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Estimating lightning current moment waveforms from satellite optical measurements

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[1] From July 2004 to June 2007, the FORMOSAT-2/ISUAL spectrophotometer and Duke magnetometer observed clear optical and radio signatures of 12 sprite-producing lightning events. In 10 of these, 777.4-nm luminosity normalized to a distance of 3000 km was almost linearly correlated with current moment with a scaling factor of ~0.82 MR/kAkm. This finding provides a possible new way to remotely measure lightning current moment, which is critical for understanding the production of sprites, through satellite-based optical measurements. The remaining 2 events had anomalously large scaling factors of ~3 and ~8 MR/kAkm. The concurrent images showed two coincident bright cores of lightning, which suggests complex in-cloud lightning processes may sometimes affect the optical-radio relationship. **Citation:** Adachi, T., S. A. Cummer, J. Li, Y. Takahashi, R.-R. Hsu, H.-T. Su, A. B. Chen, S. B. Mende, and H. U. Frey (2009), Estimating lightning current moment waveforms from satellite optical measurements, *Geophys. Res. Lett.*, *36*, L18808, doi:10.1029/2009GL039911.

1. Introduction

[2] Sprites are one of several kinds of high altitude transient luminous events (TLEs) that occur above active thunderstorms. It is now broadly accepted that the quasi-electrostatic field induced by lightning is the driving force of sprites [*Pasko et al.*, 1997]. More recently, the role of transients in lightning such as M-component process has also been suggested [e.g., *Asano et al.*, 2009]. To clarify electrodynamic coupling processes between sprites and lightning, past experimental studies inferred lightning charge moment change (the product of the thundercloud charge transfer and its altitude) that is linearly correlated with high altitude quasi-electrostatic field. Two different estimation techniques have been used: the sferic analysis [e.g., *Cummer and Inan*, 1997; *Cummer and Inan*, 2000] and the Schumann resonance analysis techniques [e.g., *Burke and Jones*, 1992; *Huang et al.*, 1999]. These techniques have shown thresholds of sprite production of 600–1000 C km that are roughly consistent with theoretical predictions. It was found in some cases, however, that sprites were produced by lightning with extremely small charge moment changes [e.g., *Cummer*, 2003]. More detailed analysis of optical and electromagnetic data are required to fully understand the lighting-sprite coupling processes.

[3] The ISUAL payload on FORMOSAT-2 satellite comprehensively measures the optical characteristics of sprites and lightning occurring all over the world. It provides precise spectral observations from which one can derive the electron energies and electric fields in sprites [e.g., *Adachi et al.*, 2006]. The optical emission of cloud illumination was also used to infer lighting processes [e.g., *Frey et al.*, 2005]. Furthermore, by combining the total charge moment change derived from Schuman resonance radio signatures with photometric behavior observed by the ISUAL, *Adachi et al.* [2008] derived the lightning current moment changes and found their strong relations with the production of halos and/or sprites. These studies are based on an assumption that the optical signature of cloud illumination is a good qualitative/quantitative indicator of electrical property in lightning [e.g., *Campos et al.*, 2009, and references therein]. In support of this assumption, *Cummer et al.* [2006] found strongly-correlated behaviors in ISUAL photometric and ULF magnetic field signatures in two lightning events. From a statistical viewpoint, however, the optical-radio correlations were never tested in sprite-producing lightning, and this is the purpose of the present study.

2. Instrumentation and Observation

[4] FORMOSAT-2/ISUAL spectrophotometer data and Duke magnetometer data were analyzed to infer the optical emission intensity and current moment in sprite-producing lightning, respectively. The FORMOSAT-2 satellite flies on a sun-synchronous (9:30–21:30 LT) polar orbit at an altitude of 891 km and carries a scientific payload named ISUAL [*Chern et al.*, 2003]. ISUAL consists of an imager with a six-color filter wheel, a six-color spectrophotometer (SP) and a dual-color array photometer (AP). It observes lightning and TLEs in the Earth's limb direction and, for the first time, reveals their global distributions [*Chen et al.*, 2008] with precise spectral information [e.g., *Adachi et al.*, 2008]. In the present study, ISUAL SP data were used to derive the optical emission intensity of lightning. The SP consists of six channels that cover different wavelength ranges, and channel 5 (SP5: 774–785 nm) primarily observes the lightning atomic oxygen emission line at 777.4 nm critical for this analysis. All photometer channels have a 5 degree (vertical) × 20 degree (horizontal) field-of-view with a

