AN OPERATIONAL VHF BROADBAND DIGITAL INTERFEROMETER AND THUNDERSTORM OBSERVATIONS

Takeshi Morimoto, Zen Kawasaki*, and Tomoo Ushio

Lightning Research Group of Osaka University (LRG-OU),
2-1 Yamada-oka, Suita, Osaka, JAPAN
morimoto@comm.eng.osaka-u.ac.jp

ABSTRACT

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, at present, the first result is obtained by the advanced system. The real-time display of azimuth-and-elevation mapping of lightning discharges is actualized on the feature that single DITF operation provides them without any data communication with other sites. 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.

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.

VHF BROADBAND DIGITAL INTERFEROMETER

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

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

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

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

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. 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 $\pm 2\pi$, $\pm 4\pi$, $\cdots$, 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

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

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.
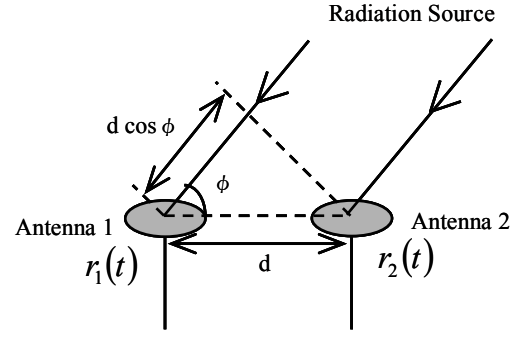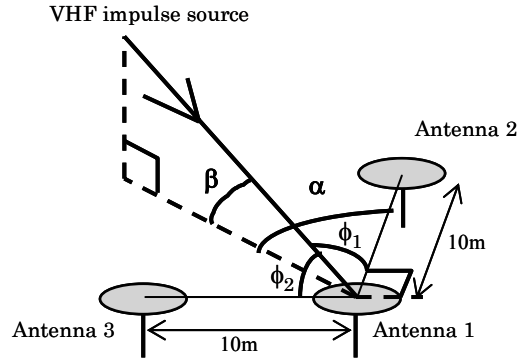

Fig. 1.   The simplest radio interferometer.

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.

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 (2D) 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 (3D) 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).

Instrumentations

Fig. 3 illustrates a block diagram of one unit of the VHF broadband DITF for 2D 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 (Δt=2ns) 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.

After the validation of the application of the broadband DITF technique to lightning monitoring, the advanced system is developed by virtue of recent progress of electronics. Significant improvement can be expected from its specially 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. 4. 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 1/2.5μs 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. 4 are located, while the second and third impulses in Fig. 4 cannot be seen by the experimental system, and this is a major improvement of the system.
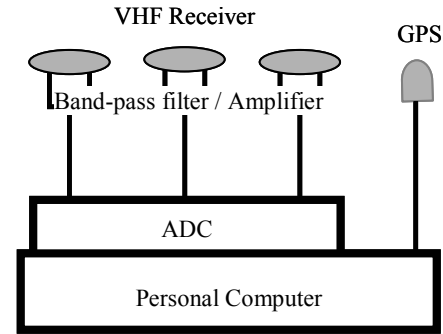

Fig. 3. Block diagram of the one unit of the broadband DITF for two-dimensional mapping.
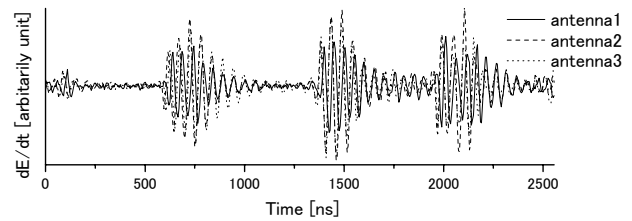

Fig. 4. Typical waveform of VHF impulse captured by the advanced system.

OPERATIONAL VHF BROADBAND DIGITAL INTERFEROMETER FOR THUNDERSTORM MONITORING

We operated both of the experimental and advanced system at the same location to compare their results. Fig. 5 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 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. 5(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. 5. This is easily resolvable by changing the size of its memory.

