SOLAR X-RAY FLARES INFLUENCE ON VLF/LF SIGNALS IN DIFFERENT MIDDLE-LATITUDES PATHS

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Abstract. Sudden Phase Anomalies (SPAs) of VLF/LF signals recorded in Graz (Austria), Sheffield (UK) and Moscow (Russia) stations during two solar flares of intensity class X1.0 and M3.8 in November 2013 are examined. Data from seven transmitters in frequency range from about 20 to 45 kHz are used for the analysis. SPAs were observed in middle-latitudes paths with length from 200 to 7000 km and different orientation. Solar X-ray burst data were taken from the satellite GOES observations in the band of 0.1-0.8 nm. SPA characteristics like types, onset times, growth times, duration of SPA events and their amplitudes are studied. Observed SPAs are positive in 24 cases and they are negative in 2 cases regardless of the length or orientation of paths or signal frequency. The amplitude of SPAs in different paths varies from 10 to 230 degrees and no clear correlation between amplitude of SPAs and intensity of the solar flares or length of the paths are found. The SPAs begin within 3 and 4 minutes after the start of the first and second flare events, respectively. The time of growth for the first event is from 4 to 23 minutes and for the second event it is only 2-5 minutes. The duration is longer for the first event (~1h20 min-2 h) and it is shorter for the weaker flare (~30 min-1h30min).

Introduction

During the most solar X-ray flares the electron density is greatly enhanced and ionization is usually produced below the normal D-region (e.g. Chilton et al., 1963), so this region responds dramatically. To study of the D region behavior the Very Low and Low Frequency (VLF/LF) wave measurements are used because these waves are reflected by the D region, and the received signals inherently contain information of the reflection height of the region and its variability. This is a great advantage, as these heights are too high to study them by using balloons, and too low for in-situ measurements of satellites. Moreover, measurements with the use of rockets are very transient and spatially limited. Since Kreplin et al. (1962) have reported the relationship between flare time X-ray bursts and Sudden Phase Anomalies (SPAs), numerous works have been published on the study of flare characteristics and SPA phenomenology (e.g. Mitra, 1974; Muraoka, 1977; Kamada, 1985; Khan et al., 2005). Thomson et al. (2005) modeled the D region electron densities as functions of X-ray flux up to the level of the great X45 flare. During this great flare, they found that the reflecting height was about 17 km below the normal midday level (about 70 km).

In present work we investigate SPA characteristics from VLF/LF signals recorded in three European middle latitude VLF stations during two solar flares of intensity class X1.0 and M3.8 in November 2013.

Used data

Data from the receiving stations in Graz (Austria), Sheffield (UK) and Moscow (Russia) were used for the analysis. The stations are equipment with UltraMSK receivers which can record simultaneously both the amplitude and phase of MSK (Minimum Shift Key) modulated signals in frequency range 10-50 kHz from several navigational or time service VLF/LF transmitters. MSK signals have fixed frequencies in narrow band 50-100 Hz around the main frequency and adequate phase stability. The receivers provide measurements with time resolutions ranging from 50 msec to 60 sec. For our purpose we used sampling frequency of 20 sec. In every station the amplitude and phase of VLF/LF signals from seven transmitters were considered. The relative locations of the transmitters and our observing stations are plotted in Figure 1. The length of sub-ionosperic wave paths ranged from about 200 to near 7000 km and their orientation was different.

Solar X-ray burst data were taken from the satellite GOES-15 observations in the band of 0.1-0.8 nm (long) with time resolution of 1 min (http://www.swpc.noaa.gov/ftpmenu/lists/xray.html).

