



HOKKAIDO UNIVERSITY

Title	Horizontal distributions of sprites derived from the JEM-GLIMS nadir observations
Author(s)	Sato, M.; Mihara, M.; Adachi, T. et al.
Citation	Journal of geophysical research atmospheres, 121(7), 3171-3194 https://doi.org/10.1002/2015JD024311
Issue Date	2016-04-17
Doc URL	https://hdl.handle.net/2115/64171
Rights	Copyright 2016 American Geophysical Union.
Type	journal article
File Information	Sato_et_al-2016-Journal_of_Geophysical_Research__Atmospheres.pdf



RESEARCH ARTICLE

10.1002/2015JD024311

Key Points:

- Data processing techniques are introduced to distinguish sprite emissions from lightning emissions
- The locations of sprite emissions are displaced by 8–20 km from the parent lightning emissions
- The quantitative spatial distributions of sprites are derived from the JEM-GLIMS nadir observations

Correspondence to:

S. Mitsuteru,
msato@ep.sci.hokudai.ac.jp

Citation:

Sato, M., et al. (2016), Horizontal distributions of sprites derived from the JEM-GLIMS nadir observations, *J. Geophys. Res. Atmos.*, 121, 3171–3194, doi:10.1002/2015JD024311.

Received 4 OCT 2015

Accepted 3 MAR 2016

Accepted article online 7 MAR 2016

Published online 8 APR 2016

Horizontal distributions of sprites derived from the JEM-GLIMS nadir observations

M. Sato¹, M. Mihara², T. Adachi³, T. Ushio⁴, T. Morimoto⁵, M. Kikuchi⁶, H. Kikuchi⁴, M. Suzuki⁷, A. Yamazaki⁷, Y. Takahashi¹, U. Inan⁸, I. Linscott⁸, R. Ishida⁹, Y. Sakamoto¹⁰, K. Yoshida¹⁰, and Y. Hobara¹¹
¹Faculty of Science, Hokkaido University, Sapporo, Japan, ²Department of Cosmospaces, Hokkaido University, Sapporo, Japan, ³Meteorological Research Institute, Tsukuba, Japan, ⁴Faculty of Engineering, Osaka University, Suita, Japan, ⁵Faculty of Science and Engineering, Kinki University, Higashiosaka, Japan, ⁶National Institute of Polar Research, Tachikawa, Japan, ⁷Institute of Space and Astronautical Science, JAXA, Sagami-hara, Japan, ⁸Department of Electrical Engineering, Stanford University, Stanford, California, USA, ⁹Faculty of Engineering, Osaka Prefecture University, Sakai, Japan, ¹⁰Department of Engineering, Tohoku University, Sendai, Japan, ¹¹Faculty of Informatics and Engineering, University of Electro-Communications, Chofu, Japan

Abstract Global Lightning and Sprite Measurements on Japanese Experiment Module (JEM-GLIMS) started the nadir observations of lightning discharges and transient luminous events (TLEs) from the International Space Station (ISS) since November 2012. In the nadir observations, JEM-GLIMS optical instruments have to simultaneously detect incomparably intense lightning emissions and weak TLE emissions. To distinguish TLEs, especially sprite events, from lightning events, combined data analytical methods are adopted: (1) a subtraction of the wideband camera image from the narrowband camera image, (2) a calculation of the intensity ratio between different photometer channels, and (3) an estimation of the polarization and charge moment changes for the TLE-producing lightning discharges. We succeeded in identifying numbers of sprite events using the combined analytical methods, and here we report three sprite events detected by JEM-GLIMS as a case study. In the subtracted images, sprite emissions are located over the area of the sprite-producing lightning emissions. However, these sprites and sprite-producing lightning discharges did not occur at the nadir point of the ISS. For this reason, the geometry conversion of the sprite and sprite-producing lightning emissions as observed from the point just over the sprite-producing lightning discharges is performed. In the geometry-converted images, the locations of the sprite emissions are clearly displaced by 8–20 km from the peak positions of the sprite-producing lightning emissions. Thus, the first quantitative spatial distributions of sprites and sprite-producing lightning discharges from the JEM-GLIMS nadir observations are revealed.

1. Introduction

Sprites are one of the prevalent types of transient luminous events (TLEs) occurring in the stratosphere and mesosphere, and they are typically excited by intense positive cloud-to-ground (+CG) discharges [Franz et al., 1990; Sentman et al., 1995; Lyons, 1996]. Numbers of the ground-based optical observations using low-light television cameras, telescopes, and high-speed cameras revealed that sprites develop vertically in the altitude range of 50–90 km and that they typically have fine structures of streamer discharges [Gerken and Inan, 2003; Moudry et al., 2003; Kanmae et al., 2007; Stenbaek-Nielsen et al., 2010]. Theoretical studies on the mechanisms of the sprite generation and streamer development were also intensively conducted [Pasko et al., 1997, 1998; Ebert et al., 2006, 2011; Liu and Pasko, 2006; Luque et al., 2007; Luque and Ebert, 2012; Pasko, 2010; Qin et al., 2011, 2012]. These theoretical studies succeeded in establishing reasonable models explaining the vertical motion of sprites above the parent CG discharges and the detailed spatiotemporal evolution of sprite streamers. In contrast, the physical conditions determining the horizontal distributions of sprites, the number of sprite elements, and the displacement between the sprite location and the location of the parent CG discharge are not well understood. Qin et al. [2011] pointed out that the significant inhomogeneities of the mesospheric conductivity (i.e., electron density perturbations) are the important factor defining the formation location of sprite streamers. Such mesospheric conductivity inhomogeneities can be triggered by meteoric dust particles [Wescott et al., 2001; Zabolotin and Wright, 2001], atmospheric gravity waves [Sentman et al., 2003], and the

interference of electromagnetic pulses emitted by in-cloud lightning currents [Valdivia *et al.*, 1997; Cho and Rycroft, 1998; Ohkubo *et al.*, 2005; Marshall *et al.*, 2007]. However, a conclusive piece of observational evidence has not been obtained so far.

In order to clarify the physical conditions determining the spatial distribution of sprites and the displacement of the sprite location from the location of the parent CG discharges, detailed horizontal structures of sprites, in-cloud structures of the parent CG discharges, and their electrical properties are of key importance. To identify the horizontal distribution of sprites from ground-based and aircraft optical observations, simultaneous detection of sprites from multiple observation sites and associated triangulation analyses for the optical image data are required. So far, there are some publications reporting the spatial distributions of sprites derived from the multisite optical observations [Wescott *et al.*, 1998, 2001; São Sabbas *et al.*, 2003; Vadislavsky *et al.*, 2009; Stenbaek-Nielsen *et al.*, 2010; Kanmae *et al.*, 2012; Gameraota *et al.*, 2011; Lu *et al.*, 2013; Kobayashi *et al.*, 2012]. Wescott *et al.* [1998, 2001] analyzed optical images obtained from two ground sites and succeeded in estimating the detailed three-dimensional structures of sprites and the relation between their locations and the locations of the parent CG discharges. São Sabbas *et al.* [2003] performed a statistical analysis of 40 sprite events and found that the maximum and average distances between the triangulated nadir point of sprite events and the location of parent +CG discharges are ~ 82 km and 40 km, respectively. Vadislavsky *et al.* [2009] analyzed image data of sprites excited by winter thunderstorms over the Eastern Mediterranean and found the circular arrangements of columniform sprite elements. Stenbaek-Nielsen *et al.* [2010] and Kanmae *et al.* [2012] conducted simultaneous optical observations from two ground sites using two high-speed cameras and clarified the onset altitude of sprites and the detailed spatiotemporal development of sprite streamers. Lu *et al.* [2013] analyzed ground-based optical images of sprites obtained simultaneously at multisites and compared the Lightning Mapping Array (LMA) data. They studied the relation between the sprite locations and the ground locations of the sprite-producing strokes derived from the triangulation analysis and the National Lightning Detection Network (NLDN), and they compared the sprite locations with detailed in-cloud current structures of the sprite-producing strokes. They found that prompt sprites produced within 20 ms after the parent stroke are less horizontally displaced (typically <30 km) from the ground stroke than delayed sprites occurring over 40 ms after the parent stroke with significant lateral offsets (>30 km) and that both prompt and delayed sprites are usually centered within 30 km of the geometric center of relevant LMA sources [Lu *et al.*, 2013]. Kobayashi *et al.* [2012] performed triangulation analyses for the high-speed camera images obtained from the two jet aircrafts and succeeded in identifying very detailed three-dimensional structures of sprite streamers. Despite these leading studies, feasibility to simultaneously detect sprites from the multiple observation sites is generally low due to the limitation of the geographical and weather conditions. Even though we conduct such observations, the possible observation area is limited to the land region. For the comprehensive detection of sprites over the oceanic and land regions and for the identification of the horizontal distribution of sprites and the displacement between sprite location and the sprite-producing lightning location, nadir observations of lightning and sprites from space are essential.

Optical observations of TLEs from space were intensively conducted since the 1990s, such as from the Space Shuttle [Boeck *et al.*, 1998; Yair *et al.*, 2003, 2004], the International Space Station (ISS) [Blanc *et al.*, 2004; Jehl *et al.*, 2013; Yair *et al.*, 2013], and the FORMOSAT-2 satellite [Frey *et al.*, 2005; Mende *et al.*, 2005; Chen *et al.*, 2008; Chang *et al.*, 2010]. From these observations, the spatial and temporal characteristics of sprites, the differences of the occurrence types, and the optical intensities at the different emission lines were clarified. However, since most of these observations used the limb-viewing technique to easily and efficiently detect TLEs, it was difficult to precisely estimate the horizontal distributions of TLEs, especially those of sprites. In a few cases, nadir observations of lightning and TLEs were conducted from the ISS [Blanc *et al.*, 2004; Yair *et al.*, 2013]. Blanc *et al.* [2004] first reported the nadir-view images of lightning and possible sprite emissions detected by wideband and narrowband CCD cameras. Unfortunately, the electrical properties of the parent lightning discharges of the possible sprite events were not presented since the time accuracy of the recorded data was approximately ± 1 s. Recently, Yair *et al.* [2013] presented a clear color sprite image obtained by the nadir observations from the ISS using a high-sensitive electron multiplication CCD camera. In that image, the obvious displacement of the spot-like sprite emission from the parent lightning emission was confirmed. However, these nadir observations of lightning and TLEs were conducted under the campaign-based missions. Thus, the variations of the horizontal distributions of sprites, the relation between the sprite location and the sprite-producing lightning location, the regional similarities/differences, and the seasonal variation of TLEs are yet to be elucidated.

Global Lightning and Sprite Measurements on Japanese Experiment Module (JEM-GLIMS) is a space mission to conduct first continuous nadir observations of lightning discharges and TLEs from the ISS [Ushio *et al.*, 2011]. The main scientific objectives of this mission are (1) the detection of sprites by the nadir observations from the ISS, (2) the identification of the derailed horizontal distribution of sprites, and (3) the clarification of the physical conditions determining the horizontal distributions of sprites [Sato *et al.*, 2015]. For these purposes, JEM-GLIMS uses two types of optical instruments and two types of electromagnetic wave receivers. Owing to the orbital characteristics of the ISS, JEM-GLIMS realizes scanning measurements over all local time areas, which is a great advantage of this mission.

Here we report techniques to distinguish the faint sprite emissions from the incomparably brighter lightning emissions in nadir observation data. Then we introduce three sprite events detected by JEM-GLIMS optical instruments and present detailed spatial distributions of the observed sprite and sprite-producing lightning emissions. JEM-GLIMS optical instruments and data that were used in this study are introduced in section 2. The data processing methods to identify sprite events using JEM-GLIMS optical data and ground-based ELF observation data are presented in section 3. In section 4, three examples of the observed sprite events are shown. The geometry-converted sprite images and the validity of the geometry conversion are presented in sections 5 and 6. Finally, the summary of this report is presented in section 7.

2. Observations and Data

2.1. JEM-GLIMS Nadir Observations and Optical Data

In order to measure optical emissions of lightning discharges and related TLEs and to detect the electromagnetic waves excited by lightning discharges, JEM-GLIMS is composed of two optical instruments, two electromagnetic wave receivers, and an onboard computer [Ushio *et al.*, 2011; Sato *et al.*, 2011a, 2011b; Morimoto *et al.*, 2011; Kikuchi *et al.*, 2011; Sato *et al.*, 2015]. JEM-GLIMS was launched in July 2012 and started the continuous nadir observations in November 2012. The orbital inclination of the ISS is 51° , and typical orbital altitude and the speed of the ISS are 410 km and 8 km/s, respectively. The JEM-GLIMS observations of lightning and TLEs are conducted when the ISS is in the Earth's shadow and above the nightside.

In this study, JEM-GLIMS optical data obtained by two complementary metal oxide semiconductor (CMOS) cameras (LSI: Lightning and Sprite Imager) and six-channel spectrophotometers (PH: Photometer) are analyzed. The LSI aims for acquiring morphological image data of lightning and TLE optical emissions and consists of wideband ($\lambda = 768\text{--}830$ nm) and narrowband ($\lambda = 760\text{--}775$ nm) cameras, denoted as LSI-1 and LSI-2, respectively [Sato *et al.*, 2011a]. The LSI-1 mainly measures the lightning emissions, while the LSI-2 mainly measures N_2 1P(3,1) ($\lambda = 762.7$ nm) emissions of TLEs because the continuum lightning emissions in the 760–775 nm wavelength range are partially absorbed by O_2 molecules in the atmosphere [Sato *et al.*, 2015]. As the field of view (FOV) of the LSI is $28.3^\circ \times 28.3^\circ$ and the pixel size of the CMOS sensor is 512×512 , spatial resolution becomes $400 \text{ m} \times 400 \text{ m}$ at the ground level and $320 \text{ m} \times 320 \text{ m}$ at 80 km altitude. The sampling time of the LSI is 32.8 ms. Six-channel spectrophotometers are another optical instrument and aim for acquiring light curve data of lightning and TLE optical emissions [Sato *et al.*, 2011b]. Each photometer, denoted by PH1–PH6, was equipped with a different optical band-pass filter: PH1 ($\lambda = 150\text{--}280$ nm), PH2 ($\lambda = 332\text{--}342$ nm), PH3 ($\lambda = 755\text{--}766$ nm), PH4 ($\lambda = 599\text{--}900$ nm), PH5 ($\lambda = 310\text{--}321$ nm), and PH6 ($\lambda = 386\text{--}397$ nm). These photometers are designed to measure far-ultraviolet (FUV) emissions come from the N_2 Lyman-Birge-Hopfield (LBH) band system and near UV and visible emissions come from N_2 1P, N_2 2P, and N_2^+ 1N band systems. The PH1–PH3, PH5, and PH6 have a conical FOV of 42.7° , while the PH4 has a conical FOV of 86.8° . The sampling time of the PH system is 50 μs . JEM-GLIMS uses the event triggering technique. LSI image data are obtained for four consecutive frames from one frame before the trigger time, while PH light curve data are recorded from 100 ms before the trigger time to 412 ms after the trigger time [Sato *et al.*, 2015]. JEM-GLIMS is equipped with a Global Positioning System (GPS) receiver to obtain the precise coordinated universal time (UTC) when JEM-GLIMS detects an event. The time accuracy of the GPS is in the order of microseconds [Sato *et al.*, 2015].

