ANALYSIS OF THE CONDITIONS FOR THE RADIO WAVES PROPAGATION IN THE WAVEGUIDE "EARTH-IONOSPHERE" ON THE PATHS "NOVOSIBIRSK-ULAN-UDE" AND "KOMSOMOLSK-ON-AMUR-ULAN-UDE" DURING MAGNETIC STORMS AUGUST 31-SEPTEMBER 12, 2017

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Abstract. In order to analyze the radio waves propagation conditions in non-uniform impedance channels, the amplitude and additional phase of the electromagnetic field of the VLF radio navigation system RSDN-20 were measured. The radio paths of latitudinal strike have been studied: path 1 "Novosibirsk - Ulan-Ude ", the length is 1580 km; path 2 "Komsomolsk-on-Amur - Ulan-Ude", the length is 2080 km. The daily variations of the amplitude and the additional phase of the 11.9 and 14.88 kHz radio signals are considered.

1 INTRODUCTION

The results of studies of the propagation of VLF radio waves indicate a significant change in the amplitude-phase characteristics of signals during X-ray solar flares. In [1-3], changes in the parameters of the D region during an X-class flare on September 6, 2017 are analyzed. The main factor influencing the parameters of the VLF signal in the "Earth-ionosphere" waveguide is an increase in the electron density in the lower layers of the ionosphere and the related change in the geometry of the waveguide. The results of the studies show that under strong heliogeophysical perturbations, including X-ray flares, the ionization of the D region can increase substantially, reaching values of 10^{6} $cm^{-3.}$ The purpose of the article is to analyze the conditions for the propagation of VLF waves in the "Earth-ionosphere" waveguide on the paths No. 1 "Novosibirsk-Ulan-Ude" and No. 2 "Komsomolsk-on-Amur-Ulan-Ude" during magnetic storms August 31- September 12 2017 and X-ray solar flare X class on September 6, 2017**.**

2 EXPERIMENT

The digital measuring system has a reference frequency standard based on the Trimble

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Thunderbolt-B GPS receiver with a daily frequency instability of 10^{-12}. In [4], the results of measurements of the amplitude and the additional phase of the VLF electromagnetic field of the pulsed-phase radio navigation system RSDN-20 on two radiopath of latitudinal strike are analyzed: path No 1 "Novosibirsk-Ulan-Ude", length - 1580 km; path No 2 "Komsomolsk-on-Amur - Ulan-Ude", length - 2080 km. Figures 1 and 2 show the diurnal variations of the amplitude and the additional phase of the radio signals 11.9 and 14.88 kHz from August 31 to September 12, 2017 on the paths No. 1 and No. 2. The top panel of Figure 1 shows the geomagnetic situation on the Earth (Kp - index), which at that time was very complicated. August 31, 2, 5, 8 and 9 September 2017 marked the magnetic storms, reaching 8 and 9 September the level of very strong storms, when Kp - index increased to 8 units out of 9 possible. An X-ray solar flare of the X class took place on September 6, 2017 [1-3]. On other days of the first decade of September, both an excited magnetosphere and magnetic storms with Kp = 5 were often observed. Figure 1 shows the diurnal variations of the amplitude and the additional phase of the signal at a frequency of 11.9 kHz on the paths No. 1 and No. 2, when in the middle latitudes the day is approximately 1-1.5 hours longer than the night. The eastern path No. 2 is longer than the western path No. 1 by 500 km, so the signal level is almost always lower. In ordinary geomagnetic conditions, the day and night levels of the amplitude and phase of the radio signal are clearly separated. The daily level of the signal amplitude in the first half of September on path No. 2 is stable, on average from 0.1 to 0.13 relative units (hereinafter referred to as r.u.). At night, the signal is on average 1.5 to 2 times higher and varies from 0.15 to 0.24 r.u.. The displacement of the terminator lines on the eastern and western paths is approximately 1-2 hours. The additional phase φ also has regular daily variations up to 120 °. Significant differences on the paths No. 1 and No. 2 are observed in the signal amplitude level during magnetic storms. On September 5, 8, 9 and 10, on path 1, the nighttime levels are significantly below daytime, the amplitude decreases to 6 times. This phenomenon was noted for the first time in the observation period from 2013. The phase of the signal behaves also anomalously, often there is a "bounce" and even a phase failure. The levels of the received signal in the daytime naturally and smoothly change with a maximum at noon time, at night the amplitude is generally higher than in the daytime, but it is subject to rapid and deep fluctuations.

