Morimoto *et al. Earth, Planets and Space* (2016) 68:145
DOI 10.1186/s40623-016-0522-1

Earth, Planets and Space

LETTER

Open Access

An overview of VHF lightning observations by digital interferometry from ISS/JEM-GLIMS

Takeshi Morimoto[1*], Hiroshi Kikuchi[2], Mitsuteru Sato[3], Tomoo Ushio[2], Atsushi Yamazaki[4], Makoto Suzuki[4], Ryohei Ishida[5], Yuji Sakamoto[6], Kazuya Yoshida[6], Yasuhide Hobara[7], Takuki Sano[4], Takumi Abe[4] and Zen-Ichiro Kawasaki[2]

Abstract:
The Global Lightning and sprIte MeasurementS (GLIMS) mission has been conducted at the Exposed Facility of Japanese Experiment Module (JEM-EF) of the International Space Station for more than 30 months. This paper focuses on an electromagnetic (EM) payload of JEM-GLIMS mission, the very high frequency (VHF) broadband digital InTerFerometer (VITF). The JEM-GLIMS mission is designed to conduct comprehensive observations with both EM and optical payloads for lightning activities and related transient luminous events. Its nominal operation continued from November 2012 to December 2014. The extended operation followed for eight months. Through the operation period, the VITF collected more than two million VHF EM waveforms in almost 18,700 datasets. The number of VITF observations synchronized with optical signal is 8049. Active VHF radiations are detected in about 70 % of optical observations without obvious regional or seasonal dependency. Estimations of the EM direction-of-arrival (DOA) are attempted using the broadband digital interferometry. Some results agree with the optical observations, even though DOA estimation is problematic because of a very short antenna baseline and multiple pulses over a short time period, namely burst-type EM waveforms. The world's first lightning observations by means of space-borne VHF interferometry are achieved in this mission. This paper summarizes VITF instruments, the recorded VHF EM signals, and the results of DOA estimations by means of digital interferometry as a preliminary report after termination of the mission.

Keywords: Digital interferometry, Direction-of-arrival estimation, International Space Station, Lightning discharge, VHF EM radiation

Background

The efficacy of global environmental monitoring from space has been demonstrated since the 1960s. Many earth observing satellites have been launched, producing outstanding contributions including satellites observations associated with lightning observations. The Optical Transient Detector (OTD) on Microlab-1 satellite was launched in 1995 and the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM) satellite in 1997 revealed the global distribution of lightning activities with optical observations (Christian et al. 2003; Boccippio et al. 2000). The array of Low-Energy X-Ray Imaging Sensors (ALEXIS) satellite and the Fast On-orbit Recording of Transient Events (FORTE) satellite were launched in 1993 and 1997, respectively. They recorded many transionospheric pulse pair (TIPP) waveforms by electromagnetic (EM) radio observations (Jacobson et al. 1999; Tierney et al. 2002). The ISS-b satellite, which was launched in 1978 and measured short-wave EM noise, can be considered as the first space-borne EM observation satellite for lightning (Kotaki et al. 1983). The Maido-1 satellite (Nakamura and Hashimoto 2005; Kikuchi et al. 2010, 2013) is the world's first specialized satellite for lightning observation that is the predecessor project of this study. A microsatellite, Chibis-M of the Space Research Institute of the Russian Academy of

*Correspondence: morimoto@ele.kindai.ac.jp
[1] Kindai University, Higashiosaka City, Osaka 5778502, Japan
Full list of author information is available at the end of the article

Sciences which was launched in 2012, has also conducted EM lightning observations in VHF band (Zelenyi et al. 2014).

The authors have been developing the ground-based very high frequency (VHF) broadband Digital InTerFerometer (DITF) to image precise lightning channels and to extensively monitor lightning activities. The remarkable feature of DITF is its ultra-wide bandwidth (from 25 to 100 MHz) and implicit redundancy for estimating VHF source locations (Mardiana et al. 2000; Morimoto et al. 2004). We applied DITF to the space-borne measurement system and joined Maido-1 satellite and Global Lightning and sprIte MeasurementS (GLIMS) projects as mission scientists. GLIMS is a mission on the Exposed Facility (EF) of Japanese Experiment Module (JEM) on the International Space Station (ISS). Both missions intend to implement lightning observation from space by detecting VHF broadband EM signals associated with lightning discharges as a gradual approach to space-borne lightning monitoring by means of EM observations (Morimoto et al. 2011). Observations of the JEM-GLIMS mission were conducted for 32 months and terminated on August 24, 2015. This paper describes the instrument of an EM payload on the JEM-GLIMS mission, called the VHF broadband digital InTerFerometer (VITF), and provides a preliminary report of its observation results. It also introduces the world's first lightning observations by means of space-borne VHF interferometry.