2.2. Ground-Based Lightning Observation Data

Most researchers believe that a decisively important factor to TLE production is the charge moment change (CMC) and the impulsive CMC (iCMC) of the parent positive CG discharges. Numerous observational and theoretical studies have shown that there are thresholds for the parent flash CMC, above which the probability of sprite generation is high [Cummer and Inan, 1997; Hu *et al.*, 2002, 2007; Cummer, 2003;

Cummer and Lyons, 2005; Li et al., 2008]. For the CMC and polarity estimations of the lightning discharges detected by JEM-GLIMS, ELF magnetic field waveform data obtained by the Global ELF Observation Network maintained by Hokkaido University are used. In this study, ELF data measured at Syowa station (39.01°E, 69.02°S), Antarctica and Esrange station (21.10°E, 67.88°N), Sweden are analyzed. At these stations, magnetic field perturbations in the 1–100 Hz frequency range in the north-south and east-west directions are detected by two orthogonal search coil magnetometers, and the waveform data are continuously recorded with the sampling frequency of 400 Hz [Sato et al., 2003]. Besides the ELF data, lightning data obtained from the World-Wide Lightning Location Network (WWLLN) [Rodger et al., 2004, 2005, 2009; Abarca et al., 2010; Hutchins et al., 2012] and the NLDN [Cummins et al., 1998; Orville and Huffines, 2001; Cummins and Murphy, 2009] are used to verify the occurrence time and location of the lightning discharges detected by JEM-GLIMS.

3. Methodology of Data Processing

As the nadir observations have to simultaneously measure both the extremely strong lightning emissions and the weak TLE emissions from the ISS, the spatiotemporal separation between these emissions is difficult. In the limb observations of the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) on board the FORMOSAT-2 satellite, the separation between lightning and TLE emissions is rather easy due to the vertical separation in the image, but for the JEM-GLIMS observations, such a separation does not exist and therefore distinguishing between lightning and TLE emissions is much more complex. In order to validate the occurrence of TLEs from the JEM-GLIMS optical data, a comparison of the results derived from the following three analyses are required: (1) a subtraction of the appropriately scaled LSI-1 image from the LSI-2 image, (2) a calculation of the intensity ratio between the different PH channels, and (3) estimations of the polarization and CMC for the lightning discharges of the suspected parent flash [Sato et al., 2015]. The following subsections describe these data processing techniques in detail.

3.1. Image Subtraction of LSI Data

As described in section 2.1, the LSI-1 and LSI-2 observe lightning emissions and TLE emissions, respectively. In the wavelength range of 760–775 nm, which is the passband of the LSI-2, a majority of the optical emissions radiated from the troposphere and propagated into space are absorbed by O₂ molecules in the atmosphere. For example, using the Moderate Resolution Atmospheric Transmission (MODTRAN) code, the modeled atmospheric transmittance calculated by assuming the light source located at 4 km altitude and the propagation in the zenith direction is ~0.4, as shown in Sato et al. [2015, Figure 14]. In contrast, the transmittance calculated by assuming the light source located at 70 km altitude and the zenith propagation is ~1.0. Thus, some of the continuum lightning emissions can be detected by the LSI-2, which is already proved in the previous studies [Blanc et al., 2004, 2006, 2007]. From this reason, a subtraction of the appropriately scaled LSI-1 image from the LSI-2 image is needed to extract only the TLE emissions.

The image subtraction procedure is first proposed by Blanc et al. [2004]. More recently, Blanc et al. [2012] first suggested the subtraction of images to detect TLEs in nadir images taken by two cameras having a similar configuration. We use basically the same image subtraction procedure. As a first step, the flat-field correction and dark image subtraction are performed to LSI-1 and LSI-2 images using the calibration data. As a next step, the difference of the alignment between the LSI-1 and LSI-2 images is corrected. The pixel values to shift the LSI-1 image have been empirically determined from the statistical analysis of the images where the spot-like emissions originated in city lights are measured. Finally, the image subtraction of the LSI-1 image from the LSI-2 image is performed. The subtraction procedure is described as the following equation:

$$I(x, y)_{\text{sub}} = I(x, y)_{(\text{LSI-2})} - \frac{I(x, y)_{(\text{LSI-1})}}{\alpha(x, y)} \quad (1)$$

where x and y are the coordinate of the image, and $I(x, y)_{\text{sub}}$, $I(x, y)_{(\text{LSI-2})}$, and $I(x, y)_{(\text{LSI-1})}$ are the subtracted, LSI-2, and LSI-1 data, respectively. α is the scaling factor applied to the LSI-1 data, which determines the expected intensities of lightning emissions contained within the LSI-2 image. This scaling factor is defined as the following function:

$$\alpha(x, y) = \frac{1}{A + B \cdot I(x, y)_{(\text{LSI-2})}} \quad (2)$$

where A and B are the constant determined by the statistical analysis of the JEM-GLIMS lightning events, which is expressed as the following equation:

$$\frac{I(x, y)_{(\text{LSI-1})|_{\text{LNG}}}}{I(x, y)_{(\text{LSI-2})|_{\text{LNG}}}} = \frac{1}{A + B \cdot I(x, y)_{(\text{LSI-2})|_{\text{LNG}}}} \quad (3)$$

where $I(x, y)_{(\text{LSI-1})|_{\text{LNG}}}$ and $I(x, y)_{(\text{LSI-2})|_{\text{LNG}}}$ are LSI-1 and LSI-2 data in lightning events, respectively. From JEM-GLIMS optical images obtained during the period between January and December 2013, we selected a total of 210 lightning events, where there is no FUV signals from N_2 LBH emissions and where lightning optical emissions are confirmed by both the LSI-1 and the LSI-2. Using these lightning data, the intensity ratio $I(x, y)_{(\text{LSI-1})|_{\text{LNG}}}/I(x, y)_{(\text{LSI-2})|_{\text{LNG}}}$ was calculated as a function of $I(x, y)_{(\text{LSI-2})|_{\text{LNG}}}$. Finally, the constants A and B were estimated by the least squares fitting. The number and standard deviation (σ) of A and B are statistically determined to be $A = 2.46 \times 10^{-3}$ ($\sigma = 1.64 \times 10^{-3}$) and $B = 1.36 \times 10^{-3}$ ($\sigma = 4.01 \times 10^{-4}$), respectively. The correlation coefficient for the least squares fitting is $R = 0.89$. A detailed description of the subtraction procedure is given in Mihara *et al.* [2014], Sato *et al.* [2014], and Mihara [2015].

3.2. Peak Intensity Ratio of PH Data

The absolute intensities of lightning and TLE emissions at the different wavelength bands are precisely measured by the six PH channels. During the propagation of lightning optical emissions radiated at the troposphere to the ISS, these emissions are absorbed or scattered in the atmosphere. In contrast, optical emissions of TLEs do not suffer from the atmospheric absorption or scattering during the propagation to the ISS because TLEs mainly occur in the mesosphere. Thus, the intensity ratio between the different PH channels for lightning events differs from that for TLEs. Adachi *et al.* [2013a, 2013b] analyzed optical data of lightning events and TLEs obtained by the ISUAL spectrophotometer (SP) and the JEM-GLIMS PH data of lightning events, and they calculated the intensity ratio of these events. In their studies, ISUAL SP data of 17,835 lightning events, 145 sprite and halo events, and 1502 elves events detected in 2004 are statistically analyzed. The intensity ratio between SP4 ($\lambda = 658\text{--}753$ nm) and SP2 ($\lambda = 334\text{--}341$ nm) for these events and the occurrence probability are statistically calculated. They estimated that the occurrence probability of sprites becomes $>80\%$ when SP2/SP4 is greater than 14.8. As a next step, the JEM-GLIMS PH data of 202 lightning events detected for the period between November 2012 and June 2013 are also analyzed. The intensity ratio between the PH4 ($\lambda = 599\text{--}900$ nm) and the PH2 ($\lambda = 332\text{--}342$ nm) for these lightning events is statistically calculated. The estimated occurrence probability of lightning events derived from PH2/PH4 is highly consistent with that derived from SP2/SP4. Based on this quantitative comparison, we concluded that when the ratio PH2/PH4 is higher than 14.8 then the occurrence probability of sprites is $>80\%$ in the JEM-GLIMS case [Adachi *et al.*, 2013a, 2013b; Sato *et al.*, 2013].

3.3. Electrical Properties of Parent CG Discharges

Using ELF magnetic field waveform data, it is possible to estimate the occurrence time, polarity, propagation path, and CMC value of intense CG discharges. Especially, CMC is an important physical parameter to judge the occurrence of sprites [Hu *et al.*, 2002; Sato and Fukunishi, 2003]. The relation between the power spectrum of the observed magnetic field waveform being perpendicular to the wave propagation path (H_ϕ) and the source current moment spectrum of intense CG discharges ($I \cdot dl$) is given by the following equation:

$$H_\phi(f, \theta) = \frac{I \cdot dl(f)}{4\pi R_E h_0} \sum_n \frac{2n+1}{n(n+1) - \nu(\nu+1)} P_n^1(\cos \theta) \quad (4)$$

where f , θ , R_E , h_0 , n , and ν are the frequency, the angular distance between a source and an observer, the radius of the Earth, the reflection height of ELF waves, the mode number, and the complex propagation constant, respectively, and P_n^1 is the associated Legendre polynomials of order n and first degree [Huang *et al.*, 1999; Füllekrug and Constable, 2000]. Assuming that the lightning current moment waveform has a shape of the exponential decay with a time constant τ , the current moment spectrum is

$$I \cdot dl(f) = \frac{I_0 \cdot dl}{i \cdot 2\pi f + 1/\tau} \quad (5)$$

By fitting the modeled current moment spectrum of equation (5) to the current moment spectrum observationally obtained by equation (4), the peak current moment $I_0 \cdot dl$ and the time constant τ are estimated.

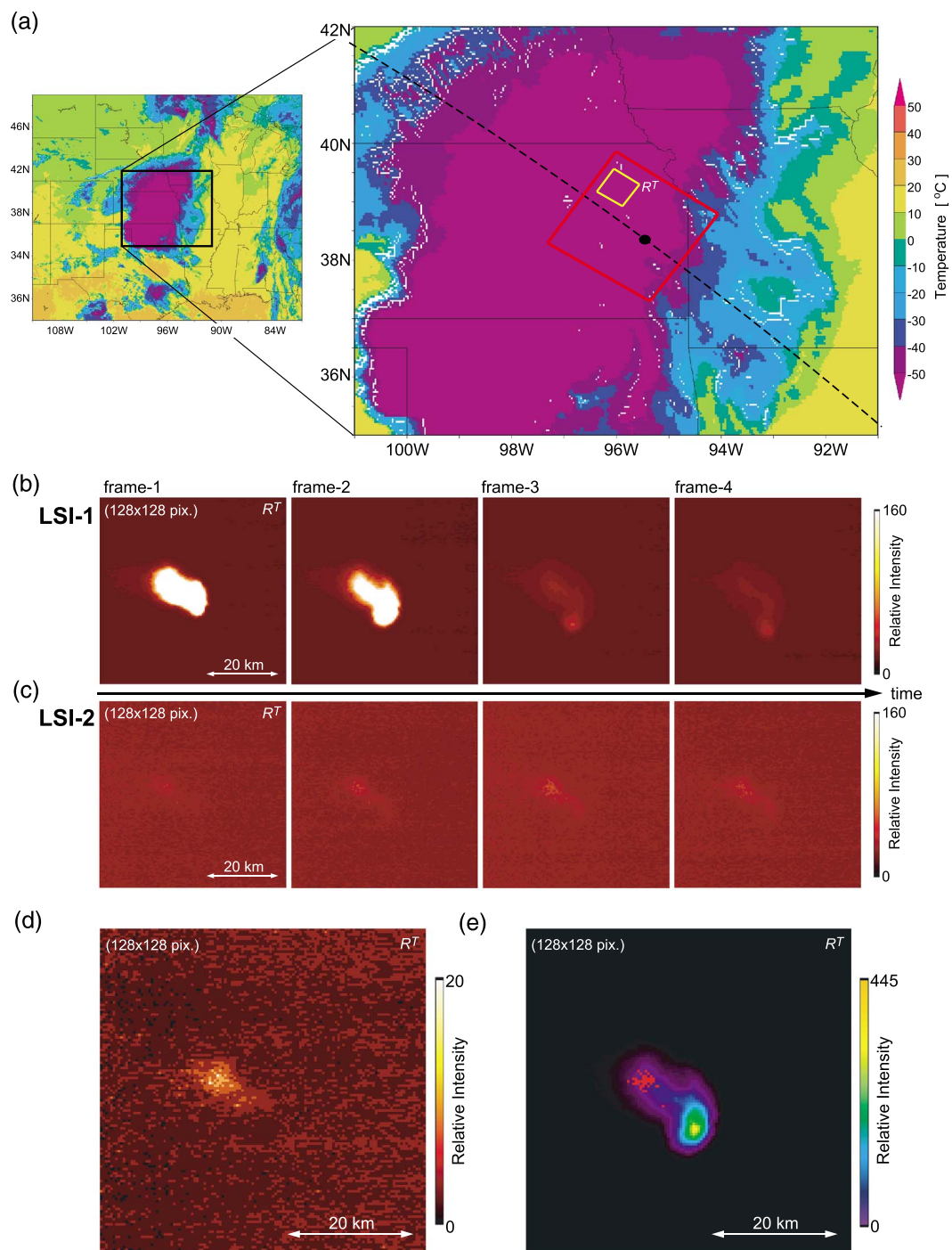


Figure 1. (a) IR brightness temperature image measured by the GOES satellite at 06:30 UT on 12 June 2014. The dashed line and the solid circle are the trajectory of the ISS footprint and the ISS footprint at the detection time of the event, respectively. The red and yellow squares are the FOV of the LSI at the detection time of the event and the area of the expanded LSI images in Figures 1b–1e, respectively. (b and c) Four consecutive expanded images of the LSI-1 and LSI-2 cropped from the original 512×512 size data. (d) Result of the image subtraction for the frame-2 images shown in Figures 1b and 1c. (e) LSI-1 image (rainbow color) overplotted by the subtracted optical emissions in Figure 1d (red color).

