Anticorrelation Between Sunspot Number and Spectral Resonance Structures of ELF Magnetic Variations Detected at Kawatabi, Miyagi, Japan

Tomoko Nakagawa, Taiki Sato, and Chihiro Kumagai

Abstract – Spectral resonance structures in the frequency range from 0.5 to 8 Hz were found in the extremely low-frequency magnetic field data obtained at Kawatabi, Osaki, Miyagi Prefecture, Japan (magnetic latitude 30.55°N, longitude 149.97°W, dipole $L \sim 1.35$) during the period from December 18, 1998, to June 2, 2016. The data were obtained using an induction magnetometer with the sensor placed in the North–South direction at a sampling frequency of 128 Hz, and they were Fourier transformed every 8 s, and averaged for 2 min. The dynamic spectra showed structured enhancements at approximately 1, 2, 2.5, 3.5, and 4.5 Hz. The occurrence of the spectral resonance structure in Kawatabi was restricted to the nighttime from 17 to 06 LT. Although the data coverage was limited to as low as 51%, nearly two decades of observations show a clear anticorrelation between the occurrence of the spectral resonance structures and the sunspot number, which is consistent with the model of an ionospheric cavity with minimum Alfvén velocity.

1. Introduction

The dynamic spectra of geomagnetic field variations in the extremely low-frequency (ELF) range exhibit the most prominent features of the Schumann resonance at 8, 15, 21, 27, . . . Hz (Figure 1). Below the fundamental mode of the Schumann resonance, we sometimes see another set of evenly spaced stripes in the frequency domain at approximately 1, 2, 2.5, 3.5, 4.5, . . . Hz (Figure 2). This is called a spectral resonance structure (SRS) and was found by Belyaev et al. [1, 2] for the first time at a midlatitude station with an L value of 2.65. The SRSs were detected at high ($L = 5.2$) [3], mid ($L = 2.1$) [4], and low latitudes ($L = 1.3, 1.2, 1.08$) [5–7]. All the SRSs were observed during the night [3–7], and the occurrence rate was high during the September to January periods [3, 4]. The frequency difference between adjacent maxima increased in winter [4, 5]. The occurrence rate showed an anticorrelation with the Kp index [4].

They are thought to be generated by an ionospheric Alfvén resonator, which is an ionospheric cavity with a minimum Alfvén velocity bounded by the E layer and a steep gradient in plasma density above the maximum of the F layer at several hundred kilometers. The energy source is considered to be the broadband noise of lightning discharge due to thunderstorm activities [8, 9], although the relationship with the world thunderstorm center is not so simple [10].

Yahnin et al. [3] calculated the reflection coefficient of the upper ionosphere based on the IRI-95 models of the altitude profiles of the ionospheric electron density in the solar maximum (1999) and minimum (1995) and showed that the density gradient at the topside of the cavity was steeper in the solar minimum, resulting in a larger reflection coefficient and larger frequency differences between the adjacent maxima in the winter of 1995. Observations from 1995 to 1999 showed that the occurrence rate and frequency interval of SRS decreased from the years of solar minimum to solar maximum [3].

The present study reports 18 years of observations of SRS made at $L \sim 1.35$ and its relationship with the 11-year cycle of solar activity.

2. Data

The magnetic field variation data used in this study were obtained at Kawatabi, Osaki, Miyagi Prefecture, Japan (geographic latitude 38.75°N, longitude 140.77°E, magnetic latitude 30.55°N, longitude 149.97°W, dipole $L \sim 1.35$) from December 11, 1998 to June 2, 2016, using an EL-12 induction magnetometer constructed by Tierra Technica Co. Ltd. It has a single sensor with a 30,000-turn coil and a permalloy core. The sensor was placed in the north–south direction and aligned with the local magnetic field. It detects magnetic field variations from 0.1 to 44 Hz at a sampling frequency of 128 Hz. Figure 3 shows the history of data coverage. The overall coverage of over 18 years was 51%.

The data were Fourier transformed every 8 s, averaged for 2 min to reduce fluctuations in the spectra, and corrected for the frequency response of the magnetometer. The dynamic spectra thus produced are available on the website https://ice-tohtech.jp/nakagawa/elfdata/. Figures 1 and 2 show examples of the dynamic spectra.

