Monitoring Global Lightning and the Lower Ionosphere with Schumann Resonances

Booklet of Thesis

Tamás Bozóki

Supervisors:
Gabriella Sátori DSc
Research Professor Emeritus, Institute of Earth Physics and Space Science (ELKH EPSS)

Gábor Szabó DSc
Professor, Department of Optics and Quantum Electronics, University of Szeged

University of Szeged
Faculty of Science and Informatics
Doctoral School of Physics

Szeged
2022

Introduction and Objectives

Schumann resonances (SRs) are the global electromagnetic (EM) resonances of the Earth-ionosphere cavity (Schumann, 1952, Price, 2016). In the lowest part (<100 Hz) of the extremely low frequency (ELF; 3 Hz - 3 kHz) band EM waves radiated by lightning can propagate with very low attenuation (~0.5 dB/Mm) in the waveguide formed by the Earth's surface and the lowest part of the ionosphere, and can travel a number of times around the globe before losing most of their energy. It is the constructive interference of these waves propagating in opposite directions (direct and antipodal waves) that creates the SRs which can be observed at ~8, ~14, ~20, etc. Hz. The approximate number of 30-100 lightning strokes per second worldwide maintains SRs quasi-continuously. SRs are known as a powerful tool to investigate global lightning activity and large-scale changes in the state of the lower ionosphere (Nickolaenko and Hayakawa, 2014). More generally, SRs can be considered as a research tool to study both the Earth's climate and space weather.

These two areas are perhaps the two most important research directions connected to SRs. It is important to highlight that the two areas of research can by no means be considered independent, as the effects associated with them are present together in the SR data (along with other additional effects). To obtain reliable results on global lightning activity, one needs to be convinced of the stability of the Earth-ionosphere cavity over the period of interest (or be able to eliminate the space weather-related effects). On the other hand, one needs to know the lightning-related variations in SR records to infer changes in the state of the lower ionosphere.

It is a long-sought goal of SR research to reconstruct (to invert) the intensity and distribution of global lightning activity based on SR measurements. There have been many attempts in this field in the past, but the methods developed have not reached the point of application, like the investigation of specific scientific questions based on inverted lightning distributions or quasi-real-time data provision. Even though there is a significant interest in investigating global lightning activity with climatological purposes, this is at present severely limited by the detection efficiency of available lightning monitoring technologies (Williams and Mareev, 2014). A geophysical inversion consists of two basic parts: the forward model and the inversion algorithm. In the present case, the forward model determines the SRs expected from a given distribution of global lightning activity, while the inversion algorithm reconstructs the global lightning distribution through iteration steps, which would produce SR spectra closest to the actual measurements. The main strength of SR-based monitoring of global lightning activity is that it does not suffer from detection efficiency problems as, due to the very low attenuation of lightning radiated ELF waves, all lightning strokes with vertical extent contribute to the measured EM fields (Williams and Mareev, 2014). This fact makes the method an excellent tool for climatological studies. Based on a few distant observation sites on the globe the inversion algorithm determines the charge moment change distribution of lightning activity in the unit of C^2km^2/s which can be regarded as a new parameter characterising the global climate. Furthermore, it should be emphasized that this approach gives the intensity of lightning activity in an absolute physical quantity, which is not biased by the artificial event selection typical of other satellite and ground-based lightning monitoring methods.

One of the main objectives of my PhD was the development of a new SR inversion model. The main milestones of this development process are described in the first part of the dissertation. The second part of the dissertation presents two separate studies. The first study demonstrates, with results related to the El Niño-Southern Oscillation (ENSO), that SRs are a powerful tool to investigate global lightning activity even without the inversion. The second study shows how SR measurements can be used to detect changes in the properties of the lower ionosphere associated with space weather.

Methods and Division of Labor

The development of the SR inversion was primarily a theoretical task, with the main focus on implementing and testing the different steps. The mathematical development and the implementation of the models was carried out by Dr. Ernő Prácser (ELKH EPSS), while the author of this dissertation, in addition to the joint thinking and planning, mainly took an important role in the validation of the models (e.g., in the design and evaluation of synthetic tests) and in the understanding of the physical background of the phenomenon. Based on the SR model for a homogeneous cavity resonator implemented in Fortran by Dr. Ernő Prácser, the author has created a Python version of the program, which he has made freely available to the scientific community. The preparation (preprocessing) of real measurement data as input for the SR inversion process was also one of the author's tasks, but the preliminary results were not included in the dissertation due to the lack of published output.

