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Analysis of the solar terminator shift determined from the VLF signal amplitude in the period around the intense seismic activity in Central Italy from 25 October to 3 November 2016

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Abstract

Since the middle of the last century, numerous studies indicate the possibility that ionospheric perturbations can be precursors of earthquakes (EQs). At the same time, different types of perturbations related to various ionospheric areas were observed. Among them, shifts in the times of occurrence of minimum amplitudes of very low/low frequency (VLF/LF) signals used for monitoring the lower ionosphere in the sunrise and sunset periods (the so-called Solar terminator time - STT) are shown in several studies. In this paper, we analyse STT of the 20.27 kHz ICV signal emitted in Italy and recorded in Serbia in the period from October 15 to November 13, 2016. This period includes 10 days (October 25 - November 3, 2016) when 981 EQs with the minimum magnitude of 2 out of which 31 had the minimum amplitude of 4 were registered in Central Italy. The obtained results show that the STT shifts during sunrise are predominantly due to seasonal changes, while the additional sudden shifts (most pronounced before and at the beginning of intense seismic activity (PISA) in Central Italy) are observed during sunset.

1. Introduction

Although studies connecting ionospheric perturbations with seismic activity began to be published in the mid-sixties of the last century (Davies and Baker, 1965; Leonard et al., 1965), this topic is still relevant and is the subject of numerous researches in recent years (He et al., 2022; Molina et al., 2022). In addition to theoretical studies and models that indicate the influence of lithospheric processes on the upper atmosphere through waves and the influence of the electric field (see, for example, Pulinets and Ouzounov, 2011), the analyses are based on data recorded by various forms of monitoring. First of all, these techniques are based on propagation of the Global Navigation Satellite System (GNSS) signals (their characteristic variations can predominantly be associated with the upper ionosphere perturbations due to

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the significantly higher electron density that affects the signal propagation more than in the lower ionosphere (Molina et al., 2022)), and very low/low frequency (VLF/LF) signals (they are used for the lower ionosphere observations (Hayakawa, 2007)), as well as on monitoring by satellites orbiting in the ionosphere (Němec et al., 2009)).

Processing of recorded amplitudes and phases of VLF signals shows several types of changes that can be considered as possible earthquake (EQ) precursors. They refer to changes in the values of these parameters and the solar terminator time (STT) shift, usually visible a few days before the individual EQs, and the reduction of the signal amplitude/phase noise a few tens of minutes before EQ (Hayakawa, 1996; Molchanov et al., 1998; Yamauchi et al., 2007; Biagi et al., 2001a; Rozhnoi et al., 2010; Biagi et al., 2006; Hayakawa et al., 2010; Miyaki et al., 2001; Molchanov et al., 2001; Rozhnoi et al., 2004; Nina et al., 2020, 2021, 2022).

The subject of this research is the examination of STT shifts during a one-month time interval that includes a ten-day period of intense seismic activity (PISA) occurred in Central Italy in 2016. We analyse the ICV signal whose path from the transmitter in Sardinia (Italy) to the receiver in Belgrade (Serbia) passes close to the area where almost a thousand EQs of minimum magnitude 2 were recorded during the considered PISA.

2. Observations and study area

The research presented in this paper is based on the analysis of STTs determined from the ICV signal amplitude time evolution. This signal is used to monitor the lower ionosphere between the transmitter and receiver locations in Isola di Tavolara (Sardinia, Italy) and Belgrade (Serbia), respectively. In this study, we consider the time period from October 15 to November 13, 2016. It begins 10 days before and ends 10 days after PISA (October 25 - November 3, 2016), which enables us to analyse possible connection between the STT shifts in both sunrise and sunset periods and seismic activities during PISA when 981 EQs of minimum magnitude 2 were recorded (http://www.emsc-csem.org/Earthquake/).

