Deducing Locations and Charge Moment Changes of Lightning Discharges by ELF Network Observations in Japan

Yasuhide Hobara∗† Member, Takahiro Inoue∗∗ Non-member
Masashi Hayakawa* Senior Member, Kazuo Shiokawa∗*** Non-member

(Manuscript received Dec. 21, 2012, revised May 5, 2013)

The electromagnetic radiations from lightning discharges have been intensively studied for a long time in different frequency ranges. Recent observations of electromagnetic radiations from lightning in the ELF (extremely low frequency) range are recognized as a powerful tool to obtain one of the most important properties of lightning discharges; the charge moment change (QCM). This paper demonstrates that spatio-temporal distributions of lightning discharges together with their charge moment change (CMC) can be obtained by using newly developed domestic ELF observation network. This is the first time to obtain such type of distribution using only ELF observations in the spatial scale of Japan (a few thousands km). We found that the obtained lightning source distributions both over the Pacific Ocean and the Sea of Japan are originated from the thunderstorm active regions confirmed by other measurements such as WWLLN. Statistical properties of the charge moment changes indicate that both number and CMC of positive CGs are superior to those of negative CGs. Moreover considerably large CMC with both polarities are identified for the CGs over the Pacific Ocean as well as those with positive polarity over the Sea of Japan.

Keywords: ELF transient, charge moment change, red sprite, thunderstorm activity

1. Introduction

Wide-band electromagnetic waves are generated in association with cloud to ground flashes (CGFs) in the troposphere. Among them, powerful transient radiations from intensive CGFs in the Extremely Low Frequency (ELF) range can propagate over significantly long distances (> 10 Mm) in the Earth-ionosphere waveguide (EIWG) due to rather small attenuation and are observed globally as ELF transients [1].

One of the most important electrical properties of lightning discharges is the vertical charge moment change (CMC) in contrast to the peak current (Ip), the property observed from the conventional lightning detection network.

Recent applications of ELF transient observations include the global distribution of energetic lightning exciting the so-called ELF transient or Q-burst [2,3] by a single location technique using the multi-component measurement [4–7]. Since lightning discharges with large CMC are recognized as a proxy of transient luminous events (TLEs) such as red sprites [5–9], red sprites have been observed frequently in the Hokuriku area where many lightning discharges with a large amount of charge are expected during the winter thunderstorm activity [10–12]. Moreover, strong perturbation at the bottom of ionosphere (D/E regions) is observed by receiving VLF/LF transmitter signals over sprite producing thunderstorms indicative of the electrodynamic coupling between the tropospheric lightning and overlaying ionosphere [13].

Despite the usefulness of ELF measurement in the sense of CMC estimation from a remote site, due to relatively large locating error expected from the single location method (typically ~ few hundreds km), no detailed spatial distribution of CGs with CMC around Japan has been obtained. Moreover, meteorological conditions for winter and summer thunderstorm activities in relation with TLEs have not been understood well [14].

We have newly set up a new ELF observation station in Kagoshima, Japan in addition to the existing station in Moshiri Hokkaido, Japan to establish the network observations of ELF transients and to deduce the detailed spatio-temporal lightning distribution with CMC around Japan and Asia. This is the first attempt to use an ELF network observation with separation distance of a few thousands km scale applied to a rather small area to deduce more precise determination both of location and QCM of lightning discharges in comparison to the previous works for world-wide detection of very energetic lightning but rather large locating error (~500 km) [5–7].

In this paper, we demonstrate the capability of the energetic lightning properties around Japan such as temporal and...
regional dependences (over Pacific Ocean and the Sea of Japan) from our initial results. In future we are going to use lightning information with CMC for natural disaster monitoring and mitigation due to severe weather, and also provide useful information promoting renewable energy power plant such as wind farm and solar power because serious damage of the facilities is expected from the lightning with rather large CMC. Furthermore providing the intensive lightning locations with CMC information is very useful for the several new spacecraft missions to monitor TLE with intensive lightning discharges from the space by Japanese ISS (International Space Station) GLIMS and French micro-satellite TARANIS.

