

Article

Unusual Sunrise and Sunset Terminator Variations in the Behavior of Sub-Ionospheric VLF Phase and Amplitude Signals Prior to the Mw7.8 Turkey Syria Earthquake of 6 February 2023

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Abstract: We report on the recent earthquakes (EQs) that occurred, with the main shock on 6 February 2023, principally in the central southern part of Turkey and northwestern Syria. This region is predisposed to earthquakes because of the tectonic plate movements between Anatolian, Arabian, and African plates. The seismic epicenter was localized at 37.08°E and 37.17°N with depth in the order of 10 km and magnitude Mw7.8. We use Graz's very-low-frequency VLF facility (15.43°E, 47.06°N) to investigate the amplitude variation in the Denizköy VLF transmitter, localized in the Didim district of Aydın Province in the western part of the Anatolian region in Turkey. Denizköy VLF transmitter is known as Bafa transmitter (27.31°E, 37.40°N), radiating at a frequency of 26.7 kHz under the callsign TBB. This signal is detected daily by the Graz facility with an appropriate signal-to-noise ratio, predominantly during night observations. We study in this analysis the variations of TBB amplitude and phase signals as detected by the Graz facility two weeks before the earthquake occurrence. It is essential to note that the TBB VLF transmitter station and the Graz facility are included in the preparation seismic area, as derived from the Dobrovolsky relationship. We have applied the multi-terminators method (MTM), revealing anomalies occurring at sunset and sunrise terminator occasions and derived from the amplitude and the phase. Minima and maxima of the TBB signal are linked to three terminators, i.e., Graz facility, TBB transmitter, and EQ epicenter, by considering the MTM method. We show that the significant anomalies are those linked to the EQ epicenter. This leads us to make evident the precursor seismic anomaly, which appears more than one week (i.e., 27 January 2023) before EQ occurrence. They can be considered the trace, the sign, and the residue of the sub-ionospheric propagation of the TBB transmitter signal disturbed along its ray path above the preparation EQ zone. We find that the sunrise–sunset anomalies are associated with tectonic regions. One is associated with the Arabian–African tectonic plates with latitudinal stresses in the south–north direction, and the second with the African–Anatolian tectonic plates with longitudinal stresses in the east–west direction. The terminator time shift anomalies prior to EQ are probably due to the lowering (i.e., minima) and raising (i.e., maxima) of the ionospheric electron density generated by atmospheric gravity waves.

Keywords: earthquake precursors; TBB VLF transmitters; sub-ionospheric wave propagation

1. Introduction

The interest in the seismo-electromagnetic (SEM) effects started more than two decades ago when electric and magnetic perturbations associated with earthquakes were reported [1]. It concerns a large frequency range starting from DC and up to several tens of gigahertz. Ref. [2] listed and detailed in his book on ‘the earthquake prediction with radio techniques’ several frequency bandwidths where SEM phenomena have been observed: DC/ULF (3 Hz to 30 Hz), ELF (30 Hz to 3 kHz), VLF/LF (3 kHz to 300 kHz), MF (300 kHz to 30 MHz), and HF/VHF/SHF (30 MHz to 3 GHz). The multiplicity of bandwidths is directly related to the large diversity of SEM phenomena ([3–5]), showing a clear complexity in the comprehension of the generation mechanisms. Despite this complexity, earthquake precursor anomalies have been principally detected in three key regions: the lithosphere, the atmosphere, and the ionosphere. Later on, the main physical model developed is the LAIC for lithosphere-atmosphere-ionosphere coupling, where the basic ideas were reported in the book ‘ionospheric precursors of earthquakes’ by [6]. The authors insisted on the ionization mechanism of atmospheric gases produced by α -active radon and freed in active tectonic regions over faults and plate borders. Hence, atmospheric electricity can be considered the main source of the ionospheric disturbances recorded above seismic active areas. The LAIC model provides a synergy between the three layers, from the surface and up to the ionosphere, and generates processes that can explain the so-called short-term earthquake precursors as given in [7]. The upgraded version of the LAIC model is shown to generate ionospheric disturbances through three channels: acoustic waves (AWs), vertical thermal convection, and the change in ionosphere potential [8]. Besides the LAIC radon ionization model, two other models have been proposed: (a) the rock atmosphere ionosphere coupling (RAIC) model [9] and the ionospheric total electron content (ITEC) model [10]. RAIC model is based on the rock experimental investigations that revealed that a stressed rock can trigger positive holes as charge movers and produce upward currents and electric fields [11]. The stressed RAIC model assumes the presence of an atmospheric upward electric field and current related to stressed lithospheric rocks, which disturbed the ionosphere above the earthquake preparation region. The authors estimated at a magnetic latitude of -30° a current flowing into the atmosphere and ionosphere on the dayside in the order of 200 nA m^{-2} with an electric field of about 8 mV m^{-1} [12]. However, it has been shown, using numerical simulations based on the finite element method [13], that adequate atmospheric electrical conductivity may be considered to explain the magnitude of the ionospheric electric field above the seismic preparation zone. The ITEC model is based on anomalies observed in the total electron content above seismic areas, as recorded by ground-based receivers of the global positioning system (GPS). TEC variations preceding EQs allowed to identify particular anomalies from a few days to a few weeks ([14,15]). Such TEC anomalies are explained within the electromagnetic channel in the frame of the lithosphere–atmosphere–ionosphere system. The physical mechanism at the origin of EQ-induced TEC anomalies is linked to vertical plasma drift $\mathbf{E} \times \mathbf{B}$ of the F2 layer [16].

Several methods have been considered in the investigations of ionospheric disturbances preceding earthquake occurrences. One of those methods is the terminator time (TT) method based on the time shift of transmitter signals at sunrise and/or sunset terminators at the VLF/LF reception station [17,18]. The daily monitored transmitter signal, in the absence of anomalies, does not exhibit a terminator time shift. Hence, the minima of amplitude and phase happen at the sunrise terminator time of the formation of the D-layer and the inverse for the sunset terminator, i.e., resulting in the time of the dissipation of the D-layer, as detailed in [19]. TT method made evident the presence of anomalies in the sub-ionospheric transmitter signals, as reported in several papers [20–24]. The anomalies are linked to the disturbances of the amplitude and/or the phase of the transmitter signals, principally through the E- and D-layers during the radio wave propagations [25–27]. More recently, ref. [28] enhanced this method by considering terminators at the reception facility and also the terminators at transmitter stations in the case of the Croatian EQ, which occurred in the Zagreb region on two occasions on 22 March 2020 and 29 December

2020. In [28], sub-ionospheric transmitter signals have been investigated, allowing to make evident the presence of time shift anomalies that happen inside the Dobrovolsky preparation zone [29] constrained to the Graz Zagreb surrounding region. The disturbed ionospheric area is considered to be of the same order of magnitude as the area estimated from [29]. The first originality of this work is the combining of the time shift anomalies to the Graz facility terminator and in addition to transmitter terminators, which have not been considered in previous studies [17]. The second newness is the use of the degree of anomaly correlation between transmitter amplitude signals leading to tracking the time evolution of the presumed preseismic areas. This allowed to show the expansion of the seismic preparation zone to the Anatolian tectonic plate.

The variations of the amplitude and the phase of sub-ionospheric transmitter signals are subject to fluctuations that happen in the Earth's atmosphere and disturb the ionosphere [30] prior to earthquake occurrence. Such fluctuations have different modulation periods: 1 min–10 min for acoustic waves (AWs), 10 min–a few hours for atmospheric gravity waves (AGWs), and days for planetary waves (PWs) [31]. In this study, we emphasize that AWs and AGWs waves are assumed to be generated by oscillations above the EQ preparation zone due mainly to atmospheric fluctuations of pressure and temperature. In this case, the wave flux energy is considered to be proportional to the product of wind speed squared and the atmospheric density. This energy propagates upward and amplifies because of the reduction in the atmospheric air density with height when the vertical velocity increases [32]. This energy interacts with the ionospheric plasma and disturbs the transmitter signal propagation, as first proposed by [33]. Later on, several studies provide evidence of AGWs in VLF signals before EQ occurrence [34–43].

In this work, we investigate the strong earthquake that occurred in Turkey on 6 February 2023. Several studies make evident the presence of precursor anomalies (e.g., [44,45]) and also co-seismic ionospheric disturbances (e.g., [46,47]). The paper is laid out as follows: The amplitude and phase data sets of the TBB VLF radio signal are investigated in the next section, while the multi-terminators method and the time shifts of minima and maxima, which happened at sunrises and sunsets, are detailed in Section 3. Three main topics are addressed in Section 4, and they concern the terminator anomalies linked to the EQ epicenter region, the geographical locations of sunrise and sunset anomalies with the emergence of seismic sub-areas, the probable scenario that may explain the relationship between the anomaly sub-areas and the tectonic plate dynamics, and the plausible physical mechanisms at the origin of EQ terminator time shift anomalies. The main outcomes are summarized in Section 5.

2. TBB VLF Amplitude and Phase Investigations

2.1. Features of Turkey–Syrian Earthquakes on 6 February 2023 and Dobrovolsky Preseismic Area

On 6 February 2023, two large earthquakes occurred near the Turkish towns of Gaziantep (37.17°N; 37.08°E) and Ekinozue (38.11°N; 37.24°E), close to the Syrian boundary, with magnitudes of Mw 7.8 and Mw 7.6, respectively. Figure 1 shows the geographic locations of the Gaziantep Turkey–Syrian EQ (37.17°N; 37.08°E), the TBB transmitter (37.40°N; 27.31°E), and the Graz facility (47.03°N; 15.46°E). The distances EQ–Graz Facility, EQ–TBB Transmitter, and Graz Facility–TBB Transmitter are found, respectively, to be equal to 2085 km, 863 km, and 1449 km. The seismic preparation zone (golden arrows shown in Figure 1) is derived from the Dobrovolsky relationship [29] $\rho = 10^{0.43M}$ (km), where ρ is the radius of the preparation zone and M is the earthquake magnitude. In our case, the magnitude is equal to Mw7.8, which leads to obtaining a Dobrovolsky radius in the order of 2260 km. This means that the TBB transmitter and also the Graz facility are inside the preparation zone, as displayed in Figure 1.

