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Key Points:

- Short-term ionospheric reactions to GRBs are studied for the first time
- Short-term ionospheric reactions are confirmed during and after GRB events
- Statistical analysis indicates possibility of direct and secondary ionization

Supporting Information:

- Supporting Information S1

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Detection of short-term response of the low ionosphere on gamma ray bursts

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Abstract In this paper, we study the possibility of detection of short-term terrestrial lower ionospheric response to gamma ray bursts (GRBs) using a statistical analysis of perturbations of six very low or low-frequency (VLF/LF) radio signals emitted by transmitters located worldwide and recorded by VLF/LF receiver located in Belgrade (Serbia). We consider a sample of 54 short-lasting GRBs (shorter than 1 min) detected by the Swift satellite during the period 2009–2012. We find that a statistically significant perturbation can be present in the low ionosphere, and reactions on GRBs may be observed immediately after the beginning of the GRB event or with a time delay of 60 s–90 s.

1. Introduction

Gamma ray bursts (GRBs) are known as the most energetic phenomena in the universe where a huge amount of energy is released and their investigation is of a great astrophysical importance (see, for review, *Gehrels et al.* [2009], and references therein). Consequently, there is a question: how much can a GRB event disturb the Earth atmosphere, especially the ionosphere? It is expected that photons with a minimum energy of a few keV can influence the electrical conductivity of the ionosphere; however, the very low ionization cross section for these photons in the ionosphere may provide an effective transit of GRBs without significant perturbation in the ionosphere.

On the other hand, the recording of a GRB event in the ionosphere is a very complex task since many physical phenomena perturb the ionosphere including lightning, electron precipitation, solar activity, and more. Also, GRBs and observed part of the ionosphere may have different characteristics during a GRB event. Therefore, it is very hard to prove that a particular perturbation, observed close to a GRB event, is related to it.

The ionospheric perturbation caused by a particular GRB can be confirmed if it is sufficiently intensive and long lasting as reported by *Inan et al.* [2007a] that the atmosphere exposed to the impact of radiation was disturbed more than 1 h at altitudes below about 70 km. The modeling of electron density perturbations for this case shows that the variation of this parameter increases toward the lower heights and reaches a rise of 4 orders of magnitude at an altitude of about 20 km. Although satellites have recorded an average of about one GRB per day, these intensive ionospheric reactions are very rare and only a few such events have been recorded. An indication of a long-term ionospheric perturbation was first reported by *Fishman and Inan* [1988] for the GRB30801 event. They proposed that a network of VLF signal monitors may provide some relevant information on GRBs and their influence on the ionosphere. However, after this report, there are only a few papers which reported the detection of long-term ionospheric perturbations due to GRB events: GRB030329 [*Maeda et al.*, 2005], GRB041227 [*Inan et al.*, 2007a; *Huang et al.*, 2008], GRB 060124 [*Hudec et al.*, 2010], GRB090122 [*Tanaka et al.*, 2010], GRB080320A [*Hudec et al.*, 2010], and GRB080319D [*Slosiar et al.*, 2011]. An effort for the indirect detection of GRBs by their ionospheric response observed by VLF/LF signals and discussion on its possible impact on the GRB science and investigations, in general, has been given in *Slosiar et al.* [2011].

However, there are no investigations of low intensive ionospheric perturbations. The aim of this paper is to present possible short-duration ionospheric perturbations caused by GRB events. We used VLF (3 kHz–30 kHz) and LF (30 kHz–300 kHz) radio signals to detect ionosphere disturbances in a short period around GRB events for 54 GRBs observed by Swift during 2009–2012.

2. Observations

In this study, we are trying to explore any perturbation in the ionosphere which may be connected with a GRB event and we are using a statistical analysis to find ionospheric perturbations in the period of a GRB event. Consequently, we search for any ionospheric perturbation around the GRB event. To determine time intervals around a GRB event recording by satellite we first analyzed several studies related to the low ionospheric reactions to GRBs.

2.1. The Observed Time Intervals and Duration of Ionospheric Perturbations

During X-ray flares, there is a time delay between the start of satellite recording and the moment when perturbation is observed in the ionosphere. One can expect the same to be true for GRBs. Moreover, this was confirmed during the GRB041227 event [see *Inan et al.*, 2007a], and GRB080319D and GRB080320A events [*Hudec et al.*, 2010].

The durations of ionospheric perturbations, presented in previous works, connected with GRB events are usually long term as can be seen, for example, in *Inan et al.* [2007a] (longer than 1 h) and *Chakrabarti et al.* [2010] (several seconds) and they depend on considered location [*Tanaka et al.*, 2010]. However, short-term perturbations are also presented during relevant long-term reaction [*Inan et al.*, 2007a]. Here we consider that short-duration ionospheric perturbations last less than 1 s and others we consider as long term. Therefore, for our investigation we use the VLF/LF data with a time resolution of 0.02 s.

One should consider that the ionospheric perturbations can appear during and after a GRB event; we consider an interval of 4 min around the GRB event, i.e., 2 min before and 2 min after the start of the GRB event recorded by the Swift satellite. It allows us to compare perturbations that occur immediately before and after the beginning of the GRB event. Figure 1 shows an example of short-term amplitude perturbations of signal (top) emitted by transmitters shown in the map (bottom) and recorded with Belgrade receiver less than 10 s after the GRB110223B event observed at 21:25:48 UT on 23 February 2010.

2.2. Experimental Setup

A low ionospheric electron density disturbance perturbs subionospheric VLF/LF signals which propagate in the Earth-ionosphere waveguide on Great Circle Paths (GCPs). The reflection of VLF/LF signal occurs below 85 km and depends on the local electron density. The electron density indicates ionospheric perturbation: this causes time variations of the VLF/LF wave trajectory and, consequently, recorded wave amplitude and phase [*Grubor et al.*, 2008].