As the decay time constant of lightning currents is generally very short compared to that of ELF waves, CMC can be estimated from $(I_0 \cdot dl) \cdot \tau = (I_0 \cdot \tau) \cdot dl = Q \cdot dl$, where Q is the charge amount of discharges [Huang *et al.*, 1999]. Hu *et al.* [2002] reported that the occurrence probability of sprites is 90% when CMC of the parent CG discharges is greater than 1000 C·km.

4. JEM-GLIMS Sprite Events

For the period between November 2012 and June 2015, JEM-GLIMS succeeded in detecting 7910 lightning events containing 672 TLEs. This section focuses on three sprite events among these events as a case study and presents detailed spatiotemporal characteristics of these optical emissions.

4.1. Event #1: 06:41:15 UT on June 12 2014

JEM-GLIMS detected a lightning event over the Great Plains, USA at 06:41:15.68565 UT on 12 June 2014, when the ISS was located at (95.43°W, 38.35°N) and 415.6 km altitude. Figure 1a shows the infrared (IR) brightness temperature image measured by the Geostationary Operational Environmental Satellite (GOES) at 06:30 UT, where the trajectory of the ISS footprint (dashed line), the footprint of the ISS at the detection time of the event (solid circle), and the LSI FOV at the detection time of the event (red square) are also drawn. It is clear that a huge mesoscale convective system (MCS) was developed below the ISS and that the LSI observed the region of the highest cloud top, where the cloud temperature was mostly below -50°C . Using the Mass Spectrometer Incoherent Scatter (MSISE-90) model, the altitude of the -50°C temperature level within the LSI FOV is calculated to be ~ 11.5 km.

Figures 1b and 1c are the four consecutive images of the LSI-1 and LSI-2, respectively. The images denoted by frame-2 are obtained at the trigger time issued by the PH. The pixel size of these images is 128×128 cropped from the original 512×512 size data. The area of these expanded images is indicated by the yellow square in Figure 1a, where R^T denotes the right-top corner. In Figure 1b, the lightning emission started near the center of the frame-1 image, developed toward the bottom at frame-2, and decayed at frame-3. The diameter of the lightning emission was approximately 30 km. In Figure 1c, the dim emission appeared near the center of the frame-1 image, but its position, shape, and luminosity did not change from frame-1 to frame-4. Figure 1d is the result of the image subtraction for the frame-2 images in Figures 1b and 1c and is derived from equation (1). In this figure, a cluster of the weak emissions is confirmed. In order to clarify the difference in the spatial distributions of the lightning emission and the cluster of the weak emissions, the subtracted image in Figure 1d was overplotted on the LSI-1 image, which is presented in Figure 1e. In this figure, the lightning emission measured by the LSI-1 is drawn by the rainbow color, while the weak clustered emission, where the intensity levels exceed 5 times the standard deviation (σ), is drawn by red color. As the weak clustered emission appeared in the upper left direction from the peak position of the lightning emission, the weak clustered emission is likely to be the sprite optical emission.

The solid lines in Figure 2a are the absolute optical intensity curves measured by the six PH channels for the time interval between $t = -1.0$ ms and $t = 4.0$ ms, where the time at $t = 0$ ms is the trigger time at 06:41:15.68565 UT. In this plot, intense lightning emissions lasting ~ 2 ms were detected at the trigger time. The fact that the impulsive FUV emission was detected by the PH1 strongly suggests the occurrence of a TLE. Dashed lines at the PH2–PH5 are the fitting curves using the PH6 light curve data, and the solid triangle at each panel indicates the estimated peak intensity. The absolute peak intensities of the PH1–PH6 are estimated to be 2.56×10^{-6} , 4.31×10^{-4} , 3.25×10^{-4} , 2.04×10^{-2} , 4.20×10^{-5} , and 4.37×10^{-4} W/m², respectively. From these values, the absolute peak intensities normalized by the unit wavelength (i.e., W/m²/nm) are calculated. Then the ratio of each normalized absolute peak intensity to that of the PH4 is estimated. Figure 2b is a plot of the intensity ratio for lightning events (blue line) and this event (red line). Note that the blue line in this figure was derived from the statistical analysis of 202 lightning events measured by JEM-GLIMS. In addition, note that the PH1/PH4 ratio for lightning events is not plotted since there is no FUV emission in lightning events. It is found that the intensity ratio of this event shows marked enhancement compared with that of lightning events and that the PH2/PH4 ratio is 19.1. As described in section 3.2, the occurrence probability of sprites is $>80\%$ when PH2/PH4 is greater than 14.8. Thus, the result shown in Figure 2b strongly supports the occurrence of sprites in this event.

ELF magnetic field waveform data obtained at Esrange station in the time period 06:41:15.4–16.4 UT are presented in Figure 3a. After the trigger time of the PH denoted by the dashed line, a transient Schumann

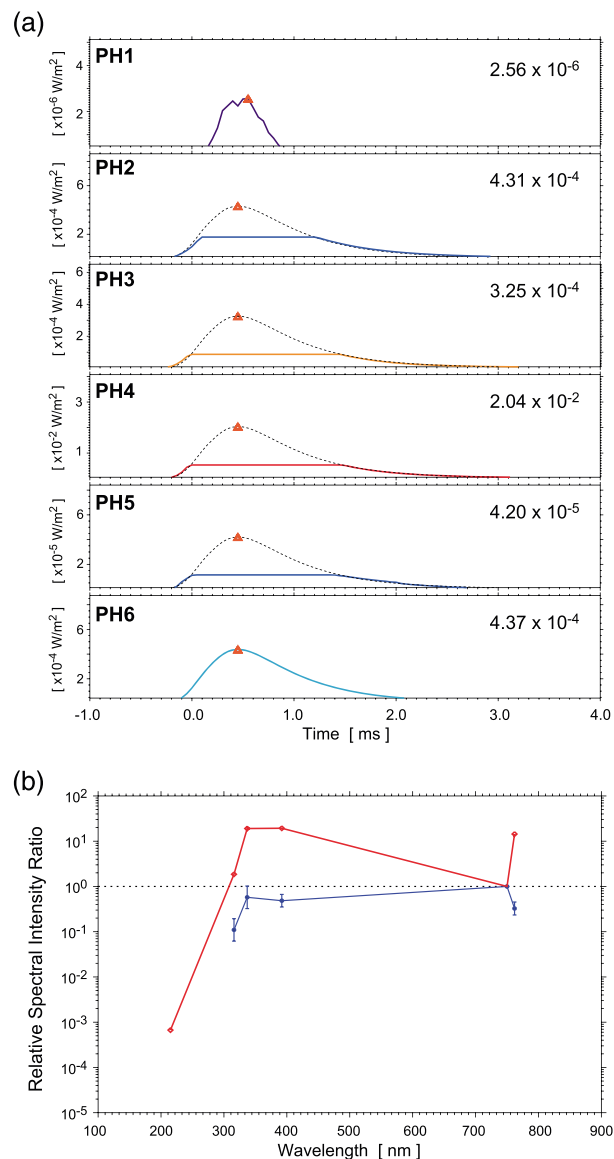


Figure 2. (a) Absolute optical intensity curves measured by the six PH channels for the time interval between $t = -1.0$ ms and $t = 4.0$ ms, where $t = 0.0$ ms is the trigger time (06:41:15.68565 UT). Dashed lines at the PH2–PH5 are the fitting curves using the PH6 data. Solid triangle at each panel indicates the peak intensity. (b) Relative spectral intensity ratio for the lightning events (blue line) and the event shown in Figure 2a (red line).

resonance (SR) waveform denoted by the vertical arrow was detected at 06:41:15.715 UT. As the ISS was located at (95.43°W, 38.35°N), the distance from Esrange station to the ISS is 7.08 Mm. Assuming that the transient SR wave was excited by the lightning discharge detected by JEM-GLIMS and that a propagation velocity of SR waves is $v = 0.8c$ [Füllekrug and Constable, 2000; Sato and Fukunishi, 2003], the propagation time is 29.5 ms. In addition, assuming that the lightning emissions were radiated at 10 km altitude, the traveling time of the optical emissions to the ISS is estimated to be 1.35 ms. Thus, the expected time of the wave arrival at Esrange station would be 06:41:15.71380 UT. This estimated time compares well with the time when the transient SR wave was actually observed. The solid line in Figure 3b is the propagation path of the transient SR wave derived from the waveform data in Figure 3a. The dark area in this figure corresponds to the nightside. The bearing angle of the ISS footprint from the Esrange station is 308.5°, and the bearing angle of the propagation path of the transient SR wave is 290.5°, which is calculated by using the same method presented in Sato and Fukunishi [2003] and Sato et al. [2008]. As these bearing angles are also comparable, we concluded that the transient SR wave detected at Esrange station was actually excited by the lightning discharge

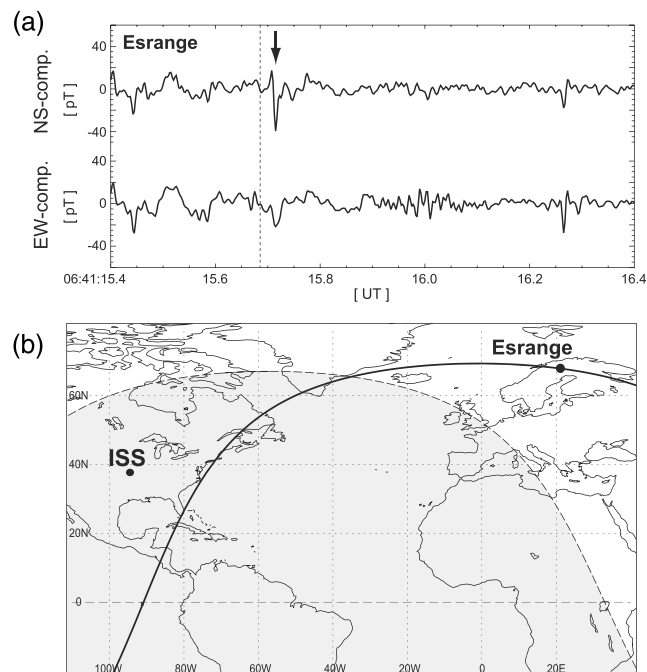


Figure 3. (a) ELF magnetic field waveforms in the geographical north-south and east-west components measured at Esrange station, Sweden in the time period 06:41:15.4–16.4 UT. (b) Propagation path of the transient SR wave detected at 06:41:15.715 UT. The dark area corresponds to the nighttime.

detected by JEM-GLIMS. From the shape of the transient SR wave, the polarity of the lightning discharge was positive. Using equations (4) and (5), CMC was estimated to be +2946 C-km, which is considered more than enough for sprite generation [Hu et al., 2002; Cummer and Lyons, 2005].

From all the results derived from the image subtraction of the LSI data, the calculation of absolute peak intensity ratio of the PH data, and the CMC estimation of the +CG discharge, we concluded that the weak clustered emission in Figures 1d and 1e is equal to the sprite emission. From Figure 2a, the FUV sprite emission occurred simultaneously with the optical emission of the sprite-producing +CG discharge, which implies that this event was a short-delayed sprite.

4.2. Event #2: 05:08:14 UT on December 21 2013

A lightning event was detected over Mexico at 05:08:14.63340 UT on 21 December 2013. The position of the ISS was (103.64°W, 21.62°N) at 419.9 km altitude. Figure 4a is the IR brightness temperature image obtained by the GOES satellite at 05:00 UT. From this figure, it is clear that the ISS was located over the cloud band extending from the northeast to the southwest when JEM-GLIMS detected the lightning event. The highest and lowest temperature levels within the yellow square in Figure 4a are -50°C and -30°C , respectively. From the MSISE-90 model, the altitude of the -50°C temperature level within this area is calculated to be ~ 11.3 km, while that of the -30°C temperature level is ~ 8.7 km.

In Figure 4b, the lightning emission started near the center position, reached its maximum at frame 3, and decayed at frame 4. In contrast, the LSI-2 detected the structured emission at frames 3 and 4, which stayed at the same position. Figures 4d and 4e are the subtracted image for the frame-3 data. In this event, three distinct spots indicating the different points from the peak location of the lightning emission are identified in the subtracted image.

Solid lines in Figure 5a are plots of the absolute light curve data obtained by the PH at 5 ms time interval. In this event, the light curve data of the PH2–PH5 were also saturated. So these light curve data are fitted by the PH6 light curve data. The estimated peak absolute intensity of the PH1–PH6 are 5.86×10^{-7} , 2.24×10^{-4} , 1.73×10^{-4} , 9.92×10^{-3} , 3.31×10^{-5} , and 2.27×10^{-4} W/m², respectively. As shown in Figure 5b, the peak intensity ratio of this event (red line) is greater than that of lightning events (blue line), and PH2/PH4 is 20.3.