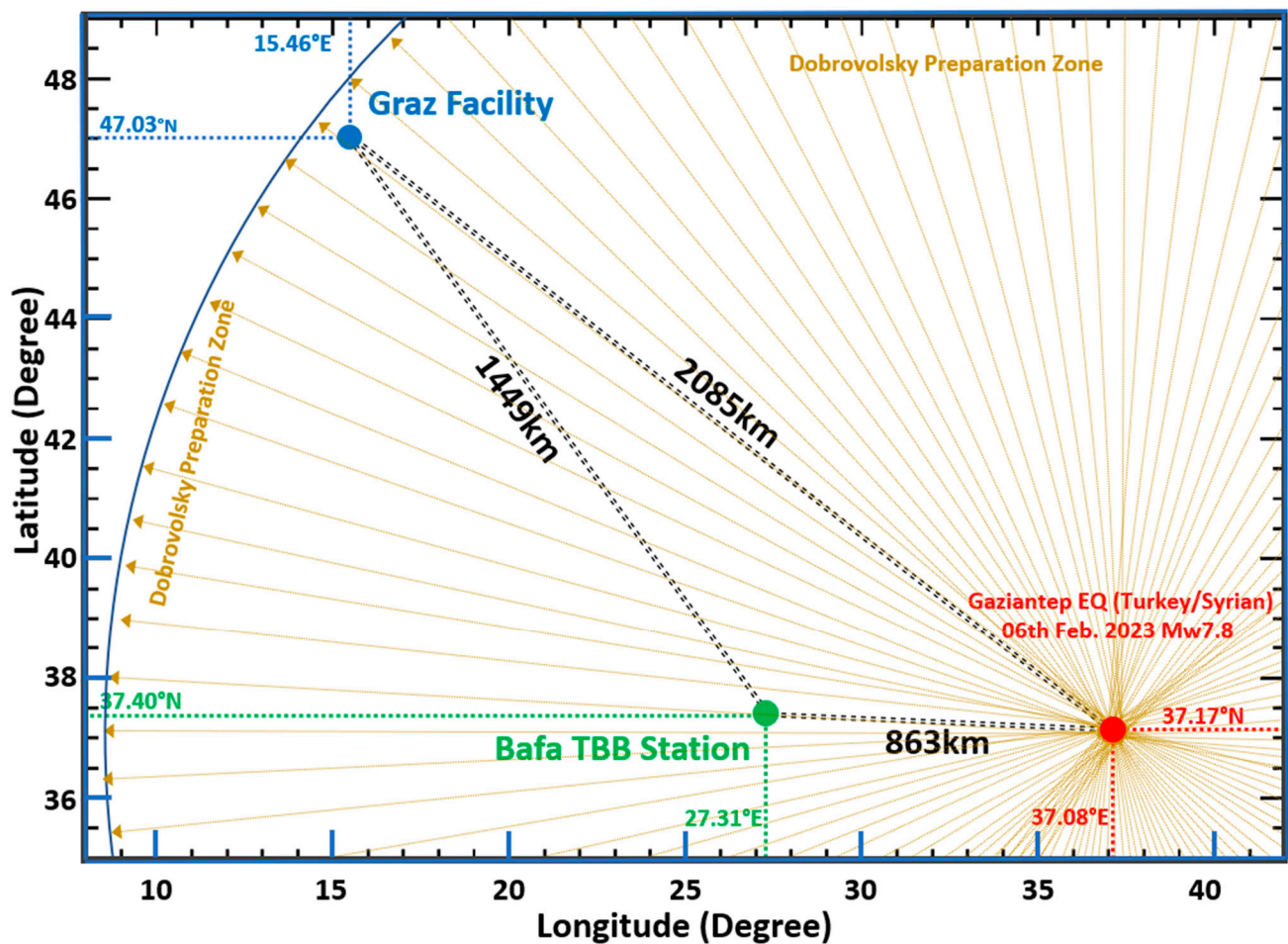


Figure 1. The seismic preparation zone (golden arrows) as derived from the Dobrovolsky relationship. The radius of the preparation area is found to be equal to 2260 km, which is bigger than the distances between the EQ epicenter, the TBB transmitter station, and the Graz facility.

Also, we note that the latitudes of TBB station and EQ epicenter are comparable, i.e., 37.17°N and 37.40°N , respectively. Since the TBB transmitter is inside the Dobrovolsky preseismic areas, the emitted signal may be subject to disturbances during its sub-ionospheric propagation. Hereafter, we describe the variation in the TBB amplitude and phase as detected by the Graz facility before the EQ occurrence.

2.2. Overview Variations in the Amplitude and the Phase of TBB Transmitter Signal

The Graz station is devoted to the observation and detection of VLF and LF transmitter signals. It has three reception systems: an UltraMSK instrument allowing to record eight VLF transmitter signals (DHO, GBS, ICV, ITS, NAA, NPM, NRK, and TBB) since 2009 to the present [48], an INFREP receiver leading to detect six VLF (GBZ, ICV, HWU, DHO, NRK, and TBB) and four LF (RRO, EU1, CH1, MCO) since 2017 to the present [49,50], and a new UltraMSK instrument permitting to observe more than 15 VLF transmitter signals (GBS, GBZ, GWU, HWU, ICV, ITS, JJI, JJY, JXN, NAA, NAU, NLM, NPM, NRK, NWC, TBB, and VTX) in operation since 2021 [51]. More details about the INFREP European Network and collected VLF-LF observations can be found on the webpage <https://infrep.iwf.oeaw.ac.at/> (accessed on 1 November 2024).

2.2.1. TBB Amplitude Variations

Figure 2 displays the daily amplitude variations covering the time interval from 29 January 2023 (029 DOY) to the earthquake day, i.e., 6 February 2023 (037 DOY). Each

panel corresponds to one observation day where the horizontal and vertical axes indicate, respectively, the time expressed in fractions of the day and the amplitude expressed in dB.

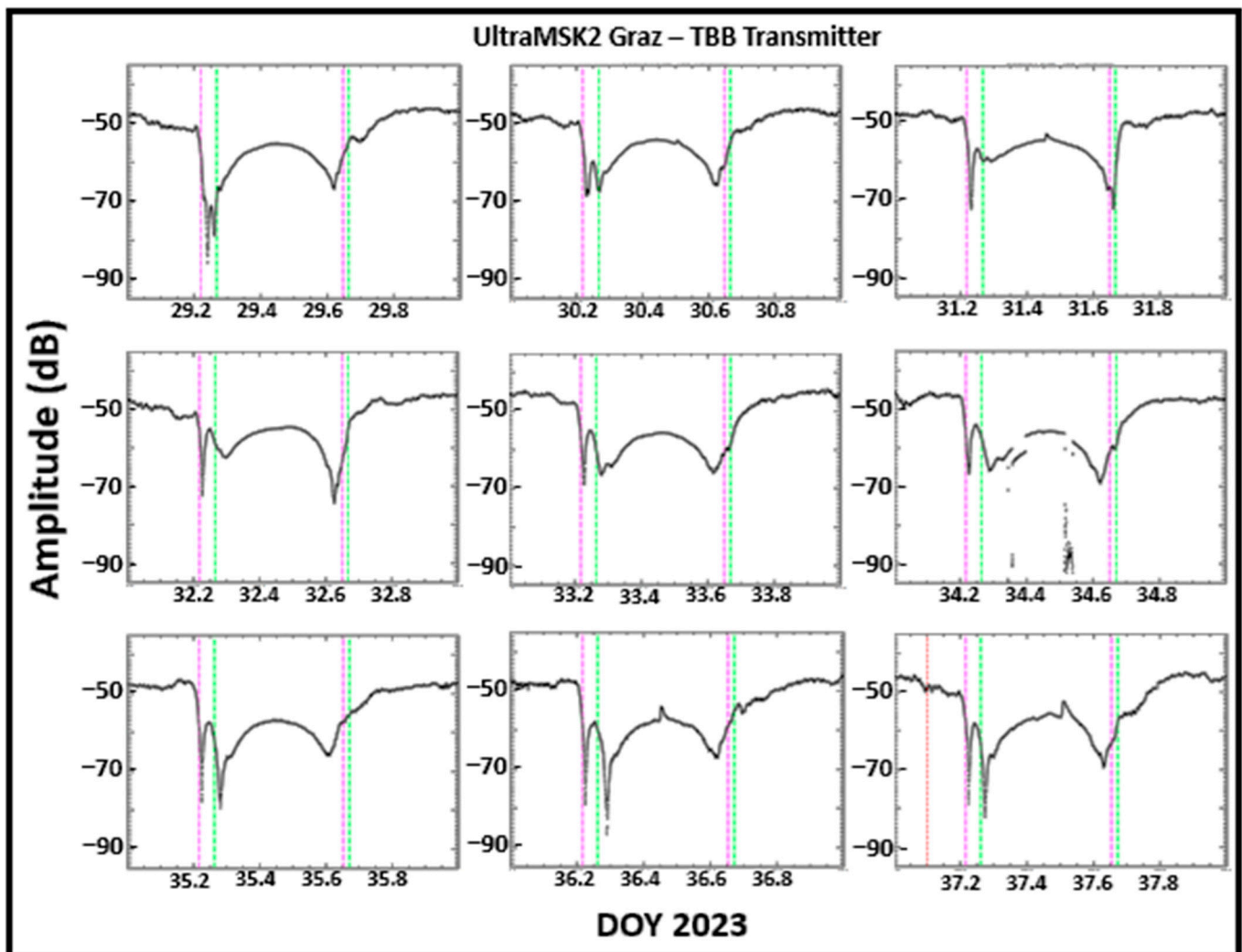


Figure 2. The amplitude variations in the TBB transmitter signal are shown from 29 January 2023 (029 DOY) to 6 February 2023 (037 DOY), the day of the earthquake occurrence. The horizontal and vertical axes indicate, respectively, the observation time in days of the year 2023 and the amplitude level in dB. The green and magenta vertical dashed lines correspond, respectively, to the terminators of the Graz facility and TBB transmitter. EQ event on 6 February 2023 (037 DOY) is designed by a dotted vertical line.

The TBB amplitude is intense, at about -50 dB, during night observation, decreases to about -55 dB on the day, and drops to about -85 dB at terminator occasions. The TBB station and Graz facility terminators are shown in Figure 2 with magenta and green vertical dashed lines, respectively. One notes that several pronounced minima are observed at sunrise terminator times, particularly on 029 DOY (-86 dB), 031 DOY (-73 dB), 035 DOY (-80 dB), 036 DOY (-87 dB), and 037 DOY (-83 dB). Those minima are smaller than -80 dB three days before earthquake occurrence. At sunset terminator time, we notice that minima are bigger than -70 dB and only on 031 DOY drops to -73 dB. At sunrise terminators, the maxima are noticed, on average, higher than -60 dB and only on 029 DOY, smaller than -70 dB. Also, at sunset terminators, maxima are observed, but with a moderate variation when compared to sunrise maxima. The TBB amplitude signal exhibits a particular drop to about -90 dB after midday on 033 DOY. Furthermore, solar effects [52] have been recorded on four occasions, i.e., 030 DOY, 031 DOY, 036 DOY, and 037 DOY. One can see an abrupt

increase in the amplitude signal from about -58 dB to -53 dB, particularly on 036 DOY and 037 DOY, and a relative enhancement of about 1 dB or 2 dB on 030 DOY and 031 DOY.

2.2.2. TBB Phase Variations

Figure 3 shows the phase variations of the TBB transmitter from 29 January to 6 February 2023. The horizontal and vertical axes design, respectively, the observation time in fractions of the day and the phase in degrees.