Figure 2 shows the diurnal variations of the amplitude and the additional phase of the signal at a frequency of 14.88 kHz of the radio transmitters RSDN-20 on the same paths. The levels of the received signal in the daytime also naturally and smoothly change with a maximum at noon time, at night the amplitude is 2-2.5 times higher than in the daytime. It is subject to rapid and deep fluctuations, as well as at a frequency of 11.9 kHz. The additional phase of the day gradually decreases from 150 ° to 100 °, and at night it increases to 300 ° - 340 °. With strong night variations of the signal amplitude (from 0.3 to 0.71 r.u.), the additional phase φ does not change significantly. On path No. 2 on the same days, the amplitude of the signal did not decrease significantly, but even increased 9, 10 and 11 September. The additional phase retained its regular daily course - maxima to 400 ° - at night and minima at 270 ° - 280 ° - during the day. Consequently, there are significant differences in spatial amplitude-phase phenomena in ordinary and anomalous geomagnetic conditions at frequencies of 11.9 and 14.88 kHz when propagation of VLF waves on the spatially separated latitudinal paths. They consist in a significant reduction in the signal level at a frequency of 11.9 kHz during a very strong magnetic storm. At a frequency of 14.88 kHz, similar phenomena are also noted, but they are less pronounced. Thus, the amplitude of the signal at night decreased not very noticeably on path No. 1 at night 5-6 and September 8-9. On the path No. 2, the signal level as a whole is always lower than on path No. 1. At the same time, the level drops at night are distinctly expressed only on 9 and

10 September. The additional phase φ has regular daily variations on the path No. 1 in the range from 420 ° to 460 °. Day and night average levels of phase φ are surely divided. For daytime conditions, φ = 420 °, for night conditions, φ = 460 °. On the graphs of Figure 2, when entering and rising the Sun, the regions of short-term loss of phase single-valuedness ("phase loss") are visible. They are probably connected with sharp changes in the level of the field during the passage of the terminator line, and also because of the influence of chaotic impulse noise of natural or technogenic origin. On the path No. 2, the diurnal course of the phase is expressed by a less stable course with frequent loss of its regularity.

