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Comparison of directly measured current and JLDN data associated with lightning strokes hitting Tokyo Skytree

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***Abstract*— Observation of lightning current by using Rogowski coils started in February 2012 at Tokyo Skytree, which is a 634-m high freestanding broadcasting tower in Tokyo, Japan. It was confirmed that more than 20 lightning flashes hit the tower in two years. Directly measured current and estimated current amplitudes of return strokes of upward and downward flashes hitting the tower observed by JLDN (Japanese lightning detection network) are compared. Relationship between reported RNSS (range normalized signal strength) at each sensor of JLDN and the directly measured current differs from stroke to stroke. The causes of the differences are investigated.**

Keywords*— *lightning current; tall structure; LEMP; LLS; NEC-4

I. INTRODUCTION

TOKYO SKYTREE® is a 634-m high freestanding broadcasting tower in Tokyo, Japan (35.71N, 139.81E) [1]. Because of its height, lightning was expected to strike the tower frequently. It was confirmed that at least 20 lightning flashes hit the tower in two years from 2012 to 2013[2]. This paper reports on comparison of the directly measured lightning current and estimated current data observed by LLS (lightning location system) manufactured by Vaisala Co. 15 negative flashes including 47 return strokes are subject to analysis.

Because the velocity of a current wave in the 634-m tower is the speed of light, electromagnetic fields associated with lightning strokes hitting the tower are more intense than those radiated from strokes directly attach to ground; thus, peak currents estimated by LLS are larger than those of directly measured current. The relationship between the estimated and measured peak values of lightning currents is investigated with the help of numerical electromagnetic analysis employing an electromagnetic model of a return stroke. Numerical Electromagnetics Code (NEC-4) based on the method of moments [3] is used for the analysis.

II. OBSERVATION

For observation of lightning current, two Rogowski coils designed for high frequency components (1.5 kHz~ 5 MHz) and low frequency components (0.5 ~ 250 kHz) were installed at a height of 497 m of the tower in the end of February 2012. Current records of 47 negative return strokes associated with 4 upward and 11 downward lightning flashes observed in 2012 and 2013 are compared with the data observed by LLS.

Analyzed LLS data were obtained by Japanese Lightning Detection Network (JLDN) [4], which is a large-scale single lightning detection network operated by Franklin Japan Co. JLDN consisted of 10 IMPACT-ESP, 9 LPATS-IV and 11 LS7001 sensors as of 2011.

Table 1 shows numbers of lightning strokes detected by JLDN. Strokes with location errors less than 2 km and time difference within few milliseconds are classified as ‘Detected’. First return strokes of downward are defined “first strokes” in the table. All the return strokes included in upward flashes are grouped into “subsequent strokes”. One of the undetected first strokes and the undetected subsequent stroke had current amplitudes smaller than 5 kA in absolute values. Another undetected first stroke was not detected because of simultaneous in-cloud discharges. The last one undetected first stoke had a location error larger than 2 km.

Table 1 Observation of lightning strokes hitting Tokyo Skytree by JLDN.

	First stroke	Subsequent stroke
Detected	8	35
No data	3	1
Total	11	36

Fig.1 shows relationships between directly observed and estimated peak currents for 40 negative return strokes. 3 data among the 43 detected strokes are lost due to saturation of the current observation system. The estimated values are consistently higher than the directly observed current peaks.

