An Operational VHF Broadband Digital Interferometer for Lightning Monitoring

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The authors have been developing a new type of lightning location and monitoring system based on a technique of “VHF broadband digital interferometry”. This paper summarizes this VHF broadband digital interferometer (DITF), together with new observations. As a first step of the development, the experimental system is installed and lightning observations are conducted. In these observations, imaging of lightning progression is obtainable in two- and/or three-dimensions. The effectiveness of our results has been confirmed by the comparisons with the results of previous studies and other observations. The evaluation of the system is discussed to improve its accuracy, and the advanced system is completed. At present, the advanced system has been completed and the first result is obtained. It is concluded that the function of the system works well, and the VHF broadband DITF for lightning monitoring is accomplished with high accuracy from the aspects of time and space resolutions.

Keywords : broadband digital interferometry, lightning discharge, electromagnetic radiation, direction-of-arrival estimation

1. Introduction

It is widely believed that lightning discharges emit fairly broadband electromagnetic (EM) waves from VLF/LF to VHF/UHF, occasionally up to SHF. Lightning discharges, both cloud-to-ground (CG) and cloud-to-cloud (CC) flashes, are the phenomena, which continue for one or two seconds. That is a main reason why from the aspect of the daily life the duration of lightning discharges can be concluded to be really short. One or two seconds in a daily life is seemed to be instantaneous. Therefore, the traditional understanding of “lightning discharges emit ultra broadband electromagnetic waves” may be correct. However, if we think about these phenomena from the aspect of science, like the comparison with the lifetime of free electrons in the atmosphere, the causes for VLF/LF and VHF/UHF waves are completely different. The VLF/LF EM waves are mainly radiated during lightning return strokes (RSs), while VHF/UHF are emitted during the progressions of breakdowns like stepped leaders. Since it is known that VHF/UHF impulses are mainly radiated from the tip of the breakdown, the locations for their sources are equivalent to imaging the lightning channel development. Moreover recent investigations suggest that locations of negative breakdown source

may give us information on positive charge distribution inside thunderclouds as well⁽¹⁾⁽²⁾.

The authors have been developing a new type of lightning location and monitoring system based on a technique of VHF broadband digital interferometry since 1995. The VHF broadband digital interferometer (DITF) has been proposed by the group of New Mexico Tech⁽³⁾ and Lightning Research Group of Osaka University (LRG-OU)⁽⁴⁾⁽⁵⁾ independently and simultaneously. LRG-OU has been working for developing the system, and accomplished the experimental system. We have been conducting thunderstorm observations using this experimental system, and validating its capability. In order to improve the performance of the system further, we have designed a special analog-to-digital converter (ADC) and amplifier. This paper presents a brief summary and current state of the broadband DITF. The evaluation of the system and the first result by the advanced system are also described.

2. VHF Broadband Digital Interferometer

2.1 Basic Concept A broadband DITF is a system to locate sources of VHF impulses based on the digital interferometric technique. The basic idea of the technique is to estimate the phase differences between the EM pulses received by a pair of spatially separated broadband antennas at various frequencies. A remarkable feature of this system is its ultra-wide detection frequency range, and it takes no account of a carrier frequency. The simplest radio interferometer consists of two separate antennas. Let us consider two broadband antennas separated horizontally above the ground with a distance d , as shown in Fig. 1. The received broadband signal, which is originated from a common source, by the antennas 1 and 2 are

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$r_1(t)$ and $r_2(t)$, respectively. These signals are digitized at a certain time interval Δt and expressed as discrete time series

$$r_i[m] = r_i(m\Delta t) \quad (i=1,2; m=0,1,\dots,N-1) \quad (1)$$

Here $\Delta t \times (N-1)$ is a total record length. The Discrete Fourier Transform (DFT) is applied to r_1 and r_2 as

$$R_i[m] = \sum_{n=0}^{N-1} r_i[n] \exp\left(-\frac{j2\pi mn}{N}\right) \quad (i=1,2) \quad (2)$$

