Publ. Astron. Obs. Belgrade No. 104 (2024), 105 - 112 *Invited Lecture*
https://doi.org/10.69646/aob104p105

REDUCTION OF THE VLF SIGNAL NOISE AS POTENTIAL EARTHQUAKE PRECURSOR: PILOT STUDIES

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Abstract. Studies of pre-earthquake disturbances in the ionosphere since the middle of the last century point to several types of potential precursors to these natural events. A large number of them are detected as disturbances in the Global navigation satellite system (GNSS) and very low / low frequency (VLF/LF) signals a few days before the earthquake. However, the analysis of the VLF signal emitted in Italy and received in Belgrade in the period around the earthquake in Kraljevo that occurred on 3 November, 2010 indicates a potentially new type of these precursors. It is visible as a reduction of the VLF signal noise which starts several minutes or several tens of minutes before earthquake. In addition, Fourier transform of the recorded data indicates wave excitations at discrete waveperiods under 1.5 s, and wave attenuations at other waveperiods. In this paper, pilot studies of the noise reduction of the amplitude and phase of the mentioned VLF signal in both time and frequency domains are presented. The data recorded by the Absolute Phase and Amplitude Logger (AbsPAL) receiver located at the Institute of Physics Belgrade on November 3, 4 and 9, 2010, and during the period of intense seismic activity when almost 1000 earthquakes occurred in Central Italy from October 25 to November 3, 2016, are analyzed. The obtained results indicate possible differences in the signal noise reduction in cases when the observed earthquake follow and not follow previous earthquakes in approximately the same area. Namely, in the first case, the signal noise reduction may already be present so that no new reductions occur before subsequent earthquakes. On the analyzed sample of 35 earthquakes of minimum magnitude 4, the signal noise is reduced in over 90% of cases. In the remaining three cases, it cannot be clearly concluded whether this reduction exists due to its reduced value over a longer time period, which can be explained by the intense seismic activity in that period.

1. INTRODUCTION

Investigations of natural disasters are one of the most striking examples of the importance of scientific studies. This primarily refers to efforts to find changes that can be considered as their precursors.

One of the natural phenomena that causes the greatest consequences for human lives and the environment in which they occur are earthquakes. There are various methods used to study the earthquakes, and attempts to establish their precursors. One of these methods is based on the analysis of very low/low frequency (VLF/LF) radio signals used to monitor the low ionosphere (Biagi et al. 2006, 2011, Hayakawa et al. 2010, Maurya et al. 2016, Molchanov et al. 1998, 2001, Nina et al. 2020, Ohya et al. 2018, Yamauchi, 2004, Yamauchi et al. 2004). The analyses of these signals are based on the processing of their amplitudes and phases in the time and frequency

domains. Changes that are considered in the time domain as potential precursors of earthquakes are manifested in variations of signal parameter values and their noise before the earthquake, as well as, the changes in solar terminator times a few days earlier. In the frequency domain, wave excitations and attenuations are observed, which are obtained by applying a wavelet transform or the Fast Fourier Transform to the sets of recorded data relevant to both signal parameters.

This paper presents pioneering studies of new potential earthquake precursors that were first observed in the analysis of data recorded by the Absolute Phase and Amplitude Logger (AbsPAL) receiver located at the Institute of Physics Belgrade in Serbia about the period around the earthquake near Kraljevo, Serbia, which occurred on November 3, 2010. This investigation is present in Nina et al. 2020, Nina et al. 2021, and Nina et al. 2022. Although the earthquake was not very strong, it was the strongest earthquake that occurred in Serbia during the period of operation of the Belgrade VLF/LF receiving station. It was the motivation for the beginning of the aforementioned research. Unlike previous studies which were mostly done with data recorded with a minute resolution, the data sets used in the three studies mentioned above have a time resolution of 0.1 s. This improvement in time resolution enabled a more detailed analysis that resulted in the changes in signal parameters starting a few minutes or a few tens of minutes before an earthquake.

2. OBSERVATIONS

2. 1. OBSERVATIONAL SETUP

The studies of the indicated new possible earthquake precursors are based on data obtained in the monitoring of the lower ionosphere with VLF signals, and recorded by the AbsPAL receiver located at the Institute of Physics Belgrade in Serbia. In the performed analyses we considered four VLF signals emitted by the VLF transmitters located in Italy (ICV transmitter), Germany (DHO transmitter), the UK (GQD transmitter), and Norway (JXN transmitter). The locations of these transmitters and receiver as well as the corresponding signal propagation paths are shown in Figure 1.

