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Application of the Schumann Resonance Spectral Decomposition for the Analysis of Earth-Ionosphere Cavity Attenuation

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1. INTRODUCTION

The measurement and assessment of global thunderstorm activity is an important and frequent aspect of both meteorological and climatic as well as geophysical research. The assessment of this activity can be considered on the basis of indicators based on the intensity and frequency of the occurrence of various phenomena and processes, such as storm clouds (Kohl 1980), their altitude, wind speed, precipitation intensity (Twardosz 2010), the frequency of atmospheric lightning discharges (Christian *et al*. 2003). Such indicators are developed on the basis of observations and results of measurements carried out on the ground surface (Nieckarz and Zięba 2013) and by instruments placed on satellites (Turman 1978, Dai 2001).

Among measurements that use electromagnetic (EM) waves to monitor lightning activity, measurements of EM waves of extremely low frequency range (ELF, 3-3000 Hz) deserve particular attention. The broadband electromagnetic excitation which is each atmospheric lightning discharge excites in this frequency range a resonance in the resonant cavity constituted by the surface of the Earth and the ionosphere (E-i). For ELF waves, which have low frequencies, both the Earth's surface and the lower part of the ionosphere, the ionospheric D, E-layer and the lower part of the F-layer are well-reflective surfaces. As a result of the multiple circulation of waves around the Earth and their mutual interference – the spectrum of ELF waves is created (Fig. 1), with a specific resonant character (Schumann 1952), the so-called Schumann resonance (SR) spectrum. In the amplitude and shape of this spectrum we can find information not only about storm activity, but also about the Earth-ionosphere cavity damping.

The previous classical analysis of the SR spectrum consists of a fitting symmetric Lorentz curves to the observational spectra (Sentman 1996, Mushtak and Williams 2002). Unfortunately, this approach leads to the determination of the values of the E-i resonator's "own" frequencies, which are different even for NS and EW antennas working within one measurement station. A new approach described under the name of the ELF spectrum decomposition is shown in the paper of Kułak *et al*. (2006), where a method of correct determination of the E-i cavity's own, i.e. the resonance frequencies (eigenfrequencies), for both perpendicularly arranged antennas working within one measurement station was described. Knowing the correct values of the cavity's own frequencies makes it possible to calculate the E-i resonant cavity damping, and is one of the elements reflecting the space weather condition in the immediate vicinity of the Earth.

The use of the power spectrum decomposition method and the acquisition of information about the E-i cavity damping based on ELF measurements made by two stations with very different locations and structures is the subject of analyses presented in this paper.

2. SOURCE OF DATA

This paper utilises the results of ELF measurements made by two ELF stations: a) the station named Hylaty in the Bieszczady Mountains (SE Poland) and b) the Yon station working in Yongsheng County, Yunnan province in China. The results of measurements collected in the period from 2011.05.31 (16:00 UTC) to 2011.06.09 (16:00 UTC) were analysed. The stations differ significantly in many respects, including the power supply, antenna and recorder design, digitalisation parameters, bandwidth. The orthodromic distance between the two stations is 6980 km.

2.1 The ELF Hylaty station (Poland, Europe)

ELF measurements in the Bieszczady Mountains (SE Poland, 22.5°E, 49.1°N) are conducted by the Astronomical Observatory of the Jagiellonian University in Kraków. Continuous measurements have been carried out since 2005. The station is equipped with two active magnetic antennas (solenoids), a recorder and a set of batteries that provide power supply for a period of over 2 months. After this time, the memory card in the recorder is replaced, and the measurement results are delivered to Kraków to be analysed and archived. The battery pack, however, is charged in the field with the use of a power generator. Charging time is about 10 hours. The recorder and batteries are placed in an underground tank, which protects the apparatus mechanically and stabilises the thermal conditions of the apparatus (Nieckarz 2016). Both antennas are arranged horizontally in accordance with the geographical directions of NS and EW, at a distance of 100 m from the recorder. The antennas are 1 m long and are powered from the recorder module. The 3 dB frequency bandwidth of the station is 0.03-55 Hz and the sampling frequency equals 175 Hz. The amplitude input range is +/- 1.8 nT with 16-bit dynamics. The station measures the signal from the antennas, which is subjected to integration and thanks to this the recorder records the values proportional to the magnetic field induction (*B*). A detailed description of the apparatus can be found in the paper by Kułak *et al*. (2014).