3. Event Selection

Before the detection of the SRS events, the spectra were averaged for 20 min to reduce spectral fluctuations. Figure 4 shows that the spectral fluctuations in the 2-min averaged spectrum were smoothed out by the 20-min

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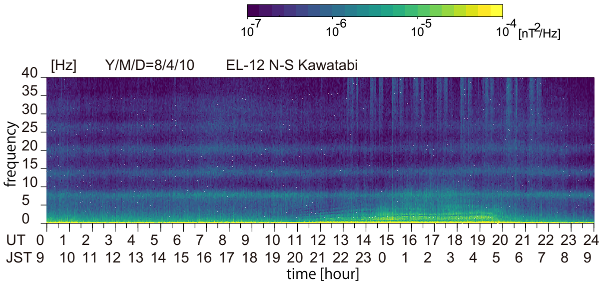

Figure 1. An example of a dynamic spectrum of low-frequency range from 0.125 to 40 Hz was observed at Kawatabi on April 10, 2008. The time is given in Universal Time and Japan Standard Time.

average, and the peaks and valleys of the power density became clearer.

The SRSs were detected using the 20-min averaged spectra, according to the following criteria:

1) More than three stripes of peak enhancements in the frequency range from 0.75 to 7.875 Hz;
2) The peak power density was more than 1.3 times larger than that of the nearby minima; and
3) The peak power density of the stripe was larger than $3\times10^{-7}\mathrm{nT}^2/\mathrm{Hz}$.

The magnetic field observations in the low ELF range suffer from interference from local thunderstorm activities, which are characterized by a sudden enhancement of power density over a wide frequency range (Figure 5). To exclude noise from the local thunderstorm, we set the following additional criteria:

4) Periods with a sharp increase in power density (5 times within 2 min) were excluded; and
5) Periods with a power density larger than $6.5\times10^{-6}\mathrm{nT}^2/\mathrm{Hz}$ over 65% of the frequency range from 0.5 to 3.5 Hz.

To distinguish the spectral resonance structures from various types of artificial broadband noise, we set the following condition:

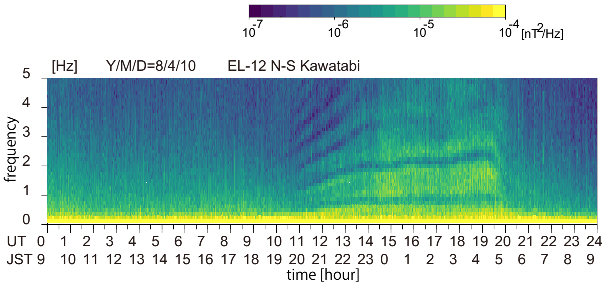

Figure 2. An example of spectral resonance structures was observed at Kawatabi on April 10, 2008. An expansion of the low-frequency range shown in Figure 1.

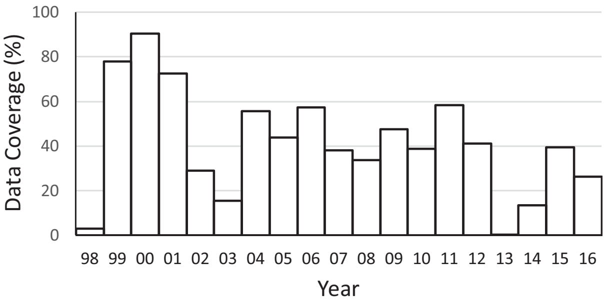

Figure 3. Data coverage of the ELF magnetic field variation at Kawatabi. Percentage of observation periods with respect to the entire period. There was only one day of observation in 2013.

6) The frequency of the first peak must be less than 1.5 Hz.

4. Results and Discussion

Figure 6 shows the distribution of the frequency separation between adjacent peaks of the spectral resonance structures detected at Kawatabi with a frequency resolution of 0.125 Hz (8-s Fourier transform). The distribution peak was observed at 0.625 Hz. No clear dependence on the local time or year was observed.

