Observation of Downward and Upward Lightning Flashes at 634-m Tower

Masaru ISHII [1,*], Mikihisa SAITO [2], Toru MIKI [2], Daiki TANAKA [2], Takatoshi SHINDO [2], Akira ASAKAWA [2], Hideki MOTOYAMA [2], Takeo SONEHARA [3], Yusuke SUZUHIGASHI [4], Hiroshi TAGUCHI [4]

1. The University of Tokyo, Tokyo, Japan
2. CRIEPI, Tokyo, Japan
3. Shoden Co., Tokyo, Japan
4. Tobu Tower Skytree Co., Tokyo, Japan

ABSTRACT: Tokyo Skytree is a 634-m high freestanding broadcasting tower in Tokyo, Japan. Direct observation of lightning current by using Rogowski coils started in February 2012. By the end of 2013, currents associated with 24 lightning flashes which hit the tower were recorded. In 2012, most of the flashes were upward as was expected; however, in 2013, most of the flashes observed in summer were downward. Ten downward negative first strokes were optically observed by a high-speed camera.

INTRODUCTION

Tokyo Skytree was constructed on a flat terrain about 8 km inland in Tokyo, Japan (35.71ºN, 139.81ºE). A pair of Rogowski coils were designed to observe high frequency components (1.5 kHz~ 5 MHz) and low frequency components (0.5 ~ 250 kHz) and were installed at a height of 497 m of the 634-m tower [Miki et al. 2012]. Lightning channels attached to the tower have been observed by a high-speed camera with 5627 fps from August 2012 [Ishii et al. 2014]. Lightning electromagnetic pulse (LEMP) waveforms are observed at three stations at 27 km, 57 km and 101 km from the tower. As of December 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 is reported on.

OBSERVED LIGHTNING CURRENTS

Tables 1 and 2 are the list of recorded lightning currents by the Rogowski coils. Existence of ICC (initial continuous current) and the rising part of waveforms of first return stroke currents are used to identify whether they were upward or downward flashes. Flash 2013-4 in Table 2 was presumably a subsequent stroke of a downward flash having multiple terminations.

* Masaru ISHII, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan 113-8656; ishii@iis.u-tokyo.ac.jp

In 2012, most of the flashes hit the tower were upward as had been expected. In 2013, among the recorded 17 flashes, all the 12 flashes in July and August, the warmest months in Tokyo, were negative downward flashes. Regarding occurrence of upward flashes, the altitude of the freezing level in the atmosphere seems to be influential.

Monthly variation of number of upward and downward flashes is shown in Fig.1. Fig. 2 shows cumulative frequency probabilities of altitudes of −10˚C for these upward and downward flashes. The −10˚C levels, where the lower charge center frequently exists in thunderclouds, are estimated from aerological data available twice a day at Tateno observatory, 48 km northeast from the tower. The two distributions for upward and downward flashes in Fig 2 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.

There is a report on the seasonality of characteristics of downward flashes, determined from the frequency of high-current flashes in each polarity [Saito et al. 2012]. In summer months, densities of negative high-current downward flashes are higher than high-current positive downward flashes. The

Table 1 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 2 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.

