2014
23rd International Lightning Detection Conference
18 - 19 March • Tucson, Arizona, USA
5th International Lightning Meteorology Conference
20 - 21 March • Tucson, Arizona, USA

An ELF Signal Associated with a Positive GC Lightning Event in Winter

Noriyasu Honma, Yasuji Hongo
Research & Development Center
Tohoku Electric Power Company, Inc.
Sendai, Japan

Fuminori Tsuchiya
Planetary Plasma & Atmospheric Research Center
Graduate School of Science, Tohoku University
Sendai, Japan

Daiki Tsurushima
Graduate School of Environmental Studies
Tohoku University
Sendai, Japan

Mitsuteru Sato, Yukihiro Takahashi
Hokkaido University
Sapporo, Japan

***Abstract*— A positive upward lightning event occurred at a mountain around a coastal area of the Sea of Japan in winter. The current waveform, the LF electric field waveforms and the ELF horizontal magnetic field waveforms associated with the event were compared. Although bipolar field pulses were observed in LF in the period of the beginning of the current waveform, the ELF magnetic field waveform was similar to the current waveform in the entire period of the current of about 70 ms. This result indicates an ELF magnetic field has a potential to show a long continuing current related to an energy of lightning.**

***Keywords*— LLS, positive lightning, upward lightning, winter, lightning current, LEMP, LF, ELF**

I. INTRODUCTION

The first IMPACT sensor base lightning location system (LLS) [Cummins, et al., 2009] in Japan had begun operating to observe cloud-to-ground (CG) lightning discharges occurring around the Tohoku region under Tohoku Electric Power Company, Inc. (Tohoku EPC) in 1994 [Honma, et al., 1998]. For lightning discharges causing transmission line faults around coastal area of the Sea of Japan in winter, however, a detection efficiency (DE) of lightning electromagnetic pulse (LEMP) waveforms was evaluated to be low [Honma, 2012]. The low DE was clear, by an observation of the LEMP waveforms using a fast antenna (FA) network of Tohoku EPC, to be caused by unique characteristics of the waveforms associated with the winter lightning. The results motivated a collaborative development of a new Vaisala's LS700x sensor with an improved ability to detect the winter lightning [Cummins, et al., 2012; Honma, et al., 2013]. The Tohoku LLS was restructured in a new configuration of six LS sensors in 2011. A practical model, however, to estimate a current flowing into the ground for the winter lightning is yet to be established.

Tohoku EPC has conducted another observation of lightning current associated with the winter lightning striking a tower at a summit of Mt. Ogami in Niigata Prefecture since 2005 [Hongo and Yokoyama, 2009]. The waveform of the current flowing through the tower has been observed by using a Rogowski coil wound around a foot of the tower. In some GCs observed at the observatory, slow rising current waveforms were overlapped with pulse series, and only bipolar field pulses to be classified as intra-cloud (IC) discharge pulses were radiated [Hongo, et al., 2011]. Even though the LLS detect one of the bipolar pulses, the LLS cannot estimate the peak current correctly.

In an extremely low frequency (ELF), transient magnetic fields associated with global lightning events have been observed because of long-range propagations inside the "Earth-ionosphere cavity". Sato et al. [2008] has observed the ELF magnetic fields in Onagawa in Miyagi Prefecture, Japan, Esrange in Sweden and Syowa in Antarctica to clarify a global distribution of intense lightning discharges and their seasonal variations. The results included the charge moments of the lightning events related to the energies.

The authors investigated a sample positive GC lightning event striking the tower at Mt. Ogami in winter by comparing the current waveform, the LF electric field waveforms and the ELF horizontal magnetic field waveform observed at a distance of 296 km from the lightning. Although bipolar field pulses were observed in low frequency (LF) in the period of the beginning of the current, the ELF magnetic field waveform was similar to the current waveform in the entire period of the current of about 70 ms, except for narrow current pulses overlapped. The similarity indicates the ELF magnetic field observation is useful to estimate the long continuing lightning currents and their charge amounts. The results are shown in this paper.

