Final report of the project

Studying our global, regional, and local electromagnetic environment with ELF transients

NKFIH OTKA K 141840 (K 115836)

Introduction

The purpose of the project was to obtain new information on the electrical properties of the geophysical environment by utilizing electromagnetic (EM) wave packets produced by extremely energetic lightning discharges in the extremely low frequency (ELF) radio band. Efforts were made to accomplish this goal in fields of scientific research which cover different regions, phenomena and processes in the litosphere-atmosphere-ionosphere system: (1) transient luminous events (TLE) occurring above electrically active thunderclouds; (2) the Earth-ionosphere EM waveguide (EIWG); and (3) the climate and its variations on global as well as on continental-regional scale.

As the benefits of using ELF transients for studying these elements of the environment have been exploited during the course of the project, it was found that various nearby objects and the ambient EM noise significantly affect the results obtained from the recorded ELF data. The influence of these local conditions of the measurements was investigated.

It was also recognized that more established results can be obtained if the investigation utilizes more data from international observation networks and the research is carried out in the framework of co-ordinated international activities. One of such activities was the Action CA15211 (ELECTRONET) of the COST Programme of the European Science Foundation. The time span of this Action (2016-2021) completely overlapped with the project period. This programme has facilitated the joint analysis of atmospheric electricity measurements in Europe and worldwide. Another relevant (still ongoing) international initiation is led by professor Earle Williams (MIT, USA), and it aims at establishing an operational solution for monitoring the distribution and intensity of the total global lighting activity and its variations using data from several ELF recording stations around the globe.

It was decided for the project team to take part in these activities (and some other international joint research works) so the project work could benefit from international collaborations and the availability of more data. While the work continued towards fulfilling the aims of the project, a few other topics, not considered in the original research plan, have been investigated, too. As a result, the project served the involvement of the project team in current and relevant international scientific research on atmospheric electricity. This has also brought young researchers in the team. One of the involved PhD students wrote his thesis in the framework of this project and earned his scientific degree recently (Bozóki, 2022).

In expense of taking time from the full completion of all initial plans, several relevant new scientific results could be obtained in research directions that are closely related with the concept of the project but have not been considered originally. These new results not only widened the circle of possible scientific utilization of the results of this project, but they also provided the foundation upon which all of the originally proposed research topics can be worked out on a higher level. This has already begun in a framework of a follow-up project (‘Elaboration of new methods for studying the near-Earth environment by extremely low frequency radiation of lightning strokes’, NKFIH OTKA K138824).

Summary of the results of the project

Electro-optical phenomena in the Earth's atmosphere

Comparison of ELF signals from not sprite-producing and sprite-producing lightning strokes demonstrated that sprite-triggering lightning strokes are more energetic (mean stroke energy 18 kJ vs. 28 kJ, respectively). Waveforms of ELF signals from sprite-producing lightning strokes indicate the presence of continuing current in the discharge process more often. The presence of continuing current indicates that a large amount of charge flows through the discharge channel (Spackova et al., 2018).

The question 'which optical characteristics of transient luminous events are connected with the charge moment change (CMC) of their parent lightning discharge' was addressed together with colleagues from South Africa. They made their first optical observations of red sprites and we deduced the electrical parameters of the sprite-parent lightning strokes from the ELF transients recorded by our measuring system at Nagycenk, Hungary. The most important result of the first joint work is the linear relationship which was found between the brightness of red sprites and the CMC of their triggering lightning strokes (Nnadih et al, 2018). In a follow-up study, maximum emission altitude and the altitude of the brightest emissions in red sprites were determined. Positive correlation (r=0.6) was found between the CMC of the sprite-parent lightning stroke and the top altitude of the produced emissions, and there was a moderate positive correlation between the CMC and the altitude of the brightest emissions (r=0.38) (Mashao et al., 2021).