2. 2. ANALYZED EVENTS

As stated in Introduction, in the studies of the aforementioned new potential earthquake precursors that have been published so far, analysis is made for two groups of earthquakes:

- Earthquakes that occurred in periods when seismic activity was not intense (in an area where there was no long-term seismic activity manifested by numerous earthquakes over a period of several days). In this case, the analysis is focused on four earthquakes whose magnitudes are above 4 and that occurred near Kraljevo in Serbia on November 3 (K1 earthquake) and 4 (K2 earthquake), 2010, in the Tyrrhenian Sea (TS earthquake) on November 3, 2010, and in the Western Mediterranean Sea on November 9, 2010. During these three days, more earthquakes of smaller magnitudes were recorded, which is why analysis is made for these as well.

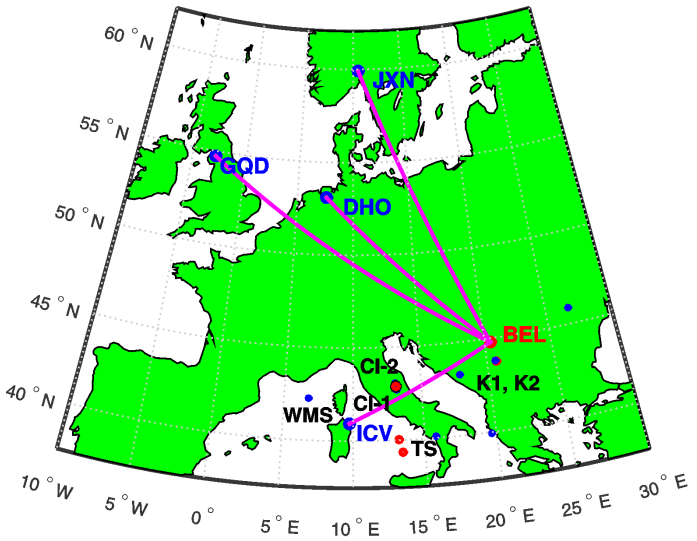

Figure 1: Propagation paths of the VLF signals recorded by the Belgrade receiver station (BEL) in Serbia and emitted by the ICV, DHO and JXN transmitters located in Italy, Germany and Norway. Blue, red and black dots mark the epicenters of considered earthquakes of magnitude $4 \leq M < 5$ (blue dots), $5 \leq M < 6$ (red dots) and $M \geq 6$ (black dots).

- Earthquakes that occurred during periods of intense seismic activity. In this case, the period from October 25 to November 3, 2016 when almost 1000 earthquakes occurred in Central Italy (dominantly grouped in the locations marked as CI-1 and CI-2 on the map) is considered.

2. 3. SIGNAL PROCESSING

In these studies of the new potential earthquake precursors, data sets related to the amplitude and phase of VLF signals recorded with the sampling period of 0.1 s were analyzed. This analysis was performed in the time and frequency domains.

In the time domain we analyze the amplitude and phase noise. These parameters are defined in the analysis of short-term disturbances of the VLF signal amplitude which follow the detection of gamma ray bursts by the Swift satellite. The used parameters are defined as the maximum absolute values of the deviations of the recorded amplitude and phase values from their smoothed curves. In order to avoid consideration of short-term effects of other phenomena (e.g. those caused by lightning), this maximum absolute value is determined after sorting the relevant deviations in the observed time interval and removing p-percent of their highest values. Specifically, we assumed that $p = 5\%$, so that, in the observed interval of e.g. 20 minutes in which 6000 values are recorded for one of these two signal parameters, the 300 highest absolute values are discarded and the highest absolute value is taken from the remaining part of the considered sample.

In the frequency domain we analyze the Fourier amplitude obtained after application of the Fast Fourier Transform to the recorded amplitude and phase.

3. RESULTS AND DISCUSSION

The research on the amplitude and phase changes of VLF signals that are considered as new potential earthquake precursors, started in 2018 at the Institute of Physics Belgrade, Serbia, and several studies on this topic have been published so far. These studies present the results published in Nina et al. 2020, Nina et al. 2021, and Nina et al. 2022, in which the amplitudes and phases of the considered VLF signals are processed in the time and frequency domains. The studies considered earthquakes that occurred in the periods when intense seismic activity in the observed area did not occur for several days as well as, in the periods when it was recorded. All the combinations of different types of analyses used on the mentioned parameters and conditions which are relevant for this research are given in the scheme in Figure 2. The specific analyses given in the mentioned studies are listed in Table 1 where "-" mark indicates that the relevant research has not yet been published.