II. OBSERVATION AND DATA

A. Lightning Current Observation

The tower at the summit of Mt. Ogami is 670 m in altitude and 17 km inland off the coast of the Sea of Japan. The waveforms of the currents flowing through the tower have been observed using the Rogowski coil system in the frequency range from 0.2 Hz to 100 kHz. The waveforms have been digitized each 1 µs and time tagged with a GPS clock. The observation had been conducted up to Feb. 2010.

B. LEMP Observation in LF

The LEMPs in LF are observed using the network of five FAs covering the Tohoku region entirely [Cummins, et al., 2012]. The FAs are operated at the same locations as the LS sensors. The observation frequency ranges from about 700 Hz to 1 MHz. The electric field waveforms sampled at each 1 µs are recorded in one channel for 8 ms, up to 15 times without dead time, and those sampled at each 0.1µs are recorded in the other channel for 0.8 ms at the same trigger time. The field waveforms recorded in the former channels are compared with the current waveform of the investigated lightning event.

C. LEMP Observation in ELF

Two orthogonal search coil magnetometers were installed first at Syowa station (69.0ºS, 39.6ºE) in 2003 to observe the horizontal magnetic fields of geomagnetic NS and EW components in the frequency range of 2-90 Hz. After that, the same observation systems were installed at Onagawa observatory (38.4ºN, 141.5ºE) in Japan and Esrange (67.9ºN, 21.1ºE) in Sweden, to observe the horizontal magnetic fields of geographical NS and EW components. With these systems, the observed waveforms are digitized at a resolution of 16 bits with a sampling rate of 400 Hz. The magnetic field waveforms observed in Onagawa are investigated in this paper.

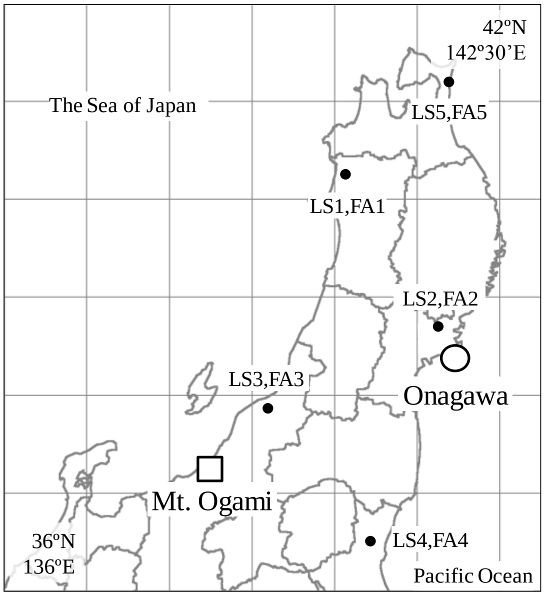

Fig. 1. Locations of the observatories with the Tohoku LS sensor network, except for the Syowa and Esrange observatories. A white square, a white circle and five dots show the locations of Mt. Ogami, the Onagawa observatory and the FAs beside the LS sensors, respectively.

The comparisons of the waveforms of the current, the vertical electric field in LF and the horizontal magnetic field in ELF, are possible in the observation period from late Dec. 2009 to Feb. 2010. Therefore, a sample lightning event occurred at Mt. Ogami at 13:05:47.02 JST on Jan. 5, 2010 was investigated. Fig. 1 shows the locations of the observatories with the configuration of the Tohoku LLS, except for the Syowa and Esrange observatories.

III. ANALYSES

A. Comparison of Current and LF Electric Field

Fig. 2 shows the investigated current waveforms (lower waveforms) with the corresponding electric field waveforms (upper waveforms) observed at FA3 shown in Fig. 1. The electric fields radiated from Mt. Ogami take 316 µs to travel 94.8 km to FA3. For the traveling time, the field waveforms are shifted earlier in Figs. 2 (a), (b) and (c).

Fig. 2 (a) shows the observed current waveforms entirely. The current increased with some changes to 26 kA at the maximum and decreased to the zero-crossing at 65 ms after the onset, then undershot with a bottom of -3 kA in amplitude up to the end of the recording. In the duration, three electric field waveforms labeled as a, b and c in the figure were observed.