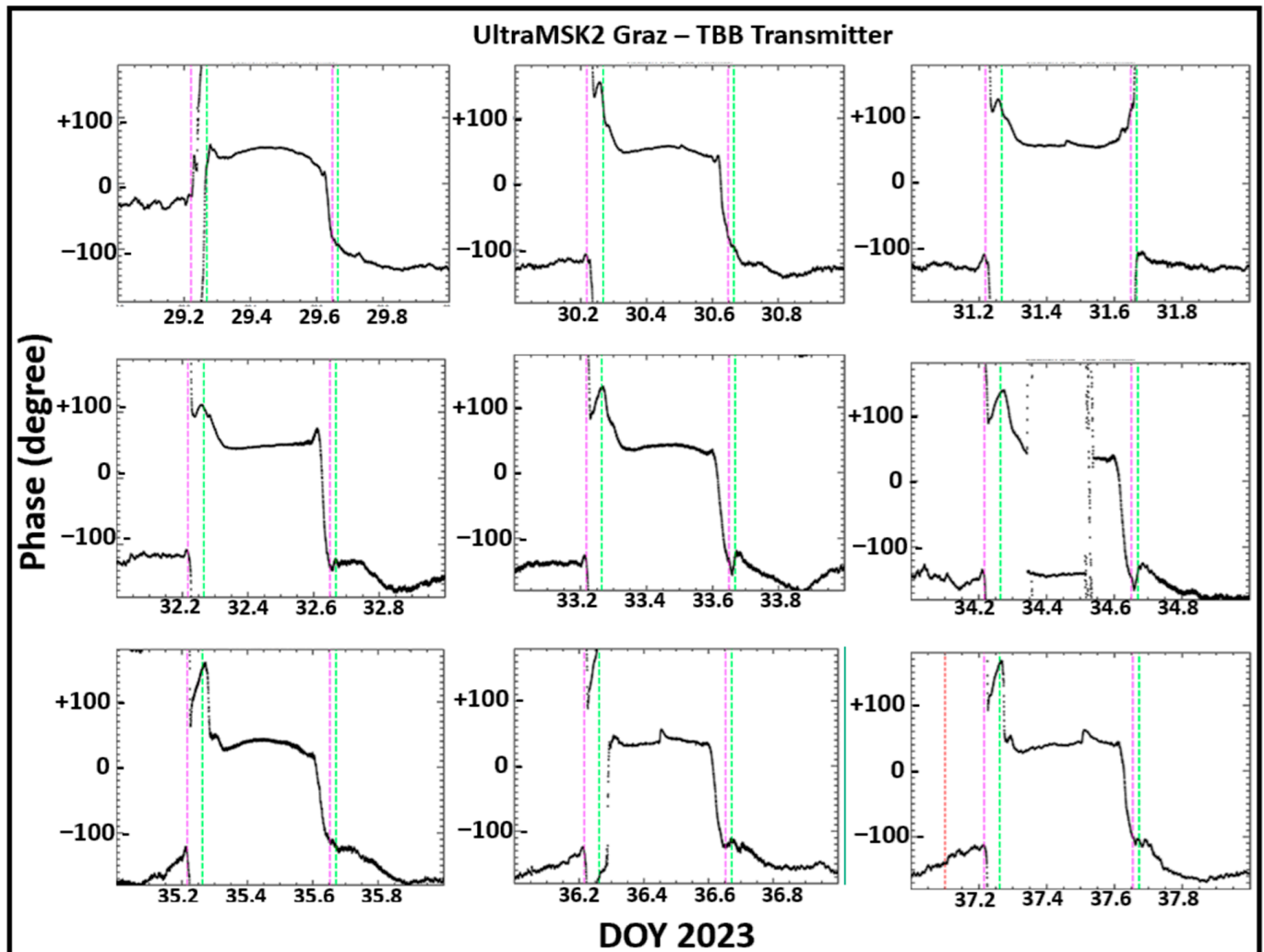


Figure 3. The phase variations of the TBB transmitter signal are shown from 29 January 2023 (029 DOY) to 6 February 2023 (037 DOY). The horizontal and vertical axes indicate the observation time in days of the year 2023 and the phase in degrees. Like in Figure 1, the green and violet vertical dashed lines correspond to the Graz facility and TBB transmitter station terminator times. The EQ event on 6 February 2023 (037 DOY) is designed by a dotted vertical line.

The phase variations exhibit, like in the case of the amplitude, a daily modulation linked to the night and day observations. It is the only common feature between both observed physical parameters, i.e., the amplitude and the phase modulations, due to the D- and E-layers influence. In Figure 3, we note the presence of particular features, like minima, maxima, and jumps of the phase, which occurred at terminator times. Those particular phase characteristics are detailed in the next sub-section. The jumps of the phase, from $+180^\circ$ to -180° , are principally observed at sunrise terminator times, and only on one occasion (031 DOY) it occurs at sunset terminator time. The night variation in the TBB signals leads to finding, on average, phases of about -130° on three occasions (i.e., 030 DOY,

031 DOY, 032 DOY) and in the order of -170° four days before EQ happening (i.e., 033 DOY, 034 DOY, 035 DOY). The day fluctuation shows, on average, a constant phase of about $+50^\circ$ for all investigated periods. The TBB transmitter phase is nearly constant during night or day observation. However, phase signal reveals on 033 DOY particular variations, from $+50^\circ$ to about -160° , a few hours after sunrise and until midday. The constant phase means a fixed angle between the VLF vertical electric monopole antenna at the Graz facility and the recorded VLF radio wave as emitted by the TBB transmitter. The phase is derived from the ratio between the minor and major axes related to the TBB ellipticity wave defined by $\tan \phi$, where ϕ is the phase. The sign of ϕ is positive and negative, respectively, when the wave is left-handed and right-handed polarized. It is important to mention that this phase is making a full rotation from -180° to $+180^\circ$, or $+180^\circ$ to -180° , at specific occasions around the sunrise and sunset terminator times. Like in Figure 2, the phase variation is subject to the solar activity effect on the same days (i.e., 030 DOY, 031 DOY, 036 DOY, 037 DOY).

3. Time Shifts of Sunrise and Sunset Using Multi-Terminators Method (MTM)

In this Section, we apply the MTM method [28] to make evident the presence of anomalies in the TBB transmitter amplitude and phase signals. In Section 3.1, we start with one example recorded on 2 February 2023, where we show how the spectral features are obtained (Section 3.1.1). This leads us in Sections 3.2 and 3.3 to characterize, respectively, the amplitude and phase anomalies recorded from 23 January 2023 (023 DOY) to 8 February 2023 (039 DOY).

3.1. Case Study of TBB Amplitude and Phase Variations as Recorded on 2 February 2023

We select 2 February 2023 to explain how we proceed to find minima and maxima around sunrise and sunset terminators as described in Section 3.1.1. The number of extrema recorded on 2 February 2023 is found to be equal to 19. This number is reduced to 8 by taking into consideration the closest minimum/maximum to a specific terminator, as detailed in Section 3.1.2. The main difference between the terminator method [17] and the multi-terminator method [28] is explained in Section 3.1.3.

3.1.1. Spectral Features Recorded on 2 February 2023

The daily amplitude and phase variations recorded on 2 February 2023 are displayed, respectively, in the left panel and right panel of Figure 4. TBB and Graz terminators are indicated, like in Figures 2 and 3, by magenta and green vertical dashed lines, respectively. The amplitude variation (left panel in Figure 4) shows the particular features that are saved for further investigation. It concerns minima and maxima occurring around the terminators and indicated by red and blue boxes in the left panel, respectively. In this case, we find three minima and two maxima at sunrise and two minima and two maxima at sunset. The phase fluctuations (right panel in Figure 4) exhibit more features. Hence, we note the presence of minima, maxima, and particular jumps around terminators. At the sunrise terminator, it occurs two minima, two maxima, and two jumps, and at the sunset terminator, three minima and two maxima. Table 1 lists the main features considered in Figure 4, where the type (minima, maxima, or jump) is given in the third column with the corresponding DOY (fractions of a day), the observation time (hours and minutes), the amplitude (expressed in dB) and the phase (expressed in degree).

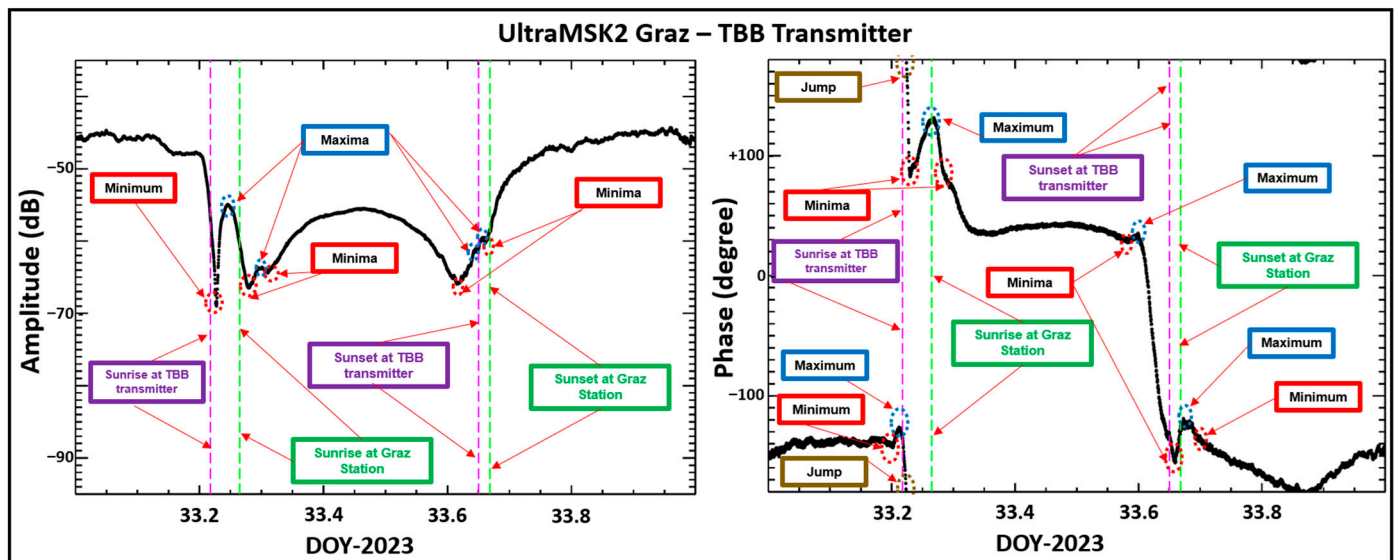


Figure 4. The multi-terminators method, applied in this study, leads to an estimate of the terminator time shift of the amplitude (left panel in Figure 4) and the phase (right panel in Figure 4) at sunrise and sunset as recorded on 2 February 2023 (033 DOY). We consider the two terminators, one at the Graz facility (green vertical dashed line) and the other at the TBB transmitter station (violet vertical dashed line). The particular features observed around both terminators for the investigated period, from 23 January (023 DOY) to 6 February 2023 (037 DOY), are stored. Minima and maxima variations are, respectively, designed by red and blue dashed boxes. Note the phase jumps (right-panel in Figure 4) at 33.2 DOY from -180° to $+180^\circ$ due to the reverse of the wave ellipticity axis around the TBB sunrise terminator. The main spectral features in Figure 4 are listed in Table 1.

Table 1. List of TBB transmitter spectral features occurring around sunrise and sunset terminators on 2 February 2023.