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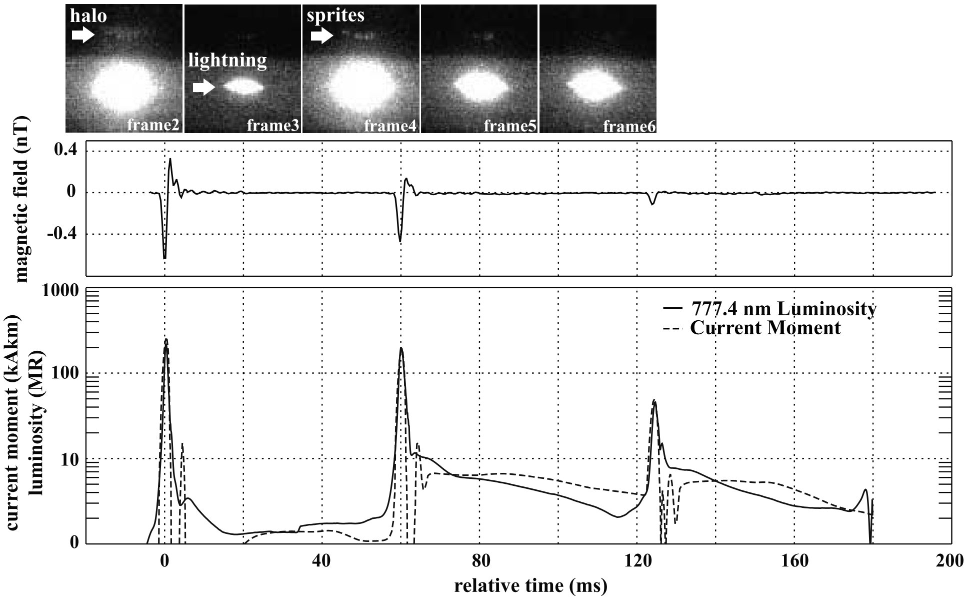

Figure 1. Typical sprite-producing lightning event observed at 06:32:28 (UT) on 13 August 2006. (top) ISUAL successive images of lightning and sprites. (middle) Magnetic field fluctuations observed at Duke University. (bottom) Comparison of 777.4-nm luminosity and current moment change in lightning.

temporal resolution of 100 μs. From the analysis of ISUAL AP data (not shown here), it was found that the contribution of sprite emission was less than 1% in the SP5 data. Careful examinations of noise level show that the minimum reliable amplitude of luminosity probably is a few MR. The other data used here were recorded by two orthogonal magnetometers continuously operated at Duke University (35.975 N, 79.100 E) that measure the magnetic field fluctuations caused by lightning. The coils span the frequency range from 0.1 Hz to 500 Hz so that slowly varying continuing currents could be reliably measured [*Cummer and Fullekrug*, 2001]. GPS timing provides the accuracy needed to identify with certainty the ISUAL-detected events. By analyzing the magnetic field data, we derive the vertical current moment change of causative lightning [*Cummer and Inan*, 2000] with time resolution limited by the bandwidth of the sensors used. Here, the minimum reliable amplitude in this study is probably 2–5 kAkm. Careful analysis shows that the current moment waveforms extracted through this approach are effectively filtered with a second order low pass 350 Hz filter so that narrow pulses are effectively widened to approximately 2 ms. This minimum time scale plays an important role in the comparison below.

[5] During the period from 4 July 2004 to 23 June 2007, 72 sprite events were observed by ISUAL within the detection coverage of Duke magnetometer and 12 of these events had sufficient quality in both the SP5 data and magnetometer data. The location of each lightning event was estimated from imager data by calculating the three-dimensional vectors of line-of-sight to the cloud illumination and by assuming the height of cloud illumination to be 10 km with an error of ±5 km. The location errors due to the accuracies in the vector calculation and the cloud height assumption are better than 0.4 degree in longitude and 0.2 degree in latitude, and do not affect the conclusions obtained in this study.