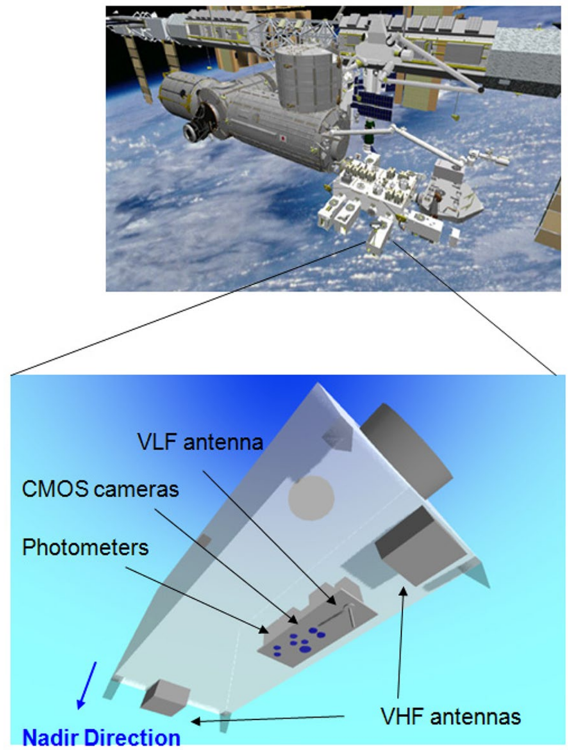

Fig. 1 JEM-GLIMS payload on the JEM-EM. The representation of the ISS is adopted from the handbook of applications of JEM-EF by JAXA

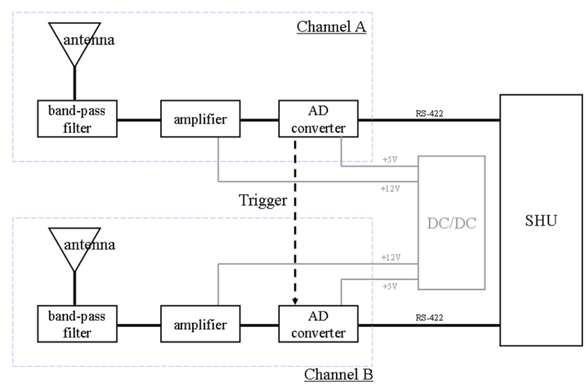

Fig. 2 Configuration diagram of the VITF

JEM-GLIMS mission

Project outline and objectives

The JEM-GLIMS mission aims to observe global distributions of lightning and lightning-associated transient luminous events (TLEs) by combining observations with radio and optical sensors. The science requirements of this mission are (1) to capture the temporal and spatial distribution of lightning and its associated phenomena and (2) to characterize the relationship between the horizontal structure of sprites and lightning discharges. In order to achieve these objectives, the integrated four sensors are installed into the Multi-mission Consolidated Equipment (MCE), which is the bus system and is mounted on JEM-EF as shown in Fig. 1. The four sensors consist of the VITF (Morimoto et al. 2011), a very low frequency (VLF) receiver, CMOS cameras at two different wavelengths (Sato et al. 2011a), and photometers at six channels (Sato et al. 2011b).

Instrument of the VITF

The VITF of the JEM-GLIMS mission is based on the VHF sensor of the Maido-1 satellite (Kikuchi et al. 2010, 2013; Morimoto et al. 2011). Figure 2 shows the configuration diagram of the VITF, which consists of two sets of antennas, band-pass filters, amplifiers, and a 2-channel AD converter. The VHF EM signals received by the antennas are digitized by the AD converter synchronized with the other channel after passing through the filter and the amplifier.

The antenna needs to be a blunt shape to ensure safety for the ISS crews and mountability on the MCE. Their sizes, weights, materials, and structures are heavily restricted from the ISS side. Broadband digital interferometry requires the antenna to have both a wide bandwidth in the VHF band and omni-directionality in the nadir direction. A patch-type antenna is designed for the mission with a size of 200 mm × 200 mm mounted on the antenna base, which is made of aluminum alloy and Teflon block, with a total height of 100 mm to obtain its bandwidth and reduce interference from other structural objects in the bottom panel of the MCE facing to the nadir direction. The antenna is covered with cloth for littering prevention and surface protection. The total mass of one antenna unit is 3.4 kg. Two identical antenna units are installed at both ends of the MCE with a distance of 1.6 m, as illustrated in Fig. 1. The actual measured value of the bandwidth of the VITF antenna with a return loss higher than −3 dB is from 70 to 100 MHz, with a resonance frequency of 88 MHz, while the simulated resonance frequency is 90 MHz. The major specifications and a photograph of the VITF antenna are listed and shown in Table 1 and Fig. 3, respectively. The signals received by the antenna are transmitted through cables to the electronics. The cables for both antennas are semirigid coaxial cables with the same length for tolerance to the exposed space environment. The band-pass filter has a 3 dB pass band from 30 to 100 MHz with 20 dB attenuation at 20 and 110 MHz. The gain of the amplifier is designed to be about 45 dB. In the case of the ground-based DITF, with an observation range of around a hundred and several tens of kilometers, the dynamic range is given more importance than the gain. A space-borne system, on the other hand, requires high gain because the intensities of received EM signals are inversely proportional to the distance between the EM radiation source and the receiving antenna. The gain of the amplifier is determined to be 45 dB, adding 20 dB to the ground-based DITF on the pretext of numerical estimation for attenuation in the propagation path (Taniguchi et al. 2006).