Figure	Type	DOY	Time (UT)	Amplitude (dB)	Phase (Degree)
Figure 4—right panel 2 February 2023 Amplitude	Sunrise	033.227	05:27	−68.99	+110.77°
	Sunrise	033.245	05:54	−54.94	+105.89°
	Sunrise	033.280	06:43	−66.48	+097.56°
	Sunrise	033.293	07:03	−63.81	+076.30°
	Sunrise	033.310	07:27	−64.42	+057.49°
	Sunset	033.615	14:46	−65.96	−004.88°
	Sunset	033.645	15:30	−61.04	−131.33°
	Sunset	033.657	15:46	−59.52	−151.95°
	Sunset	033.661	15:53	−60.15	−146.46°
	Sunset	033.672	16:08	−57.06	−122.19°
Figure 4—left panel 2 February 2023 Phase	Sunrise	033.201	04:50	−48.11	−143.32°
	Sunrise	033.212	05:05	−51.84	−126.03°
	Sunrise	033.224	05:22	−63.00	−179.98°
	Sunrise	033.224	05:22	−63.32	+177.15°
	Sunrise	033.231	05:32	−63.04	+082.86°
	Sunrise	033.266	06:23	−61.19	+130.76°
	Sunrise	033.291	07:00	−64.26	+075.69°
	Sunset	033.590	14:10	−63.12	+029.26°
	Sunset	033.600	14:23	−63.80	+035.48°
	Sunset	033.658	15:48	−59.80	−154.75°
	Sunset	033.672	16:08	−57.06	−122.19°
	Sunset	033.693	16:38	−52.09	−136.03°

3.1.2. Terminator Method Versus Multi-Terminator Method

The anomaly is associated with the time shift between the terminator time at the reception station (sunrise or sunset) and the time when the minima occur, as suggested

in [17]. The terminator method can be utilized for 2 February 2023. Table 2 lists the kept minima when considering the terminator method.

Table 2. List of TBB transmitter features when considering the terminator method [17] for the case of 2 February 2023.

Figure		Type	DOY	Time (UT)	Amplitude (dB)	Phase (Degree)
Figure 4—right panel 2 February 2023 Amplitude	Sunrise	Minimum	033.280	06:43	−66.48	+097.56°
	Sunset	Minimum	033.661	15:53	−60.15	−146.46°
Figure 4—left panel 2 February 2023 Phase	Sunrise	Minimum	033.291	07:00	−64.26	+075.69°
	Sunset	Minimum	033.658	15:48	−59.80	−154.75°

TBB transmitter features in Tables 1 and 2 have been derived by applying, respectively, the terminator method [17] and the multi-terminator method [28]. It is important to note that the number of extrema changes from one day to another, as found in our study. In the absence of an anomaly, the time shift is, on average, equal to zero. In this study, we apply the MTM method, where we increase the number of terminators from one (i.e., Graz facility terminator) to three (i.e., TBB station terminator and EQ epicenter terminator). The terminator method considers only minima close to the reception station, while the multi-terminator method studies minima but also maxima for several terminators (e.g., reception station, transmitter terminators, and EQ epicenter terminator).

3.1.3. Reduction in Selected Minima and Maxima Anomalies for the Event of 2 February 2023

In Section 3.1.1, we find 19 extrema as listed in Table 1. The selected event of 2 February 2023 originally has three minima and two maxima at sunrise and two minima and three maxima at sunset in the case of the amplitude. For the phase, we find three minima and two maxima at sunrise and three minima and two maxima at sunset. Using the closest terminator rule, the number of extrema reduces to eight for 2 February 2023 (033 DOY):

1. one minimum close to the TBB transmitter sunrise terminator for the amplitude,
2. one maximum close to the Graz station sunrise terminator for the amplitude,
3. one minimum close to the EQ epicenter sunset terminator for the amplitude,
4. one maximum close to the TBB transmitter sunset terminator for the amplitude,
5. one minimum close to the TBB transmitter sunrise terminator for the phase,
6. one maximum close to the Graz station sunrise terminator for the phase,
7. one minimum close to the TBB transmitter sunset terminator for the phase,
8. one maximum close to the Graz station sunset terminator for the phase.

The selected extrema associated with TBB signal variations are summarized in Table 3.

Table 3. List of extrema selected from Table 1 in the case of TBB transmitter signal recorded on 2 February 2023.

Figure		Type	DOY	Time (UT)	Closest Terminator
Figure 4—right panel 2 February 2023 Amplitude	Sunrise	Minimum	033.227	05:27	TBB transmitter
	Sunrise	Maximum	033.245	05:54	Graz reception
	Sunset	Minimum	033.615	14:46	EQ epicenter
	Sunset	Maximum	033.645	15:30	TBB transmitter
Figure 4—left panel 2 February 2023 Phase	Sunrise	Minimum	033.231	05:32	TBB transmitter
	Sunrise	Maximum	033.266	06:23	Graz reception
	Sunset	Minimum	033.658	15:48	TBB transmitter
	Sunset	Maximum	033.672	16:08	Graz reception

3.2. Anomalies in TBB Amplitude Signal at Sunrise and Sunset Terminators

We proceed to the estimations of the spectral features around the terminators for an extended time interval starting on 23 January 2023 and finishing on 8 February 2023. The multi-terminator method and the combined criteria considered in the case of 2 February 2023, as detailed in Section 3.1, are applied hereafter for the amplitude and phase anomalies recorded in the TBB signal.

Figure 5 shows the variations of the minima and maxima recorded around sunrise (first and second panels in Figure 5) and sunset (third and fourth panels in Figure 5) terminators versus DOY derived from the TBB amplitude signal. The horizontal and vertical axes indicate, respectively, the day of the year 2023 from 023 DOY to 040 DOY, and the terminator times expressed in hours. The red vertical dashed line was designed on the day of the earthquake occurrence, i.e., 6 February 2023 (037 DOY). The green, violet, and black lines in Figure 5 specify, respectively, the sunrise and sunset terminators at three locations: Graz VLF facility (47.03°N, 15.46°E), TBB transmitter station (37.40°N, 27.31°E) and the earthquake epicenter (37.17°N, 37.08°E).

The minimum amplitudes in the sunrise terminators (i.e., the first panel of Figure 5) appear mainly around the EQ epicenter sunrises on the first days (i.e., 023 DOY, 024 DOY, and 0263 DOY) and later on (i.e., 029 DOY, 030 DOY, 031 DOY, and 032 DOY). For TBB sunrise, minima of amplitude continuously occur but not on 027 DOY. The minima around Graz sunrise terminators are regularly observed, as shown in the first panel of Figure 5. The closest minima to a given sunrise terminator are (a) 023 DOY, 024 DOY, 026 DOY, 029 DOY, 031 DOY, and 032 DOY for EQ epicenter, (b) 025 DOY, and from 033 DOY to 039 DOY for TBB sunrise, and (c) 027 DOY and 028 DOY for Graz sunrise. The maximum amplitudes (i.e., the second panel in Figure 5) in the sunrise terminators are found to appear between TBB and EQ sunrise terminators from 023 DOY to 032 DOY and again on the day of EQ. For Graz terminators, the maxima are recorded during all 16 days. The nearest maxima to a given sunrise terminator are (a) 027 DOY and 037 DOY for the EQ terminator, (b) from 023 DOY to 026 DOY, 030 DOY, and 032 for TBB sunrise, and (c) for Graz terminators from 027 DOY to 029 DOY and later from 033 DOY to 039 DOY with the exception of 037 DOY.

The sunset amplitude minima (i.e., third panel in Figure 5) are found to occur near Graz terminators from 023 DOY to 029 DOY, 031 DOY, 033 DOY, and 036 DOY. Only a few minima are observed around TBB sunsets (i.e., 031 DOY and 038 DOY), and the other ones happen around EQ terminators (i.e., 024 DOY, from 027 DOY to 030 DOY, and from 032 DOY to 039 DOY). The adjoining minima to a given sunset terminator are (a) from 023 DOY to 026 DOY for Graz sunset, (b) one minimum (i.e., 031 DOY) for TBB terminators, and (c) all others (from 027 DOY to 030 DOY and 032 DOY to 039 DOY) for EQ terminators.

The sunset amplitude maxima (i.e., the fourth panel in Figure 5) exhibits a limited number of points per day, contrary to sunrise amplitude (minima and maxima) and sunset amplitude (minima). Maxima appears around the EQ terminator (i.e., the fourth panel in Figure 5) on eight days (i.e., from 023 DOY to 026 DOY, 032 DOY, 033 DOY, 037 DOY, and 038 DOY), six days (i.e., 027 DOY, 030 DOY, from 033 DOY to 035 DOY, and 038 DOY) nearby TBB terminators, and it decreases to five days for Graz sunset (i.e., 027 DOY, 029 DOY, 031 DOY, 036 DOY). The adjacent maxima to a specific sunset terminator are (a) from 023 DOY to 026 DOY, 032 DOY, 037 DOY and 038 DOY for EQ sunset terminators; (b) 027 DOY, 030 DOY, 033 DOY, 034 DOY and 035 DOY for TBB sunset terminators; and (c) 029 DOY, 031 DOY, and 036 DOY for Graz sunset terminators.