The propagation path of the observed 20.27 kHz VLF signal is given on the map shown in Nina et al., 2022 (Figure 1). The EQ epicentres are marked with white and magenta crosses, and blue, red and black circles for the EQ magnitudes (M) between 2 and 3, 3 and 4, 4 and 5, and 5 and 6, and for magnitudes greater than 6, respectively (the magnitude types are given in http://www.emsc-csem.org/ Earthquake/ and, for the considered EQs with M ≥ 4, in Nina et al., 2022 (Table 1)). As can be seen from this map, the locations of the epicentres are primarily grouped in the area where their distances from the ICV signal path (D) are less than 100 km

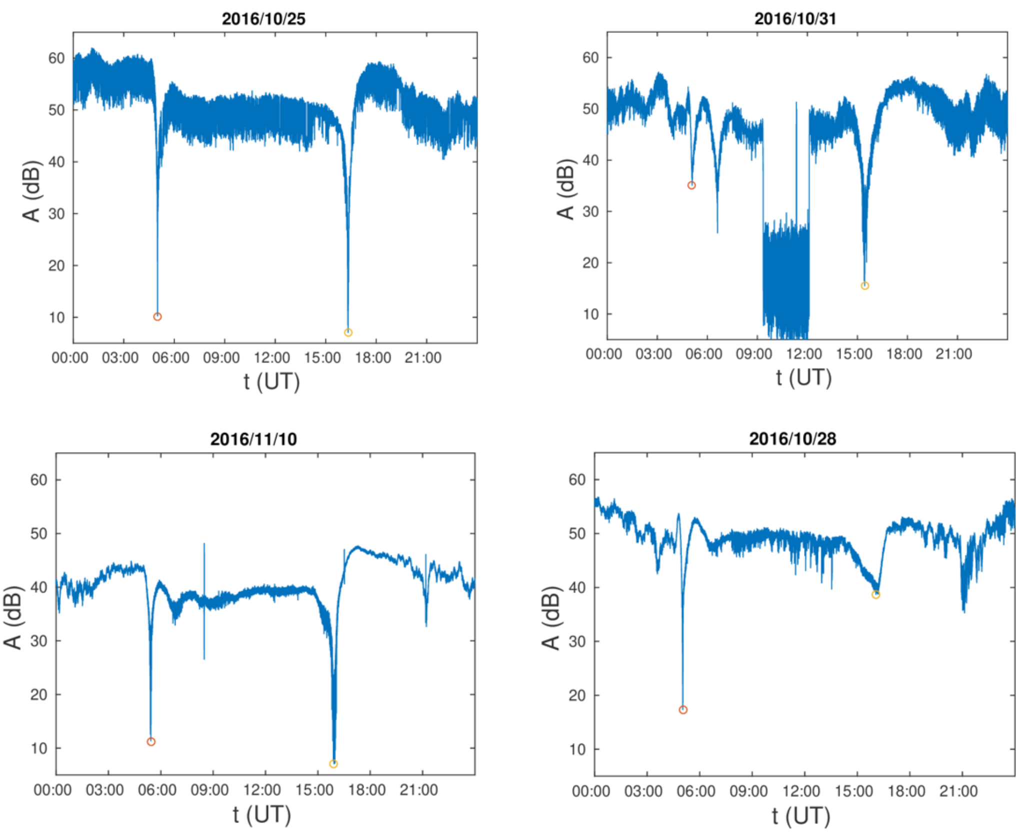

Figure 1. Examples of the ICV signal amplitude time evolutions during selected four days.

(since the greatest distance from the signal path of this group of epicenters is 99.86 km, in the analysis we chose that the border distance of the considered area is 100 km). Table 1 shows that there were 973 (99.2%) of these EQs, while there were 8 (0.8%) EQs whose epicentres were further away (D > 100 km from the ICV signal path). Given that all 8 more distant EQs had a magnitude of less than 4, it is realistic to assume that the potential impact of seismic activity on the ICV signal can primarily be related to events closer to its path.