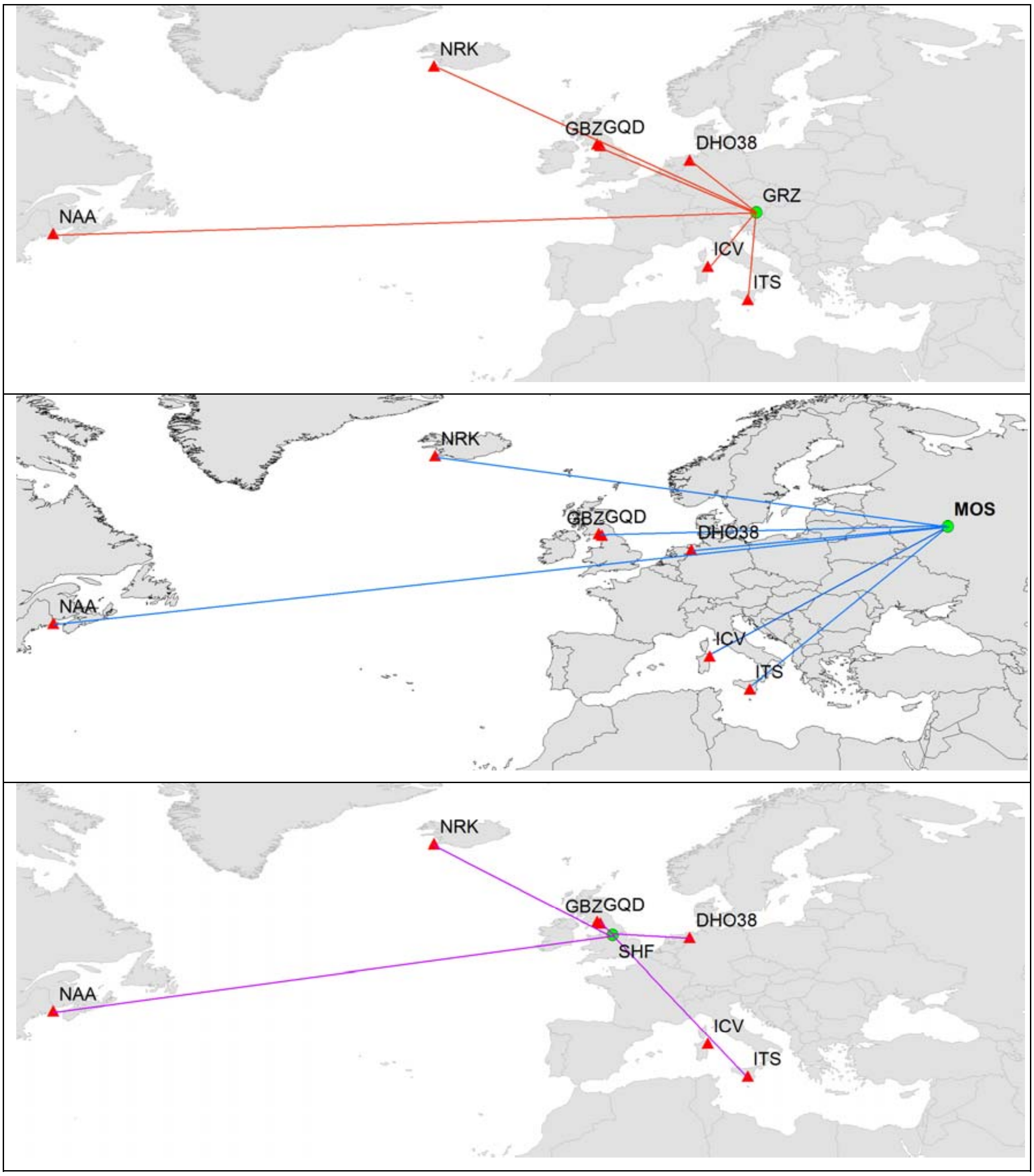

Figure 1. Positions of the receivers (green circles) in Graz (GRZ), Moscow (MOS) and Sheffield (SHF) (from top to bottom) together with the positions of the transmitters (red triangles) NAA (24.0 kHz), NRK (37.5 kHz), DHO (23.4 kHz), ICV (20.29 kHz), ITS (45.9 kHz), GBZ (19.58 kHz) and GQD (22.1 kHz).

Results

We studied SPA's characteristics like types, onset times, growth times, duration of SPA events and their amplitudes during solar X-ray flares – on November 19, 2013 (class X1.0) and November 6, 2013 (class M3.8).

A typical SPA is characterized by a sudden advance of phase followed by a rounded maximum and generally an exponential decay or a recovery phase. Typical SPAs in the NRK signal are shown in Figure 2 during X-ray burst on November 6, 2013. The character of phase and amplitude anomalies is practically identical in the all three stations. Sometimes SPAs have gradual onset (example see in Figure 3). The data from Moscow station are rather noisy because of the station location in the center of megalopolis. Unlike Graz and Sheffield, no noticeable effect is seen in the amplitude of the signal in Moscow.

