Observation of Schumann Resonances in the Earth's Ionosphere

By

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Summary Paragraph

The surface of the Earth and the lower edge of the ionosphere define a cavity in which electromagnetic waves propagate. When the cavity is excited by broadband electromagnetic sources, e.g., lightning, a resonant state can develop provided the average equatorial circumference is approximately equal to an integral number of wavelengths of the electromagnetic waves[1]. This phenomenon, known as Schumann resonance, corresponds to electromagnetic oscillations of the surface-ionosphere cavity, and has been used extensively to investigate atmospheric electricity[2]. Using measurements from the Communications/Navigation Outage Forecasting System (C/NOFS) satellite, we report, for the first time, Schumann resonance signatures detected well beyond the upper boundary of the cavity. These results offer new means for investigating atmospheric electricity, tropospheric-ionospheric coupling mechanisms related to lightning activity, and wave propagation in the ionosphere. The detection of Schumann resonances in the ionosphere calls for revisions to the existing models of extremely low frequency wave propagation in the surface-ionosphere cavity. Additionally, these measurements suggest new remote sensing capabilities for investigating atmospheric electricity at other planets.

Schumann Resonances and the Surface-Ionosphere Cavity

The Earth can be regarded as a nearly conducting sphere, wrapped in a thin dielectric atmosphere that extends up to the ionosphere, for which the conductivity is also substantial. Atmospheric electric discharges generate broadband electromagnetic waves that propagate between the surface and the lower boundary of the ionosphere (~100 km). These two layers define the surface-ionosphere cavity, which supports both longitudinal and transverse electromagnetic modes. Lightning, most frequent over continents, particularly at low latitudes, induces the development of standing waves, whose wavelength is related to the radius of the cavity. For a thin, lossless cavity, the eigenfrequencies are approximately given by $\omega_n = (c/R)(n(n+1))^{1/2}$, where *c* is the velocity of light, *R* is the Earth radius, and *n*=1,2,3,… is the corresponding eigenmode[1]. When more realistic conditions are considered, namely losses in the cavity, variability of the upper boundary, and finite ionospheric conductivity, the eigenfrequencies are somewhat lower[3]. The average measured frequencies of the five lowest eigenmodes are, approximately, 7.8, 14.3, 20.8, 27.3, and 33.8 Hz[2], which fall in the Extremely Low Frequency (ELF) range. The Q-factor is commonly defined as the ratio of the accumulated field power to the power lost in the oscillation period. The Q-factors for Schumann resonances are ~5 and provide estimates of wave propagation conditions in the cavity.

Schumann resonances have been used to investigate multiple phenomena related to the surface-ionosphere cavity, namely electromagnetic sources, properties of the medium, and boundary conditions. Since lightning is the major source of electromagnetic radiation in the ELF range, Schumann resonances are used to study the daily and seasonal variability of lightning in the cavity[2,3,4] as well as other phenomena such as tropospheric water vapor, aerosol distributions, and solar flares and geomagnetic storms[5,6,7,8].

C/NOFS Satellite and Electric Field Measurements of Schumann Resonances

The Communications/Navigation Outage Forecasting System (C/NOFS) satellite was launched in April 2008 to study the ionospheric conditions that create low latitude irregularities and scintillations[9]. C/NOFS was inserted into an elliptical orbit of 401 km perigee, 852 km apogee, and 13° inclination, and includes instrumentation for measuring the electron and ion densities and temperatures, DC electric and magnetic fields, the ion velocity and lightning flash rates, and low frequency electric field waves. C/NOFS is equipped with a vector double probe experiment with three, orthogonal pairs of 20 m tip-to-tip booms as shown in Figure 1[10]. This experiment provides vector measurements of both DC and AC (or wave) electric fields. The ELF electric field data reported here are digitized on-board at 1024 samples/s with 16 bit resolution and include a gain of 10. Successive data points are then averaged by 2 within the instrument and treated with a low pass, dual octave Butterworth filter with 3dB frequency near 192 Hz. The resulting 512 sample/s waveforms are then telemetered to the ground, where they may be rotated into different coordinate systems prior to subsequent spectral processing. The sensitivity of the electric field measurements is ~10 $nVm^{-1}Hz^{-1/2}$ in the ELF range.

An ELF spectrogram from 0-80 Hz of the total electric field component perpendicular to the magnetic field recorded during orbit 666 gathered on 31 May 2008 is presented in Figure 2. The Schumann resonances are the horizontal lines clearly evident below ~50 Hz with peaks at about 7.8, 14.0, 20.4, 26.7, and 33.0 Hz. The spectrogram in Figure 2 also reveals the rich variety of ELF waves, mostly forms of whistler mode ELF hiss, observed by probes on a satellite experiencing a changing magnetic field and plasma conditions along its orbit[11]. Temporally narrow regions of broadband electrostatic irregularities, strongest within the DC/ELF frequency range, can also be seen. In this letter, we focus on the faint, regularly-spaced horizontal spectral emissions indicative of the Schumann resonances.