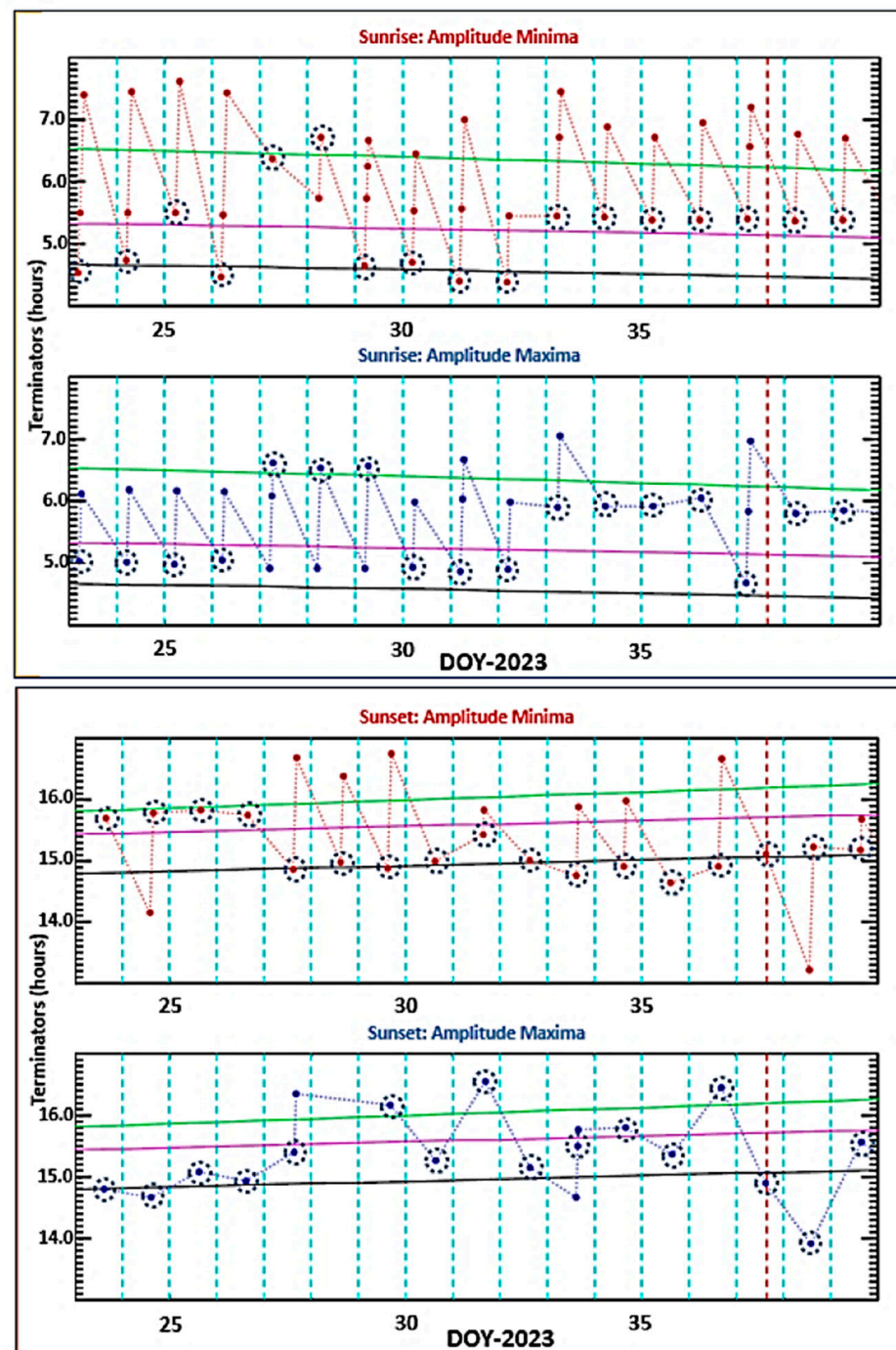


Figure 5. The minima and maxima of TBB amplitudes as recorded by the Graz facility at sunrise (first and second panels) and sunset (third and fourth panels). The horizontal and vertical axes indicate DOY 2023, and the terminator times are expressed in hours, respectively. The period starts on 23 January 2023 (023 DOY) and ends on 8 February 2023 (039 DOY). The earthquake day (037 DOY) is designed by the vertical red dashed line. The green, magenta, and black color lines indicate the sunrise or sunset terminator variations, respectively, at the Graz VLF facility (47.03°N , 15.46°E), TBB transmitter station (37.40°N , 27.31°E), and the earthquake epicenter (37.17°N , 37.08°E). The blue circles design selected minima and maxima anomalies as reported in Table 4.

3.3. Anomalies in TBB Phase Signal at Sunrise and Sunset Terminators

Figure 6 displays the sunrise (first and second panels) and the sunset (third and fourth panels) terminators derived from the phase of the TBB transmitter signal.

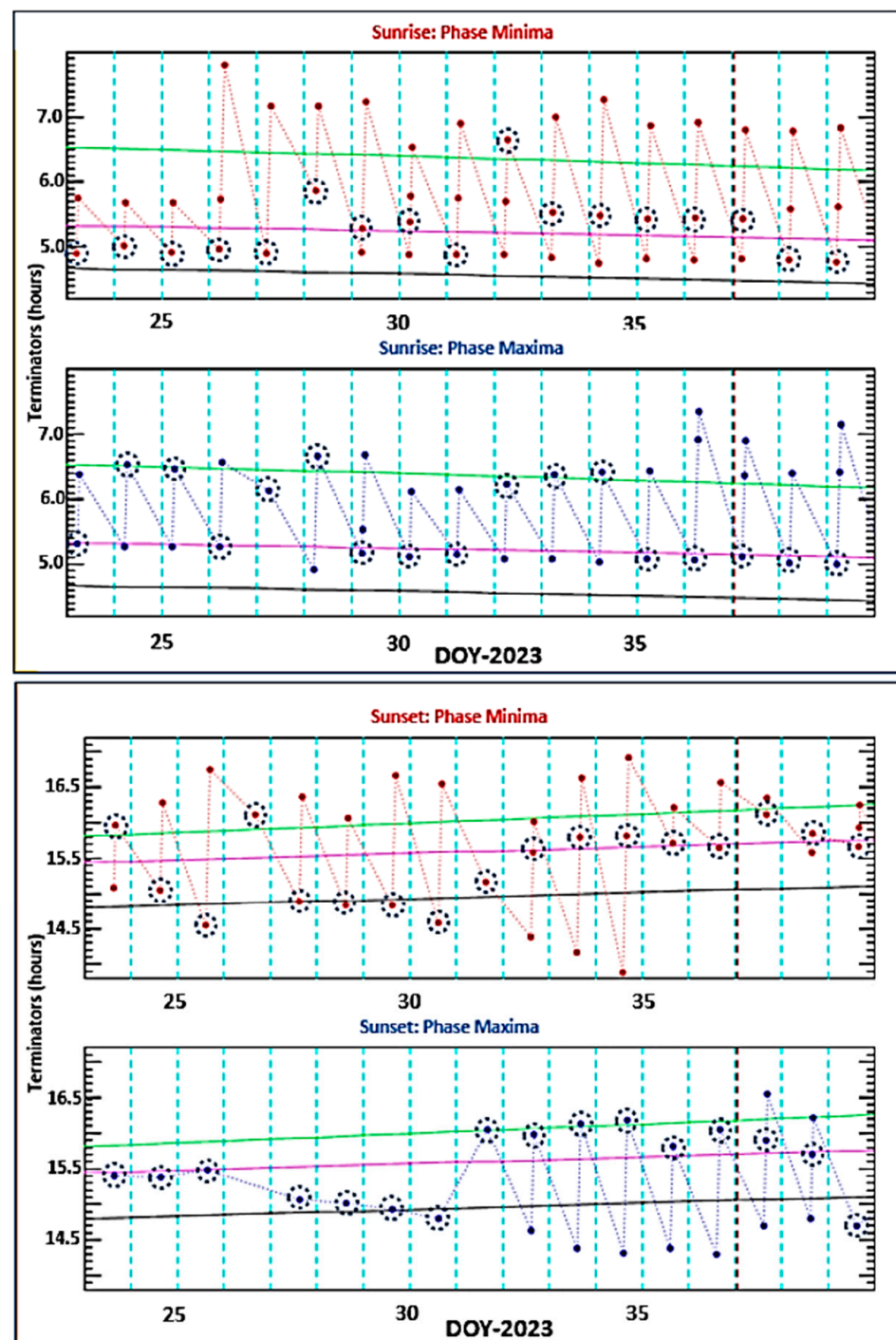


Figure 6. Like in Figure 5, but in the case of minima and maxima associated with the phase of the TBB transmitter signal, respectively, as recorded by the Graz facility at sunrise (two upper panels) and sunset (two lower panels) terminators. The blue circles design selected minima and maxima anomalies as reported in Table 4.

Horizontal and vertical axes indicate, respectively, DOY from 023 DOY to 039 DOY and terminator times expressed in hours. As shown in Figure 5, the sunrise and sunset terminators of the Graz facility (green line), TBB station (magenta line), and EQ epicenter (black line) are shown in Figure 6.

We find that several minima are associated with the phase signal, and at least three minima are observed daily. In the first panel of Figure 6, the minima occur above the EQ epicenter in the case of the sunrise terminators, close to TBB sunrise terminators,

and sometimes on or above the Graz sunrise terminators. The main minima take place around the TBB sunrise terminators. The closest minima to a given sunrise terminator are (a) 023 DOY, from 025 DOY to 027 DOY, 031 DOY, and 039 DOY for EQ terminators, (b) 024 DOY, from 028 DOY to 030 DOY, from 033 DOY to 038 DOY for TBB sunrise, and 032 DOY for Graz terminator. The phase maxima for sunrise terminators (second panel in Figure 6) are found to alter largely between Graz and TBB terminators. The adjacent maxima to a given sunrise terminator are (a) 023 DOY, 026 DOY, from 029 to 031 DOY, from 035 DOY to 039 DOY for TBB sunrises and (b) 024 DOY, 025 DOY, 027 DOY, 028 DOY, and from 032 DOY to 034 DOY for Graz terminator.

The sunset phase minima of TBB signals (third panel of Figure 6) are associated mainly with TBB and EQ sunset terminators. In the beginning and up to 030 DOY minima are around the EQ terminator and later about the TBB terminator. The nearby minima to a given terminator are (a) 023 DOY, 026 DOY, and 037 DOY for Graz sunset; (b) 024 DOY, 025 DOY, from 027 DOY to 031 DOY for EQ terminator; (c) from 032 DOY to 036 DOY, 038 DOY and 039 DOY for TBB sunset. The phase maxima of the TBB signal (fourth panel of Figure 6), which occurred at the sunset terminator, are linked first to TBB, then to EQ, and finally to Graz terminators. The closest maxima to a given sunset terminator are: (a) from 023 DOY to 025 DOY, 035 DOY, 037 DOY, and 038 DOY for TBB sunset, (b) from 027 DOY to 030 DOY and 039 DOY for EQ terminator, and (c) from 031 DOY to 034 DOY and 036 DOY for Graz sunset.

3.4. Summary of the Main Anomalies in Amplitude and Phase of TBB Signal

The main outcomes of the anomalies, as investigated in Sections 3.2 and 3.3, are summarized in Table 4. The terminators associated with Graz, TBB, and earthquake epicenter are indicated, respectively, by GR (green color), TB (magenta color), and EQ (black color). Table 4 lists in the first column minima and maxima at sunrise and sunset for the amplitude and the phase, in the second column the corresponding figures (i.e., Figure 5 for TBB amplitude and Figure 6 for TBB phase), and the next 17 columns provide the closest minima and maxima, for each day, to a given sunrise terminator or sunset terminator. Blue circles in Figures 5 and 6 indicate all selected minima and maxima anomalies, as detailed in Table 4. A total of 134 spectral features (i.e., 68 minima and 66 maxima) have been derived from TBB signal variations for the time interval from 023 DOY to 039 DOY. Only on two occasions have no maxima been observed at the sunset amplitude maxima and at the sunset phase maxima, respectively, on 028 DOY and 026 DOY.

It is possible to estimate from Table 4 the percentage of closest anomalies for given terminators. It comes that:

- Amplitude
 - Sunrise—Minima: EQ (41%), TB (47%) and GR (12%)
 - Sunrise—Maxima: EQ (07%), TB (41%) and GR (52%)
 - Sunset—Minima: EQ (70%), TB (07%) and GR (23%)
 - Sunset—Maxima: EQ (44%), TB (37%) and GR (29%)
- Phase
 - Sunrise—Minima: EQ (35%), TB (59%) and GR (06%)
 - Sunrise—Maxima: EQ (00%), TB (59%) and GR (41%)
 - Sunset—Minima: EQ (41%), TB (41%) and GR (18%)
 - Sunset—Maxima: EQ (31%), TB (38%) and GR (31%)

Table 4. List of spectral features (minima and maxima) related to TBB signal variations. The terminators associated with Graz (GR), TBB (TB), and earthquake epicenter (EQ) are indicated, respectively, by green, magenta, and black colors.