Table 1 Specifications of the VITF antenna

Antenna (one unit)	
Type	Patch type
Size	200 mm × 200 mm × 106 mm
Weight	3.4 kg
Bandwidth ($S_{11} > -3$ dB)	70–100 MHz
Directionality	Omni-directionality to the zenith

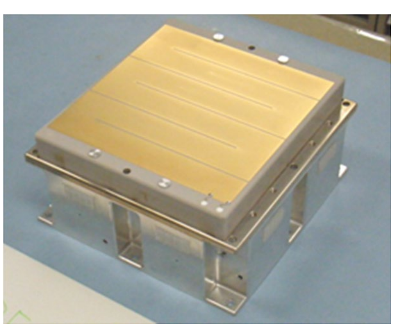

Fig. 3 VITF antenna with antenna base. Two antenna units are installed on the bottom panel of the MCE with cloth covers

It is known that thousands of impulsive EM pulses are radiated intermittently in association with lightning leader progression. The typical width of each radiation pulse is several hundred nanoseconds. The AD converter is designed to record a maximum of 130 waveforms with a duration of 2.5 μs with 200 MS/s as one dataset. When the input signal exceeds the threshold voltage, a waveform for 2.5 μs is stored in the onboard buffer of the AD converter with 25 % of pre-triggering. The input signal to the master channel A is used for detection of the triggering, and the waveform of the slave channel B is recorded in synchronization with channel A. Since the size of the onboard buffer is for 130 waveforms per channel, up to the last 130 waveforms are saved with their time stamp. The accuracy of the time stamp is maintained at a sufficient level using GPS signal, in order to compare the observations to other sensors. The AD converter is connected to the Science Instrument Handling Unit (SHU) of the JEM-GLIMS mission with a 2 Gbps RS-422 interface. The AD converter is controlled by the commands from the SHU, and the VITF captured data are transferred and temporarily stored in the SHU. The VITF operation commands are start/stop recording, waveform/status data output, data clear, threshold setting, and forced triggering to respective channels. All other sensors on the JEM-GLIMS mission are also connected to the SHU, and the timing of the data recording is managed by the SHU, which interfaces with the MCE bus system (Kikuchi et al. 2011).

The band-pass filters, the amplifiers, and the AD converter of the VITF are packaged in the box-shaped VITF electronics unit. The primary specifications of each component of the VITF electronics unit are summarized in Table 2. Figure 4 shows the manufactured VITF electronics unit installed on top of the JEM-GLIMS box unit. The size and weight of the VITF electronics unit are 180 mm × 210 mm × 60 mm and 2.4 kg, respectively.

After designing and manufacturing, various environmental tests were conducted as well as electrical tests. Vibration, impact, and thermal vacuum tests for the VITF antennas were conducted individually. The electronics unit was tested integrated with the JEM-GLIMS box unit once. The JEM-GLIMS hardware had completed its development and environmental testing, and then it was delivered to the integrator of the MCE.

Mission target of the VITF

The main objective of the VITF is lightning observations by recording VHF broadband EM waveforms received by

Table 2 Specifications of the VITF electronics unit

Outline	
Size	180 mm × 210 mm × 60 mm
Weight	2.4 kg
Communications interface	2 Gbps RS-422
DC power	8.1 W (+12, +5 V)
Band-pass filter	
3 dB pass band	30 to 100 MHz
Insertion loss	−1 dB (at center frequency)
Attenuation	−20 dB/20, 110 MHz
Input and output impedance	50 Ω
Amplifier	
Input level	−85 to −35 dBm
Gain	45 dB
Output level	1 Vp-p
Input and output impedance	50 Ω
AD converter	
Data sampling speed	200 MS/s
AD resolution	8 bit
Input channel	2 channel
Input impedance	50 Ω
Coupling	AC
Input level	1 Vp-p
Input frequency	20 to 100 MHz
Triggering	Level trigger (event trigger)
Threshold level	50 to 500 mV (10 steps variable, positive only)
Memory	Ring buffer for 130 × 2.5 μs waveforms/channel

