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RESEARCH REPORT

OBSERVATION OF THE ELF AND VLF ATMOSPHERICS AND THEIR NUMERICAL SIMULATION

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Abstract

Observations of the ELF and VLF atmospherics were carried out at the single station to obtain the waveforms of the vertical electric and horizontal magnetic fields, where the direction finding of propagation was also made. In the dynamic frequency spectrum of amplitude at Iriki, Kagoshima, the induction from the power lines was seen at the fundamental frequency, 60 Hz and its 5th and 7th harmonics.

The observed waveforms of atmospherics were compared with the waveforms of numerical simulation based on the observed propagation constants and the three lightning discharge current models, namely the return stroke current by Bruce and Golde, the intermediate current by Dennis and Pierce and the current by Al'pert. The waveforms of VLF component are similar among those models. However, the waveforms of ELF component, namely slow tails produced from the return stroke current are too small comparing with the observed slow tails. The amplitude ratio of the ELF to VLF components of observed atmospherics can be roughly explained from the intermediate current model.

1. Introduction

Propagation characteristics of the VLF electromagnetic wave have been studied by many investigators (for example see the texts of Wait, 1962 and Al'pert et al, 1970) through the observation of atmospherics as well as the artificial electromagnetic waves from VLF stations to give the phase velocity and attenuation rate of electromagnetic waves propagating in the earth-ionosphere waveguide. So as to study the propagation characteristics of the ELF electromagnetic wave, atmospherics must be still now used because the frequency of the artificial electromagnetic wave from the stations is higher than about 10 kHz. Thus the propagation constants of the ELF wave and the application to the investigation of parameters of the lower ionosphere have been studied by observing ELF atmospherics (Taylor and Sao, 1970). The phase velocity, the attenuation rate and the phase of wave impedance of electromagnetic wave with the frequencies from 50 Hz to 800 Hz were obtained in the previous work. Moreover, the waveform of the lightning discharge current, which is expected as origins of the slow tails of ELF atmospherics, was also estimated (Ogino et al, 1980).

However, origins of the slow tails and tweek atmospherics (Yamashita, 1978) with the frequency of about 2 kHz are not clearly understood because the amplitude of observed signals is too large to be estimated from the attenuation rate of the usual earth-ionosphere waveguide theory (Wait, 1962) and the typical discharge current of atmospheric sources (Bruce and Golde, 1941). On the other hand, the propagation constants of the electromagnetic wave with the frequencies from 30 Hz to 1 kHz are particularly scattered in the nighttime among several observations (see Chapman et al, 1966). It is partly because of the high sensitivity of the propagation constants to the parameters of the lower ionosphere and may be partly because of the difference of experimental methods such as the single station and two stations observations.

Observations of the ELF and VLF atmospherics at the single station have been carried out to obtain propagation constants of the electromagnetic wave in a wide frequency range and to study origins of the slow tails in ELF atmospherics. The observed waveforms were compared with those of the numerical simulation based on the typical observed propagation constants and three lightning discharge current models, namely the return stroke current (Bruce and Golde, 1941), the intermediate current (Dennis and Pierce, 1964) and the current by Al'pert (Al'pert et al, 1967). The preliminary investigations are reported in the present paper. Statistical data analysis of observed results and their quantitative comparison with the numerical simulation will be reported elsewhere.

2. Experimental Metheod

Observations of atmospherics were carried out on November 23 ∿ 29, 1979, July 4 ∿ 10 and November 28 ∿ December 4, 1980 at Nakashibetsu-cho, Hokkaido and on October 8 ∿ 14, 1979 at Iriki-cho, Kagoshima. Both sites have been suitable to detect small signals of the ELF and VLF atmospherics since the noisy electromagnetic fields induced from power lines were weak.

Only the ELF components of the vertical electric and horizontal magnetic fields of atmospherics at the single station were previously observed to study the propagation characteristics of the electromagnetic wave and atmospheric sources. In the present observation, propagation constants of the electromagnetic wave with a wide frequency range depending on the propagation direction and origins of the slow tails are particularly aimed to obtain through the simultaneous observation of the ELF and VLF components and the direction finding.