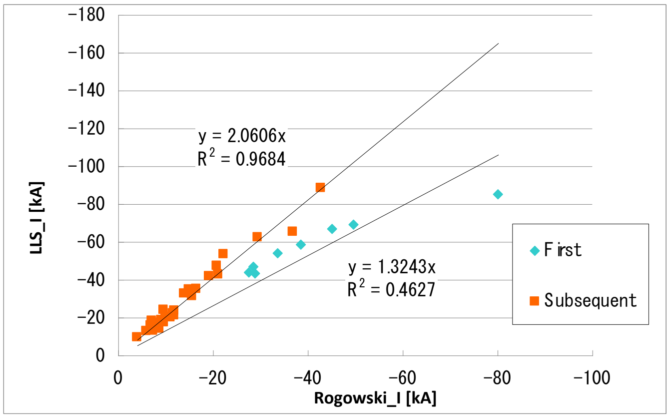


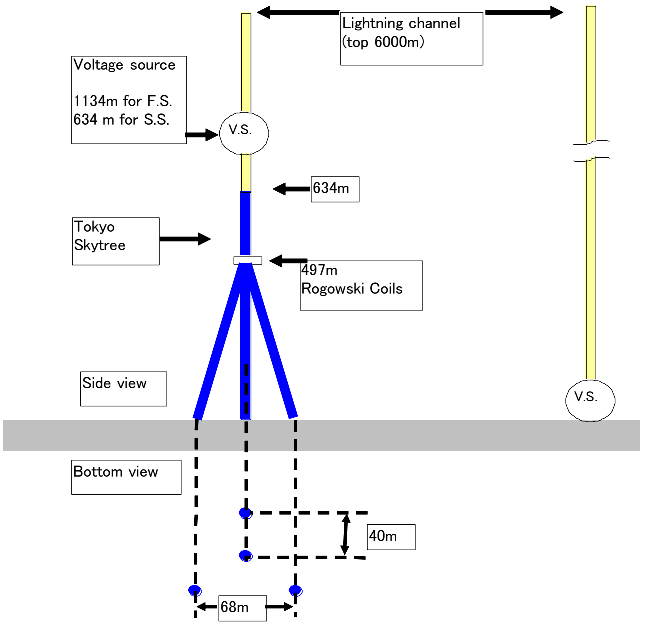
Fig. 1 Relationship between directly observed and estimated peak currents of lightning strokes.

III. NUMERICAL ANALYSIS OF ELECTROMAGNETIC FIELD WAVEFORMS

Since the velocity of a current wave in a tower is the speed of light, electromagnetic fields associated with return strokes hitting a tall structure are more intense than those radiated from strokes directly connected to ground. The electromagnetic fields associated with lightning strokes hitting Tokyo Skytree are numerically reproduced by using NEC-4.

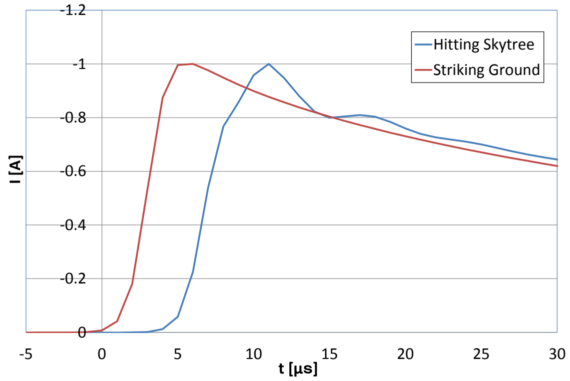
The tower is modeled by three inclined thin wires of 0.01 m radius and a vertical wire of the same radius at the center on perfectly conducting ground [5] as shown in Fig. 2(a). The vertical lightning channel is represented by an electromagnetic model, composed of a thin wire having the radius of 0.01 m and loaded by distributed resistance and inductance of 0.3 Ω/m and 6 μH/m, respectively. The apparent propagation velocity of the current wave on the model lightning channel is about 0.5c with these parameters [6].

A voltage source (V.S.) placed at heights of 1134m for first strokes and 634m for subsequent strokes generates a step-like voltage expressed by Heidler function, having a rise time of 4 μs for first strokes and 1 μs for subsequent strokes. The position of the voltage source for the case of first strokes is determined based on optical observation, which revealed that the lengths of upward connecting leaders extending from the tower top are generally longer than 400 meters [7]. The model of downward lightning strokes directly hitting ground is shown in Fig. 2 (b). This model consists of a vertical lightning channel and a voltage source at the ground level, having the same properties as those of Fig. 2 (a). These models well reproduce observed current and electromagnetic field waveforms [5][6].