The two studies presented are based on the processing and combined interpretation of SR data from several stations, independent lightning monitoring and other geophysical data. The data processing was carried out by the author while the interpretation of the results was carried out together with Dr. Gabriella Sátori

(ELKH EPSS, supervisor) and Professor Earle Williams (MIT, USA).

Theses of the Doctoral Thesis

1) The Open Source Python Package Schupy

In the dissertation, based on Bozóki et al. (2019), I present my implementation of the schupy open source python package and its first function forward_tdte, which enables the simulation of SRs generated by given lightning sources and return the theoretical electric and magnetic fields at an arbitrary geographical location. The forward_tdte function applies the analytical solution corresponding to the lossy, uniform cavity and can simulate point as well as extended sources. Schupy is available via the pip package manager system and the project's Github page. I present three case studies based on the schupy.forward_tdte function where I investigate the convergence of the theoretical spectra, the spectra of antipodal sources as well as the theoretical spectra of an extended source. These case studies demonstrate the usefulness of schupy in investigating SR-related scientific questions.

2) Comparison of Analytical and Numerical SR Models

Based on Prácser et al. (2021) I present three numerical tests to compare the analytical and numerical solutions of the TDTE. In both approaches some inaccuracy of the algorithms can be expected and this is particularly true for the non-uniform case where the day-night asymmetry of the Earth-ionosphere cavity is taken into consideration. The results show excellent agreement between the output of the analytical and numerical models (also in the non-uniform case). This agreement is a strong validation of both models. Since the two solutions are completely independent, the result proves the correctness not only of the formalisms but also of the implementations (the coding).

3) Investigating Global Lightning Activity on the ENSO Timescale

Based on Williams et al. (2021) I show that multi-station observations of SR intensity exhibit common behavior in the evolution of continental-scale lightning activity in two super El Niño events, occurring in 1997/98 and 2015/16. This is the first scientific work on the ENSO time scale which has documented the importance of the transition period preceding El Niño episodes from the point of view of lightning activity. The vertical electric field component of SR at Nagycenk, Hungary and the two horizontal magnetic field components in Rhode Island, USA in 1997, and in 2014–2015, the two horizontal magnetic field components at Hornsund, Svalbard and Eskdalemuir, United Kingdom as well as in Boulder Creek, California and Alberta, Canada exhibited considerable increases in SR intensity from some tens of percent up to a few hundred percents in the transition months preceding the two super El Niño events. Based on the UT time distribution of anomalies in SR intensity I show that in 1997 the lightning activity increased mainly in Southeast Asia, the Maritime Continent and India, i.e. the Asian chimney region. On the other hand, a global response in lightning is indicated by the anomalies in SR intensity in 2014 and 2015. I find that SR intensity records also mirror some of the important differences between the onset mechanisms of the two super El Niño events. The increase in SR intensity during the transition months is concentrated over a 2-3 month period for the 1997/98 super El Niño event. However, the 2015/16 event was built up in two stages, and in line with this, two transition periods can be identified in the SR intensity data. I confirm the SR-based results by comparing them with independent lightning observations from the Optical Transient Detector (OTD) and the World Wide Lightning Location Network (WWLLN), which also show increased lightning activity during the transition months. The increased lightning is attributable to increased instability due to thermodynamic disequilibrium between the surface and the midtroposphere during the transition. The main conclusion of the research is that variations in SR intensity may act as a precursor for the occurrence and magnitude of these extreme climate events, and in keeping with earlier findings, as a precursor to maxima in global surface air temperature.

