VHF Lightning Observations by Digital Interferometry from ISS / JEM-GLIMS

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ABSTRACT: Global Lightning and sprIte MeasurementS (GLIMS) mission is now ongoing on Exposed Facility of Japanese Experiment Module (JEM-EF) of the International Space Station (ISS). This paper focuses on an electromagnetic (EM) payload of JEM-GLIMS mission, very high frequency (VHF) broadband digital InTerFerometer (VITF). JEM-GLIMS mission is designed to conduct comprehensive observations with both EM and optical payloads for lightning activities and related transient luminous events (TLEs) expecting to give us many scientific impacts to the field. Its nominal operation is continued from December 2012. Through the operation period, VITF corrects numerous VHF EM data synchronized with optical signals. About 650 VITF datasets were obtained in January and February 2013, for instance. The 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 has difficulties caused by its very short baseline of the antennas and multiple pulses in short time, namely burst-type EM waveforms. The recorded VHF EM signals, the results of their DOA estimations and the comparisons with optical observations are introduced.

INTRODUCTION

The efficacy of global monitoring for environment from space has been demonstrated since 60's. Many earth observation satellites have been launched, and outstanding contributions are provided. As previous works for the satellite observations associated with lightning, Optical Transient Detector (OTD) on Microlab-1 satellite launched in 1995 and Lightning Imaging Sensor (LIS) on 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]. Array of Low-Energy X-Ray Imaging Sensors (ALEXIS) satellite and 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 the electromagnetic (EM) radio observations [Jacobson et al. 1999; Tierney et al. 2002]. ISS-b satellite, which

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had been launched in 1978 and measured short wave EM noise, could be said the first EM lightning observations [Kotaki et al. 1984]. Maido-1 satellite [Nakamura and Hashimoto 2005] is the world's first specialized satellite for lightning observation that is the ancestor project of this paper.

The authors have been developing the ground-based very high frequency (VHF) broadband Digital InTerFerometer (DITF) to image precise lightning channels and to monitor lightning activities widely. The remarkable feature of DITF is its ultra-wide bandwidth (from 25MHz to 100MHz) and implicit redundancy for estimating VHF source locations [Mardiana et al. 2000; Morimoto et al. 2004]. We consider an application of DITF to the space-borne measurement system, and joins Maido-1 satellite of Space Oriented Higashi-Osaka Leading Associate (SOHLA), and Global Lightning and splIte MeasurementS (GLIMS) on Exposed Facility (EF) of Japanese Experiment Module (JEM) at the International Space Station (ISS) projects as mission scientists. The both missions intend to have lightning observation from space by detecting VHF broadband EM signals associated with lightning discharges as a gradual approach to realize space-borne lightning monitoring by means of EM observations [Morimoto et al. 2011]. This paper introduces an EM payload of JEM-GLIMS mission, VHF broadband digital InTerFerometer (VITF) and its observation results.

JEM-GLIMS MISSION

Project outline and Objectives

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

- to capture temporal and spatial distribution of lightning and its associated phenomena
- to characterize the relationship between horizontal structure of sprites and lightning discharges
- to characterize the relationship between lightning/sprites and gamma emission

For the achievement of these objectives the integrated 4 sensors are installed into Multi Mission Consolidated Equipment (MCE), which is the bus system, and is mounted at JEM-EF as shown in Figure 1. The 4 sensors consist of VITF [Morimoto et al. 2011], very low frequency (VLF) receiver, CMOS cameras at two