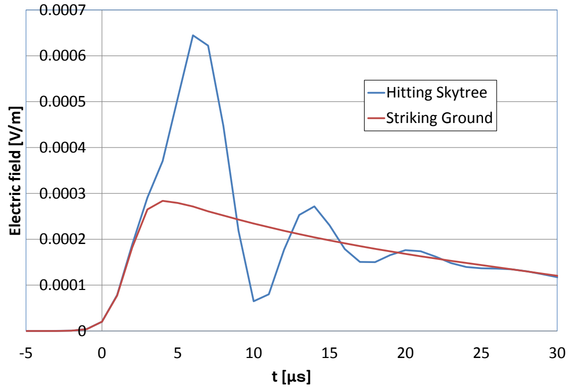


(a) Return strokes attached to the tower (b) lightning striking ground

Fig. 2 Numerical models for electromagnetic analysis.

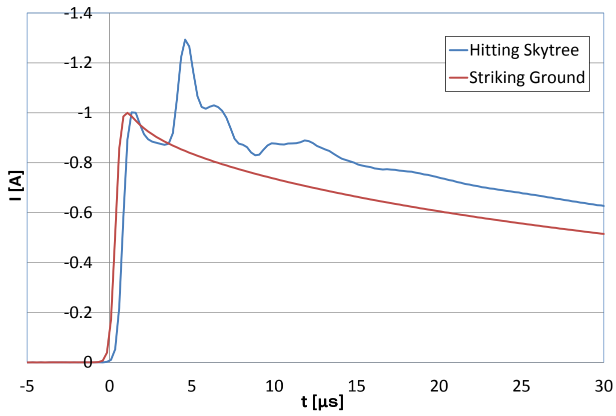


(a) Current waveforms of first return strokes

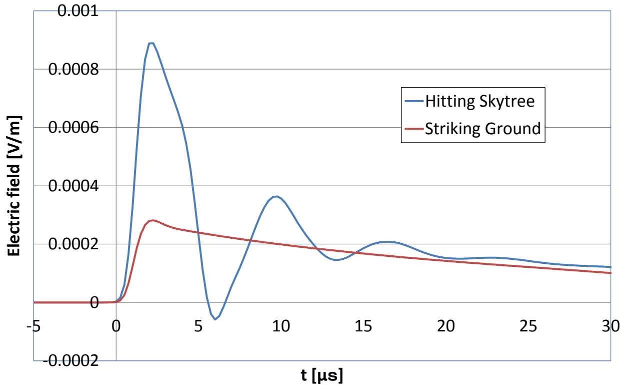


(b) Electric field waveforms associated with first return strokes at a distance of 100 km from the sources.

Fig. 3 Calculated current and electric field waveforms of first return strokes hitting 634-m tower or ground



(a) Current waveforms of subsequent strokes.



(b) Electric field waveforms associated with subsequent return strokes at a distance of 100 km from the sources.

Fig. 4 Calculated current and electric field waveforms of subsequent return strokes hitting 634-m tower or ground

Calculated currents and associated electric field waveforms at a distance of 100 km for first return strokes having the same normalized peak currents hitting the 634-m tower or ground are shown in Fig. 3. Since the upper frequency limit of a sensor of LLS is several hundred kHz, the electric field waveforms shown in Fig. 3 (b) are filtered by 400 kHz LPF (low pass filter). The calculated current waveform on the tower is that to be observed by the Rogowski coil installed at 497 m. Fig. 4 shows the same sets of waveforms for subsequent return strokes.

As seen in Figs. 3 and 4, magnitudes of the first peaks of electric field waveforms are quite different depending on the attachment point of return strokes for the same magnitude of observed peak currents. The electric field peak for the model first stroke hitting the tower is 2.3 times of that directly attaches to ground, and is 3.2 times at model subsequent strokes.

From Fig. 1, it is known that the average current peaks estimated by LLS are about 1.3 times (first strokes) and 2.1 times (subsequent strokes) of directly measured values. By eliminating the maximum datum of first strokes, the ratio for first strokes increases to 1.5. These values are about 35% smaller than the ratios obtained at the calculated model cases of Figs. 3 and 4.

Similar tendency was reported on for lightning currents observed at wind turbines on the coast of the Sea of Japan [8] and at Gaisberg tower in Austria [9]. In these datasets, estimated lightning current peaks by LLS are about 20% smaller than the direct measurements. Such tendencies may be attributed to different ground conductivities, tortuous lightning channels or the velocity of return-stroke current.

