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ALGORITHM FOR CHOOSING THE PLACE FOR THE GLOBAL SCHUMANN RESONANCE OBSERVATORY

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Abstract: We suggest an algorithm for choosing the position for the observatory of the Schumann resonance (SR). The main goal of future measurements is to estimate the intensity of the global thunderstorm activity which is the main source of the electromagnetic energy in the extremely low frequency (ELF) band from a few Hertz to some tens of Hertz. Our analyses is based on the numerical modeling of the SR background signal. It is shown that the quality of the data dramatically depends on the position of the field-site, and the polar regions are the most promising candidates for SR explorations.

1. Introduction

The global electromagnetic resonances were predicted by SCHUMANN (1952). The resonance exists due to electromagnetic waves that are trapped in the spherical dielectric cavity formed by conducting Earth and lower ionosphere. The resonance condition physically means that the EM wave of a given frequency acquires the phase delay proportional to 2π after it travels around the Earth. Amplitude of the wave grows at the resonance frequencies, since the waves meet in-phase. The Schumann resonance waves originate from the natural sources of electromagnetic radiation in the extremely low frequency (ELF) band: from the global lightning discharges. Each stroke of lightning works as a huge vertical electric antenna that sends an EM pulse into the Earth-ionosphere cavity. These random sources of EM energy (around 100 strokes per second) work independently producing natural radio noise, and the energies radiated by individual lightning strokes are summed in the resulting ELF field. Individual signals travel around the Earth's circumference three-four times before their energy is absorbed in the plasma of the lower ionosphere. Meanwhile, the SCHUMANN resonances manifest themselves as separate peaks observed in the power spectrum of natural EM noise.

Figure 1 presents the schematics of the Earth-ionosphere cavity and the sample of the real amplitude spectra of the natural ELF electromagnetic radio noise. The signal had been recorded with the vertical electric antenna installed at the roof of the building of the Department of Electronic Engineering of the University of Electro-Communications at Chofu-shi, Tokyo. Here, the frequency is plotted along the abscis-

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sa, and the field amplitude is plotted on the vertical axis in dB (relative to 1 V/m). Despite the fact that the measurements were carried out in the vicinity of a huge industrial city, the Schumann resonance peaks are clearly seen in the spectrum up to the fourth peak (fourth resonant mode) during local night.

The global thunderstorms being the source of the Schumann resonance oscillations are concentrated in tropics. Maximum of the world-wide thunderstorm activity circles the globe every day producing variations in the SR amplitudes A_N and apparent resonance frequencies F_N (see Fig. 1). The amplitude observed at a given field-site depends both on the source-observer distance and on the current lightning intensity.

Level of the global lightning activity depends on the surface temperature of the Earth through the air convection and cloud formation process (see WILLIAMS, 1992, 1999). Therefore, the intensity of the Schumann resonance reflects the current lightning intensity and may contain information on the global warming. Unfortunately, the ELF field amplitude recorded depends both on the source activity and on its distance from the observatory.

The goal of the present investigation is a search (using the computational model) for a position of the ELF observatory where the role of the movement of the lightning

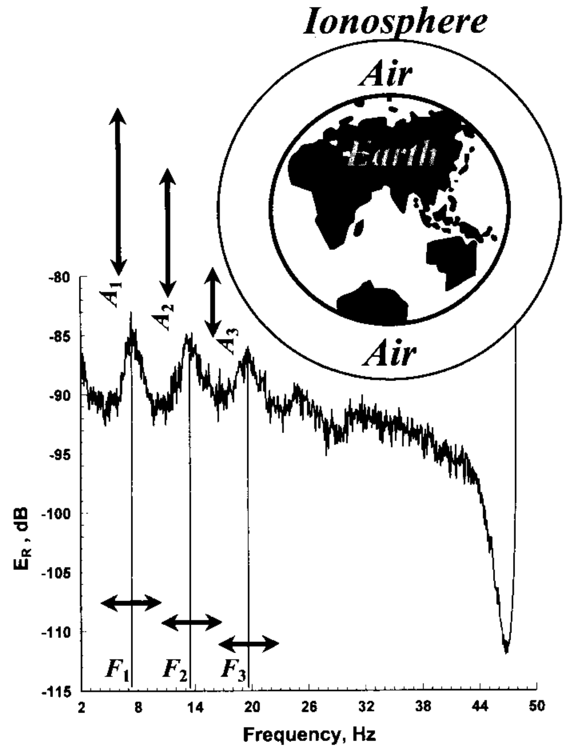

Fig. 1. Schematics of the Earth-ionosphere cavity and a sample of Schumann resonance spectrum. Vertical electric field component had been recorded at the roof of the building of the Department of Electronic Engineering of the University of Electro-Communications, Chofu-shi, Tokyo.

sources becomes insignificant. Records performed at such an observatory will reflect variations in intensity of the global thunderstorms rather than their position. This issue was discussed also in Nickolaenko (1997).