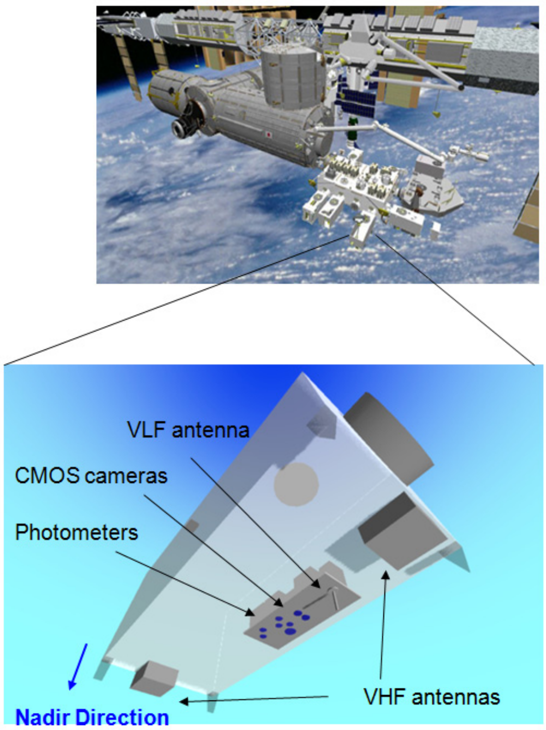

Figure 1. GLIMS payload on JEM-EM. The imaginary picture of the ISS is adopted from the handbook of the applications of JEM-EF by JAXA.

different wavelengths [Sato et al. 2011a], and photometers at six channels [Sato et al. 2011b].

VHF EM payload, VITF

VITF of JEM-GLIMS mission is developed on the heritage of VHF sensor on Maido-1 satellite. Figure 2 shows the configuration diagram of VITF. VITF consists of two sets of antennas, band-pass filters, amplifiers, and 2-channel-AD-converter. Impulsive EM radiations received by the antennas are digitized by the AD converter synchronizing both channels after through the filters and the amplifiers. The band-pass filter and the amplifier of VITF are exactly the same as the ones of VHF sensor on Maido-1 satellite. The basic specification and most of devices in the AD converter of VITF are proven by the ones of VHF sensor on Maido-1 satellite.

The antenna needs to be a blunt shape because of the safety for the ISS crews and mountability to MCE. Their sizes, weights, separation, materials and structures are heavily restricted. They are also required to have ultra-wide bandwidth in VHF band and omni-directionality to the nadir direction at the same time for the broadband digital interferometry. A patch type antenna is designed within the size of 200*200 mm. It is mounted on the antenna base made of aluminum alloy and Teflon block with the total height of 100 mm to gain its bandwidth and to reduce the interference from other structural objects in the bottom panel of MCE facing to the nadir direction. The cloth cover is put on the antenna for littering prevention and protection. The total mass of the one unit of the antenna is 3.4 kg. The same two units of antennas are installed at the both ends of MCE with the separation of 1.6 m as illustrated in Figure 1. Their bandwidths with the higher return loss than -3 dB are from 70 to 100 MHz. The simulated resonance frequency of the VITF antenna is 90 MHz and the measured value of the actual one is 88 MHz. The major specifications and the appearance of the VITF antenna are shown in Table 1 and Figure 3, respectively. The signals received by the antenna are transmitted along cables to the electronics. The cables for both antennas are semi-rigid coaxial cables with the

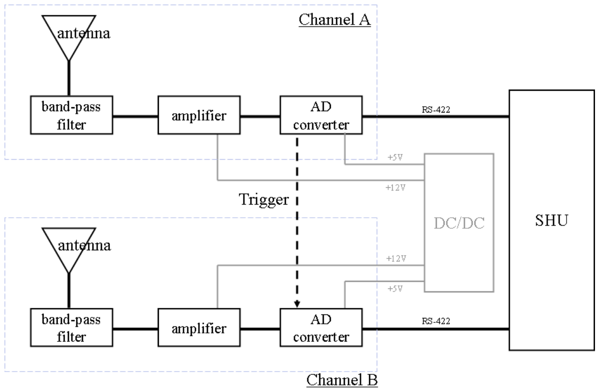

Figure 2. Configuration diagram of VITF.

Table 1. Specifications of the VITF antenna.

