Recent Studies on Schumann Resonance

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Keywords: Schumann resonance, ELF transient, lightning activity

Recent studies on Schumann resonance, natural electromagnetic resonance which occurs in the Earth-ionosphere shell-cavity, are summarized briefly.

The spherical shell region between the Earth's surface and the lower boundary of the ionosphere forms a dissipative electromagnetic resonator in the extremely low frequency (ELF) range, and the resonance is excited by worldwide lightning strokes on the ground. It is called Schumann resonance which consists the dominant part of natural electromagnetic noise in 5-50 Hz. The resonant frequencies are about 8, 14, 20, 24, ... Hz, and 8 Hz is the lowest one. The loss of the resonance is caused by collision of ionized particles and electrons accelerated by electric fields with other ionized ones and neutrals in the lower ionosphere. Our group has measured the Schumann resonance for the last 6 years, and a typical example of the spectrum is shown in Fig. 1.

Another interesting phenomenon in the Schumann resonance band is the transient signal originated by huge lightning strokes which may produce the mesospheric luminescence, and the signal is called the ELF transient. Some of recent studies on ELF transient are also addressed in this paper.

Originally, the study on Schumann resonance started from a theoretical prediction by Schumann in 1952. Then, many approaches were reported in 1960s and 70s, and the most of

them were based on the layer modeling and on the equivalent propagation constant. Recently, with the rapid growth of computational resources, numerical simulations of Schumann resonance have been reported by some groups. The advantage of numerical methods is the capability to calculate arbitrary configuration, and it would clearly appear for analyses in such natural electromagnetic phenomena if the preciseness is more required, which must become essential with the development of studies.

In 1992, Williams presented a paper on Schumann resonance as a thermometer in tropical region, and the conclusion is that a few degrees change of the surface temperature in tropics causes nonlinear increase of lightning flash rates, and those were detected by measuring Schumann resonance fluctuations. The sensitivity decreased with the increase of latitude because the atmospheric convection in distant regions from the equator is not as deep as the one in the tropics, but Schumann resonance in the middle latitude reflected the variation of surface temperature in the tropics.

It is possible to deduce lightning activity distribution from measured Schumann resonance by solving an inverse problem which have been developed during the last few years. Schumann resonance spectra which range 5-50 Hz depend strongly on the distance between the observation point and the lightning sources, and also on the height of the lower boundary of the ionosphere. The difference of the height arises from the one of the solar energy contributed to the ionization between day and night, but the influence on Schumann spectra is small. On the other hand, the distances mostly cause the variation of Schumann spectra due to the movement of global lightning centers which are considered to be most active at about 15:00 of the local time. The studies have demonstrated the possibility to realize a method to monitor instantaneous global lightning activity distribution by measuring electromagnetic fields in the ELF band. In order to accomplish the purpose, there are many issues to be overcome, for example, continuous measurement to collect complete waveform with high-rate sampling, de-noising and precise estimation of Schumann spectra, development of the forward problem including the consideration on complete ionospheric parameters and on local or temporary effects, precise identification by solving the inverse problem including specialization for this purpose, worldwide network among observatories with real-time data transfer, etc.

ELF transient is also used to identify the position of huge lightning strokes. The combination of both Schumann resonance and ELF transient methods would make it possible to draw a worldwide lightning map.

Fig. 1. An example of the spectrum of Schumann resonance: The first resonant peak is observed at about 8 Hz; The data were collected at Moshiri, Hokkaido, Japan ($44^{\circ} 20'N$ $142^{\circ} 15'E$) at 18:00UT on 15th August 2004. The discrete response at 50 Hz is the noise radiated from the commercial power supply system

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1. Physics of Schumann Resonance

The spherical shell region between the Earth's surface and the lower boundary of the ionosphere forms a dissipative electromagnetic resonator in the extremely low frequency (ELF) range, and the resonance is excited by worldwide lightning strokes on the ground⁽¹⁾. It is called Schumann resonance which is the dominant part of natural electromagnetic noise in 5-50 Hz. The resonant frequencies are about 8, 14, 20, 24, ... Hz, and 8 Hz is the lowest one. The loss of the resonance is caused by collision of ionized particles and electrons accelerated by electric fields with other ionized ones and neutrals in the lower ionosphere. Our group has measured the Schumann resonance for the last 6 years, and a typical example of the spectrum is shown in Fig. 1.