3. Correlations and Consistent Scaling Factor

[6] A typical sprite-producing lightning event observed at 06:32:28 (UT) on 13 August 2006 is shown in Figure 1. Figure 1 (top) show successive images of lightning and TLEs that were captured by ISUAL imager through a broadband red (633–751 nm) filter with an exposure time of 29 ms. The temporal variation of cloud flash illuminated by lightning discharge is roughly seen in these images. In Frame 2, a bright cloud illumination which is probably due to the return stroke and a sprite halo can be identified. The lightning brightness recovered in the next frame and subsequently increased in Frame 4 to a level comparable to the first flash in Frame 2. Structured sprite emissions accompanied the second lightning flash and slowly faded away. Figure 1 (middle) shows the corresponding magnetic field perturbations observed at Duke University. Three lightning sferics occurred at times consistent with the imager data shown at the top. Figure 1 (bottom) compares the temporal evolution of the current moment change calculated from Duke magnetic field data [*Cummer and Inan*, 2000] and the 777.4-nm luminosity observed by ISUAL SP5. For quantitative comparisons, the absolute luminosity was derived by correcting the atmospheric transmittance with MODTRAN-4 model, applying the instrumental functions including the sensitivity and incident angle dependence, and normalizing to a source-observer distance of 3000 km. Here and throughout this work, the optical data were filtered with a 512 points (= 51.2 ms) hamming window for the low amplitude, slowly varying portions to effectively reduce instrumental noise and, then, filtered with an 8 points (= 0.8 ms) hamming window for the entire period to match the time scale of optical and

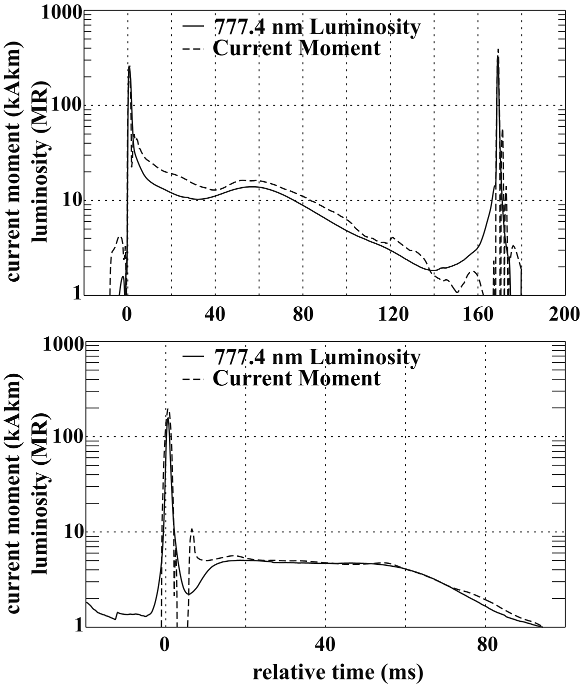

Figure 2. Typical lightning events observed (top) at 04:45:10 on 03 February 2006 and (bottom) at 06:24:32 on 24 August 2005.

radio data. Here, the low amplitude slowly-varying portion was defined as the period at which the time derivatives of luminosity do not exceed those averaged in the background noise by a factor of ten. Because ISUAL observes lightning flash through the high scattering thundercloud, the observed optical emissions would have already been smoothed as much as ~1 ms [e.g., *Koshak et al.*, 1994]. Thus, by applying the additional filter with 0.8 ms hamming window, optical data are effectively widened to ~2 ms in the same way that the extracted current moment waveform is smoothed by the limited sensor bandwidth. In this figure, it is clear that optical emission was well correlated with current moment in both the high amplitude fast portions of the flash (~2 ms time scale, 10s to 100s of kA km) and the low amplitude continuing currents (~100 ms time scale, a few kA km). Some ringing signatures that follow the high-amplitude fast portions in the current moment data are artifacts arising from analysis process and we excluded these periods from calculations of scaling factors described below. Figure 2 shows the comparison of the current moment and optical emissions of another two events observed on 03 February 2006 and 24 August 2005. Here again, 777.4-nm luminosity and current moment were closely correlated in both the fast and slow components.

[7] In order to further confirm the statistical correlation and to test if there is a quantitatively consistent scaling factor in different events, all 12 events were analyzed in the same way. Figure 3a is a scatter plot showing the statistical correlation between luminosity and current moment in 10 typical events. These events were typical in terms of the fact that only one bright core of lightning flash was seen in the imager data in contrast to the remaining 2 outlying cases which had two cores of lightning (see Section 4). Since the temporal resolutions of photometer and magnetometer are different, both data were re-sampled with the same time interval of 50 μs and, then, all the reproduced data points which are larger than the background standard noise level by a factor of two were plotted. It is found that the correlation remains extremely high (r = 0.94) even in a statistical viewpoint with a consistent scaling factor of ~0.82 MR/kA-km derived from least-squares method. Figure 3b shows scaling factors calculated in different amplitude regimes. The average values stay around ~0.82 MR/kA-km with small variations of ±20% which is within the range of standard errors of ±50%. Therefore, we conclude that the lightning luminosity was almost linearly correlated with current moment. These findings enable us to quantify the charge and current transfer characteristics of lightning from satellite-based optical measurements.