2. Theory

We describe the extremely low frequency (ELF) spectral components of an electromagnetic wave using the mode theory developed for the uniform spherical Earth-ionosphere waveguide by Wait (1962), Galejs (1972). The field components for the TEM or zero-order mode are calculated from the following formulas (Jones, 1970):

$$E_r = i\,\frac{\nu(\nu+1)}{\omega}\,\frac{M_C(\omega)}{4a^2 h\varepsilon}\,\frac{P_\nu[\cos(\pi-\theta)]}{\sin\pi\nu}, \tag{1}$$

$$H_\phi = -\frac{M_C(\omega)}{4ah}\,\frac{P_\nu^1[\cos(\pi-\theta)]}{\sin\pi\nu}. \tag{2}$$

Here, we use the spherical coordinate system (r, θ, ϕ) with the origin at the center of the Earth. The source and observer are placed at the ground surface in points $(r_s=a, \theta_s=0, \phi_s=0)$ and $(r_0=a, \theta_0=\theta, \phi_0=0)$. The spectral components of the field are measured in V×s/m and A×s/m; $\nu(\omega)$ is the dimensionless propagation constant of the ELF radio wave, ω is the circular frequency in s^{-1}, $M_C(\omega)$ is the current moment of the source in A×s×m, θ is the angular distance between the source and the observer in radians, a is the Earth's radius in meters, h is the effective height of the ionosphere in meters, ε is the dielectric constant of the free space in F/m, $P_\nu(x)$ and $P_\nu{}^1(x)$ are the Legendre and associated Legendre functions, the time dependence is $e^{i\omega t}$.

Single zero-order mode or TEM wave propagates in the ELF range between a few Hz to approximately 1.6 kHz. There are two details to be clarified before computations.

1) One has to introduce a $\nu(f)$ dependence before computations. We apply the following heuristic dependence (see Nickolaenko, 1997 for details):

$$\nu(f) = \nu_1 - i\nu_2 = \frac{(f-2)}{6} - i\,\frac{f}{100}, \tag{3}$$

where f is measured in Hz.

2) The second problem arises from the Legendre functions when we start computing fields. We apply the zonal harmonic series representations (ZHSR)

$$P_\nu[\cos(\pi-\theta)] = -\frac{\sin(\pi\nu)}{\pi\sin\theta}\sum_{n=0}^{\infty}\frac{(2n+1)P_n(\cos\theta)}{n(n+1)-\nu(\nu+1)}, \tag{4}$$

$$P_\nu{}^1[\cos(\pi-\theta)] = -\frac{\sin(\pi\nu)}{\pi\sin\theta}\sum_{n=1}^{\infty}\frac{\nu(\nu+1)(2n+1)P_n(\cos\theta)}{[n(n+1)-\nu(\nu+1)][n(n+1)-(\nu+1)(\nu+2)]}. \tag{5}$$

The series (4) and (5) converge poorly, and we have to accelerate their convergence using a special algorithm (Nickolaenko and Rabinowicz, 1974; Bliokh *et al.*, 1980; Jones and Burke, 1990; Nickolaenko and Hayakawa, 1998).

3) The continuous background ELF field originates from radiation of random independent strokes of lightning. The global rate of discharges is about 100 events per second. Therefore, about $100/8 \approx 12$ independent pulses arrive and interfere at random during the single period of the basic Schumann resonance frequency $f_1 = 8$ Hz. Only statistical processing allows to detect the resonance peaks. Moreover, the integration time for accumulating the stable power spectra estimates should exceed a few minutes (Bliokh *et al.*, 1980; Nickolaenko, 1981; Lazebny *et al.*, 1984).