The amplitude and phase of VLF/LF radio signals observed at any point can thus be used to measure the spatial and temporal characteristics of local disturbances in the lower ionosphere. The advantage of this method is that it provides continuous monitoring of a large portion of the lower ionosphere. This is achieved with VLF/LF receivers monitoring the signal, with <1 s time resolution, from VLF/LF transmitting beacons which are scattered around the world. These signal perturbations allow recording periodic and global influences as well as unforeseen and located events (for more details, see *Inan et al.* [1990], *Thomson and Clilverd* [2000], *Haldoupis et al.* [2006], *Nina and Čadež* [2013], and *Salut et al.* [2013]).

In this paper we used six radio signals in VLF and LF domains emitted from DHO (Germany), GQD (UK), ICV (Italy), NRK (Iceland), NAA (USA), and NWC (Australia) and recorded by the VLF/LF receiver located in Belgrade (Serbia) (see map in Figure 1). The characteristics of transmitters, signal propagation paths, and related amplitudes are given in Table 1.

We utilize the VLF/LF amplitudes of these transmitters recorded by the AWESOME (Atmospheric Weather Electromagnetic System for Observation Modeling and Education) receiver system [*Cohen et al.*, 2010] located in Belgrade, Serbia (a part of Stanford/AWESOME Collaboration for Global VLF Research) with the sampling period of 0.02 s.

3. Methods

3.1. The GRB Sample

In this study, we selected a GRB sample observed by the Swift satellite when the received VLF/LF signal is not significantly affected by other perturbers. This satellite contains the gamma ray telescope which covers energy range from 15 to 150 keV, X-ray telescope monitoring from 0.2 to 10 keV, and ultraviolet/optical instrument for afterglow detection. In this study we consider the first phase of GRB events, the so-called gamma phase,

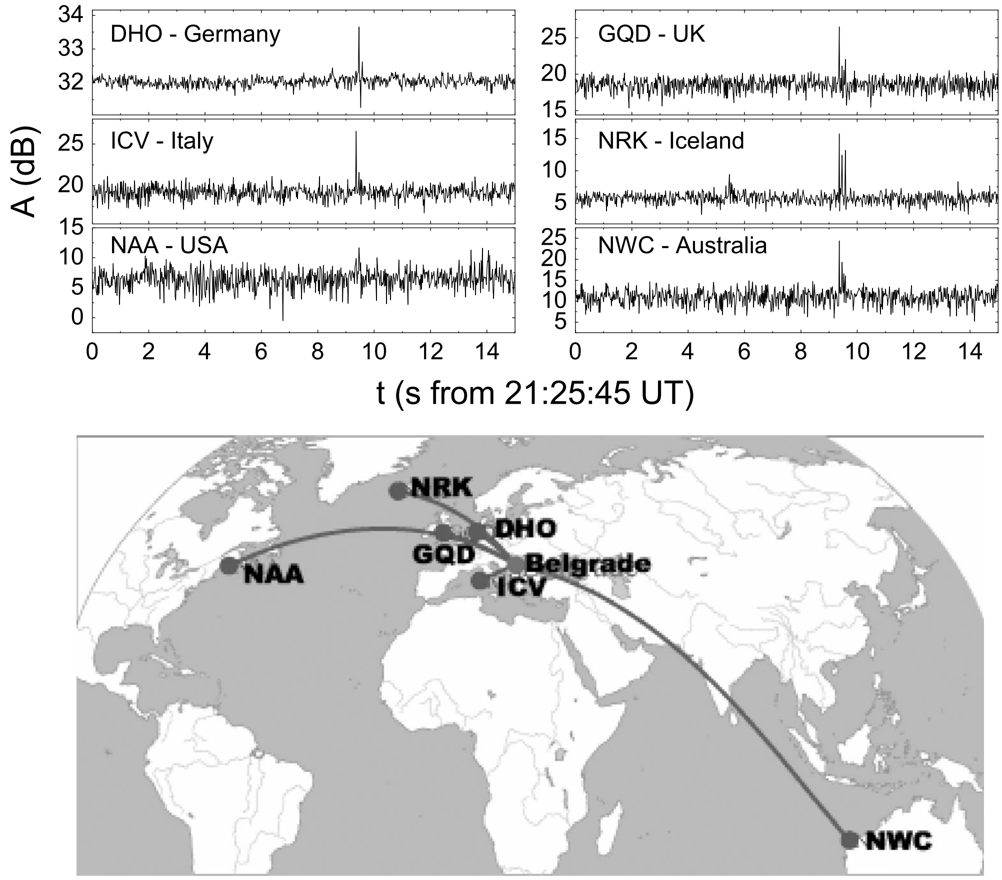

Figure 1. (top) A short-time amplitude amplification in the VLF/LF signals emitted from six transmitters (labeled at panels) and recorded by the Belgrade VLF/LF receiver possibly induced by the GRB110223B event occurred at 21:25:48 UT on 23 February 2010 less than 10 s after its beginning. (bottom) The transmitters and receiver locations and signal propagation paths indicated in the map. Transmitters and signal characteristics are given in Table 1.

with photon energies in GeV and MeV down to keV band and a time interval less then 100 s (for most of the bursts). We used data obtained by the gamma ray telescope related to the parts of hard X (12.4 keV – 124 keV) and γ radiation (above 124 keV). The time resolution of these data is 0.01 s. To analyze the whole duration of the GRBs and possible secondary reactions after the intrusion of intense high-energy radiation we selected only short-lasting GRBs, i.e., GRB events lasting less than 1 min. From the obtained data the maximum lasting of a GRB event in the sample is around 50 s.