4) Investigating the Earth-ionosphere Cavity on the Solar Cycle Timescale

Based on Bozóki et al. (2021), I analyse changes in the properties of the Earth-ionosphere cavity on the solar cycle timescale. The aim of the study was to confirm the theory that the modulation of SR intensity on the solar cycle timescale (documented originally at high latitude stations) is caused by the local deformation (decreasing height) of the Earth-ionosphere cavity associated with precipitating electrons. To this end, I compare the long-term records of the first SR magnetic mode intensity from eight different stations with the fluxes of precipitating medium energy electrons and with independently identified energetic electron precipitation (EEP) events. Although the results generally confirm the role of EEP, I also find that the EEP-effect alone cannot account for all the SR-based observations. I conclude that the combined effect of solar X-rays and EEP must be taken into account to interpret the observations. I identify four distinct factors that can play important role in shaping long-term SR intensity records: 1) X-ray related deformation of the cavity, 2) X-ray related changes in the Q-factor of the cavity, 3) EEP-related deformation of the cavity and 4) EEP-related changes in the Q-factor of the cavity. The deformation (height change) of the cavity is expected to affect SR intensity locally beneath the deformed area(s) whereas Q-factor variations are expected to introduce globally observable changes in SR intensity. I document SR intensity and Q-factor enhancements connected to individual EEP events on the daily timescale and show that the effect of certain EEP events can be identified in SR intensity records from both the Southern and Northern Hemispheres (under different sunlit conditions), from different longitudinal sectors and the EEP-related relative enhancement of SR intensity can attain values as high as 50-100%. I demonstrate the solar cycle modulation of the magnitude of the annual SR intensity variation and make efforts to quantify the ionospheric height changes associated with EEP. The effective height of the Earth–ionosphere waveguide as inferred from DEMETER satellite's measurements provide an independent view on the long-term deformation of the Earth–ionosphere cavity. I show that the largest height of the cavity can be found at mid (geomagnetic) latitudes while the waveguide is depressed at low and high (geomagnetic) latitudes which is in a general agreement with the general conclusion that the Earth–ionosphere cavity is deformed by solar X-rays dominantly over lower latitudes and by EEP dominantly over higher latitudes. I also demonstrate that the effective height of the waveguide varies on the solar cycle timescale at all (geomagnetic) latitudes and this effect is stronger at high (geomagnetic) latitudes where energetic electrons can enter the upper atmosphere along magnetic field lines. The results suggest that SR measurements can be used to monitor EEP-related changes in the lower ionosphere.

Publications Related to the Doctoral Dissertation

Prácser, E., **Bozóki, T.**, Sátori, G., Williams, E., Guha, A., and Yu, H. (2019): Reconstruction of Global Lightning Activity Based on Schumann Resonance Measurements: Model Description and Synthetic Tests. Radio Science, 54, 3, 254-267. https://doi.org/10.1029/2018RS006772

Bozóki, T., Prácser, E., Sátori, G., Dálya, G., Kapás, K., and Takátsy, J. (2019): Modeling Schumann resonances with schupy. Journal of Atmospheric and Solar-Terrestrial Physics, 196. https://doi.org/10.1016/j.jastp.2019.105144

Bór, J., Sátori, G., Barta, V., Szabóné-André, K., Szendrői, J., Wesztergom, V., **Bozóki, T.**, Buzás, A., and Koronczay, D. (2020): Measurements of atmospheric electricity in the Széchenyi István Geophysical Observatory, Hungary. History of Geo- and Space Sciences, 11, 1, 53-70. https://doi.org/10.5194/hgss-11-53-2020

Prácser, E., **Bozóki, T.**, Sátori, G., Takátsy, J., Williams, E., and Guha, A. (2021): Two Approaches for Modeling ELF Wave Propagation in the Earth-Ionosphere Cavity with Day-Night Asymmetry. IEEE Transactions on Antennas and Propagation, 69, 7. https://doi.org/10.1109/TAP.2020.3044669

Williams, E., **Bozóki, T.**, Sátori, G., Price, C., Steinbach, P., Guha, A., et al. (2021): Evolution of Global Lightning in the Transition from Cold to Warm Phase Preceding Two Super El Niño Events. Journal of Geophysical Research: Atmospheres, 126, 3. https://doi.org/10.1029/2020JD033526