To compare the cases with wind turbines with the case of the 634-m tower, numerical electromagnetic analysis for a wind turbine of 75 m in height of the tip of the blade was carried out with a model shown in Fig. 5, simulating an instrumented wind turbine with a Rogowski coil installed at the bottom of the supporting tower [10]. Only the cases of a subsequent return stroke is analyzed for the model of a wind turbine. The analyzed model of the wind turbine is a vertical single thin wire of 0.01 m radius on perfectly conducting ground. The model of the lightning channel is the same as that in Fig. 2.

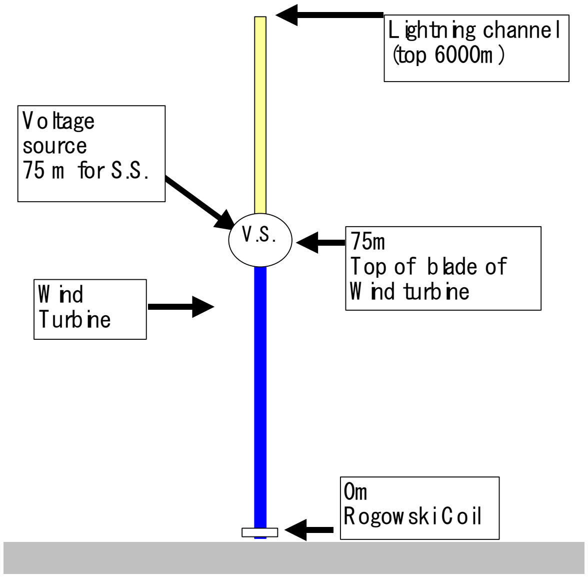
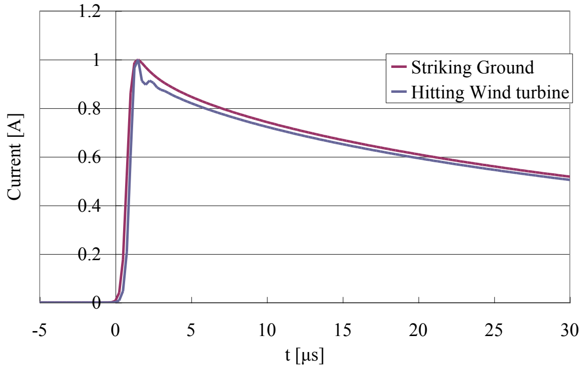
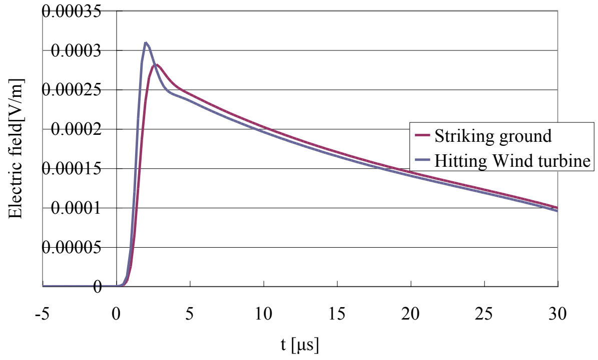


Fig. 5 Numerically analyzed models for the 75-m high wind turbine.

Calculated current and electric field waveforms at a distance of 100 km are shown in Fig. 6. In the same figure, calculated waveforms when a subsequent stroke having the same peak current is directly attached to ground are also shown for comparison. The peak of the electric field of a subsequent stroke hitting the wind turbine is about 10% higher than that associated with a stroke striking ground. Thus, the apparent 20% difference between the measured peak current and the estimated current by LLS at wind turbines in Japan can be interpreted that the estimated peak currents by LLS are actually about 30% smaller than the calculated values.



(a) Current waveforms of subsequent strokes



(b) Electric field waveforms associated with subsequent return strokes at a distance of 100 km from the sources.

