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STORM ACTIVITY OVER BALKAN REGION DURING MAY 2009

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Abstract. Intense storm activity over Balkans (40°/48° N, 12°/23° E) at the end of May 2009 was analyzed. Surveying was carried out by integration of satellite and ground-based observations. Very Low Frequency (VLF) signals (3-30 kHz) recorded by Absolute Phase and Amplitude Logger station in Belgrade (44.85° N, 20.38° E), video recordings of sprite events from ITALIAN METEOR and TLE NETWORK and lightning stroke data from European Cooperation for Lightning Detection network were inspected for possible relationship. Different type and magnitude of perturbations on monitored VLF signals were observed, even originated from same lightning discharge. Correspondence between all three examined phenomena was found, in some of analyzed cases.

1. INTRODUCTION

Although it has been investigated for many decades and from numerous different aspects, thunderstorm activity as scientific area is still under active interdisciplinary research. In recent years, thunderstorm activity is increasingly interpreted as terrestrial hazard (equally to earthquakes, landslides, tsunamis, forest fires, snow blizzard etc.), especially taking into account accompanying floods, destructive winds, damage and deaths from lightning strokes. Scientific interest in thunderstorm ranges from topics that cover indirect effects on human health (Elliot et al. 2014), to climatological studies (Cliverd et al. 2017, Romps et al. 2014, Finney et al. 2018). Physical processes involved in thunderstorm activity cover many still opened questions, broadly and diversely actively researched. Only some of them are addressed to processes of thunderstorm electrification, initiation mechanism of lightning leaders, causative mechanisms between thunderstorms and induced lower ionospheric perturbations (relatively recent results can be found in e.g. Silber and Price (2017, and references therein).

Changes in climate during recent years are more easily noticeable and more increasingly recognizable in Balkan regions. Although Balkans are still not considered as typical severe weather regions, extreme weather events like floods and landslides in 2014 (Stadtherr et al. 2016, Abolmasov et al. 2017, Djurić et al. 2017, Suto et al. 2016) and heat and cold wave in 2017 (Kew et al. 2019, Anagnostopoulou et al., 2017), suggest that soon in future, extreme weather could become habitual feature over these territories, too.

Extreme weather monitoring over Balkans, is still rare and sporadic and not much is known about electrical properties of such intense storm systems (Kolarski 2019, Kolarski 2020). To my knowledge, Balkan region in wider sense (including Adriatic coastal region both Italian and Croatian, then geographical territories of Bosnia, Croatia and Serbia and other former Yugoslavia republics) was never systematically studied in terms of atmospheric electrical properties related to storm activity and Transient Luminous Event (TLE) observations (Arnone et al., 2019). Intense storm activity from end of May 2009, that hit region of Adriatic coast and Balkan Peninsula inland, represents the unique opportunity to get insight in electrical properties and underlying mechanisms of thunderstorm systems generated over Balkans, through integrated satellite and ground-based observations.

2. EXPERIMENTAL SET-UP AND OBSERVATIONS

The survey of data from four independent sources was carried out and included data from EUMETSAT (European Organization for the Exploitation of Meteorological Satellites (http://www.eumetsat.int/)) weather satellite, data set about registered atmospheric discharges obtained from EUCLID (European Cooperation for Lightning Detection http://www.euclid.org/)) Network, data set about optically documented TLE events obtained from IMTN (ITALIAN METEOR and TLE NETWORK (http://www.imtn.it/)) network, and last data set was about Very Low Frequency (VLF) radio signal records from AbsPAL (Absolute Phase and Amplitude Logger) receiving system located in Belgrade (44.85° N; 20.38° E), from Institute of Physics' database. The presented analysis takes the VLF signal amplitude and phase delay data as the basic data set related to two other ground-based datasets. VLF (3-30 kHz) signal records, video records of sprite events and detected lightning strokes data were analyzed in detail, in order to find coincidence and possible relationship between these three phenomena during the stormy night 27^{th} – 28^{th} of May, 2009, while satellite data were only qualitatively analyzed.