The phase difference (θ_{12}) of signals r_1 and r_2 for each frequency component is given by

$$\theta_{12}[m] = \tan^{-1} \frac{\text{Im } R_1[m]}{\text{Re } R_1[m]} - \tan^{-1} \frac{\text{Im } R_2[m]}{\text{Re } R_2[m]} \quad (3)$$

In practice, the Fast Fourier Transform (FFT) is applied for data processing. Thus, $N/2$ Fourier components are taken into account. When the phase difference goes through more than one cycle in high frequency component, there is the possibility of the fringe ambiguity^{(6)~(8)}. We remove the ambiguity using the feature that the phase difference should be linear dependence with frequency. In particular, we displace θ_{12} for the high frequencies over $\pm 2\pi$, $\pm 4\pi$, $\dots$, and then select only a series of θ_{12} s that crosses the origin. This process is described in more detail in (5).

For the case where the source is sufficiently distant to be approximated by a plane wave from the antennas' positions, the angle of incidence $\phi[m]$ defined in Fig. 1 can be interpreted with $\theta[m]$ by

$$\phi[m] = \cos^{-1} \frac{c\theta[m]}{2\pi fd} \quad (4)$$

Where c is the speed of light in vacuum ($\sim 3 \times 10^8$ m/s). We adopt the arithmetic mean value for all Fourier frequency components as the angle of incidence of the signal.

A radio interferometer as a two-element array gives the location of an EM source in the one-dimension, namely the angle of incidence. Two pairs of antennas and two independent baselines are imperative for two-dimensional mapping in azimuth and elevation format. In our system, we use three sensors, which are equipped at three apexes of a level isosceles right-angled triangle. We define linearly independent two couples of antennas with a separation of 10m as shown in Fig. 2. In this arrangement, antennas 1 and 2 form the first baseline, and antennas 1 and 3 form the second baseline. Note that these baselines are perpendicular to each other. From the angle of incidence ϕ_1 and ϕ_2 against to each baseline, the direction of an EM source can be estimated as azimuth (α) and elevation (β) by the following equations.

$$\alpha = \tan^{-1} \frac{\cos \phi_1}{\cos \phi_2} \quad (5)$$

$$\beta = \cos^{-1} \frac{\cos \phi_1}{\cos \alpha} \quad (6)$$

Three-dimensional localization of EM sources can be accomplished by a synchronized operation of two units of interferometers as in Fig. 2 with a proper separation using Global Positioning System (GPS). Fig. 3 gives a conventional algorithm for three-dimensional imaging by triangulation.

2.2 Computational Simulation of Broadband Digital Interferometry In this subsection, a computational approach

Fig. 1. The simplest radio interferometer

Fig. 2. Antenna arrangement of a perpendicular baseline interferometer for two-dimensional mapping. The antennas 1 and 2 form the first baseline, and the antennas 1 and 3 form the second baseline

Fig. 3. Triangulation scheme. Each site provides azimuth-elevation mapping of radiation source

is carried out in order to demonstrate the effectiveness of the broadband DITF. As a computational scheme, the finite-difference time-domain (FDTD) method is used⁽⁹⁾. In the FDTD method, the whole space considered is divided into the small region called 'cell', and the EM field components are distributed on the basis of the Yee algorithm. The time variation of fields is followed step by step with the discretized time, which satisfies the Courant condition. For the case where the wave-object interaction must be considered in the open region, the computational space has to be truncated by absorbing boundaries. In this paper, an 8-layered Berenger's PML is adopted.

The broadband DITF shown in Fig.1 is considered. The separation between the antennas d is set to 2.0 m, while it is 10m in our experimental system. However, this computational demonstration clarifies the effectiveness and future works of the

DITF. A plane wave is considered as a wave source, since sources are sufficient distant from the antennas. It should be noted that the return loss of this antenna depends on the frequency of EM waves (smaller than 3dB at least over the above frequency band). However, it does not matter since the phase difference between the antennas is essential to the direction-of-arrival (DOA) estimation with the interferometry. Also note that the EM fields are calculated in the three-dimensions, while the DOA estimation is carried out in the one-dimension for simplicity.