The Schumann resonance spectrum in Fig. 1 was measured by induction-coil magnetometers with magnetic cores. The important components of electromagnetic fields of Schumann resonance are the horizontal components of the magnetic field and the vertical component of the electric field, taking into consideration that the measurement is performed on the Earth's ground with relatively high conductivity. For the measurement, quiet electromagnetic environment is necessary to avoid the noise generated by human activity, and rural areas are preferable for the observation site (e.g. at our observation site, Moshiri, the intensity of noise radiated from commercial power supply system is less than 0.4 nT peak-to-peak). For the detection of the magnetic fields in the Schumann resonance band, it is appropriate to use an induction coil because of their enough sensitivity as well as low-noise characteristics⁽²⁾. For the measurement of the vertical electric field, capacitive antennas are handy and compact⁽³⁾. The antennas comprise an insulated can at the height of several meters above the ground. The details on the Schumann resonance measurement are described in the literature⁽¹⁾.

Schumann resonance spectra vary hourly, and the variation depends mostly on the location of the source lightnings. The variation in characteristics of the

Fig. 1. An example of the spectrum of Schumann resonance: The first resonant peak is observed at about 8 Hz; The data were collected at Moshiri, Hokkaido, Japan (44° 20'N 142° 15'E) at 18:00UT on 15th August 2004. The discrete response at 50 Hz is the noise radiated from the commercial power supply system

propagation media, i.e. the atmosphere, may cause potentially the change of the Schumann spectra, but the effect is much smaller than the source location. For example, the very intense γ -ray burst (GRB) event occurred on 27 August 1998, but there was no significant difference between the spectrum during the event and the typical ones although very low frequency (VLF) signals were strongly disturbed⁽⁴⁾. It is difficult in observation to evaluate quantitatively the effects of the variation in the atmosphere and the ionospheric height because of the uncertainty of the source distribution. But, the Schumann resonance spectra would not be perturbed clearly unless some parameters change over the entire globe, which is deduced from the fact that a Schumann spectrum is the synthesis of responses of many lightning sources with many propagation paths.

Another interesting phenomenon in the Schumann resonance band is the transient signal originated by huge lightning strokes which may produce the mesospheric luminescence such as sprites, and the signal is called the ELF transient. Some of recent studies on ELF transient are also addressed in this paper.

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2. Theoretical Studies on Schumann Resonance

Originally, the study on Schumann resonance started from a theoretical prediction by Schumann in 1952. Then, many approaches were reported in 1960s and 70s, and the most of them were based on the layer modeling and on the equivalent propagation constant, and the literatures are found in the reference book by Nickolaenko and Hayakawa⁽¹⁾. The most of these approaches are formulated in the frequency domain, but Nickolaenko developed a technique to accelerate the convergence appearing in the inverse Fourier transform to obtain the time-domain solution⁽⁵⁾. Mushtak and Williams summarized the proposed layer models and the validity⁽⁶⁾.

Recently, with the rapid growth of computational resources, numerical simulations of Schumann resonance have been reported by some groups. In 2003, Morente et al. reported the computation by the transmission line matrix (TLM) method⁽⁷⁾ and since 2002 the ELF propagation has been computed by using the finite difference time domain (FDTD) method⁽⁸⁾⁻⁽¹¹⁾ and improved by using hexagonal cells⁽¹²⁾. Ando et al. have presented the simulation by the finite difference method in the frequency domain, and have introduced much more realistic parameters in the lower ionosphere⁽¹³⁾⁽¹⁴⁾ by using IRI-2000, NRL-MSISE00 models, empirical models of atmospheric and ionospheric density, composition, and temperature⁽¹⁵⁾⁽¹⁶⁾.