EUMETSAT satellite documented 6 hours of intense storm activity over Central and Southeast Europe, from 9 o'clock p.m. on 27^{th} to 3 o'clock a.m. on 28^{th} of May 2009. During this stormy night, the core of the storm activity that occured and started over northern italian adraiatic cost, was moving eastward to and along Dalmatian adriatic coastal region and then further towards and into the Balkan Peninsula inland. On qualitatively analyzed satellite graphic material, storm activity is rounded by generalized frames and plotted in different colours, from black to blue, on each of the hourly satellite shots. The first and the last frames from satellite graphic material, with storm activity rounded in pink, are given in

Fig 1. Generalised movement and enlarged position of the storm system's core with legend of colours used are given in Figs. 2 and 3, respectively.

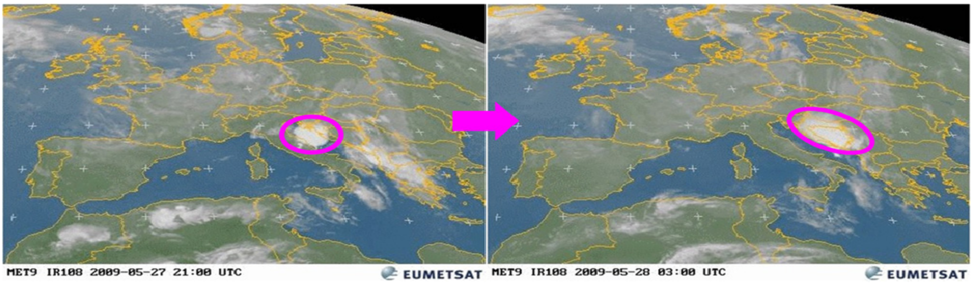


Figure 1: EUMETSAT weather satellite data registrations over Central and Southeast Europe during the stormy night 27th – 28th of May, 2009, first and last hourly frames.

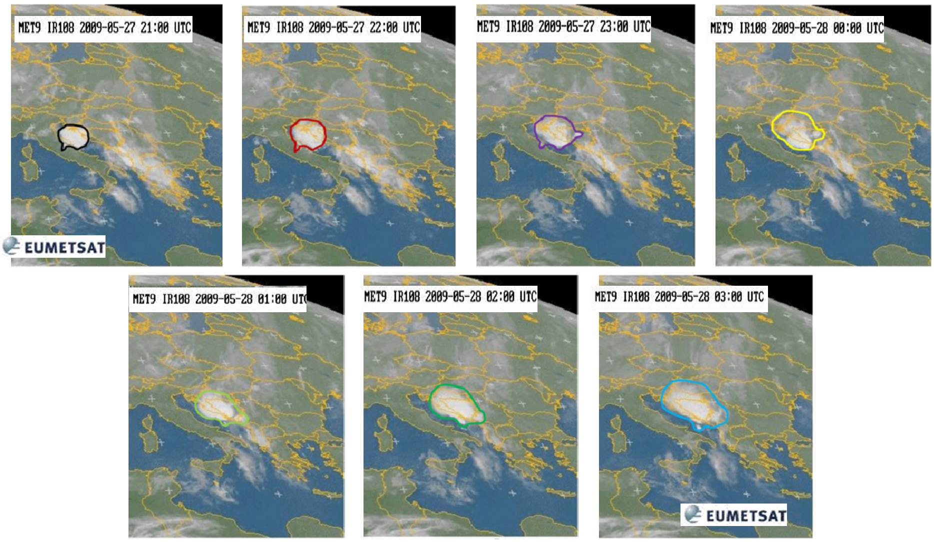
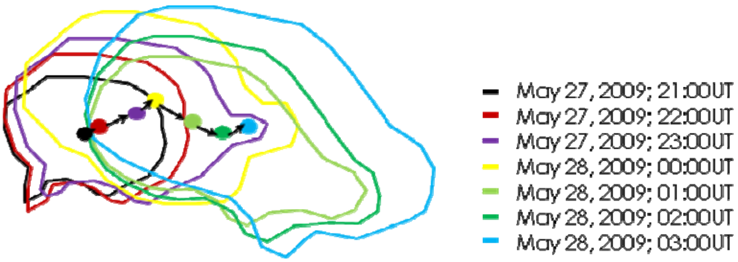