Our own record set of optical TLE observations over Central Europe has been utilized in a different way in the framework of another international collaboration. Studying the climatology of TLEs in Europe and over the Mediterranean Sea showed that nighttime lightning recorded by the World Wide Lightning Location Network (WWLLN) can be used to infer occurrences of TLEs. The global average occurrence rate of TLEs estimated upon this finding was 2.6 TLE per minute. The study, based on optical TLE observations in Europe between 2009 and 2013, pointed out characteristic differences between the areal distributions of WWLLN-detected lightning strokes and the distributions of TLE observations within the studied area. This suggests that the geographical distribution of extreme lightning responsible for TLE production, as well as for energetic ELF transients, can differ from the geographical distribution of general lightning. The database of optical observations has been published together with the results (Arnone et al., 2020).

We continued observing TLEs in Central Europe from Sopron and Baja stations in Hungary. Altogether 1492 TLEs of different types were captured in the project period between 2016 and 2020. Preliminary evaluation of the records from Baja, together with the description of the instrumentation and methodology of the observations, has been published (Bór et al, 2021). It was found that most red sprites were observed in June, while the highest number of sprite halos was registered in September within the examined time period.

These publications, together with the activity on Facebook for keeping together a community of professional as well as citizen observers and scientists, were part of the efforts to organize a network of observers (e.g., Horálek et al., 2016) on the globe to support space-borne observations of TLEs. One mission of such, the Atmosphere-Space Interaction Monitor (ASIM) was actually started in 2018 (Neubert et al, 2019). We have not observed any TLE simultaneously with the ASIM instruments yet, but our observations have been uploaded regularly to the data center of the mission for possible scientific utilization.

Joint analysis of optical records from Hungary and from the Czech Republic showed that subsequent sprite-parent lightning strokes in 'dancing' sprite events occurred no further than 30 km from the closest preceding sprite entity in the analyzed cases. Taking into account previously published knowledge on the formation of sprite producing lightning flashes and incorporating electric current variation of the lightning strokes inferred from the corresponding transient ELF signals recorded in Poland, an explanation was provided on the formation of giant contiguous lightning flashes extending to hundreds of kms in the stratiform cloud region of thunderstorms. It was shown that these extreme lightning events can transport several hundred coulombs of electric charge to the ground in discrete steps (Bór et al., 2018a).

Characterization of the climate on global and on continental-regional scales

Since lightning is recognized as an indicator of the state and variation of the climate (Williams, 2005; Aich et al., 2018), efforts have been made in the framework of this project to characterize the global lightning activity and the fraction of it due to extreme lightning strokes which produce ELF transients. Paying attention to the latter is also justified by the results found in connection with the climatology of TLEs in Europe (Arnone et al., 2020).

A procedure has been developed to automate finding Q-bursts, i.e., lightning-induced ELF transients, in the records from Nagycenk, Hungary (Bór et al., 2018b). This method was used to compare the global number and source location distributions of Q-bursts detected by our system with the statistics of lightning strokes detected by the WWLLN, as well as with the variations of Schumann resonance (SR) intensity at Nagycenk (Szabóné André et al., 2020). The results from a 5-day time period in November, 2014 revealed that 70-80% of Q-bursts have a corresponding entry in the WWLLN database, but only 0.07-0.21% of the WWLLN-detected lightning strokes leave a recognizable Q-burst signature in the time series at Nagycenk. The number of the WWLLN detections is unrealistically smaller when the global lightning activity is centered on areas of lower network coverage (e.g., in Africa). The number of Q-bursts does not show such bias (Figure 1). An extended analysis covering the whole month showed that the day-to-day variation of the detected number of events is similar in the three datasets but the relative day-to-day changes can be different (Figure 2).

These initial results pointed out the importance of having information on the actual local meteorological conditions of the measurements, and the need for understanding how completely SR measurements from a single observation site represent the intensity of total global lightning activity. Additionally, SR is the natural background for ELF transients, so it is important to understand its variations in order to interpret the climatology of energetic lightning strokes correctly. These aspects have led the team to study SR more carefully in the framework of this project.