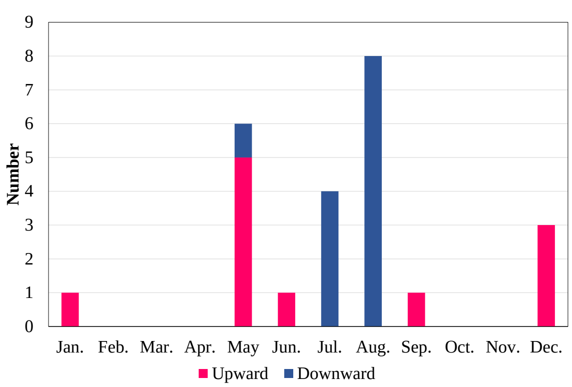


Fig. 1 Monthly variation of number of flashes hitting Tokyo Skytree

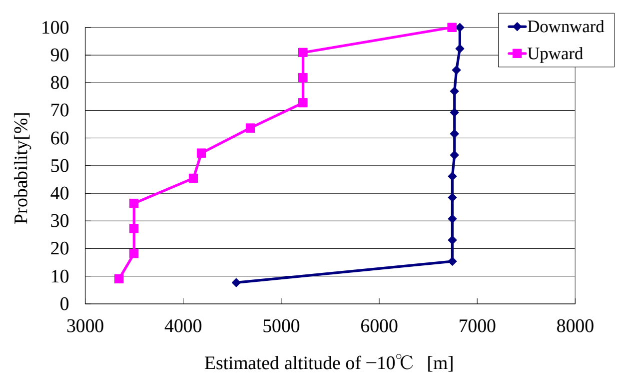
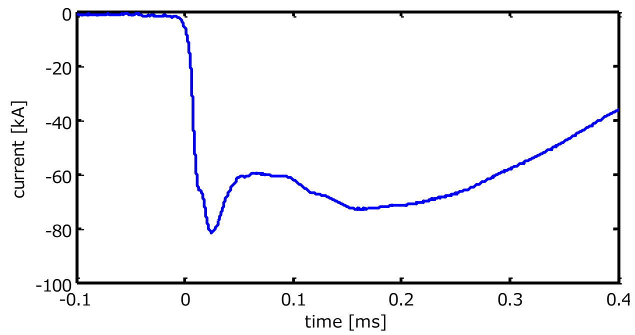
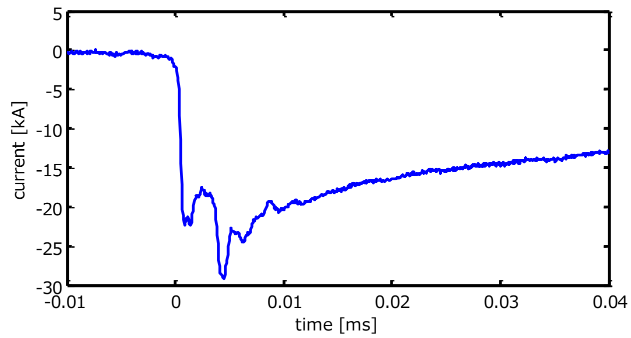


Fig. 2 Difference of cumulative frequencies of −10˚C altitude depending on the type of flashes when they hit the tower.



(a) First return stroke



(b) Second return stroke

Fig. 3 Current waveforms of return strokes in negative downward flash (Flash 2013-7).

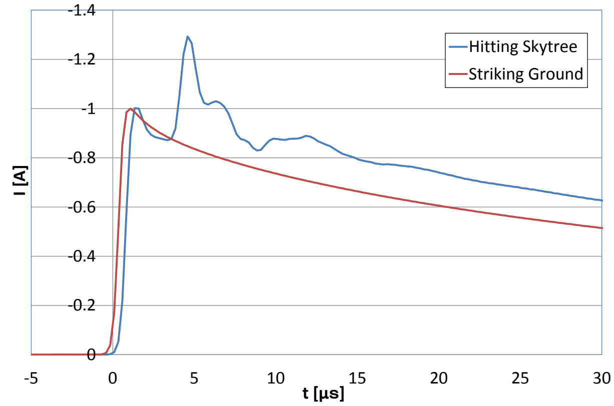


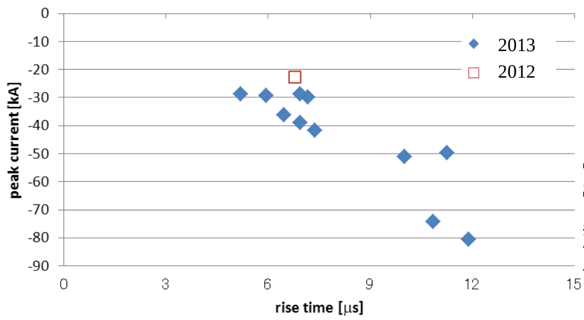
Fig. 4 Calculated current waveforms of subsequent return strokes hitting 634-m tower or ground by using an electromagnetic model of return stroke.

lower limit of the monthly averaged altitude of −10ºC for summer months was reportedly 5.7 km, which agrees to the boundary of the height of −10ºC altitude seen in Fig. 2.

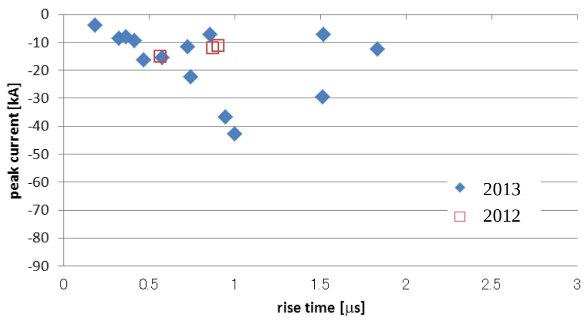
Fig. 3 shows examples of return stroke waveforms of a negative downward flash. The current waveform of a first return stroke is hardly influenced by the tower due to its slow rise. Current pulses before the onset of first return strokes, associated with steps of downward stepped leaders, are hardly visible at the vertical scale of Fig. 3.