To estimate the GRBs duration in the selected sample we used the so-called radiation intensity criteria; i.e., we start measurements at the moment when the radiation of pulses in a GRB light curve exceeds background noise by 10%. The duration is then measured in such a way to include all of the existing peaks

Table 1. Characteristics of Transmitters, Signal Propagation Paths, and Number of GRB Events Related to VLF/LF Signal Propagation During Daytime, Nighttime, and ST Conditions

Transmitter				Signal Path	Number of GRBs		
Sign	Location	Frequency (kHz)	Power (kW)	Length (km)	Daytime	Nighttime	ST
DHO	Rhauderfehn, Germany	23.4	800	1304	13	28	10
GQD	Anthorn, UK	22.1	200	1935	16	28	10
ICV	Isola di Tavolara, Italy	20.27	20	976	16	28	10
NRK	Grindavik, Island	37.5	800	3230	16	28	10
NAA	Cutler, Maine, USA	24.0	1000	6548	11	20	23
NWC	North West Cape, Australia	19.8	1000	11974	15	8	31

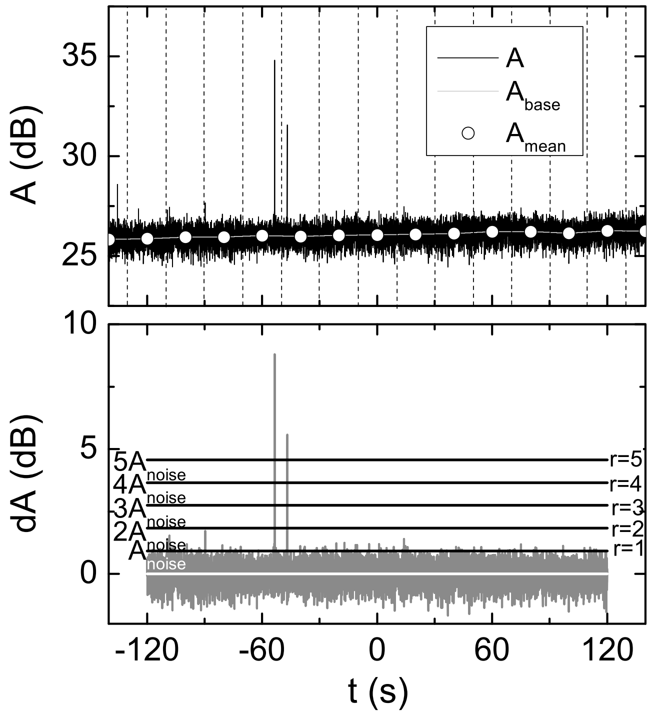

Figure 2. The method for peak determination in a VLF/LF signal. (top) Determination of baseline amplitude, A_{base}, (gray line) by interpolation of averaged amplitude, A_{mean}, (scatters) within 20 s intervals. (bottom) Determination of levels r that is 2 to 5 times larger than noise level. Amplitude noise A_{noise} is defined as the maximum absolute value of dA (deviation of recorded amplitude A of baseline amplitude A_{base}) after elimination p = 2% of its largest and lowest values.

in the observed light curve. This approach is good enough for our purpose, since we expect that sudden or sharp increase of the radiation could possibly produce some ionization events. Using the criteria mentioned above, we are able to select 54 GRBs in the period 2009–2012 (see Table S1 in the supporting information).

3.2. Signal Processing

In this study we developed a method for accounting peaks in the VLF/LF signal. We compare the signal 2 min before and 2 min after a GRB to find a number of peaks before and after the GRB event. The tendency of signal amplitude and its noise depends on signal characteristics and properties of the medium where it is propagating. Therefore, first, we found unperturbed signal amplitude, the so-called baseline, A_{base} as it is illustrated in Figure 2 (top). To find the noise level we calculated deviations of recorded amplitude $A(t)$ from A_{base} ($dA(t) = A(t) - A_{base(t)}$). Amplitude noise A_{noise} is defined as the maximum absolute value of dA after elimination $p = 2\%$ of maximum and minimum values of dA (see Figure 2, bottom). The detailed analysis shows that the noise level dependent on p affects only the value r (see equation (1)) at which the signal response detections start without essential effects on visualization of detections (see Figure S2 and its explanation in the supporting information). In the present analysis we fix p to 2% to provide better visibility without loss of significant information.

Peak classification is determined quantitatively by the ratio of deviations of the recorded amplitude $A(t)$ from the amplitude of the base curve $A_{base}(t)$ at the time t and the noise amplitude A_{noise} as follows:

$$\frac{A(t) - A_{base}(t)}{A_{noise}} \geq r \tag{1}$$

for $r = 2$, 3, 4, and 5 (see Figure 2, bottom). In the analysis we found that there is no big difference between the number of peaks for $r = 3$, 4, and 5; therefore, here we will present the results for $r = 2$ and 3.

To find statistical significance of appearing peaks in time interval (shown in Figures 3 and 4) we calculated