Fig. 2 (b) shows the earlier portion of the same current waveform as shown in Fig. 2 (a) over an expanded time axis. In the beginning duration of the current for about 120 ms, positive pulses of several ms widths existed. Around the zero-crossing, some narrow pulses of negative polarity appeared. After the pulses, narrow bipolar pulses were seen over the undershooting portion entirely as shown in fig. 2 (a). For the electric fields, the bipolar pulse series were observed only in the beginning duration of increasing currents for about 20 ms.

Fig. 2 (c) shows the current waveform for 3 ms around the onset, and the corresponding electric field waveform. Both waveforms were overlapped with narrow pulses for about 1 ms from the onset, and from 1.3 ms after the onset. The pulses seemed to be positive and asymmetric for the currents, and negative and bipolar for the electric fields. The pulses' times and amplitudes for both the current waveform and the field waveform seemed to be correlative. Based on the features of the waveforms, the field pulse series in LF were thought to be radiation components associated with the currents flowing along the channel grounding at Mt. Ogami. No field change, however, corresponding to low frequency components of the current was observed. This is estimated to be due to limited sensitivity of FA in low frequency.

In the duration of the earlier part of the undershooting portion of the current, electric fields "b" and "c" were observed as shown in Fig. 2 (a). The former field waveform "b" shown over an expanded time axis in Fig. 2 (d) had characteristic features as a smooth concave front after a clear onset, and was followed by a tail with a longer duration than the front. The lightning discharge radiating such a specific field pulse is classified easily as a typical positive CG (+CG) [Honma, 2012]. The +CG, located at 37.4 km east of Mt. Ogami based on arrival times of the fields observed at FAs 2, 3 and 4, occurred 143.7 ms after the onset of the current. If the +CG was caused by a leader progressing from the lightning event occurred at Mt. Ogami, the relation between the locations and the times of these two lightning events corresponds to a speed of the leader of 2.6×10^5 ms^{-1}. The speed agrees well with that of the horizontally progressing negative leader of 3×10^5 ms^{-1} estimated in another winter lightning study on lightning flashes with multiple terminations at the ground [Honma, et al., 2012]. According to a hypothesis on the leader progression proposed in the study, negative leaders progress horizontally for up to 40-50 km, after the cessation of the progression, new positive leaders progress from the end of the leaders, and some of them reach the ground to make +CGs. This hypothesis is applied to explain the +CG investigated in this paper.

The electric field takes 264 μs to travel 79.2 km to FA3. For the traveling time, the field waveforms are shifted earlier in Fig. 2 (d). Some asymmetric positive current pulses with significantly larger amplitudes than the other pulses, were observed about 290 μs after the field pulses. The time difference corresponds to time for the current pulses to travel back from the +CG to Mt. Ogami for the distance of 37.4 km with a speed of about 0.43 c. The speed along the actual channel, estimated to be around half the light speed, is consistent with the other reported traveling speeds of currents along channels [Rakov and Uman, 2003]. So the observed current pulses were estimated to propagate from the +CG. The current pulses, however, were only narrow pulses and the features were apparently different from the corresponding characteristic field pulses. The difference indicates a low conductive base of the upward branching channel of the +GC.

In the period of the undershooting portion of the current in Fig. 2 (a), no corresponding field change was observed, except for field waveform “c”. This feature was different from the relation between the field and the current in the duration of the earlier positive portion of the current. The difference of the relations indicated that the current pulse series over the undershooting portion were probably not actual. This portion