The advantage of numerical methods is the capability to study arbitrary configuration, and it would clearly appear for analyses in such natural electromagnetic phenomena if the preciseness is more required, which must become essential with the development of studies. Therefore, many researchers in this ELF study should pay more attention to numerical methods. There, however, exist some disadvantages the main of which is the consumption of computational resources. The difficulty may be avoided by the choice of methods. For example, it is more appropriate to calculate Schumann resonances by using the frequency-domain method, and the time-domain analysis is useful to simulate the ELF transient propagation.

3. Schumann Resonance as a Thermometer Covering Wide Region

In 1992, Williams presented a paper on Schumann resonance as a thermometer in tropical region⁽¹⁷⁾. The conclusion is that a few degrees change of the surface temperature in tropics causes nonlinear increase of lightning flash rates, and those were detected by measuring Schumann resonance fluctuations. The sensitivity decreased with the increase of latitude because the atmospheric convection in distant regions from the equator is not as deep as the one in the tropics, but Schumann resonance in the middle latitude reflected the variation of surface temperature in the tropics. After the paper by Williams, some reports were published, but they discussed "Schumann resonance thermometer" not in tropics but in the globe. In 2004, Sekiguchi et al. have tried to

differentiate the contributions into different latitude zones⁽¹⁸⁾.

The most papers associated with the above topic treat Schumann resonance spectrum as one parameter. But the spectrum consists of contributions from many sources all over the globe, and it would be difficult to develop the studies without the decomposition of measured Schumann resonance into individual contributions.

4. Global Lightning Identification by Schumann Resonance

It is possible to deduce lightning activity distribution from measured Schumann resonance by solving an inverse problem which have been developed during the last few years. Schumann resonance spectra in the frequency range of 5-50 Hz depend strongly on the distance between the observation point and the lightning sources, and also on the height of the lower boundary of the ionosphere. The difference of the height arises from the one of the solar energy contributed to the ionization between day and night, but the influence on Schumann spectra is small as mentioned in Sec.1. On the other hand, the distances mostly cause the variation of Schumann spectra due to the movement of global lightning centers which are considered to be most active at about 15:00 of the local time.

In 2001, Shvets developed the inverse problem with the Tikhonov's regularization, and examined the performance by numerical experiments⁽¹⁹⁾. The basic methodology consists of the calculation of Schumann spectra (the forward problem) and the decomposition of measured data into the calculated elemental spectra (the inverse problem). The report adopted the layer approximation as the calculation. Ando and Hayakawa applied the method to data measured in Japan during about one year, but they computed the spectra by the finite difference method⁽¹³⁾ because it is essential for the inverse problem to prepare more exact response from elemental sources and the layer approximation is insufficient. Ando et al. have extended it to diminish the influence of noise included in the observed data⁽¹⁴⁾, and the results showed successfully some reasonable characteristics: (1) the existence of main three lightning-active regions, (2) their seasonal variation in position, and (3) their daily variation in time.

These studies demonstrate the possibility to realize a method to monitor instantaneous global lightning activity distribution by measuring electromagnetic fields in the ELF band, and such monitoring systems have not been realized yet till today. In order to accomplish the purpose, there are many issues to be overcome, for example, continuous measurement to collect complete waveform with high-rate sampling, de-noising and precise estimation of Schumann spectra, development of the forward problem including the consideration on complete ionospheric parameters and on local or temporary effects (e.g. solar flares or γ -ray bursts), precise identification by solving the inverse problem including specialization for this purpose, worldwide network among observatories with real-time data transfer, etc. Ando et al. have

already developed the data processing toward the purpose, and the method is based on the linear prediction to extract Schumann resonance component correctly from observed data⁽²⁰⁾. The system would serve as a powerful tool for meteorology and environmental engineering if realized. Of course, it is essentially impossible to detect individual lightning strokes because of temporal and spatial resolution obtained from ELF fields, but the characteristics of the system is not necessarily disadvantageous because the important factors in the system are the activity of the lightning distribution and the location, and the exact position of strokes is not significant.

ELF transient is also used to identify the position of huge lightning strokes⁽²¹⁾. The combination of both Schumann resonance and ELF transient methods would make it possible to draw a worldwide lightning map, which would contribute to the studies of lightning physics, global warming, and global meteorological anomalies.

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