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Review of the Location of VHF Pulses Associated with Lightning Discharge

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This article gives a brief summary on VHF pulse radiation associated with lightning discharges and its location. There are two independent techniques: Time of Arrival and Interferometry. VHF pulses are believed to be emitted during all of the processes of a lightning discharge. Thus, the mapping of VHF pulses associated with lightning yields information not only on lightning channel, but also on the charge distribution. On the other hand, both systems have advantages and disadvantages over each other, and this article summarizes both principles.

Introduction

Lightning discharges radiate electromagnetic waves in a broadband frequency range, from ELF/VLF up to VHF/UHF/SHF. Moreover, Gamma and X-ray radiation have been recorded recently during lightning activity, and the physical mechanism of their generation has become a current topic among the researchers involved with these. The cause of each frequency range radiation is related to an individual lightning discharge process and its progression. Though lightning discharges are phenomena that last only one or two seconds, they consist of processes such as preliminarily breakdown, stepped leader progression, first return stroke, junction process, dart leader progression and subsequent return stroke in the case of a cloud-to-ground flash. In addition, a cloud flash includes the processes of preliminarily breakdown, leader progression, leader encountering a highly charged region, K process and recoil streamer. Among these various processes, ELF/VLF radiation is mainly associated with lightning return strokes and VHF/UHF/SHF radiation is believed to be related to the progression of the tip of a breakdown. In other words, VHF/UHF/SHF radiation is expected to be detectable throughout a lightning discharge, from its very beginning up until its termination and dying-out. Additionally, the detection and location of VHF emissions associated with lightning discharges can be an early warning and alert for rocket launching, as evidenced by the success of Lightning Detection and Ranging systems (LDAR). Thus, the objective of this review article is to offer a brief discussion, in particular on VHF observations from the aspect of lightning location technology development. The technologies reviewed in this article are “Time of Arrival” and “Interferometry”. Physical interpretations of VHF radiation unveiled recently are also introduced.

Time of arrival

Lightning location systems by a time-of-arrival (TOA) technique detecting VHF pulses associated with lightning discharges are categorized into two groups: a very-short-baseline with antenna separation of the order of ten meters and a short-baseline with antenna separation of the order of ten kilometers. In the case of short-baseline TOA for three-dimensional locations, at least four antennas are required and, generally speaking, a TOA system consists of more than five antennas, for redundancy, to obtain the higher imaging accuracy with the aid of a chi-square goodness-of-fit test for example.

The very-short-baseline TOA system is considered. The antenna separation for this technique is 30 to 300 m, receiving a frequency range from 30 to 100 MHz [1]. Though the VHF pulses, which are detected by several antennas, are not easy to identify and/or discriminate from each other, the very-short-baseline technique may overcome this difficulty because, given the velocity of electromagnetic waves, the closely spaced antennas can be considered to have almost identical positions, with the pulses arriving at all antennas within an amount of time that is very short compared to the time interval between pulses. Basically, the very-short-baseline technique is useful for estimating the azimuth and elevation of VHF sources. The very-short-baseline technique led to the development by the author’s group in the 1990s of the broadband interferometer, which will be presented in detail in § “ Lightning Mapping Array (LMA) and Digital Interferometer (DITF) “

The short-baseline technique had been used for the development of two independent systems. The first is the short-baseline time of arrival system presented by Proctor [2], [3]. He deployed five VHF antennas with operating frequencies of 253 and 355 MHz, with baselines ranging from 10 to 40km. At that time, automatic time synchronization between antennas was not available because of it being the pre-GPS era and his laborious work is really respectable. With his own eyes and his wide experience, he conducted the identification of numerous VHF pulses recorded on magnetic tapes at five different locations. His series of papers give rather clear images of the time sequence of lightning initiations, leader propagations and return strokes. He showed the typical velocity of the stepped leader progression and return stroke. One of the most impressive results of lightning location is shown in figure 1.