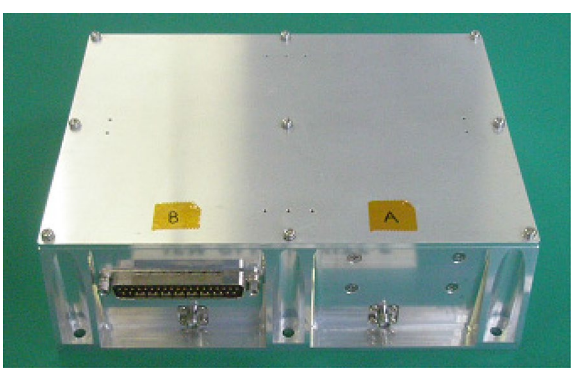

Fig. 4 VITF electronics unit

the antennas and estimating their source locations. The VITF is expected to provide location and time information for lightning leader developments. The expected accuracy of the VITF estimation for the direction-of-arrival (DOA) of the VHF EM source is 1.5° based on the experience of the ground-based DITF (Nakamura et al. 2009; Stock et al. 2014). When the ISS altitude is 400 km, the VITF with two antennas is able to identify the location of the EM source as a doughnut-shaped ring with a width of 10 km. This resolution at the Earth's surface is equivalent to the typical size of a thundercloud. The VITF localizes the lightning activity on the scale of a thundercloud by combining with the observations of the optical sensors on the JEM-GLIMS payload as well as other observations such as satellite imaging, and ground-based lightning, and/or weather radar observations. The range of the lightning leader extension is also given. The information for horizontal distance and temporal relationship between VHF EM sources corresponding to the lightning processes and TLEs might help clarify the mechanism of TLE initiation.

Observation results

Global lightning observations of JEM-GLIMS

The MCE equipped with the JEM-GLIMS mission payload was successfully launched on July 21, 2012, and transported and installed to the ISS. After the initial check and maintenance, its nominal operation was conducted from November 2012 through December 2014. An extended operation followed until August 2015. Through the operation period, the VITF collected numerous VHF EM observations synchronized with optical signals. In the former operation period from January 2013 to July 2014, 394,407 VITF waveforms were obtained as 4071 datasets. Additional 1,777,106 waveforms were captured as 14,624 datasets in the following 13 months from August 2014 to August 2015. Much more frequent operations of the VITF alone were conducted in the latter period than in the former period to collect many additional observations to bolster the data required for the statistical studies such as producing a global map or regional distribution by means of VHF observations. The data acquisition was triggered when the VITF recorded 100 EM pulses exceeded the threshold level within 100 ms in this mode. Optical signals were not recorded in this mode, but the frequency of VHF EM radiation was obtained continuously.

Figure 5 represents the locations of the ISS where JEM-GLIMS photometers captured optical signals from lightning for the entire observation period of 32 months from January 2013 to August 2015. The timing of data acquisition was controlled by the optical sensor of the JEM-GLIMS. Namely, the simultaneous EM and optical observations were triggered by the optical signal. The details of the observation sequence and trigger method are given in Sato et al. (2015). All the dots in Fig. 5 correspond to the optical signal records, and red dots show active VHF signals. About 70 % (5538 of 8049) of the optical observations are accompanied with VHF radiation. While this ratio depends on the threshold level