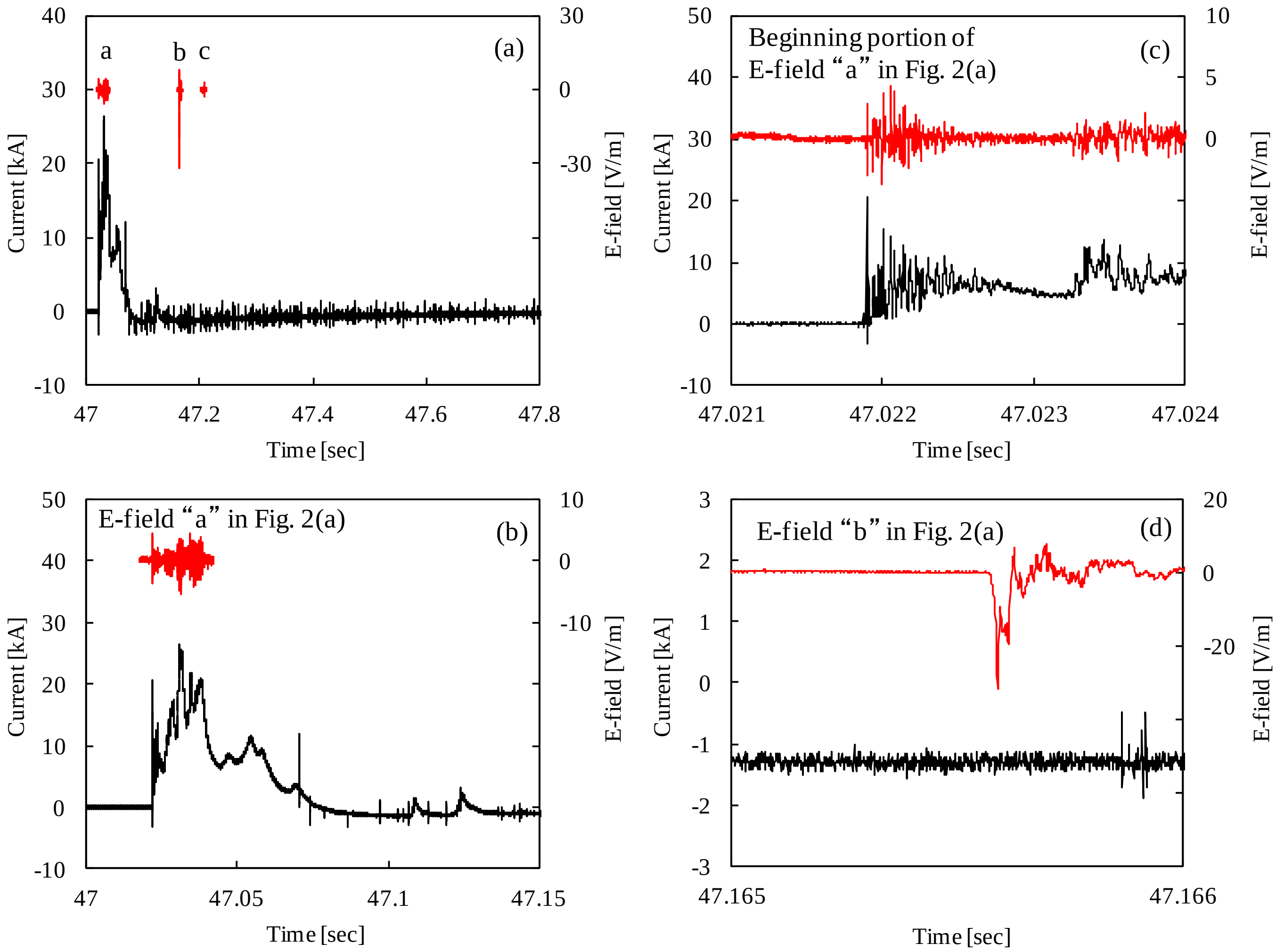

Fig. 2. Sample current waveforms observed at Mt. Ogami and corresponding electric field waveforms observed at FA3. The current was 26 kA in peak amplitude and the duration of the positive portion was 65 ms. This portion was followed by an undershoot overlapped with pulses up to the end of the recording. The earlier portions of those current and field waveforms, their beginning portions and a portion corresponding to another +CG are shown over expanded time axes in figures (b), (c) and (d), respectively.

was also estimated to be due to the insufficient sensitivity of the Rogowski coil system in low frequency. Thus, in the undershooting portion, the actual current should be understood to be in positive polarity and to decrease to zero asymptotically in amplitude.