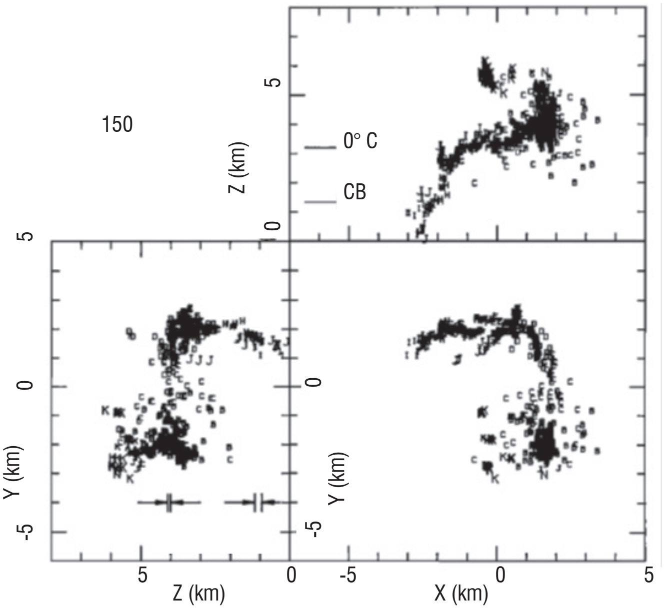


Figure 1 - VHF source locations in a plane view and two elevation views of a flash (adapted from [3]).

The second type of TOA equipment is the Lightning Detection and Ranging (LDAR) system operated at a central frequency range of between 56 and 75 MHz. LDAR was deployed for practical purposes by Lennon and Pochler [4]. According to the author's understanding, LDAR was designed for assessing the threat of triggered lightning to launches at the time of the Apollo-Soyuz mission, as a quasi-real-time operation system. As described before, the identification of VHF pulses is the key procedure for real-time operation. For this, time synchronization is accomplished by common triggering using radio signals for LDAR. However, LDAR still has the disadvantage of not allowing location for VHF burst pulses emitted by processes like K-changes or recoil streamers. As the author has described, the key point of the short-baseline time-of-arrival technique is the identification of VHF pulses and this is why this technique is mainly effective for isolated VHF pulses associated with leader progressions. Figure 2 gives an example of a LDAR observation result.

Interferometry

The interferometry technique is the alternative method to locate VHF pulses associated with lightning discharges. The principle of the interferometer is to measure the phase difference between VHF pulses received by pairs of appropriately spaced antennas. In other words, this technique is principally the same as an FM broadcasting receiver. Since the VHF pulses emitted by lightning discharge do not include the carrier frequency, two antennas are required to estimate the phase difference.

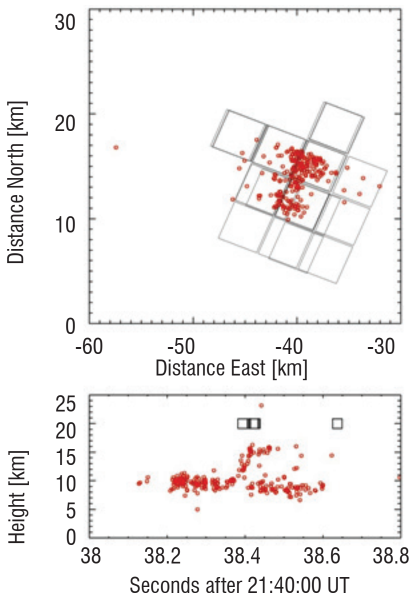


Figure 2 - Example of a cloud flash at 21:40:36 (UTC) on the15th of August 1998 with an overlay of LDAR sources and TRMM/LIS events. Circles and rectangles indicate the LDAR sources and LIS events, respectively. (Adapted from [5])