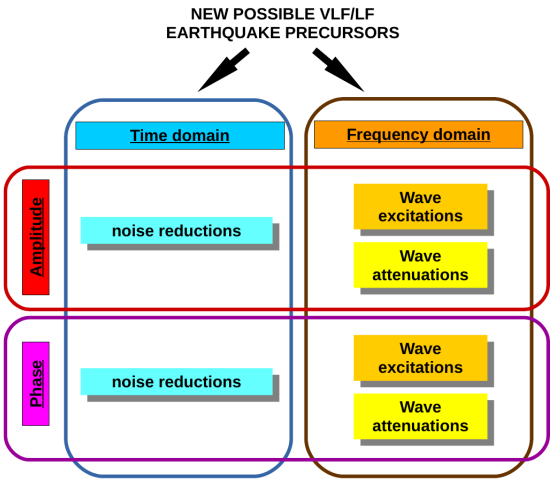

Figure 2: Scheme of the relevant analyses of the signal parameters (amplitude and phase) in the time and frequency domains.

3. 1. ANALYSES IN THE TIME DOMAIN

The first relevant analysis (Nina et al. 2020) is provided for the ICV, DHO, and GQD amplitudes on November 3, 4, and 9, 2010 with focus on the period around Kraljevo earthquake that occurred on November 3, 2010. It shows that the ICV amplitude noise reductions occur a few minutes or tens of minutes before many earthquakes that occurred in those days. The mentioned reduction is recorded at 8 out of 10 earthquakes with a minimum magnitude of 2.5 that occurred near Kraljevo (on 3, 4, and November 9, 2010). Also, 13 of the recorded 15 amplitude noise reductions during those three days can be accompanied by earthquakes with epicentres close to the propagation path of the observed VLF signal.

The amplitude noise reduction is recorded before all four earthquakes with the magnitude larger then 4 which occurred during the observed three days. In this case,

Table 1: References to the studies of ICV signal amplitude and phase in the case of non-intensive seismic activity occurrences (upper half) which are conducted in time and frequency domains in the periods around K1, TS, K2, and WMS earthquakes, respectively; and in the case of earthquakes in Central Italy, during the intensive seismic activity (bottom half). Terms [1], [2], and [3] refer to the studies reported in Nina et al. 2020, Nina et al. 2021, and Nina et al. 2022, respectively.

Domain	Amplitude	Phase
No intensive seismic activity		
Time	[1],[1],[1],[1]	[2],[2],[2],[2]
Frequency	[1],-,-,-	[2],[2],[2],[2]
Intensive seismic activity		
Time	[3]	-
Frequency	-	-

the similar reduction of the phase noise is also recorded (Nina et al. 2021). The amplitude noise reduction is also observed before the earthquakes with magnitude greater than 4 which are not preceded by strong earthquakes during the period of intense seismic activity in central Italy from October 25 to November 3, 2016 (Nina et al. 2022).

The results given in Nina et al. 2020 show that in the case when multiple earthquakes occur in a short time interval in an area, only one long-term amplitude noise reduction can be associated with all of them. This is important for the detection of relevant precursors before a particular earthquake during intense seismic activities. As study of the ICV signal amplitude noise reduction during the period of intense seismic activity when almost 1000 earthquakes occurred in Central Italy shows, many earthquakes occurred during a period of one amplitude noise reduction. At the same time, no significant variations are detected in those reductions, which makes it impossible to detect the precursors of individual earthquakes.

The integration of the studies given in Nina et al. 2020 and shows that over 90% of 35 analyzed cases occurred during periods when the amplitude noise is reduced. In the remaining three cases, it cannot be clearly concluded whether this reduction exists due to its reduced value over a longer time period, which can be explained by the intense seismic activity in that period.

An example of precursors which preceded the two earthquakes that occurred on November 9, 2010 (their characteristics are given in `http://www.emsc-csem.org/Earthquake/`) is given in Figure 3. As can be seen, there are two successive amplitude noise reductions and each of them is followed by earthquakes after several tents of minutes. This example is interesting for two reasons. First, both of these earthquakes have a small magnitude (2.5 and 3.2, respectively), which indicates a potentially very high sensitivity of the presented method. And secondly, the earthquakes occurred in a short time interval (at 01:32:14 UT, and 02:24:24 UT, respectively) but in different locations (in Central Italy and in Serbia). Based on the time evolution of the amplitude noise, it can be seen that the second noise reduction builds on the first one before its end, which indicates the temporal closeness (but spatial distance) of the observed earthquakes.