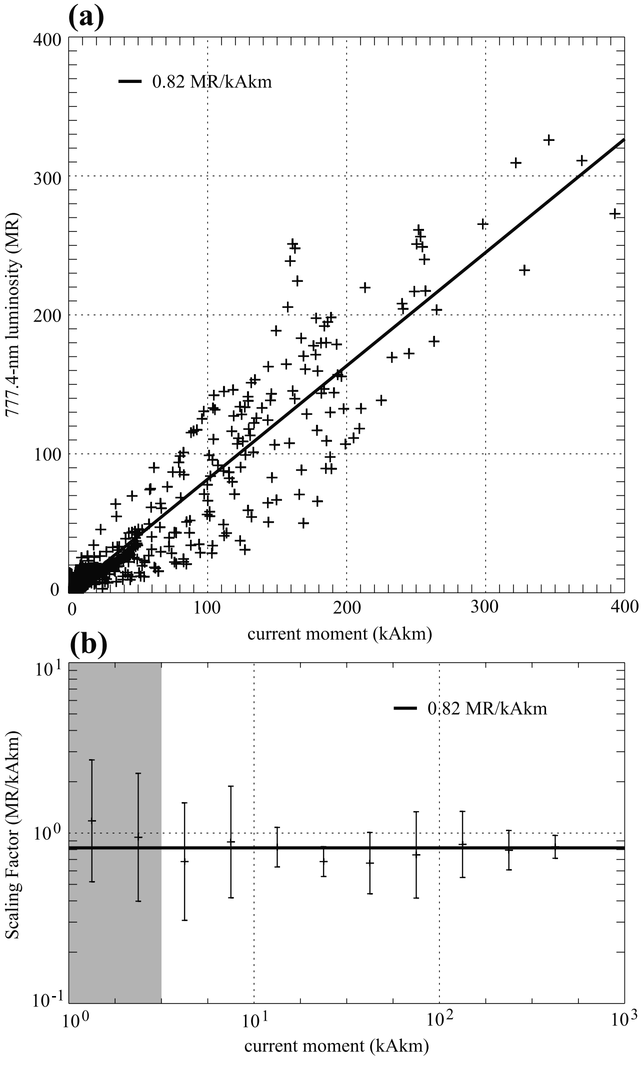

Figure 3. (a) Scatter plot of luminosity vs current moment in 10 typical events. More than ten thousand data points are plotted. (b) Scaling factors calculated in different amplitude regimes. Error bars represent standard deviations. Note that data in grey shaded area would have significant errors since the minimum reliable amplitude in this study is probably 2–5 kAkm.

