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

Observation of lightning at Tokyo Skytree

Masaru ISHII, Mikihisa SAITO
The University of Tokyo
Tokyo, Japan
ishii@iis.u-tokyo.ac.jp

Toru MIKI, Daiki TANAKA,
Takatoshi SHINDO,
Akira ASAKAWA,
Hideki MOTOYAMA
CRIEPI

Yusuke SUZUHIGASHI,
Hiroshi TAGUCHI
TOBU TOWER SKYTREE Co., Ltd.
Tokyo, Japan

***Abstract*— Tokyo Skytree is a 634-m high freestanding broadcasting tower in Tokyo, Japan. Direct observation of lightning current started in February 2012, and a high-speed camera was set at 1.2 km from the tower in August 2012. As of December 2013, 24 lightning current data hitting the tower have been observed. In 2012, most of the flashes were upward as was expected; however, in 2013 most of the flashes were downward. Ten upward connecting leaders preceding downward negative first strokes were optically observed by using a high-speed camera. 3-dimensional progression velocities and lengths of these upward leaders were analyzed. Summary of these observations is reported on.**

Keywords—lightning current; connecting leader; high-speed camera; tall structure; LEMP.

I. INTRODUCTION

TOKYO SKYTREE® is a 634-m high freestanding broadcasting tower in Tokyo, Japan (35.71N, 139.81E). Direct observation of lightning current started in February 2012 [1][2], and high-speed cameras were set 6 months later [3][4]. By September 2013, 24 lightning flashes hitting the tower, 11 upward and 13 downward, were observed, including LEMP waveforms associated with return strokes generated at the tower. Summary of the observation with some analysis on the LEMP waveforms is reported on.

II. OBSERVED LIGHTNING CURRENTS

For observation of lightning current, two Rogowski coils designed to observe high frequency components (1.5 kHz~ 5 MHz) and low frequency components (0.5 ~ 250 kHz) are installed at a height of 497 m of the tower [1]. Tables 1 and 2 are the list of observed lightning currents. Existence of ICC (initial continuous current) and the waveform of first return stroke currents are used to identify whether they were upward or downward flashes. No. 4 in Table 2 was presumably a downward flash having multiple terminations. In 2012, most of the flashes hitting the tower were upward as was expected, however in 2013, majority of the flashes were downward. The difference seems to come from difference of the season in which majority of lightning hits to the tower occurred; that is, most of the observed flashes occurred in May in 2012, whereas in 2013, majority of flashes occurred in summer months from July to September.

TABLE I. LIGHTNING CURRENT DATA OBSERVED IN 2012

No.	Date	Triggered time	Downward /Upward	Positive /Negative /Bipolar	Return Stroke [times]
1	5/18	01:43:49	U	N	6
2	5/18	12:35:59	U	N	0
3	5/22	13:14:29	U	N	1
4	5/22	13:19:54	U	N	1
5	5/22	13:28:06	U	N	4
6	5/28	15:33:11	D	N	2
7	6/1	15:54:13	U	B	0
sum			U:6, D:1	N:6,B:1	14

TABLE II. LIGHTNING CURRENT DATA OBSERVED IN 2013.

No.	Date	Triggered time	Downward /Upward	Positive /Negative /Bipolar	Return Stroke [times]
1	1/14	12:37:17	U	B	0
2	7/8	15:47:50	D	N	5
3	7/8	15:55:23	D	N	1
4	7/8	16:09:31	D*	N	1
5	7/8	16:11:47	D	N	1
6	8/6	15:21:33	D	N	2
7	8/21	16:29:51	D	N	7
8	8/21	16:55:07	D	N	1
9	8/21	22:31:54	D	N	3
10	8/21	22:35:17	D	N	11
11	8/21	22:43:00	D	N	1
12	8/21	22:44:08	D	N	7
13	8/21	22:57:34	D	N	5
14	9/5	09:35:04	U	N	1
15	12/10	09:11:06	U	B	12
16	12/10	09:14:19	U	N	0
17	12/20	15:13:07	U	N	3
sum			U:5, D:12	N:15,B:2	61

* 1st stroke didn't hit the tower.