The simple block diagram of the obsrving equipment and an example of the schematic waveforms of atmospheric signals are shown in Fig.1. The VLF and ELF components of the vertical electric field of the electromagnetic wave, E_{VLF} and E_{ELF} were detected by a vertical antenna of 2 m or 5 m length, the ELF component of the horizontal magnetic field, H_{ELF} was done by a rectangular loop antenna (4 m x 8 m and 40 turns). In that case, the detections of the ELF and VLF components are made, respectively, through the band-pass filter from 15 Hz to 1.7 kHz and the band-pass filter from 65 Hz to 8 kHz, where each frequency means the value of 3 dB down. Moreover, a crossed loop antenna is used to find the propagation

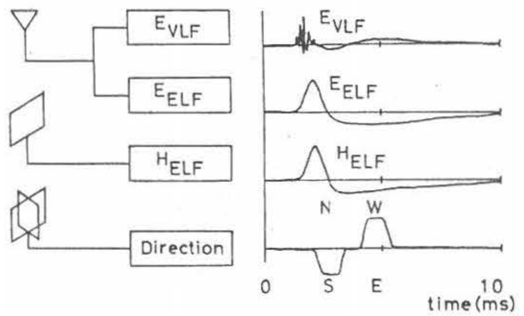

Fig.1 Block diagram of the observing equipment and schematic waveforms of atmospheric signals.

direction of atmospherics with the tuning frequency, 7 kHz. The two components (NS,EW) of a direction are recorded by the amplitudes of pulses with the interval of 1 ms as is shown in the bottom figure. The waveforms of atmospherics in Fig.1 were recorded in an analogue data recorder and later they are analyzed by the computer through the digital data conversion.

3. Observations

Dynamic frequency spectrum of amplitude on the vertical electric field of ELF atmospherics is shown in Fig.2, where the time is given by JST (Japan Standard Time). The observation was done on October 11, 1979 at Iriki. In the figure, a thick part means a large amplitude of the electric field, then the detection of atmospherics is made by thick vertical lines spreading toward high frequency. Atmospherics of a small amplitude are frequently detected and more than ten atmospherics with the large amplitude, which have thick vertical lines over 300 Hz, are seen for two minutes. The number of the strong atmospherics at noon usually increases more than two times, since the thunderstorms become active in South-East Asia. The interference noise induced from the power lines is also

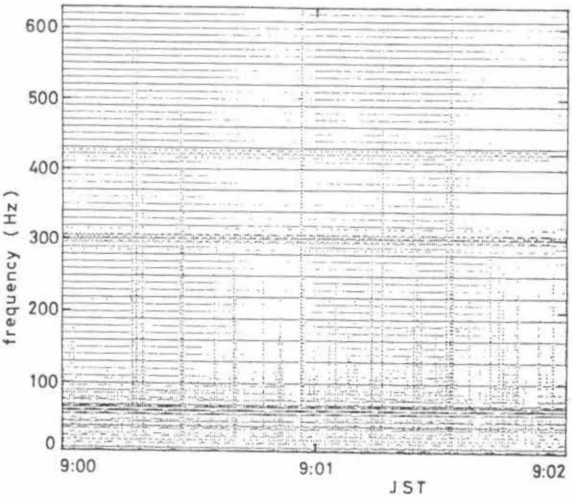

Fig.2 Dynamic frequency spectrum of amplitude on the vertical electric field of ELF atmospherics.

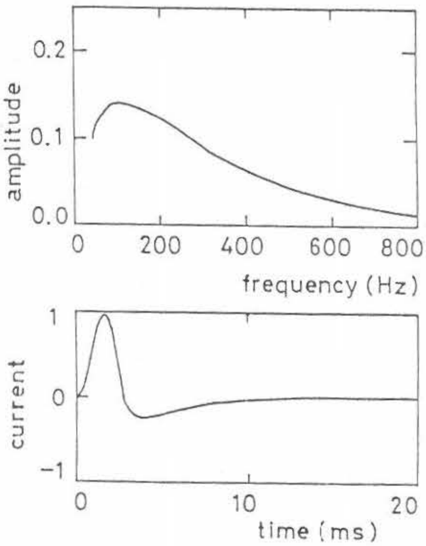

Fig.3 Normalized frequency spectrum and the waveform of the lightning discharge current for the ELF component in the daytime.

remarkably seen at the fundamental frequency, 60 Hz and its 5th and 7th harmonics.