An amount of electric charge (Q) flowing through the investigated +GC is calculated by integrating the observed current. The Q for the entire recording period was calculated as -22 coulombs, which was the total of the Qs of 474 coulombs for the first positive portion and -496 coulombs for the following negative portion. The influence, however, of the undershooting portion to the positive portion was estimated to be 12 % in amplitude at the maximum, based on a comparison of the bottom value of the undershooting portion of -3 kA and the positive peak value of 26 kA. Assuming the influence for the Q to be 6 %, half the undershooting ratio, the actual Q of the entire current was roughly estimated to be 500 coulombs.

In recent winter lightning researches, positive GCs (+GCs) were classified based on their intense field pulses and their characteristic waveforms [Ishii and Saito, 2009]. The +GCs are thought to begin with a connection of a downward positive leader and a negative leader progressing upward from a grounded structure [Rakov, 2003; Ishii and Saito, 2009; Honma, 2012]. In accordance with the concept, an existence of the upward negative leader is the only difference of the discharge process of the +GC from that of the +CG. The negative leader progression generally radiates field pulses. The beginning portion of the investigated current was composed of not only the lower frequency components but also the narrow pulses seen in Fig. 2 (c). In amplitudes, the pulses decreased with the increase of the current of the lower frequency component up to 47.0227 seconds, and few pulses were observed in the period of the decreasing current.

Based on the features of the current changes, the current was estimated to be brought by the negative leader progressing into a positive charge region in the cloud. The features of the corresponding field pulses resembled with those associated with neither a stepped leader progression in the -CG nor a preliminary breakdown process. The complicated features of the fields may be caused by the reflections of the current along the relatively short channel terminating at the ground. After 47.0233 seconds in Fig. 2 (c), pulses were seen both in the field waveforms and the current ones. These pulses were guessed to be produced by the negative leader's restart of the progression or by the progression of the other branched negative leaders.

For the first pulse of the lower frequency component of the current in Fig. 2 (c), the rise time of the current was about 0.7 ms, which was very slow. The amplitude of the same component seemed to increase in 14 ms and reach the maximum value of about 20 kA in Fig. 2 (b). Comparing the current value with the peak currents of +GCs estimated by the LLS in the same manner as for the -CG, the currents in this event were much lower than the peak currents of the +GCs [Ishii and Saito, 2009l; Honma, 2012]. The above characteristic differences of this event is estimated to be due to the upward negative leader progression from the ground without connection with the downward leader. Then the investigated lightning event should be classified as a different type of +GC, and as a perfect upward positive lightning. The current brought only by the upward negative leader progression continues in the duration of the leader progression. The perfect +GC is hard to detect for the LLS, because only the field pulse series are radiated in LF. Even though one of the pulses is detected, no exact information on the current is estimated. In fact, the Tohoku LLS consisting of six LS sensors detected the +CG, but could not detect the +GC.

B. Comparison of Current and ELF Magnetic Field

Fig. 3 shows the waveforms of the geographical NS and EW components of the ELF magnetic field pulses observed in Onagawa which was coincident with the lightning event that occurred at Mt. Ogami as investigated above. The polarities were positive for the northeast direction. There were two major pulses and the onset times were 47.0275 and 47.1725 seconds, respectively. Assuming a delay of about 6 ms, these times were coincident with the onset times of the +GC and the +CG, respectively. According to the results of an electromagnetic field simulation for an ionospheric propagation of the LEMP in ELF, of which the detail is described in the next subsection C, the LEMP is observed with a delay of about 0.3 ms at a distance of 300 km. Then the delay of about 5.7 ms is due to the observation system in Onagawa.