All the current waveforms of subsequent strokes have characteristic oscillation at their wave fronts as seen in Fig. 3(b). By using an electromagnetic model, the current waveform to be observed at 497 m of the tower is calculated by postulating a smooth triangular subsequent-stroke current which would be the waveform if the same stroke directly hits ground [Saito et al. 2014]. The model of the tower is composed of thin wires having discontinuity of structure only at the 497-m point. Both the smooth waveform and calculated current waveform are shown in Fig. 4. In the model, multiple reflections of current waves occur at only three points, namely at the tower top, 497 m and bottom, nevertheless, the calculated current waveform to be observed at the 497-m point reproduces the observed waveform in detail. This result justifies the postulation in the electromagnetic model, and it is known that the peak current of a subsequent return stroke observed at the 497-m point is enhanced about 30% compared to the case when the same stroke directly hits ground.

Fig. 5 shows relationships between the rise time and the initial current peak for negative first return strokes and subsequent strokes of downward flashes. There is distinct difference in the rise times of first and subsequent return strokes. Positive correlation seems to exist between the rise time and the initial peak



(a) First strokes



(b) Subsequent strokes

Fig. 5 Distribution of rise time and peak current.

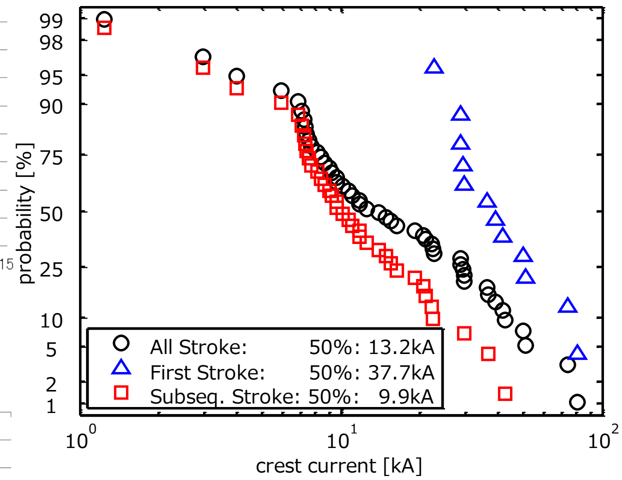


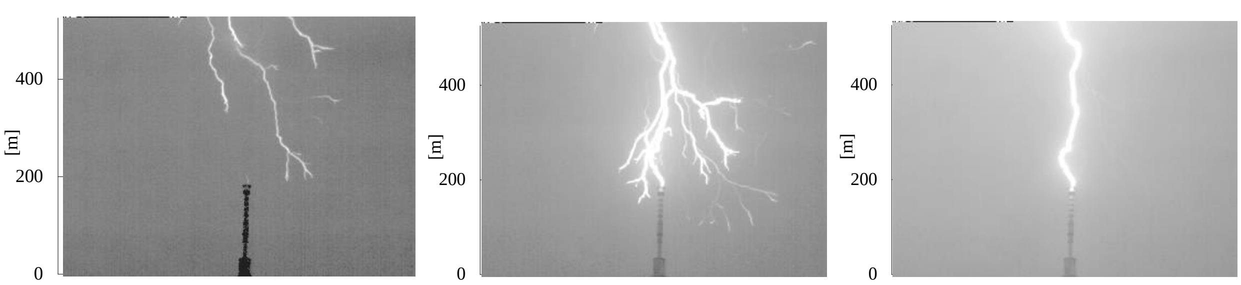
Fig. 6 Cumulative distribution of peak currents of negative downward flashes.

of first return stroke currents.

Fig. 6 shows cumulative distributions of peak currents. There also is clear difference between first and subsequent strokes. The geometric mean of subsequent stroke currents is similar to other observations, however, that of first strokes is larger than 25 -30 kA at other observations.

OPTICAL IMAGES

Ten negative downward flashes were imaged by the high-speed camera in summer of 2013. In the 7 cases, upward connecting leaders were imaged, but except one case, upward leaders extended more than 300 m and the connection points with downward stepped leaders were outside of the field of view. In the three cases, upward connecting leaders were not imaged due to poor visibility. Examples of images for Flash 2013-7 are shown in Fig. 7.



(a) Frame 1789 (8 frames (1.4 ms) before the RS).