This experimental fact is interpreted with the help of Poisson pulse succession. In this case the power spectra and the spectra of Poynting vector components become a sum of exclusively second-order statistical moments of individual pulses. In other words, when the noise is a Poisson succession, the cross-products of individual pulses do not contribute into the second statistical moments of the signal, and this fact is know as Campbell theorem. Physically, this fact is usually expressed by the statement that the intensities of individual pulses are summed in the power spectra.

Formally, the result means that when computing the SR background signal one may use relations (1) and (2) for the individual strokes and simply apply an averaging procedure to the intensities of individual pulses. For instance, the average intensity of vertical electric filed component for a known distance distribution of the strokes $W(\theta_K)$ is found using the averaging of contributions from individual discharges (Bliokh *et al.*, 1980; Nickolaenko, 1997):

$$\text{Power }(E_r) = \int \left| i\,\frac{\nu(\nu+1)}{\omega}\,\frac{M_C(\omega)}{4a^2 h\varepsilon}\,\frac{P_\nu[\cos(\pi-\theta_K)]}{\sin \pi\nu} \right|^2 W(\theta_K)\sin\theta_K\, d\theta_K. \qquad (6)$$

Here, θ_K is the distance from the observatory to the K-th random discharge.

3. Model of the Global Lightning Activity

There are three centers of the global thunderstorm activity. They are situated in Africa, America and South-East Asia. Lightning activity within each of them covers a wide area, having the characteristic size of a few tens of degrees, Nickolaenko and Rabinowicz (1995), Nickolaenko *et al.* (1996). It varies in time and reaches the maximum level during local afternoon. Hence, during a day, the Asian thunderstorms become active first (around 08 hr UT). Then, the lightning activity shifts to African continent (15 hr UT). Finally, the maximum of the global thunderstorms arrives to America (around 20 hr UT). This is the way the "diurnal source motion" occurs with respect to a given observatory. Such a motion is the reason of the diurnal amplitude and frequency variations observed in the SR spectra. The instantaneous intensity depends on both the current activity of the source and its distance. The peak frequency of a particular mode depends only on the source-observer separation (Ogawa *et al.*, 1968; Galejs, 1972; Ogawa and Otsuka, 1973; Bliokh *et al.*, 1980; Bormotov *et al.*, 1972; Korol and Nickolaenko, 1985; Lazebny *et al.*, 1987). Thus, the Schumann resonance becomes a tool for monitoring the world-wide thunderstorm dynamics from a single or a few observatories.

We use a model that accounts both for the temporal variations of the source intensities and for their positions. We borrowed the time dependence of intensities in each center from the geophysical data (WMO, 1956). In our model, these diurnal variations remain the same throughout the year. The yearly drifts of the positions of the global thunderstorms were based on the same geophysical data with a slight modifications allowing to describe the long-term SR records (Nickolaenko *et al.*, 1998).

Figure 2 depicts temporal variations of the global lightning activity. The universal (GMT) time is plotted along the horizontal axis. We show variations of the thunderstorm intensity in three global centers: Africa, Central America and South-East Asia (WMO, 1956). Maximum of lightning activity at any particular center occurs in the local afternoon. The thunderstorm activity "strides" from one continent to another and thus circles the globe. The particular center dominates during a few hours a day. This allowed us to introduce the model of a single equatorial thunderstorm center that circles the globe during the day, see *e.g.* Ogawa *et al.* (1968), Galejs (1972), Ogawa and Otsuka (1973), Bliokh *et al.* (1980), Bormotov *et al.* (1972), Lazebny *et al.* (1987), Nickolaenko and Rabinowicz (1995).

Such a model is proved to be efficient for the first SR mode having the wavelength of 40000 km. The small structures like continents are not resolved by such a wave. Total lightning activity of the Earth is shown in Fig. 2 as well. It is easy to see that the

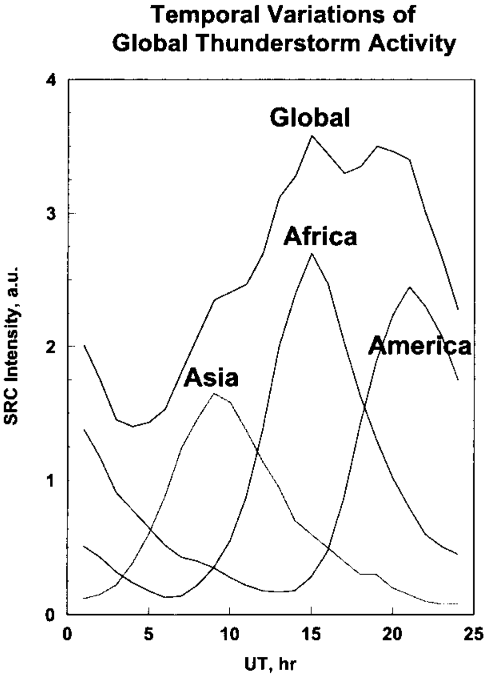

Fig. 2. Diurnal variations of the global lightning activity.