Single station of the VHF broadband DITF provides the VHF impulse source location in 2D, namely azi-

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	1μs × 2000segments	2.5μs × 2048segments
	Memory	1MW/ch (8-bit)	1.024MW/ch (16-bit)
	Dead time	～70μs	～1μs

muth-and-elevation. It means that we are able to image lightning channels in 2D without any data communication with other sites. This is a one of significant advantages of the system to other techniques for EM radiation source localization. In this section, we actualize the real-time display of 2D mapping of lightning discharges on the advantage and increases in computing capability.

In our system, waveforms of VHF impulses less than size of on-board memory in 1 s are stored as one dataset. In other words the maximum number of VHF impulses is 2000 in the case of the experimental system and the maximum duration is 1 s for one dataset. It takes less than 1 s to apply the mapping process described in the section 2-1 for one dataset. If we process the data for every data acquisition immediately, the 2D mapping of lightning discharge is displayed in at most 1 s on the observation site. Of course this real-time display is accessible through the Internet.
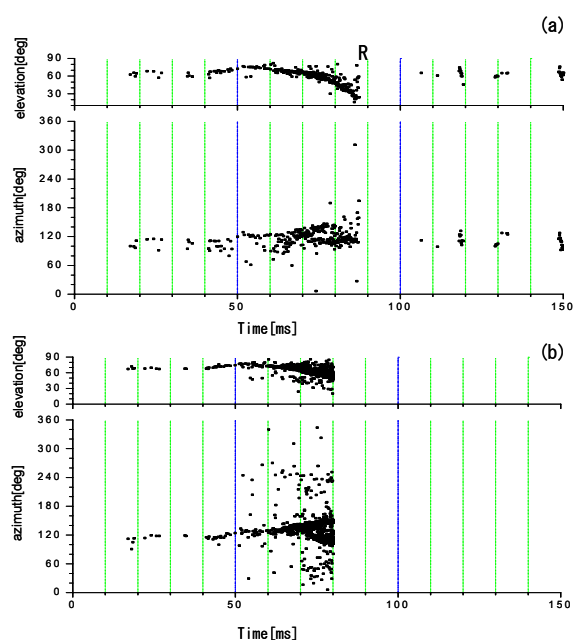

Fig. 5. 2D mapping of the same negative CG recorded on 1 September, 2003 at 1625:28 h (LT) in Gifu by the experimental system (a) and by the advanced system (b), respectively.

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 2D and/or 3D 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. 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 2D 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 resent results, and we conclude an operational system for lightning monitoring is accomplished with high accuracy from the aspects of time and space.

ACKNOWLEDGEMENTS

REFERENCES

[1] L.M.Coleman, T.C.Marshall, M.Stolzenburg, T.Hamlin, P.R.Krehbiel, W.Rison, and R.J.Thomas : "Effect of charge and electrostatic potential on lightning propagation", J. Geophys. Res., 108(D9), doi:10.1029/2002JD002718 (2003)

[2] T.A.Warner, J.H.Helsdon Jr., and A.G.Detwiler : "Aircraft observations of a lightning channel in STEPS", Geophys. Res. Lett., 30(19), doi:10.1029/2003GL017334 (2003)

[3] X.M.Shao, D.N.Holden, and P.R.Krehbiel : "Broadband radio interferometry for lightning observations", Geophys. Res. Lett., Vol.23, No.15, pp.1917-1920 (1996)

[4] T.Ushio, Z.Kawasaki, Y.Ohta, and K.Matsuura : "Broadband interferometric measurement of rocket triggered lightning in Japan", Geophys. Res. Lett., Vol.24, No.22, pp.2769-2772 (1997)

[5] R.Mardiana, and Z.Kawasaki : "Broadband radio interferometer utilizing sequential triggering technique for locating fast-moving electromagnetic sources emitted from lightning", IEEE Trans. on Instrumentation and measurement, Vol.49, No.2, pp.376-381 (2000)