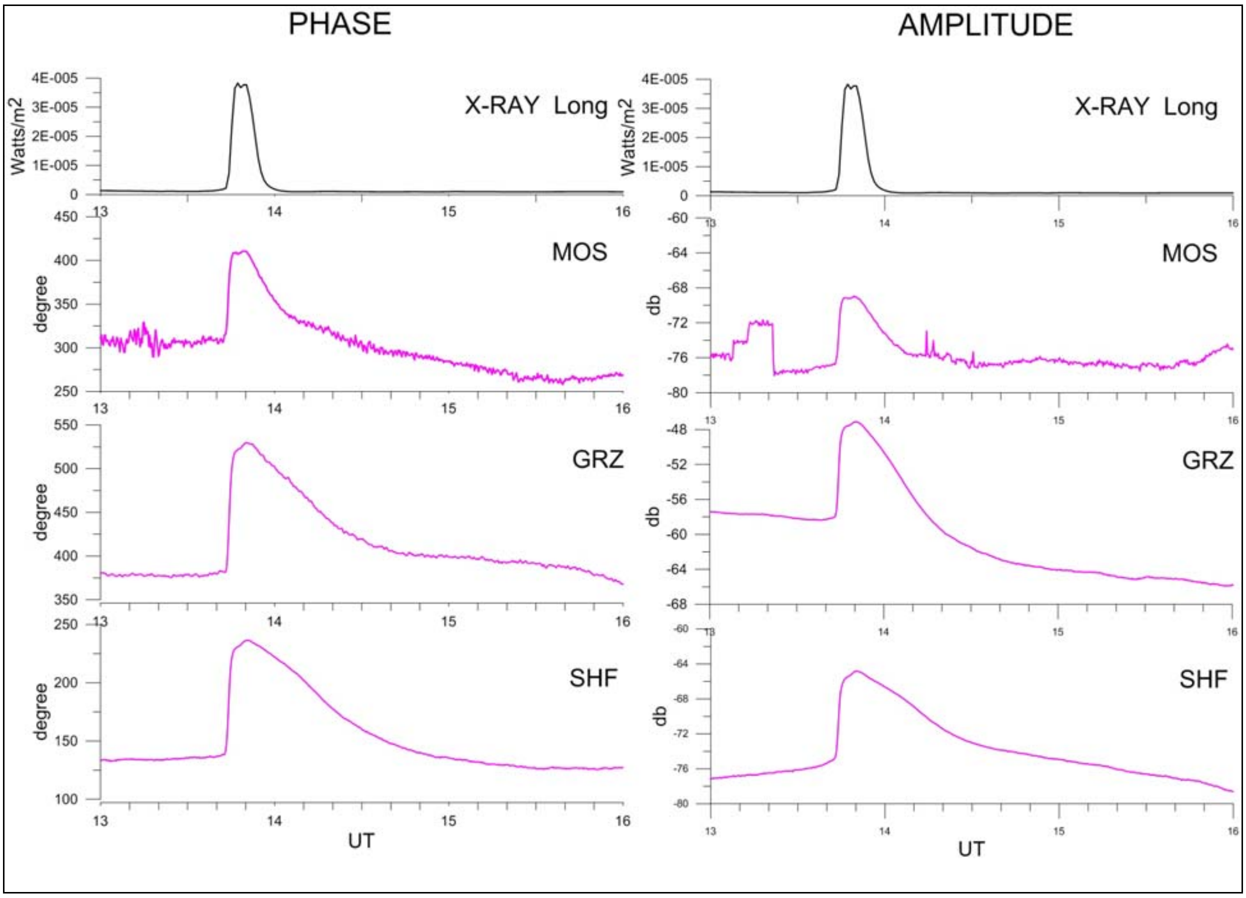

Figure 2. SPAs recorded in the NRK signal at Moscow, Graz and Sheffield receiving stations during X-Ray burst on November 6, 2013. Top panel shows X-ray observed in the GOES satellite.