Fig. 1 shows cumulative frequency probability of altitudes of −10˚C depending on the type of flashes hitting the tower. The altitudes are estimated from aerological data of the day obtained at Tateno observatory (36.05N, 140.13E), 48 km northeast from the tower. Since radiosonde observation is only twice a day (9:00, 2100 JST), the average of −10˚C altitudes observed before and after a flash is used for the data in Fig. 1. The −10ºC altitude is known to be the height where charge separation actively occurs in convective clouds.

In summer, densities of negative high-current CG (cloud-to-ground) flashes are generally higher than high-current positive CGs. In other months, positive high-current CGs prevail. Seasonality of each month related to this lightning characteristic can be identified from the monthly averaged altitude of –10°C level of atmospheric temperature [5], and it was reported that 5.7 km was the lower limit of the monthly averaged altitude of –10°C as summer months.

The two distributions for upward and downward flashes shown in Fig 1 are distinctively different. Downward flashes to the tower occurred when the altitude of −10ºC was higher than 6 km except only one datum. In contrast, except one datum, upward flashes occurred when the −10ºC altitude was lower than 5.5 km. It is interesting that this border of the height of −10ºC altitude, 5.5 to 6 km, agrees to 5.7 km, which was reported to be the lower limit [5] of the monthly averaged altitude of −10ºC for summer months.

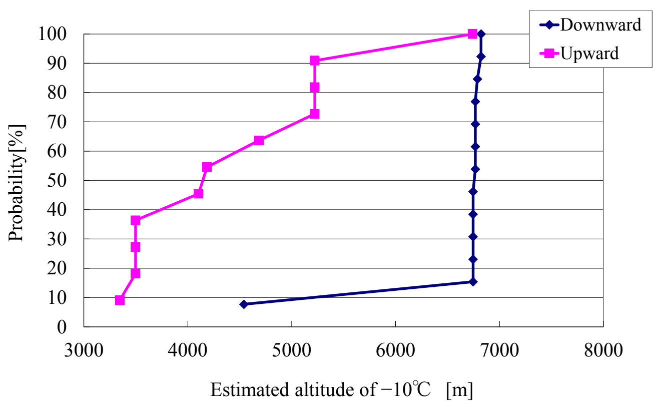


Fig. 1. Difference of cumulative frequencies of −10˚C altitude depending on the type of flashes when they hit the tower.

III. Optical Images

Lightning channels attached to the tower have been observed by two high-speed cameras from August 2012 [3][4]. Their specifications are shown in Table 3. The internal angle of the two cameras is 127˚, so the 3-dimensional structure of imaged lightning channels can be known. The frame rate of Casio camera is too low to observe progress of upward leaders.

Ten negative downward flashes were imaged in summer of 2013. Table 4 shows properties of imaged upward connecting leaders preceding the first return strokes of negative downward flashes. Common flash numbers with Table 2 are employed. In the second column of Table 4, “over” means the upward leaders extended outside of field of view of the camera before connection with downward stepped leaders. An example of such cases, Flash 2013-7 imaged by Fastec camera, is shown in Fig. 2.

TABLE III. Specifications of High-Speed Cameras.

	FPS	Resolution	Data length	Distance	Azimuth
Fastec HiSpec1	5627	320x240	1s	1.2 km	SSE
CASIO EXILIM EX-F1S	600	432x192	variable	4.4 km	WNW

TABLE IV. Imaged Upward Connecting Leaders Preceding First Return Stroke of Negative Downward Flashes in 2013.