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

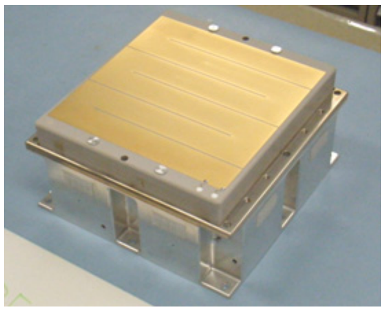

Figure 3. VITF antenna with antenna base. Two units of the antennas are installed the bottom panel of MCE with cloth covers.

same lengths for the tolerance to the exposed space environment.

The band-pass filter and the amplifier of VITF are the copies of the ones of VHF sensor on Maido-1 satellite. 3 dB pass band of the filter is from 30 to 100 MHz with 20 dB attenuation at 20 and 110 MHz. The gain of the amplifier is designed to about 45 dB. In the case of the ground-based DITF with the observation range of around hundred and tens kilometers, the dynamic range is put more stress 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 EM radiation source and the receiving antenna. Since the variation of the length of the propagation path is small in the case of satellite observation, the gain of the amplifier is determined to be 45 dB adding 20 dB to the ground-based DITF thorough the numerical estimation for the attenuation in the propagation path [Taniguchi et al. 2006; Kikuchi et al. 2010].

Thousands of impulsive EM pulses are radiated intermittently in association with lightning leader progression. The typical pulse width of each radiation is hundreds nanoseconds. The AD converter is designed to record 130 waveforms with the 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 on the onboard-buffer of the AD converter with the 25 % of pre-triggering. The basic specification and most of devices in the AD converter of VITF are the same as the ones of VHF sensor on Maido-1 satellite. The AD converter is expanded two channels in VITF. The input signal to the channel A is used for detection of the triggering and the waveform of the channel B is recorded in synchronization with the channel A. Since the size of the onboard-buffer is for 130 waveforms per channel, up to the last 130

Table 2. Specifications of the VITF electronics unit.

Outline	
Size	180 * 210 * 60 mm
Weight	2.4 kg
Communications interface	2Gbps RS-422
DC power	8.1 W (+12, +5 V)
Band-pass filter	
3 dB pass band	30 ~ 100 MHz
Insertion loss	-1 dB (at center frequency)
Attenuation	-20 dB / 20, 110 MHz
In- and out-put impedance	50 Ω
Amplifier	
Input level	-85 ~ -35 dBm
Gain	45 dB
Output level	1 Vp-p
In- and out-put 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 ~ 100 MHz
Triggering	Level trigger (event trigger)
Threshold level	50 ~ 500 mV (10 steps variable, positive only)
Memory	Ring-buffer for 130 * 2.5 μsec waveforms / channel

waveforms are saved with their time stamp. The sufficient accuracy of the time stamp to compare the data by other sensors is maintained using GPS signal. The AD converter is connected to Science Instrument Handling Unit (SHU) of JEM-GLIMS mission with 2Gbps RS-422 interface. The AD converter is controlled by the commands from SHU and the captured data of VITF are transferred and temporarily stored in SHU. The operation commands of VITF are start/stop recording, waveform/status data output, data clear, threshold setting, and forced triggering to respective channels. All other sensors on JEM-GLIMS mission are also connected to SHU and the timing of the data recording is dominated by SHU which interfaces with MCE bus system [Kikuchi et al. 2011].

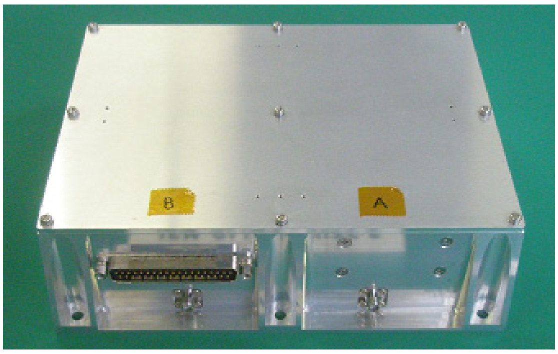

Figure 4. VITF electronics unit.