In Fig.3 are shown the normalized frequency spectrum of amplitude and the waveform of the lightning discharge current on the ELF component in the daytime. Since the method of data analysis was previously reported (Ogino et al, 1980), it is briefly mentioned here. Obtaining the propagation distance from the separation time between the VLF and ELF components of atmospherics (Wait, 1962 and Sao et al, 1980), The propagation constants and the spectra of sources can be calculated by using a couple of observed atmospherics. The quantities averaged over many pairs are expected to give typical ones. The frequency spectrum of amplitude has the maximum near 100 Hz and decreases to about a tenth times at 800 Hz. The pulse width of the lightning discharge current is 2 ∿ 3 ms in the ELF component.

In Fig.4 are shown the waveforms of the VLF and ELF components of the vertical electric field detected by the observing system in Fig.1. The propagation distance is determined by the formula of Wait (Wait, 1962) through the separation time between the VLF and ELF atmospherics. The VLF component composed of a wavepattern with 5 ∿ 10 cycles continues for about 0.6 ∿ 0.8 ms and the ELF component with a half cycle or a cycle follows it. The amplitude ratio of the ELF to VLF components roughly increases with the propagation distance and is 0.2 ∿ 0.6 for atmospherics with a propagation distance longer than 2 Mm. The amplitude ratio is much larger than that estimated from the observed propagation constants and the return stroke current, as is discussed later.

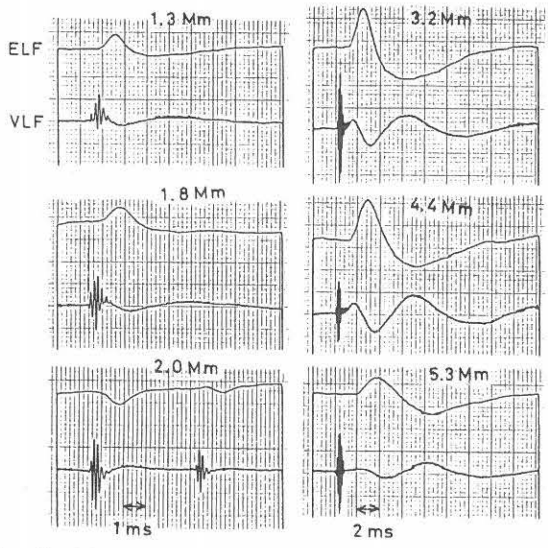

Fig.4 Waveforms of the VLF and ELF components of the vertical electric field on atmospherics.

4. Numerical Simulation

Based on the three lightning discharge current models, a numerical simulation of atmospherics was carried out in order to compare with the observed waveforms in Fig.4, where typical propagation constants obtained from the observations were also used.

The observed propagation constants in the daytime are shown in Fig.5 by the symbols of SR, T-S, S-S, CJTC (Chapman et al, 1966), C&M (Chapman et al, 1956) and OSJO (Ogino et al, 1980). The propagation constants symbolized with SR, T-S and S-S were given from the Schumann resonance, two stations and single station observations, respectively. In the present simulation, the values on smooth lines drawn at the center of the observed results are used as a typical propagation constants.

Secondly, the three models of lightning discharge current, namely return stroke current (Bruce and Golde, 1941), intermediate current (Dennis and Pierce, 1964) and current by Al'pert (Al'pert et al, 1967) shown by the table are used as atmospheric sources. Here, the current density, I and the velocity of return stroke, v and lightning discharge current moment, Ids are assumed to be given in the following form,

$$I = i_o(e^{-\alpha t} - e^{-\beta t}) + i_1(e^{-\gamma t} - e^{-\delta t}) \quad (1)$$

