Ground based measurements of ionospheric turbulence manifestations induced by the VLF transmitter

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ABSTRACT

The experimental results on the detection of artificial plasma modification produced in the ionosphere by the VLF transmitter are presented. The analysis of TEC variations and Ionosonde data was used for the diagnostics of ionospheric turbulence. The results of numerical simulation of the VLF wave propagation in the ionosphere were applied for selection of an appropriate GPS satellite beam that comes to the GPS receiver through the ionospheric region perturbed by the powerful VLF waves. Quite different TEC variations curve was observed for the control day when the transmitter was out of operation. Operation of the VLF transmitter resulted in the appearance of F-spread in Ionosonde data. The F-spread was consistently observed during VLF transmitter operation at a night.

1. INTRODUCTION

The strong fluctuations of numbers of surrounding plasma parameters were reported in DEMERER satellite studies when passing above the operating VLF stations at altitudes about 700 km [*Parrot, et al.*, 2007]. Particularly appreciable variations of electron density and quasi-static electric field (frequency range of 0–1 kHz) were detected when the satellite passed the center of the disturbed region over the VLF station situated near Nizhny Novgorod [*Rapoport*, et al., 2010]. The area of observed phenomena has the dimension of 400-500 km in diameter and has been shifted in the magnetic zenith direction. Some heuristic presupposition led us to believe that such manifestations of turbulence in the upper ionosphere can be detected by ground methods. That is why we have ~~conducted~~ a focused experiment in 2014 September.

2. EQUIPMENT AND DATA PROCESSING

The digital VLF receiver was located 18 kilometers to the North from the powerful transmitters for monitoring VLF signals round-the-clock in the range of 15 - 20 kHz and storing data on hard disk. The GPS receiver and the CADI Ionosonde were located 130 km eastward from the VLF transmitter. The Ionosonde operated in a 15 minute mode.

The numerical simulation of the VLF electromagnetic field spatial distribution in the topside ionosphere was used to select the satellite beams that come to the GPS signals receiver through the modified by powerful VLF transmitter region.

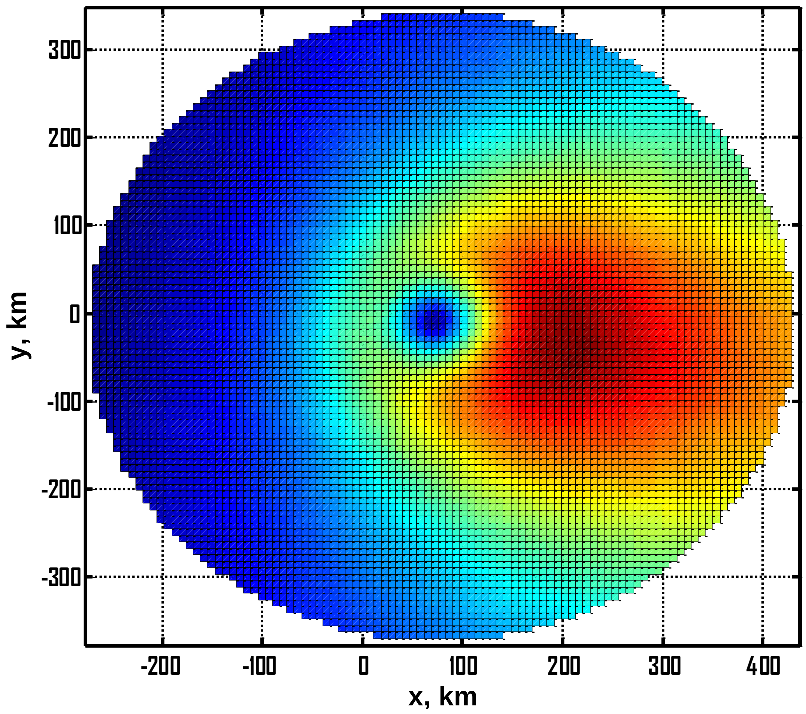

Fig. 1. VLF field amplitude distribution at the altitude of 500 km above the Earth's surface.