		DOY	023	024	025	026	027	028	029	030	031	032	033	034	035	036	037	038	039
Sunrise																			
Amplitude Minima	Figure 5 1st Panel	Time	EQ	EQ	TB	EQ	GR	GR	EQ	EQ	EQ	EQ	TB	TB	TB	TB	TB	TB	TB
Amplitude Maxima	Figure 5 2nd Panel	Time	TB	TB	TB	TB	GR	GR	GR	TB	TB	TB	GR	GR	GR	GR	EQ	GR	GR
		DOY	023	024	025	026	027	028	029	030	031	032	033	034	035	036	037	038	039
Sunset																			
Amplitude Minima	Figure 5 3rd Panel	Time	GR	GR	GR	GR	EQ	EQ	EQ	EQ	TB	EQ	EQ	EQ	EQ	EQ	EQ	EQ	EQ
Amplitude Maxima	Figure 5 4th Panel	Time	EQ	EQ	EQ	EQ	TB		GR	TB	GR	EQ	TB	TB	TB	GR	EQ	EQ	TB
		DOY	023	024	025	026	027	028	029	030	031	032	033	034	035	036	037	038	039
Sunrise																			
Phase Minima	Figure 6 1st Panel	Time	EQ	TB	EQ	EQ	EQ	TB	TB	TB	EQ	GR	TB	TB	TB	TB	TB	TB	EQ
Phase Maxima	Figure 6 2nd Panel	Time	TB	GR	GR	TB	GR	GR	TB	TB	TB	GR	GR	GR	TB	TB	TB	TB	TB
		DOY	023	024	025	026	027	028	029	030	031	032	033	034	035	036	037	038	039
Sunset																			
Phase Minima	Figure 6 3rd Panel	Time	GR	EQ	EQ	GR	EQ	EQ	EQ	EQ	EQ	TB	TB	TB	TB	TB	GR	TB	TB
Phase Maxima	Figure 6 4th Panel	Time	TB	TB	TB		EQ	EQ	EQ	EQ	GR	GR	GR	GR	TB	GR	TB	TB	EQ
		DOY	023	024	025	026	027	028	029	030	031	032	033	034	035	036	037	038	039

4. Discussion

The investigated amplitude and phase anomalies are discussed in this section, where we emphasize three aspects: the significant observation date when the anomaly becomes noticeable; the geographical latitude and longitude locations of the precursor earthquake regions; a scenario is suggested to explain the time and the dynamic evolution of the precursor seismic regions; and finally, a physical mechanism is proposed in relation with the lowering and raising of ionospheric boundaries.

4.1. Significant Terminator Anomalies Recorded by Graz Facility Are Those Linked to EQ Epicenter Regions

It is well known that the amplitude and phase variations emitted by VLF/LF transmitter signals and detected by a reception station are subject to the daily Earth's rotation. Those variations exhibit particularly minima at sunrise and sunset terminators associated with the reception facility. Several investigations (e.g., [17,22–24]) have shown that the time shift of the minima can be considered as EQ precursors. Our recent work [28] led us to find a relationship between the shifted minima and transmitter terminators in the case of the 2020 Croatian Earthquakes. The preseismic ionospheric disturbances linked to the Dobrovolsky preparation zone involve the absence of minima at Graz terminators and the appearance of minima at transmitter terminators. In this analysis of Turkey–Syrian EQ, we make evident the presence of shifted anomaly minima related to a transmitter station (i.e., TBB transmitter) and also to the EQ epicenter region. Hence, the amplitude and phase anomalies, as detailed in Section 3, are most significant when they happen close to EQ epicenter terminators, important when near TBB terminators, and not worth mentioning when close to Graz terminators. Evidently, the preparation EQ zone, defined by Dobrovolsky radius, included Graz and TBB stations; nevertheless, the main preseismic ionospheric disturbances are essentially in the surrounding epicenter areas and extend up to Graz station. The weighty percentage of 70% (see Section 3.4) is found to be related to EQ epicenter terminators when considering sunset minima derived from TBB amplitude signal (third panel of Figure 5), and about 60% related to TBB sunrise terminators as estimated from TBB phase signal (second panel of Figure 6). It comes as a first result that the anomaly appears on 27 January 2023 (027 DOY), more than one week before the EQ occurrence, i.e., 6 February 2023 (037 DOY).

4.2. Geographical Longitude and Latitude Locations of Terminator Anomalies

We have derived spectral anomaly features (i.e., minima and maxima) from TBB amplitude and phase variations. Those features occurred mainly before and after the sunrise and sunset terminators, as detailed in Table 4. We have collected more than 130 anomalies. One can consider that the sunrise or sunset anomaly is caused by a terminator at a specific longitude different from the local one (i.e., Graz terminator). In Table 4, for example, we list at sunrise an anomaly recorded at 04:32 UT for the amplitude minima when the sunrise terminator of Graz station is 06:32 UT for the date of 23 January 2023 (DOY 023). The difference in two hours (i.e., $06:32 - 04:32 = 02:00$ UT) means a change in longitude of 30° degrees since one hour corresponds to 15 degrees. The anomaly at 04:32 UT is linked to a geographical region located in the eastern part of Graz station with a longitude of more than 40° E. This simple method can be applied to all 130 anomalies, allowing us to estimate approximatively the anomaly terminator longitudes. However, this simple way of making longitude estimations is ambiguous because it only provides the longitude of the sunrise terminator or the sunset terminator but no information about the corresponding latitude.

So, it is suitable to consider that a specific geographical location produces the sunrise and also the sunset terminator anomalies for a given day. Using spherical trigonometry equations [53], one can estimate the sunrise and sunset terminators for a given geographical point (i.e., where the longitude and the latitude are known) on the Earth. This leads us to calculate the corresponding terminator by entering the following features: (a) the observation day between 23 January 2023 (DOY 023) and 8 February 2023 (DOY 029),

(b) the longitude from 15°E (close to Graz's longitude) to 37°E (adjacent to EQ epicenter) with 1° interval, and (c) the latitude between 37°N (close to EQ epicenter latitude) and 47°N (near to Graz's latitude) with 1° interval. For a given observation date, we derive 253 terminators (11×23) and for the investigated period (i.e., from 23 January (DOY 023) to 8 February (DOY 039)), a total of 4301 terminators (253×17). Those computed terminators are compared to the anomalies listed in Table 4. This permits us to find in the collected terminators those which are equal, or almost equal, to the ones of Table 4 and to derive the corresponding longitudes and latitudes. Figure 7 displays the anomaly geographical locations in the case of the amplitude (i.e., two upper panels and red color) and the phase (i.e., two lower panels and green color points). The horizontal and vertical axes indicate, respectively, the geographical longitude and latitude. The black points design the locations of the EQ epicenter (37.08°E, 37.17°N), the TBB transmitter station (27.31°E, 37.40°N), and the Graz Facility (15.46°E, 47.03°N). Tables 5 and 6 give the geographical coordinates of points displayed in Figure 7.

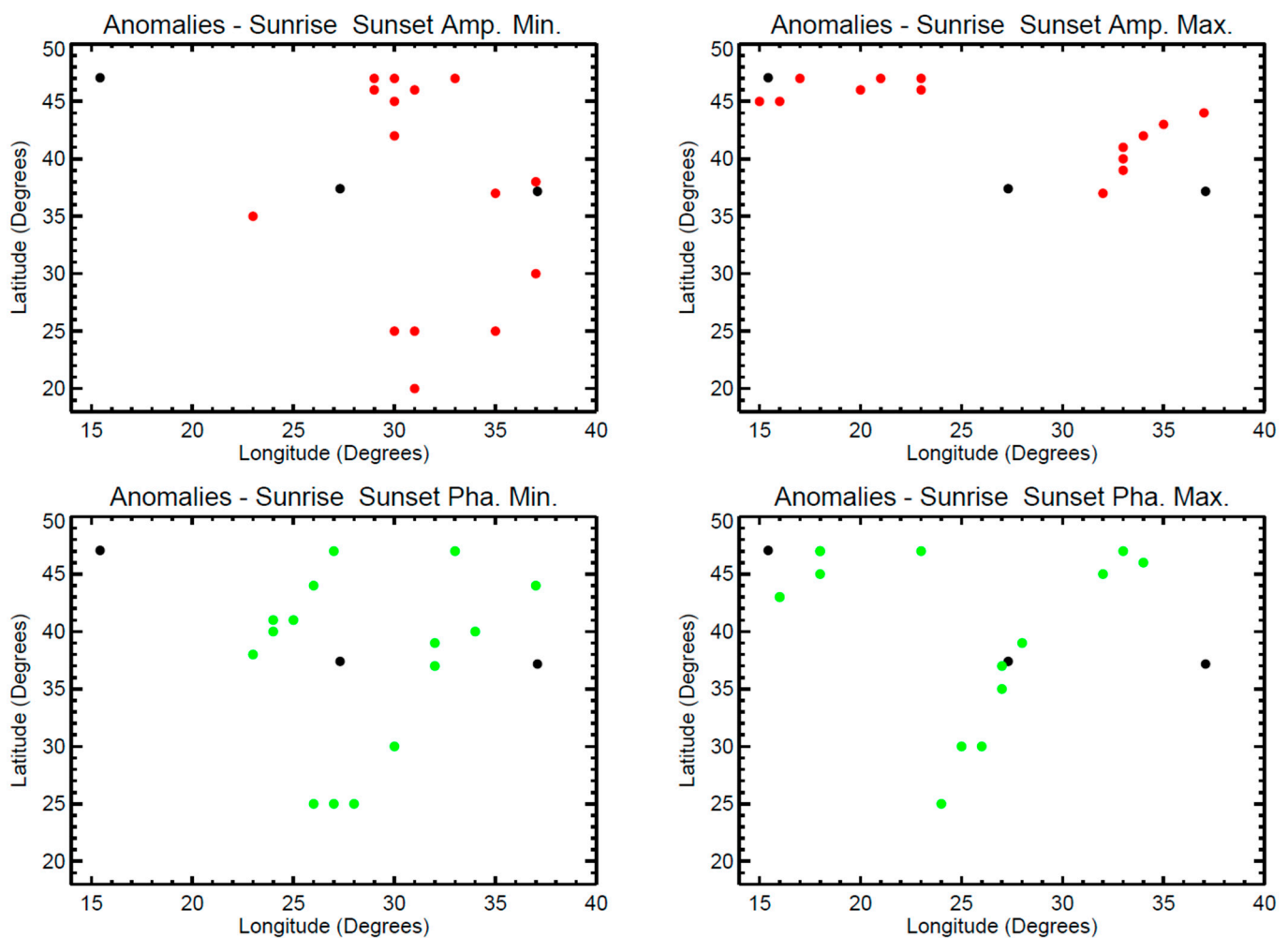


Figure 7. Anomaly locations taking into consideration sunrise and sunset terminators for minima and maxima of amplitude (first two panels with red color points) and phase (second two panels with green color points). The black points indicate Graz Facility (15.46°E, 47.03°N), TBB transmitter station (27.31°E, 37.40°N), and EQ epicenter (37.08°E, 37.17°N).

Table 5. List of longitude and latitude geographical coordinates of anomalies linked to minima as listed in Table 4.