$$v = v_o(e^{-at} - e^{-bt}) \quad (2)$$

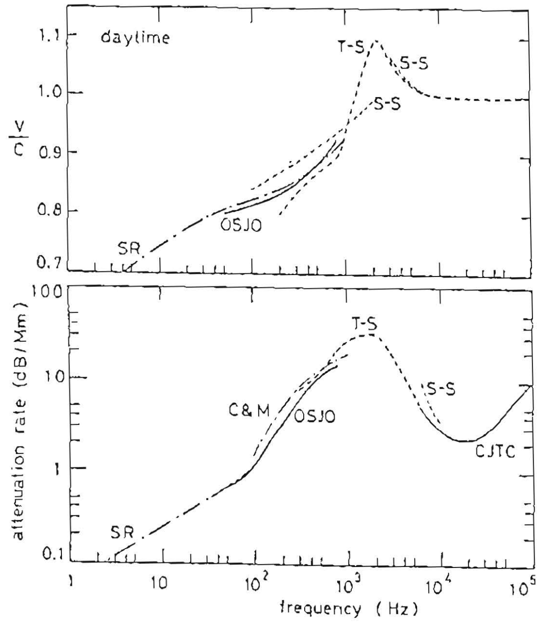

Fig.5 Examples of the propagation constants of the electromagnetic wave in the daytime.

	i_o (A)	α (s^{-1})	β (s^{-1})	i_1 (A)	γ (s^{-1})	δ (s^{-1})
return stroke current	3×10^4	2×10^4	2×10^5			
intermediate current	3×10^4	2×10^4	2×10^5	2.5×10^3	10^3	$=\beta$
current by Al'pert		10^3	10^5			

able Parameters of the three models on the lightning discharge current.

$$Ids = I\int_0^t v\,dt \quad , \tag{3}$$

where typical values on v are $v_o = 8\times10^7$ m/s, $a = 3\times10^4\ s^{-1}$ and $b = 8\times10^5\ s^{-1}$ (for example see Iwata, 1970). The decay constant of the intermediate current, γ incidentally agrees with the decay constant, α of the current by Al'pert, where he determined α so as to explain the large amplitude of the observed ELF atmospherics. The decay constant of current with the order of $10^3\ s^{-1}$ was also introduced by Jones to explain the ELF aspects of radiation (Jones, 1970).

In such a case, the vertical electric field, E radiated from the source is given by the following expression (Wait, 1962)

$$E = \frac{\eta Ids}{h(c\rho)^{1/2}} \left(\frac{\rho/a}{\sin \rho/a}\right)^{1/2} f^{1/2} \sum_{n=0}^{\infty} \delta_n s_n^{3/2}\, e^{i\omega t - ik(s_n-1)\rho}, \tag{4}$$

where $\eta=120\pi$ is the intrinsic impedance of vacuum, h=70 km the ionosphere height in the daytime, c the velocity of light, ρ the propagation distance, a the radius of the earth, $\omega=2\pi f$ the angular frequency of waves, $k=\omega/c$, $\delta_o \simeq 1/2$ and $\delta_1 \simeq 1$ the height gain functions. Furthermore, $s_n = s_{nr} + is_{ni}$ are determined from v/c and the attenuation rate, α (dB/Mm) through the relations,

$$s_{nr} = c/v$$

$$s_{ni} = -5.497\ \alpha/f \ ,$$

where only the zeroth TM mode of n=0 is extracted for f < 2 kHz, otherwise only the first TM mode of n=1 is extracted, because those modes are dominant in each frequency range.

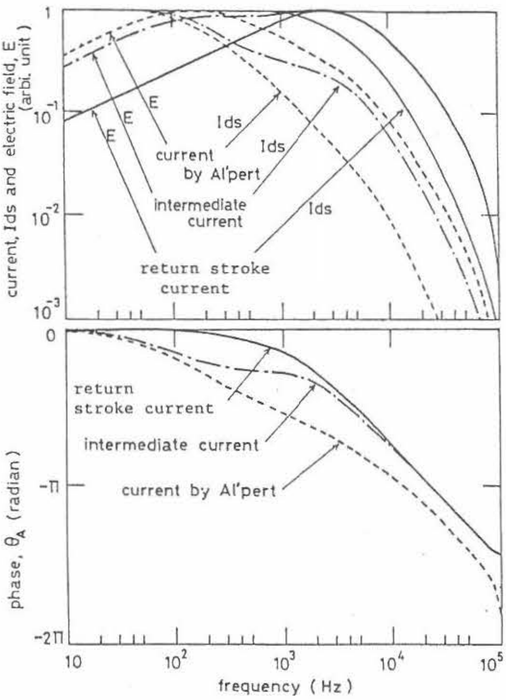

Fig.6 Normalized frequency spectra of discharge current, Ids and radiated vertical electric field, E and the phase spectra of Ids or E at a source point.