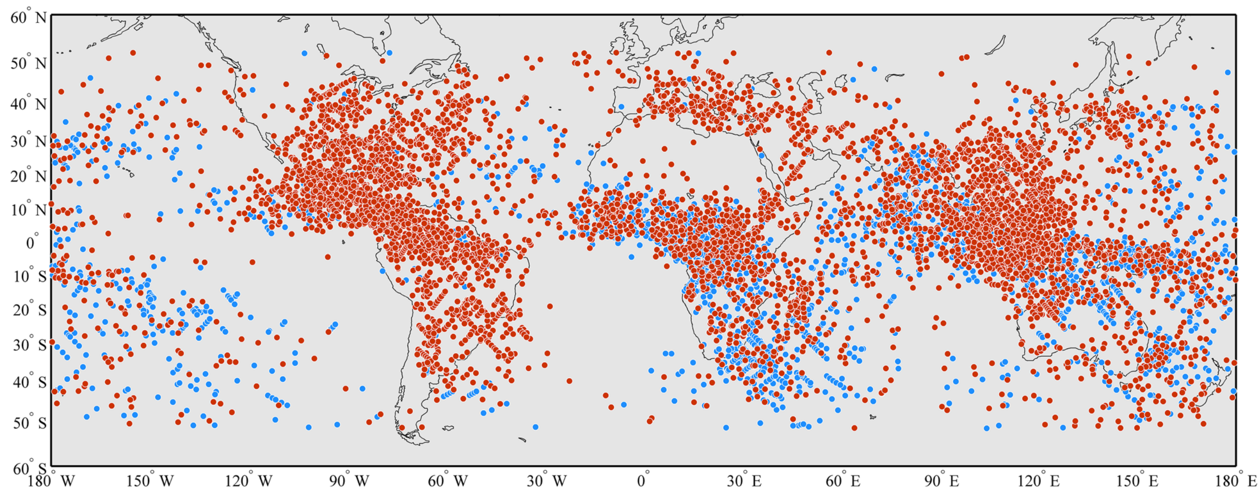

Fig. 5 Locations of detected optical and VHF signals. *Red dot* VHF observations with optical signals, 5538 events; *blue dot* optical signal only, 2511 events

of the data acquisition, neither regional nor seasonal dependency was found. As noted in Sato et al. (2016), more than 90 % of optical signals do not record TLEs but only lightning discharges.

DOA estimation by digital interferometry

Two antennas of the VITF are installed at the bottom panel of MCE with a distance of 1.6 m. The distance between the two antennas is not sufficient, but DOA estimation can be attempted based on the digital interferometric technique (Mardiana and Kawasaki 2000; Morimoto et al. 2004). The principle of this technique is to calculate the phase differences between the EM waveforms received by a pair of antennas at various frequencies. Figure 6 shows an example of (a) a pair of typical waveforms captured by the two antennas of VITF and (b) the operation of broadband digital interferometry for VHF signals recorded by the VITF. Now let us express the received broadband signals, which originate from a common source, acquired by the two VITF antennas as $r_A(t)$ and $r_B(t)$. These signals are digitized at a certain time interval Δt and expressed in a discrete time series

$$r_{A,B}[m] = r_{A.B}(m\Delta t) \quad \{m = 0, 1, \ldots, N-1\} \tag{1}$$

Here, Δt is 5 ns at a sampling rate of 200 MS/s. Since \N\ is set to 128 in our calculation, the record length $\Delta t \times (N-1)$ of each pulse is 635 ns. A discrete Fourier transform (DFT) is applied to r_A and r_B as

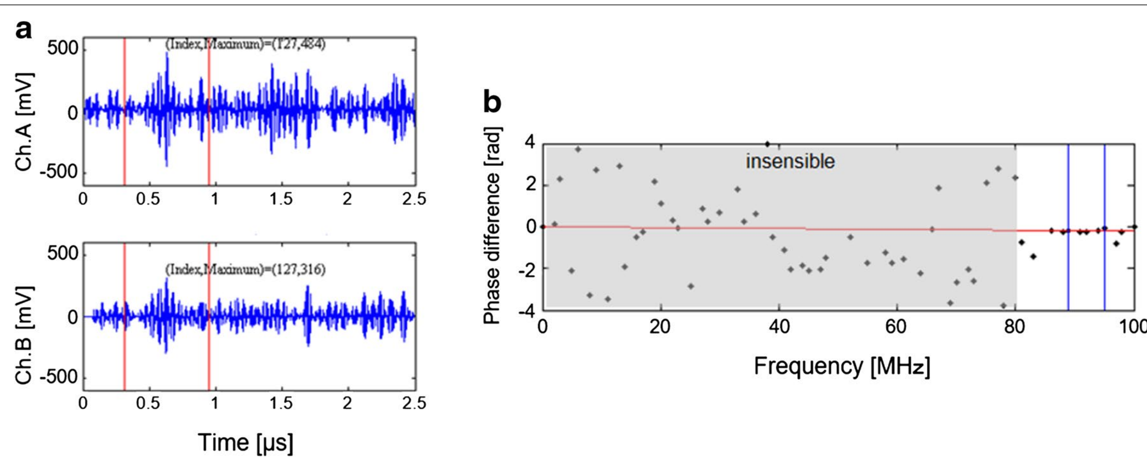

Fig. 6 An example of **a** a pair of typical waveforms simultaneously captured by the two VITF antennas and **b** operation of broadband digital interferometry

$$R_{A,B}[m] = \sum_{n=0}^{N-1} r_{A,B}[n] \exp^{\frac{j2\pi mn}{N}} \quad (2)$$

The phase difference θ_{AB} between signals r_A and r_B for each Fourier frequency component is given by:

$$\theta_{A,B}[m] = \tan^{-1}\frac{\mathrm{Im}R_B[m]}{\mathrm{Re}R_B[m]} - \tan^{-1}\frac{\mathrm{Im}R_A[m]}{\mathrm{Re}R_A[m]} \quad (3)$$