Bozóki, T., Sátori, G., Williams, E., Mironova, I., Steinbach, P., Bland E.C., et al. (2021): Solar Cycle-Modulated Deformation of the Earth–Ionosphere Cavity. Frontiers in Earth Science, 9. https://doi.org/10.3389/feart.2021.689127

Conference Abstracts Related to the Doctoral Dissertation

Bozoki, T., Pracser, E., Satori, G., Williams, E., Guha, A., Yu, H., et al. (2019): Reconstruction of global lightning activity based on multi-station Schumann Resonance measurements. EGU General Assembly 2019, 7-12 April 2019, Vienna, Austria. Geophysical Research Abstracts, Vol. 21, Abstract No. EGU2019-4172, oral

Prácser, E., **Bozóki, T.**, Sátori, G., Bór, J., Williams, E., Liu, Y., et al. (2019): Inferring Global Lightning Activity based on Multi-station Schumann Resonance Measurements – The Nelson-Pracser Approach. 27th International Union of Geodesy and Geophysics (IUGG) General Assembly, 8-18 July 2019, Montreal, Canada. Symposium JA04b Global Electrodynamics and Energetics of Atmospheric Regions from Ground to Space (IAGA, IAMAS), Abstract: IUGG19-3094, invited oral

Bozóki, T., Sátori, G., Steinbach, P., Bór, J., Pető, T., Williams, E., and Mironova, I. (2020): The applicability of the lowest part of the ELF frequency range (<100 Hz) for remote sensing of the atmosphere-ionosphere-magnetosphere system. VERSIM 2020 Virtual Meeting, 16-20 November 2020, online, poster (online)

Bozoki, T., Satori, G., Pracser, E., Bor, J., Szabone Andre, K., Rodríguez-Camacho, J., et al. (2020): Schupy: a python package for modeling and analyzing Schumann resonances. EGU General Assembly 2020, 4-8 May 2020, online, https://doi.org/10.5194/egusphere-egu2020-4872, display

Bozóki, T., Prácser, E., Sátori, G., Kulak, A., Mlynarczyk, J., and Williams, E. (2021): Modeling ELF waves in the non-uniform Earth-ionosphere cavity. EGU General Assembly 2021, 19-30 April 2021, online, https://doi.org/10.5194/egusphere-egu21-3973, vPICO (online)

Bozóki, T., Prácser, E., Sátori, G., Bór, J., Williams, E., Liu, Y., et al. (2021): Charge moment change-based characterization of global lightning activity via the inversion of Schumann resonance measurements. IAGA-IASPEI 2021 Joint Scientific Assembly, 21-27 August 2021, online, Abstract No: 344, oral (online)

Bozóki, T., Sátori, G., Williams, E., Mironova, I., Steinbach, P., Bland, E., et al. (2021): Long-term changes in the Earth-ionosphere cavity caused by solar X-rays and energetic electron precipitation. IAGA-IASPEI 2021 Joint Scientific Assembly, 21-27 August 2021, online, Abstract No: 343, oral (online)

Bozóki, T., Sátori, G., Williams, E., Mironova, I., Steinbach, P., Bland, E., et al. (2021): Energetic Electron Precipitation-related Changes in the Earth-Ionosphere Cavity as Indicated by Schumann Resonance Measurements. AGU Fall Meeting, 13-17 December 2021, New Orleans, USA. Paper SM25C-2026, poster (online)

References

Nickolaenko, A. P., and Hayakawa, M. (2014): Schumann Resonance for Tyros. Japan: Springer. Retrieved from https://doi.org/10.1007/978-4-431-54358-9

Price, C. (2016): ELF electromagnetic waves from lightning: The Schumann resonances. Atmosphere, 7(9). https://doi.org/10.3390/atmos7090116

Schumann, W. O. (1952): Über die strahlungslosen Eigenschwingungen einer leitenden Kugel, die von einer Luftschicht und einer Ionosphärenhülle umgeben ist. Zeitschrift und Naturfirschung, 7(2), 149–154. https://doi.org/10.1515/zna-1952-0202

Williams, E. R., and Mareev, E. A. (2014): Recent progress on the global electrical circuit. Atmospheric Research, 135–136, 208–227. https://doi.org/10.1016/j.atmosres.2013.05.015