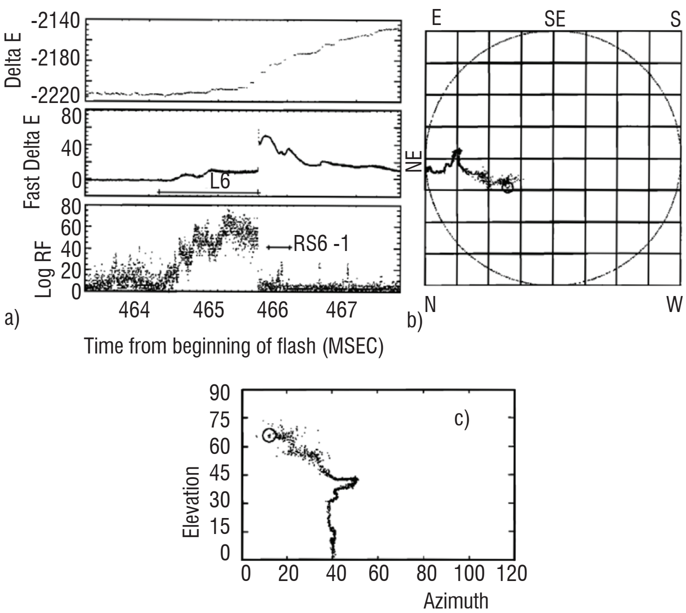


Figure 3 - Observations for a sixth stroke of a cloud-to-ground flash; (a) delta E, fast delta E, and log RF waveforms, (b) VHF source locations in a projection plane and (c) VHF source locations in an azimuth-elevation format. (adapted from[8]).

The first interferometer was designed by Hayenga and Warwick [6], [7]. The operating frequency of their interferometer was 34.3 MHz with a 3.4 MHz bandwidth. The interferometer consisted of three antennas installed at the three apexes of an isosceles right triangle. The spacing between two interferometer antennas is about 15 m, which corresponds to two wavelengths of the center frequency. Two pairs of antennas are able to measure the phase differences and these are recorded on magnetic tape. We can derive the VHF pulse incidence angle relative to the interferometer as the azimuth and elevation. In the early 1990s a series of papers by the New Mexico Institute of Mining and Technology (NMIMT) introduced a new version of their interferometer as a more practical system. Moreover, they applied the idea of combining two baseline lengths to overcome the fringe ambiguity. The series of papers showed the various scientific interpretations of the lightning mechanism and phenomena such as charge distributions, leader progressions including attempted leader, cloud discharges and K events. One of the NMIMT interferometer observations is shown in figure 3 [8].

The Office National d'Études et de Recherches Aérospatiales (Onera) group also developed their own interferometer independently from NMIMT in the 1980s [9], [10]. Figure 4 shows a block diagram for the concept of Onera's interferometer. Normally, using one set of three and/or several antennas for the interferometry (the term 'interferometer unit' is used hereafter) gives us only the VHF pulse incidence angle relative to the observation site in azimuth and elevation. Then Onera group used the GPS time synchronization technique, with a spacing of tens and/or hundreds kilometers between several interferometer units, and two-dimensional mapping of VHF pulses on the ground plane was available for monitoring lightning activity. Moreover, three-dimensional images of lightning progression were obtained for scientific investigation. It may be noticed that an ordinary triangulation was applied for both two and three-dimensional mapping. The triangulation is a weak point of the interferometer for three-dimensional imaging of lightning. However, the Onera system finally became commercially available with an operational system named SAFIR, the operating frequency of which ranges from 110 MHz to 118 MHz, because this frequency band is dedicated to aviation and there is less contamination by artificial signals and noises. Many SAFIR systems are currently deployed all over the world.

The author's group operated SAFIR as the first user outside of France and showed that the location of VHF pulses and thunder cloud development were highly correlated, as a function of time and space [11]. It was possible to conclude that the total number of VHF pulses detected by an interferometer was linearly proportional to the possible amount of precipitation. In addition, the VHF pulse location may sometimes imply the location of solid precipitation particles such as graupel and hail. This fact has led the author and others to assess the ability of VHF lightning mapping to identify charge distribution and polarity within electrified clouds. The rimming electrification theory [12] for charge separation within thunderclouds is considered to be consistent with the VHF source distributions.