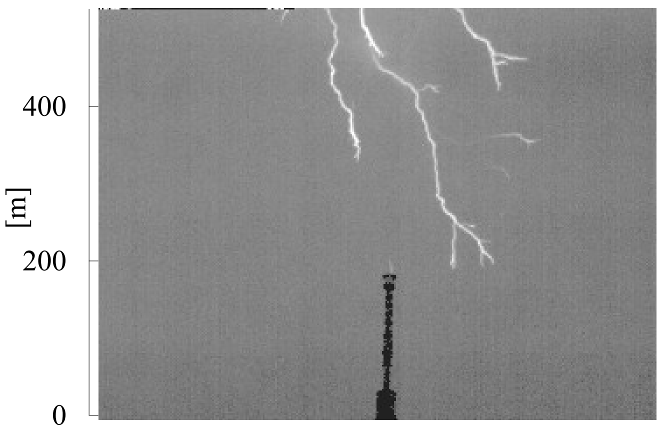
No.	2-D length of connecting leader	2-D progression velocity [m/s]
2013-2	300 m or over	Underexposure
2013-3	400 m or over	Underexposure
2013-5	500 m or over	1.5E+05
2013-6	450 m or over	1.3E+05
2013-7	350 m or over	2.8E+05
2013-8	450 m or over	1.7E+05
2013-9	200 m	1.1E+05
2013-11	-	Poor visibility
2013-12	-	Poor visibility
2013-13	-	Poor visibility

In Fig. 2(a), an upward connecting leader of about 30 m in length is visible at the top of the tower. After 1.2 ms, in Fig. 2(b), the bright upward leader extended up beyond the field of view of the camera, manifesting its length being longer than 350 m. In the next frame not shown here, connection occurred and the frame whited out. Fig. 2(c) shows an image about 1 ms after the occurrence of the first return stroke, showing the only path where the return-stroke current was flowing.

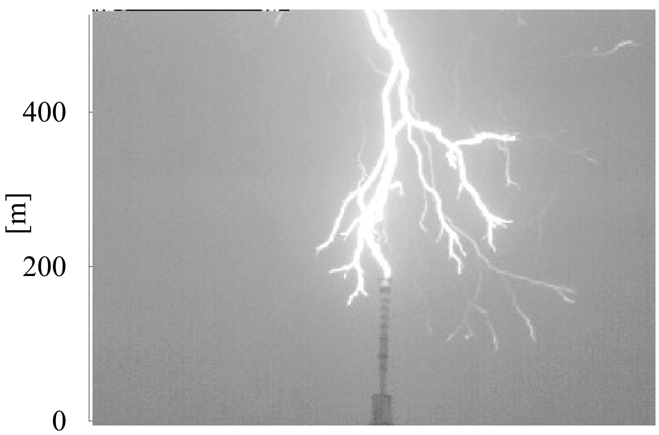
Four flashes out of the 7 imaged flashes in Table 4 generated upward connecting leaders of at least 400m in length. 2-D progression velocities of the upward connecting leaders were 1 to 3 x 10^5 m/s, accelerating just before connection. A third high-speed camera is planned to be installed to observe the 3-D velocity and the full length of upward leaders.

IV. Observation and Reproduction of LEMP Waveforms

Lightning electromagnetic pulse (LEMP) waveforms are observed at Abiko (27 km from Tokyo Skytree), Yokosuka (57 km) and Akagi (101 km). Fig. 3 shows location of each station relative to Tokyo Skytree [1]. A number of LEMP waveforms associated with lightning strokes hitting the 634-m tower were observed simultaneously with directly observed pulse current waveforms. 3-D geometry of the lower part of lightning channels for some flashes is also available. These datasets are useful to interpret information available by LLS (Lightning location systems).



(a) Frame 1789 (8 frames (1.4 ms) before the first return stroke).



(b) Frame 1796 (1 frame (0.2 ms) before first return stroke).

(c) Frame 1803 (6 frames (1ms) after first return stroke).

Fig. 2 Upward connecting leader and return stroke imaged by high-speed camera (Flash 2013-7).

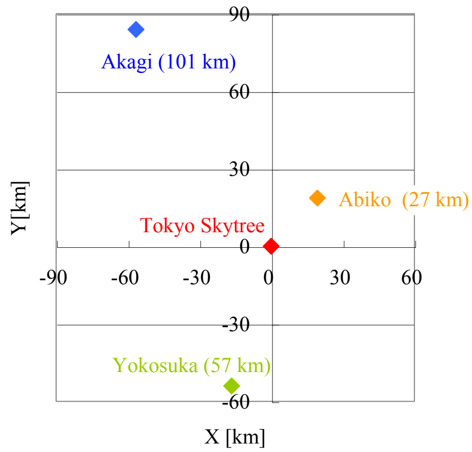


Fig. 3 Relative locations of electromagnetic-field observation sites.