In practice, a fast Fourier transform (FFT) is applied for the date processing, and $N/2$ (=64) Fourier components are taken into account. In the case of the waveforms in Fig. 6a, the parts between the red lines are selected as r_A and r_B. The calculated phase differences $\theta_{AB}[m]$ are plotted at each Fourier frequency in Fig. 6b. The phase difference should have a linear dependence with a frequency in the bandwidth of the antenna, from 85 to 100 MHz in this case. The red line crossing the origin fitted to the calculated phase differences by the least-square method is drawn in Fig. 6b. The focused frequency range is fine-tuned with waveforms. For the case where the EM source is sufficiently distant from the antenna array to be approximated as a plane wave, the slope of the fitted line corresponds to the incident angle against the baseline of the antennas. The DOA can be estimated as 94° for the VHF waveforms shown in Fig. 6.

An optical sensor of the JEM-GLIMS, LSI, records the lightning image at the same time as VITF. Figure 7 shows the LSI image superimposed on the estimated DOA of 94° with VITF. The distance depicted by Fig. 7 is equal to 200 km on a side. If the LSI image is taken to be a phenomenon on a horizontal plane, the estimated DOA corresponds to a hyperbola on the plane, as illustrated in Fig. 8. The estimated DOA is therefore drawn as a hyperbola in Fig. 7. Figure 7 shows a good agreement between the VHF DOA estimation and optical observations. Even

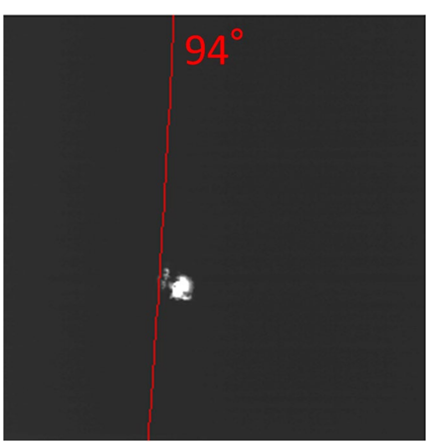

Fig. 7 LSI image superimposed with the VITF using estimated DOA

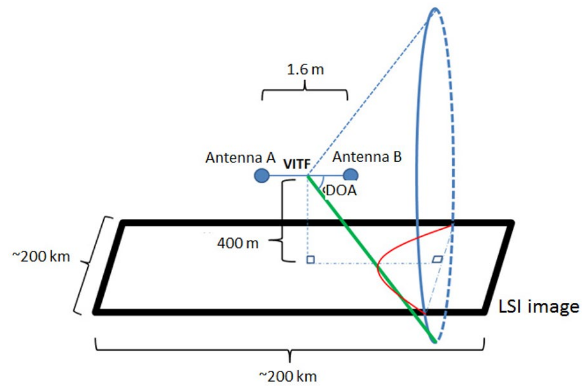

Fig. 8 Comparison model between DOA estimation and an optical image

though DOA estimation is problematic due to the very short antenna baseline of 1.6 m and multiple pulses over a short time period, many results with high signal-to-noise ratios (SNRs) and isolated VHF pulses agree with optical observations. The status of the analysis of the joint VHF and optical dataset is that more time is required to compute DOAs for all VITF impulses. The quantitative and statistical results will be reported a following paper after the completion of this analysis. A new location method of VHF radiation sources, combining the interferometry as described above and the measurements of the ionospheric propagation delay, is proposed in Kikuchi et al. (2016).

Summary and future work

The JEM-GLIMS mission was conducted on the ISS to observe global distributions of lightning and lightning-associated TLEs by combining observations with radio and optical sensors. Though the early results of each sensor are reported in Sato et al. (2015), this paper focuses on the EM payload of the JEM-GLIMS mission (i.e., VITF) and serves as an initial overview of its observational results after the termination of the mission. The VITF consists of a pair of VHF broadband antennas and electronics to record VHF EM waveforms from lightning discharges. It is designed to estimate the DOA with about 10-km resolution, which is equivalent to the scale of a thundercloud. This means that the VITF is able to monitor thunderclouds with global lightning activity. Comprehensive analyses on the VITF and optical observations of lightning and TLEs during the JEM-GLIMS mission are expected to provide us with new scientific insights and understanding.