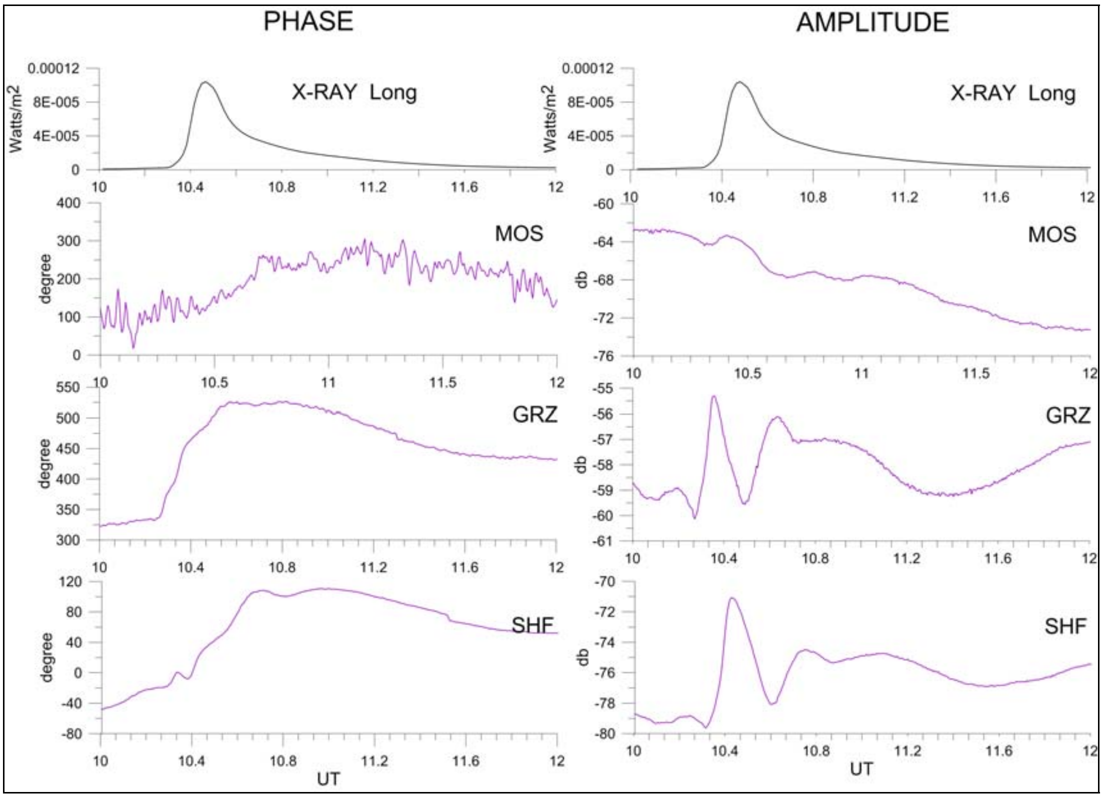

Figure 3. SPAs recorded in the NAA signal at Moscow, Graz and Sheffield receiving stations during X-Ray burst on November 19, 2013.