Amplitude Minima					Amplitude Minima			
Figure 7: Upper-Left Panel					Figure 7: Lower-Left Panel			
DOY	Sunrise UT	Sunset UT	Longitude Degree	Latitude Degree	Sunrise UT	Sunrise UT	Longitude Degree	Latitude Degree
023	04:32	15:42	31°E	20°N	04:54	15:58	27°E	25°N
024	04:44	15:47	30°E	25°N	05:01	15:03	32°E	39°N
025	05:30	15:30	23°E	35°N	04:55	13:33	37°E	44°N
026	04:38	15:45	31°E	25°N	04:58	16:07	26°E	25°N
027	06:22	14:52	---	---	04:54	14:53	34°E	40°N
028	06:43	14:59	---	---	05:52	14:50	---	---
029	04:39	14:53	37°E	38°N	05:47	14:50	27°E	47°N
030	04:42	15:00	35°E	37°N	05:23	14:35	33°E	47°N
031	04:24	15:26	35°E	25°N	04:53	15:10	32°E	37°N
032	04:23	15:01	37°E	30°N	06:36	15:35	---	---
033	05:27	14:46	30°E	42°N	05:32	15:48	24°E	41°N
034	05:26	14:55	30°E	45°N	05:29	15:49	24°E	40°N
035	05:23	14:39	33°E	47°N	05:26	15:43	25°E	41°N
036	05:23	14:55	31°E	46°N	05:27	15:39	26°E	44°N
037	05:24	15:00	30°E	47°N	05:24	16:07	23°E	38°N
038	05:22	15:14	29°E	47°N	04:48	15:51	28°E	25°N
039	05:23	15:11	29°E	46°N	04:46	15:40	30°E	30°N

Table 6. List of longitude and latitude geographical coordinates of anomalies linked to maxima as listed in Table 4.

Amplitude Maxima					Amplitude Maxima			
Figure 7: Upper-Right Panel					Figure 7: Lower-Right Panel			
DOY	Sunrise UT	Sunset UT	Longitude Degree	Latitude Degree	Sunrise UT	Sunrise UT	Longitude Degree	Latitude Degree
023	05:02	14:48	34°E	42°N	05:19	15:24	28°E	39°N
024	05:01	14:40	35°E	43°N	06:32	15:23	18°E	47°N
025	04:59	15:05	33°E	39°N	06:28	15:29	18°E	47°N
026	05:03	14:56	33°E	41°N	05:19	---	---	---
027	06:37	15:24	17°E	47°N	06:08	15:04	23°E	47°N
028	06:32	---	---	---	06:40	15:01	---	---
029	06:34	16:10	15°E	45°N	05:10	14:56	32°E	45°N
030	04:56	15:16	32°E	37°N	05:07	14:48	34°E	46°N
031	04:52	16:33	22°E	10°N	05:09	16:03	24°E	25°N
032	04:54	15:09	33°E	40°N	06:14	15:59	18°E	45°N
033	05:54	15:30	21°E	47°N	06:23	16:08	16°E	43°N
034	05:55	15:48	20°E	46°N	06:25	16:11	16°E	43°N
035	05:55	15:22	23°E	47°N	05:05	15:49	27°E	35°N
036	06:03	16:27	16°E	45°N	05:04	16:03	25°E	30°N
037	04:41	14:54	37°E	44°N	05:07	15:54	26°E	30°N
038	05:48	13:55	---	---	05:01	15:42	27°E	37°N
039	05:51	15:34	23°E	46°N	05:00	14:42	33°E	47°N

Table 5 lists the minima of:

- the amplitude for a given DOY (first column), the sunrise (second column), the sunset (third column), longitude (fourth column), and latitude (fifth column). Those points are shown in the upper-left panel of Figure 7.

- the phase for a given DOY (first column), the sunrise (sixth column), the sunset (seventh column), the longitude (eighth column), and latitude (ninth column). Those points are shown in the lower-left panel of Figure 7.

Similarly, Table 6 indicates maxima of:

- the amplitude for a given DOY (first column), the sunrise (second column), the sunset (third column), longitude (fourth column), and latitude (fifth column). Those points are shown in the upper-right panel of Figure 7.
- the phase for a given DOY (first column), the sunrise (sixth column), the sunset (seventh column), the longitude (eighth column), and latitude (ninth column). Those points are shown in the lower-right panel of Figure 7.

The amplitude minimum anomalies (upper-left panel of Figure 7) appear as two nearly parallel bands: one from 31°E to 37°E and between 20°N and 38°N (hereafter called Band_Am_Min1), and the other from 23°E to 33°E and between 35°N and 47°N (hereafter called Band_Am_Min2). The first and second bands include, respectively, EQ epicenter and TBB station. The amplitude maximum anomalies (upper-right panel of Figure 7) also exhibit two bands but not parallels: one from 32°E to 37°E and between 37°N and 44°N (hereafter called Band_Am_Max1), and the other from 15°E to 23°E and between 45°N and 47°N (hereafter called Band_Am_Max2). In this case, the first band is observed between the EQ epicenter and TBB station, and the second band is close to Graz station.

The phase minimum anomalies (lower-left panel of Figure 7) show two nearly parallel bands: 26–37°E in longitudes and 25°N and 44°N in latitude (hereafter called Band_Ph_Min1), and the other 23–27°E and 38–47°N (hereafter called Band_Ph_Min2). The first and second bands happen, respectively, between EQ-TBB and TBB-GRZ. The phase maximum anomalies (lower-right panel of Figure 7) also display two parallel bands: one 24–33°E and 25°N and 47°N (hereafter called Band_Ph_Max1), and the other one 16–18°E and 43–47°N (hereafter called Band_Ph_Max2). In this case, the first band includes TBB station, and the second one is near Graz station.

Table 7 summarizes the main features of terminator anomalies as derived from Figure 7. In the first column is given the figure panel followed by the name, the beginning and the end of the first band (i.e., from second to fourth columns), and the same features for the second band (i.e., from five to seven columns).

Table 7. Main anomalies bands as derived from Figure 7.

Figure 7	Name	Band1 Begin	End	Name	Band2 Begin	End
Upper-left panel	Band_Am_Min1	31°E-20°N	37°E-38°N	Band_Am_Min2	23°E-35°N	33°E-47°N
Upper-right panel	Band_Am_Max1	32°E-37°N	37°E-44°N	Band_Am_Max2	15°E-45°N	23°E-47°N
Lower-left panel	Band_Ph_Min1	26°E-25°N	37°E-44°N	Band_Ph_Min2	15°E-45°N	23°E-47°N
Lower-right panel	Band_Ph_Max1	24°E-25°N	33°E-47°N	Band_Ph_Max2	16°E-43°N	18°E-47°N

4.3. Scenario of the Dynamics of the Radio Preparation Seismic Zone

Figure 8 displays the eastern part of the Mediterranean Sea with the surrounding countries. The fourth bands, as listed in Table 7, are shown in Figure 8 with red, green, blue, and magenta colors, respectively, for Band_Am_Min1, Band_Am_Min2, Band_Ph_Min1, and Band_Ph_Min2. The anomaly terminator days are given for each band, allowing us to track the time evolution of the radio preparation zone.

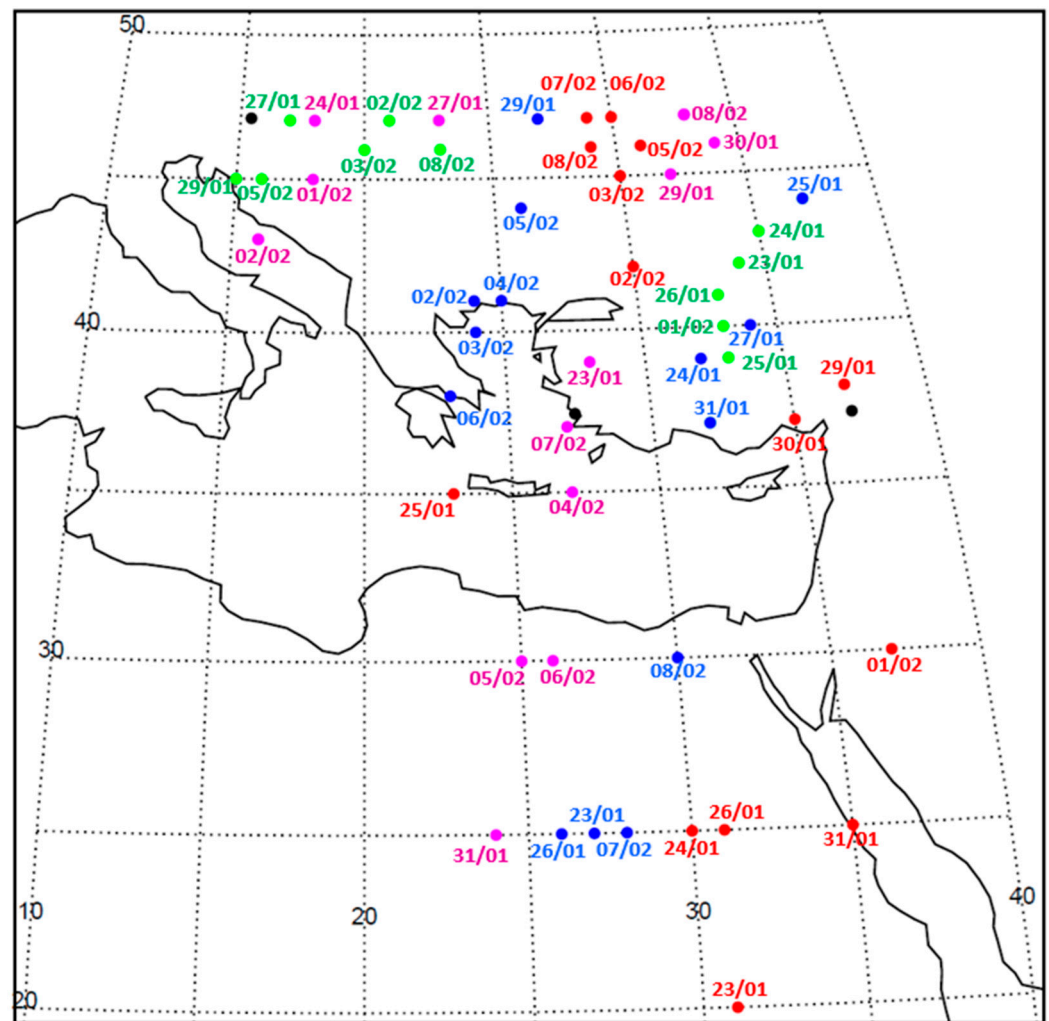


Figure 8. Geographical locations of the four bands as listed in Table 7. The horizontal and vertical axes indicate, respectively, the geographical longitude and latitude. The black points indicate Graz Facility (15.46°E, 47.03°N), TBB transmitter station (27.31°E, 37.40°N), and EQ epicenter (37.08°E, 37.17°N). The color points design the amplitude minimum anomalies (red color, Band_Am_Min1), the amplitude maximum anomalies (green color, Band_Am_Min2), the phase minimum anomalies (blue color, Band_Ph_Min1), and the phase maximum anomalies (magenta color, Band_Am_Min1). Each point is linked to the corresponding observation date (e.g., 24/01 to 24 January 2023).

It is possible to define different sub-areas considered to be part of the preparation zone. Hence, in Figure 9, we connect points that first belong to the same band and second those that have consecutive observation anomaly days. The sub-areas that exhibit latitudinal and longitudinal broadenings are shown, respectively, in the left panel and the right panel of Figure 9.