Figure 7a shows the local time distribution of the spectral resonance structures detected at Kawatabi. There is a clear concentration at nighttime from local

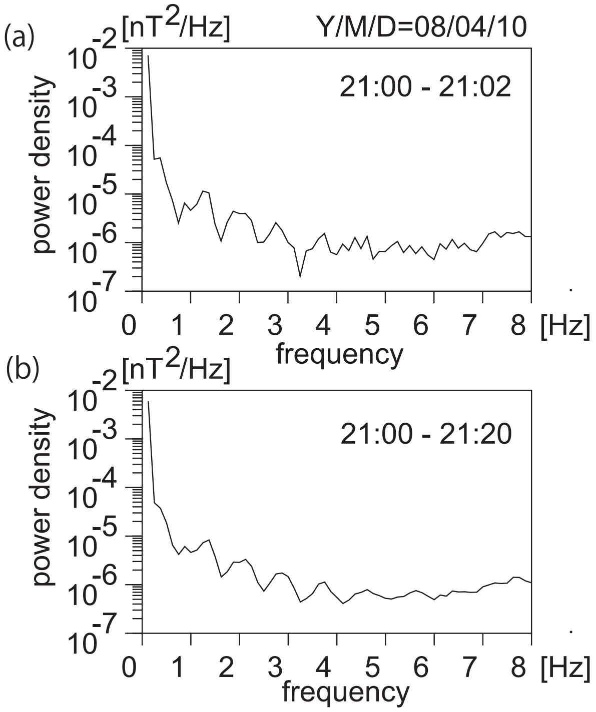

Figure 4. Comparison of the (Top) 2-min averaged, and (Bottom) 20-min averaged spectra of magnetic field variation obtained at Kawatabi.

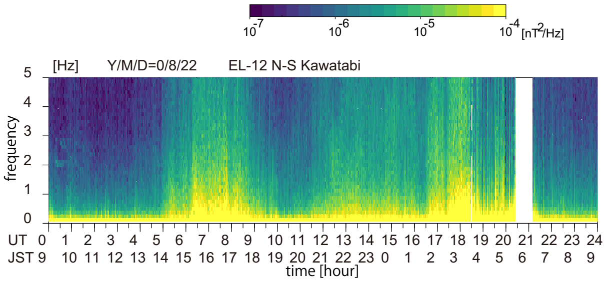

Figure 5. An example of local thunderstorm activity observed at Kawatabi on August 22, 2000. The blank at 21 UT is caused by signal saturation due to large-amplitude magnetic field variations.

time 18 to 04, which is characteristic of the spectral resonance structures. The nighttime concentration is clearer in Figure 7b, which shows the occurrence rate of the spectral resonance structures detected by visual inspection of the dynamic spectra. The small percentages of daytime events in Figure 7a are not real but are misdetected by artificial noise. A major source of noise is the oscillation of a nearby 15-m radio antenna standing in the observation site at approximately 40 m from the magnetometer, which is blown by the strong wind in early spring in Japan. Figure 8 shows an example of a noise oscillation. They are characterized by fixed frequencies and variable intensities.

Figure 9 shows the occurrence rate of the spectral resonance structures for the 18 years from 1998 to 2016. The occurrence rate was high from 2005 to 2010. Note that the occurrence rate was not available for 2013, during which only one day of observation was conducted. The overlaid red curve represents the sunspot number. A clear anticorrelation is observed between them.

The anticorrelation found in Kawatabi ($L \sim 1.35$) is consistent with that found in a previous report by Yahnin [3] at higher latitudes ($L = 5.2$), and in accordance with their Figure 4, the reflection coefficient is larger at the solar minimum than at the solar maximum because of the steeper density gradient of the upper ionosphere. Because the solar activity is well correlated with the solar extreme ultraviolet radiation, which ionizes neutral atoms, intense extreme ultraviolet during the daytime at the solar maximum enhances the ion production rate and heats the neutral atoms to raise them upward. The high ion production rate intensifies an upward force of the pressure gradient above the peak of the F layer, increasing the plasma scale heights at the altitude. Thus, the plasma density gradient is less steep at the solar maximum. During nighttime, recombination of the ion species decreases upward diffusion, and it is expected that the density profile above the peak of the F layer is approximated as a function of altitude measured from the peak and scale height [12]. At the solar minimum, a lower altitude of the peak and smaller scale height would result in a steeper density gradient than that at the solar maximum, providing favorable conditions for an ionospheric Alfvén resonator.

