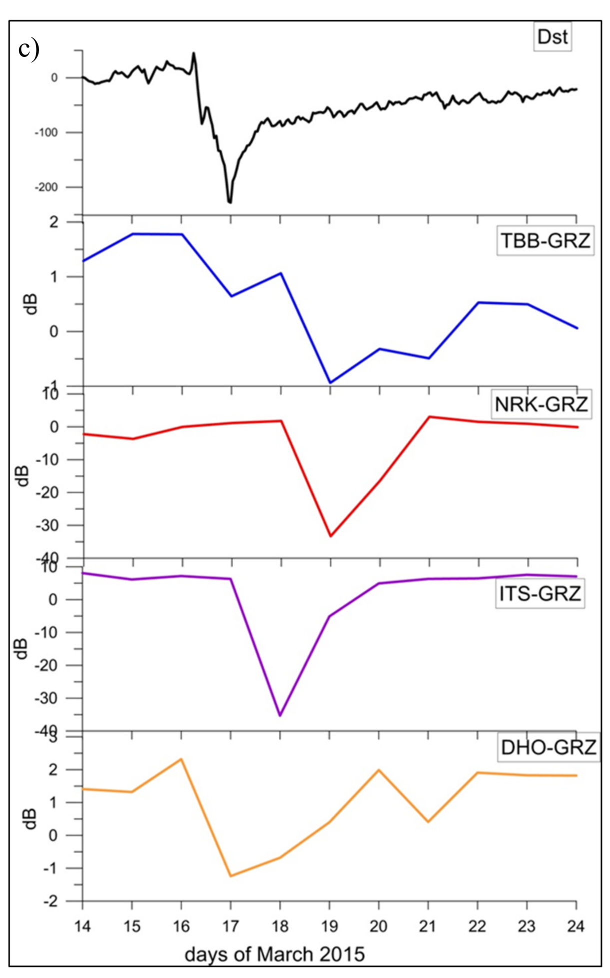

Fig. 4. *An example of anomalies in the amplitudes of several signals at the Graz station. Residual (dA) signal averaged over night time is shown.*