$$\sigma_i = \frac{x_i - \overline{X}}{\overline{X}} \cdot 100\%, \tag{2}$$

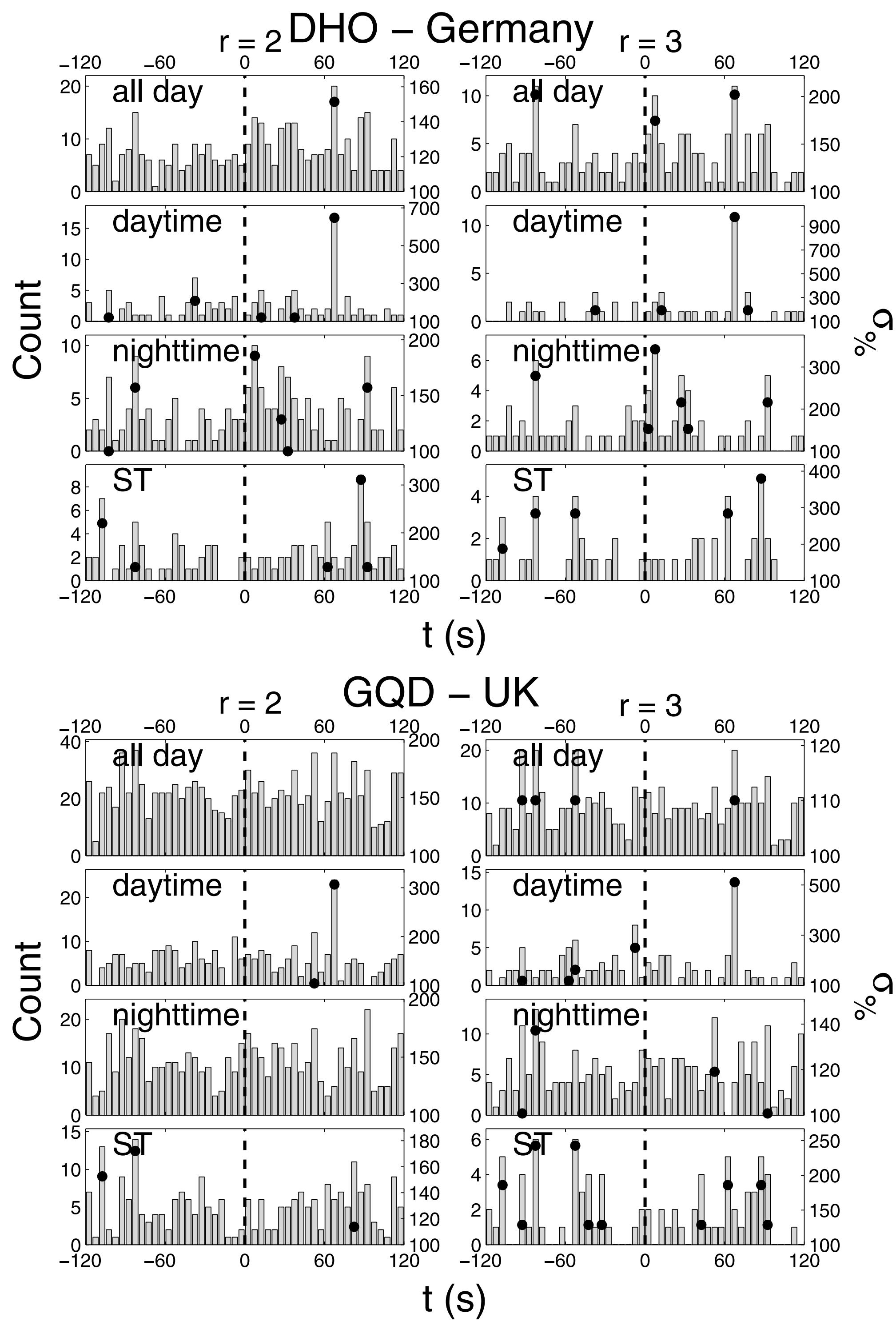

Figure 3. Histograms of number of peaks for signals emitted by different transmitters (noted on plots) accounted in time bins of 5 s for (left) $r = 2$ and (right) $r = 3$. The vertical lines denote the time of the satellite GRB recording and the black points indicate the statistically significant increase of peak numbers within bins indicated by values of σ given by equation (2) (right axes). For each transmitter the whole sample, daytime, nighttime, and ST conditions are given (from top to bottom).