Fig. 4 shows the phase difference between the antennas 1 and 2 for the angle of incidence of 60° . A regression line calculated from the method of least squares is also presented. Note that the reason for an obvious difference between the numerical value and the regression line at 70 MHz is that the power level at the frequency band is smaller than that at other frequency bands. On the basis of the phase difference in Fig.4, an estimated angle of the pulse is plotted in Fig. 5. From this figure, the estimated angle at 100 MHz is 58.5° , which is close to the ideal value of 60° . Similarly, reasonable agreement is obtained with the ideal value in the frequency range between 85 MHz and 120 MHz. A scheme for the determination of the angle of incidence, a weighting function dependent on the SN ratio of the EM pulse is used⁽¹⁰⁾. From these results, one can state that our broadband DITF is effective to estimate the DOA of EM pulses. It should be noted that main reason for the error is the mutual impedance between the antennas. We have been developing a compensation scheme of this effect⁽¹¹⁾⁽¹²⁾.

Fig. 4. Phase difference between the antennas; The separation between the antennas is 2.0 m

Fig. 5. Estimated DOA. The ideal value of the angle is 60°

2.3 Instrumentations Fig. 6 illustrates a block diagram of one unit of the VHF broadband DITF for two-dimensional mapping. As a VHF receiver, we use circular flat-plate antenna, which has a diameter of 30cm. The received broadband signal is limited its bandwidth and amplified by a band-pass filter and an amplifier equipped beneath the sensor, respectively. Then the signal transmitted through a coaxial cable is digitized by a three-channel ADC synchronizing with the signals from the other two antennas, and then stored in a personal computer (PC). As a first step of the development, we install an experimental system using a commercially available high-speed digital oscilloscope (LeCroy9374) with a sampling rate of 500MHz ($\Delta t = 2\text{ns}$) and an 8-bit resolution. This is controlled by the PC through the IEEE-488 interface bus. The band-pass filter with the pass band of 10-250MHz and a logarithmic amplifier to compensate for an insufficient resolution are equipped. The original waveform and Fourier spectrum of a typical VHF impulse captured by the experimental system are given in Figs. 7 and 8, respectively. In Fig. 7, the output of the logarithmic amplifier (a) and the estimated input (b) are shown. In Fig. 8, it is noted that the dominant frequency range of VHF impulses associated with lightning discharge is up to 100MHz. The output of logarithmic amplifier is unsigned though the polarity of the VHF pulse has significant physical meaning, in narrow bipolar event (NBE) for instance.

After the validation of the application of the broadband DITF technique to lightning monitoring as described later, the advanced system is developed by virtue of recent progress of electronics. Significant improvement can be expected from its specially

Fig. 6. Block diagram of the one unit of the broadband DITF for two-dimensional mapping

Fig. 7. Typical waveform of VHF impulse captured by the experimental system

Table 1. Specifications of the experimental and the advanced broadband DITF systems

		Experimental system	Advanced system
Band-pass filter	Pass band	10 — 250MHz	25 — 100MHz
Amplifier	Input range (in)	-70 — 5dBm	-85 — -15dBm, -75 — -5dBm -65 — 5dBm, -55 — 15dBm (with 10dB-step variable attenuator)
	Output range (out)	out[mV] = 3.33[dBm]+300 (logarithmic amplification)	out[dBm] = in[dBm]+25 (linear amplification)
ADC	Sampling rate	500MHz	200MHz
	Resolution	8-bit	10-bit
	Time of data acquisition	1 μ s $\times$ 2000segments	2.5 μ s $\times$ 2048segments
	Memory	1MW/ch (8-bit)	1.024MW/ch (16-bit)
	Dead time	$\sim$ 70 μ s	$\sim$ 1 μ s