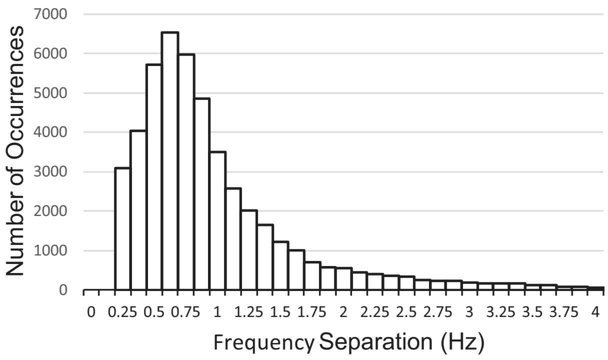

Figure 6. Frequency separation between harmonics of spectral resonance structure events detected in Kawatabi from 1998 to 2016.

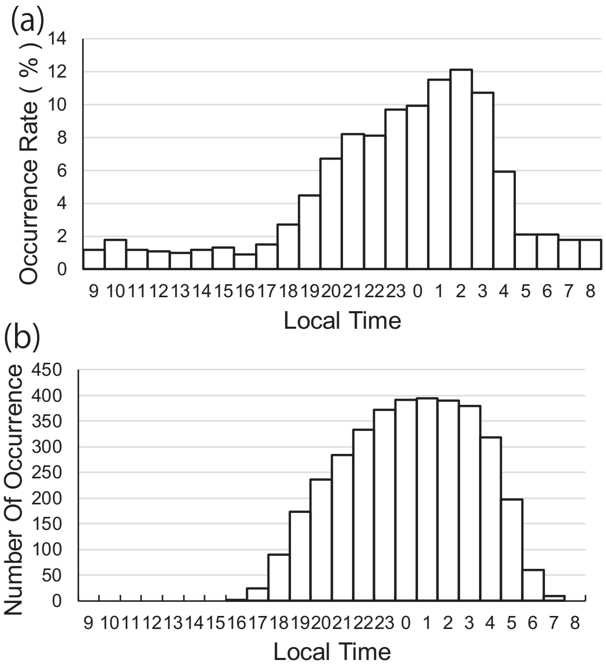

Figure 7. Local time distribution of spectral resonance structure events detected in Kawatabi from 1998 to 2016. (a) Automatic detection using 20-min averaged spectra. (b) Visual inspection of 2-min averaged spectra.

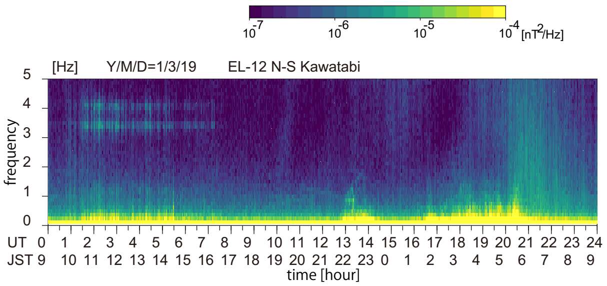

Figure 8. An example of artificial noise at 3.5 and 4.1 Hz due to the oscillation of a nearby 15-m radio antenna blown by strong wind in Kawatabi at 10-17 JST on March 19, 2001.

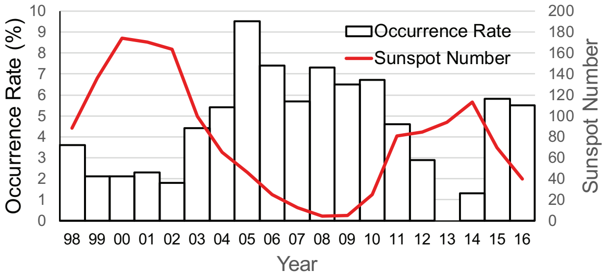

Figure 9. The occurrence rate of spectral resonance structures at Kawatabi from December 11, 1998, to June 2, 2016. The occurrence rate was unavailable in 2013 due to the lack of observation. The red curve is the sunspot number (Sunspot data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels [11]).