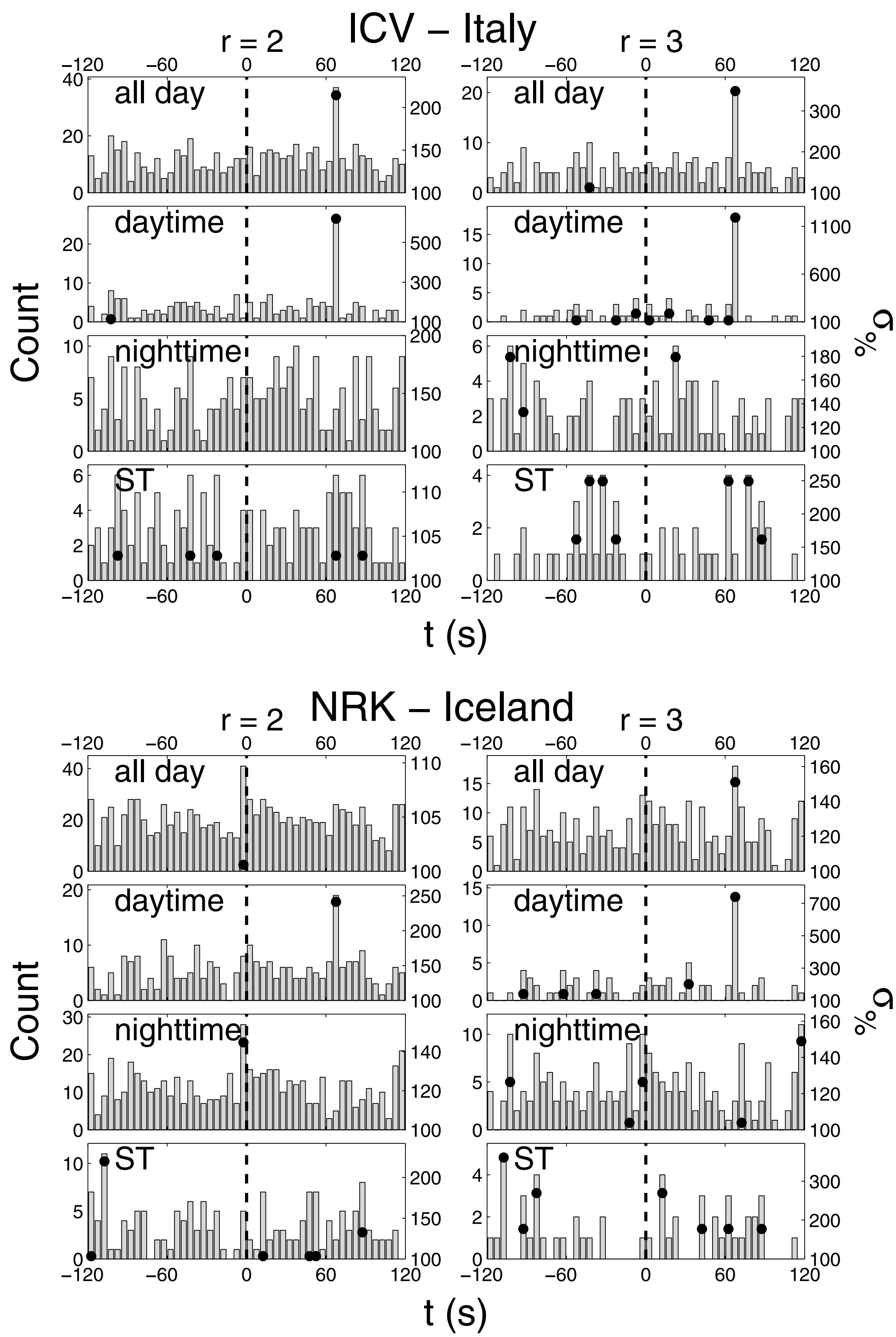

Figure 3. (continued)

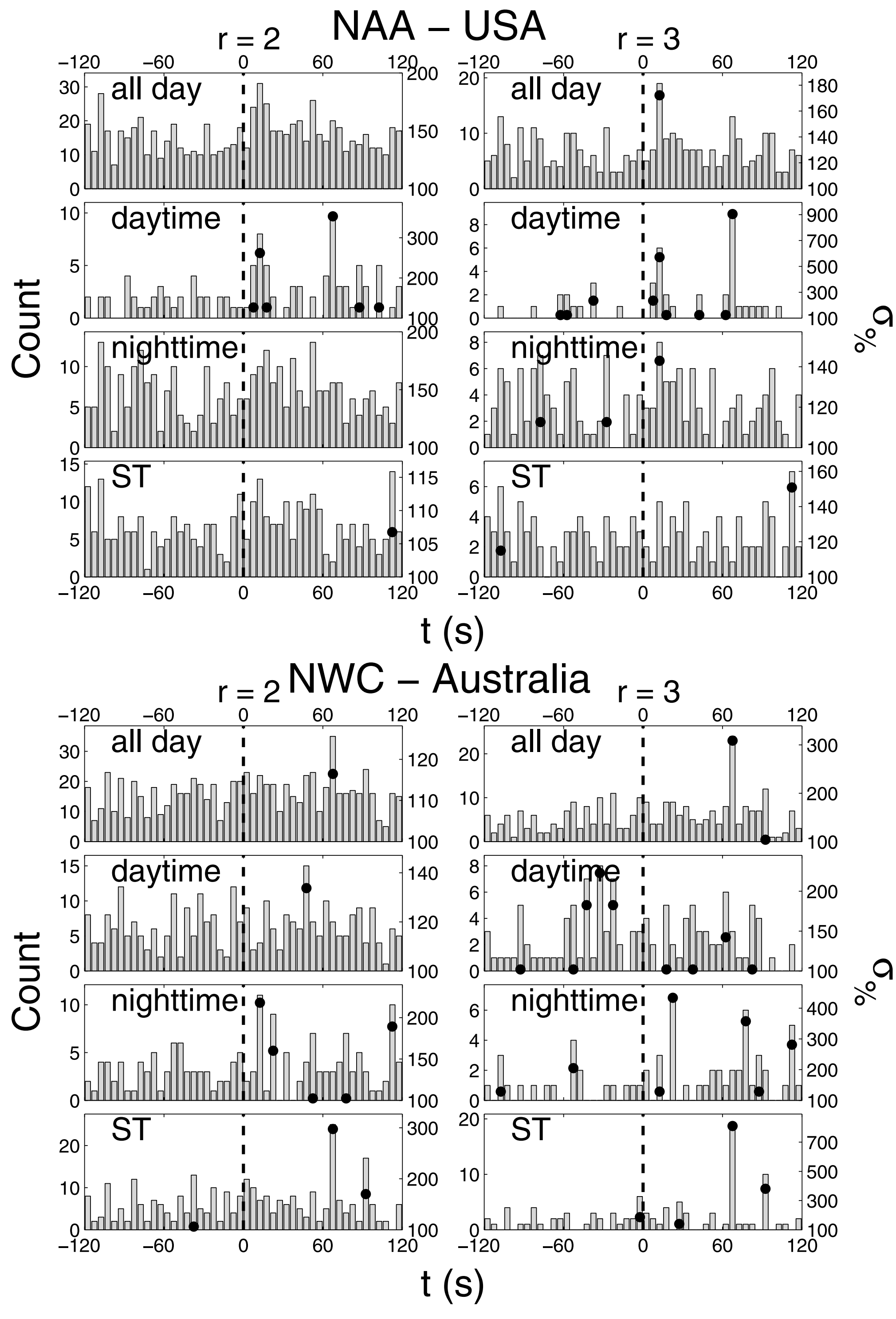

Figure 3. (continued)