Bearing in mind that a large number of factors affect the propagation of a VLF signal, the analysis of the possible impact of seismic activities on its characteristics, including the non-periodic changes in STT, requires the exclusion of other factors that may have an impact on the obtained results. As stated in Biagi et al., 2011 and Nina et al., 2020, these factors are primarily related to meteorological and geomagnetic conditions, extraterrestrial radiation, and non-natural conditions that are based on changes in emission and reception (caused, for example, by the influence of additional electric and electronic devices near the receiver). In the analysis of possible influences of the mentioned factors given in Nina et al. 2022, it is shown that they did not have a significant contribution to the signal characteristics in the observed time period. In addition, it should be noted that several individual EQs were recorded close to the observed ICV signal propagation path in other areas, but the maximum magnitude of these EQs was only 4.2 (the corresponding event occurred in Bosnia and Herzegovina on 31 October, 2016), which is why their significant impact on the STT shift is not expected. This conclusion is based on previous studies where corresponding changes are recorded for only much stronger earthquakes (see, for example, Hayakawa et al., 1996 and Biswas et al., 2022).

3. Signal processing

VLF signal receivers record two signal characteristics: amplitude and phase. The first of these parameters is significantly more stable and more suitable for multi-day analyses, which is the reason why its temporal evolution is the subject of this study. The used data are recorded by the Absolute Phase and Amplitude Logger (AbsPAL) receiver in Belgrade, Serbia. This receiver records two sets of data with time samplings of 0.1 s and 1 min. Unlike the analysis of the signal characteristics (the amplitude and phase) of noise reductions which requires data with a better time resolution (Nina et al., 2020, 2021, 2022), the second data set is more suitable for the STT analysis due to the elimination of short-lasting peaks caused by various influences whose effects on a VLF signal we cannot precisely determine.

Table 1. Number of the considered EQs of the magnitudes (M) between 2 and 3, 3 and 4, 4 and 5, and 5 and 6, and for M greater than 6, and the domains of the distances between the considered epicentres and ICV signal propagation path (D).

	D<100 km		D>100 km	
Magnitude	N_o	Range of D (km)	N_o	Range of D (km)
2≤M<3	604	18.91 - 99.86	5	168.12 - 258.83
3≤M<4	338	31.01 - 88.21	3	216.38 - 217.98
4≤M<5	28	47.85 - 86.85	0	-
5≤M<6	1	67.17	0	-
M≥6	2	63.95 and 71.14	0	-

As stated in Introduction, the non-periodic STT shifts before and after the occurrence of individual EQs are presented in several studies. In this paper, we analyse STT before, during and after the observed PISA.

Generally speaking, signal amplitudes at the sunrise and sunset periods have characteristic forms of temporal evolution that are manifested in pronounced minima. As can be seen in Figure 1, the number of these amplitude minima is not unambiguous. In addition, their determination in some cases is not simple. This can be seen in the case of the amplitude minimum (about 7 UT) from which the signal starts to rise to its maximum daytime value. These minima are in some cases pronounced (e.g. October 31, 2016), in others they are weaker (e.g. October 28 and November 10, 2016), while in some days they are not visible at all (e.g. October 25, 2016). For this reason, in this study we observe the times of the minimum amplitude during the sunrise period (from 4:30 UT to 6:00 UT), and the sunset period (from 15:00 UT to 17:00 UT) in which the analysed minima are clearly defined and present every day.

4. Results and discussion

In order to examine the STT shifts during the periods of sunrise (sunrise time (SRT) shift) and sunset (sunset time (SST) shift), it is necessary to observe a longer time period, which in its middle part includes the considered EQ day or PISA. In this study, we observe the time period from 15 October to 14 November, 2016 which includes PISA starting on 25 October and ending on 3 November, 2016. Here it should be indicated that the AbsPAL receiver did not record a quality signal during 4 sunrise and 5 sunset periods, which is why the corresponding data of SRT and SST for the corresponding days are missing.

