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ELF Radio Waves in the Service of Studying the Lithosphere-Atmosphere-Ionosphere System

Tamás Bozóki*[(1)], Gabriella Sátori[(1)], Earle Williams[(2)], Ernő Prácser[(1)], Karolina Szabóné André[(1)], Péter Steinbach[(3)(4)], István Bozsó[(1)], András Horváth[(1)(5)], Lukács Kuslits[(1)], Máté Timkó[(1)], Anirban Guha[(5)], Yakun Liu[(2)], and József Bór[(1)]

(1) Institute of Earth Physics and Space Science (EPSS), Sopron, Hungary; e-mail: bozoki.tamas@epss.hu
(2) Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
(3) ELKH-ELTE Space Research Group, Budapest, Hungary
(4) Department of Geophysics and Space Science, Eötvös Loránd University, Budapest, Hungary
(5) Faculty of Information Technology and Bionics, Peter Pazmany Catholic University, Budapest, Hungary
(6) Department of Physics, Tripura University, Agartala, India

At the lowest end of the radio spectrum, in the extremely low frequency (ELF) band (3 Hz - 3 kHz), lightning is by far the most dominant source of natural electromagnetic (EM) waves, the energy of which completely fills the cavity formed by the Earth's surface and the lowest part of the ionosphere. Due to the very weak attenuation they suffer during their propagation in the Earth-ionosphere waveguide (about 0.5 dB/Mm), these EM waves can travel around the Earth several times before their energy is dissipated. Constructive interference of EM waves propagating in opposite directions from the same source (direct and antipodal waves) leads to the formation of global EM resonances, known as Schumann resonances (SRs), with resonance frequencies around 8, 14, 20, etc. Hz. While the EM radiation of the most powerful lightning strokes ("mesoscale lightning") can excite SRs on an individual basis (so called Q-bursts or SR transients), most of the "common" lightning strokes produce a quasi-steady "background" field in which the individual pulses cannot be distinguished.

ELF radio waves have been used for decades to study certain parts of the lithosphere-atmosphere-ionosphere system. The aim of this contribution is to review some selected results from recent years, which have been achieved in large part in the framework of a fruitful collaboration between the Massachusetts Institute of Technology (MIT, USA) and the Institute of Earth Physics and Space Science (EPSS, Hungary). An important common feature of the results presented is that they are based on measurements from a relatively high number (3-18) of ELF stations located in distant locations around the world, highlighting the importance of collaboration between different research groups in order to obtain a deeper and more established understanding of the changes in the global resonance field and, consequently, those of the phenomenon under study.

The general behavior of global lightning activity is well known, mainly owing to satellite optical measurements. Several papers have also shown that variations in SRs are consistent with this general behavior. What can provide novelty in this area is the investigation of situations when global lightning activity deviates from this general behavior, and especially in those cases (e.g., on certain time scales) when the information available from state-of-the-art lightning monitoring techniques is limited. Three such examples will be presented: day-to-day variations in the global lightning activity, changes in global lightning activity associated with Super El Nino events, and the enormous lightning activity in the 2022 Hunga-Tonga volcanic eruption. For the latter case, we will describe our novel machine learning-based approach to analyze Q-burst events.

Regarding the use of ELF radio waves to study the lower ionosphere, we will show how the X-ray emission of the Sun and the energetic electrons precipitating from the magnetosphere deform the Earth-ionosphere cavity resonator on the solar-cycle timescale based on SR measurements. Finally, we will summarize how the underground detection of Q-bursts can be used to determine the frequency-dependent attenuation of ELF-band radio waves in the Earth's crust as well as the electrical properties of the overlaying medium.