(b) Frame 1796 (1 frame (0.2 ms) before the RS)

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

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

In Fig. 7(a), an upward connecting leader of about 30 m in length emerged from the top of the tower. At this time, the current was too small to be detected. After 1.2 ms, in Fig. 7(b), the bright upward leader with branches extended up beyond the field of view of the camera. At this time, the length of the upward leader already exceeded 350 m. Connection occurred in 180 μs and the next frame, not shown here, whited out. Fig. 7(c) is an image of the return-stroke channel about 1 ms after the occurrence of connection, and it is known that the connection point of upward and downward leaders was outside of the field of view.

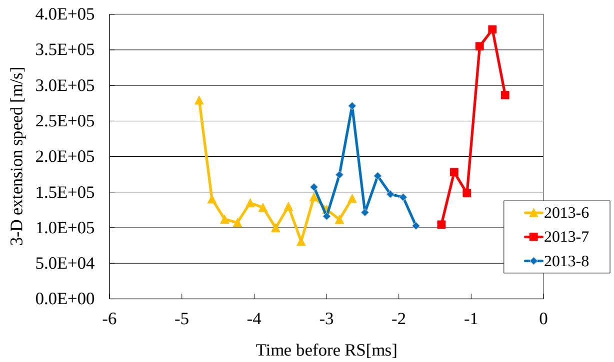


Fig. 8 Time-variation of 3-D velocities of upward leaders before onset of return strokes.

In some cases, 3-D structures of the channel were known from images of a low frame-rate camera in a different direction, and 3-D velocities of upward leaders are available. Relationship between the time before connection and the 3-D velocity of upward leaders for Flashes 2013-6, -7, and -8 are shown in Fig. 8. It was reported that upward leaders accelerate when they get close to downward leaders [Lu et al. 2013, Warner 2010]. Such tendency was seen at Flash 2013-7, which is the only case where behavior of the tip of the upward leader was observed until 1ms or less before connection of leaders. At Flashes 2013-6 and -7, the velocities of upward leaders were about 1 to 1.5 x 10^5 m/s and rather stable until about 2 ms before connection.

CONCLUSIONS

Currents and images of upward and downward lightning flashes striking a 634-m tower in Tokyo, Japan have been observed by Rogowski coils and high-speed cameras since 2012. By the end of 2013, 27 flashes striking the tower were confirmed, and current waveforms of 24 flashes were recorded. 3 out of 24 flashes were upward bipolar flashes initiated by positive upward leaders, and the rest were negative flashes. Of the 27 confirmed flashes, negative downward flashes were 14, and their occurrence condition is discussed. Among them, 7 upward connecting leaders preceding first return strokes were optically observed. The recorded highest current, -81 kA, was associated with the first stroke of a negative downward flash.

REFERENCES

Ishii, M., M. Saito, T. Miki, D. Tanaka, T. Shindo, A. Asakawa, H. Motoyama, Y. Suhigashi, and H. Taguchi, 2014: Observation of lightning at Tokyo Skytree, in *Proceedings*, 23rd Int. Lightning Detection Conference (ILDC), Tucson, AZ, U.S.A.

Lu, W., L. Chen, Y. Ma, V. A. Rakov, Y. Gao, Y. Zhang, Q. Yin, and Y. Zhang, 2013: Lightning attachment process involving connection of the downward negative leader to the lateral surface of the upward connecting leader. *Geophys. Res. Lett.*, **40**, 5531–5535, doi:10.1002/2013GL058060.

Miki, T., T. Shindo, A. Asakawa, H. Motoyama, M. Ishii, M. Saito, Y. Suzuhigashi and K. Fukuda, 2012: Lightning current observations at TOKYO SKYTREE, in *Proceedings*, CIGRE C4 Colloquium, Hakodate, Japan, V-5.

Saito, M., M. Ishii, F. Fujii and M. Matsui, 2012 : Seasonal Variation of Frequency of High Current Lightning Discharges Observed by JLDN. *IEE of Japan Trans. P&E*, **132**, 536-541.

Saito M., M. Ishii and A. Sugita, 2014 : Comparison of directly measured current and JLDN data associated with lightning strokes hitting Tokyo Skytree, in *Proceedings*, 23rd Int. Lightning Detection Conference (ILDC), Tucson, AZ, U.S.A.

Warner, T. A., 2010 : Upward leader development from tall towers in response to downward stepped leaders, in *Proceedings*, 30th International Conference on Lightning Protection, Cagliari, Italy