2.2 The ELF Yongsheng station (China, Asia)

The Yon ELF station conducts ELF measurements in Yongsheng County (100.8°E, 26.7°N), Yunnan province in China. It was established in 2009 with the original intention to monitor earthquakes so that only magnetic component (B_{NS}, B_{EW}) antennas are installed. The 3 dB frequency bandwidth of the station is 3–29 Hz, and the sampling frequency equals to 100 Hz. The sampling data is saved to a local computer, and then they are available via the Internet in quasi-real-time (Ouyang *et al*. 2015). All of it is powered from the power grid. The station measures the signal from the antennas and does not use the integrating ratio. As a consequence, the recorded signal is proportional to the magnetic field induction derivative (*dB/dt*).

2.3 Comparison of ELF spectrum

Figure 1 presents power spectra obtained in both stations. There are clear differences in the nature of the spectra, especially in the bandwidth of both measuring systems. The spectra also contain narrow lines and distortions in various frequency ranges, which indicates a diverse level of electromagnetic noise from human activity (power grids, proximity of populated areas and roads).

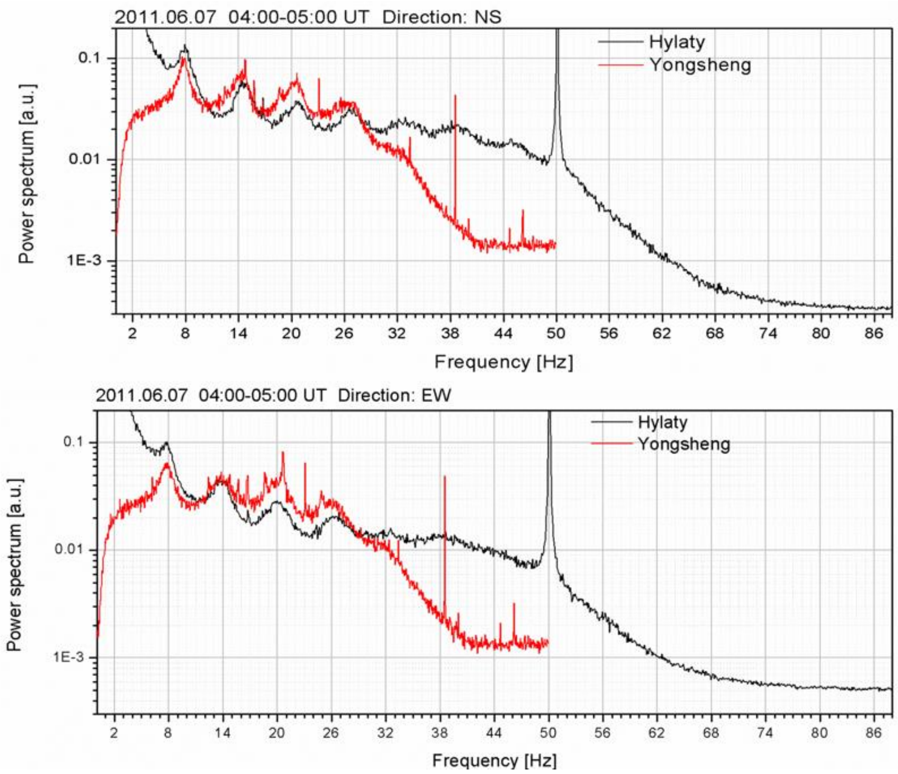

Fig. 1. The comparison of average hourly radiation power spectra in the ELF range, which were recorded with NS antennas (the upper graph) and EW antennas (the bottom graph) by the ELF Hylaty station in the Bieszczady Mountains (black line) and the ELF Yon station in Yongsheng (red line).

3. METHOD OF ANALYSIS

Firstly, average daily power spectra were calculated for the collected measurement results for each station and each antenna separately using Fast Fourier Transform algorithm (Cooley and Tukey 1965). Next, analytical power spectrum was fitted to each spectrum, in accordance with formula in Eq. 1 in the 4–24 Hz frequency range, where: $|B_t(f)|^2$ – is the theoretical summary power spectrum; w – the amplitude of the power spectrum of white noise; z – the amplitude of the colour spectrum noise; α – spectral parameter of colour noise; n – is the number of resonance mode; a_n – describes the power of the n resonance mode, the value of which depends on the distance of the signal source from the measurement station; e_n – is the asymmetry parameter; f_n and Γ_n are mean reduced resonance frequency and a half of the reduced resonance width.

$$|B_t(f)|^2 = w + \frac{z}{f^\alpha} + \sum_{n=1}^{3} \frac{a_n \cdot [1 + e_n \cdot (f - f_n)]}{(f - f_n)^2 + (\Gamma_n)^2} \qquad (1)$$

The selected frequency range includes the first three Schumann resonance modes, and at the same time can be applied to both types of data. The applied analytical formula was developed and applied in the paper by Kułak *et al*. (2006), with the use of test spectra obtained from a numerical model based on the application of the two-dimensional telegraph equations (TDTE) and tested for a small sample of real spectra recorded by the ELF Hylaty station (Kułak *et al*. 2006), and has also been successfully used to determine the distance between the African storm centre and the Hylaty station (Dyrda *et al*. 2014).