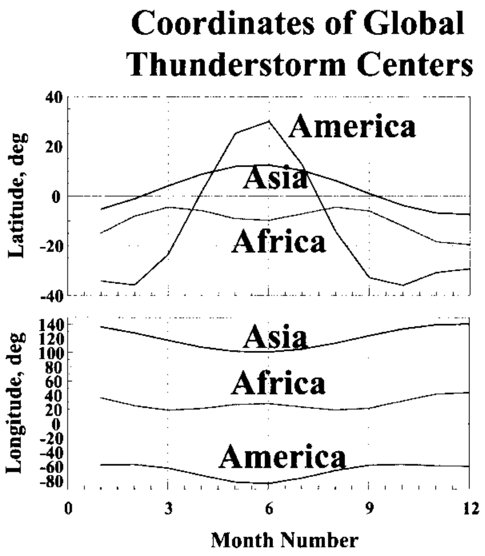

Fig. 3. Seasonal drifts of the global thunderstorm centers.

cumulative thunderstorm intensity varies by a factor of 2.5 during the day.

Figure 3 depicts seasonal variations of the coordinates of the global centers. Seasonal variations in the source position and the estimate for the size of zone covered by lightning strokes are based on the climatological data (WMO, 1956). This information was modified to fit the long-term SR records performed at Nagycenk observatory (Hungary) in 1993-1995 (see NICKOLAENKO *et al.*, 1998 for details).

The upper frame in Fig. 3 demonstrates annual drift of the thunderstorm centers along latitude. The lower frame in the same figure shows their longitudinal shifts. The frames illustrate movement of the centers of circular zones uniformly covered with the lightning flashes. We postulate that each zone has 5 Mm in diameter. This is in accord with published results (BORMOTOV *et al.*, 1972; LAZEBNY *et al.*, 1987; NICKOLAENKO and RABINOWICZ, 1995). We suppose that the lightning activity is uniformly distributed within these circular areas.

Intensity of individual sources varies in time as Fig. 2 shows.

Seasonal drift of the world-wide lightning activity gives rise to changes of the median source-observer distances. We show annual variations of these distances for the Tokyo observatory in Fig. 4 together with the width of zones covered by lightning. Month of year is plotted on the abscissa. The source distance is shown along the ordinate. Patterned belts present the width of the gap between maximum and minimum distances.

We had explained how the computational scheme works. Having in mind the SR wavelength, readers should not ascribe the field-sites precisely to geographical sites. Say, "Tokyo" in this paper and the name "Aso" in NICKOLAENKO (1997) actually mean a point somewhere in Japan because the shift of a few hundred kilometers does not matter (when the distance to thunderstorms is a few thousand kilometers). For the same reason, the results for Hungarian observatory (we used coordinates of the

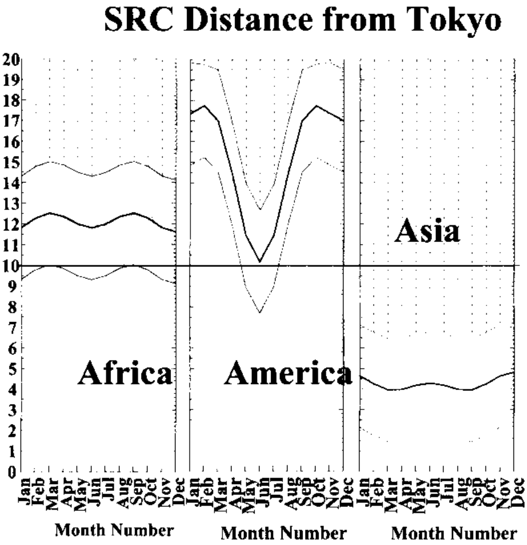

Fig. 4. Annual variations of the source-observer distances for an observer at Tokyo.

Nagycenk field-site) are valid for central Europe, say Germany, as well.