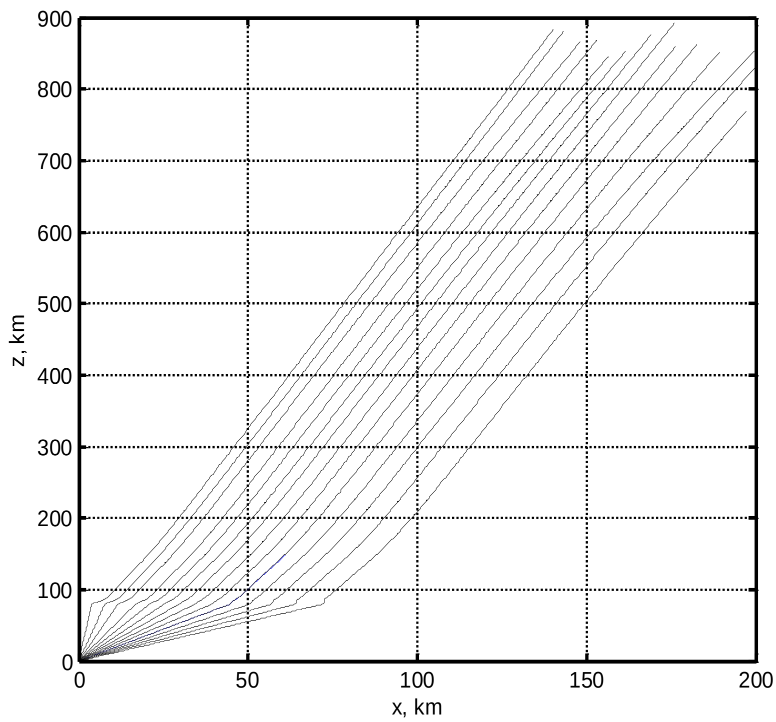

Fig. 2. Ray paths in the plane of the magnetic meridian for the 15 kHz frequency

The numerical simulation was performed using the ray-tracing approach; (see e.g. [*Kimura*, (1985)]). A model of the lower ionosphere boundary proposed in the paper [*Kotik*, et al. (1978)] was used. The detailed results of simulation will be published elsewhere.

Calculation of the ray trajectories and the electric field amplitude are made for the nighttime ionosphere in the IRI-2012 model. Numerical simulation of VLF waves in the ionosphere at middle latitudes showed that the maximum of the VLF field amplitude observed along the direction of Earth's magnetic field to the south of the transmitter.

Fig. 1 shows the VLF field amplitude distribution at the altitude of 500 km above the earth's surface and Fig. 2 shows beam trajectories in the magnetic meridian plane of the incident angles from 2° to 20° with respect to the vertical. It was assumed that the transmitter placed on the Earth's surface at the point with coordinates x = 0, y = 0. It can be seen that at altitudes above 200 km waves propagate almost along the lines of the geomagnetic field.

Fig. 3 shows the Earth projection of intersection traces of radio beams from GPS satellites and the ionosphere at 500 km altitude for the 2014-September-21. An asterisk denotes the location of the VLF transmitter, and a cross-point shows the GPS receiver and CADI Ionosonde position. The grid on Fig. 3 has 100 km step in both directions.

Isolines are made in standard colors and match the intensity of the VLF field with a minimum in the plane of the magnetic meridian at a distance of about 70 km and a maximum at a distance of about 240 km in the same direction. Thickening of the trajectories corresponding to the interval of the transmitter operation, the circles on the trajectories indicate the hour and ten minute time marks.

The data from GPS satellites were taken with 1 Hz frequency and stored at the laboratory server. The obtained time series of TEC variations were detrended using moving averaging with a 10-20-minute time window in order to remove variations with larger periods for further analysis.

The frequency analysis of TEC variations by the FFT method does not make sense since the time of GPS satellite flight is only 2-3 hours, which is comparable to periods of major variations. The most indicative method for analysis of such variations is Wavelet transformation. We have applied this method for analysis of the detrended TEC curve by obtaining so-called scalograms. A scalogram reflects the dependence of the energy distribution of the testing signal on the frequency and time. The horizontal axis shows the time and the vertical axis shows periods of TEC variations. The intensity is displayed by colors.