Fig. 8. Fourier spectrum of a typical VHF impulse

Fig. 9. Typical waveform of VHF impulse captured by the advanced system

developed ADC, which has a 200MHz sampling rate and a 10-bit resolution. The three-channel ADC is on one board and plugged in to ordinary PCI-bus of a PC. The band-pass filter with the pass band of 25-100MHz and a linear amplifier are also manufactured. A representative VHF impulse captured by the advanced system is given in Fig. 9. The specifications of experimental and advanced systems are summarized in Table 1. Because of such high-speed digitization, the whole VHF radiation from a lightning flash cannot be recorded continuously. To overcome this difficulty we applied a sequential triggering technique. Namely the memory on the digitizer is divided into 2000/2048 segments to store signals for 1/2.5 μ s and here after it is called “event triggering”. Dead time in Tab.1 means the instrumental interval between segments when signal cannot be recorded. We apply the mapping process described in the section 2.1 to each VHF impulse, which has at

most 500ns pulse width. This means that the sources of three VHF impulses shown in Fig. 9 are located, while one source for the signal in Fig. 7. In other words, the second and third impulses in Fig. 9 cannot be seen by the experimental system, and this is a major improvement of the system.

3. Observation Results and its Validations

3.1 Three-dimensional Localizations The authors have conducted lightning observations in Darwin and Gifu during summer thunderstorm seasons, and in Fukui during winter periods using the experimental system. Figs. 10 and 11 give three-dimensional images of lightning progression captured by the broadband DITF for the events recorded on 4 January, 2002 at 2159:36 h and on 30 December, 2001 at 0316:55 h local time (LT) in the duration of '01-'02 winter thunderstorm observation campaign in Fukui, respectively. All mappings and locations in this paper, excepting Fig. 15(b), are represented by the experimental system. Each figure shows the relative electric field change in the top panel and locations of the VHF impulse sources in three panels from the bottom as a function of time. The second and third panels give west-east and south-north distances from the observation site1. The bottom is the altitude. The site2 is located at 0.6km east and 5.0km south of the site1. The electric field changes are recorded by a common slow antenna at the site1. We adopt the traditional atmospheric sign convention to present an electric field change. Therefore, the character “R” in Fig. 10 indicates the occurrence of a RS, and the event in Fig. 10 is classified into negative CG flash. In the period prior to occurrence of RS, that is leader propagation phase, the lightning channel toward the ground is visualized. Since an abrupt change is not noticeable for the electric field change of Fig. 11, this event is classified as a CC flash. The lightning channel with branching inside thundercloud is well visualized. In the 15 events visualized during the same campaign, the progression velocities of negative leaders and negative breakdowns are known to be the range of 1.0-3.0 $\times$ 10⁵m/s without significant differences between them. The results in our other campaigns indicate the same order, and they are consistent with the velocity of downward negative leaders measured by optical emissions⁽¹³⁾⁽¹⁴⁾.

Fig. 12 shows three-dimensional VHF impulse sources for a CG flash recorded on 16 November, 2002 at 1226:44 h (LT) in the '02 Darwin campaign. They are superimposed on the vertical cross section of radar echo at the same time drawn by

Fig. 10. Three-dimensional imaging of lightning channel corresponds to a negative CG recorded on 4 January, 2002 at 2159:36 h and on 30 December, (LT) in Fukui

Fig. 11. Similar to Fig.10 but CC recorded on 30 December, 2001 at 0316:55 h (LT)

Fig. 12. Three-dimensional VHF impulse sources located by the broadband DITF superimposed on the cross section of radar echo recorded on 16 November, 2002 at 1226:44 h (LT) in Darwin

plan-position-indicator (PPI) scanning of a C-band radar at variable elevations. Impulse sources drawn in Fig. 12 are located within 1.5km from the vertical plane of the cross section. In this figure, an active core with intensity of more than 50dBz is observed. The locations of VHF impulse sources are concentrated around the core. This coincidence is understandable in common sense.

The consistencies of these results with previous studies and other observations are clear evidences that the broadband DITFs work well.