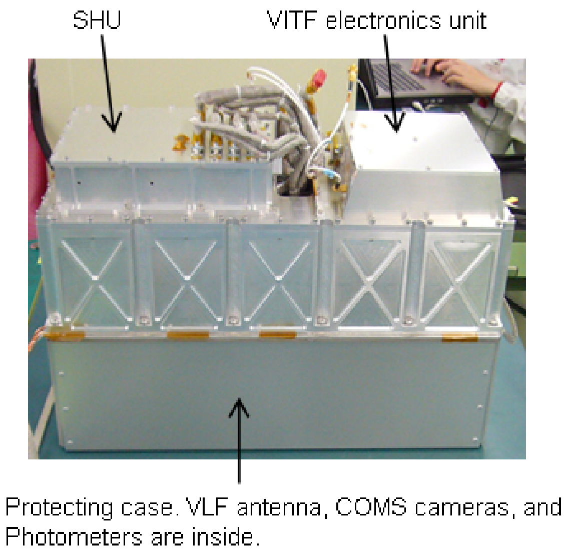

Figure 5. JEM-GLIMS integration.

The band-pass filters, the amplifiers, and the AD converter are unified in a 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 and it is installed of the top of the JEM-GLIMS box unit as shown in Figure 5. The size and weight of the VITF electronics unit are 180 * 210 * 60 mm and 2.4 kg, respectively.

After the designing and manufacturing, various environmental tests were conducted as well as electrical tests. Vibration, impact and thermal vacuum tests for the VITF antennas were held solo. The electronics unit was tested as the integrated the JEM-GLIMS box unit. JEM-GLIMS mission had been completed their development and delivered to the integrator of MCE.

Mission target of VITF

The main objective of VITF is the lightning observations by recording VHF broadband EM waveforms received by the antennas and estimating their source locations. 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 VHF EM source is 1.5° through the experience of the ground-based DITF [Nakamura et al. 2009]. In the case that the ISS altitude is 400 km, VITF is able to identify the location of EM source as a doughnut shape ring with the width of 10 km. This resolution at the earth surface is equivalent to the typical size of a thundercloud. Combining with the observation data of the optical sensors on JEM-GLIMS mission and other results like satellite imaging, and ground-based lightning and/or weather radar observations VITF localizes the lightning activity in the scale of a thundercloud. The range of extension is also given. The information for horizontal distance and temporal relationship between VHF EM sources that are corresponding to the lightning activities and TLEs might contribute to clarify the mechanism of TLE initiation.

OBSERVATION RESULTS

Global lightning observations of JEM-GLIMS

JEM-GIMS mission payload was successfully launched at the end of July 2012, and transported and installed to the ISS. After the initial checkout and maintenance, its nominal operation has been continuing since December 2012. Through the operation period, VITF corrects numerous VHF EM data synchronized with optical signals. Figure 6 shows a pair of typical waveforms captured by the two antennas of VITF simultaneously. About 650 VITF datasets were obtained in January and February 2013, for instance. Figure 7 represents the locations of the ISS where VITF captured VHF signals that considered from lightning for the 8 months from January to September 2013. The timing of data acquisition is controlled by the optical sensor of JEM-GLIMS through this period. Namely, the EM and optical sensors data are recorded triggered by the optical sensor. All dots in Figure 7 correspond to the records for optical signals, and red dots are VHF signals. 1,278 of 2,020 optical observations, about 60%, are accompanied with VHF radiation in this period. While this ratio depends on the threshold level of the data acquisition, neither regional nor seasonal dependency can be seen obviously. Though the discrimination is in progress, most optical signals do not record TLEs but lightning discharges.