Transient signals bias the spectral properties of time series. Q-bursts in ELF records from Nagycenk (Hungary), Belsk (Poland), and Rhode Island (USA) were used to examine this biasing effect in the SR frequency band (below 100 Hz). It was found that an adaptive threshold can be given in the distribution of data values (16 times the core width of the distribution), above which a data segment contains transients which significantly bias SR modal parameters, first of all the obtained resonant frequencies (Guha et al., 2017).

Two approaches and the corresponding analytical and numerical models have been developed to reconstruct the intensity of the global thunderstorm activity via inversion of Schumann resonance (SR) records measured at different locations on the Earth (Prácser et al., 2019, 2021). An open source code package (“schupy”) has been created to support the utilization of the analytical model (Bozóki et al., 2019a). The corresponding inversion method can provide the global distribution of general lightning activity at any given time. The performance of the inversion method was critically evaluated by numerical tests and it was found to be well usable. At the same time, the need for improvements has also been noted in order to achieve better agreement between the modeled and the corresponding measured SR spectra. Although this work is still in progress, practically it has become possible to compare the global distributions of Q-bursts with global lightning distributions obtained from SR measurements using this approach (Bozóki et al., 2021a).

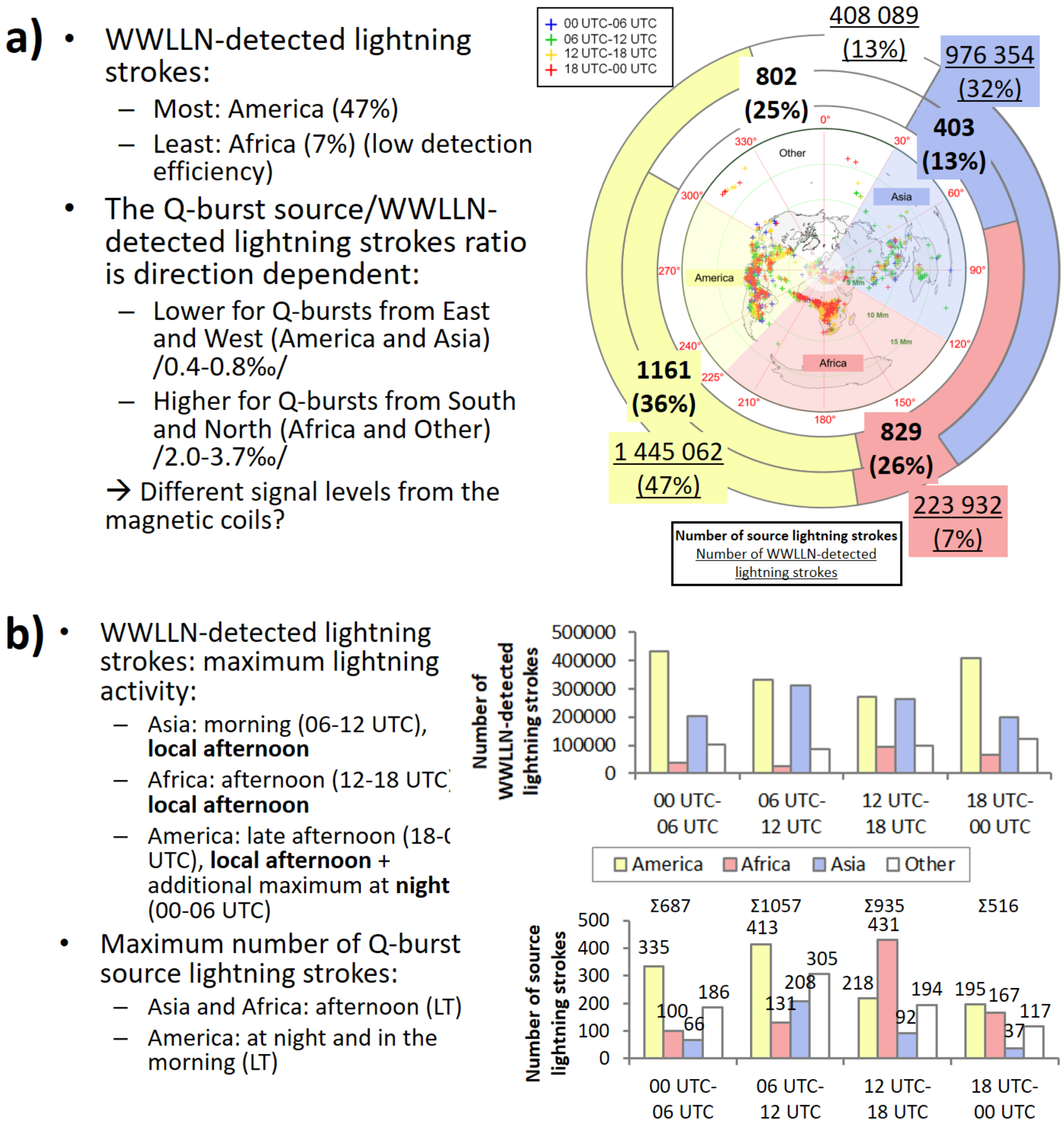

Figure 1. Number (a) and diurnal variation (b) of lightning strokes detected by WWLLN in the time period 30 October - 4 November, 2014, and the same for the identified source lightning strokes of Q-bursts detected at Nagycenk. Adopted from Szabóné André et al., (2020).

In addition to verifying the created models, ELF data from several ELF recording stations on the globe were processed to find signatures of large-scale variations of global lightning activity in SR parameters. It has been shown that SR intensity records document a common behaviour in the evolution of continental-scale lightning activity in the transition from cold to warm phase preceding two super El Niño events, occurring in 1997/98 and 2015/16. SR-based results are supported by comparisons to independent lightning observations from the Optical Transient Detector and the WWLLN, which also exhibit increased lightning activity in the transition months. It has been suggested that SR intensity variations might be applied in the future to predict the occurrence of these extreme climate events (Williams et al., 2021).