Relationship of channel geometry and radiated electric field waveforms are analyzed by using a numerical electromagnetic model. Examples are shown in Figs. 4 and 5. Observed and calculated waveforms for a subsequent stroke current of Flash 2012-1 are shown in Fig. 4 [2]. NEC-4 (Numerical electromagnetics code), a code based on the method of moments, is employed for the numerical electromagnetic analysis. According to the numerical analysis, channel geometry hardly affects the current waveform.

Electric field waveforms, associated with the same stroke of Flash 2012-1, to be observed at the three remote observation sites are shown in Fig. 5. Actually observed electric field waveforms are also shown. Because of inclination of the lightning channel, the electric field waveform observed at each site in different direction differs each other. In the calculation, actually observed 3-D geometry of the lightning channel is incorporated in the numerical model [2], and the observed electric field waveforms are well reproduced as seen in Fig. 5. Geometry of the lower part of a lightning channel considerably influences the peak and the waveform of LEMP.

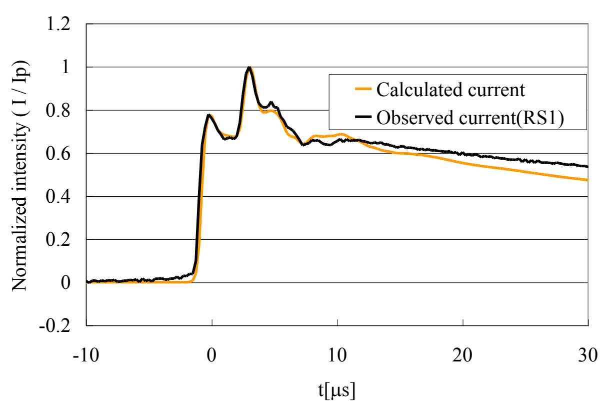
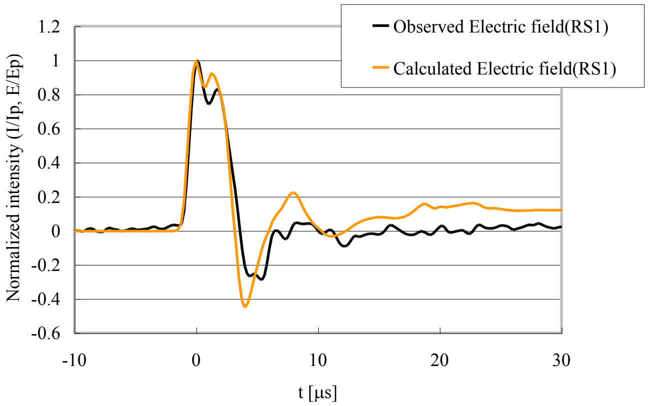
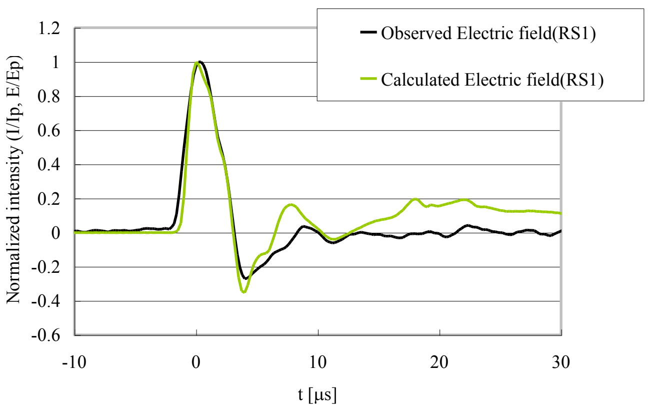