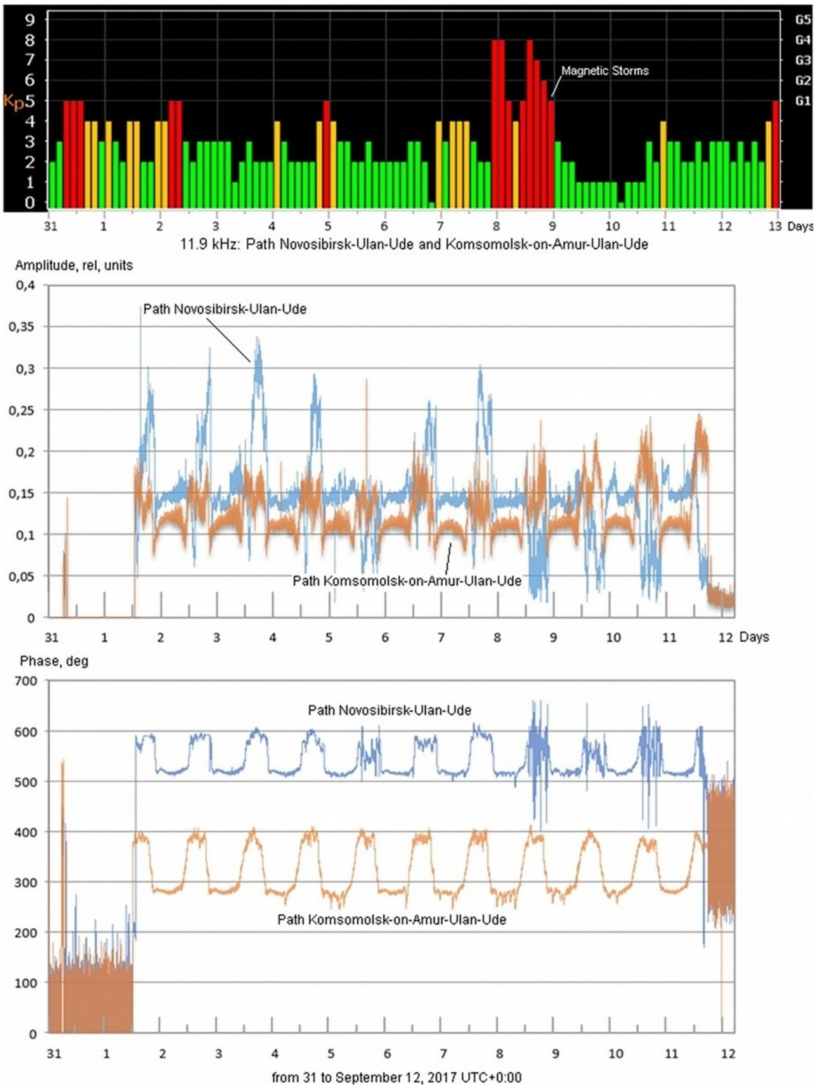

Figure 1. Daily variations of the amplitude and the additional phase φ of the radio signals RSDN-20 on the paths No. 1 Novosibirsk-Ulan-Ude and No. 2 Komsomolsk-on-Amur-Ulan-Ude at a frequency of 11.9 kHz. The top panel shows the geomagnetic situation for the period from August 31 to September 12, 2017.