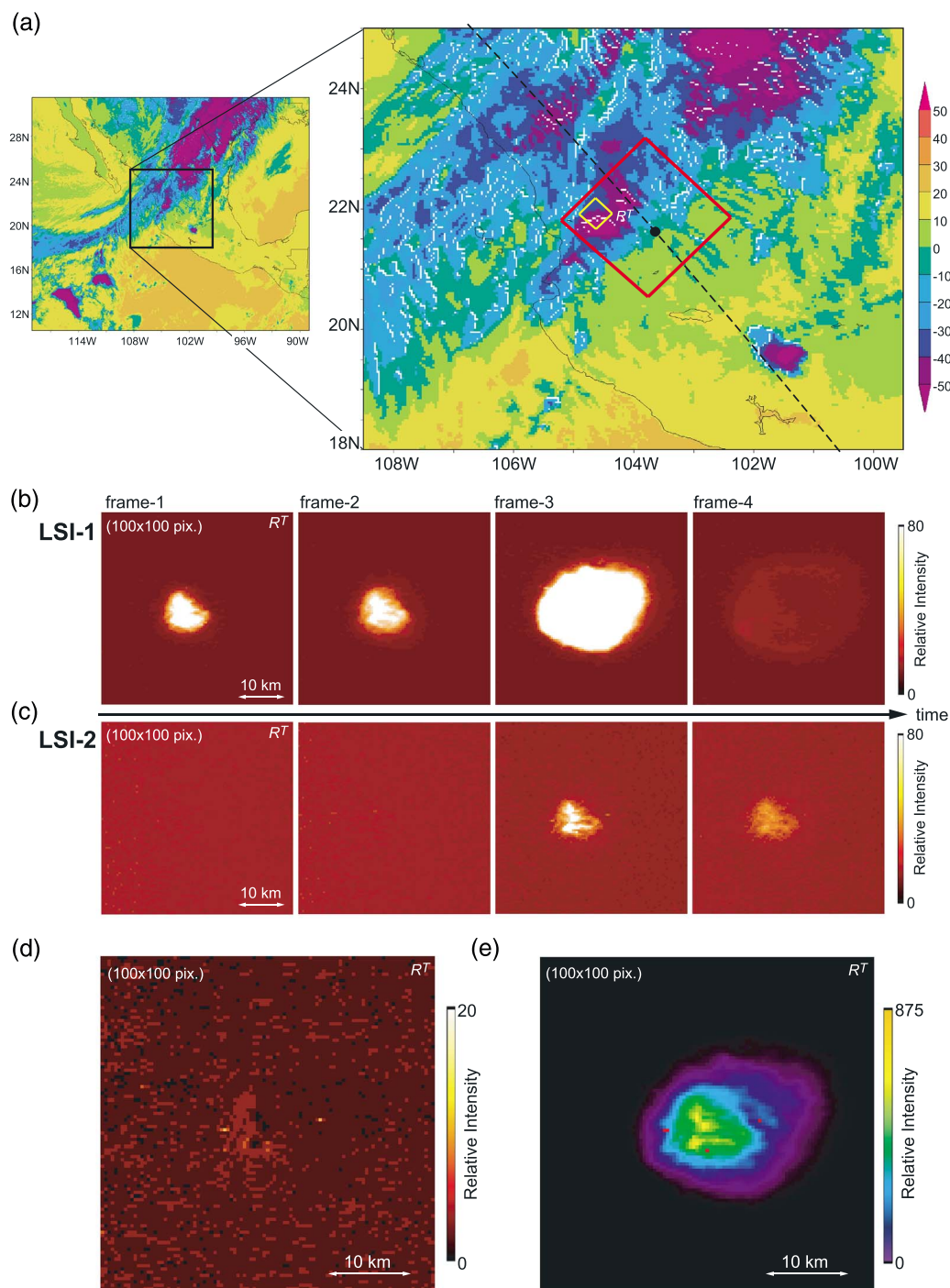


Figure 4. (a) IR brightness temperature image measured by the GOES satellite at 05:00 UT on 21 December 2013. The dashed line and the solid circle are the trajectory of the ISS footprint and the ISS footprint at the detection time of the event, respectively. The red and yellow squares are the FOV of the LSI at the detection time of the event and the area of the expanded LSI images in Figures 4b–4e, respectively. (b and c) Four consecutive expanded images of the LSI-1 and LSI-2 cropped from the original 512×512 size data. (d) Result of the image subtraction for the frame-3 images shown in Figures 4b and 4c. (e) LSI-1 image (rainbow color) overplotted by the subtracted optical emissions shown in Figure 4d (red color).

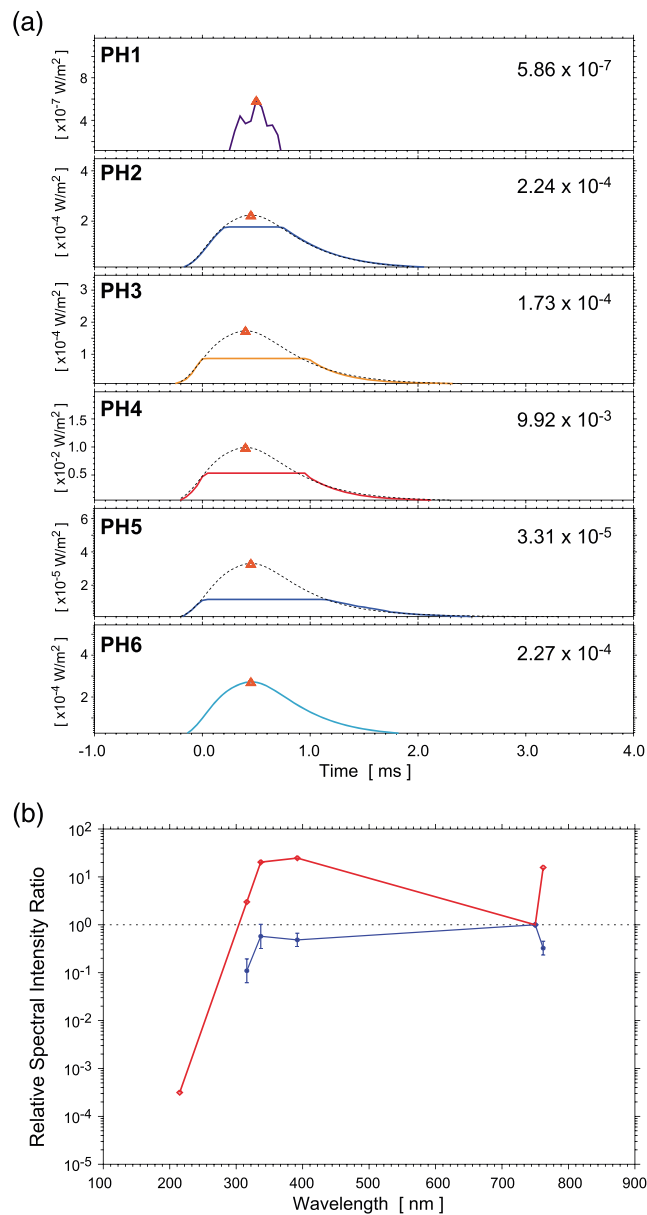


Figure 5. (a) Absolute optical intensity curves measured by the six PH channels for the time interval between $t = -1.0$ ms and $t = 4.0$ ms, where $t = 0.0$ ms is the trigger time (05:08:14.63340 UT). Dashed lines at the PH2–PH5 are the fitting curves using the PH6 data. Solid triangle at each panel indicates the peak intensity. (b) Relative spectral intensity ratio for the lightning events (blue line) and the event shown in Figure 5a (red line).

Figure 6a is a plot of ELF magnetic field waveform data acquired at Syowa station in the time period of 05:08:14.4–15.4 UT. Considering the optical propagation time of 1.37 ms from the assumed light source at the 10 km altitude to the 419.9 km ISS altitude, the distance of 14.2 Mm from the ISS footprint to Syowa station, and the wave propagation time of 59.1 ms with an assumed propagation velocity of $v = 0.8c$, the expected time of the wave arrival at Syowa station would be 05:08:14.69113 UT. In Figure 6a, a transient SR waveform denoted by an arrow was detected at 05:08:14.692 UT. The solid line in Figure 6b is the propagation path of the transient SR waveform. The bearing angle of the ISS footprint from the Syowa station and the bearing angle of the propagation path are 224.7° and 225.0° , respectively. Thus, we concluded that the transient SR waveform detected at 05:08:14.692 UT was excited by the lightning discharge detected by JEM-GLIMS. The CMC value of this lightning discharge was estimated to be +1573 C-km, which is strong enough to induce sprites.

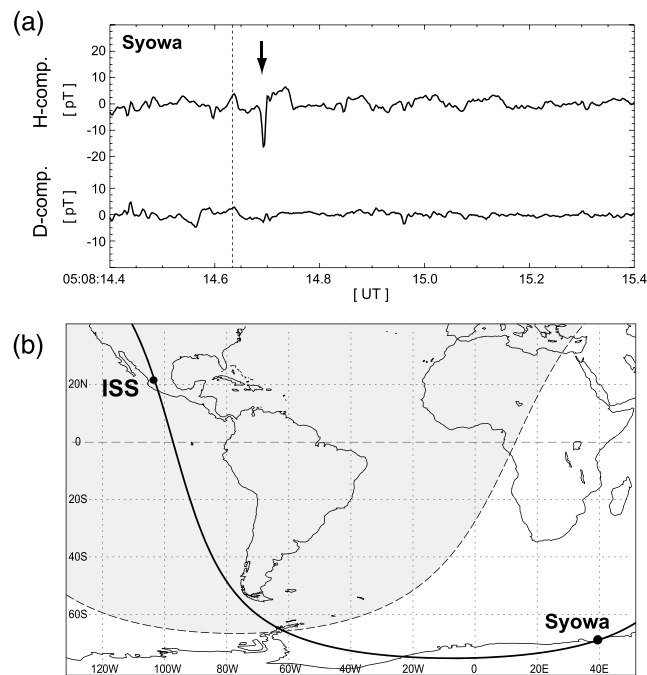


Figure 6. (a) ELF magnetic field waveforms in the magnetic north-south and east-west components measured at Syowa station, Antarctica in the time period 05:08:14.4–15.4 UT. The declination angle at Syowa station is -48.489° (westward from the geographical north). (b) Propagation path of the transient SR wave detected at 05:08:14.692 UT. The dark area corresponds to the nightside.

Considering all of the above results, the three spots shown in Figures 4d and 4e are judged to be sprite emissions. Based on the PH signals shown in Figure 5a, we can deduce that this event was also a short-delayed sprite.

4.3. Event #3: 03:48:24 UT on June 10 2014

A strong lightning emission was detected by JEM-GLIMS optical instrument over Guinea, Africa at 03:48:24.74035 UT on 10 June 2014, when the ISS was located at (9.74°W , 10.59°N) and 413.3 km altitude. Figure 7a is the IR brightness temperature image measured by the METEOSAT satellite at 04:00 UT on 10 June 2014. At the footprint of the ISS, a huge MCS was located, and the cloud top temperature was below -50°C . The altitude of the -50°C temperature level within the LSI FOV is estimated to be ~ 11.7 km using the MSISE-90 model.

In this event, lightning optical emissions appeared near the lower left at frame 1 and expanded toward the upper right until frame 4 in Figure 7b. In Figure 7c, no optical emission was detected at frame 1, but bright optical emissions appeared at frame 2 and expanded toward the upper right until frame 4 like the lightning optical emissions in Figure 7b. Figures 7d and 7e are the results of the image subtraction for the frame-2 data. From Figure 7e, the subtracted optical emission is located at the lower left from the peak position of the lightning emissions. As shown in Figure 7d, a bright spot within the dim emissions is confirmed in this event.

Figure 8a is the light curve plot of the PH. The saturated light curve data of the PH2–PH5 are fitted by the light curve data of the PH6, and the peak intensities are estimated to be 3.11×10^{-6} , 3.45×10^{-4} , 2.08×10^{-4} , 1.34×10^{-2} , 4.35×10^{-5} , and $5.12 \times 10^{-4} \text{ W/m}^2$, respectively. The ratio of these peak intensities normalized by the unit wavelength to the peak intensity of the PH4 is calculated and plotted in Figure 8b. Compared to the ratio of the JEM-GLIMS lightning events (blue line), the ratio of this event shows clear enhancement. PH2/PH4 is estimated to be 23.1.

Figure 9a shows the waveform plot of the ELF magnetic field data obtained at Esrange station in the time period of 03:48:24.5–25.5 UT on 10 June 2014. After the event trigger time of JEM-GLIMS denoted by the dashed line in Figure 9a, a transient SR wave was detected at 03:48:24.772 UT indicated by the arrow.