Figure 2: Generalized movement of the storm system's core as registered by EUMETSAT weather satellite over Balkans from 9 o'clock p.m. on 27th to 3 o'clock a.m. on 28th of May 2009 during the stormy night of May 27 – 28, 2009.



a) b)

Figure 3: a) Generalized position and movement of the storm system's core as registered by EUMETSAT weather satellite over Balkans during the stormy night 27th – 28th of May, 2009 and b) legend of colours used

The second data set analyzed was about lightning stroke events. For this particular night, over the observed geographical area enclosed within 12 to 23 degrees east in longitude and 40 to 48 degrees north in latitude, in period of 6 hours, EUCLID network reported intense storm activity with almost 22000 lightning stoke events, both of cloud-to-ground (CG) and inter-cloud (IC) type. Peak current distribution regarding the type of strokes and their peak current intensity and polarity is given in Fig. 4, while as projected on Earth's surface is given in Fig. 5. Stroke event distribution regarding the number of reported events by type is given in Fig. 6. The predominant are stroke events with negative polarity and with relatively small peak currents, which accounts for more than 2/3 of total strokes reported. The predominant are CG type of stroke events, which accounts for about 98% of total strokes reported, and among them those with negative polarity and with relatively small peak currents. In this data set there were only about 2% stroke events of IC type, with about 300 strokes, with similar peak current intensities.

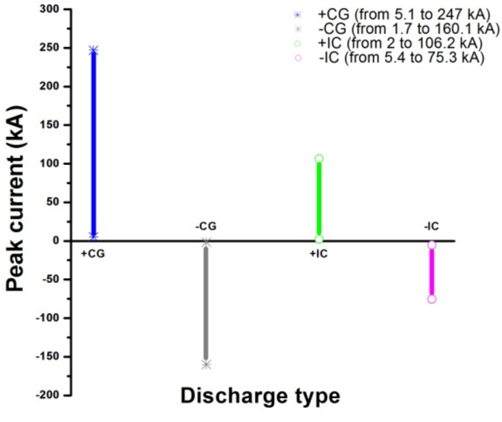


Figure 4: Peak currents distribution with peak currents from 160 kA (–CG) to 247 kA (+CG), as reported by EUCLID network.

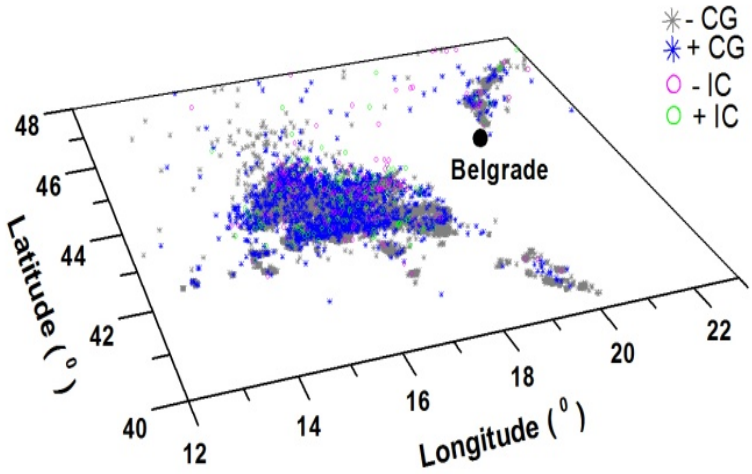


Figure 5: Stroke event distribution – projection on Earth's surface, as reported by EUCLID network.

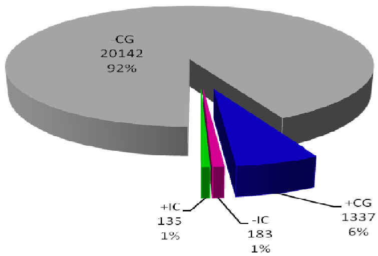


Figure 6: Stroke event distribution – number of reported events, as reported by EUCLID network.