In Fig.6 are shown the normalized frequency spectra of amplitude of discharge current moment, Ids and radiated vertical electric field, E and then the phase spectra of Ids or E at a source point. As is understood from the fact that the decay constant of intermediate current equals the decay constant of the current by Al'pert, the intermediate current model has just intermediate character of the other two models. It is paticularly noted that the electric field, E radiated from the current by Al'pert has the amplitude of about 5 times electric field from the return stroke current in the frequency range less than 300 Hz.

In Fig.7 are shown the simulated waveforms in the short time, which mainly correspond to the VLF component of atmospherics. The difference between waveforms depending on the two current models is not remarkable. The duration time of the VLF component is about 0.5 ms which is comparable with the statistical value of 0.6 ms or the observed value shown in Fig.4, though the smooth discharge current models and only the single mode of the earth-ionosphere waveguide theory are used in the present numerical simulation.

In Fig.8 are shown the simulated waveforms in the long time, where the ELF component as well as VLF component of atmospherics are included. The amplitude ratios of the ELF to VLF com-

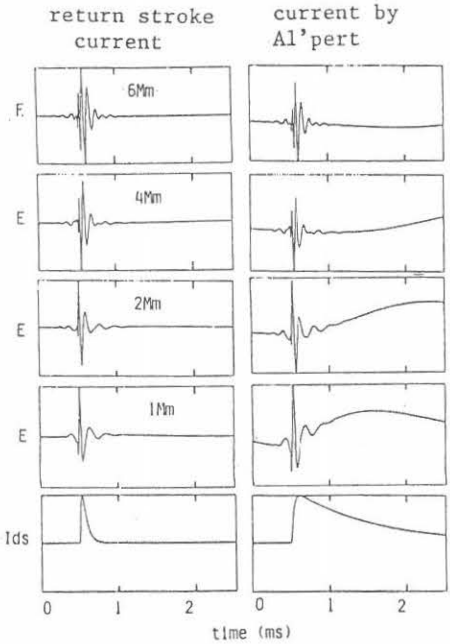

Fig.7 Simulated waveforms of the VLF atmospherics, E at several propagation distances and the current profiles of sources, Ids.

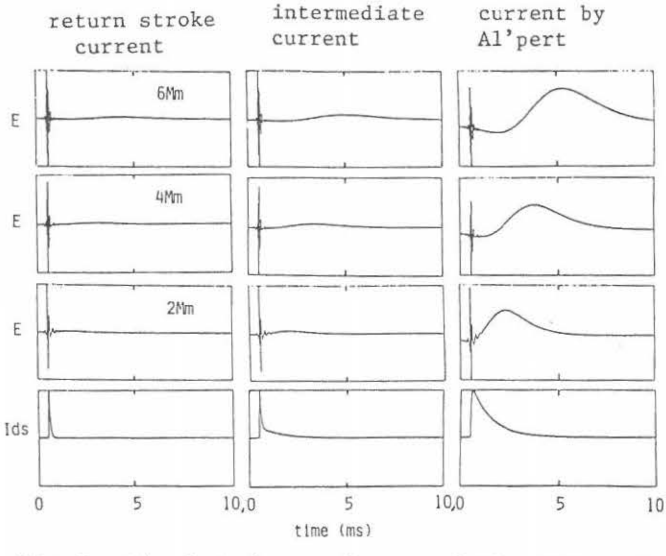

Fig.8 Simulated waveforms of the VLF and ELF atmospherics and the current profiles of sources.

ponents at 4Mm are 0.01 for the return stroke current, 0.08 for the intermediate current and 0.41 for the current by Al'pert. The frequency characteristics of the VLF band-pass filter should be considered when the simulated waveforms are compared with the observed waveforms in Fig.4. The VLF component becomes small by approximately three times when the simulated waveform is modified by the attenuation effect through the filter. Therefore, the intermediate current model with the attenuation of filter gives the amplitude ratio of 0.24 and can roughly produce the observed waveforms of atmospherics. The ELF component produced from the return stroke current model is too small comparing with the observed waveforms of atmospherics.