The JEM-GLIMS mission payload was successfully launched, transported, and installed to the ISS in July and August 2012. After the initial check and maintenance, its nominal operation continued from November 2012 to December 2014. The extended operation followed for 8 months. Through the entire operation period, VITF collected over two million VHF EM waveforms. Focusing on the synchronized observations with optical sensors, 5538 out of 8049 optical events, about 70 % are accompanied by active VHF radiations. DOA estimates of the received VHF pulses are attempted using the broadband digital interferometry. The results for high SNR and isolated VHF pulses agree with the optical observations, even though DOA estimation is problematic because of the very short antenna baseline. The JEM-GLIMS mission represents the world's first space-borne lightning location by EM DOA estimation.

The JEM-GLIMS also has an operation mode that acquires only the VITF observations. Optical observations were not recorded in this mode; however, about 1.5 million waveforms in 1300 datasets of VHF EM radiation were obtained across the globe. Kikuchi et al. (2016) propose a new location method of VHF radiation sources by combining the interferometry in this study with measurements of the ionospheric propagation delay. A global lighting map by means of space-borne VHF observation is expected to be provided. Statistical studies involving regional, seasonal, and local time dependencies will be implemented in our future work. Sato et al. (2016) establish a method to distinguish weak optical emissions of sprites from incomparably intense lightning emissions and succeed in identifying 672 TLE events in the JEM-GLIMS observations. Detailed comparison between characteristics of VHF and optical emissions, especially for the TLE events, has begun. A comprehensive analysis of VHF and optical observations on lightning introduced in this paper is also in progress.

Authors' contributions
TM is responsible for the VITF development and observation. TM and HK analyzed VITF data, and MS analyzed optical data. TM, HK, SM, TU, and MS contributed to the study and discussion associated with the data interpretation. RI, YS, KY, and ZIK contributed significantly to the design, development, manufacture, and test of the VITF. All authors worked for the JEM-GLIMS mission throughout, from instrumentation to operation and analysis. All authors read and approved the final manuscript.

Author details
[1] Kindai University, Higashiosaka City, Osaka 5778502, Japan. [2] Osaka University, Suita, Osaka 5650871, Japan. [3] Hokkaido University, Sapporo, Hokkaido 0600808, Japan. [4] Institute of Space and Astronautical Science of JAXA, Sagamihara, Kanagawa 2525210, Japan. [5] Osaka Prefecture University, Sakai, Osaka 5998531, Japan. [6] Tohoku University, Sendai, Miyagi 9808579, Japan. [7] The University of Electro-Communications, Chofu, Tokyo 1828585, Japan.

Acknowledgements
The authors cordially acknowledge the engineers of companies that contributed toward development, especially Advanced Engineering Services Co., Ltd., Dainichi Denshi Co., Ltd., Japan Communication Equipment Co., Ltd., AD Co., Ltd., and Meisei Electric Co., Ltd. The authors also thank JAXA's full support for the JEM-GLIMS continuous operation and data acquisition. We also acknowledge the editor and reviewers considerably improved the quality of the paper. This work was supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (B) 24340117 and 16H04055.

Received: 7 March 2016 Accepted: 4 August 2016
Published online: 15 August 2016

References

Boccippio DJ, Goodman SJ, Heckman S (2000) Regional difference in tropical lightning distributions. J Appl Meteorol 39:2231–2248

Christian HJ, Blakeslee RJ, Boccippio DJ, Boeck WL, Buechler DE, Driscoll KT, Goodman SJ, Hall JM, Koshak WJ, Mach DM, Stewart MF (2003) Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. J Geophys Res 108(D1):4005. doi:10.1029/2002JD002347

Jacobson AR, Knox SO, Frenz R, Enemark DC (1999) FORTE observations of lightning radio-frequency signatures: capabilities and basic results. Radio Sci 34(2):337–354

Kikuchi H, Morimoto T, Ushio T, Kawasaki Z (2010) Wideband radio wave observations of lightning discharge by Maido-1 satellite. IEICE Trans Commun E93-B(8):2226–2227

Kikuchi M, Sato M, Yamazaki A, Suzuki M, Ushio T (2011) Development of Science Data Handling Unit (SHU) for Global Lightning and Sprite Measurements (GLIMS) onboard Japanese Experiment Module (JEM) of ISS. IEEJ Trans Fundam Mater 131(12):989–993

Kikuchi H, Yoshida S, Morimoto T, Ushio T, Kawasaki Z (2013) VHF radio wave observations by Maido-1 satellite and evaluation of its relationship with lightning discharges. IEICE Trans Commun E96-B(3):880–886

Kikuchi H, Morimoto T, Sato M, Ushio T, Kikuchi M, Yamazaki A, Suzuki M, Ishida R, Sakamoto Y, Kawasaki Z (2016) Direction-of-arrival estimation of VHF signals recorded on the International Space Station and simultaneous of optical lighting. IEEE Trans Geosci Remote Sens 54(7):3868–3877