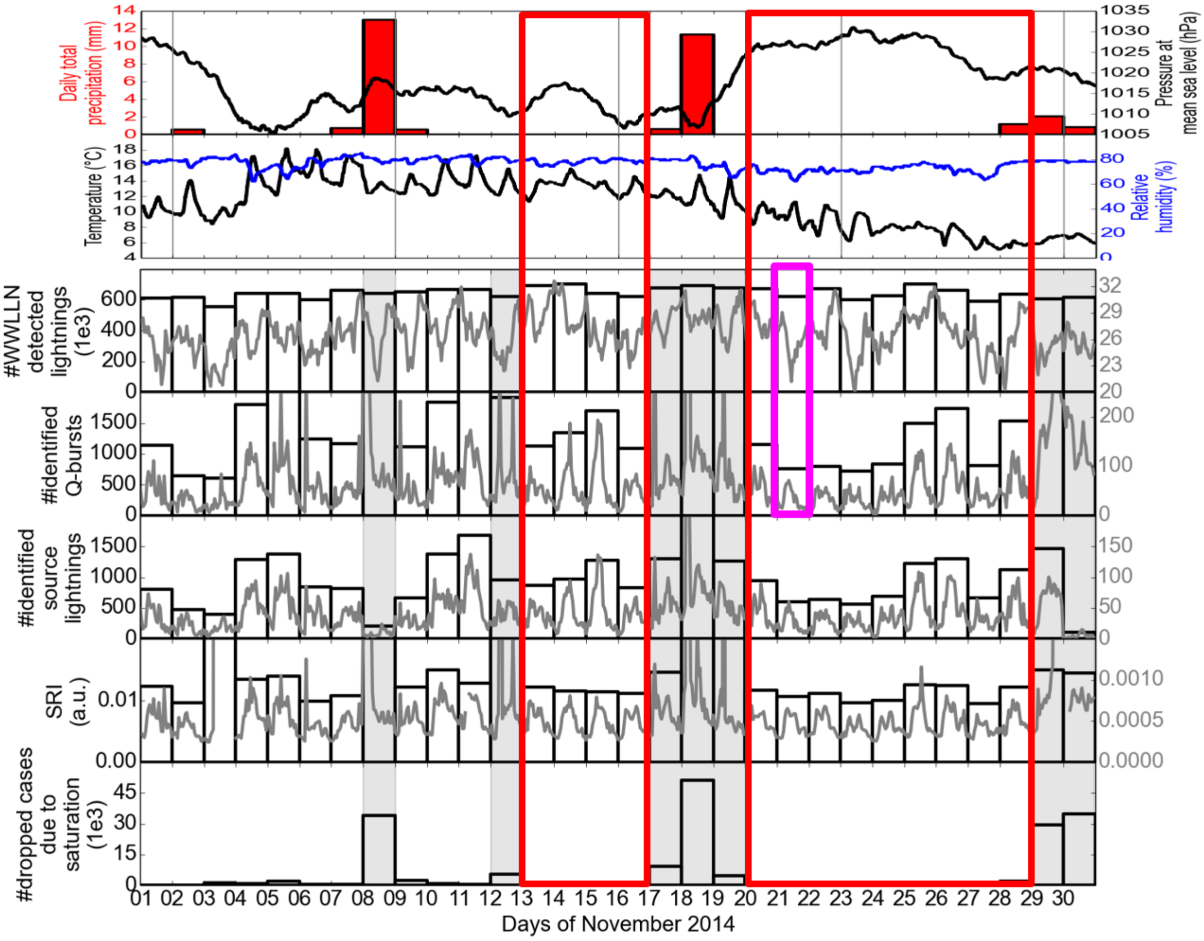

Figure 2. Meteorological parameters and Schumann resonance intensities (SRI, the sum of spectral power at the first three resonance modes) at Nagycenk, Hungary in November, 2014, together with the number of lightning strokes detected by the WWLLN and the number of identified source lightning strokes of Q-bursts observed at Nagycenk. The lowest plot shows the number of candidate Q-burst events which were omitted due to saturation of the signal. Daily total numbers are plotted as bars, hourly variations of the numbers are shown by gray curves. Red rectangles indicate longer periods when all data is in the normal range. Magenta rectangle marks a day when the variations of the number of Q-bursts and WWLLN detections are conspicuously different. Adopted from Szabóné André et al., (2020).

EM properties of the Earth-ionosphere waveguide

Observations of red sprites were used in a study discussing the relation of electric activity of thunderstorms to the dynamics of overlying sporadic E (E_S) layers which are integral part of the upper boundary layer of the EIWG. The results suggest that thunderstorms may affect E_S layers significantly in the production period of red sprites, but no direct physical mechanism was unambiguously identified which connects E_S layer variations to the simultaneously appearing red sprites. The observed effect may occur primarily due to subsequently produced atmospheric gravity waves (AGW). AGWs may destroy or sometimes reinforce E_S layers (Barta et al., 2017).

SR has also been used to infer modifications of the lower ionosphere, i.e., the upper boundary of the EIWG, due to space weather events. The response of SR parameters, examined at several receiving stations, was considered for two extraordinary solar events from Solar Cycle 23: the Bastille Day event (July 14, 2000) and the Halloween event (October/November

2003). Distinct differences were noted in the ionospheric depths of penetration for X-rays and solar protons with correspondingly distinct signs of the SR frequency response (Sátori et al., 2016). At the same time, the observed general immunity of SR amplitudes to these extreme external perturbations serves to remind that the amplitude parameter is largely controlled by lightning activity with the Earth-ionosphere cavity. On the other hand, SR intensity records were found to indicate that the height of the Earth-ionosphere cavity resonator may change by 15-25 km at high latitudes due to precipitating 30-300 keV electrons on the solar cycle timescale (Bozóki et al., 2021b). The geomagnetic latitude-dependent effect of precipitating electrons in association with the intense (St. Patrick day) geomagnetic storm in 2015 was shown, too (Bozóki et al., 2017a).