Due to local storm activity it was not possible to perform spectrum analysis for every hour. Some results were rejected due to the huge interferences coming from very close discharges. The majority of such cases concerned the Hylaty station.

For all qualified observational spectra from both stations, analyses were carried out using the identical fitting procedure, in which noise and the first three resonance modes were taken into account.

4. RESULTS

As a result of fitting the analytic function (Eq. 1) to the spectra obtained from measurements, the following were determined: frequency value, full width at half maximum, asymmetry coefficient and amplitude for each *n*-th resonance peak (f_n, Γ_n, e_n, a_n). Frequency course f_1 for both stations and for each antenna (NS and EW) as a function of time is shown in Fig. 2. The graph shows that courses of value f_1 in both antennas are characterised by the distinctly cyclical variability (especially in the Hylaty station) and are mutually correlated. Large diurnal variations of the determined average hourly frequencies f_1 partly result from storms that occurred in the vicinity of the Hylaty station, which hindered the analysis of power spectra; however, aspect of diurnal variation of f_1 is not the subject of this paper.

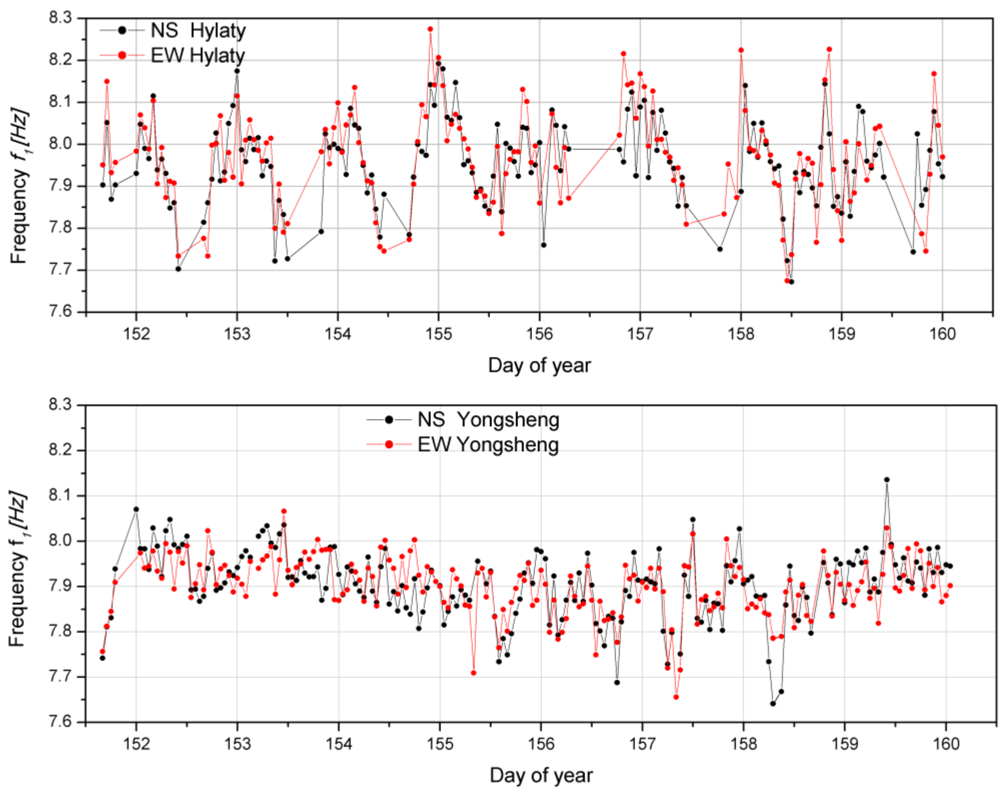

Fig. 2. Waveforms of hourly frequency values $f_{1,NS}$ (black) and $f_{1,EW}$ (red) of the first Schumann resonance mode determined on the basis of measurements conducted by the Hylaty ELF station (the upper graph) and Yon ELF station (the bottom graph) from 2011.05.31 (16:00 UTC) to 2011.06.09 (16:00 UTC).

Based on the results shown in the graph (Fig. 2), the average frequency values for the first resonant peak for both antennas were calculated for each station ($<f_1>_{NS}$, $<f_1>_{EW}$) and presented in the table (Table 1) along with their standard deviation (*SD*). The standard error of the mean in all cases does not exceed ±0.01 Hz. It is easy to see that the $<f_1>$ values in Table 1 are consistent.