4. Results and Discussion

The main goal of the SR measurements discussed lies in obtaining variations of the global thunderstorm activity. Recorded amplitude of the Schumann resonance signal depends on both the source intensity and the source distance. Therefore, particular measurement/processing techniques should be used (KOROL and NICKOLAENKO, 1985; NICKOLAENKO *et al.*, 1996) compensating for the source distance, or a special position of the observatory should be sought (NICKOLAENKO, 1997) where the motion of global thunderstorms does not play an important role. We consider below a set of field-site positions and model the ELF receivers of two possible kinds:

- The narrow-band receiver that is tuned to the first Schumann resonance mode 8 of Hz frequency and measures the field intensity
- The wide-band receiver that records the ELF intensity in the band of six SR modes from 4–40 Hz.

The narrow-band receiver or Schumann resonance mode tracker was introduced by Nelson and had been used in the early SR monitoring (NELSON, 1967; TRAN and POLK, 1976; SAO *et al.*, 1973). It remains a popular device nowadays. Updated digital version of the tracker is used in the measurements by Hungarian group (SÁTORI *et al.*, 1996). The main advantage on the narrow-band monitoring technique lies in the simplicity of its performance. The disadvantage (from the viewpoint of intensity monitoring) is its potential sensitivity to the source position.

The wide-band receiver automatically overlays the individual SR modes, and each of them has different distance patterns. Therefore, it is less sensitive to the source distance (KOROL and NICKOLAENKO, 1985). Numerical simulations show that the wide-band intensity varies by a factor of three for the distance range from 4 to 19 Mm and by the factor of two for the interval from 5.5 to 15.5 Mm, and it rapidly increases for the distances beyond these intervals (NICKOLAENKO, 1997; NICKOLAENKO *et al.*, 1998). Wide-band receivers are used in Japan, USA, England, Hungary, Israel, Russia (see *e.g.* SENTMAN and FRASER, 1991; BURKE and JONES, 1996; FÜLLEKRUG and FRASER-SMITH, 1998; WILLIAMS, 1999; HOBARA *et al.*, 1999; BELYAEV *et al.*, 1999).

We include the following observatories in our analysis

1) Japan: 35.5°N, 134°E,
2) Israel: 30.6°N, 35°E,
3) Hungary: 47.6°N, 16.7°E,
4) U.S.A. (Rhode Island): 47°N, 71°W,
5) South Pole: 89°S, 134°E.

Schumann resonance measurements are currently performed at these sites except the South Pole. The actual list of the SR observatories is longer. For instance, we do not include Fairbanks and San Francisco (USA), Silberborne (Germany), Lehta (Russia) having in mind the problems of displaying too many plots in the same figures. Five frames are quite enough for a figure and for demonstration of idea.

Figure 5 depicts amplitude variations of the first SR mode computed for each site. The model ELF receiver has a uniform amplitude response in the frequency range from

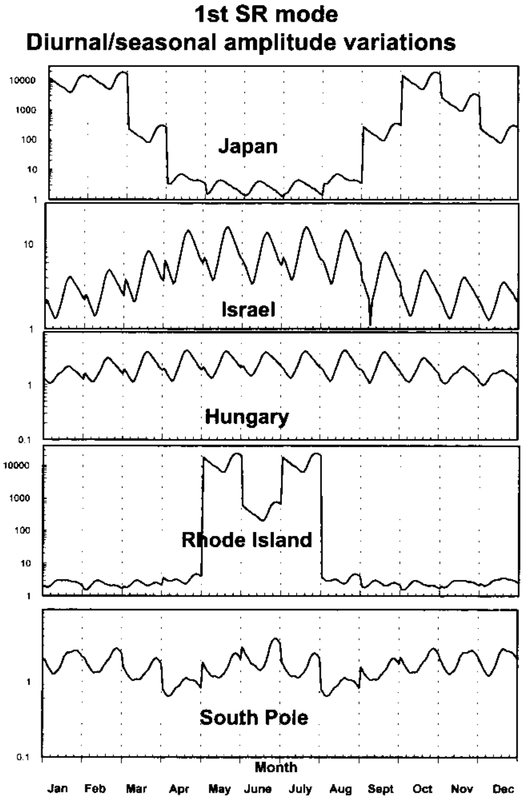

Fig. 5. Diurnal/seasonal amplitude variations at the first Schumann resonance mode.