Below the spectrogram in Figure 2 is a bar which indicates when the satellite was in local eclipse. The lowest panel shows the satellite's path and altitude. Gray-shaded regions show where the earth's surface was in shadow.

The resonances reported here are typical of those observed during essentially every C/NOFS orbit. They are primarily observed during nighttime conditions, suggesting the resonant wave energy cannot efficiently penetrate the more dense daytime plasma. Note the resonances generally appear when the satellite is over the night side of the Earth and do not seem to depend on when the satellite itself is in shadow. The resonances observed by C/NOFS show somewhat larger amplitudes at the lower altitudes within the orbital confines of the satellite, and some variations with season have been observed. Investigation of these effects requires a large number of orbits and is currently underway.

Figure 3 provides the average spectra of the entire ELF data ensemble corresponding to the nighttime observations in Figure 2. Definitive peaks are shown for the lowest seven modes. The spectral components are shown separately, along with smooth curves representing the estimated background (upper panel), and then (lower panel) with the background subtracted and Gaussian fits computed (and the square root taken). The values of the peaks derived from these fits correspond quite well to average ground measurements. In addition to the peak frequencies, the fits also provide the Q–factor for each eigenmode that characterizes each resonator mode's center frequency relative to its bandwidth. These Q values are ~ 3.5, 4.5, 6.2, 7.7, and 8.2 for the first five modes, as determined from the "full width at half maximum" analysis of the fits shown in Figure 3.

No electric field wave component along the magnetic field has been observed. The electric field power perpendicular to the magnetic field direction in the meridional component (i.e., the near outward component, at low latitudes) has been shown to be significantly larger than that in the zonal (i.e., east-west) component. Detailed polarization analysis is currently underway.

Discussion and Summary

The Schumann resonances detected by the electric field probes on the C/NOFS satellite have been identified by their distinctive frequency pattern. This pattern agrees well with the ground-based observations of Schumann resonances[2,3]. Though generally weak in amplitude, such waves are a common phenomena in the C/NOFS electric field data, identified throughout the ~3 year satellite lifetime.

The electric field of the first peak is ~0.25 $\mu Vm^{-1}Hz^{-1/2}$, about three orders of magnitude lower than ground-based measurements[2,4]. That the resonances are not observed during the daytime on the space-based platform may be due to the fact that the daytime plasma density is an order of magnitude higher than at night, and the ionospheric layer, the roof of the resonant cavity, is lower during the day[12]. Indeed, the C/NOFS perigee of 401 km is well above the lowest altitudes of the daytime ionosphere lower ledge (~90 km). These factors would both contribute to a dampening of the resonant wave energy reaching the satellite.

A larger question is why wave energy associated with the Schumann resonances is detected at all in the ionosphere. As the spherical cavity waveguide is bounded by conductors on each side, this energy would not be expected to penetrate into the ionosphere, and certainly not to altitudes above 400 km, if the walls were perfectly conducting[13,14]. The Schumann resonance modes, like other low-frequency modes, are able to leak into the ionosphere, particularly at night when the plasma density is lower. A leaky cavity has also been deemed necessary to explain the observed peak frequencies and Q values[2]. Anisotropy and other factors are believed to play key roles in the leakage mechanism[12].

Ultimately, the source of energy of the Schumann resonances is tropospheric lightning. Indeed, multi-point ground-based observations of Schumann resonances can be used to locate the lightning sources[15], even though the resonant wave energy fills the global waveguide. The strengths of the Schumann resonances observed in space should depend on the collective strength of the lightning activity in the troposphere. Both seasonal dependencies and correlations with actual lightning indicators have been noted in the Schumann resonance data observed by the C/NOFS satellite and these results will be reported in a subsequent communication.

The absence of previous space-based observations of such waves may be due to the continuous measurements afforded by the C/NOFS satellite, to the long antennae and highly sensitive electric field receiver that returned the broadband time series data, and to the low inclination orbit which permits long observing periods at night. An additional reason may be that the measurements were gathered during an exceptionally low solar minimum, which has created lower than typical plasma density values[16].

The discovery of ELF waves leaking from the Earth surface-ionosphere cavity prompts a new approach to the investigation of ELF waves in the space environments of other planets. Schumann resonances have been proposed to exist in planets with atmospheres, from Venus to

Neptune, and even in Saturn's moon, Titan[17]. Moreover, inconclusive measurements have been reported for Mars and Titan[18,19,20]. Therefore, the present "leaky cavity" model provides a means of studying the longitudinal modes of planetary cavities from orbit. Remote monitoring can also be combined with in situ measurements gathered by descent probes, buoyant vessels, or landers. The discovery of Schumann resonances in the Earth's ionosphere has important implications for the detection of similar phenomena at other planets and moons with ionospheres, providing a means to remotely infer the permittivities and conductivities of the surface, atmosphere, and charged layers (i.e., ionospheres) as well as evidence of lightning activity within the cavity[21].