Fig. 6 Calculated current and electric field waveforms of subsequent return strokes hitting a 75-m wind turbine or ground

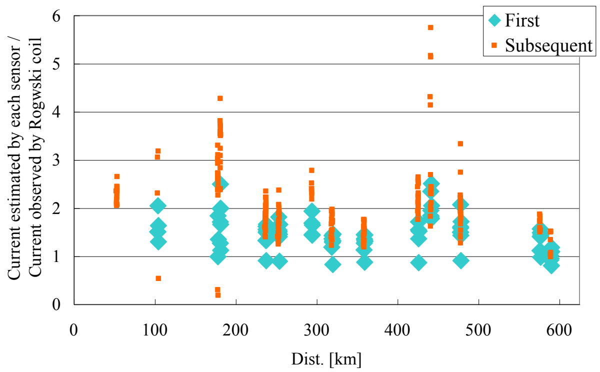
IV. ATTENUATION OF ELECTROMAGNETIC FIELD

LLS manufactured by Vaisala Co. used to employ Eq. (1) to estimate lightning peak current from observed peak of LEMP [9]:

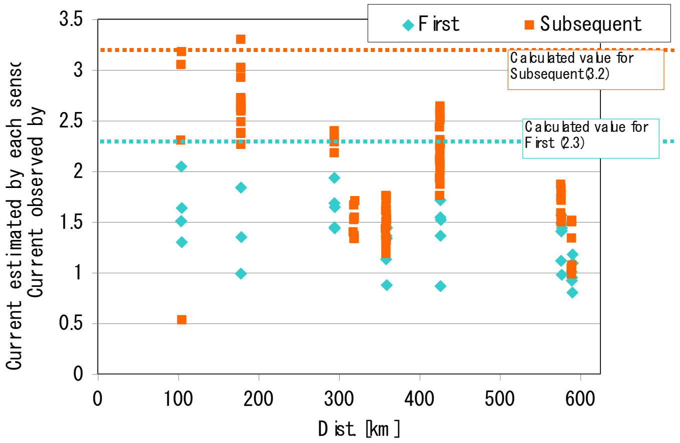
$$I\,[\mathrm{kA}] = 0.185 \times ss \times \left(\frac{r}{100}\right)^{b} \times \exp\left(\frac{r-100}{L}\right) \quad (1)$$

where ss is the observed signal strength in "LLP unit", r is the distance in km between a sensor and estimated location of a lightning stroke, and b and L are parameters to compensate attenuation of electromagnetic ground wave due to finite ground conductivity. At JLDN, b=1 and L=1000 are employed, which are default values of the system based on observation results in North America. Estimated lightning peak currents reported by JLDN are averages of reported values of participating sensors within 625 km from located lightning strokes.

To investigate the aspect of attenuation of LEMP around Tokyo due to finite ground conductivity, lightning data produced by return strokes which hit the 634-m tower are examined. Relations between the distance and the ratio of estimated peak current to directly measured peak current at each sensor are shown in Fig. 7. Fig. 7 (a) shows all the available data for 14 sensors. Dispersion of the ratio is large. This result may be influenced by detection of wrong peaks of LEMP. So, data of LS and IMPACT sensors for selected lightning strokes which were located by using both angle and timing information are shown in Fig. 7 (b). Dotted lines indicate calculated ratios by using model current waveforms shown in Figs. 3 and 4.



(a) All data (LS, IMPACT and LPATS sensors)



(b) Data of LS and IMPACT sensors for selected return strokes which were located by using information of both angle and timing.

Fig. 7 Relation between distance to a sensor and ratio of estimated peak current to directly observed peak current at each sensor.

From Fig. 7 (b), it is clear that the ratio decreases with the distance, which indicates that compensation of attenuation of LEMP depending on the distance is insufficient. This means that attenuation of LEMP around Tokyo is severer than in the environment which produced b=1 and L=1000 in Eq. (1). Severer attenuation can be compensated by reducing the value of L, if Eq. (1) is kept used.