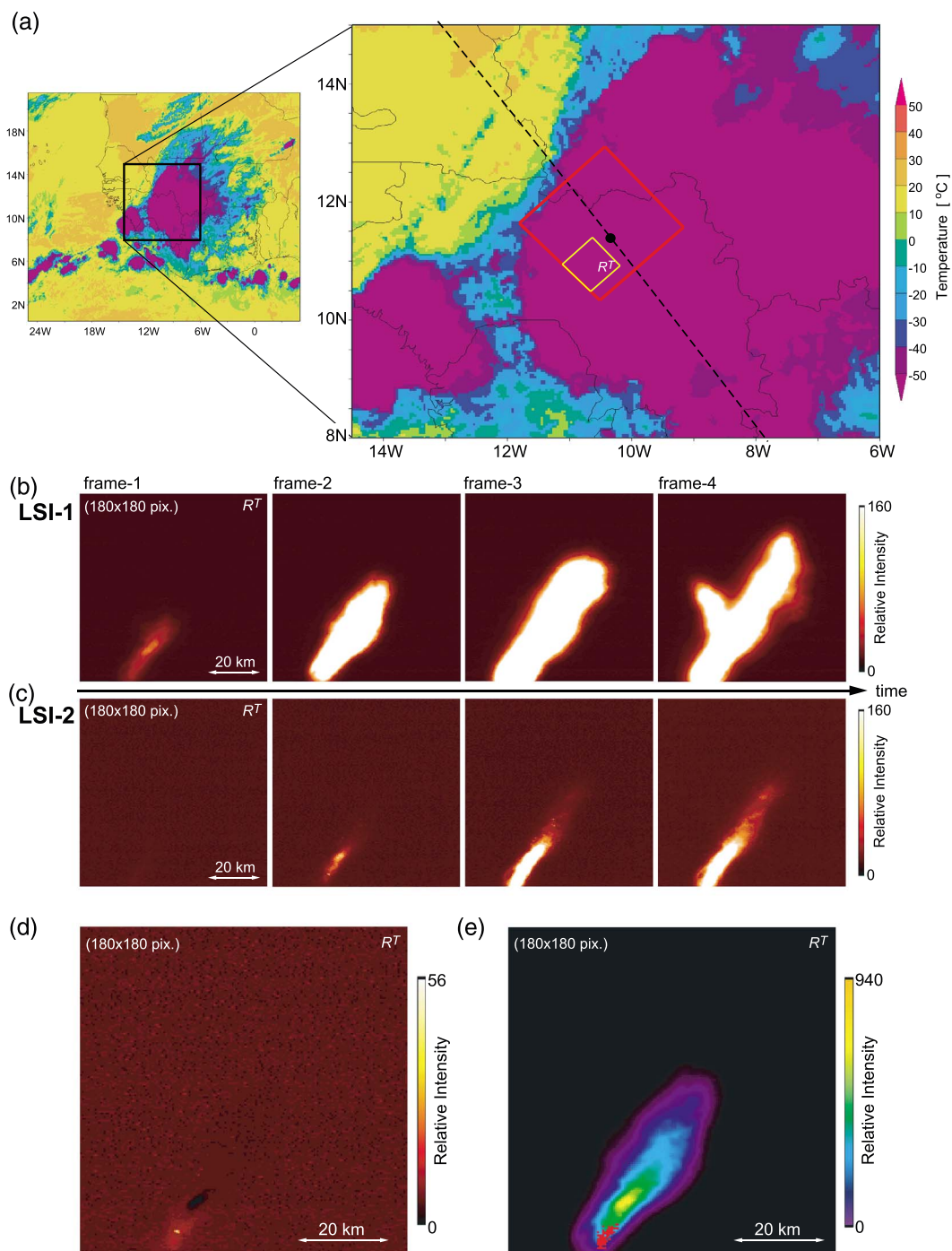


Figure 7. (a) IR brightness temperature image measured by the METEOSAT satellite at 04:00 UT on 10 June 2014. The dashed line and the solid circle are the trajectory of the ISS footprint and the footprint of the ISS at the detection time of the event, respectively. The red and yellow squares are the FOV of the LSI at the detection time of the event and the area of the expanded LSI images in Figures 7b–7e, respectively. (b and c) Four consecutive expanded images of the LSI-1 and LSI-2 cropped from the original 512×512 size data. (d) Result of the image subtraction for the frame-2 images shown in Figures 7b and 7c. (e) LSI-1 image (rainbow color) overplotted by the subtracted optical emissions in Figure 7d (red color).

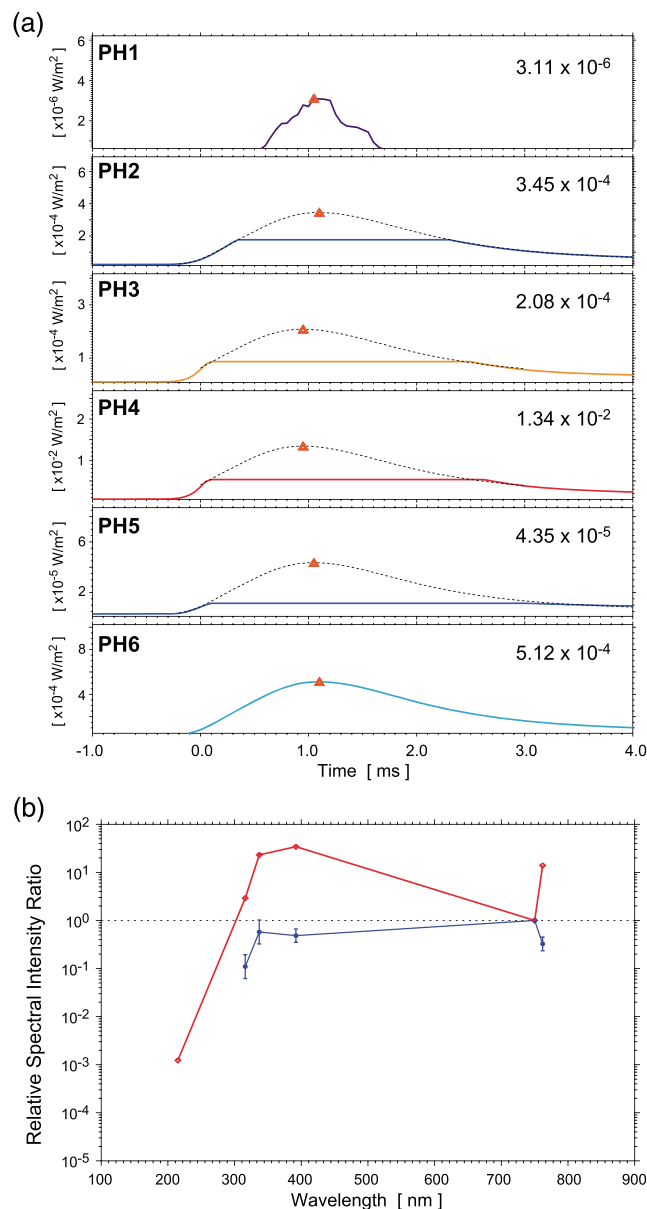


Figure 8. (a) Absolute optical intensity curves measured by the six PH channels for the time interval between $t = -1.0$ ms and $t = 4.0$ ms, where $t = 0.0$ ms is the trigger time (03:48:24.74035 UT). Dashed lines at the PH2–PH5 are the fitting curves using the PH6 data. Solid triangle at each panel indicates the peak intensity. (b) Relative spectral intensity ratio for the lightning events (blue line) and the event shown in Figure 8a (red line).

The distance between the ISS footprint when the event was detected and Esrange station is 6.76 Mm. Using the same assumption as events #1 and #2, the expected detection time of the transient SR wave at Esrange station is 03:48:24.76721 UT, which shows good agreement with the actual detection time. As shown in Figure 9b, the propagation path of the transient SR wave is well directed to the location of the ISS footprint. The bearing angle of the propagation path at Esrange station and the bearing angle of the ISS footprint from Esrange station are 221.9° and 215.3° , respectively. Thus, we concluded that the transient SR wave was excited by the lightning discharge detected by JEM-GLIMS. The CMC value is +3776 C-km.

From all of the above results, we concluded that the optical emission in Figure 7d was the sprite emissions and that this event was a short-delayed sprite because of the temporal changes in the PH signals shown in Figure 8a.

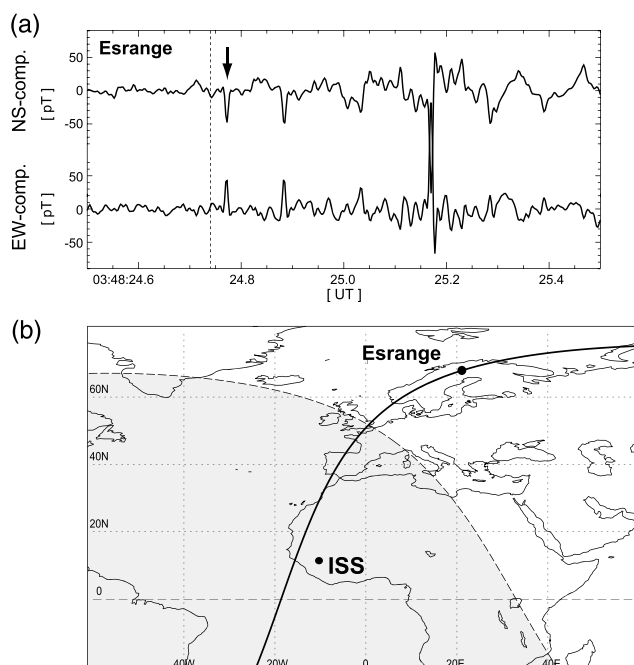


Figure 9. (a) ELF magnetic field waveforms in the geographical north-south and east-west components measured at ESRANGE station in the time period 03:48:24.5–25.5 UT. (b) Propagation path of the transient SR wave detected at 03:48:24.772 UT. The dark area corresponds to the nightside.

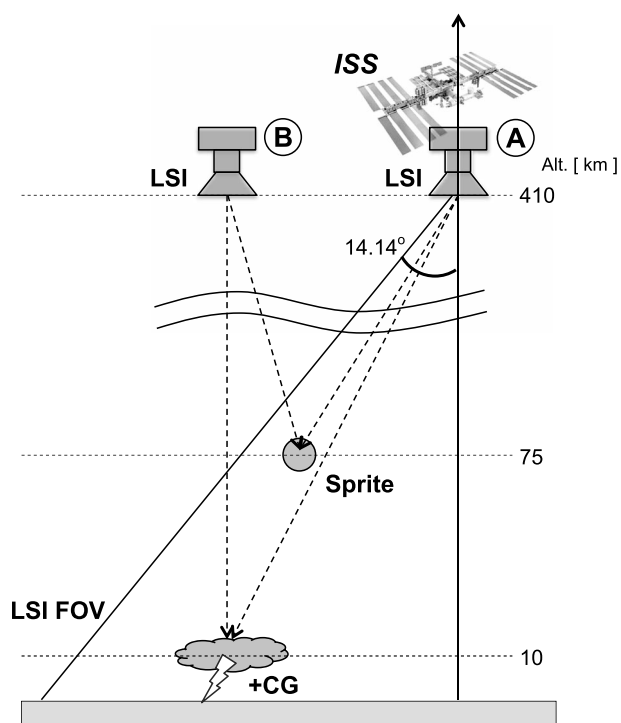


Figure 10. Schematic showing the observation geometry of sprites and sprite-producing lightning discharges and the FOV of the LSI. A and B are the position of the LSI at the ISS and above the sprite-producing lightning discharges, respectively.

5. Spatial Distribution of Sprites

5.1. Geometry-Converted Sprite Images

In many cases, optical emissions of lightning and TLEs detected by JEM-GLIMS typically occurred away from the nadir point of the ISS. As indicated by the yellow squares in Figures 1a, 4a, and 7a, the lightning and sprite emissions were detected near the edge of the LSI FOV. If the LSI observed these optical emissions just above the sprite-producing lightning discharges, the spatial distributions of lightning and sprites shown in Figures 1e, 4e, and 7e would be different because the occurrence altitudes of lightning and sprites are different. In order to estimate the actual spatial distributions of the lightning and sprite emissions, the observation geometry must be corrected in the LSI images.

Figure 10 is a schematic showing the observation geometry of lightning and sprite emissions. The typical orbital altitude of the ISS is 410 km, and the altitudes of sprites and sprite-producing lightning discharges are assumed to be 75 km and 10 km, respectively. When sprites and sprite-producing lightning discharges occurred away from the nadir point of the ISS and when sprites were slightly displaced from the parent lightning discharges, the LSI locating at the position [Ⓐ] in Figure 10 would observe these emissions in almost the same directions. However, such LSI images do not present the accurate spatial distributions of sprites and sprite-producing lightning discharges. By using the ISS location and attitude data and by assuming the sprite and lightning altitudes, the geometry of sprites and sprite-producing lightning discharges in the LSI images can be corrected as observed by the LSI locating at the position [Ⓑ] in Figure 10. That is, the geographical coordinates (longitude and latitude) of each pixel in the LSI-1 image are first calculated using above assumptions. Similarly, the geographical coordinates of each pixel in the subtracted image are calculated as a next step. Finally, the lightning and sprite emissions are replotted in the same longitudinal and latitudinal pixel coordinates. This geometry conversion was applied to Figures 1e, 4e, and 7e.

Figures 11a and 11b are the geometry-converted LSI images with the 512×512 and 128×128 size data for event #1, respectively. In these figures, the lightning and sprite emissions are drawn by the rainbow and red colors, respectively. In Figure 11a, the nadir point of the ISS and center of the LSI FOV are marked by the red and white closed squares. As shown in Figure 11a, the lightning and sprite emissions occurred with ~ 109 km offset from the nadir point and were detected near the edge of the LSI FOV. By comparing Figure 11b with Figure 1e, the location of the sprite emission apparently shifted to the nadir direction by ~ 17 km. Note that there was no strong lightning emission just below the sprite emission, which suggests that there was actually no lightning emission or that the optical emission was too weak to be detected by the LSI. Figures 11c and 11d are the geometry-converted LSI images with the 512×512 and 100×100 size data for event #2, respectively, and the format of these figures is the same as Figures 11a and 11b. As shown in Figure 11c, the lightning and sprite emissions were detected near the lower left of the LSI FOV. After the geometry conversion, the three sprite spots denoted by [Ⓐ], [Ⓑ], and [Ⓒ] in Figure 11d moved from the region just above the lightning emissions as shown in Figure 4e to the nadir direction by ~ 16 km on average. Figures 11e and 11f are the geometry-converted LSI images with 512×512 and 180×180 size data for event #3, respectively, and the format of these figures is also the same as Figures 11a and 11b. In this event, the lightning and sprite emissions were detected near the lower middle edge of the LSI FOV as shown in Figure 11e. By comparing Figure 11f with Figure 7e, the sprite emissions are shifted relative to the nadir direction by ~ 15 km.

In Figures 1e, 4e, and 7e, the sprite emissions were located in the region overlapping with the lightning emissions. However, in the geometry-converted images of Figures 11b, 11d, and 11f, the clear displacement between the positions of the peak lightning emissions and the sprite emissions is confirming the occurrence of sprite emissions.

5.2. Validity of the Geometry Conversion

As presented in section 5.1, the geometry conversion of the LSI images rearranged the distributions of the lightning and sprite emissions from Figures 1e, 4e, and 7e to Figures 11b, 11d, and 11f. In order to check the validity of the geometry conversion method, we performed simple model calculations estimating images of lightning and sprite emissions before and after the geometry conversion. As an example of the model calculation, the lightning and sprite emissions presented in event #1 are referred.