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Author Contributions

All of the authors made significant contributions to this work. F.S. both discovered the Schumann resonances in the C/NOFS electric field data set and interpreted the findings. R.P. assisted with the analysis and interpretation, and, as Principal Investigator of the electric field instrument, configured the instrument to gather the continuous broadband ELF wave data. H.F. carried out the detailed analysis shown in Figures 2 and 3. All authors discussed the results and contributed to the writing of the paper.

Competing Financial Interests

The authors declare no competing financial interests.

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Figure Captions

Figure 1. A sketch of the C/NOFS satellite showing the three orthogonal pairs of 20 m tip-to-tip electric field double probes.

Figure 2. Spectrogram of ELF electric field data for one complete orbit of the C/NOFS satellite. See text for details.

Figure 3. Average spectra of the ELF electric fields for the nighttime portion of the data in Figure 2. The upper panel shows the complete spectra including the background levels. The lower panel shows the same data with the background contributions removed and superimposed Gaussian fits of each mode.

References

1. Schumann, W. O. (1952), On the free oscillations of a conducting sphere which is surrounded by an air layer and an ionosphere shell (in German), *Z. Naturforsch*. **7A**, 149–154.

2. Sentman, D. D. (1995), Schumann resonances, in *Handbook of Atmospheric Electrodynamics I*, 1st ed., ed. by H. Volland (CRC Press, Boca Raton, 1995), pp. 267–298.

3. Balser, M., Wagner, C. A. (1960), Observations of earth-ionosphere cavity resonances, *Nature,* **188**, 638-641, doi:10.1038/188638a0.

4. Nickolaenko, A. P., Hayakawa, M. (2002), *Resonances in the Earth-ionosphere cavity*, Kluwer Acad., Dordrecht, Netherlands.

5. Williams, E. R. (1992), The Schumann resonance: a global tropical thermometer, *Science,* **256**, 1184–1186, doi:10.1126/science.256.5060.1184.

6. Schlegel, K., Füllekrug, M. (1999) Schumann resonance parameter changes during high-energy particle precipitation, *Journal Geophysical Research*, **104**, 10111-10118.

7. Price, C. (2000), Evidence for a link between global lightning activity and upper tropospheric water vapour, *Nature*, **406**, 290-293.

8. Williams, E. R., Sátori, G. (2004), Lightning, thermodynamic and hydrological comparison of the two tropical continental chimneys, *J. Atmos. Solar-Terr. Physics,* **66**, 1213-1231.

9. de la Beaujardiere, O., et al. (2004), C/NOFS: a mission to forecast scintillations, *J. Atmos. Solar-Terr. Phys.,* **66**, 1573-1591.

10. Pfaff, R., et al. (2010), Observations of DC electric fields in the low-latitude ionosphere and their variations with local time, longitude, and plasma density during extreme solar minimum, *J. Geophys. Res.* **115**, A12324, doi:10.1029/2010JA016023.

11. Smith, R. L., Brice, N. (1964), Propagation in multi-component plasmas, *J. Geophys. Res.,* **69**, 5029-5040.

12. Madden, T., Thompson, W. (1965), Low-frequency electromagnetic oscillations of earth-ionosphere cavity, *Rev. Geophys.,* **3**, 211-254.

13. Greifinger, C., Greifinger, P. (1978), Approximate method for determining ELF eigenvalues in the Earth-ionosphere waveguide, *Radio Science,* **13**, 831-837.

14. Sentman, D. D. (1990), Approximate Schumann resonance parameters for a two scale-height ionosphere, *J. Atmos. Solar-Terr. Phys.,* **52**, 35-46.

15. Shvets A.V., Hobara Y., Hayakawa M. (2010), Variations of the global lightning distribution revealed from three-station Schumann resonance measurements, *J. Geophys. Res*., **115**, A12316, doi: 10.1029/2010JA015851.

16. Heelis, R.A., et al. (2009), Behavior of the O+/H+ transition height during the extreme solar minimum of 2008, *Geophys. Res. Lett.,* **36**, L00C03, doi:10.1029/2009GL038652.

17. Simões, F., et al. (2008), Schumann resonances as a means of investigating the electromagnetic environment in the Solar System, *Space Science Reviews,* **137**, 455-471.

18. Simões, F., et al. (2007), A new numerical model for the simulation of ELF wave propagation and the computation of eigenmodes in the atmosphere of Titan: did Huygens observe any Schumann resonance?, *Planet. Space Sci*., **55**, 1978-1989.

19. Béghin, C., et al. (2007), A Schumann-like resonance on Titan driven by Saturn's magnetosphere possibly revealed by the Huygens Probe, *Icarus,* **191**, 251-266, doi:10.1016/j.icarus.2007.04.005.

20. Ruf, C., et al. (2009), Emission of non-thermal microwave radiation by a martian dust storm, *Geophys. Res. Lett.*,**36**, L13202, doi:10.1029/2009GL038715.

21. Simões, F., et al. (2008), The Schumann resonance: a tool for exploring the atmospheric environment and the subsurface of the planets and their satellites, *Icarus,* **194**, 30-41.