Fig. 13. Dispersions in terms of the angle of incidence (a) and two-dimensional source mapping (b) for all observed VHF impulses. This event is the CC flash recorded on 29 January, 2001 at 1240:03 h (LT) in Fukui

Fig. 14. The same as Fig. 13, but for VHF impulses with small dispersions

3.2 Error Evaluations and Improving the Accuracy

It is important to investigate the accuracy of the source locations determined by the broadband DITF to improve its accuracy in further study. One of the common procedures is the installation of additional antennas that is redundant antennas those are used to apply the least square error method. The calibration of location errors by means of artificial VHF signals from given sources might be another idea.

The error evaluation by comparing with already established narrowband system and with all-sky video camera has been reported in our previous papers⁽¹⁵⁾⁽¹⁶⁾. The result showed that the average discrepancy for azimuth direction is less than 1° with standard deviation of 4.5° and for elevation direction is less than 2° with standard deviation of 5.0°.

In case of a broadband DITF we can use the redundant of Fourier spectrum, because tens of Fourier components exist for each VHF impulse. As mentioned before, the arithmetic mean of angles of incidence for each Fourier components is applied to estimate one pair of azimuth and elevation. Fig. 13 shows the dispersions in terms of angle of incidence (a) and the estimated azimuths and elevations (b) for all observed VHF impulses as a function of time corresponds to the CC flash recorded on 29 January, 2001 at 1240:03 h (LT) in Fukui. Apparently the dispersions are large, but it is because some highlighted datasets with large dispersion. If we throw them, the lightning channel with branching becomes clear as shown in Fig. 14(b). The dispersions shown in Fig. 14(a) range less than 0.2 rad that constitutes 58% of Fig.13.

Fig. 15. Two-dimensional mapping of the same negative CG by the experimental system (a) and by the advanced system (b), respectively. This event is the CC flash recorded on 1 September, 2003 at 1625:28 h (LT) in Gifu

3.3 Progress in the Advanced System In this subsection, we show the first observation result by the advanced system described before to appreciate the progress achieved in this system. We operated both of the experimental and advanced system at the same location to compare their results. Fig. 15 gives the estimated azimuths and elevations of the same negative CG flash, which are recorded by the experimental system (a) and by the advanced system (b), respectively, in time domain. This event is the CC flash recorded on 1 September, 2003 at 1625:28 h (LT) in Gifu. The relative electric field change (not shown) indicates the occurrence of RS at the time of the character “R” in the figure. Both results show the leader propagations toward the ground. Comparing both results, it is noticed that the mapping by the advanced system have higher time resolution. Furthermore, the branching of the leader progression can be seen clearer in the azimuth in Fig. 15(b). The advantages of dead time and resolution of the ADC and the linearity of the amplifier (see Table 1) are responsible for these progresses. Because of its shorter dead time, the memory became full in the middle of the leader propagation in the event of Fig. 15. This is easily resolvable by changing the size of its memory.

4. Summary

A VHF broadband DITF has been developed in order to image lightning channel. Lightning observations were conducted and imaging of lightning progression is realized in two- and/or three-dimensions using the experimental system. In order to validate the application of the broadband DITF technique to lightning monitoring we compared our observations with observations by video camera, narrowband interferometer, weather radar, and so forth. The consistencies of these results with previous studies are explicit evidences for the effectiveness of the system. The error evaluated in terms of dispersions, Fourier

components, and interactions can contribute to improve the accuracy. At present, the advanced system has been completed with some specific parts and the first result is shown. Furthermore, the mutual coupling between the antennas composing the DITF was estimated numerically and a compensation scheme of this effect was proposed.

It should be accented that two-dimensional mapping can be given in quasi real-time. Quasi real-time means the interval from data acquisition to output of the mapping for a flash is an instant (at most one second). The short baselines are responsible for the feature in the sense of that the data transfer from other sites is not needed. This suggests the superiority of interferometry to a time-of-arrival (TOA) technique.

In this paper the VHF broadband DITF was summarized with some recent results, and we conclude an operational system for lightning monitoring is accomplished with high accuracy from the aspects of time and space.

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