Ratios of the EW component and NS ones (EW/NS ratios) of the first pulse were around 0.74 at absolute magnitudes of the NS components over 100 nT. Based on the ratios, the incoming direction of the LEMP was estimated to be 53.5º westward from a southward direction, which was 10.3º southward relative to the direction of Mt. Ogami. The EW/NS ratio of the second pulse was 0.78, which corresponded to the incoming direction of the pulse to be 52.0º westward from a southward direction, which was 7.3º southward relative to the direction of the +CG. The direction error of 3.0º was smaller than that for the first pulse. The direction errors, which may reflect the horizontal spreads of the lightning channels, were estimated to be mainly due to an installation of the orthogonal magnetometers, for example a horizontal rotation of the placement of the magnetometers or due to the calibration of

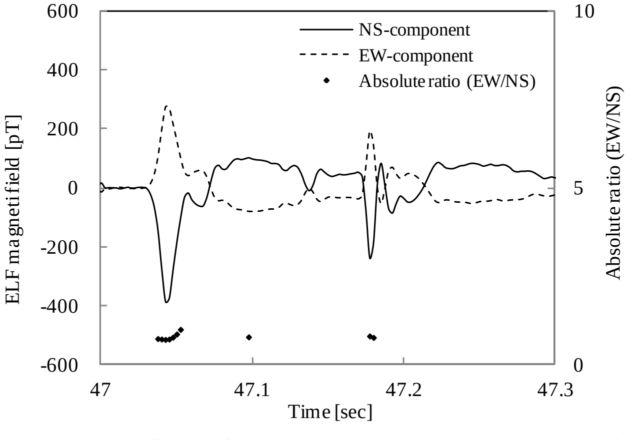

Fig. 3. Waveforms of geographical NS and EW components of ELF magnetic field in Onagawa associated with lightning that occurred at Mt. Ogami as investigated above. Note that polarities were positive in northeast direction. Both waveforms were similar, and absolute EW/NS ratios were about 0.70 at magnitudes of NS components over 100 pT.

their sensitivities. Induction noise of 50 Hz originating with power lines was also influential, in spite of attempts to reduce the noise.

For the EW-component of the first pulse, the field increased to about 275 pT at the peak, then undershot to -80 pT at the bottom and ended with two small positive pulses. The features of the field changes resembled the coincident current waveform shown in Fig. 2 (b), except for the narrow current pulses. The undershooting portion, however, was significantly deeper than that of the current waveform. The difference was estimated to be due to the limited frequency range of 2-90 Hz of the ELF observation. The waveform of the second pulse resembled that of the first pulse, except for the steep undershooting just after the peak. The difference probably depends on the discharge features of +GC/+CG.

C. Reproduction of LEMP in ELF

In order to reproduce the observed ELF magnetic field associated with the investigated +GC, the FDTD method was applied to simulate the propagation of the electromagnetic field excited with the current along a simple vertical channel at the center of the radial simulation space in the cylindrical coordinates [Baba and Rakov, 2011]. The current waveform shown in Fig. 2 (b) was uniformly set along the channel of 4 km in height. The field pulse radially propagates in the cavity between horizontal perfectly conductive plates which were effective as the ground and ionosphere in ELF. The modeled ionosphere in the daytime and at night was 76 km and 84 km in altitude, respectively. The horizontal magnetic field, reproduced at a distance of 296 km from the +GC, was filtered at a higher cut-off frequency of 90 Hz with an attenuation rate of -48 dB/octave, and at a lower cut-off frequency of 2 Hz with the attenuation rate of -24 dB/octave.

Fig. 4 shows the reproduced field in ELF overlapped with a power of the observed NS/EW components. Those waveforms agreed well, except for the features around the peak, and the differences in amplitudes. This indicated that the observed ELF waveforms were mainly composed of induction components associated with the lightning current, due to much shorter propagation distance than a tenth of the 3,300 km wave length corresponding to the maximum in the ELF observation frequency range of 90 Hz. Assuming the ratio of the observed peak value to the simulated one to be 0.6, the length of the channel should be 2.4 km actually.

A vertical component of the current flowing along the channel produces a horizontal magnetic field. The current, injected into the end of the leader channel, progressing upward from the ground, reflects positively at the ground and negatively at the end of the channel. The ELF magnetic field, the wave length is much longer than the channel height, has no detail information on the current flow along the vertical component of the channel. The difference, however, between the first peaks of the ELF field waveform and the current waveform indicates the simple model of the uniform distribution of the current along the vertical channel as applied for the above simulation, not to be sufficient to reproduce the ELF fields completely, based on the current observed at the channel base. A negative leader is generally thought to be easy to branch. In fact, one of the branches was estimated to progress horizontally for more than 37.4 km in this investigated event. The branch channel probably makes the current complicated. Therefore, it's necessary for the better reproduction of the ELF field waveform, finer model of the channel is necessary.