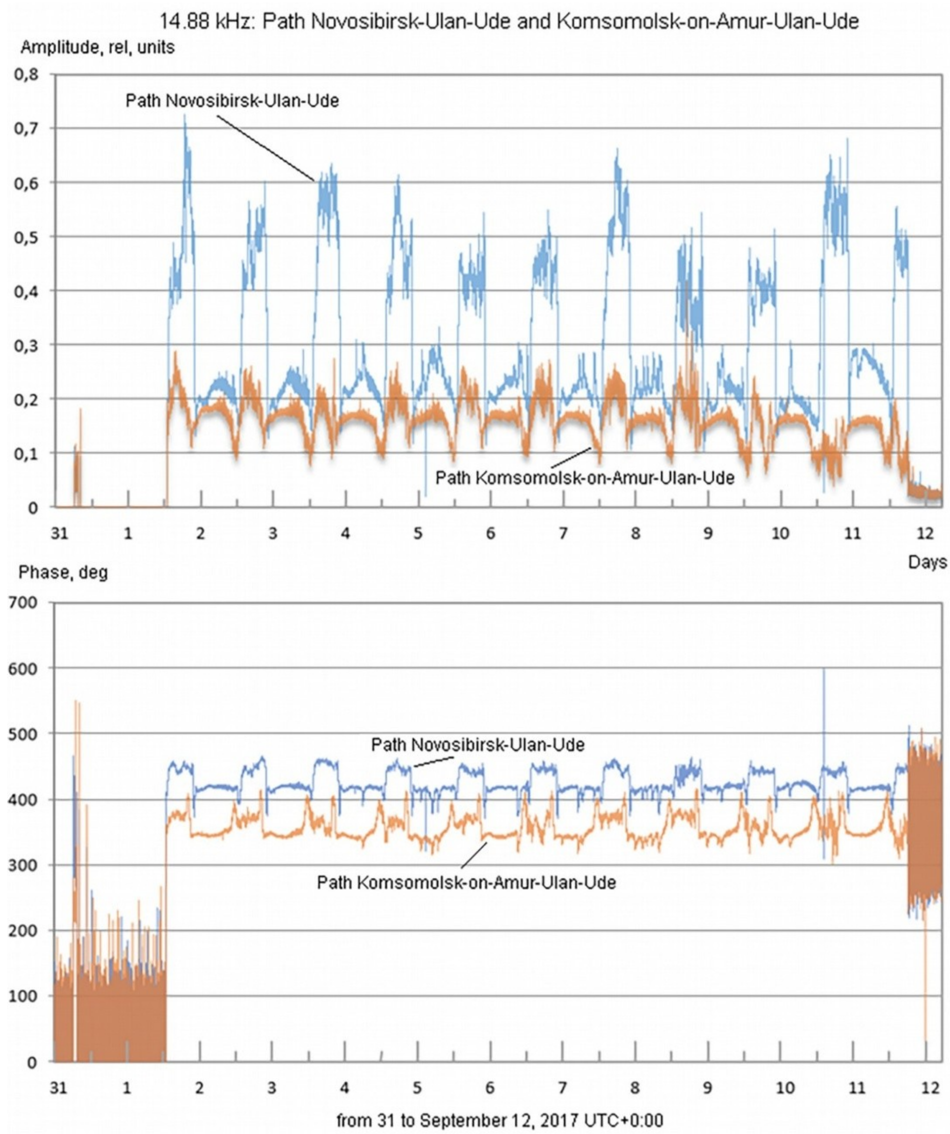

Figure 2. Daily variations of the amplitude and the additional phase of the radio signals RSDN-20 on the paths Novosibirsk-Ulan-Ude and Komsomolsk-on-Amur-Ulan-Ude at a frequency of 14.88 kHz.

3 DISCUSSION OF RESULTS

In more detail, the amplitude variation of the signals on paths No. 1 and No. 2 is traced in Figures 3 and 4. In these figures, the daily variations of the median amplitude of the RSDN-20 radio signals on the paths No. 1 and No. 2 at the frequencies 11.9 and 14.88 kHz were obtained after decimation and passing the array of measurements through the Savitsky-Golay digital smoothing polynomial filter (MATLAB program). This filter is optimal in the sense that it minimizes errors by the method of least squares by approximating "noisy" data with polynomial windows. The Savitsky-Golay filter works much better than standard FIR filters, which tend to filter out a significant part of the high-frequency "noisy" signal. Figure 3 clearly shows an abnormally large decrease in the amplitude of the signal at 11.9 kHz at night 5, 8, 9, 10 and even September 11. At the same time, signal amplitude growth was noted on 9, 10 and 11 September on path No. 2. At the frequency of 14.88 kHz (Figure 4), similar phenomena in the signal level were also noted, but they are less pronounced. At this frequency, the signal amplitude decreases at night on path No. 1 of 5-6 and September 8-9. On the path No.2, the signal level as a whole is always lower than on path No. 1. At the same time, the level drops at night are clearly expressed only on September 10 and 11.

4 CONCLUSION

Significant differences in the spatial amplitude-phase phenomena in the ordinary and anomalous geomagnetic conditions at frequencies of 11.9 and 14.88 kHz are established in the propagation of VLF waves on the spatially separated latitudinal paths. They consist in a significant reduction in the signal level at a frequency of 11.9 kHz during a very strong magnetic storm. At a frequency of 14.88 kHz, similar phenomena are also noted, but they are less pronounced. Analysis of diurnal variations of the median amplitude of 11.9 and 14.88 kHz radio signals on the paths No. 1 and No. 2 obtained after decimation and transmission of the array of measurements through the Savitsky-Golay digital smoothing filter (MATLAB program) confirmed these significant differences in the spatial amplitude-phase phenomena in the ordinary and anomalous geomagnetic conditions..