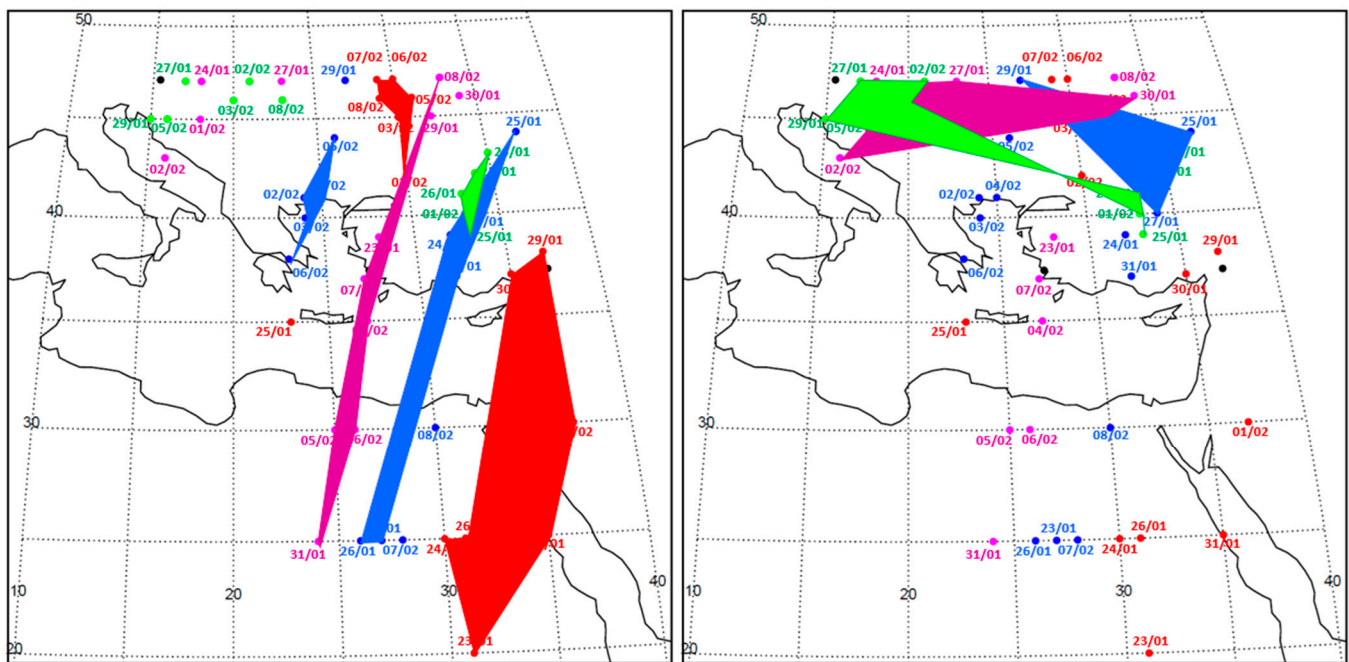


Figure 9. Geographical locations of the sub-areas that belong to the preparation earthquake zone. The sub-areas that are specific to given bands are shown with red, green, blue, and magenta colors corresponding to the amplitude minimum anomalies (Band_Am_Min1), the amplitude maximum anomalies (Band_Am_Min2), the phase minimum anomalies (Band_Ph_Min1) and the phase maximum anomalies (Band_Am_Min1). Latitudinal and longitudinal expansions are displayed, respectively, in the left and right panels.

The largest preparation sub-area is linked to Band_Am_Min1, as shown in the left panel of Figure 9. The anomaly appears on 23 January (023 DOY) and persists until 31 January (031 DOY). It mainly covers the Arabian tectonic plate. Parallel to this Arabian sub-area, we find two other sub-areas that mainly extend in latitudes, i.e., Band_Ph_Min1 and Band_Ph_Max1. The anomaly develops from 23 January (023 DOY) and to 31 January (032 DOY) for Band_Ph_Min1 and from 23 January (023 DOY) and to 08 February (039 DOY) for Band_Ph_Max1. Both start in the African tectonic plate, go across the eastern part of the Mediterranean Sea, intersect with the Anatolian tectonic plate, and end in the northern part of the Black Sea. Three smaller sub-areas exhibit latitudinal extensions: (a) one appears in the eastern part of the north Anatolian fault and ends in the Black Sea, covers the time period of 23 January (023 DOY) and to 1 February (032 DOY), and belongs to Band_Am_Max1. (b) The second occurs in the western part of the Black Sea, belongs to Band_Am_Min2, starts on 3 February (034 DOY) and finishes on 8 February (039 DOY). (c) The third develops in the Aegean Sea and extends to the Eurasian tectonic plate, begins on 2 February (033 DOY) until 06 February (037 DOY), and is linked to Band_Ph_Min2.

The preparation sub-areas that show longitudinal enlargement are observed at latitudes greater than 40°N, as displayed in the right panel of Figure 9. The first one emerges from the north Anatolian fault, crosses and ends in the Black Sea, starts on 25 January (025 DOY), and ends four days later. It is a combination of anomalies from Band_Ph_Min1 and Band_Ph_Min2. The second sub-area covers the Eurasian tectonic plate and extends to the northern part of the Black Sea. The observation time is from 24 January (024 DOY) to 02 February (033 DOY), and it is a mixture of anomalies from Band_Ph_Max1 and Band_Ph_Max2. The third one extends from the north Anatolian fault to the Eurasian tectonic plate and is a pattern of Band_Am_Max1 and Band_Am_Max2, as shown in the left panel of Figure 9. The anomalies appear on 23 January (023 DOY) and end on 8 February (039 DOY).

The geographical anomaly features and the corresponding observations lead us to consider three main steps, which develop, progress, and take place in the preparation seismic zone before the occurrence of the earthquakes on 6 February 2023 (037 DOY). The first step is mainly linked to the anomalies in the Arabian tectonic plate, which occupied an important geographical space, on average, of about 4.5° in longitude and 15° in latitude. The initial motion starts in the common tectonic region of the African and Arabian plates (32°E , 20°N) on 23 January (023 DOY) but ends in the EQ region (at about 37°E , 38°N) six days (031 DOY) before the seismic event happens. Like the first one, the second step appears on 23 January (023 DOY) at the latitude of about 25°N linked originally only to the African tectonic plate, crosses the Anatolian tectonic plate, and finishes in the northern part of the Black Sea. In this second step, it concerns two sub-areas that occupied a geographical space limited in longitude to less than 1.25° but extended to more than 20° in latitudes. One comes to an end six days (031 DOY) before EQ occurrence, like the Arabian tectonic anomaly, and the other one remains until 8 February 2023 (039 DOY). In this step, we note the apparition of three localized anomalies, smaller in size compared to previous ones. The first sub-area anomalies are found principally in the eastern part of the Black Sea above the north Anatolian fault (23 January—023 DOY to 01 February—032 DOY), the second in the western part of the Black Sea and extended to the Eurasia tectonic plate (3 February—034 DOY to 8 February—039 DOY), and the third one in the Eurasia tectonic plate (2 February—033 DOY to 6 February—037 DOY). The third step occurs in a geographical space starting in the eastern part of the north Anatolian fault (23 January—023 DOY), crossing the Black Sea from eastern to western, and finishing in the Eurasia tectonic plate. Three sub-areas are concerned, which develop from 23 January (023 DOY) to 1 February (032 DOY), 03 (034 DOY) to 08 (039 DOY) February, and 02 (033 DOY) to 06 (037 DOY) February, respectively.

The combination of those three steps leads us to suggest a probable dynamic development of the preseismic preparation zone. The main tectonic motions occur for the most part and are essentially in the Arabian tectonic plate and also in the African tectonic one. The generated tectonic seismic energy progresses in the south–north direction up to the east Anatolian fault for the Arabian tectonic plate, and for the African one, it continues through the Mediterranean Sea, beyond the northern part of the Black Sea, and reaching the Eurasia tectonic plate. The accumulated seismic energy is focalized and concentrated in latitudinal stresses below 40°N and more dispersed above this limit, where to start to occur the longitudinal stresses. This sudden and progressive transition of the seismic energy from latitudinal to longitudinal stresses is mainly due to the contacts, the frictions and the interactions of both the African and Eurasia tectonic plates. Also, the tectonic motions in the east–west direction of the Anatolian plate provide a second effect where the stresses are longitudinally oriented.

4.4. Physical Mechanisms at the Origin of EQ Terminator Time Shift Anomalies

In this analysis, the applied method is based on the estimation of the time shift of the minima and maxima for a given terminator, taking into consideration the amplitude and phase variations of the TBB transmitter. Two physical processes may be considered, the first one proposed by [21] and the second by [33]. The terminator time is formed as an interface between the ground wave and the sky wave [21]. During EQ, the path length of the sky wave decreases due to the lowering of the ionosphere boundary and, consequently, modifying the ground wave. Terminator time shift is due to the destructive interference between ground and sky waves [21]. However, this physical process does not explain how the ionospheric electron density is lowered prior to EQ. Probably, the ionospheric plasma lowering is due to the presence of preseismic acoustic waves and atmospheric gravity waves [33]. Hence, one can see in Figures 5 and 6 that the terminator time shift anomaly fluctuates from a few minutes to half an hour when considering the closest minima or maxima to given terminators. Such time shifts may be comparable to the periodic time scales related to AWs and AGWs [30,33]. It comes that the terminator time shift anomalies

are the consequence of the ionospheric lowering (i.e., minima) and raising (i.e., maxima) generated by acoustic waves and atmospheric gravity waves.

5. Conclusions

The acoustic (AWs) and atmospheric gravity waves (AGWs) are probably at the origin of the ionospheric disturbances, which involve terminator time shift anomalies linked to the amplitude and the phase of the TBB transmitter signal as detected by the Graz facility. The terminator time shift prior to EQ is probably due to the lowering (i.e., minima) and the raising (i.e., maxima) of ionospheric plasma generated by atmospheric waves. Such anomalies have been investigated in the case of the Turkey–Syria earthquake of 6 February 2023. The preparation zone has been derived from the Dobrovolsky relationship. This led us to guess and infer that the TBB transmitter signal is probably subject to disturbances during its radio wave propagation in the ionosphere and can be detected by the Graz facility. The transmitter station and also the Graz facility are found to be bordered by the Dobrovolsky preseismic area. We have applied the multi-terminators method [28], which has allowed us to emphasize the spectral features that occurred in the amplitude and the phase of the TBB signal at sunrise and sunset terminators two weeks before the occurrence of the Anatolian EQ. A total of more than 130 anomalies related to minima and maxima derived from the amplitude and the phase are considered. We show that those anomalies may provide the geographical longitude of a given anomaly but not the latitude. This latitudinal difficulty has been resolved by linking, for a given observation day, sunrise and sunset terminators of minimum anomalies or sunrise and sunset terminators of maximum anomalies as derived from the amplitude and the phase of the TBB signal. This has allowed us to find the geographical locations of the sunrise–sunset terminator for a given date and to analyze the seismic preparation zone related to the African, Arabian, Anatolian, and Eurasia tectonic plates. It comes that two weeks before the EQ occurrence, a large seismic preparation zone was linked to Arabian and African tectonic plates, followed by two other zones that extended from African to Anatolian tectonic plates through the Mediterranean Sea. Those exhibit latitudinal stresses oriented in the south–north direction. Several days before EQ happens, additionally, smaller seismic preparation regions are found principally in the Black Sea. Those smaller regions extend from the Anatolian to the Eurasia tectonic plates and display longitudinal stresses oriented in east–west directions.

Our results provide new perspectives toward a better comprehension of earthquake precursors using ionospheric radio sounding techniques (e.g., multi-terminators method). This technique needs to be merged with ionospheric plasma parameters [54] and space observations like CSES satellites [55,56]. This will lead to an emphasis on EQ forecasting by localizing and delimiting the most probable sub-seismic areas.

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