5. Conclusions

We conducted 18 years of observations of lower ELF range magnetic field variation at Kawatabi, Miyagi Prefecture, Japan ($L \sim 1.35$), and found the resonance spectral structure with a typical frequency separation of 0.625 Hz. They exhibited a clear anticorrelation with sunspot numbers, in accordance with the model in which the ionospheric reflection coefficient was higher because of the steeper density gradient of the upper boundary of the ionospheric cavity during the solar minimum.

6. Acknowledgments

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7. References

1. P. P. Belyaev, S. V. Polyakov, V. O. Rapoport, V. Yu. Trakhtengerts, "Experimental Studies of the Spectral Resonance Structure of the Atmospheric Electromagnetic Noise Background Within the Range of Short-Period Geomagnetic Pulsations," *Radiophysics and Quantum Electronics*, **32**, June 1989, pp. 491–501.
2. P. P. Belyaev, S. V. Polyakov, V. O. Rapoport, and V. Y. Trakhtengerts, "The Ionospheric Alfvén Resonator," *Journal of Atmospheric and Terrestrial Physics*, **52**, 9, September 1990, pp. 781–788.
3. A. G. Yahnin, N. V. Semenova, A. A. Ostapenko, J. Kangas, J. Manninen, and T. Turunen, "Morphology of the Spectral Resonance Structure of the Electromagnetic Background Noise in the Range of 0.1–4 Hz at L = 5.2," *Annales Geophysicae*, **21**, 3, March 2003, pp. 779–786.
4. O. Molchanov, A. Schekotov, E. Fedorov, and M. Hayakawa, "Ionospheric Alfven resonance at Middle Latitudes: Results of Observations at Kamchatka," *Physics and Chemistry of the Earth*, **29**, 4–9, December 2004, pp. 649–655.
5. T. Bösinger, C. Haldoupis, P. P. Belyaev, M. N. Yakunin, N. V. Semenova, et al., "Special Properties of the Ionospheric Alfvén Resonator Observed at a Low-Latitude Station (L = 1.3)," *Journal of Geophysical Research*, **107**, A10, 1281, October 2022, pp. SIA4-1–SIA4-9.
6. M. Nosé, M. Uyeshima, J. Kawai, H. Hase, "Ionospheric Alfvén resonator observed at low-latitude ground station, Muroto," *Journal of Geophysical Research, Space*, **122**, 7, July 2017, pp. 7240–7255.
7. P. Adhitya, M. Nosé, J. Bulusu, G. Vichare, and K. Shinha, "Observation of Ionospheric Alfven Resonator with Double Spectral Resonance Structures at Low Latitude Station Shillong (dipole L=1.08)," *Earth, Planets and Space*, **74**, 169, November 2022.
8. V. V. Surkov, M. Hayakawa, A. Y. Schekotov, E. N. Federov, and O. A. Molchanov, "Ionospheric Alfvén Resonator Excitation Due to Nearby Thunderstorms," *Journal of Geophysical Research*, **111**, A1, January 2006, A01303.
9. A. Schekotov, V. Pilipenko, K. Shiokawa, and E. Fedorov, "ULF Impulsive Magnetic Response at Mid-Latitudes to Lightning Activity," *Earth, Planets and Space*, **63**, February 2011, pp. 119–128.
10. E. Fedorov, A. Ju. Schekotov, O. A. Molchanov, M. Hayakawa, V. V. Surkov, and V. A. Gladichev, "An Energy Source for the Mid-Latitude IAR: World Thunderstorm Centers, Nearby Discharges or Neutral Wind Fluctuations?," *Physics and Chemistry of the Earth*, **31**, 4–9, 2006, pp. 462–468.
11. SILSO, World Data Center, "Sunspot Number and Long-term Solar Observations, Royal Observatory of Belgium, Online Sunspot Number catalogue," http://www.sidc.be/SILSO/ (Accessed 5 March 2023).
12. L. Liu, W. Wan, X. Yue, B. Zhao, B. Ning, et al., "The Dependence of Plasma Density in the Topside Ionosphere on the Solar Activity Level," *Annales Geophysicae*, **25**, 6, June 2007, pp. 1337–1343.