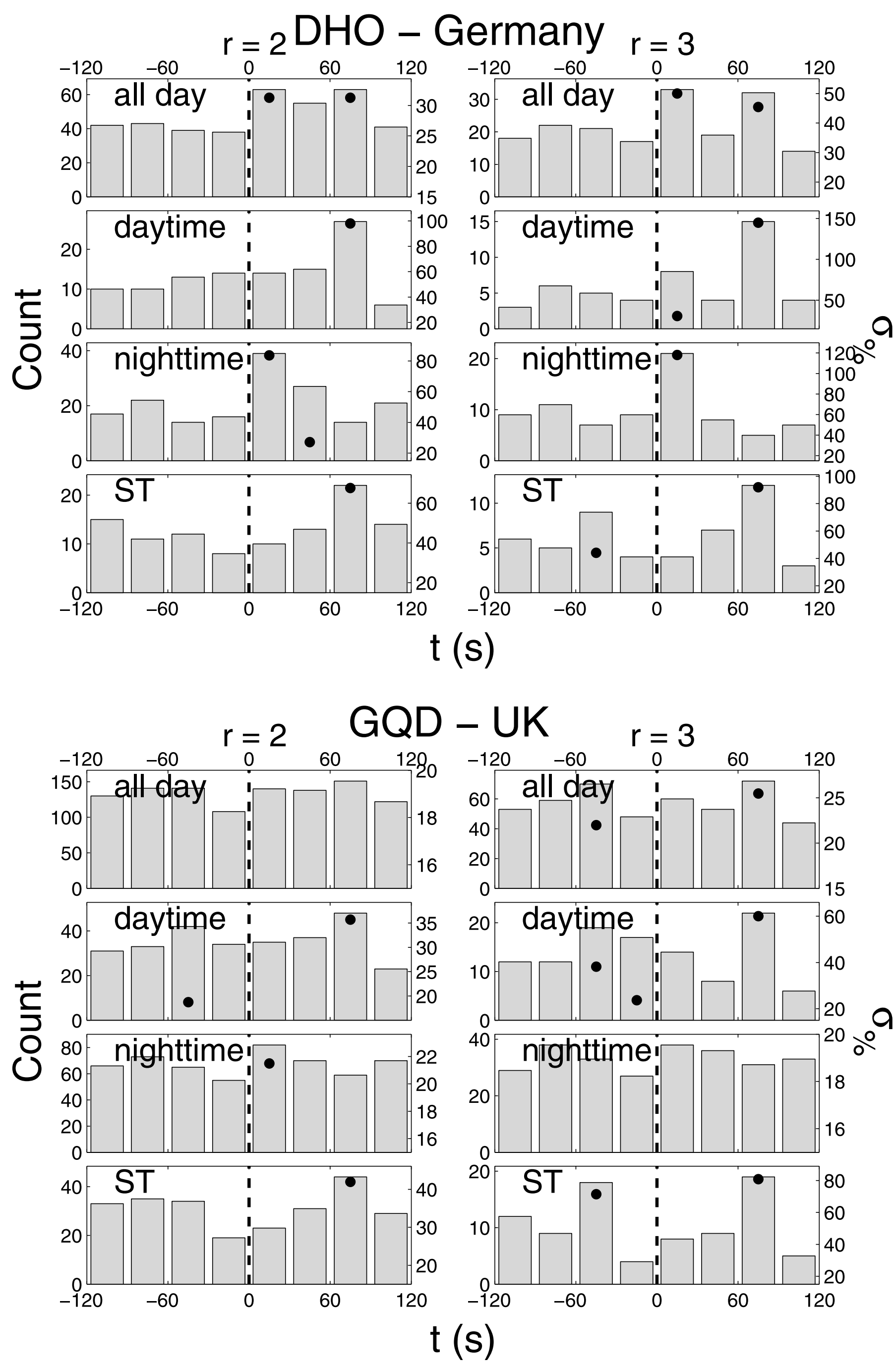

Figure 4. The same as in Figure 3 but for wider bins of 30 s.

where x_i is the corresponding number of peaks in the bin i and $\overline{X}$ is the averaged number of peaks in the whole interval, i.e.,

$$\overline{X} = \frac{1}{N}\sum_i x_i, \quad i = 1, ..., N. \tag{3}$$

In addition, only values of σ_i higher than 15% in the case of 30 s bins and 100% higher in the case of 5 s bins are marked with black circles in Figures 3 and 4.