In the upper panel of Figure 2 where the time evolution of SRT is shown, the seasonal changes manifested in the SRT shift towards daytime (DT) from day to day can be clearly

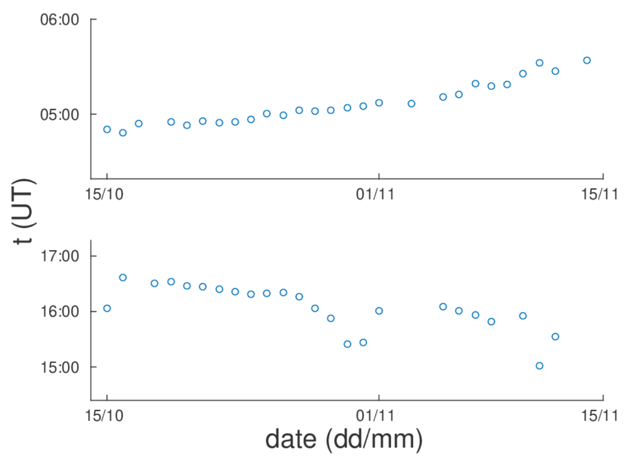

Figure 2. Time evolutions of the sunrise (upper panel) and sunset (bottom panel) time shifts in the considered time period.

visible. Additional changes that can potentially be related to intense seismic activity in Central Italy are not observed. In contrast to SRT, the time evolution of SST (lower panel of Figure 2) indicates a combination of the influence of several phenomena. In addition to the tendency of the SST shift towards DT with days, additional changes are also visible in three time intervals. The first of them is visible as a SST shift towards DT as compared to the expected time in quiet conditions and it relates only on the first observed day. Much more interesting are the changes in the middle of the observed time interval. The beginning of the deviation from the expected SRT evolution shape is manifested in a slight STT shift towards nighttime (NT) on 22 and 23 October 22, i.e. three and two days before PISA. After that, a sharp shift of SST towards DT is noticeable. It reaches more than half an hour from the expected value during quiet conditions on 28 October. From 29 October, SST shifts towards NT and returns to the expected values that reach around 6 October, with a previous larger shift towards NT. These non-periodic changes have a quasi-symmetrical shape in relation to the day of minimum SST. On the third and second day from the end of the observed time interval, the SST shifts towards NT and DT, respectively, are seen, but on the next day the SST is already similar to its expected value in the case without the influence of sudden events.

As mentioned in the Introduction, several studies have analyzed STT in time periods around several EQs. A comparison of the data obtained in this research with the results of two other studies related to EQs that occurred in Kobe, Japan (Hayakawa et al., 1996), and near the Samos island in Greece (Biswas et al., 2022) are given in Table 2. The basic characteristics given in them are the existence of the SRT and SST shift in both days before and after the EQ. As can be seen from Table 2, these parameters do not have the same characteristics for all the mentioned cases.

Sudden changes in STT (defined as the time of the minimum phase of the Omega signal recorded near Tokyo, Japan, in Hayakawa et al., 1996) are observed before Kobe EQ (M=7.2) that occurred on 17 January, 1995. In contrast to the results obtained in our study, the STT shift is only towards NT and is visible both at sunrise and at sunset, but it is not significantly expressed in the days after the EQ day.

The analysis of the STT shifts in the period around the time of Niigata EQ that occurred in Japan (23 October, 2004) with magnitude of 6.8 indicates the importance of signal selection in determining the characteristics of possible EQ precursors (Yamauchi et al., 2006). As can be seen from Table 2,

Table 2. Sunrise (SRT) and sunset (SST) time shifts toward daytime (DT) and night time (NT) before, during and after the considered EQs in this study, and Kobe EQ and EQ near the Samos island, Greece.

No	EQ epicentre	Reference	VLF transmitter / receiver location	SRT shift toward			SST shift toward		
				before EQ	During PISA or EQ day	After EQ	before EQ	During PISA or EQ day	After EQ
1	Central Italy	This study	ICV (Italy) / Belgrade (Serbia)	-	-	-	NT – DT (DT is dominated)	DT – NT (DT is dominated)	NT
2	Kobe, Japan	Hayakawa et al., 1996	Omega (Japan) / Inubo (Japan)	NT	-	-	NT	NT	-
3	Niigata	Yamauchi et al., 2006	JJY (Japan) / MCR (Japan)	DT	-	NT		No data	
			JJY (Japan) / KOC (Japan)	DT	-	-		No data	
			JJI (Japan) / CHO (Japan)		No data		DT	-	NT
			JJI (Japan) / CBA (Japan)		No data		NT	-	-
			JJI (Japan) / MCR (Japan)		No data		-	-	-
			JJI (Japan) / KOC (Japan)		No data		-	-	-
3	Near Samos island, Greece	Biswas et al., 2022	ISR (Israel) / Athens (Greece)	NT	NT	DT	DT	-	-
			TBB (Turkey) / Athens (Greece)	DT-NT	No data	NT	NT-DT	-	-