The average number of JLDN sensors used for locating lightning strokes to wind turbines is 6.7, and is 10.7 for lightning strokes hitting the 634-m tower. This means that more attenuated signals are employed to estimate the peak lightning currents at the 634-m tower, which increases the difference between the estimated and measured peak currents than for those observed at wind turbines. Therefore, 35 % difference and 20% difference between the estimated and measured peak lightning currents at the 634-m tower and at wind turbines are consistent.

V. DISPERSION OF RATIO OF ESTIMATED PEAK CURRENT TO MEASURED PEAK CURRENT

Fig. 7 (b) still shows large dispersion of the ratio of estimated peak current to measured peak current, even for subsequent strokes. To investigate the cause of the large dispersion, data of two flashes which include multiple subsequent return strokes are chosen. Flash-1 (201205180143) was an upward negative flash including 6 subsequent strokes. Flash-11 (201308211629) was a downward negative flash including 1 first stroke and 6 subsequent strokes.

Fig. 8 shows the data for the two flashes, which is a part of Fig. 7 (b). Not all the strokes were detected by each sensor. On the average, data of Flash-11 show larger ratios than those of Flash-1, which can be attributed to different geometry of lightning channels. Dispersions by strokes of the same flash, which have the same channel geometry, are attributed to variation of the velocity of return-stroke current of individual subsequent strokes of the same flash.

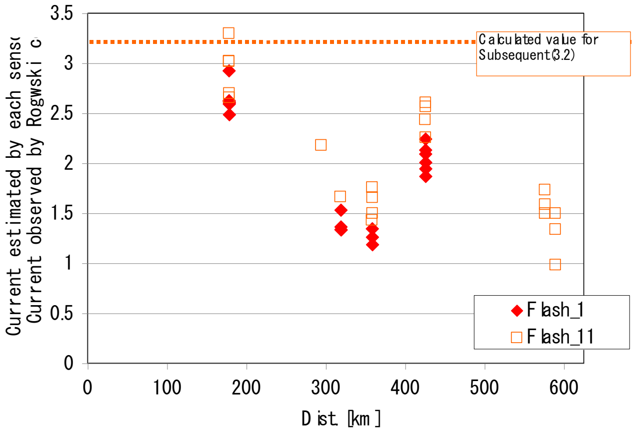


Fig. 8 Ratios of estimated to measured peak current for two flashes extracted from Fig. 7 (b).

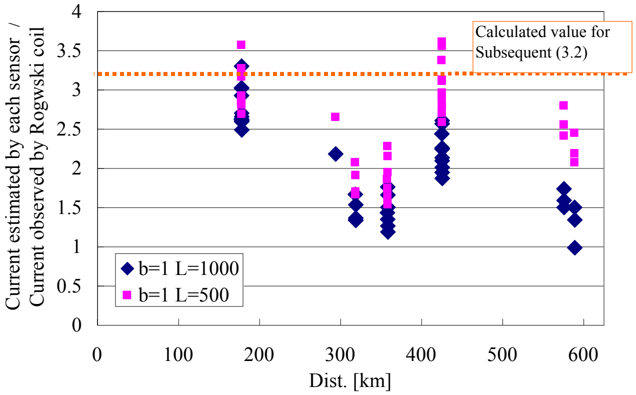


Fig. 9 Different attenuation factor in Eq. (1) is given to data of Fig. 8.

Result of compensation of attenuation is shown in Fig. 9 by using the same data in Fig. 8. In this figure, both cases for L=500 and L=1000 by using Eq. (1) is shown. Attenuation in larger distances can be compensated by applying a smaller value of L in Eq. (1), but dependence of attenuation on direction seems to exist.

VI. CONCLUSION

Lightning return-stroke currents estimated by LLS and those directly observed at Tokyo Skytree in 2012 and 2013 are compared. Electromagnetic field waveforms generated by return strokes attached to the 634-m tower are reproduced by numerical electromagnetic analysis by using NEC-4. Estimated current values by LLS are about 35% lower than calculated values based of the directly measured currents. This result is consistent with the difference between estimated and measured return stroke currents observed at wind turbines during winter, if the attenuation of LEMP in Japan is severer than the default setting to estimate peak currents from electromagnetic field peaks. Other causes of dispersion of lightning peak currents estimated by individual sensors are also discussed.

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