It has been already demonstrated that the atmospheric electric potential gradient (PG) depends on the global state of the global electric circuit (GEC) (Aplin and Harrison, 2014). Since the Earth's surface and the lower ionosphere are considered as two equipotential surfaces in the GEC (Rycroft et al, 2012), properly processed and interpreted global-scale PG variations can be used as an independent reference in comparison with any quantity that characterizes the EIWG. Efforts have been made in this project to obtain a well established PG-based reference for such comparisons.

The PG has been measured since 1962 at Nagycenk, Hungary. The history and the changing local environment of this measurement of exceptional temporal coverage, along with other atmospheric electricity (AE) measurements on site, has been reviewed (Bór et al., 2020). Buzás et al. (2021) showed that the electrostatic shielding effect of buildings and trees surrounding the area of measurements at Nagycenk cannot be neglected. The time-varying local electrical damping factor due to the growing trees at Nagycenk was quantified using historical PG records and electrostatic modelling. This way, PG measurements at Nagycenk were corrected for this bias back until 1962, and long term trends and in the corrected time series were reconsidered. Note that the change of the damping factor due cutting down some trees in the observatory recently has been determined, too (Buzás and Bór, 2021).

PG data from Nagycek, Hungary were converted into a standardized format, were merged with corresponding local meteorological data and were uploaded to the central database of the international project 'GLObal Coordination of Atmospheric Electricity Measurements' (GloCAEM). The database contains similar data from 17 monitoring stations on four continents. These stations were classified by the suitability of their data for studying the near-Earth environment. First published results from the project demonstrated that averaging data measured at different stations in fair weather conditions yields a globally representative diurnal variation which justifies the usability of the data for studying day-to-day variations of the GEC with unprecedented reliability (Nicoll et al., 2019).

Investigations using ELF transients have been carried out, too. The error of the ELF data-based source direction estimate of distant lightning strokes has been determined and examined. It was found that (1) the local anisotropic conductivity of the Earth's crust at NCK can affect the polarization properties of ELF waves significantly; (2) the caused effect depends on the azimuth of signal arrival; and (3) by correcting for this effect, the accuracy of ELF data-based source azimuth estimates can be improved significantly (Bór et al., 2016).

To investigate further the local effect of the Earth's crust on ELF transients, field measurements were made at the surface and in a mine shaft in the Mátra hills in Hungary by joining efforts with the NKFIH project "Geophysical noise in gravitational wave detection" (K124366). ELF transients detected both in the Mátra hills and at the reference ELF stations (Nagycenk, Hungary and Hylaty, Poland) were analysed. It was confirmed that the frequency dependence of the wave attenuation in the Earth's crust is exponential. Integrated local resistivity of the crust in the Mátra hills (70 Ωm) as well as the skin depth of electromagnetic waves in the Earth's crust at SR peak frequencies (up to 1500 m) could also be determined (Bór et al., 2022a).

Other results related to the project

Published scientific results

Historical PG records clearly show an anomaly in 1986 in connection with the nuclear accident in Chernobyl. This led to a joint analysis of AE measurements related to atmospheric effects of catastrophic nuclear accidents, also considering the Fukushima case in 2011. The results demonstrate that atmospheric conductivity is the most sensitive parameter for surveying the properties and the spreading of radioactive contamination in the atmosphere. On the other hand, the PG well mirrors both short and long time scale variation of the local composition and deposition of airborne radioactive materials (Dragović et al., 2020).

Links between the variations of PG as well as SR parameters and continental scale atmospheric circulation types (CT) in Europe have been studied to examine the sensitivity of the biosphere to variations of the electrical state of the atmosphere. It was shown that different CT unquestionably affect the near-ground electric state of the atmosphere but in different ways, especially when dust/particle transport is involved in the air circulation. It was concluded that the atmospheric electric environment deserves to be included in CT-related bioclimatic studies. This implicates possible utilization of the results of Q-burst-related studies in a wider area of research (Kourtidis et al, 2021).