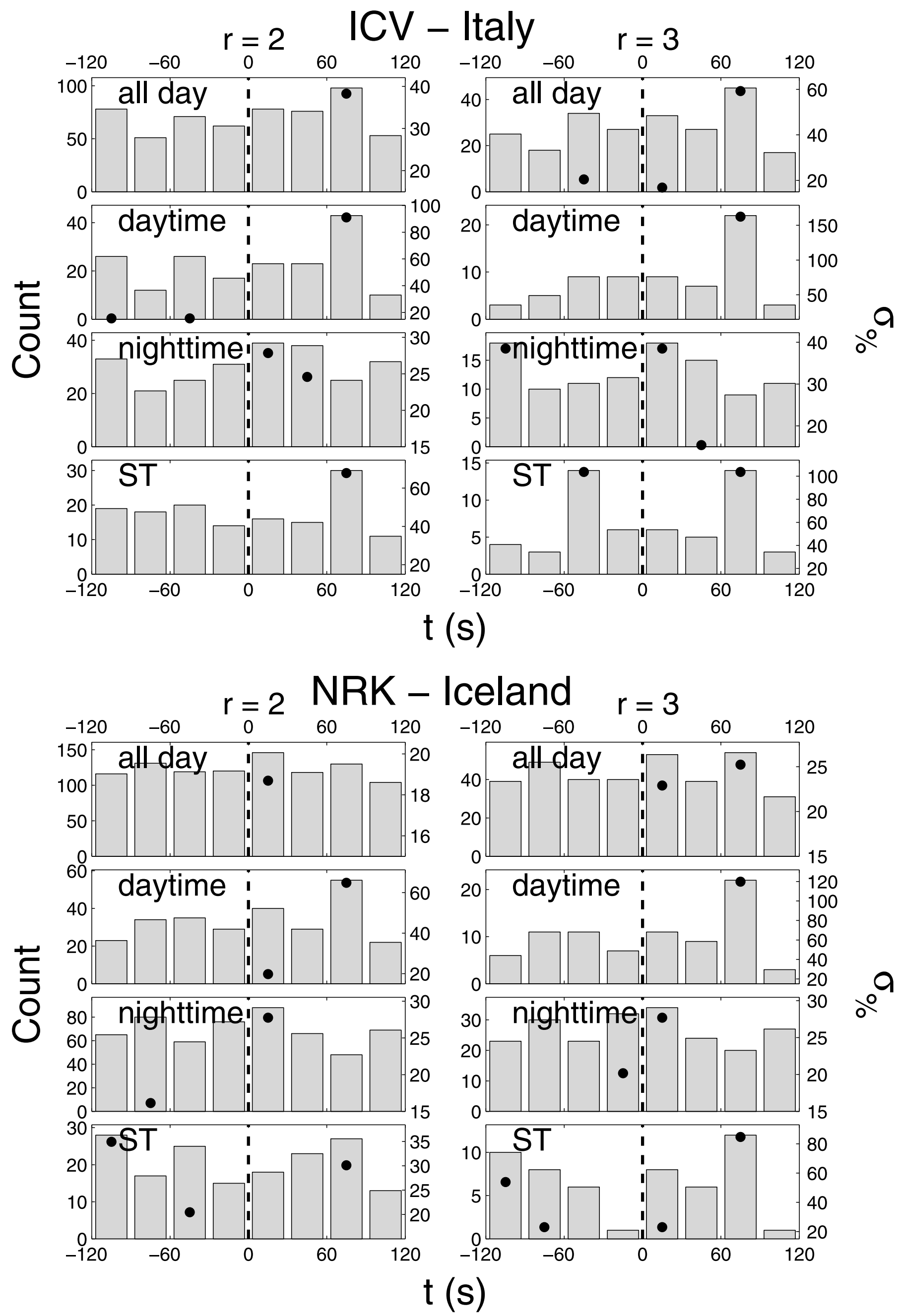

Figure 4. (continued)

It is well known that ionosphere is different during daytime and nighttime conditions. Therefore, our sample is additionally divided into three subsamples: signals obtained during daytime and nighttime, and periods when the solar terminator (ST) affects considered ionosphere part resulting into a nonstationary behavior of the recorded VLF/LF signal amplitude (see Figures 3 and 4).

Additionally, we apply the technique as given in *Inan et al.* [2007b]. However, contrary to the case of *Inan et al.* [2007b], the analysis of our sample shows that this method cannot account for short-term and temporary impacts from ionospheric natural fluctuations (see Figure S1 in the supporting information). Therefore, we will consider our method in further analysis.