6.5 to 9.5 Hz. The abscissa in the plot is divided into 12 strips shown with dotted lines (month of a year). Daily (24 hr) amplitude variations are shown within these strips, this is why some plots contain discontinuities in the figure. The abrupt changes appearing in the median level of the amplitudes for Japanese and American sites are explained by their close position to Asian or to American thunderstorm centers.

We removed diurnal variations in Fig. 6 to show the average amplitude for the first SR mode. The month of the year is shown along the abscissa. Higher sensitivity of American and Japanese observatories toward the source seasonal drifts is seen more clearly in this figure. We must mention that some observatories in the USA have minor sensitivity to the source movement, *e.g.* the Fairbanks field-site (see NICKOLAENKO, 1997).

Modeling showed that variations induced by the source motion are reduced dramatically (two-three orders in magnitude) when the observer applies the wide-band amplitude monitoring. To illustrate advantage of the wide-band registrations, we plot the results computed for the ELF amplitude in the 4–40 Hz range in Fig. 7. Variations caused by the source distance are reduced by an order in magnitude, but still remain high for the Japanese and the US observatories.

It is easy to formulate a physical conclusion from the model results. Centers of the global lightning activity are positioned in the tropical zone over the continents. The solid ground is distributed non-uniformly over the Earth. The seasonal drifts along continents may move the active zones into close vicinity of an observatory. Hence, we

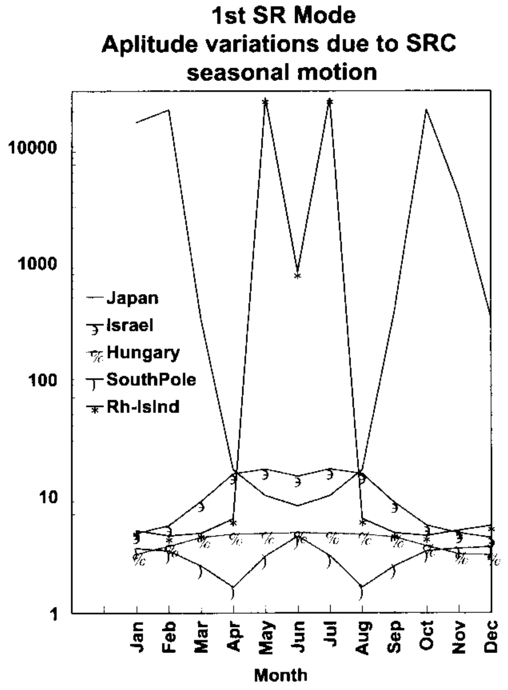
1st SR Mode
Aplitude variations due to SRC seasonal motion

Fig. 6. Amplitude variations due to source motion.

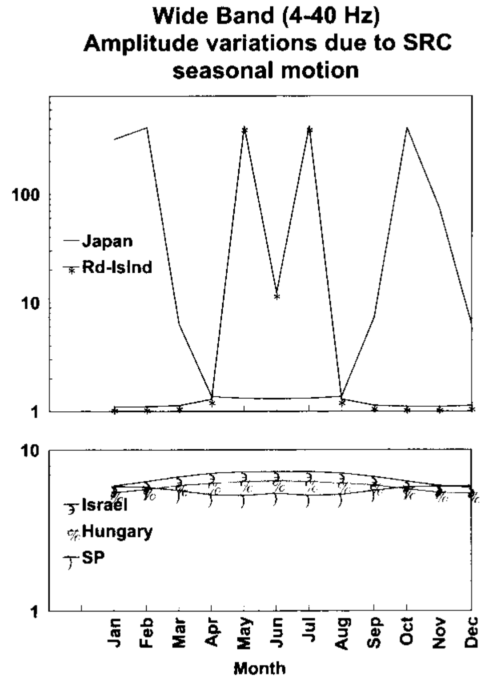
Wide Band (4-40 Hz)
Amplitude variations due to SRC seasonal motion

Fig. 7. Seasonal variations of the wide-band amplitude.

should search for an "equi-distant" placement of the observer in respect to the centers. It should have the seasonally unvarying distances from all three thunderstorm centers: $D_i(T) = D_i$, and the same distances are desirable: $D_i = D_k$. The Fairbanks (USA) and Nagycenk (Hungary) are close to such optimal positions in the northern hemisphere.

The Geo Electromagnetic Index (GEMI) is a more informative parameter of the quality of the ELF data. GEMI is the ratio of the ELF field amplitude recorded to the current intensity of the global thunderstorm activity shown in Fig. 2 as "Total".