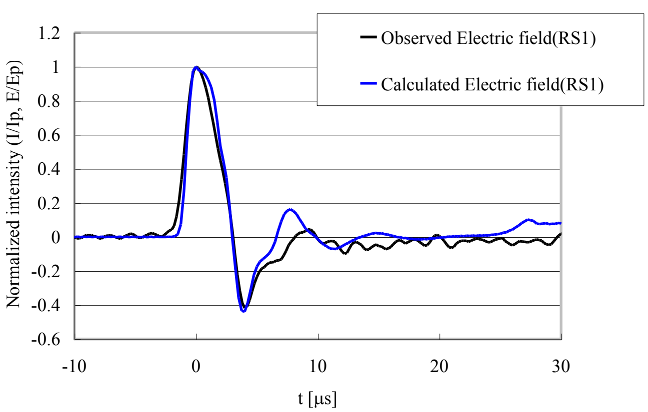
Fig. 4 Observed and reproduced current waveforms of a subsequent stroke of Flash 2012-1.



(a) Abiko



(b) Yokosuka



(c) Akagi

Fig. 5 Observed e-field waveforms (Flash 2012-1) and calculated e-field waveforms for an inclined lightning channel.

TABLE V. CALCULATED RATIOS OF PEAK VALUES OF LEMP RADIATED FROM INCLINED LIGHTNING CHANNEL (FLASH 2012-1) RELATIVE TO THOSE FROM VERTICAL LIGHTNING CHANNEL.

	Abiko	Yokosuka	Akagi
Ratio[%]	81	94	86

Table 5 shows the calculated peak values of LEMP over perfectly conducting ground at three positions in the same direction and distance as the three observation sites, for the channel geometry of Flash 2012-1, normalized to the values for a vertical lightning channel. These values are to be reflected to the RNSS (Range normalized signal strength) values calculated from reports from sensors of LLS, resulting in scattering of RNSS at each sensor and a lower value of estimated lightning current.

V. CONCLUSION

Currents, electric field waveforms, and images of lightning channels associated with lightning flashes striking Tokyo Skytree, a 634-m freestanding tower in Tokyo, Japan, are under observation. By September 2013, 24 lightning hits to the tower were observed. Among them, 10 upward connecting leaders preceding first return strokes of negative downward flashes were optically observed. The observed current and electromagnetic field waveforms are analyzed by using the method of moments, taking account of the channel geometry.

REFERENCES

[1] T. Miki, T. Shindo, A. Asakawa, H. Motoyama, M. Ishii, M. Saito, Y. Suzuhigashi, K. Fukuda, "Lightning current observations at TOKYO SKYTREE", CIGRE C4 Colloquium, V-5, Hakodate, Japan (2012-10).

[2] M. Ishii, M. Saito, T. Miki, D. Tanaka, T.Shindo, A. Asakawa, H. Motoyama, Y. Suhigashi, H. Taguchi, "Reproduction of electromagnetic field waveforms and tower currents of return strokes struck Tokyo Skytree", XII Int. Symp. On Lightning Protection (SIPDA), III-3, Belo Horizonte, Brazil (2013-10).

[3] M. Ishii, M. Saito, T. Sonehara, "Downward lightning hitting Tokyo Skytree observed by high-speed camera", IEE of Japan Trans. P&E, Vol. 134, No. 1, pp. - (2014-1) (in Japanese).

[4] D. Tanaka, T. Miki, M. Miki, T. Shindo, A. Asakawa, H. Motoyama, M. Saito, M. Ishii, A Kumada, K Hidaka, "Optical observation of the lightning strikes to TOKYO SKYTREE using consumer digital camera", IEEJ Joint Technical Meeting on Electrical Discharges, Switching and Protection, and High Voltage Engineering, ED-13-148/SP-13-71/HV-13-109, Kagoshima, Japan (2013-11) (in Japanese).

[5] M. Saito, M. Ishii, F. Fujii, M. Matsui, "Seasonal Variation of Frequency of High Current Lightning Discharges Observed by JLDN", IEE of Japan Trans. P&E, Vol. 132, No. 6, pp. 536-541 (2012-6).