Figure 12a is a schematic showing the geometry of lightning and sprite emissions and the locations of the LSI, which is the assumption for the model calculation. Based on Figures 11a and 11b, the following five conditions are assumed: (1) the optical emission of lightning discharge is located at 81.7 km away from the ISS nadir point and at 10 km altitude, (2) the shape of the lightning emission is determined by a Gaussian distribution with

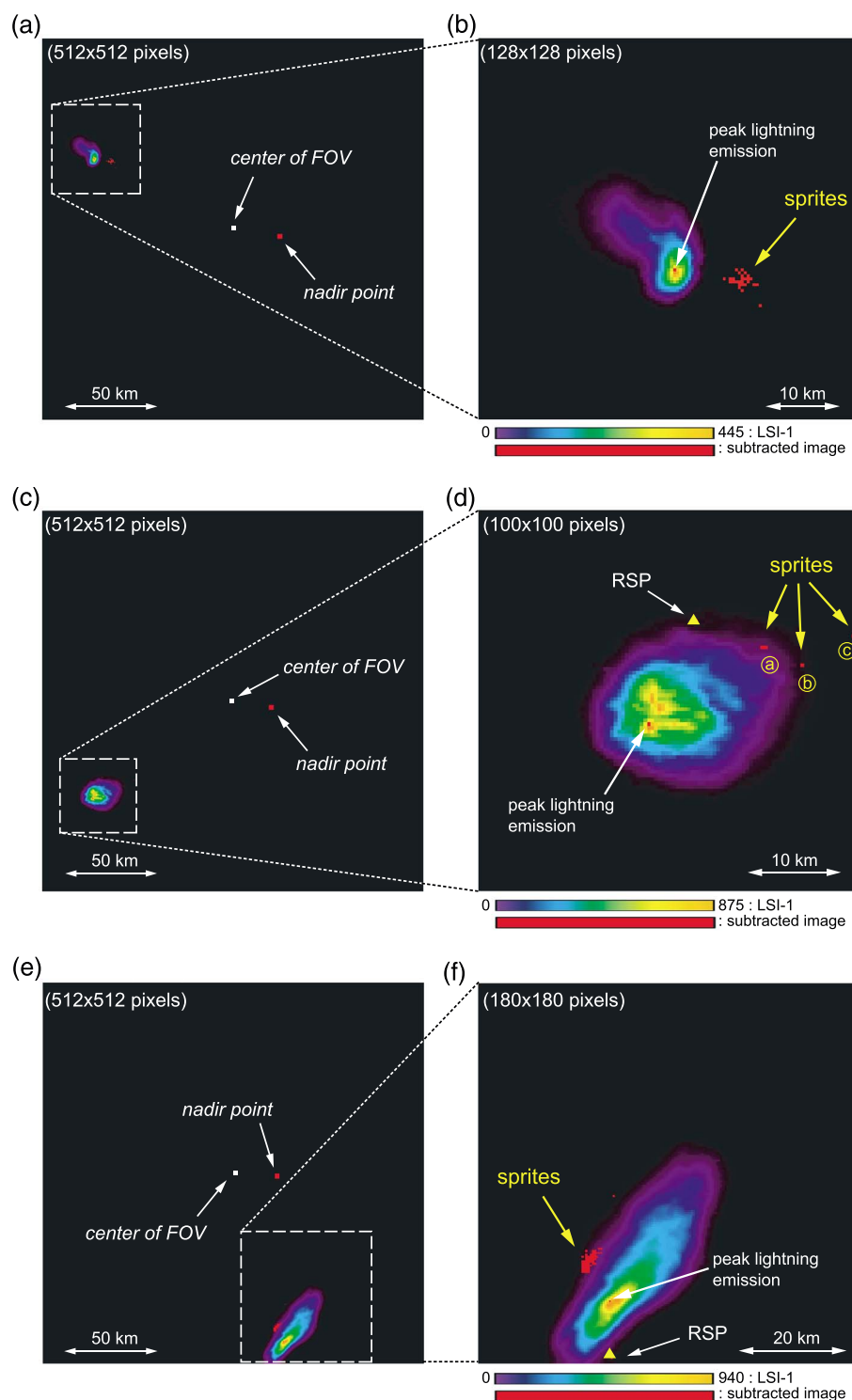


Figure 11. (a and b) Geometry-converted images of lightning and sprite emissions for event #1 with the 512×512 and 128×128 size data, respectively. The locations of the ISS nadir point and the center of the LSI FOV are denoted by the red and white dots, respectively. (c and d) Same as Figures 11a and 11b except for event #2. The expanded image in Figure 11d is 100×100 size data. In this figure, each sprite spot is marked with (a), (b), and (c), and the return stroke point (RSP) detected by WWLLN is denoted by the yellow triangle. (e and f) Same as Figures 11a and 11b except for event #3. The expanded image in Figure 11f is 180×180 size data. RSP detected by WWLLN is also denoted by the yellow triangle in Figure 11f.

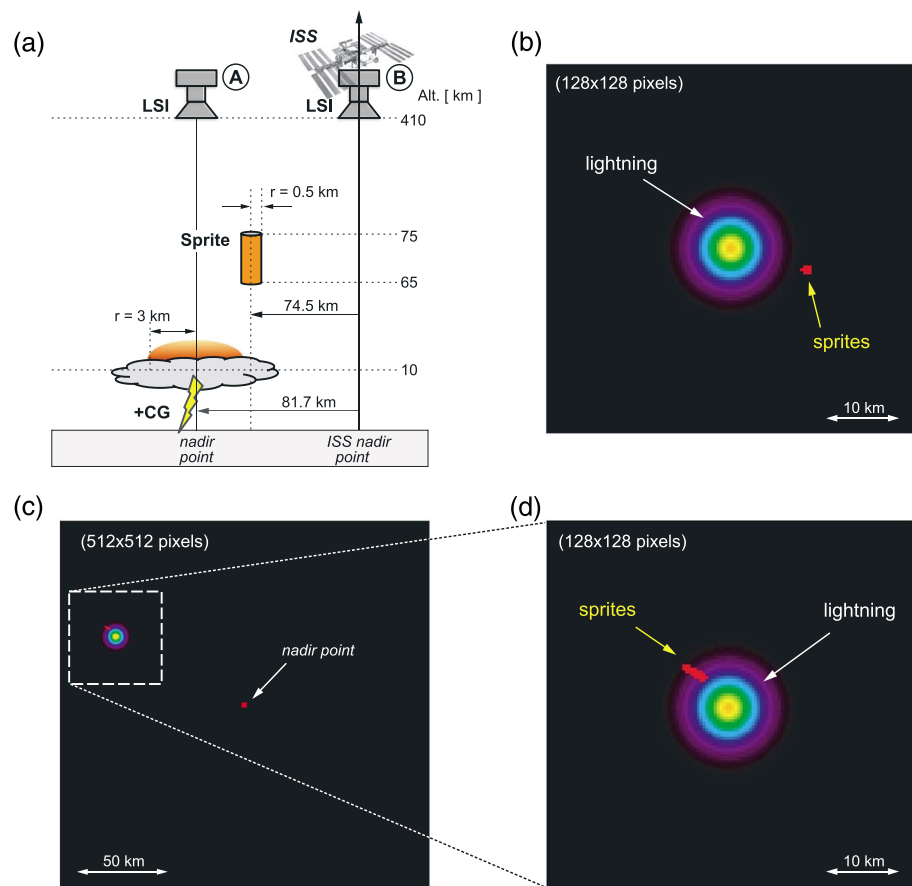


Figure 12. (a) Schematic showing the occurrence geometry of the sprite and the sprite-producing CG discharge for the model calculation. The positions of the LSI over the sprite-producing CG discharge and at the ISS are denoted by ① and ②, respectively. (b) Simulated image of lightning and sprites as observed by the LSI locating at ①. (c and d) Simulated 512×512 and 128×128 size images of lightning and sprite emissions as observed by the LSI locating at ②, respectively.

the radius of 3 km, (3) the sprite emission is located at 74.5 km away from the ISS nadir point, (4) the sprite emission has a cylindrical shape ranging from 65 km to 75 km altitude with the radius of 0.5 km, and (5) the LSI is located at the positions ① and ② at 410 km altitude and directed in the nadir. Then the expected image measured by the LSI locating at the position ① is calculated and shown in Figure 12b, where the lightning and sprite emissions are drawn by the rainbow and red colors, respectively. By comparing Figure 11b with Figure 12b, the distribution of the lightning and sprite emissions is comparable. As a next step, the image measured by the LSI locating at the position ② is reconstructed and presented in Figures 12c and 12d, where the image size is 512×512 and 128×128 , respectively. It is found that the location of the sprite emission has moved to the opposite direction of the nadir point and that the distance between the sprite emission and the center of the lightning emission is 21 pixels at maximum. By comparing Figure 12d with Figure 1e, the distribution of lightning and sprite emissions is quite consistent. In Figure 1e, the distance between the sprite emission and the peak location of the lightning emission is ~ 30 pixels, which is good agreement with the model calculations. Therefore, we concluded that the geometry conversion is correctly applied to Figures 1e, 4e, and 7e and that the distribution of sprites shown in Figures 11b, 11d, and 11f is reasonable.

5.3. Spatial Distribution of Sprites and Parent Lightning Discharges

The vertical length of sprite emissions in time-accumulated camera images is typically > 10 km. So when the sprite emission is detected near the edge of the LSI FOV, the LSI will measure the vertical structure of the sprite. In event #1, the displacement of the sprite emission from the parent +CG discharge is estimated to be ~ 9.7 km. If we assume that the altitude of the sprite emission was 75 km and that the altitude of the sprite-producing lightning emission was 14 km or 6.0 km, the displacement is estimated to be 8.3 km and 11 km, respectively. In addition, if we assume that the altitude of the sprite was 80 km or 70 km and that the

altitude of the parent lightning was 10 km, the displacement becomes 11 km and 8.0 km, respectively. Thus, we think that the error margin of the estimated displacement (~ 9.7 km) is an order of ± 2 km. The return stroke point of the parent +CG discharge is checked using the NLDN and WWLLN data. The location of the peak lightning emission in Figure 11b is (96.13°W, 39.21°N). From the ISS position and altitude, the propagation time of the optical emissions radiated at 10 km altitude is calculated to be 1.40 ms. Then the expected occurrence time of the sprite-producing lightning discharges is 06:41:15.68425 UT. The NLDN detected a +CG discharge at 06:41:15.677 UT at (96.80°W, 39.99°N), where 7.25 ms time difference from the expected occurrence time of the sprite-producing lightning discharges and the 217.3 km horizontal displacement from the location of the peak lightning emission exist. Similarly, the WWLLN detected a lightning stroke at 06:41:15.550016 UT at (96.84°W, 39.75°N), where 134 ms time difference and the 197.6 km horizontal displacement exist. In fact, the locations of the lightning discharges detected by NLDN and WWLLN are out of the LSI FOV in Figure 11a. However, the transient SR wave shown in Figure 3a was surely detected at Esrange station. Consequently, we concluded that the lightning discharges detected by NLDN and WWLLN differ from the lightning discharge detected by JEM-GLIMS and that these networks could not detect the sprite-producing +CG discharge.

In event #2, the distance between each sprite spot in Figure 11d is $\textcircled{a}-\textcircled{b} = 4.57$ km, $\textcircled{a}-\textcircled{c} = 9.92$ km, and $\textcircled{b}-\textcircled{c} = 6.58$ km, respectively. The distance between the peak lightning emission and the sprite spots is 25.1 km at maximum, 15.8 km at minimum, and 19.8 km on average. The error margin of the average displacement is also estimated to be an order of ± 2 km. In this event, WWLLN detected a lightning stroke at 05:08:14.631433 UT at (104.55°W, 22.01°N). From the ISS position and altitude and the event trigger time recorded by the PH, the expected occurrence time of the sprite-producing +CG discharge is 05:08:14.63199 UT, which is only 0.56 ms time difference from the detection time of WWLLN. In Figure 11d, the return stroke point (RSP) estimated by WWLLN is denoted by the yellow closed triangle. The distance between the location of the peak lightning emission and RSP is 12.32 km. Assuming that the location of the peak lightning emission corresponds to the return stroke point, the distance of 12.32 km seems to be slightly larger than the WWLLN location accuracy of <10 km reported by *Rodger et al.* [2009]. However, we concluded that the lightning discharges detected by JEM-GLIMS and WWLLN are the same event according to the coincidence of the occurrence time. The distance between RSP and the three sprite spots is 11.7 km on average.

In event #3, the distance between the sprite emission and the parent +CG discharge is ~ 8.6 km with the error of ± 2 km. WWLLN detected the lightning stroke at 03:48:24.738382 UT at (10.97°W, 10.81°N), which is comparable to the expected occurrence time of the sprite-producing +CG discharges (03:48:24.73896 UT) derived from the ISS position and altitude and the location of the peak lightning emission. RSP estimated by WWLLN is indicated by the yellow closed triangle in Figure 11f, and the distance between RSP and the location of the peak lightning emission is 9.6 km. Thus, we identified the lightning stroke detected by WWLLN as being the same event detected by JEM-GLIMS. The distance between RSP and the sprite emission is ~ 18.1 km.

The spatial distributions of the sprites and the sprite-producing +CG discharges presented in Figures 11b, 11d, and 11f showed that the sprites occurred with a certain spatial offset from the peak optical emission point of the parent +CG discharges. These characteristics are fairly consistent with that presented in Figure 4 by *Yair et al.* [2013]. They analyzed the image data obtained from nadir observations from the ISS using an electron multiplication CCD camera and showed that the location of the spot-like sprite emission was displaced from the optical emission area of the parent lightning discharge.