3. RESALTS OF THE EXPERIMENTS

We have selected several magnetically quiet days in 2014 September for the analysis. The date of 2014-09-21 was especially interesting. We observed a rather intensive VLF transmitter operation and the passing of four GPS satellites between 21:00 and 24:00 UT. Rays of two satellites (G7 and G8) crossed the region of interest southward of the station, and the other two (G9 and G13) passed this area on the periphery. Comparison of the TEC registrations on various trajectories shows the qualitative differences in their behaviors. The

TEC variations for G7 and G8 satellites were maximal during the passage of the impact area and reduced when withdrawn from it (see Fig. 4). At the same time the amplitude of TEC variation was only half for the peripheral G13 satellite. A quite different TEC variations curve was observed for the controlling day September 23 when the transmitter was out of operation (see Fig. 4). The amplitude of TEC variation was three times less compared to September 21. Another interesting passage was observed 09.29 when the track of the satellite crossed the center of the impact area. The TEC variation was characterized by growing of the small scale fluctuations as the satellite approached the center of the area.

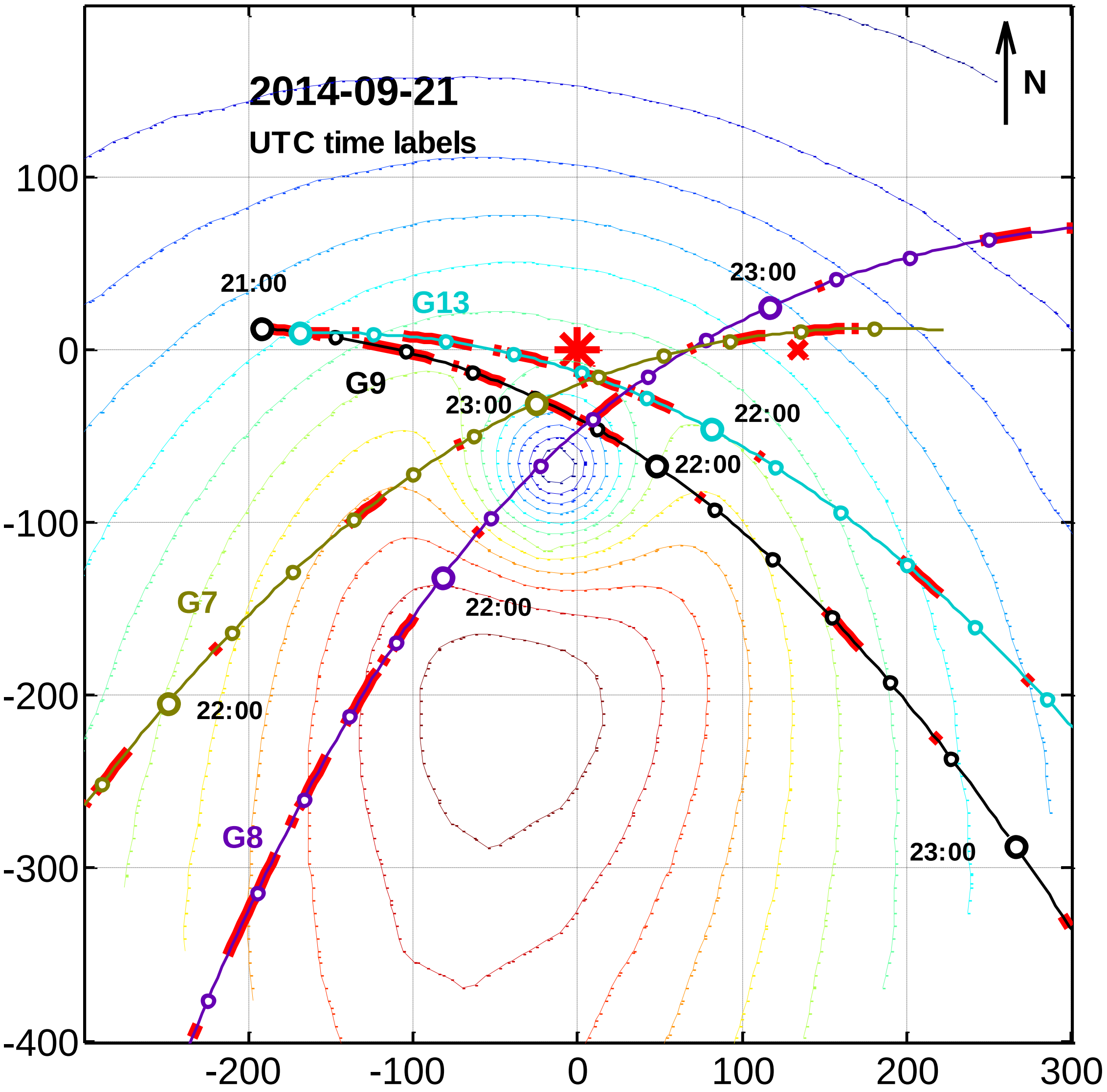

Fig. 3. Earth projection of intersection traces of radio beams from GPS satellites and the ionosphere at 500 km altitude for the 2014-September-21 (GPS satellites G7, G8, G9 and G13). Thickening (in red) of the trajectories corresponding to the intervals of the transmitter operation, the circles on the trajectories indicate the hour and ten minute time marks. Isolines are made match the intensity of the VLF field with a minimum to the south-west from the transmitter at a distance of about 70 km and a maximum at a distance of about 240 km in the same direction.

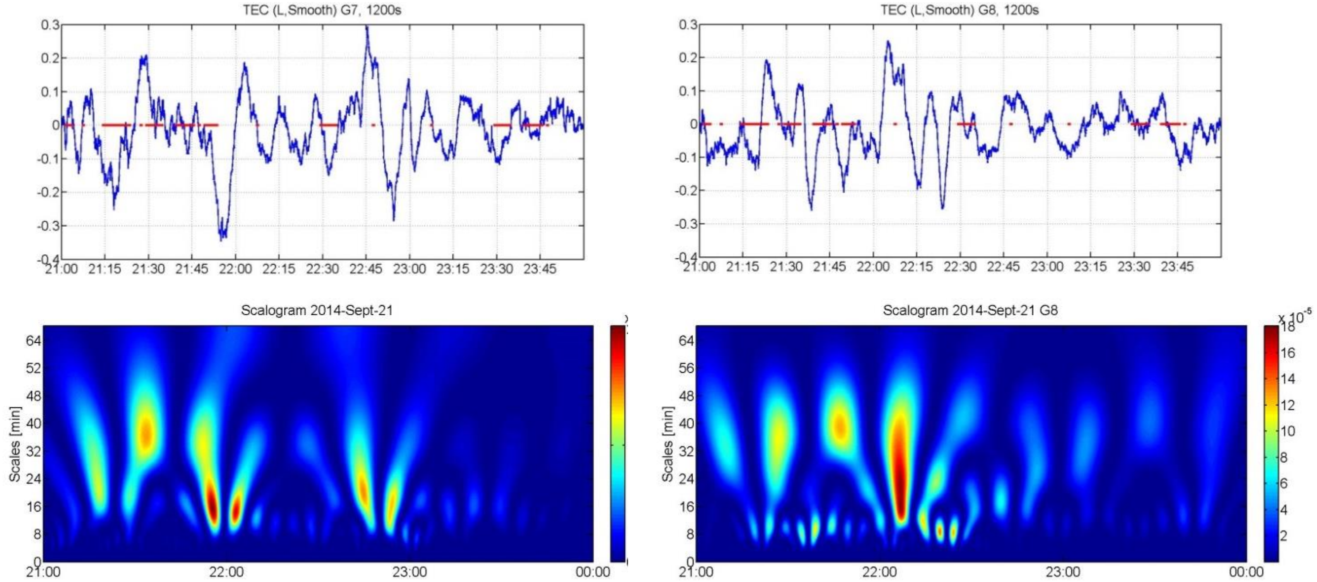

Fig. 4. TEC variations for G7 and G8 satellites (upper panel) and their scalograms (lower panel) for 2014-September-09 from 21:00 to 24:00 UT. Red lines on the upper panel denotes the time of VLF transmitter operation.