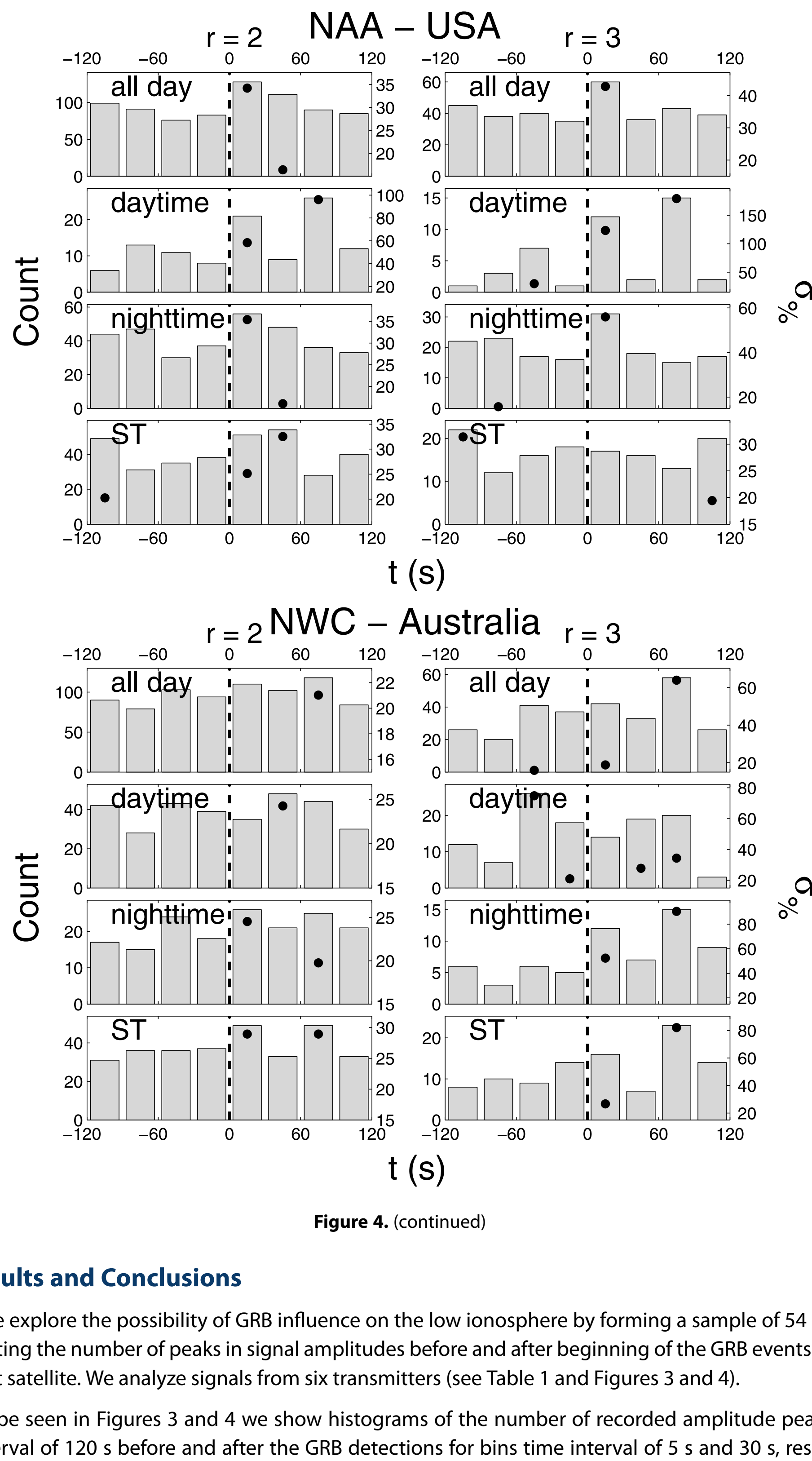

Figure 4. (continued)

4. Results and Conclusions

Here we explore the possibility of GRB influence on the low ionosphere by forming a sample of 54 GRBs and accounting the number of peaks in signal amplitudes before and after beginning of the GRB events recorded by Swift satellite. We analyze signals from six transmitters (see Table 1 and Figures 3 and 4).

As can be seen in Figures 3 and 4 we show histograms of the number of recorded amplitude peaks within the interval of 120 s before and after the GRB detections for bins time interval of 5 s and 30 s, respectively. Additionally, we separately considered daytime, nighttime, and ST subsamples (see Figures 3 and 4). The statistical analysis is given for the considered six signals recorded in Belgrade and 54 GRB events (except for the DHO signal from Germany that was used for 51 cases). Here we consider the number of peaks with $r = 2$ and 3 times larger amplitude than the noise amplitude A_{noise} (for a particular transmitter panel, left and right, respectively). For a particular transmitter panel, from top to bottom, we show the whole sample, daytime, and ST conditions, respectively.

As can be seen in Figure 3 in the case of narrow bins (NB), two time domains (TD) with jumps in the histograms can be noticed: (1) immediately after the beginning of the satellite recording of GRB (NB-TD1) and (2) some time after the beginning of the GRBs (NB-TD2).

1. *NB-TD1*. In the period after the satellite recordings of GRB, the peaks are noticeable for signals from Germany and Australia (nighttime conditions), and USA (both daytime and nighttime conditions).
2. *NB-TD2*. Increase of amplitude peak numbers after intrusion of the observed radiation, recorded within interval 65 s–70 s, is noticeable in all signals.
   In any case, the analysis for NB-TD1 and NB-TD2 shows that the presence of considered reaction is statistically important in histograms with bin width of 5 s and that there exists a certain time interval from the recording of GRBs by satellite until the detected ionospheric perturbations.

The increase in number of amplitude peaks during and after GRB events is clearly seen in all six transmitter signals when the bin width is expanded from 5 s to 30 s (wide bins, WB). In this case one can notice (see Figure 4) the following:

1. *WB-TD1*. In the first 30 s, the most important jumps in the number of amplitude peaks are again recorded in all cases within the day period that depends on the signal. Also, the most important increases of intensive amplitude peaks are recorded during nighttime (for signals from Germany, Italy, and USA) in periods 30 s–60 s after the GRB beginnings.
2. *WB-TD2*. Increase of amplitude peak number within the period of 60 s–90 s from the beginning of the GRBs recording by satellite is significant for all transmitters in the daytime condition. Also, it is present during periods of ST influence on all signals except those from USA (for this signal, increase is present in the next bin) and Australia during nighttime.

This definitely confirms the presence of observed short-term perturbations and their appearance after the start of the GRB detection by satellite.

Comparison of results for different bin widths shows more clear confirmation of the GRB detectability by VLF/LF radio signals for the wider temporal bins which suggests that intensification of the ionospheric plasma ionization starts with different "delays" with respect to the satellite GRB recording. This conclusion and the occurrence of relevant peaks in the histograms after GRB duration indicate possible secondary processes that affect ionization in the low ionosphere.

Finally, we can point out the most important conclusion of this study: it confirms detectability of a short-term reaction of the low ionosphere to GRBs which does not cause intense long-term reactions in general. The important perturbations of the low ionospheric plasma occur at different times in relation to the beginning of GRB events which indicates a possibility of detection of ionization by the primary GRB radiation as well as by some of its secondary effects. The presented study indicates the possibility of intensive ionospheric perturbations during the whole day.

Obtained results in this paper show that a detailed analysis of GRB influence on the ionosphere is needed. This study will be in focus of our upcoming research. In addition, we want to point out that presented model for extraction of intensive peaks from the noise and further processing can be applied to different events.

Acknowledgments

The data for this paper collected by Swift satellite are available at NASA's Goddard Space Flight Center. Data set name: Old Swift Trigger and Burst Information (for 2009–2012). http://gcn.gsfc.nasa.gov/swift2009_grbs.html, http://gcn.gsfc.nasa.gov/swift2010_grbs.html, http://gcn.gsfc.nasa.gov/swift2011_grbs.html, and http://gcn.gsfc.nasa.gov/swift2012_grbs.html. The used data are also given in the supporting information Table S1. Requests for the VLF/LF data used for analysis can be directed to the corresponding author. The authors are thankful to the Ministry of Education, Science and Technological Development of the Republic of Serbia for the support of this work within the projects 176001, 176002, and III44002. The authors are also grateful to Vladimir M. Čadež, Morris Cohen, and an anonymous referee for very useful suggestions and comments.

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