The third data set analyzed was about TLE events. During this particular night, by IMTN network within 6 hours of intense storm activity, several dozens of TLE events were reported and optically documented from Ferrara station (44.82° N, 11.62° E) UFOcaptureV2 camera (directed with az. 150.49° and ev. 24.57° and with AOVs 122.8° and 97.1° horizontal and vertical, respectively, looking from the 45° N towards SE), oriented SE and with FOV covering area from Adriatic Sea and coast towards inner regions of Balkan Peninsula. According to obtained video material, within the area enclosed by 12-16 degrees east in longitude and 42-46 degrees north in latitude, there were 71 sprites and 10 halos in total documented between 21:42:11.4 UT on 27th and 02:18:55.0 UT on 28th of May 2009, with vast majority of the reported TLE activity located slightly over the horizon. Some of the sprite events reported by Ferrara station on night 27th – 28th of May, 2009 are given in Fig. 7, with sprite events rounded by yellow ellipse.

Schematic diagrams of locations, orientation and field of view of IMTN network cameras dedicated for observation of night-time phenomena such as meteors and TLE events, mostly over Italian land and sea, but also over surrounding areas including back of the Adriatic sea and further towards Balkans, which was particularly significant for this analysis, can be found at www.imtn.it (Fig. 8).

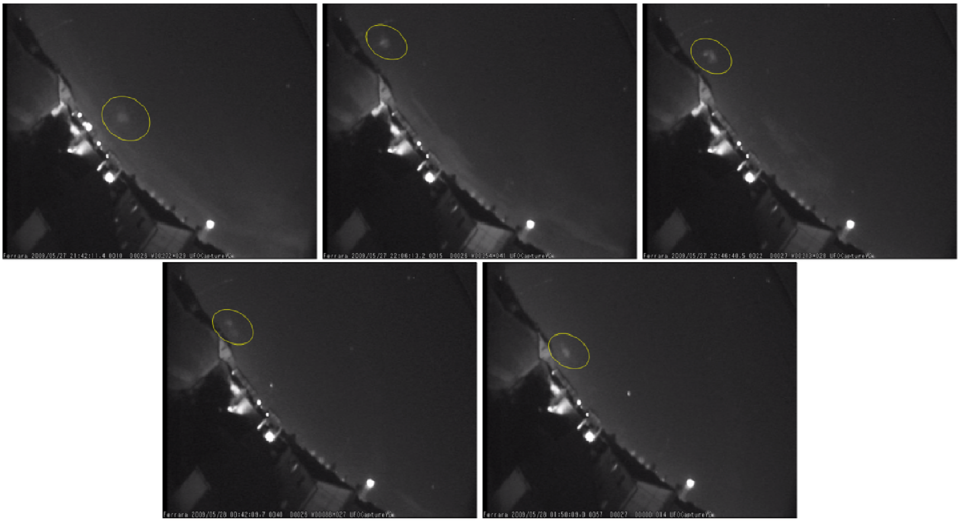


Figure 7: Some sprite events reported by Ferrara station on night 27^{th} – 28^{th} of May, 2009.

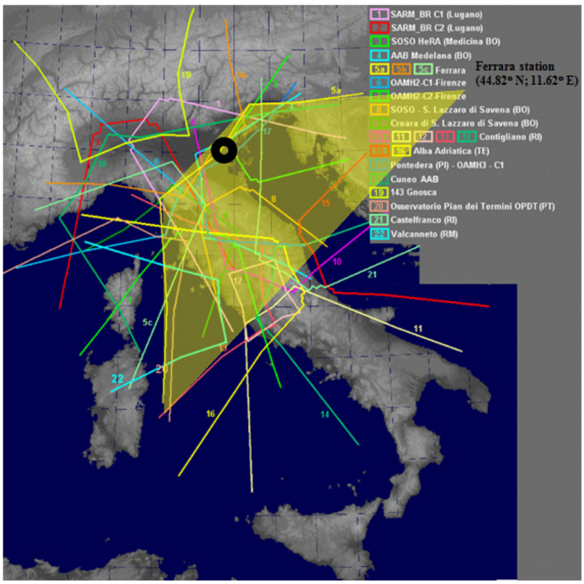


Figure 8: ITALIAN METEOR and TLE NETWORK (IMTN) with Ferrara station (black circle) with FOV (yellow polygon) covering area from Adriatic Sea and coast towards inner regions of Balkan Peninsula.