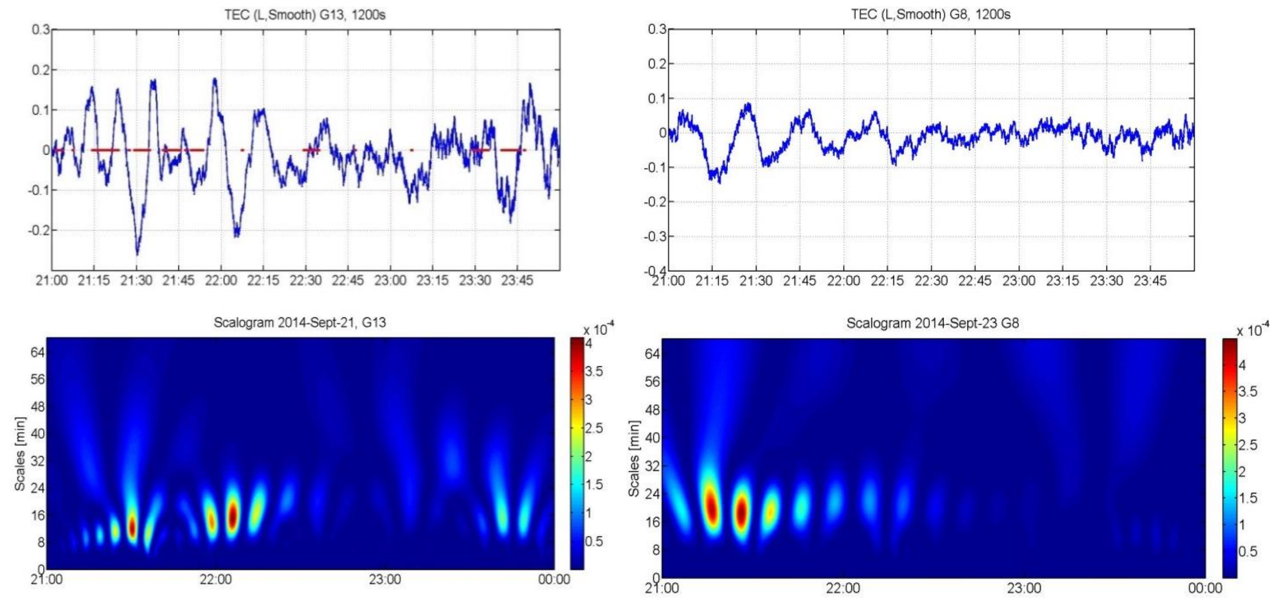

Fig. 5. TEC variations and scalogram for peripheral satellite G13 for 2014-September-21 (left panel) and the same for satellite G8 for 2014-September-23 (right panel) from 21:00 to 24:00 UT when the VLF transmitter was out of operation. Red lines on the upper panel denote the time of VLF transmitter operation

The ionograms from CADI Ionosonde shown that VLF transmitter operation during 30 minutes in the evening in 2014 September 29 led to the appearance of F-scattering in the ionosphere. F-spread was observed consistently during VLF transmitter operation at night (see Fig. 6). Pause in the transmitter operation up to 15 minutes did not affect the degree of F-scattering