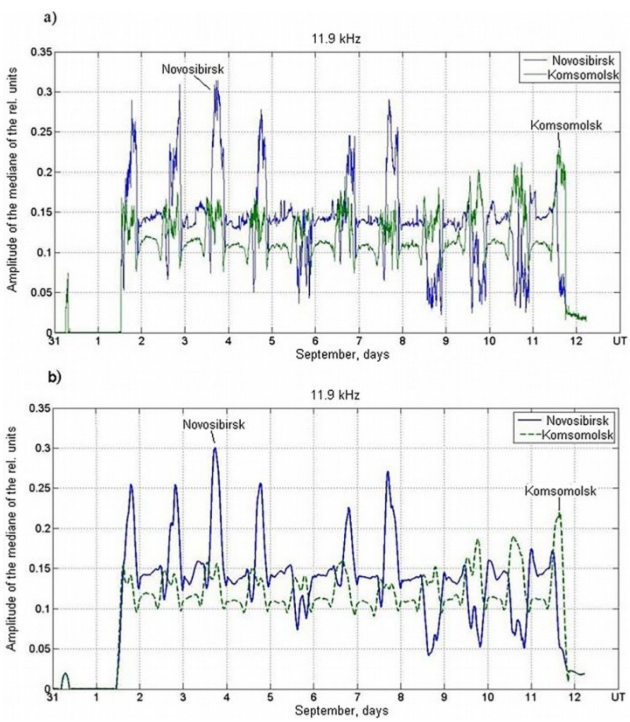

Figure 3. Daily variation of the median amplitude of radio signals RSDN-20 on the routes Novosibirsk-Ulan-Ude and Komsomolsk-on-Amur-Ulan-Ude at a frequency of 11.9 kHz.

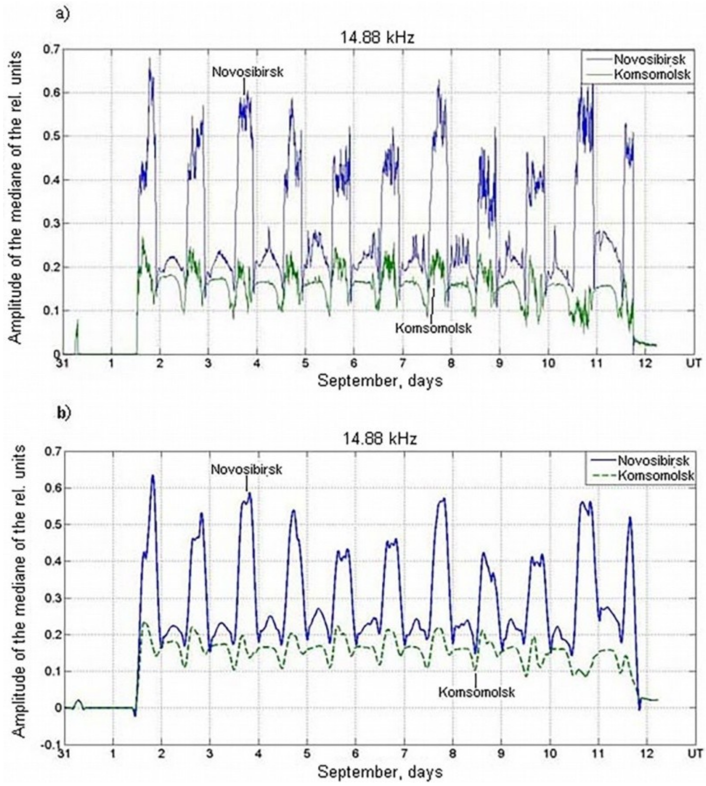

Figure 4. Daily variations of the median amplitude of radio signals RSDN-20 on the routes Novosibirsk-Ulan-Ude and Komsomolsk-on-Amur-Ulan-Ude at a frequency of 14.88 kHz.

ACKNOWLEDGMENTS

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