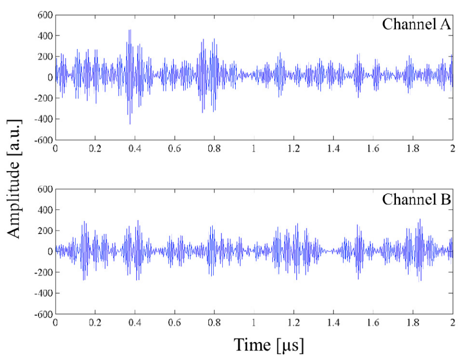

Figure 6. VHF waveforms recorded by VITF.

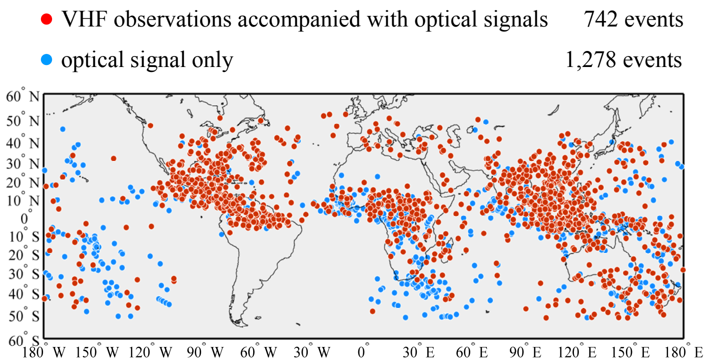

Figure 7. Locations of detected optical and VHF signals.

DOA estimation

Two antennas of VITF are installed at the bottom panel of MCE with 1.6 m separation. The distance between 2 antennas is not enough, but DOA estimation could 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 8 shows an example of the operation of broadband digital interferometry to the recorded VHF signals by VITF. The Fast Fourier Transform (FFT) is applied for the part of the received

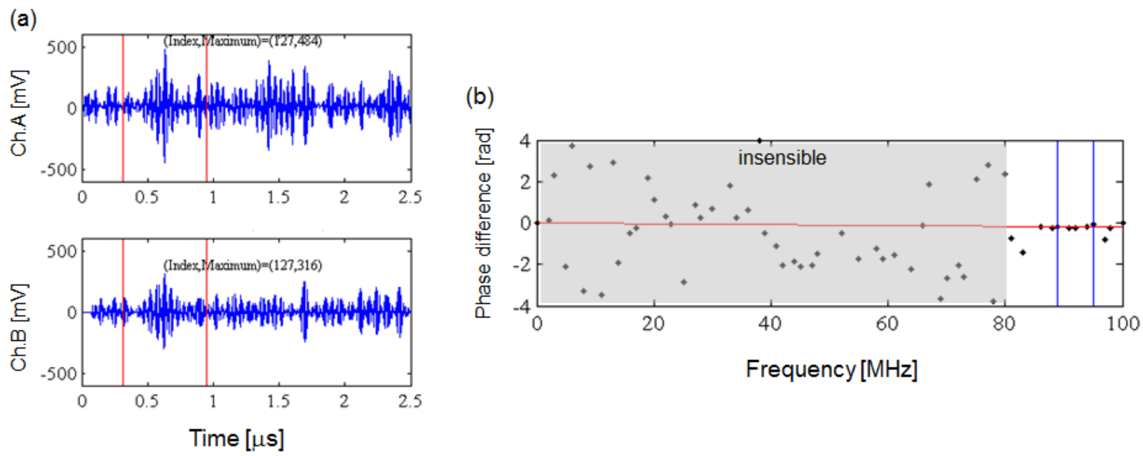

Figure 8. Operation of broadband digital interferometry to the recorded VHF signals by VITF.

VHF impulsive waveforms between the red lines in Figure 8(a). The calculated phase differences between the waveforms of antennas A and B are plotted at each Fourier components in Figure 8(b). The phase difference should have liner dependence with frequency in the bandwidth of the antenna, from 70 to 100 MHz. The fitted red line crossing the origin to the calculated phase differences by the least-square method is drawn in Figure 8(b). The focused frequency range is fine-tuned with waveforms. For the case where the EM source is sufficiently distant to be approximated by a plane wave from the antenna array, the slope of the fitted line corresponds to the angle of the incidence against the baseline of the antennas. The DOA could be estimated as 94° for the VHF waveforms in Figure 8.