Within fourth dataset, propagation paths of VLF signals, emitted from different directions towards Belgrade AbsPAl receiver from transmitters located in different parts of the world, were analyzed. This data set was used as basic dataset. It is important to notice that Belgrade AbsPAl receiving system operates in stable mode from 2004, with first records made at the end of 2003. System contains 6 channels with 5 dedicated for VLF signals receiving and 1 reserved for system's time synchronization with GPS satellites. During the stormy night 27th –28th of May, 2009, these 5 signals were recorded: signal from USA with code name NAA emitted on frequency 24.0 kHz, signal from UK with code name GQD emitted on frequency 22.1 kHz, signal from Australia with code name NWC emitted on frequency 19.8 kHz, signal from Germany with code name DHO emitted on frequency 23.4 kHz and signal from France with code name FTA emitted on frequency 20.9 kHz. Characteristics of VLF signal transmitters are given in Table 1.Three propagation paths of VLF signals transmitted from USA, UK and Germany towards Belgrade receiver were analyzed in detail (bold in Table 1) and are given in Fig. 9. Signal emitted from USA – NAA/24.0 kHz, with Great Circle Path (GCP) distance of about 6.5 Mm is partly over-land and partly over-sea signal trace, with most of the path over sea. Signal emitted from UK – GQD/ 22.1 kHz, with GCP distance of about 2 Mm is partly over-land and partly over-sea signal trace, with most of the path over land. Signal emitted from Germany – DHO/23.4 kHz, with GCP distance of about 1.3 Mm has over-land path.

Table 1: List of VLF transmitters

VLF signal code and frequency	Transmitter location	Emitted power	GCP distance
NAA/24.0 kHz	**Maine, USA (44.63 N; 67.28 W)**	**1000 kW**	**6547 km**
GQD/22.1 kHz	**Skelton, UK (54.72 N; 2.88 W)**	**500 kW**	**1982 km**
NWC/19.8 kHz	H. E. Holt, Australia (27.2 S; 114.98 E)	1000 kW	11975 km
DHO/23.4 kHz	**Rhauderfehn, Germany (53.08 N; 7.62 E)**	**800 kW**	**1301 km**
FTA/20.9 kHz	Sainte-Assise, France (48.54 N; 2.58 E)	400 kW	1413 km

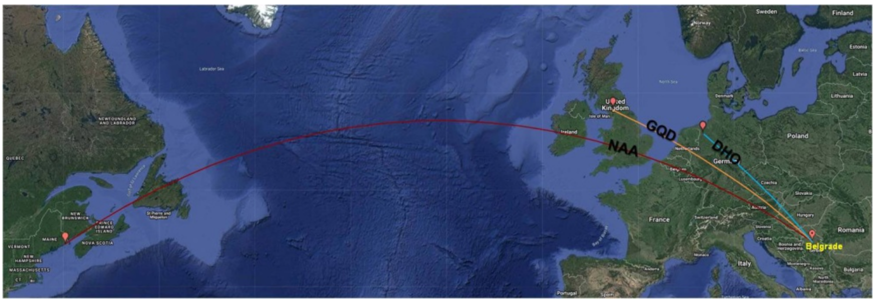


Figure 9: VLF signals' GCPs as registered by Belgrade AbsPAL receiver system located at the Institute of Physics (44.85° N; 20.38° E), in Serbia, on night 27th – 28th of May, 2009.

Integrated analyzed data from all ground-based sources during this particular night, over area of interest are given in Fig. 10. VLF signal traces, recorded by

Belgrade AbsPAL receiver are presented with thick black solid lines. Stroke events reported by EUCLID network, within 2-minute time intervals enclosing each of TLEs optically documented by IMTN network, are presented by black squares. Ferrara station camera's FOV is presented with thin dashed black line. Area enclosing all TLEs optically documented by IMTN network is presented with white dash-dotted somewhat thicker line. Analyzed VLF signals, coming from left, pass over region that was hit by the storm activity reported by EUMETSAT. It should be kept in mind that this graph is projection and because the Earth's surface is curved, these signal traces are even closer to each other, especially near Belgrade receiver.