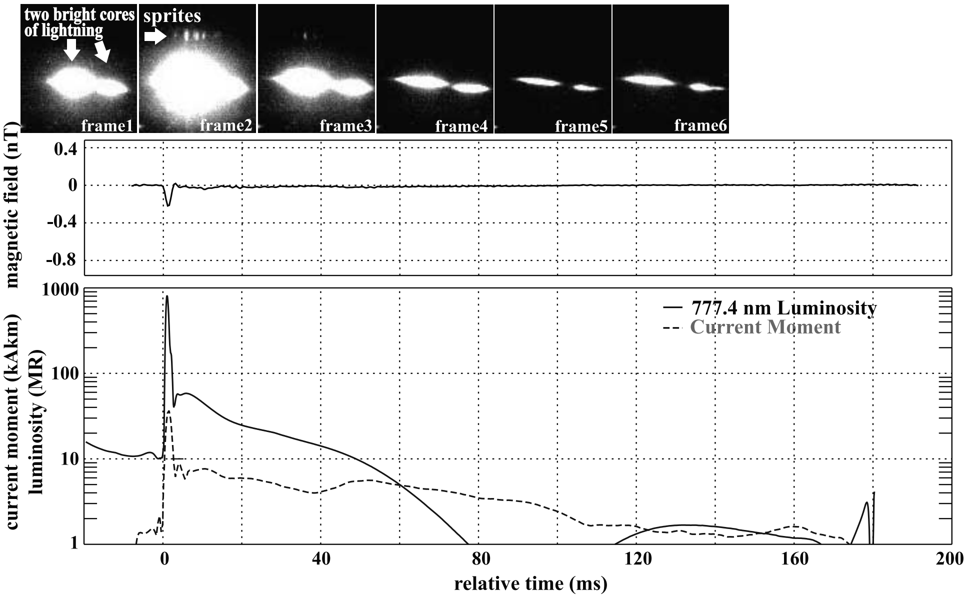

Figure 4. Outlying lightning event observed at 04:56:57 (UT) on 25 February 2007. (top) ISUAL images. Two bright cores of lightning are clearly found in contrast to the simple one bright core in the typical events in Figure 1. (middle) Duke magnetic field data. (bottom) Comparison of luminosity and current moment. This event is optically much "brighter" than the typical events.

[8] In 7 out of 10 typical events, the occurrence time of sprites were precisely determined from the ISUAL AP data (not shown). The estimated delay time t_d, defined as the time difference between the initiation of lighting and sprites, was in the range of 0.8–6.4 ms. The charge moment required for the initiation of sprites was calculated by the time integration of current moment from t = 0 to t_d. Here, the current moment was estimated by the sferics analysis method and the luminosity-current correlation method based on ISUAL SP5 data. Charge moment changes calculated from the magnetic field data were in the range of 200–2200 C-km while those calculated from ISUAL were 220–2200 C-km. The discrepancies in individual event ranged from ~0% (below the analysis errors) to ~40%. It is clear that the results obtained from two methods were consistent with each other and also with past experimental studies [e.g., *Huang et al.*, 1999; *Cummer*, 2003]. Consequently, the new analysis method is a useful way to estimate the current moment waveform and charge moment change of sprite-producing lightning based on satellite optical data alone.

4. Outlying Cases

[9] In two cases, the scaling factors were significantly higher than those found in the other 10. Figure 4 shows one of the outlying lightning events observed at 04:56:57 (UT) on 25 February 2007. This lighting event had two bright cores: a brighter core on the left and a somewhat weaker core on the right. It suggests that this event contained more complicated processes such as ground flash which strikes ground at more than one point [*Kitagawa et al.*, 1962] or significant in-cloud horizontal activity accompanied with vertical ground stroke. The scaling factor was found to be ~8 MR/kAkm, which indicates this was optically much "brighter" than the typical events. The other outlying event (not shown) observed at 04:48:43 (UT) on 06 March 2006 also had a "bright" scaling factor of ~3 MR/kAkm and also exhibited two distinct cores of lightning optical emissions. Since these two events were not extraordinary in terms of the occurrence locations, occurrence period, and source-observer distances in the ISUAL and Duke measurements, the obtained outlying scaling factor is not due to errors in observation and analysis processes.

[10] As the reason for two bright cores of lightning flash as well as the "bright" scaling factors, unusually long or high altitude horizontal components of the overall cloud-to-ground lightning channels are one possible candidate. Since ISUAL observes lightning from space, the optical emissions from horizontal in-cloud channels are brighter than those from low-altitude cloud-to-ground channel that are more severely attenuated by thick atmosphere and thundercloud. On the other hand, the horizontal in-cloud components of the overall channels are not discernible in the Duke magnetometer, because it detects only the horizontal magnetic field components of radio waves radiated from the vertical current of source lightning. Consequently, horizontal in-cloud lightning channels could make the optical/electric scaling factor much "brighter" as found in these two cases.

5. Conclusions

[11] A strong correlation in sprite-producing lightning was found between the 777.4-nm brightness normalized to a distance of 3000 km and vertical current moment waveform. In 10 out of 12 events, the scaling factors between these two parameters were found to be ~0.82 MR/kAkm with standard errors of ±50%. Remarkably, the validity of this scaling factor spans the relatively high amplitude fast portions of the flash (~2 ms time scale, 10s to 100s of kA km)

to the low amplitude continuing currents (~100 ms time scale, a few kA km). This finding provides a possible new way to derive lightning current/charge moment change from optical measurements. The remaining two events, however, had much higher scaling factors of ~3 and ~8 MR/kAkm, respectively. The concurrent imager data suggested presence of complicated lightning processes which would significantly increase the optical/radio scaling factor. Further studies are required on these outlying cases.

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