6. Discussion

6.1. Displacement of the Sprite Emissions

From Figures 11b, 11d, and 11f, the horizontal displacement of sprite emissions from the location of the peak emission from the parent lightning is estimated to be 9.7, ~ 20 , and 8.6 km, respectively. In events #2 and #3, the horizontal displacement of the sprite locations from the parent lightning discharges detected by WWLLN is ~ 12 and ~ 18 km, respectively. Basically, the horizontal displacement of the sprite locations from the return stroke point of the parent CG discharges is reported to be 50 km at maximum in the previous studies [*Lyons*, 1996; *Wescott et al.*, 2001; *Soula et al.*, 2010]. *Yair et al.* [2013] reported that the horizontal displacement was estimated to be ~ 27 km in the sprite event detected by the nadir observations from the ISS. In addition, *Lu et al.* [2013] pointed out that sprites produced by lightning discharges with iCMCs of $+200$ C·km and having short time delay from the parent lightning discharges are typically centered within 30 km of the return stroke point of the parent stroke and that sprites with long delay time from the parent lightning discharges are

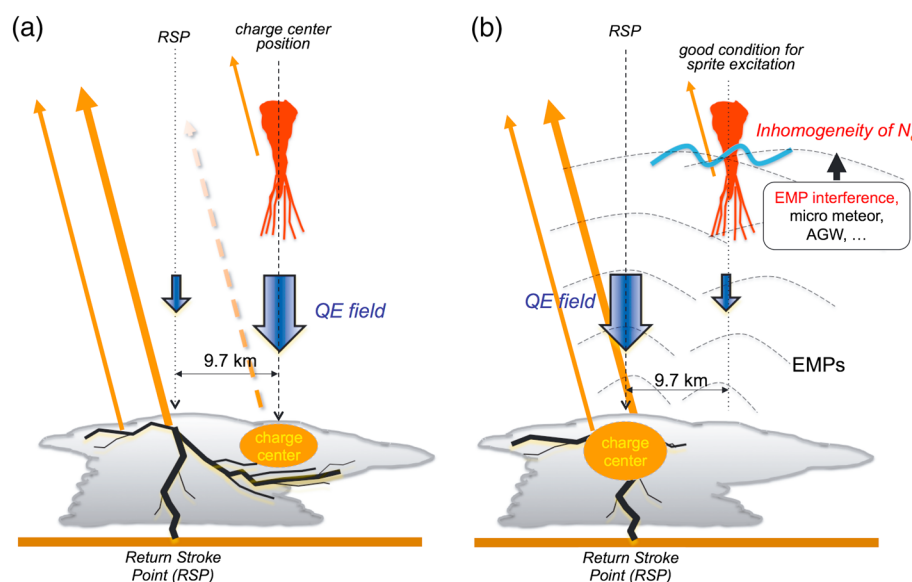


Figure 13. (a and b) Two possible scenarios explaining the lightning current structures in the thundercloud and the occurrence conditions of sprites for event #1.

typically displaced by >30 km (45 km on average) from the return stroke point of the parent stroke, regardless of the amplitude of iCMCs. Considering that the three events detected by JEM-GLIMS were the short-delayed sprites as presented in sections 4.1–4.3, the estimated displacement is well comparable to that reported by *Lu et al.* [2013]. Thus, we can conclude that the displacement and distribution of the sprites in these events are reasonably estimated.

6.2. Possible Occurrence Conditions of Sprites

As shown in Figures 11b, 11d, and 11f, there was no intense lightning emission just below the sprite emission, which was enough to be detected by the LSI. Here we considered the occurrence conditions of the sprite and the sprite-producing +CG discharge in event #1, as an example. We think that there are at least two scenarios to explain the conditions, and these scenarios are schematically shown in Figure 13.

The first scenario is schematically shown in Figure 13a. In this scenario, we considered that the lightning currents locating at the left side of the return stroke point in the thundercloud flowed near the cloud top, while the lightning currents at the right side of the return stroke point flowed near the lower part of the thundercloud. We also assumed that the center of the charges neutralized by the lightning discharge was located at the right side with 9.7 km horizontal offset from the return stroke point. As the strongest quasi-electrostatic (QE) field would be created just above the charge center, sprites would be excited just above the charge center with the horizontal displacement of 9.7 km according to the prediction of the QE model. The optical emissions of the lightning currents flowing near the cloud top, return stroke, and sprites were strong enough to reach the ISS. However, the optical emissions of the lightning currents flowing at the right side of the return stroke point would be severely scattered in the thundercloud. As the intensity of the scattered emissions would be below the detection sensitivity of the LSI, the optical emissions of the sprite and the parent lightning discharge were obtained by the LSI as shown in Figure 11b.

The second scenario is schematically presented in Figure 13b. In this scenario, the lightning currents had a vertical return stroke channel and horizontal current channels in the thundercloud at the left side of the return stroke point. At the right side of the return stroke point, there was very weak or no lightning current in the thundercloud. In this case, the position of the center of the neutralized charges was located near the return stroke point. Then the strongest QE field would be initiated above the center of the neutralized charges, while the weaker QE field would be excited above the position displaced by 9.7 km from the return stroke point. However, some conditions that could easily excite sprites even under the weak QE field were already established before the weak QE field may have been already established before the initiation of the sprite. Consequently, sprite was occurred with a horizontal shift of 9.7 km, and the LSI detected the sprite and lightning optical emissions as presented in Figure 11b.

We expect that these two scenarios may be applicable not only to the sprite event #1 but also to the sprite events #2 and #3. Recently, it is suggested that such occurrence conditions are closely related with the spatial inhomogeneity of the conductivity at the sprite altitude, that is, the inhomogeneity of the electron density (N_e) [Qin *et al.*, 2011, 2012]. There are many possibilities to create such conductivity inhomogeneity, such as the interference of the electromagnetic pulses (EMPs) radiated by the in-cloud lightning currents, atmospheric gravity waves, and micrometeors. Only from JEM-GLIMS optical data, it is not easy to clarify the origin of the conductivity inhomogeneity. However, JEM-GLIMS equips the VHF interferometer (VITF), which enables us to estimate the spatiotemporal development of the lightning current channels in thunderclouds. So we expect that more realistic spatiotemporal development and distribution of the in-cloud lightning currents in the sprite events can be derived from the VITF data. In addition to this, the lightning and sprite emissions in event #1 were detected near the LMA, which also enables us to precisely determine the spatiotemporal evolution of the in-cloud lightning currents and confirm if a lightning really occurred in that place. From the further detailed data analysis of VITF and LMA data, the effect of EMPs on the generation of the conductivity inhomogeneity at the sprite altitude can be quantitatively evaluated. At the same platform as JEM-GLIMS, VISI (Visible and Infrared Spectral Imager) of the ISS-Ionosphere, Mesosphere, Upper Atmosphere and Plasmasphere Mapping mission is installed and measures the OH airglow emissions [Akiya *et al.*, 2014]. From the detailed comparison between the spatial distributions of sprites detected by JEM-GLIMS and the OH airglow distributions measured by VISI, we expect that the effect of atmospheric gravity waves on the conductivity inhomogeneity at 85 km can be evaluated. The results derived from such detailed data analysis will be summarized in future papers.

7. Summary

In this paper, three sprite events observed by JEM-GLIMS are presented as a case study. In order to distinguish the weak sprite emissions from the incomparably more intense lightning emissions, three data processing techniques are used: (1) a subtraction of the appropriately scaled LSI-1 image from the LSI-2 image, (2) a calculation of the intensity ratio between the different PH channels, and (3) an estimation of the polarization and CMC for the parent CG discharges using ground-based ELF observation data. From the image subtraction procedure, detailed spatial distributions of sprites and their parent lightning discharges are obtained. The sprite emissions are found to be located over the lightning emissions in the subtracted images of Figures 1e, 4e, and 7e. However, in the geometry-converted images shown in Figures 11b, 11d, and 11f, the locations of the sprite emissions are clearly displaced by 8–20 km from the peak positions of the parent CG discharges and the return stroke positions detected by NLDN and WWLLN. In order to validate the geometry conversion method, a simple model calculation estimating images of lightning and sprite emissions before and after the geometry conversion is performed. As an example of the model calculation, we chose the lightning and sprite emissions of event #1. Then the spatial distribution of the lightning and sprite emissions in the modeled images of Figures 12b and 12d agrees well with that in the actual LSI images in Figures 11b and 1e, which suggests that the rearrangement of the sprite emissions by the geometry conversion is correct. The possible characteristics of the sprite-producing CG discharges and related occurrence conditions of the sprite in event #1 are discussed. We proposed two scenarios describing the spatial distributions of the sprite and the sprite-producing CG discharge shown in Figure 11b. In the first scenario, the locations of the return stroke and the center of the charges neutralized by the lightning discharge are different as shown in Figure 13a. Above the center of the neutralized charges shifted by 9.7 km from the return stroke point, the strongest QE field is generated and excites the sprite emission. In the second scenario, the locations of the return stroke and the center of the neutralized charges are almost the same as shown in Figure 13b, and the strongest QE field is generated above the return stroke point. However, in this case, some conditions related to mesospheric conductivity inhomogeneity existing before the initiation of sprites [Qin *et al.*, 2011, 2013]. There are many possibilities to create such conductivity inhomogeneity, such as the interference of EMPs radiated by the in-cloud lightning currents [Valdivia *et al.*, 1997; Cho and Rycroft, 1998, 2001; Marshall *et al.*, 2007], atmospheric gravity waves, and micrometeors. Only from JEM-GLIMS optical data, it is not easy to clarify the origin of the conductivity inhomogeneity. In order to identify the occurrence conditions of sprites, we need further detailed analyses using VHF pulse data obtained by VITF on board JEM-GLIMS and LMA data, and we need a quantitative comparison between the spatial distributions of sprites and the spatiotemporal evolution of the in-cloud lightning currents, which will be summarized in future papers.

Acknowledgments

This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (B) Number 24340117 and MEXT KAKENHI Grant-in-Aid for Specially Promoted Research Number 19002002. JEM-GLIMS and Sowa ELF data presented in this study are available upon request from the corresponding author, Mitsuteru Sato (msato@ep.sci.hokudai.ac.jp). IR cloud images were obtained from the Web page of Goddard Earth Sciences Data and Information Services Center (GES DISC) (<http://disc.sci.gsfc.nasa.gov>). We used the MSISE-90 model at the Virtual Ionosphere, Thermosphere, Mesosphere Observatory (VITMO), NASA (http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html). NLDN data were obtained from Global Hydrology Resource Center (GHRC) (<https://ghrc.nsstc.nasa.gov>). WWLLN data were kindly provided by R. Holzworth (University Washington, USA). All data analyses were performed using the Interactive Data Language (IDL) version 8.2. The authors thank Yoav Yair and two other anonymous reviewers for their comments and suggestions to improve this paper.

References

- Abarca, S., K. Corbosiero, and T. Galarneau Jr. (2010), An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth, *J. Geophys. Res.*, **115**, D18206, doi:10.1029/2009JD013411.
- Adachi, T., et al. (2013a), Nadir observation of lightning and TLEs by JEM-GLIMS: Comparison with ISUAL Limb observation, Abstract PEM09-04 presented at 2013 Fall Meeting, AGU, Makuhari, 19–24 May.
- Adachi, T., et al. (2013b), Detection method of lightning and TLEs by JEM-GLIMS Nadir observation, Abstract AE33A-0317 presented at 2013 Fall Meeting, AGU, San Francisco, Calif., 9–13 Dec.
- Akiya, Y., A. Saito, T. Sakano, Y. Hozumi, A. Yamazaki, Y. Otsuka, M. Nishioka, and T. Tsugawa (2014), First spaceborne observation of the entire concentric airglow structure caused by tropospheric disturbance, *Geophys. Res. Lett.*, **41**, 6943–6948, doi:10.1002/2014GL01403.
- Blanc, E., T. Farges, R. Roche, D. Brebion, T. Hua, A. Labarthe, and V. Melnikov (2004), Nadir observations of sprites from the International Space Station, *J. Geophys. Res.*, **109**, A02306, doi:10.1029/2003JA009972.
- Blanc, E., T. Farges, D. Brebion, A. Labarthe, and V. Melnikov (2006), Observations of sprites from space at the nadir: The LSO experiment on board of the International Space Station, in *Sprites, elves and Intense Lightning Discharges*, NATO Sci. Ser. II, vol. 225, pp. 151–166, Springer.
- Blanc, E., et al. (2007), Main results of LSO (Lightning and Sprite Observations) on board of the International Space Station, *Microgravity Sci. Technol.*, **19**, 80–84.
- Blanc, E., T. Farges, A. Jehl, R. Binet, P. Hébert, F. Le Mer-Dachard, K. Ravel, and M. Sato (2012), Taranis MCP: A joint instrument for accurate monitoring of transient luminous event in the upper atmosphere, *Proc. Intl. Conf. Space Optics*, 9–12.
- Boeck, W., Jr. Vaughan, O., R. Blakeslee, B. Vonnegut, and M. Brook (1998), The role of the space shuttle videotapes in the discovery of sprites, jets and elves, *J. Atmos. Sol. Terr. Phys.*, **60**, 669–677, doi:10.1016/S1364-6826(98)00025-X.
- Chang, S., et al. (2010), ISUAL far-ultraviolet events, elves, and lightning current, *J. Geophys. Res.*, **115**, A00E46, doi:10.1029/2009JA014861.
- Chen, A. B., et al. (2008), Global distributions and occurrence rates of transient luminous events, *J. Geophys. Res.*, **113**, A08306, doi:10.1029/2008JA013101.
- Cho, M., and M. J. Rycroft (1998), Computer simulation of the electric field structure and optical emission from cloud-top to the ionosphere, *J. Atmos. Sol. Terr. Phys.*, **60**, 871–888.
- Cho, M., and M. Rycroft (2001), Non-uniform ionisation of the upper atmosphere due to the electromagnetic pulse from a horizontal lightning discharge, *J. Atmos. Sol. Terr. Phys.*, **63**(6), 559–580, doi:10.1016/S1364-6826(00)00235-2.
- Cummer, S., and U. Inan (1997), Measurement of charge transfer in sprite-producing lightning using ELF radio atmospherics, *Geophys. Res. Lett.*, **24**(14), 1731–1734.
- Cummer, S. (2003), Current moment in sprite-producing lightning, *J. Atmos. Sol. Terr. Phys.*, **65**, 499–508, doi:10.1016/S1364-6826(02)00318-8.
- Cummer, S., and W. Lyons (2005), Implications of lightning charge moment changes for sprite initiation, *J. Geophys. Res.*, **110**, A04304, doi:10.1029/2004JA010812.
- Cummins, K., 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. EMC*, **51**(3), 499–518, doi:10.1109/TEMC.2009.2023450.
- Cummins, K., M. Murphy, E. Bardo, W. Hiscoc, R. Pyle, and A. Pifer (1998), A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, **103**(D8), 9035–9044, doi:10.1029/98JD00153.
- Ebert, U., et al. (2006), The multiscale nature of streamers, *Plasma Sources Sci. Technol.*, **15**, S118—S129, doi:10.1088/0963-0252/15/2/S14.
- Ebert, U., et al. (2011), Multiple scales in streamer discharges, with an emphasis on moving boundary approximations, *Nonlinearity*, **24**, C1—C26, doi:10.1088/0951-7715/24/1/C01.
- Franz, R., R. Nemzek, and J. Winckler (1990), Television image of a large upward electrical discharge above a thunderstorm, *Science*, **264**, 48–51.
- Frey, H., et al. (2005), Beta-type stepped leader of elve-producing lightning, *Geophys. Res. Lett.*, **32**, L13824, doi:10.1029/2005GL020380.
- Füllekrug, M., and S. Constable (2000), Global triangulation of intense lightning discharges, *Geophys. Res. Lett.*, **27**, 333–336, doi:10.1029/1999GL003684.
- Gamerota, W., S. Cummer, J. Li, H. Stenbaek-Nielsen, R. Haaland, and M. McHarg (2011), Comparison of sprite initiation altitudes between observations and models, *J. Geophys. Res.*, **116**, A02317, doi:10.1029/2010JA016095.
- Gerken, E., and U. Inan (2003), Observations of decameter-scale morphologies in sprites, *J. Atmos. Sol. Terr. Phys.*, **65**(5), 567–572, doi:10.1016/S1364-6826(02)00333-4.
- Hu, W., S. Cummer, W. Lyons, and T. Nelson (2002), Lightning charge moment changes for the initiation of sprites, *Geophys. Res. Lett.*, **29**(8), 1279, doi:10.1029/2001GL014593.
- Hu, W., S. Cummer, and W. Lyons (2007), Testing sprite initiation theory using lightning measurements and modeled electromagnetic fields, *J. Geophys. Res.*, **112**, D13115, doi:10.1029/2006JD007939.
- Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, and C. Wong (1999), Criteria for sprites and elves based on Schumann resonance observations, *J. Geophys. Res.*, **104**(D14), 16,943–16,964, doi:10.1029/1999JD900139.
- Hutchins, M., R. Holzworth, J. Brundell, and C. Rodger (2012), Relative detection efficiency of the World Wide Lightning Location Network, *Radio Sci.*, **47**, RS6005, doi:10.1029/2012RS005049.
- Jehl, A., T. Farges, and E. Blanc (2013), Color pictures of sprites from non-dedicated observation on board the International Space Station, *J. Geophys. Res. Space Physics*, **118**, 454–461, doi:10.1029/2012JA018144.
- Kanmae, T., H. Stenbaek-Nielsen, and M. McHarg (2007), Altitude resolved sprite spectra with 3 ms temporal resolution, *Geophys. Res. Lett.*, **34**, L07810, doi:10.1029/2006GL028608.
- Kanmae, T., H. Stenbaek-Nielsen, M. McHarg, and R. Haaland (2012), Diameter-speed relation of sprite streamers, *J. Phys. D: Appl. Phys.*, **45**(1–11), doi:10.1088/0022-3727/45/27/275203.
- Kikuchi, M., et al. (2011), Development of science data handling unit (SHU) for Global Lightning And Sprite Measurements (GLIMS) onboard Japanese experiment module (JEM) of ISS, *IEEE Trans. Fundam. Mater.*, **131**(12), 989–993, doi:10.1541/ieefms.131.989.
- Kobayashi, N., et al. (2012), Spatial and temporal evolution of sprite streamers derived from high-speed camera data in aircraft observation campaign, Abstract AE43A-0242 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3–7 Dec.
- Li, J., S. Cummer, W. Lyons, and T. Nelson (2008), Coordinated analysis of delayed sprites with high-speed images and remote electro magnetic fields, *J. Geophys. Res.*, **113**, D20206, doi:10.1029/2008JD010008.
- Liu, N., and V. Pasko (2006), Effects of photoionization on similarity properties of streamers at various pressures in air, *J. Phys. D: Appl. Phys.*, **39**, 327–334, doi:10.1088/0022-3727/39/2/013.
- Lu, G., et al. (2013), Coordinated observations of sprites and in-cloud lightning flash structure, *J. Geophys. Res. Atmos.*, **118**, 6607–6632, doi:10.1002/jgrd.50459.