two VLF signals emitted by JJY and JJI transmitters and recorded at four receivers (MCR, KOC, CHO and CBA) are considered in this study. Two (JJY-MCR and JJY-KOC) and four (JJI-CHO, JJI-CBA, JJI- MCR and JJI-KOC) signal paths are considered in analysis of the SRT and SST shifts, respectively. The significant SRT shifts before EQ toward DT are recorded for two signal paths, while the SST shift toward NT is visible for one path after EQ. The significant SST shifts are recorded before (toward DT and NT) and after (toward NT) EQ for two and one paths, respectively, and they are not recorded for two paths. The importance of signal selection in corresponding research is also indicated in analysis of the period around the time of EQ that occurred near the Samos island, Greece (30 October, 2020) with magnitude of 6.9 (Biswas et al., 2022). In this study, the ISR and TBB signals emitted in Israel and Turkey, respectively, and recorded in Athens, Greece, are analyzed. The SRT shifts are visible both before and after the EQ day in both signals, as well as on that day (towards NT) for the ISR signals (the TBB signal was not recorded in that period, so the corresponding information is not available). However, the shifts are not directed towards the same time of the day (SRT is shifted towards NT and in both directions before EQ, and towards DT and NT after EQ day for the ISR and TBB signal, respectively; SST is shifted towards DT and towards both times of the day for ISR and TBB signal, respectively, before EQ). Based on the presented data, it can be seen that the SST shifts are detected before EQs in all cases, as well as that they can be registered on the day of EQ or PISA and endure during the following days. In all cases, they can be directed both to DT and to NT.

The explanation of the STT shifts is very complicated due to the large number of simultaneous influences on a VLF signal and data that only provide information on integral changes in the amplitude and phase of the considered signal throughout the Earth-ionosphere waveguide through which it extends and its boundaries. A possible explanation for these changes lies in the change in the height of the reflection of a VLF signal from the ionosphere. The study presented in Yoshida et al., 2008 shows a SST modeling for different signal reflection heights (h) for a relatively small distance between the transmitter and receiver (less than 2000 km). This study shows that for the JJY signal registered in Kochi (786 km away from the JJY transmitter) a decrease in h of 2 km causes SRT and SST shifts to later and to earlier hours, respectively, which is usually observed in the experiments in periods around the Kobe EQ.

5. Conclusions

In this paper, we analysed the shifts in solar terminator times detected by the ICV signal emitted in Italy and recorded in Serbia during a period of one month which includes the period of intense seismic activity recorded in Central Italy. We analysed both the sunrise and sunset periods.

The obtained results related to the observed time period indicate:

- Absence of the sudden shifts in the solar terminator time during the sunrise period. In this time intervals, only changes in the solar terminator time which are a clear consequence of seasonal changes are recorded.

- Existence of non-periodic variations of solar terminator times during sunset. These changes occur in combination with the expected periodic seasonal changes in which the solar terminator time continuously decreases due to earlier sunset.

Comparison with other analyses indicates that the sunset time shifts were detected before an earthquake in all considered cases, and that they can be registered on the day when an earthquake occurred or during a period of intense seismic activity, and persist during the following days. In all cases, they can be directed to both the daytime and nighttime.

This research represents an extension of the previous studies which primarily refer to strong individual earthquakes to the examination of potential precursors of intense seismic activity manifested in a large number of earthquakes during a time period of several days. In addition, due to the complexity of analyses of characteristics of radio signals used to monitor the ionosphere, a statistical analysis that includes a large number of earthquakes and periods of intense seismic activity is necessary for drawing reliable conclusions. For this reason, the presented study can be included in the corresponding wider research and its results can be used in different statistical analyses.

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