2. Charge Moment Change Estimation (CMC)

Electromagnetic emissions in the ELF range from a CGF propagates in the EIWG as a QTEM mode consisting of the vertical electric field and horizontal magnetic field components are well described by the following equations (1) (17).

\[
E_l = i \frac{I(f)ds \nu(\nu + 1)P^\nu_0(-\cos \theta)}{4a^2 \varepsilon_0 2\pi f h \sin(\pi \nu)} \quad [\text{Vm}^{-1}\text{Hz}^{-1}]
\]

\[
H_\varphi = -\frac{I(f)ds P^\nu_0(-\cos \theta)}{4ah \sin(\pi \nu)} \quad [\text{Am}^{-1}\text{Hz}^{-1}]
\]

\(I(f)ds\) is the current moment, \(P^\nu_0\) are associated Legendre functions with complex subscripts \(\nu\) representing propagation constant, \(h\) is the thickness of the waveguide, \(\varepsilon_0\) is the dielectric constant of free space, and \(a\) is the Earth radius. The angle \(\theta\) is the great circle angular distance between the lightning source and receiving field site.

Given the calibrated frequency spectra for either the vertical electric field component or horizontal magnetic field component, one can derive the source current moment \(I(f)ds\) by using one of above-mentioned equations. Since the characteristic duration of most lightning discharges is smaller than the propagation time of the round the world, \(I(f)ds\) is simplified to the vertical charge moment change \(Qds\) (C-km).

3. ELF Transient Observation

A new ELF field site was installed by the University of Electro-Communications (UEC) and is located in Tarumizu (TRU), Kagoshima (geographic coordinates: 44.37°N, 142.26°E) in the territory of Solar Terrestrial Environment Laboratory (STE) of Nagoya University. The two horizontal magnetic waveforms are continuously recorded by a pair of induction coils with a sampling rate of 4 kHz and upper cutoff frequency of 1 kHz.

The similar system with the same sampling frequency and bandwidth was installed in Moshiri (MSR), Hokkaido and has been operated by UEC since 1996. This existing system was located in the STE Laboratory, Moshiri observatory. In MSR, the vertical electric field observed in addition to the two horizontal magnetic field components enables us to determine the unique arrival direction of transient waves. Above-mentioned waveforms are GPS time stamped and are able to be compared with each other in the absolute time coordinate system.

4. Observational Results

4.1 Case Study

ELF transient waveforms observed in the distant field site were processed as follows. First, the power line radiation and its harmonics were removed by a digital filtering technique. Second, transient signals are identified by imposing the threshold value such as 10 times of the standard deviation of the total field intensity. Third, the transient events from the same lightning source are identified both by occurrence time and arrival direction calculated by a goniometric method by using 2 magnetic field components. Fourth, the lightning source locations are obtained by a conventional triangulation technique, and corresponding CMCs and discharge polarities are calculated.

Figures 1(a)–(d) demonstrate an example of typical ELF time series originated from lightning discharges around Japan. Figures 1(a) and (b) indicate the magnetic waveforms for two horizontal components at MSR, while Figures 1(c) and (d) indicate the same format as Figures 1(a) and (b) but for TRU. As is seen from the figures, an ELF transient from the same lightning discharge is clearly identifiable at two stations around the time of 13:45:35.5 (UT) on March 9, 2011. The difference in amplitude between the two orthogonal magnetic components at each station suggests the arrival direction of the ELF radiation (i.e. lightning source direction).
Fig. 2. Magnetic hodograms of ELF transients originated from the same lightning source.

Fig. 3. Locating CGF source by using an ELF transient simultaneously observed at MSR and TRU.

Figures 2(a) and (b) show the magnetic hodograms of ELF transients simultaneously observed in the two field sites, MSR and TRU. As is seen from Fig. 2, both of the hodograms indicate almost linear polarization, so that the conventional goniometric technique is applicable to obtain the wave normal direction $k$ (i.e., direction of the wave propagation). It is found that the ELF transient arrives from the South-East at MSR, whilst the transient from the same lightning arrives from the East at TRU.