Consider an ideal place for the ELF observatory that we have found and now, perform a monitoring there of the wide-band ELF amplitude. Since our position is

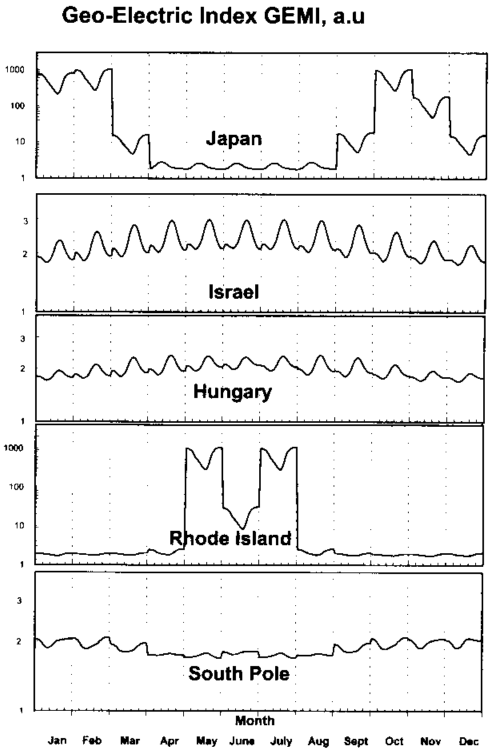

Fig. 8. Diurnal/seasonal variations of the wide-band ELF Geo-Electro-Magnetic Index.

Table 1. Maximum annual/diurnal variations in the GEMI for different field-sites.

Observatory	Coordinates	Max diurnal GEMI variation, times	Max annual GEMI variation, times
Japan	35.5° N, 134° E	4	500
Israel	30.6° N, 35° E	1.5	1.2
Hungary	47.6° N, 16.7° E	1.5	1.3
Rhode Island (USA)	47° N, 71° W	3	500
South Pole	89° S, 134° E	1.1	1.15

ideal, the diurnal variations recorded are proportional to the intensity of the planetary thunderstorms, and their position plays no role. In this case, the GEMI index remains constant in time. Particular value of this constant may vary from one ideal site to another, because relevant source-observer distances may be different (remaining constant in time). Hence, the temporal stability of the GEMI indicates the expected accuracy of presentation of the global thunderstorm activity by the Schumann resonance monitoring at a given place.

We had calculated the GEMI values for the same set of observatories and plot the results in Fig. 8. Modeling shows that the South Pole observatory supports monitoring of the global thunderstorm activity with uncertainty lower then 10%. In this context, the ELF data recorded in Antarctica (FÜLLEKRUG and FRASER-SMITH, 1998) are of special interest.

Table 1 presents maximum and minimum estimates for the diurnal variations of GEMI at the field-sites. Numbers in the table characterize the expected quality of the observatories as monitoring places. Again, one may see that measurements in polar region provide accurate global data. Naturally, we do not discuss here any problems connected with performing the ELF measurements in severe conditions of polar zone.

5. Conclusion

Results of numerical modeling show that some SR observatories appear to be suitably placed. Therefore, the records in these sites could be of great practical value for estimating variations in the level of global thunderstorm activity. Simultaneously, we must point out that present results were obtained with the numerical modeling, and therefore, they depend on the parameters of the model applied. We had based our model on multiply checked climatological data and had upgraded these using recent long-term SR records. Still, none can guarantee complete coincidence of the model and practical results for a particular observatory. Model is just a model, and it cannot account for all the features of reality.

Still, positioning an ELF observatory in the polar region appears to be a good and rather sensible solution: the poles are at equi-distant position from the tropical belt by definition. Numerical modeling supports this idea. Authors understand that the measurements in polar zone will raise additional problems both scientific and technical.

We would like to emphasize as well that the procedure developed allows obtaining numerical estimates of the quality of an arbitrary SR field site.

The results presented lead to following conclusions:

- The wide-band measurement technique has obvious advantages, and the wide-band receivers should be preferred in the monitoring of the global thunderstorm activity based on the Schumann resonance electromagnetic data.
- This task could not be performed at any place. There are specific places on the planet where the seasonal movement of thunderstorms produces minor impact on the data. The best of such places are the South and North Poles.
- The software developed allows to estimate the rank of the SR observatory as a place for collecting data on the level of the global thunderstorm activity.

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