5. Discussions and Conclusions

A simultaneous observation of the ELF and VLF atmospherics including the direction finding was carried out to study propagation characteristics of the electromagnetic wave and origins of the slow tails. The preliminary results were reported on the dynamic spectrum and lightning discharge current in the ELF component.

In the comparison of the ELF and VLF components of atmospheric waveforms, the amplitude ratio of the ELF to VLF components is much larger than that expected from the observed propagation constants and the return stroke current of lightning discharge. Al'pert gave a decay constant of the lightning discharge current, 10^3 s^{-1} so as to explain the amplitude spectra of both the ELF and VLF components of atmospherics. The value incidentally agrees with the decay constant of the intermediate current by Dennis and Pierce. In order to compare with the observed waveforms, the waveforms of atmospherics were simulated with several propagation distances using the return stroke current, the intermediate current and the current by Al'pert. The waveforms of VLF component are similar between the three current models. The amplitude ratio of the ELF to VLF components of the observed atmospherics can be roughly explained from the intermediate current model, however is too large to be radiated from the return stroke current. Moreover, the current by Al'pert is regarded as a limit case to the intermediate current because the decay constant is same. Thus it is expected that the slow tails are mainly originated from the lightning discharge current with a decay constant of the order of 10^3 s^{-1} instead of the return stroke current with a decay constant of the order of 10^4 s^{-1}. The feature is also supported from the estimated lightning discharge current through observed ELF atmospherics.

Amplitude and phase spectra of the simultaneously observed ELF and VLF atmospherics and their quantitative comparison with simulated results will be reported in near future.

Acknowledgements

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References

Al'pert, Ya.L., D.S. Fligel and G.A. Michailova: The propagation of atmospherics in the earth-ionosphere waveguide, J. Atmo. & Terr. Phys., 29, 29-42 (1967)

Al'pert, Ya.L. and D.S. Fligel: Propagation of ELF and VLF waves near the earth, p.27, Consultants Bureau, New York (1970)

Bruce, C.E.R. and R.H. Golde: The lightning discharge, J.I.E.E., 88(II), 487-505 (1941)

Chapman, F.W. and R.C.V. Macario: Propagation of audio-frequency radio waves to great distances, Nature, 177, 930-933 (1956)

Chapman, F.W., D.L. Jones, J.D.W. Todd and R.A. Callinor: Observation on the propagation constant of the earth-ionosphere waveguide in the frequency band 8c/s to 16kc/s, Radio Sci., 1, 1273-1282 (1966)

Dennis, A.S. and E.T. Pierce: The return stroke of a lightning flash to earth as a source of VLF atmospherics, J. Res. NBS/USNC-URSI, 68D, (Radio Science) 777-794 (1964)

Iwata, A.: Calculation of waveforms radiating from return strokes, Proc. Res. Inst. Atmospherics, Nagoya Univ., 17, 115-123 (1970)

Jones, D.L.: Electromagnetic radiation from multiple return strokes of lightning, J. Atmo. & Terr. Phys., 32, 1077-1093 (1970)

Ogino, T., K. Sao, H. Jindoh and K. Ohta: Observation of propagation constants and phase of wave impedance for ELF atmospherics, Trans. Inst. Elect. Comm. Engrs. Japan (in Japanese), 63-B, 1232-1238 (1980)

Sao, K. and H. Jindoh: Analysis of errors of location of thunderstorms in Asia, Trans. Inst. Elect. Comm. Engrs. Japan (in Japanese), 63-B, 553-558 (1980)

Taylor, W.L. and K. Sao: ELF attenuation rates and phase velocities observed from slow-tail components of atmospherics, Radio Sci., 5, 1453-1460 (1970)

Wait, J.R.: Electromagnetic Waves in Stratified Media, p.314, Pergamon Press (1962)

Yamashita, M.: Propagation of tweek atmospherics, J. Atmo. & Terr. Phys., 40, 151-156 (1978)