A test was made in the geophysical observatory at Nagycenk to identify the origin of ELF-band noise in the measurements. The ambient noise level in the horizontal components of the magnetic field is very strong which strictly prohibits studying SR in the magnetic field and increases the uncertainty of Q-burst analysis, too. It was found that the noise level is direction specific at Nagycenk, and the infrastructure, as well as human activities in the observatory contribute to it significantly (Bozóki et al., 2021c).

ELF field measurements were organized in the Hortobágy and near Margyargencs, Hungary to survey the observability of Q-bursts, Schumann resonances, and properties of the ELF noise environment in the magnetic field in Hungary. The measurements have been evaluated so far from the point of view of noise level, because a location for a new SR measuring site is sought where magnetic measurements more suitable for studying SR and Q-bursts can be made. The detection of Q-bursts and SR under low ELF noise conditions was confirmed at both the test sites (Bozóki et al., 2021d).

Preliminary scientific results presented so far on conferences

Simultaneously appearing spectral resonance structures (SRS) corresponding to discrete excitations of the Ionospheric Alfven resonances (IARs) in the lower ionosphere were identified at Nagycenk, Hungary, and at Hylaty, Poland. The observed SRS provide information on the extent and intensity of transient perturbations of the upper boundary of the EIWG (Nieckarz et al., 2016).

Upon seeking other independent sources of information on the momentary state of the Earth-ionosphere waveguide, to what ELF data-based results can be compared, utilization of whistler waves was considered which propagate in the waveguide before they enter into the plasmasphere and got detected by a satellite. An analysis tool was developed and tested successfully on wide-band ground records yielded by the AWDANet global plasma environment analysis network and on satellite VLF waveforms (tweeks) collected in low Earth orbit (LEO) passes. Using LEO satellite waveforms in this model, ionospheric conditions can be mapped along the oblique path up to the recording spacecraft (Steinbach et al., 2018).

Joint analysis of observation of the Van Allen Probes satellites and SR data suggest that SR may be excited occasionally by electromagnetic processes in the magnetosphere, namely plasmaspheric hiss, the energy of which can leak in the Earth-ionosphere cavity under specified conditions (Bozóki et al., 2018).

Investigation of historical thunderday (TD) records can reveal long-term trends in the regional variation of thunderstorm activity. Joint analysis of TD and PG data revealed that fair weather PG amplitudes recorded at Nagycenk correlate significantly positively with TD variations observed within a range of 150 km around the measuring site (Buzás et al., 2019a). This enables analysing regional changes in the electrical environment back to 1900 using existing historical TD records as a proxy.

Technical developments

Although fully automated operation of the optical observation system for capturing TLEs could not be achieved yet, developments have been designed and some of them were already implemented to make the observations easier and to make this activity possibly part of a citizen science project. For instance, the complex task of switching off the system was automated, and the conception of a flexible remote controlling and monitoring system was set up (Bór and Szabó, 2021).

A malfunctioning magnetic induction coil in the SR recording system at Nagycenk was replaced by a LEMI-120 type antenna. The challenging task of integrating a different coil in the original data acquisition system has been solved.

The electric ball antenna, too, had to be renewed at Nagycenk. The supporting mast was repaired and the old preamplifier was replaced by a more reliable, low-noise, robust, modular amplifier-filter electronics of new design. This way, recording of the electric field variations in the SR recording system, a key measurement of the project, could be continued. Together with the maintenance of the hardware, pre-processing and quasi-realtime displaying of the measured SR data has been renewed (Szabóné André et al., 2021).

Informative dissemination and reports

Results of the project have been presented to the wider scientific community and to the public in reports, conference presentations and papers, both in English and in Hungarian (Bozóki et al., 2017b, 2019b, 2020, 2022; Bór et al., 2017, 2019, 2022b; Buzás and Bór, 2022; Buzás et al., 2019b; Prácser and Bozóki, 2021; Steinbach et al., 2017; Szabóné André et al., 2019, 2022).

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József Bór (PI)

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