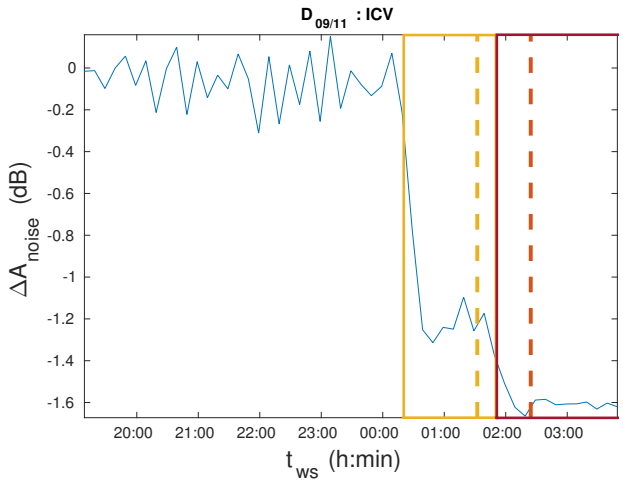

Figure 3: The time evolution of the amplitude noise with respect to its value in a quiet condition ΔA_{noise} in the period around the two earthquakes which times are indicated by vertical dashed lines. The yellow box indicates the period in which the decrease in amplitude noise can be associated with the first earthquake, while the additional decrease in the period indicated by the red box can be associated with the second earthquake.

3. 2. ANALYSES IN THE FREQUENCY DOMAIN

The detection of wave excitations with periods T below 1.5 s and their attenuations for also small values of T is firstly presented on the example of the Mw 5.4 earthquake that occurred near Kraljevo on November 3, 2010 in Nina et al. 2020.

Examples of the increase and decrease of the Fourier amplitude for the two values of T showing the relevant excitation and attenuation, respectively, are given in Figure 4.

Very similar characteristics are obtained in the analyses of the wave excitations and attenuations in the ICV signal phase in the periods around four earthquakes (Nina et al. 2022). The only difference that can be observed in these cases is the attenuation of the waves at all periods relevant to the analysis (up to half the duration of the phase noise reduction in the analyzed cases).

4. SUMMARY

In this study, we present the pioneer research of the new types of potential earthquake precursors manifested as 1) the reduction of the noise of the VLF signal amplitude and phase starting several minutes or several tens of minutes before an earthquake, and 2) wave excitations and attenuations at short wave periods.

The main obtained results indicate the following:

- 90% of the analyzed earthquakes with the magnitude larger than 4 occurred in the periods when the amplitude noise reduction is recorded.

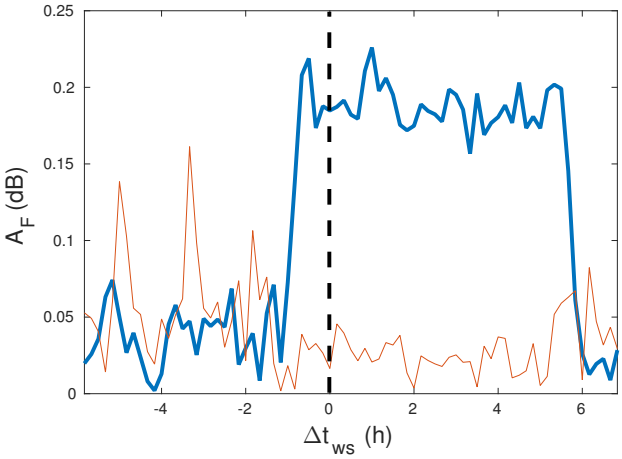

Figure 4: Examples of the Fourier amplitude time evolution A_{F} given for two wave periods for which excitations (blue line) and attenuations (red line) of waves with beginnings before the earthquake are detected. The vertical dashed line indicates the time of the earthquake, and the time difference from that time Δt_{ws} is given on the x-axis.

- Studies of phase characteristics in all four analyzed cases show that the reductions in its noise, as well as, wave excitation at periods below 1.5 s and attenuation of waves with other periods below several minutes, are also registered for this signal parameter. As in the case of the amplitude, all these changes last several tens of minutes and begin before the occurrence of the analyzed earthquakes.

- A reduction in the amplitude noise can be associated with more earthquakes. This can affect the possibility of detecting isolated significant reductions that can be associated with a particular earthquake. In other words, if several earthquakes are registered in a certain area in a short time interval, reductions in the amplitude noise do not have to occur individually for each earthquake, but one can last during the occurrence of several earthquakes. This means that during the seismically active period or in the case of several earthquakes in a small area that occur within a few hours, amplitude noise reductions are not precursors to individual earthquakes, but only to the first in a series, and that during the entire period of amplitude noise reduction, other earthquakes can be expected.

Finally, we would like to emphasize that, although the presented analyses refer to an insufficient number of earthquakes to be able to claim with certainty that the mentioned changes are precursors of earthquakes, the obtained results indicate a significant possibility that they are. For this reason, it is necessary to continue with this research. Also, it is important to emphasize that in addition to relevant studies, the development of new networks of VLF receivers as well as new software for automatic data analysis and alerting is necessary.

Acknowledgements

The author acknowledges funding provided by the Institute of Physics Belgrade through the support by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (contract no. 451-03-66/2024-03/1).

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