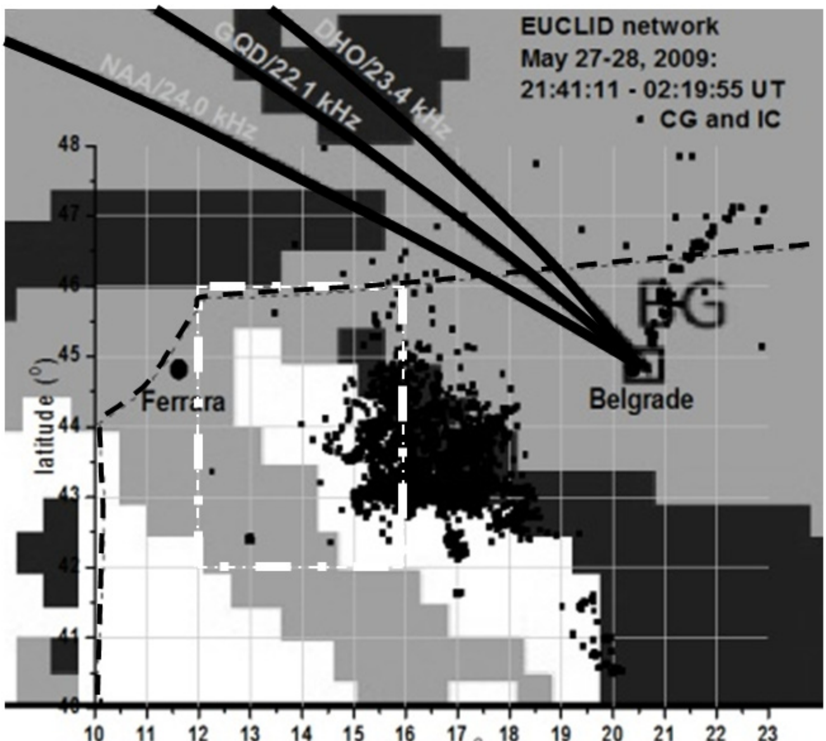
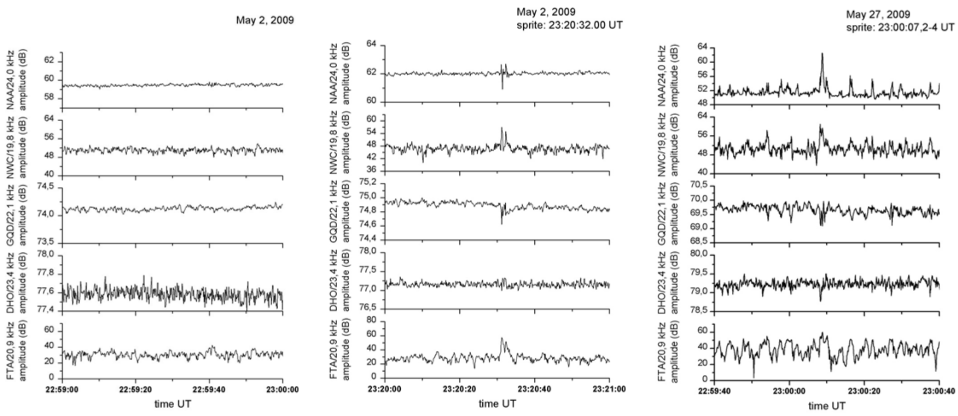


Figure 10: Integrated data from ground-based observations on night 27th – 28th of May, 2009: analyzed VLF signals received in Belgrade (thick solid black lines), strokes reported by EUCLID network (filled small black squares) and TLEs documented by IMTN network (within area enclosed by white rectangular of dash-dotted somewhat thicker line) (Ferrara station (44.82° N; 11.62° E) presented by black filled circle with FOW presented by thin dashed black line and Belgrade AbsPAL receiver (44.85° N; 20.38° E) presented by big hollow black square).