An optical sensor of GLIMS, LSI, records the lightning image at the same time. Figure 9 is the LSI image superimposed by the estimated DOA of 94° with VITF. The side of Figure 9 corresponds approximately to 200 km. If the LSI image is supposed to be a phenomenon at a plane, an estimated DOA corresponds to a hyperbola on the plane as illustrated in Figure 10. The estimated DOA is drawn as a hyperbola in Figure 9. Figure 9 shows a good agreement of the VHF DOA estimation with the optical observations.

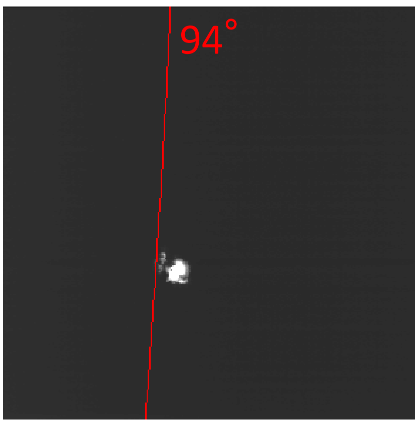

Figure 9. LSI image superimposed by the estimated DOA with VITF.

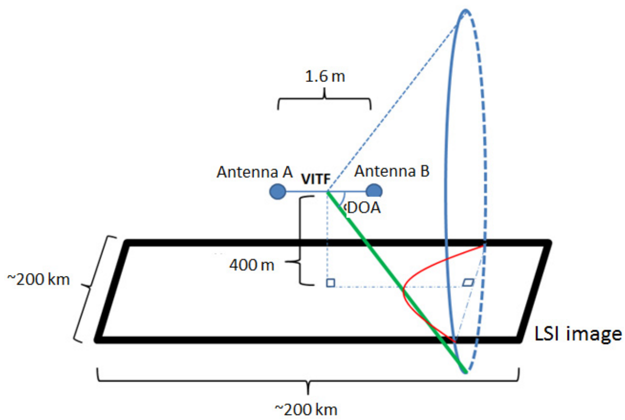

Figure 10. Comparison model between the DOA estimation and the optical image.

Even though DOA estimation has difficulties caused by its very short baseline of the antennas and multiple pulses in short time, many results with high signal-to-noise ratio and isolate VHF pulse agree with the optical observations.

CONCLUSIONS

JEM-GLIMS mission has been going on the ISS to observe global distributions of lightning and lightning-associated TLEs by combining observations with radio and optical sensors. This paper introduces the primary observation results of an EM payload of JEM-GLIMS mission, VITF. 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 that is equivalent to the scale of a thundercloud. It means that VITF is able to monitor thunderclouds with lightning activities globally. Comprehensive observations with the optical payloads of JEM-GLIMS mission for lightning activities and TLEs are expected to give us many scientific impacts to the field.

JEM-GIMS mission payload was successfully launched at the end of July 2012, and transported and installed to the ISS. After the initial checkout and maintenance, its nominal operation has been continuing from December 2012. Through the operation period, VITF corrects numerous VHF EM data synchronized with optical signals. 1,278 events with active VHF radiations out of 2,020 optical observations, about 60%, are observed for the 8 months from January to September 2013, for instance. The DOA estimations of the received VHF pulses are attempted using the broadband digital interferometry. Some results agree with the optical observations, even though DOA estimation has difficulties caused by its very short baseline of the antennas and multiple pulses in short time, namely burst-type EM waveforms. It is the worlds' first space-borne lightning location by EM DOA estimation. The results on narrow bipolar pulses (NBPs) and/or transionospheric pulse pairs (TIPPs) are also expected as well as TLEs. JEM-GLIMS also has an operation mode depending on VITF observations. The data acquisition is triggered when VITF records 100 EM pulses with higher intensity than the threshold level within 100 ms in this mode. Optical data are not recorded in this mode but the frequency of VHF EM radiation is obtained continuously. The world's first global lightning distribution by means of space-borne VHF observation could be expected.