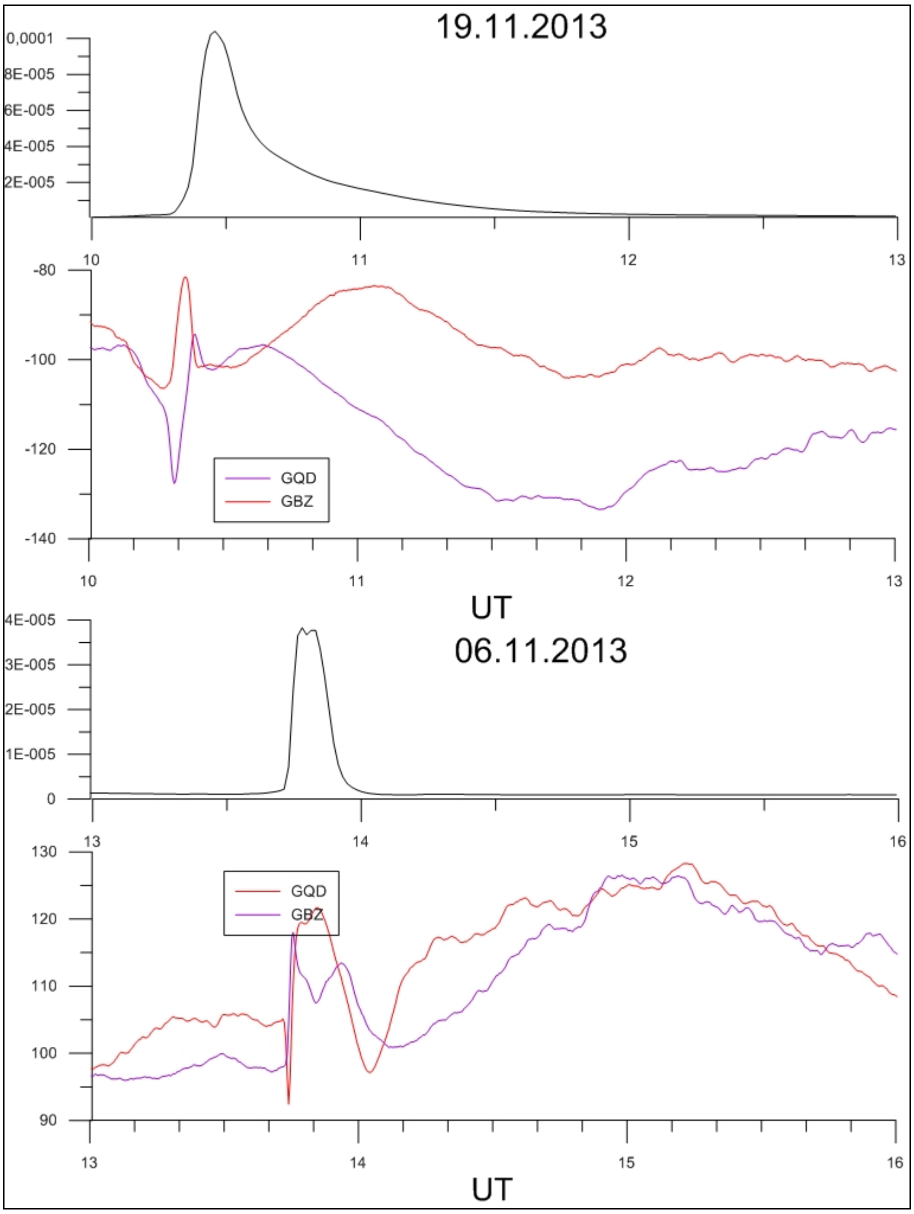

Figure 4. SPAs recorded in the phase of the GQD and CBZ signals at Sheffield receiving stations during X-ray burst on November 19 (top panel) and November 6, 2013 (bottom panel).

Infrequently, events have either a complex onset or complex phase variation (Figure 4). In the Figure the signals from the two nearest transmitters-GBZ and GQD are shown for the two X-ray flares recorded at the Sheffield station. It is the most interesting result. The distance between the transmitters and the receiver is about 200 km and VLF wave's propagation has multi-mode type, unlike all the other paths where the propagation is one-mode. All the previous investigations of SPAs (including mentioned above) were made for very long paths.

The classification of events as simple (S), gradual (G) and complex (C) types of SPAs was made by Kamada (1985). The majority of the SPAs we observed for both flares were of S type. This is in conformity with Khan et al. (2005) while Kamada (1985) reported that he mainly identified G type of anomalies.

The SPAs show varied temporal development. The onset time is generally defined as time difference between beginning of the flare and start of SPA. SPAs in all the paths for the x-ray flare on November 19 (class X1.0) began within three minutes of the start of the flare event, and for the x-ray flare on November 6 (less intensive) the onset time was four minutes. This is in good agreement with Deshpande et al. (1972) who found a delay of 3–4 minutes between beginnings of X-ray and SPA events.

Table 1. SPAs in the VLF/LF signals on November 19, 2013 (class X1.0, active region 1893, X-Ray 0.1-0.8, Amax=0.000104 Watts/m^2, Tstart=10:14, Δt=8 min)