Figure 3 demonstrates the location of the CGF obtained from the triangulation technique based on two arrival directions in Fig. 2. The determined CGF position is found to be over the Pacific Ocean in the geographical coordinate system of $32.5^\circ$N and $147.7^\circ$E. Corresponding calculated CMC is $-396$ C·km (negative CGF).

Figure 4 illustrates the image from the meteorological satellite around the occurrence time of the observed ELF transient in Fig. 3 (14 UT on March 9, 2011). Since the developed cloud system corresponding to the low pressure is identified over the Pacific Ocean around the calculated onset location of the ELF transient source, the identified ELF source is from the lightning discharge from the thunderstorm activity.
Fig. 6. Temporal dependence of the CG locations estimated by ELF network measurement on March 25, 2011

4.2 Spatial Distributions of CGF with Qds
Figures 5(a) and (b) show the spatial distributions of CGFs on March 25, 2011 for the positive and negative CGFs respectively. The color of each dot (individual CGF) stands for the amount of CMC with its polarity. As is seen from the figure, two active thunderstorm centers are clearly identified over the Pacific Ocean by our ELF network observations. Both positive and negative flashes have similar spatial distributions.

Another typical thunderstorm center is located over the Sea of Japan in March (not shown).

Temporal migration of the ELF transient sources (i.e. lightning discharges with an intensive energy in ELF range) over the day of March 25, 2011 is shown in Fig. 6. Each picture indicates the lightning locations for a four-hour time interval. The color of each lightning discharge corresponds to the amount of CMC with a polarity indicated in the bar graph.
on the right hand side of figures. As seen from the figures, the lightning activity started in the local morning (0–4 UT) off the coast of Shikoku with small amount of CMC values (Qds < 500 C·km). Then the storm developed and reached the mature stage (4–20 UT). The number of lightning flashes reached a maximum and intensive lightning flashes with very large CMC (> 1000 C·km) are identifiable for both polarities (dark red and blue for very energetic positive and negative flashes). These events are energetic enough to excite TLEs such as red sprites. Among these energetic events, positive events tend to surpass in number than negative events, which is described in detail in the next section. During the course of thunderstorm development, the active thunderstorm area migrated toward the east and was separated by several areas (8–20 UT). Finally in the dawn to the morning, the thunderstorm activity decayed.

Figure 7 shows the spatial distributions of estimated CGs by ELF observations and corresponding distributions obtained from VLF network measurement by WWLLN (World Wide Lightning Location Network) for three different storm days. Since WWLLN provides only the information of onset location of VLF sources (CGs) but with rather high spatial pointing accuracy (~ a few km), we can compare the locating accuracy of our ELF measurement.

As seen from the figures, active thunderstorms over Pacific areas obtained by WWLLN are in rather good agreement with those from ELF sources from our network measurement, which indicates that our ELF measurement properly tracks the lightning discharges from active thunderstorms in this region. Although lightning activities around the coast of Sea of Japan (Hokuriku) were identified for three days by WWLLN, the ELF network observed lightning only on March 9. This discrepancy between the two measurements can be due to the increase of the local background noise in particular at TRU...
station during the lightning activity leading to the smaller reception of the triggered events (local time of thunderstorm activities between the Pacific and Sea of Japan is different in general).

5. Statistical Properties

Figures 8(a) to (c) show the histograms indicating the regional dependence of the CMC, and Table 1 summarizes the number of these CMC distributions. As is seen from Fig. 8(a), the number of lightning events monotonically decreases with increasing CMC for both polarities but the total number detected by ELF transients for positive CGFs is larger than that for negatives. One of the most remarkable findings in this paper is that the median value of the CMC from Pacific CGFs is considerably larger than that of the Sea of Japan for both polarities (Table 1) because CMC values over the Pacific Ocean have not been obtained before despite the fact that active thunderstorms are identified both by ground and satellite measurements in this region during winter. The number of positive CGFs is much larger than negatives over the Sea of Japan indicating typical nature of winter thunderstorm activity in the region of Hokuriku, whilst the number of positives and negatives are comparable for CGFs over the Pacific Ocean (Figs. 8(b) and (c), and Table 1). The difference in CMC between two regions can be due to the different meteorological conditions of thunderstorm activities (Pacific Ocean and Sea of Japan) during the early spring season. Physical mechanisms of these differences will be investigated in detail.

