Three-dimensional lightning observations and consideration to charge distribution inside thunderclouds using the broadband interferometer

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ABSTRACT: The Lightning Research Group of Osaka University (LRGOU) has been developing a broadband radio interferometer to locate sources of VHF impulse radiation caused by lightning discharges in four dimensions, that means time and space. The lightning observations have been conducted in Darwin, Australia during summer thunderstorm seasons and in Fukui, Japan during winter periods. Imaging of the propagating channel is given.

Negative breakdowns may progress inside the thundercloud during the continuing current, which happen after positive return strokes (RS) eventually. Since VHF impulses are radiated from mainly negative breakdowns, their source location gives the positive charge distribution. In other words, the broadband interferometer may visualize not only negative leader progressions but also give information on positive charge distribution inside thunderclouds. Consulting radar observations confirms this interpretation.

INTRODUCTION

LRGOU has been developing a new type of lightning location and monitoring system based on a technique of VHF broadband digital interferometry [*Ushio et al.*, 1989 ; *Mardiana et al.*, 2000 ; *Mardiana et al.*, 2000 ; *Kawasaki et al.*, 2000]. The basic principle of broadband interferometry is the relative phase estimation for each Fourier component of a VHF impulse detected by a pair of antennas with a proper separation. It should be noticed that the phase information of an electromagnetic (EM) signal, strictly speaking the phase difference between two antennas, enables us to calculate the incident angle of the EM source against the antenna array.

Since it is known that VHF impulses are mainly radiated from the tip of the breakdown like the stepped leader tip especially in case of a negative breakdown, the VHF impulse source location is equivalent to imaging the lightning channel development. Moreover, the source location associated with the negative breakdown after the occurrence of return strokes (RS) or during the continuing current, with follows a positive RS, gives the positive charge distribution inside the thundercloud. In other words we are able to get images of positive charge distribution by VHF observations.

This paper presents a brief summary about the broadband interferometer, and then gives the consideration to the charge distribution inside the thunderclouds using observed results.

BROADBAND INTERFEROMETER SYSTEM

A broadband interferometer is a system to locate a source of VHF impulse based on the digital interferometric technique. A remarkable feature of the broadband interferometer is its wide detection frequency range, and this system takes no account of a carrier frequency. The system observes the electric field change due to a lightning discharge in the frequency range between 25MHz and 250MHz, and Fast Fourier Transform (FFT) is applied to calculate Fourier components of the received EM pulse. Computed phase difference for each Fourier component between two antennas is a function of the incident angle of the EM pulse against the baseline. A couple of antennas as a two-element-array of the broadband interferometer is able to estimate the incident angle. Two pair of antennas, and two baselines are not coincident, enable two-

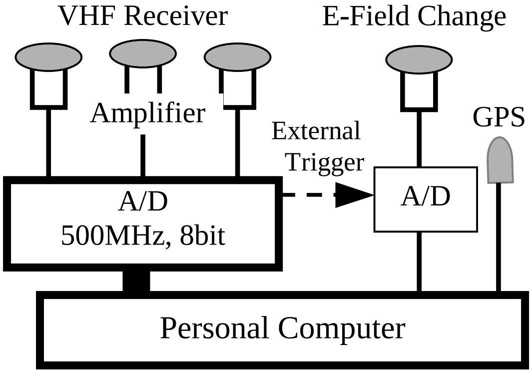

Figure1. A block diagram of the broadband interferometer.

dimensional mapping of sources, like 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, and we define linearly independent two couples of sensors with 10m distance. Figure1 is a block diagram of one unit of the broadband interferometer. We use circular flat-plate antenna witch has a diameter of 30cm, and its bandwidth is calibrated to be between 25MHz and 250MHz. The received broadband signals are amplified by amplifiers equipped just under antennas, and are digitized at a rate of 500MHz with 8-bit resolution. Two thousands EM pulses with about 60 micro-second dead time after one EM pulse recording for one lightning flash within 1 second can be observed. Notice that “two thousands” are the maximum, and the total amount of observed EM pulse number depends on the event’s feature and distance. An additional sensor to measure the electric field change is equipped. This sensor is used to discriminate cloud-to-ground (CG) strokes and to know the polarity of lightning discharges in case of CG flashes. Global positioning system (GPS) receiver is also set up to get the accurate time of the lightning occurrence.

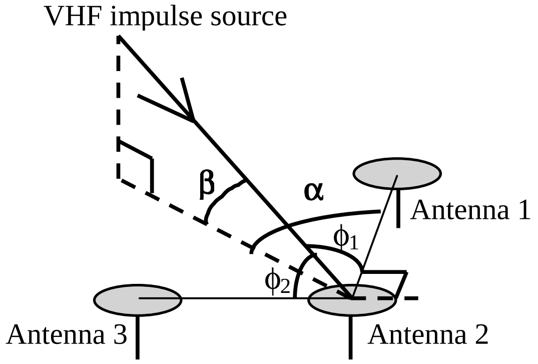

Figure2. The antennas arrangement and the schema of the VHF impulse source location.