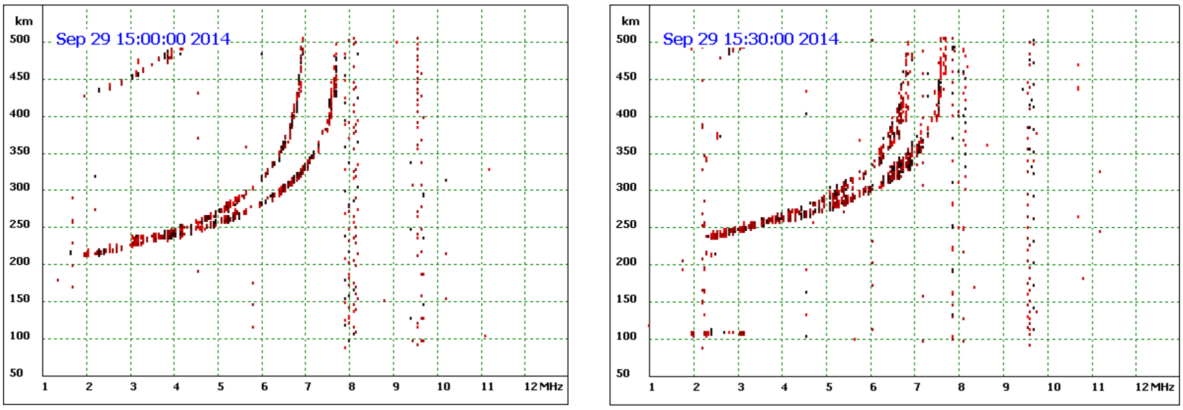

Fig. 6. The Ionograms from CADI Ionosonde on 2014 September 29. Left panel - 15:00 UT (corresponds to the start of VLF transmitter operation) and right panel - 15:30 UT (transmitter was switched off).

4. CONCLUSIONS

All TEC variation records obtained in our 2014 September experiment are characterized by increase of small-scale fluctuations as the GPS satellite approaches the center of the VLF radiation maximum domain in the topside ionosphere. Quite a different TEC variations curve was observed for the controlling day when the transmitter was out of operation with TEC variation amplitude three times smaller compared to September 21.

Wavelet scalograms were calculated for all TEC variation records (see Fig. 4 and 5). As one can see from Fig. 4 the most intense TEC variations and scalogram structure with 8-10 minute periods were observed for the G8 satellite of which the track was closest to the center of the impact area for time term 21:30-22:00. Similar structures for TEC scalograms were observed for others satellites on 2014-September-21.

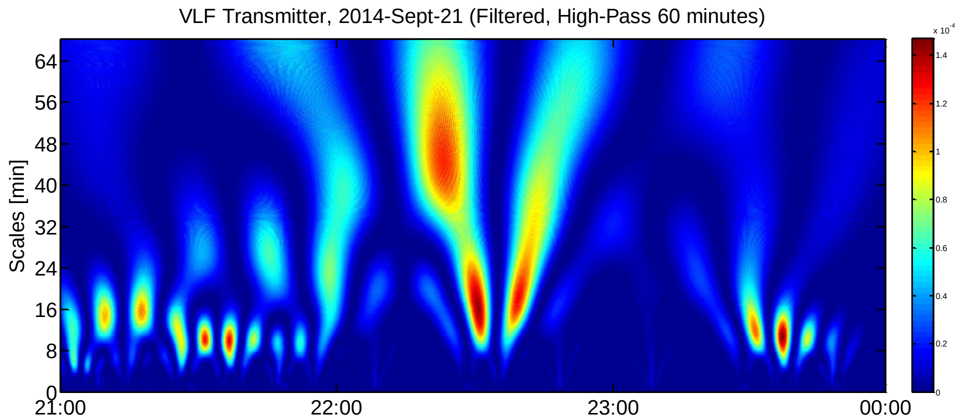

Fig. 6. The scalogram for the VLF transmitter operation time consequence of on 2014-September-21, (direct measurement).

The stored by VLF receiver the time consequence of VLF transmitter operation was underwent processing by wavelet transformation like TEC data. The result is shown in Fig.6. As one can see the structure with the same period of 8-10 minutes also was observed at the same time. Such coincidence is evidence of causality between two time series – transmitter timetable and TEC variations.

It should be noted that the scalogram structure with a period of about 18 minutes was observed for night 2014-September-23 (see Fig.4, right panel). In our opinion such an event can be caused by natural long periodic gravity wave in the topside ionosphere.

Another comment should be made about the F-scattering while the transmitter was in operation. Generally speaking F-spread is a characteristic of the night ionograms. Therefore, to analyze the effect of the VLF transmitter on the ionosphere the evening time was chosen when the attenuation of VLF waves in the lower ionosphere is already weak and the natural spread does not yet developed.

Our study shows the possibility of researching the topside ionospheric plasma modification by VLF transmitters by ground based methods. It is obvious that it is necessary to collect statistics and add to the experiment data on signal variations from low-orbit satellites.

ACKNOWLEDGEMENTS
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