The effect of the ionosphere to the propagation of the LEMP was investigated by the electromagnetic simulations in the same manner as described above. The lightning current was modeled with a Gaussian pulse having a peak amplitude of 1 kA and full width at half maximum (FWHM) of 4 ms, corresponding to the frequency of about 90 Hz at the maximum. Based on the results, peak amplitudes of the LEMPs simulated at different propagation distances under or without the ionosphere in the daytime are shown in Fig. 5. The logarithmic

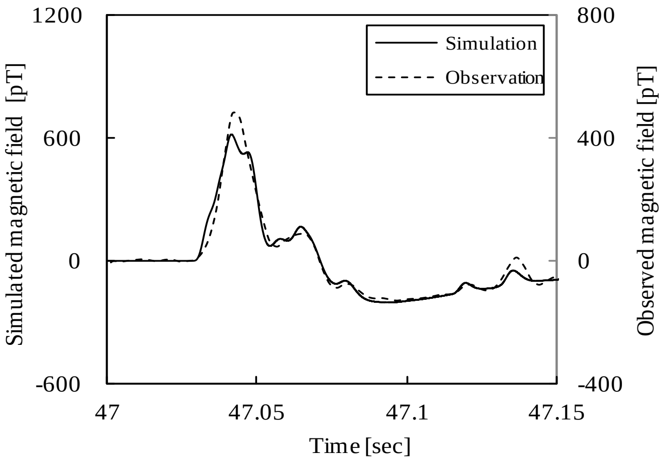

Fig. 4 Horizontal magnetic field waveform was simulated based on lightning current observed at Mt. Ogami shown in Fig. 2 (b) using the FDTD method. The waveform was filtered at higher cut-off frequency of 90 Hz and at lower one of 2 Hz, and overlapped with ELF magnetic field waveform observed at Onagawa observatory. These waveforms are well matched.

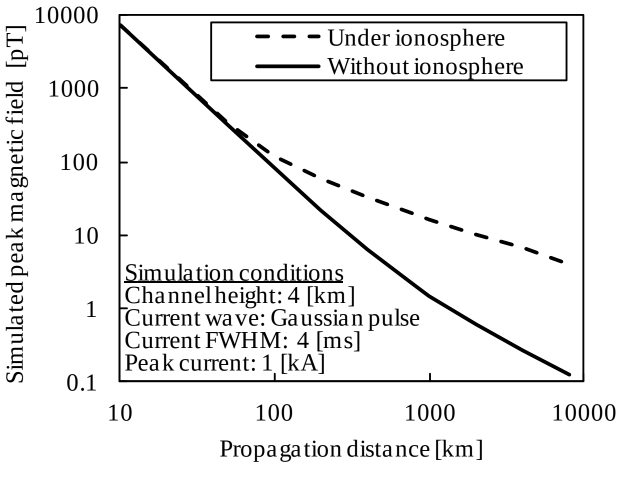

Fig. 5 Logarithmic peak amplitudes of simulated horizontal magnetic field pulses propagated under or without the ionosphere in the daytime, depending on logarithmic propagation distances. The fields are associated with a current with a Gaussian pulse having peak amplitude of 1 kA and FWHM of 4 ms corresponding to the frequencyof about 90 Hz at the maximum.

peak amplitudes decrease with the increase of the logarithmic propagation distance regardless of the propagation under or without the ionosphere in the daytime. The decreasing rates were -0.8 and -1.6 on averages in the range of the propagation distances from 100 km to 1000 km, respectively. It’s clear that the attenuation of the magnetic field pulse in ELF is lower than that without the ionosphere for the propagation over about 100 km.