- Luque, A., U. Ebert, C. Montijn, and W. Hundsdorfer (2007), Photoionization in negative streamers: Fast computations and two propagation modes, *Appl. Phys. Lett.*, **90**, 081501, doi:10.1063/1.2435934.
- Luque, A., and U. Ebert (2012), Density models for streamer discharges: Beyond cylindrical symmetry and homogeneous media, *J. Comput. Phys.*, **231**, 904–918, doi:10.1016/j.jcp.2011.04.019.
- Lyons, W. (1996), Sprite observations above the U.S. high plains in relation to their parent thunderstorm systems, *J. Geophys. Res.*, **101**, 29,641–29,652.
- Marshall, R., U. Inan, and W. Lyons (2007), Very low frequency sferic bursts, sprites, and their association with lightning activity, *J. Geophys. Res.*, **112**, D22105, doi:10.1029/2007JD008857.
- Mende, S., H. Frey, R. Hsu, H. Su, A. Chen, L. Lee, D. Sentman, Y. Takahashi, and H. Fukunishi (2005), D region ionization by lightning-induced electromagnetic pulses, *J. Geophys. Res.*, **110**, A11312, doi:10.1029/2005JA011064.
- Mihara, M., M. Sato, T. Adachi, Y. Takahashi, T. Ushio, T. Morimoto, M. Suzuki, and A. Yamazaki (2014), Horizontal distributions of sprites measured by lightning and sprite imager onboard JEM-GLIMS, Abstract PEM07–03, presented at 2014 Fall Meeting, AGU, Yokohama, 28 Apr.–2 May.
- Mihara, M. (2015), Horizontal distributions of sprites and their relation to the parent lightning discharges derived from JEM-GLIMS nadir observations, Master thesis, Hokkaido Univ.
- Morimoto, T., H. Kikuchi, M. Sato, M. Suzuki, A. Yamazaki, and T. Ushio (2011), VHF lightning observations on JEM-GLIMS mission: Gradual approach to realize space-borne VHF broadband digital interferometer, *IEEJ Trans. Fundam. Mater.*, **131**(12), 977–982, doi:10.1541/ieejfms.131.977.
- Moudry, D., H. Stenbaek-Nielsen, D. Sentman, and E. Wescott (2003), Imaging of elves, halos and sprite initiation at 1 ms time resolution, *J. Atmos. Sol. Terr. Phys.*, **65**, 509–518, doi:10.1016/S1364-6826(02)00323-1.
- Ohkubo, A., H. Fukunishi, Y. Takahashi, and T. Adachi (2005), VLF/ELF sferic evidence for in-cloud discharge activity producing sprites, *Geophys. Res. Lett.*, **32**, L04812, doi:10.1029/2004GL021943.
- Orville, R., and G. Huffines (2001), Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98, *Mon. Weather Rev.*, **129**, 1179–1193.
- Pasko, V., U. Inan, T. Bell, and Y. Taranenko (1997), Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, *J. Geophys. Res.*, **102**, 4529–4561, doi:10.1029/96JA03528.
- Pasko, V., U. Inan, and T. Bell (1998), Spatial structure of sprites, *Geophys. Res. Lett.*, **25**, 2123–2126.
- Pasko, V. (2010), Recent advances in theory of transient luminous events, *J. Geophys. Res.*, **115**, A00E35, doi:10.1029/2009JA014860.
- Qin, J., S. Celestin, and V. Pasko (2011), On the inception of streamers from sprite halo events produced by lightning discharges with positive and negative polarity, *J. Geophys. Res.*, **116**, A06305, doi:10.1029/2010JA016366.
- Qin, J., S. Celestin, and V. Pasko (2012), Formation of single and double-headed streamers in sprite-halo events, *Geophys. Res. Lett.*, **39**, L05810, doi:10.1029/2012GL051088.
- Qin, J., S. Celestin, and V. Pasko (2013), Dependence of positive and negative sprite morphology on lightning characteristics and upper atmospheric ambient conditions, *J. Geophys. Res. Space Physics*, **118**, 2623–2638, doi:10.1029/2012JA017908.
- Rodger, C., J. Brundell, R. Dowden, and N. Thomson (2004), Location accuracy of long distance VLF lightning location network, *Ann. Geophys.*, **22**, 747–758.
- Rodger, C., J. Brundell, and R. Dowden (2005), Location accuracy of VLF World Wide Lightning Location (WWLL) network: Post-algorithm upgrade, *Ann. Geophys.*, **23**, 277–290.
- Rodger, C., J. Brundell, R. Holzworth, and E. Lay (2009), Growing detection efficiency of the World Wide Lightning Location Network, *Am. Inst. Phys. Conf. Proc.*, **1118**, 15–20, doi:10.1063/1.3137706.
- São Sabbas, F., D. Sentman, E. Wescott, O. Pinto Jr., O. Mendes Jr., and M. Taylor (2003), Statistical analysis of space-time relationships between sprites and lightning, *J. Atmos. Sol. Terr. Phys.*, **65**, 525–535, doi:10.1016/S1364-6826(02)00326-7.
- Sato, M., H. Fukunishi, M. Kikuchi, H. Yamagishi, and W. Lyons (2003), Validation of sprite-inducing cloud-to-ground lightning based on ELF observations at Syowa station in Antarctica, *J. Atmos. Sol. Terr. Phys.*, **65**, 607–614, doi:10.1016/S1364-6826(02)00327-9.
- Sato, M., and H. Fukunishi (2003), Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events, *Geophys. Res. Lett.*, **30**(16), 1859, doi:10.1029/2003GL017291.
- Sato, M., Y. Takahashi, A. Yoshida, and T. Adachi (2008), Global distribution of intense lightning discharges and their seasonal variations, *J. Phys. D: Appl. Phys.*, **41**(234011), doi:10.1088/0022-3727/41/23/234011.
- Sato, M., Y. Takahashi, M. Kikuchi, M. Suzuki, A. Yamazaki, and T. Ushio (2011a), Lightning and Sprite Imager (LSI) onboard JEM-GLIMS, *IEEJ Trans. Fundam. Mater.*, **131**(12), 994–999, doi:10.1541/ieejfms.131.994.
- Sato, M., Y. Takahashi, M. Suzuki, A. Yamazaki, and T. Ushio (2011b), Six-channel spectrophotometers (PH) onboard JEM-GLIMS, *IEEJ Trans. Fundam. Mater.*, **131**(12), 1000–1005, doi:10.1541/ieejfms.131.1000.
- Sato, M., et al. (2013), Photometric characteristics of sprites and elves derived from JEM-GLIMS Nadir observations, Abstract AE32A–03 presented at 2013 Fall Meeting, AGU, San Francisco, Calif., 9–13 Dec.
- Sato, M., T. Adachi, M. Mihara, T. Ushio, T. Morimoto, H. Kikuchi, M. Suzuki, A. Yamazaki, and Y. Takahashi (2014), Spatiotemporal characteristics of sprites and sprite-related VHF signals measured by JEM-GLIMS, Abstract AE31B–3412 presented at 2014 Fall Meeting, AGU, San Francisco, Calif., 15–19 Dec.
- Sato, M., et al. (2015), Overview and early results of the Global Lightning and Sprite Measurements mission, *J. Geophys. Res. Atmos.*, **120**, 3822–3851, doi:10.1002/2014JD022428.
- Sentman, D., E. Wescott, D. Osborne, D. Hampton, and M. Heavner (1995), Preliminary results of the Sprites94 aircraft campaign: Red sprites, *Geophys. Res. Lett.*, **22**, 1205–1208.
- Sentman, D., et al. (2003), Simultaneous observations of mesospheric gravity waves and sprites generated by a midwestern thunderstorm, *J. Atmos. Sol. Terr. Phys.*, **65**, 537–550.
- Soula, S., et al. (2010), Characteristics and conditions of production of transient luminous events observed over a maritime storm, *J. Geophys. Res.*, **115**, D16118, doi:10.1029/2009JD012066.
- Stenbaek-Nielsen, H., R. Haaland, M. McHarg, B. Hensley, and T. Kanmae (2010), Sprite initiation altitude measured by triangulation, *J. Geophys. Res.*, **115**, A00E12, doi:10.1029/2009JA014543.
- Ushio, T., et al. (2011), The Global Lightning and Sprite Measurement (GLIMS) mission of the International Space Station: Concept and overview, *IEEJ Trans. Fundam. Mater.*, **131**(12), 971–976, doi:10.1541/ieejfms.131.971.
- Vadislavsky, E., Y. Yair, C. Erlick, C. Price, E. Greenberg, R. Yaniv, B. Ziv, N. Reicher, and A. Devir (2009), Indication for circular organization of column sprite elements associated with Eastern Mediterranean winter thunderstorms, *J. Atmos. Sol. Terr. Phys.*, **71**, 1835–1839, doi:10.1016/j.jastp.20.09.07.001.

- Valdivia, J., G. Milikh, and K. Papadopoulos (1997), Red sprites: Lightning as a fractal antenna, *Geophys. Res. Lett.*, *24*(24), 3169–3172, doi:10.1029/97GL03188.
- Wescott, E., D. Sentman, M. Heavner, D. Hampton, W. Lyons, and T. Nelson (1998), Observations of 'columniform' sprites, *J. Atmos. Sol. Terr. Phys.*, *60*, 733–740, doi:10.1016/S1364-6826(98)00029-7.
- Wescott, E., H. Stenbaek-Nielsen, D. Sentman, M. Heavner, D. Moudry, and F. São Sabbas (2001), Triangulation of sprites, associated halos and their possible relation to causative lightning and micrometeors, *J. Geophys. Res.*, *106*, 10467–10477, doi:10.1029/2000JA000182.
- Yair, Y., C. Price, Z. Levin, J. Joseph, P. Israelevitch, A. Devir, M. Moalem, B. Ziv, and M. Asfur (2003), Sprite observations from the space shuttle during the Mediterranean Israeli Dust Experiment (MEIDEX), *J. Atmos. Sol. Terr. Phys.*, *65*, 635–642, doi:10.1016/S1364-6826(02)00332-2.
- Yair, Y., P. Israelevich, A. Devir, M. Moalem, C. Price, J. Joseph, Z. Levin, B. Ziv, A. Sternlieb, and A. Teller (2004), New observations of sprites from the space shuttle, *J. Geophys. Res.*, *109*, D15201, doi:10.1029/2003JD004497.
- Yair, Y., L. Rubanenko, K. Mezuman, G. Elhalel, M. Pariente, M. Glickman-Pariente, B. Ziv, Y. Takahashi, and T. Inoue (2013), New color images of transient luminous events from dedicated observations on the International Space Station, *J. Atmos. Sol. Terr. Phys.*, *102*, 140–147, doi:10.1016/j.jastp.2013.05.004.
- Zabotin, N., and J. Wright (2001), Role of meteoric dust in sprite formation, *Geophys. Res. Lett.*, *28*, 2593–2596, doi:10.1029/2000GL012699.