Effects from electron and proton out of space fluxes

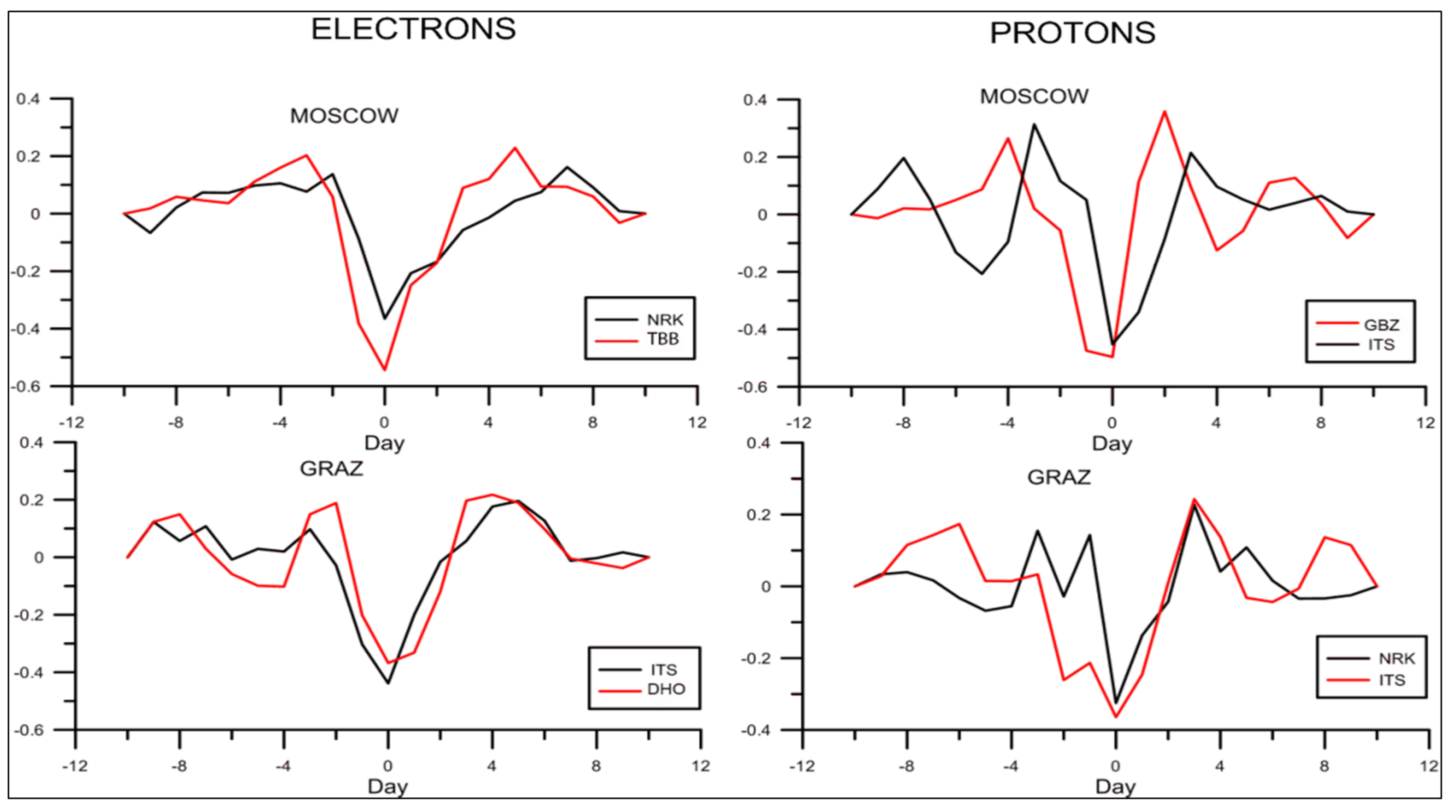

Fig. 5. *Cross-covariance functions for the average residual amplitude in nighttime of several signals receiving in Moscow and Graz stations and the electron (left) and proton (right) fluxes (GOES the satellite). Axis Y is the correlation coefficient.*