Table 1

The average frequency values of the first resonance mode calculated for the Hylaty ELF and Yon ELF stations for the NS and EW directions; the *SD* is the standard deviation

Station	Direction NS $<f_1>_{NS}$ ±*SD*	Direction EW $<f_1>_{EW}$ ±*SD*
ELF Hylaty	7.96 ±0.10	7.97 ±0.12
ELF Yon	7.90 ±0.10	7.90 ±0.07

The maximum value of the average is 7.97 Hz and the minimum 7.90 Hz, thus the average value span is 0.07 Hz. However, within one station the difference between frequencies $<f_1>$ for NS and EW directions does not occur or is very small (0.01 Hz) for the ELF Yon and ELF Hylaty stations, respectively.

The calculated average frequency f_1, based on all values from the table (Table 1), is 7.93 Hz. Knowing the f_1 value we can, based on the results presented in the paper (Kułak *et al*. 2006), determine the average damping value of the Earth-ionosphere resonant cavity (χ) in the analysed period, which amounted to $\chi = 3.43 \times 10^{-6}\ \Omega\ m^{-1}Hz^{-1/2}$.

5. CONCLUSIONS

In spite of significant differences in the construction of the measuring apparatus, the frequency range of the recorded frequencies (Hylaty: 0.03–55 Hz, Yon: 3–29 Hz) and recorded physical quantity (Hylaty: B – magnetic field induction, Yon: *dB*/*dt* – a derivative of magnetic induction), the same frequency, within the limits of the error, of the first Schumann resonance mode (f_1) in NS and EW antennas for both stations was obtained.

The obtained result indicates that the application of the asymmetrical model to the Schumann resonance spectrum is correct and allows for the correct determination of the average frequency value of the first SR mode despite using the apparatus with different characteristics. As a consequence, it is possible to determine the E-i resonant cavity damping value, which for the analysed period 2011/05/31 – 2011/06/09 was $3.43 \times 10^{-6}\ \Omega\ m^{-1}Hz^{-1/2}$.

The data from the analysed period was included in detailed analysis in the Passive Interval (PI) of 24 Solar Cycle (Zięba and Nieckarz 2014), and from the classical point of view, it is classified into the growth phase of the 24th solar cycle, in which the average sunspot number is 90.4. The obtained result of the E-i cavity damping is close to the damping range obtained by another method (Kułak *et al*. 2003) for the growth phase of the 23th solar cycle.

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ZASTOSOWANIE METODY DEKOMPOZYCJI WIDMA REZONANSU SCHUMANNA W CELU ANALIZY TŁUMIENIA WNĘKI ZIEMIA-JONOSFERA

Streszczenie

Celem pracy jest wyznaczenie tłumienia (χ) wnęki rezonansowej Ziemia-jonosfera (Z-j) na podstawie częstotliwości własnej pierwszego modu rezonansowego (f_1) wyznaczonej z widm mocy sygnału ekstremalnie niskiej częstotliwości ELF (ang. Extremely Low Frequency), metodą dekompozycji (Kułak i in. 2006), a zmierzonego z wykorzystaniem stacji pomiarowych o diametralnie różnej budowie.

W pracy wykorzystano wyniki pomiarów, które wykonano magnetycznymi antenami horyzontalnymi (NS i EW) pracującymi w stacji ELF Hylaty (SE Polska, 22.5°E, 49.1°N) oraz stacji ELF Yon (kanton Yongsheng, prowincja Yunan w Chinach, 100.8°E, 26.7°N). Okres pomiaru obejmuje 9 dób (2011.05.31 – 2011.06.09). Stacje odległe są od siebie o 6980 km i różnią się znacząco zarówno konstrukcją jak i charakterystyką toru pomiarowego.

W niniejszej pracy wykazano, że analizując wyniki pomiarów ELF wykonanych dwiema różnymi stacjami pomiarowymi o różnych lokalizacjach na globie, metoda dekompozycji w pozwala wyznaczyć zgodną dla obu stacji średnią częstotliwość (f_1) wnęki rezonansowej Z-j.

Badany okres przypada na fazę wzrostu w 24 cyklu słonecznym. Korzystając z obliczonej średniej wartości f_1 równej 7.93 Hz oraz wyników pracy (Kułak i in. 2006) wyznaczono dla tego okresu średnią wartość tłumienia wnęki Z-j, która wyniosła $\chi = 3.43 \times 10^{-6}\ \Omega\ \mathrm{m}^{-1}\mathrm{Hz}^{-1/2}$ i jest zbliżona do zakresu tłumień uzyskanych inną metodą (Kułak i in. 2003) dla fazy wzrostu w 23. cyklu słonecznym.