IV. SUMMARY

A positive GC lightning event occurred at Mt. Ogami in the coastal area of the Sea of Japan in winter. The lightning current waveform was observed, and the peak current and the amount of the electric charge were 26 kA and about 500 coulombs, respectively. The event was, however, not detected by the LLS, because only narrow field pulse series were radiated in LF. The electromagnetic feature, different from those of the known type of +GC radiating intense field pulses, were estimated to be caused by the negative leader progressing upward from the ground without connection with the other leaders.

At the Onagawa observatory at a distance of 296 km from the +GC, the horizontal magnetic field pulse was observed in ELF. The waveform resembled the observed current waveform. The similarity indicated the investigated ELF magnetic field was mostly composed of the induction component.

The LEMP propagation inside the “Earth-ionosphere cavity” was simulated using the FDTD method. Considering the frequency response characteristics of the ELF observation system, the observed ELF magnetic field waveform well matched with the observed current waveform. The lightning channel was estimated to be around 2.4 km in height, which was within the range of the reported channel heights in winter.

When the propagation distance ranges approximately from 100 km to 1000 km, the logarithmic amplitude of the ELF magnetic field attenuates by a factor of -0.8 on average with the logarithmic distance of the propagation under the ionosphere. The attenuation rate is comparable to that of the radiation field in LF. The effect of the ionosphere enables the observation of the magnetic field produced by the long continuing lightning current in ELF.

The ELF field propagation under the ionosphere has been used to observe charge moments of the lightning events in the world. It’s first confirmed by the authors, however, that the horizontal ELF magnetic field was the induction component in the above propagation range, comparing with the observed current. The observation of the lightning ELF magnetic fields will be useful to estimate the lightning current waveforms related to the amounts of the electric charges flowing into the ground. In addition, the observation enables locating the lightning event complementary to the LLS observing LF signals.

ACKNOWLEDGMENT

The authors would like to thank Mr. Takaaki Konno and Mr. Yousuke Komatsu for their contribution on the analyses.

REFERENCES

Baba, Y. and V. Rakov (2011), Simulation of corona at lightning-triggering wire: Current, charge transfer, and the field-reduction effect, J. Geophys. Res., 116, D21115.

Cummins, K. L., and M. Murphy (2009), An overview of lightning locating systems: history, techniques, and data uses, with an in-depth look at the U.S. NLDN, IEEE Trans. on EC, 51 (3), 499-518.

Cummins, K. L., N. Honma, A. E. Pifer, T. Rogers, and M. Tatsumi (2012), Improved detection of winter lightning in the Tohoku region of Japan using Vaisala’s LS700x technology, IEEJ Trans. PE, 132, 6, 529-535.

Honma, N, F. Suzuki, Y. Miyake, M. Ishii, and S. Hidayat (1998), Propagation effect on field waveforms in relation to time-of-arrival technique in lightning location, J.Geophys.Res., 103 (D12), 14141-14145.

Honma, N. (2012), Performance of the Tohoku IMPACT sensor network in winter lightning detection, IEEJ Trans. PE, 132, 6, 579-587.

Honma, N., D. Tsurushima and Konno (2012), Horizontal distribution of lightning discharges in a single event in winter, Proceedings of 2012 CIGRE SC C4 Colloquium in Japan, I-4.

Honma, N. (2013), Improved location performance of the Tohoku IMPACT sensor network in winter lightning detection, IEEJ Trans. PE, 132, 6, 579-587.

Hongo, Y. and S. Yokoyama (2009), Observation results of characteristics of winter lightning and experimental results on lightning protection for wind turbines, CIGRE SC C4 2009 Kushiro Colloquium.

Hongo, Y., N. Honma and H. Honda (2011), Observation of lightning current waveforms at Ogami mountainous area in Niigata prefecture, The papers of technical meeting on high voltage engineering, IEE Japan, HV-11-102.

Ishii, M. and Saito (2009), Lightning electric field characteristics associated with transmission-line faults in winter, IEEE Trans. EMC, 51, 3, 459-465.

Rakov, V. A., and M. A. Uman (2003), Lightning: Physics and Effects, Cambridge Univ. Press, New York.

Sato, M., Y. Takahashi, A. Yoshida and T. Adachi (2008), Global distribution of intense lightning discharge and their seasonal variations, J. Appl. Phys., 41, 234011.