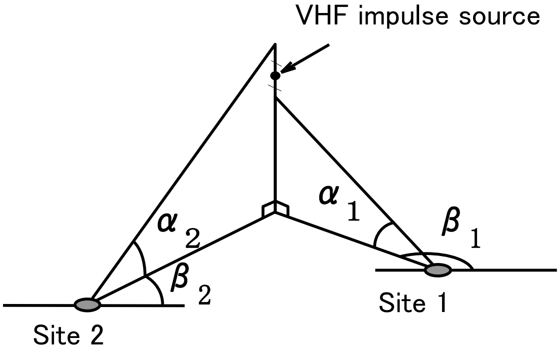

Figure3. A triangulation scheme. Each site provides azimuth-elevation mapping of radiation source.

Figure2 shows the antennas arrangement and the schema of the VHF impulse source location. Using three sensors, the direction of an impulse source can be estimated as azimuth (α) and elevation (β) through the following equations.

$$\alpha = \tan^{-1} (\cos\phi_1 / \cos\phi_2) \qquad (1)$$

$$\beta = \cos^{-1} (\cos\phi_1 / \cos\alpha) \qquad (2)$$

where ϕ_1 and ϕ_2 are incident angles relative to each sensor baseline.

A tow-unit operation with a proper distance separation enables the three-dimensional mapping of VHF impulse sources. Figure3 gives a conventional algorithm for three-dimensional mapping.

OBSERVATION RESULTS

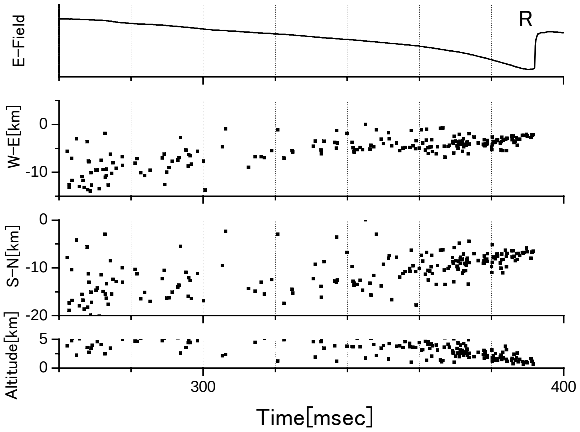

Figure4. The 3D mapping of lightning channel and related electric field change correspond to –CG

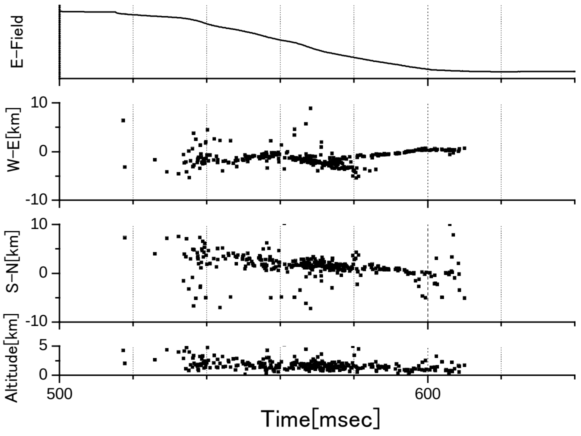

Figure5. The 3D mapping of lightning channel and related electric field change correspond to CC.

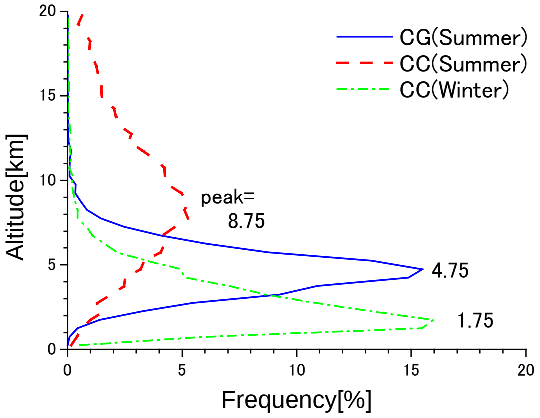

Figure6. The VHF impulse source distribution as a function of altitude corresponding to CG and CC flashes, and seasonal dependency.

Figures4 and 5 give three-dimensional images of lightning progressions by the broadband interferometer. Both flashes are recorded during ’01-’02 winter thunderstorm observation campaign in Fukui. 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 the third panels give west-east and south-north distance from the observation site1 respectively. The bottom is the altitude. The character “R” in Fig.4 indicates an abrupt electric field change, which denotes the occurrence of a RS. In this paper we adopt the traditional atmospheric convention to present an electric field change, so an abrupt positive change means that negative charges are lowered from the cloud to the ground. In this meaning the event of Fig.4 is discriminated negative CG flash. In the period prior to occurrence of RS, that is leader propagation phase, the lightning channel toward to the ground is visualized. Since in the electric field change of Fig.5 an abrupt change is not noticeable, this event is a cloud-to-cloud (CC) flash. The lightning channel with branching inside thundercloud is visualized. During the same campaign we recorded fifteen events and their lightning channels are visualized like Figs.4 and 5. The progression velocity of negative leaders and negative breakdowns is known to be the range of 1.0-3.0*10^5m/s.