Path	Power, kW	Frequency, kHz	Length, km	Orien-tation	Sign of SPA*	Type**	Amax, degree	Tstart	Growth, min	Dura-tion
NAA-GRZ	1000	24.0	6000	W-E	+	G	200	10:17	23	1:43
NAA-SHF	1000	24.0	4700	W-E	+	G	100	10:17	23	1:43
NRK-GRZ	100	37.5	3000	N-S	+	S	233	10:17	9	1:53
NRK-SHF	100	37.5	1700	N-S	+	S	110	10:17	9	1:53
ITS-GRZ	unknown	45.9	1100	S-N	+	S	75	10:17	9	2:03
ITS-SHF	unknown	45.9	2200	S-N	+	S	73	10:17	9	2:03
GBZ-GRZ-	30	19.58	1500	N-S	+	S	23	10:17	4	1:43
GBZ-SHF	30	19.58	200	N-S	-	C	30	10:17	3	1:43
GQD-SHF	60	22.1	200	N-S	+	C	19	10:17	4	1:43
ICV-GRZ	unknown	20.27	850	S-N	+	S	12	10:17	10	1:13
DHO-GRZ	800	23.4	900	N-S	+	S	100	10:17	4	2:30
DHO-SHF	800	23.4	600	E-W	+	S	125	10:17	20	1:23

* Sign is +, if SPA and X-Ray curves have the same direction, and sign is -, if SPA has downward direction
** S-simple, G-gradual, C-complex

Table 2. SPAs in the VLF/LF signals on November 6, 2013 (class M3.8, active region 1890, X-Ray 0.1-0.8nm, Amax=0.0000383 Watts/m^2, Tstart=13:39, Δt=7 min)

Path	Frequency, kHz	Length, km	Orienta-tion	Sign of SPA*	Type**	Amax, degree	Tstart	Growth, min	Duration, min
NAA-MOS	24.0	7000	W-E	+	S	100	13:43	3	1:30
NAA-GRZ	24.0	6000	W-E	+	S	185	13:43	3	1:30
NAA-SHF	24.0	4700	W-E	+	S	134	13:43	3	1:30
NRK-MOS	37.5	3500	W-E	+	S	125	13:43	3	40
NRK-GRZ	37.5	3000	N-S	+	S	150	13:43	4	40
NRK-SHF	37.5	1700	N-S	+	S	110	13:43	5	40
GBZ-MOS	19.58	2500	W-E	+	S	25	13:43	3	25
GBZ-GRZ-	19.58	1500	N-S	+	S	50	13:43	3	55
GBZ-SHF	19.58	200	N-S	+	C	15	13:43	3	50
DHO-MOS	23.4	2000	W-E	+	S	80	13:43	3	30
DHO-GRZ	23.4	900	N-S	+	S	200	13:43	3	35
DHO-SHF	23.4	600	E-W	+	S	75	13:43	3	40
GQD-MOS	22.1	2500	W-E	-	C	10	13:43	2	30
GQD-SHF	22.1	200	N-S	+	C	20	13:43	2	30

The time taken from the beginning of the event to reach the maximum is normally denoted as the time of growth of SPA. The time of growth for the first event (X1.0) was from 4 to 23 minutes and for the second event (M3.8) it was only 2-5 minutes. This does not contradict to Deshpande et al. (1972) who reported the average times of growth of 10 minutes for SPAs.

The duration of SPA event, i.e., the time from the beginning of the event to recovery normally varies from 30 minutes to 2–3 hours (Chilton et al., 1963). In the present investigation, the duration was found to be longer for the first event (~1h20 min-2 h) and it is shorter for the weaker flare (~30 min-1h30min). As it can be seen in the typical SPA records shown in Figure 2, the recovery part of the phase anomaly is very nearly exponential in conformity with earlier observations (e.g. Chilton et al., 1964).

All SPAs characteristics together with the information about the X-ray flares and wave paths under investigation are presented in Table 1 (for the event on November 19) and Table 2 (for the event on November 6).

Conclusion

In this study we investigated SPAs in VLF/LF signals propagating in the middle latitude paths during two solar flares of intensity class X1.0 and M3.8 in November 2013. On the whole analysis was made for 17 paths with length from 200 to 7000 km and different orientation. We have found that the observed SPAs were positive in 24 cases and they were negative in 2 cases regardless of the length or orientation of paths or signal frequency. The amplitude of SPAs in different paths varies from 10 to 230 degrees and no clear correlation between amplitude of SPAs and intensity of the solar flares, transmitter power or length of the paths were found. The SPAs began within 3 and 4 minutes after the start of the first and second flare events, respectively. The time of growth for the first event was from 4 to 23 minutes and for the second r event it was only 2-5 minutes. The duration was longer for the first event (~1h20 min-2 h) and it was shorter for the weaker flare (~30 min-1h30min).

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