3. RESULTS AND DISCUSSION

Lower Ionosphere, as the lowest ionospheric region, extends in height from 50 to 90 km in altitude range, overlapping with atmospheric regions of mesosphere and lower thermosphere. Earth-Ionosphere waveguide is limited with Earth's surface at its lower boundary and lower ionospheric D-region (50-90 km) lower boundary, at its upper limit. Employing VLF radio signals for exploration of the lower Ionosphere, nowadays is widely used remote sensing technique. VLF radio signals, globally propagating through Earth-Ionosphere waveguide, are dependent on electron density changes that take place in the lower ionosphere, as induced by variety of phenomena from extraterrestrial to terrestrial origin. Ionospheric conductivity perturbations caused by lightning activity, as one of the agents of terrestrial origin, usually produce VLF signal amplitude and phase delay disturbances of small amount and of duration on time scale from several ms to several tens of ms, sometimes at levels of VLF signal noise, but in some cases can produce significant striking long-lasting VLF signal disturbances (detailed analysis is beyond the scope of this paper, form more details see e.g. Silber and Price 2017, and references therein).

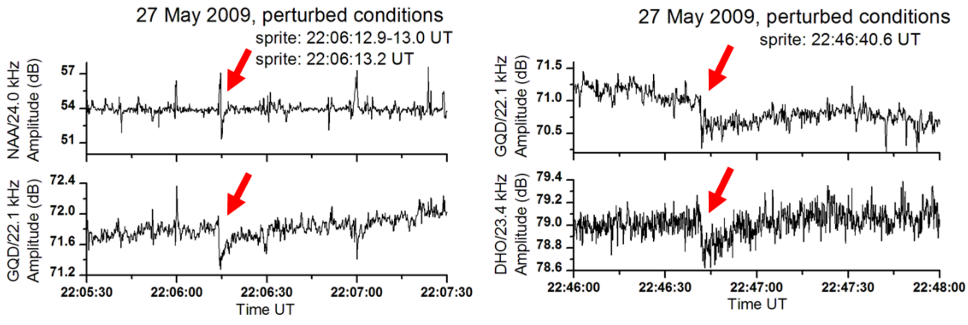
In conducted analysis, focus was on ionization changes along the propagation path of VLF radio signals induced by the strong release of energy by atmospheric lightning discharges. The increased ionization is apparent in the perturbation of the signal amplitude and phase delay with respect to regular undisturbed ionospheric conditions. The perturbations can manifest themselves thorough increase or decrease, or as complex - both increase and decrease of VLF signal Amplitude and Phase delay. Examples of different propagation conditions within Earth-Ionosphere waveguide, within 1min time intervals, during May 2009 are given in Fig. 11. On the left panel, the example of unperturbed propagation conditions on 2nd of May is given. The typical example of perturbed propagation conditions, with isolated VLF perturbation from night 27th – 28th of May is shown on the middle panel. The typical example of severely perturbed propagation conditions with numerous VLF perturbations characteristic for intense storm activity during night 27th – 28th of May is given on right panel. The effects of induced ionization changes have been observed along different propagation paths during the entire night 27th –28th of May, 2009, but the idea was to inspect in detail narow time intervals in which the sprite events were reported and optically documented by cameras. On the other hand, VLF traces with obvious, strong and clear perturbations such as typically on NAA and GQD signals were chosen for further detailed analysis.



a) b) c)

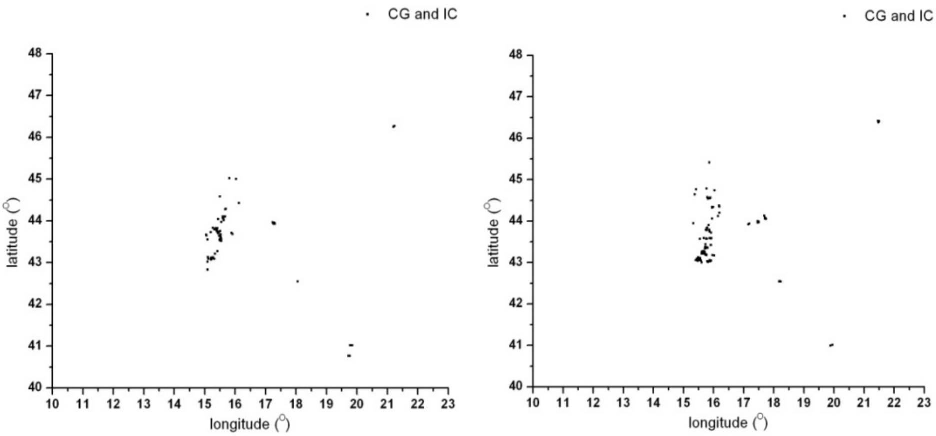
Figure 11: Different radiopropagation conditions within Earth-ionosphere waveguide during May 2009: a) unperturbed propagation conditions, b) perturbed propagation conditions with isolated VLF perturbation and c) severly perturbed propagation conditions.