Influence of the total solar eclipse

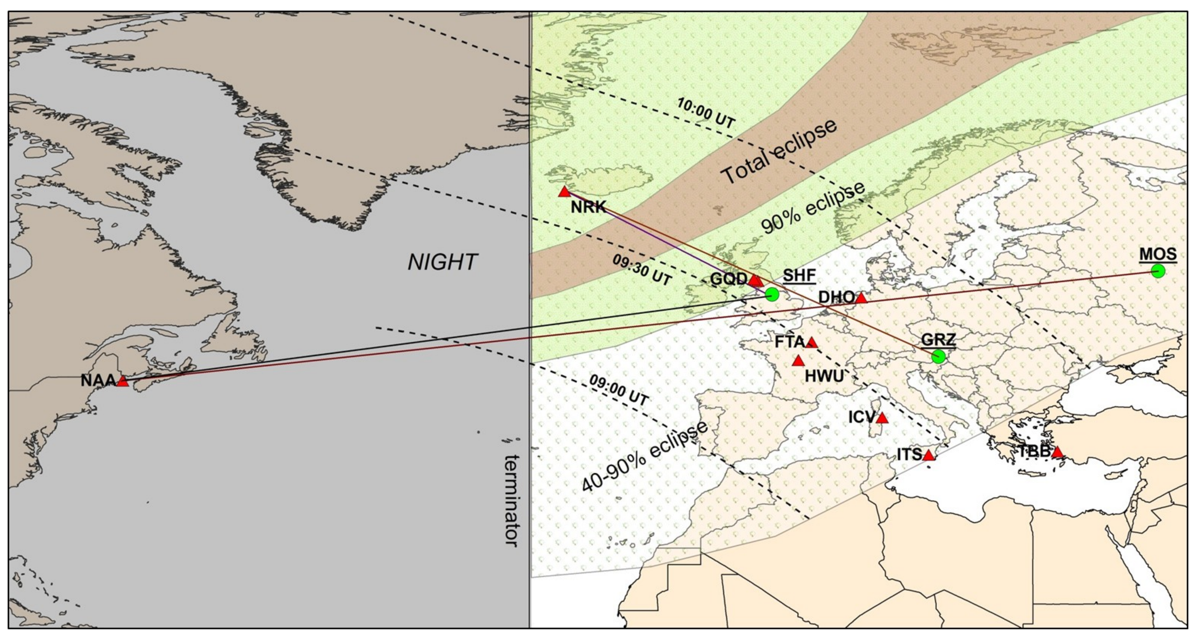

Fig. 6. *The network of VLF/LF observation in Europe together with the obscuration's degree during the total solar eclipse on 20 March 2015 (timeanddate.com). The positions of the receivers in Moscow (MOS), Graz, Austria (GRZ) and Sheffield, the UK (SHF) are shown by green circles. The positions of transmitters NRK (37,5 kHz) in Iceland, GQD (22,1 kHz) in the UK, ICV (20,27 kHz) in Sardinia, ITS (45,9 kHz) in Sicily, TBB (26,7 kHz) in Turkey, DHO (23,4 kHz) in Germany, FTA (20,9 kHz) and HWU (21,75 kHz) in France and NAA (24,0 kHz) in the USA are shown by red triangles. Four long paths which crossed the area of 90-100% of obscuration (NAA-MOS, NAA-SHF, NRK-SHF u NRK-GRZ), are shown by straight lines. The double vertical line shows the position of the morning terminator at the altitude of 100 km for 07:40 UT.*

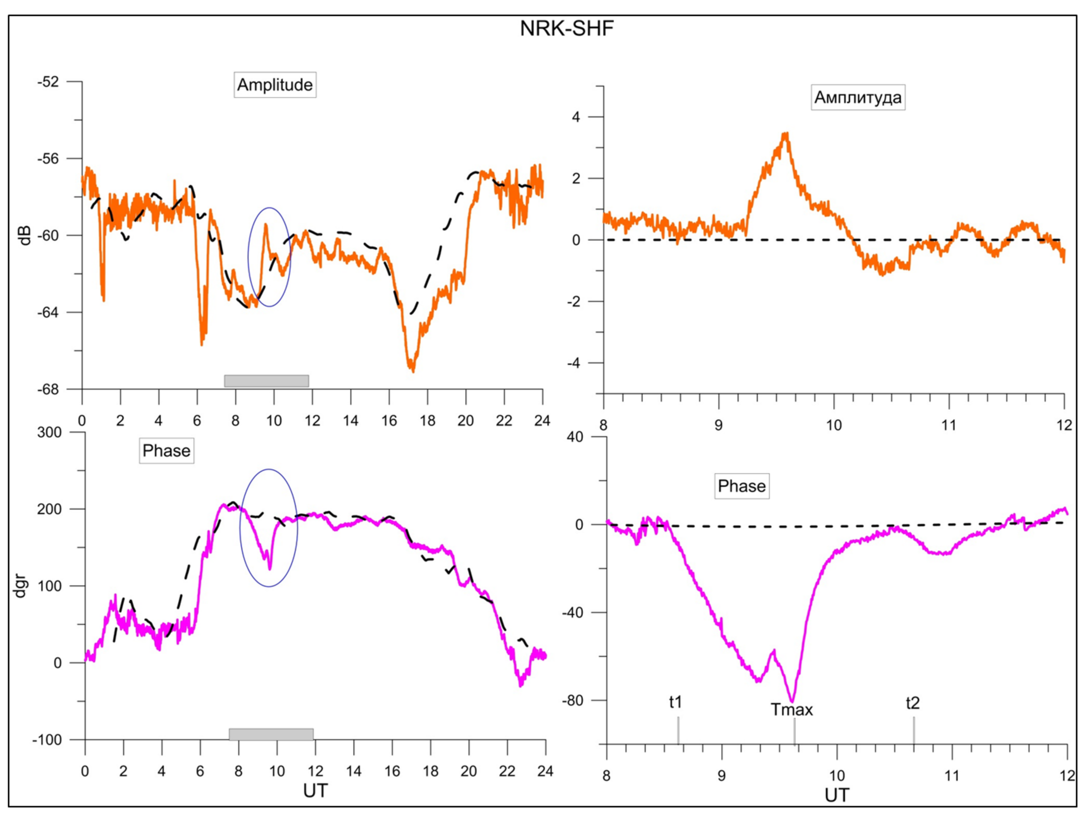

Fig. 7. *Amplitude (top panels) and phase (bottom panels) variations of NRK (37,5 kHz) signal recorded on 20 March 2015 at the Sheffield station. The current signal (solid line) together with monthly averaged signal (dotted line) are shown on the left. The left graphs show the signal variations during 24 hours, right graphs show the difference between real signal during the eclipse and monthly averaged signal. The period of obscuration are shown by the grey rectangles on X-axis. The ellipses indicate the amplitude and phase anomalies caused be the eclipse. t1 u t2 correspond to the times of the first and last contact in Reykjavik. (Iceland) where the transmitter is installed. Tmax indicates the time of the largest obscuration which was 97% in Reykjavik.*