Kotaki M, Kuriki I, Katoh C (1983) Radio noise spectrum above the ionosphere at high frequency band. IEICE Trans Communications. J67-B(1):9–16 **(in Japanese)**

Mardiana R, Kawasaki Z (2000) Broadband radio interferometer utilizing a sequential triggering technique for locating fast-moving electromagnetic sources emitting from lightning. IEEE Trans Instrum Meas 49(2):376–381

Mardiana R, Kawasaki Z, Morimoto T (2000) Three-dimensional lightning observations of cloud-to-ground flashes using broadband interferometers. J Atmos Sol Terr Phys 64(1):91–103

Morimoto T, Hirata A, Kawasaki Z, Ushio T, Matsumoto A, Lee JH (2004) An operational VHF broadband digital interferometer for lightning monitoring. IEEJ Trans Fundam Mater 124(12):1232–1238

Morimoto T, Kikuchi H, Sato M, Suzuki M, Yamazaki A, Ushio T (2011) VHF lightning observations on JEM-GLIMS mission—gradual approach to realizing space-borne VHF broadband digital interferometer. IEEJ Trans Fundam Mater 131(12):977–982

Nakamura Y, Hashimoto H (2005) SOHLA-1, a low cost satellite development with technology transfer program of JAXA. In: 56th International Astronautical Congress, IAC-05-B5.6.B.08, Fukuoka, Japan

Nakamura Y, Morimoto T, Ushio T, Kawasaki Z-I (2009) An error of the VHF broadband digital interferometer. IEEJ Trans Fundam Mater 129(8):525–530 **(in Japanese)**

Sato M, Takahashi Y, Kikuchi M, Suzuki M, Yamazaki A, Ushio T (2011a) Lightning and Sprite Imager (LSI) onboard J 369 EM-GLIMS. IEEJ Trans Fundam Mater 131(12):994–999

Sato M, Takahashi Y, Suzuki M, Yamazaki A, Ushio T (2011b) Six-Channel Spectrophotometers (PH) Onboard JEM-GLIMS. IEEJ Trans Fundam Mater 131(12):1000–1005

Sato M, Ushio T, Morimoto T, Kikuchi M, Kikuchi H, Adachi T, Suzuki M, Yamazaki A, Takahashi Y, Inan U, Linscott I, Ishida R, Sakamoto Y, Yoshida K, Hobara Y, Sano T, Abe T, Nakamura M, Oda H, Kawasaki ZI (2015) Overview and early results of the Global Lightning and Sprite Measurements mission. J Geophys Res Atmos. doi:10.1002/2014JD022428

Sato M, Mihara M, Adachi T, Ushio T, Morimoto T, Kikuchi M, Kikuchi H, Suzuki M, Yamazaki A, Takahashi Y, Inan U, Linscott I, Ishida R, Sakamoto Y, Yoshida K, Hobara Y (2016) Horizontal distributions of sprites derived from the JEM-GLIMS nadir observations. J Geophys Res Atmos. doi:10.1002/2015JD024311

Stock MG, Akita M, Krehbiel PR, Rison W, Edens HE, Kawasaki Z, Stanley MA (2014) Continuous broadband dig 385 ital interferometry of lightning using a generalized cross-correlation algorithm. J Geophys Res Atmos. doi:10.1002/2013JD020217

Taniguchi T, Hirata A, Morimoto T, Kawasaki Z (2006) Propagation characteristics of wideband electromagnetic wave in the ionosphere. IEEJ Trans Fundam Mater 126(11):1173–1176 **(in Japanese)**

Tierney HE, Jacobson AR, Roussel-Dupre R, Beasley WH (2002) Trans ionospheric pulse pairs originating in maritime, continental and coastal thunderstorms: pulse energy ratios. Radio Sci 37(3):1039. doi:10.1029/2001RS002506

Zelenyi LM, Gurevich AV, Klimov SI, Angarov VN, Batanov OV, Bogomolov AV, Bogomolov VV, Bodnar L, Vavilov DI, Vladimirova GA, Garipov GK, Gotlib VM, Dobriyan MB, Dolgonosov MS, Ivlev NA, Kalyuzhnyi AV, Karedin VN, Karpenko SO, Kozlov VM, Kozlov IV, Korepanov VE, Lizunov AA, Ledkov AA, Nazarov VN, Panasyuk MI, Papkov AP, Rodin VG, Segedi P, Svertilov SI, Sukhanov AA, Ferenz C, Eysmont NA, Yashin IV (2014) The academic Chibis-M microsatellite. Cosm Res 52:87–98