Typical examples of VLF perturbations during this stormy night are given in Fig. 12 (denoted by red arrows). Two-minute time intervals enclose sprite events reported by IMTN network. Reported sprite events, VLF perturbation and reported stroke events, all are in very narrow time interval, so they belong to the same storm activity. Accompanying lightning stroke events for above mentioned two sprite cases, within observed arrea of interest (40° - 48° N; 12° - 23° E) as reported by EUCLID network, are given in Fig. 13, presented with black squares.



a) b)

Figure 12: Perturbed propagation conditions on analyzed VLF signals recorded in Belgrade during the night 27th –28th of May, 2009; typical examples of VLF perturbations as denoted by red arrows.



a) b)

Figure 13: Lightning strokes reported by EUCLID network, over area 40° - 48° N and 10° - 23° E, within 2-minute time intervals enclosing sprite events reported by IMTN network given in examples from Figure 12.

During this entire night, on all considered VLF traces, series of amplitude and phase delay perturbations were recorded. Summaries, that can be applied to all 81 cases analyzed, that were related to optically documented TLEs, are as follows:

- VLF perturbations often appeared simultaneously on all analyzed signal traces,
- although related to the same discharge event, VLF perturbations manifested themselves different in type and magnitude, which was attributed to the relative perturbed region's distance from VLF signal's GCP.
- in all 2-min time samples that enclosed each of TLE events optically documented, registered VLF perturbation corresponded to TLE event within intervals of few hundreds of ms. Even though VLF perturbation and sprite event did not exactly coincide within inspected time samples, these phenomena originated from the same storm activity.
- causative CG strokes were not found for all documented sprites. In most cases, lightning strokes were reported over observed area within inspected 2-min time samples and correspondence between two groups of phenomena, like VLF perturbations and CG strokes on one and VLF perturbations and TLE events on the other hand, was found. In some cases, correspondence between all these three types of events, was found.
- one-to-one corresponding between VLF perturbations, TLEs and lightning strokes was not found in all analyzed cases. Possible reasons are that stroke events were simply missed by EUCLID, or that sprite was not captured by IMTN camera, or that VLF perturbation might not is caused by sprite.

4. CONCLUSIONS

During the same storm activity which may include a number of strokes in narrow time interval of few hundreds of ms following types of events were noticed:
a) stroke is followed by sprite and sprite was followed by VLF perturbation,
b) initial stroke for sprite was registered and the sprite preceded or was observed during the VLF perturbation,
c) initial stroke for sprite was not registered and the sprite preceded or was observed during the VLF perturbation.

It can be concluded:
- in case a) the VLF perturbation is caused by scattering on the sprite body.
- in case b) if the sprite is preceding the VLF perturbation, the later is caused by scattering on the sprite body; however, if the sprite is observed during the VLF perturbation, the later is caused by electron density changes in waveguide due to the stroke. The appearance of the sprite during the VLF perturbation can prolong VLF perturbation duration.
- in case c) the cause of sprite and VLF perturbation was not detected.

In cases with simultaneous VLF perturbations registrations, reasonable assumption is proximity between perturbed region and receiver. During night 27th –28th of May, 2009, intense storm activity was reported both by satellite and ground-based sources, over area few hundreds of km (up to 400 km) away from Belgrade receiver. Since all analyzed VLF signal traces passed over very close to region hit by reported intense storm activity and in vicinity of the area where TLEs were documented, it is not likely that VLF perturbations were induced by some other storm activity originated outside this region.

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