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REFERENCES

Boccippio, D. J., S. J. Goodman, and S. Heckman, 2000: Regional difference in tropical lightning distributions, *Journal of Applied Meteorology*, **39**, Issue 12, 2231-2248

Christian, H. J. , R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, and M. F. Stewart, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, *Journal of Geophysical Research*, **108**, **D1**, 4005, doi:10.1029/2002JD002347

Jacobson, A. R., S. O. Knox, R. Frenz, and D. C. Enemark, 1999: FORTE observations of lightning radio-frequency signatures: Capabilities and basic results, *Radio Science*, **34**, **2**, 337-354

Kikuchi, H., R. Tanaka, T. Morimoto, Z. Kawasaki, T. Aoki, and H. Hashimoto, 2010: Observations of lightning discharges by Maido-1 satellite and radio propagation simulations, *Technical report of The Institute of Elecronics, Information and Communication Engineers*, **110(194)**, 59-62 (in Japanese)

Kikuchi, M., M. Sato, A. Yamazaki, M. Suzuki, and T. Ushio, 2011: Development of Science Data Handling Unit (SHU) for Global Lightning and Sprite Measurements (GLIMS) onboard Japanese Experiment Module (JEM) of ISS, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **131**, **12**, 989-993

Kotaki, M., I. Kuriki, C. Katoh, 1984: Radio noise spectrum above the ionosphere at high frequency band, *Transactions of The Institute of Elecronics, Information and Communication Engineers*, **J67-B**, **1**, 9-16 (in Japanese)

Mardiana, R., Z. Kawasaki, and T. Morimoto, 2000: Three-dimensional lightning observations of cloud-to-ground flashes using broadband interferometers, *Journal of Atmospheric and Solar-Terrestrial Physics*, **64**, **1**, 91-103

Mardiana, R., and Z.-I. Kawasaki, 2000: Broadband radio interferometer utilizing sequential triggering technique for locating fast-moving electromagnetic sources emitted from lightning, *IEEE Transactions on Instrumentation and Measurement*, **49**, 376-381

Morimoto, T., A. Hirata, Z. Kawasaki, T. Ushio, A. Matsumoto, and J. H. Lee, 2004: An operational VHF broadband digital interferometer for lightning monitoring, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **124**, **12**, 1232-1238

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 -, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **131**, **12**, 977-982

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

Nakamura, Y., T. Morimoto, T. Ushio, and Z.-I. Kawasaki, 2009: An error of the VHF broadband digital interferometer, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **129**, **8**, 525-530 (in Japanese)

Sato, M., Y. Takahashi, M. Kikuchi, M. Suzuki, A. Yamazaki, and T. Ushio, 2011a: Lightning and Sprite Imager (LSI) onboard JEM-GLIMS, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **131**, **12**, 994-999

Sato, M., Y. Takahashi, M. Suzuki, A. Yamazaki, and T. Ushio, 2011b: Six-Channel Spectrophotometers (PH) Onboard JEM-GLIMS, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **131**, **12**, 994-999

Taniguchi, T., A. Hirata, T. Morimoto, and Z. Kawasaki, 2006: Propagation characteristics of wideband electromagnetic wave in the ionosphere, *Transactions of The Institute of Electrical Engineers of Japan on FM*, **126**, **11**, 1173-1176

Tierney, H. E., A. R. Jacobson, R. Roussel-Dupre, and W. H. Beasley, 2002: Transionospheric pulse pairs originating in maritime, continental and coastal thunderstorms: Pulse energy ratios, *Radio Science*, **37**, **3**, 1039, doi:10.1029/2001RS002506