6. Summary

Spatio-temporal dependences of lightning locations and associated electric charge moment changes around Japan are successfully derived by using our ELF observation network. Major findings from the initial results obtained in the data during March 2011 are summarized as follows:

(1) Most thunderstorm activities are identified over the Pacific Ocean and the Sea of Japan.

(2) Mean CMC for positive flashes is much greater than that for negatives flashes.

(3) Large numbers of positive flashes are observed over the Sea of Japan

(4) CGFs with larger CMC are predominant over the Pacific Ocean

(5) Spatial distributions of the lightning derived by ELF observations are in rather good agreement with those from VLF network measurement provided by WWLLN.

Acknowledgment

The authors would like to thank Mr. Y. Ikegami and Mr. M. Sera at MSR station of STE of Nagoya University for their assistance of ELF data recording. This work is partially supported by Grant-in-Aid for Scientific Research (C) grant number 22560266 and special management expenses grants for national University corporations (for projects) from the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT), and STE Laboratory of Nagoya University collaboration research grant. The authors wish to thank the World Wide Lightning Location Network (http://wwlln.net), a collaboration among over 50 universities and institutions, for providing the lightning location data used in this paper.

![Fig. 8. Histograms indicating the number of CGF events as a function of CMC](image-url)
References


Yasuhide Hobara (Member) received the B.S., M.S. and Ph.D. degrees in Electrical Engineering from The University of Electro-Communications (UEC), Japan, in 1991, 1994, and 1997, respectively. Following his graduation from the UEC, he worked at Institute of Applied Physics (Russia), Earth Observation Research Center, JAXA, Laboratoire de Physique et Chimie de l’Environnement et de l’Espace – CNRS (France), Swedish institute of space physics (Sweden), The University of Sheffield (United Kingdom), and Tsuyama National College of Technology (Japan). He joined the Department of Communication Engineering and Informatics, Graduate School of Informatics and Engineering in UEC in 2009 where he is currently a Professor. Terrestrial and space electromagnetic environment is his main field of research including space plasma science, atmospheric electricity and seismo-electromagnetics. He is currently the head of earth environment research station in UEC.

Takahiro Inoue (Non-member) received the B.S., M.S. degrees in electrical engineering from The University of Electro-Communications (UEC), Japan, in 2010, 2012, respectively. He joined Mitsubishi Electric TOKKI Systems Corporation in 2012.

Masashi Hayakawa (Senior Member) was born in Nagoya, Japan on February 26, 1944. He received the B.E., M.E., and Doctor of Engineering degrees, all from Nagoya University in 1966, 1968 and 1974, respectively. In 1970, he joined the Research Institute of Atmospherics, Nagoya University, as a Research Associate. He became an Assistant Professor in 1978 and an Associate Professor in 1979, at the same Institute. Since 1991, he has been a Professor with the University of Electro-Communications, Tokyo, Japan and is now professor Emeritus. He has been engaged in the study of terrestrial noise environment, including space physics, atmospheric electricity, and seismo-electromagnetics. Also, his interests include signal processing, EMC, radio communication, and inversion problems. He is an author or a co-author of more than 700 research papers in the refereed journals. Dr. Hayakawa is the former (1996–1999) URSI Commission E Chair, and the former President of the Society of Atmospheric Electricity of Japan. He was Associate Editor of Radio Science, and is now Editor-Chief of J. Atmos. Electr., and on the editorial board of Indian J. Radio and Space Physics.

Kazuo Shiokawa (Non-member) received the B.S. and M.S. degree in geophysics from Tohoku University, Sendai, Japan in 1988 and 1990, respectively. He received the Ph.D. degree in science from Nagoya University, Nagoya, Japan in 1994. In 1990, he joined the Solar-Terrestrial Environment Laboratory (STEL), Nagoya University, where he is currently a Professor in the Division of Ionospheric and Magnetospheric Environment. He is also the Director of the Kagoshima Observatory of the Geospace Research Center of STEL. His research mainly concerns plasma physics in the Earth’s magnetosphere and ionosphere and dynamics of the upper atmosphere.