Figure6 shows the VHF impulse source distribution as a function of altitude corresponding to CG and CC flashes, and seasonal dependency. These are statistical results over several campaigns. Summer and winter data are obtained at Darwin and Fukui respectively, and all CGs are negative. Comparing the CG and the CC in summer thunderstorm seasons, CC has widely and highly spread than CG. During winter, VHF radiation sources are distributed lower region.

CONSIDERATION TO CHARGE DISTRIBUTION INSIDE THUNDERCLOUDS

LRGOU discovered that the UHF radiation intensity due to negative breakdown is about 20dB stronger than that of the positive breakdown by observed upward initiated lightning from a 200meters-stuck, that is uni-directional and singular polarity leader [*Kawasaki et al.*, 2002]. *Shao et al.*, [1999] reported the VHF radiation intensity due to negative leader is at least 25dB stronger than that of the positive leader and predicted that only VHF/UHF radiation due associated with the negative leader can be detectable because of the masking effect. Summarizing these, VHF radiation sources located by the broadband interferometer are mainly related to the negative breakdown, and negative breakdown,

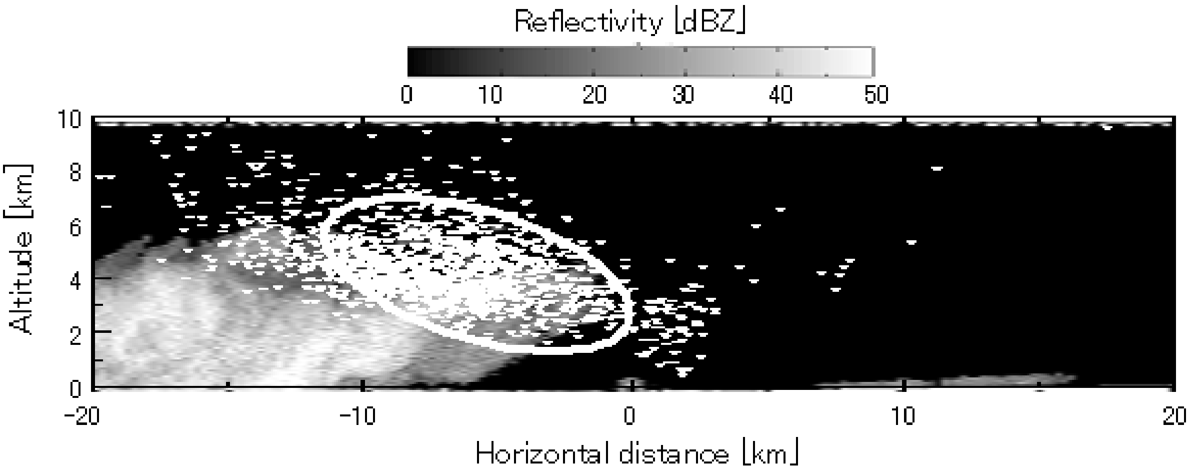

Figure7. 3D VHF impulse sources located by the broadband interferometer in 6minutes superimposed on the cross section of radar echo. The circled area is inferred as a positive charge region.

which follows a positive RS in case of CG, propagates into positive charge region. A visualization of lightning progression inside a thundercloud by the broadband interferometer could give us information on positive charge distribution. From the height distributions of VHF radiation sources shown in Fig.6 the typical altitude of charge center might be presumed as each peak value.

Figure7 shows three-dimensional VHF impulse sources for mainly recoil streamer phase located by the broadband interferometer superimposed on the cross section of radar echo by RHI scanning of an X-band radar. Impulse sources distributed within 1.5km from the vertical plane of the cross section in Fig.7 in 6minutes, which is equivalent to the interval of a volume scanning, are drawn. In this figure, an active core over 40dBz is noticeable and many VHF radiation sources are located at the edge of the core. The circled area that has dense VHF radiations could be considered a positive charge region and its volume is 350km^3. When we assume the charge density as 1nC/m^3, the quantity of positive charge that contributed to the lightning activity in this period is estimated 350C.

CONCLUSIONS

The broadband interferometer has been developed in order to image the lightning channel and to identify the positive charge distribution inside the thunderclouds. Through our lightning observation campaigns, 3D mappings of lightning channels are realized and progression velosity of negative leaders and negative breakdowns in winter thunderclouds is known to be ranged 1.0-3.0*10^{5}m/s. Since the VHF radiation sources detected by the broadband interferometer are mainly related to negative breakdown, they are able to be the positive charge location in case of continuing currents and recoil streamers. This is confirmed by Fig.7, which shows the overlay of VHF impulse sources on the RHI radar echo. The quantity of positive charge that contributes to the lightning activity is estimated. Though to make the conclusion clearly we need more data accumulations, this paper demonstrates the effectiveness in using the broadband interferometer to study charge distribution in thunderclouds.

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