Then NMIMT group has been engaged in Lightning Mapping Array (LMA) and the author's group has been working on a broadband interferometer. Moreover their achievements are highly owed to the digital signal processing techniques recently developed in 1990s. The author understands that both NMIMT LMA and Osaka BDITF are the standing digital processing techniques and, from this aspect, there is some discrepancy between these two systems and the previously developed VHF mapping systems. These issues will be presented in the next chapter with scientific discussions.

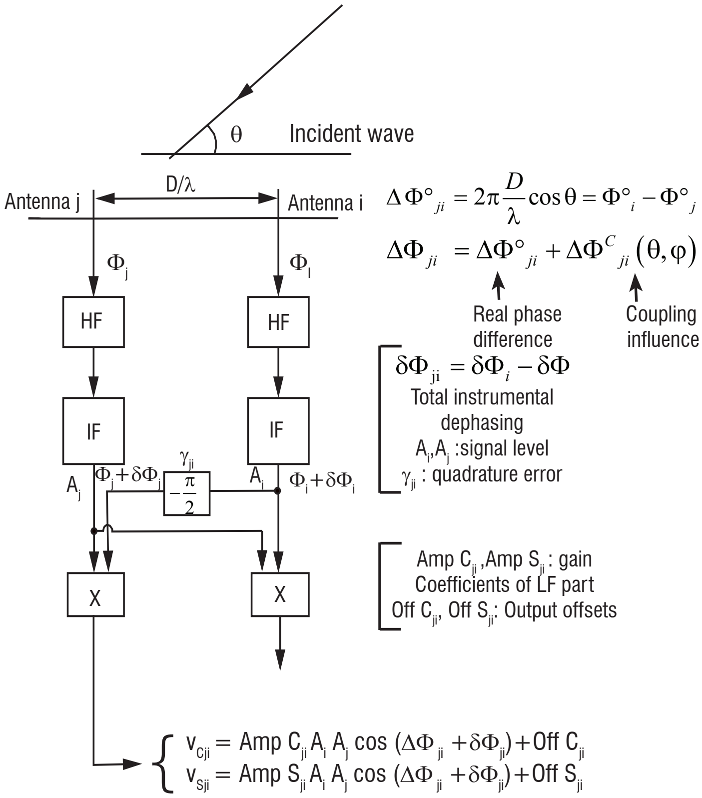


Figure 4 - Modeling of an interferometric couple with amplitude and errors. (adapted from [9]).

Lightning Mapping Array and Digital Interferometer

At the very beginning of this section, the author lists the four possible VHF radiation mechanisms associated with lightning discharges. These are: (1) a negative breakdown penetrating into a positive charge region, (2) a negative breakdown propagating in a free space, (3) a positive breakdown penetrating into a negative charge region, and (4) a positive breakdown propagating in a free space. The knowledge about the radiation intensity discrepancy between a negative and positive breakdown is additionally important. The intensity due to a negative breakdown is about 20 dB stronger than that of a positive breakdown [13], [14]. Since a bidirectional breakdown progression is expected for lightning discharges in the air, that means discharges without metal electrodes, the VHF radiation associated with a positive breakdown is not normally noticeable at the early stage of a discharge because of the masking effect. On the other hand, the progression velocity of a negative breakdown is about ten times faster than that of a positive breakdown and this is why the positive breakdown may still continue after a negative breakdown encounters the positive charge dominated region. Thus, the VHF radiation by a positive breakdown during the late stage of progression may be detectable. If all of these conditions are taken into account, the following interpretations are concluded. A large volume of locations with rather strong VHF pulse emission may correspond to a positive charge region. A time sequence of successive locations organized as a thin filament with a strong emission of VHF pulses may correspond to a negative breakdown, or we can say leader progression, in free space. A mass of weak VHF pulse emissions may correspond to a negative charge region. Finally, a time sequence of successive locations organized as a thin filament of rather weak VHF pulse emissions may correspond to a positive leader progression in virgin air.

The VHF emission by a return stroke is much less, since the return stroke runs along the pre-ionized channel. It should be noticed that automatic discrimination and grouping for four categories cannot be performed yet, because the intensity of the VHF pulses is relative. The above mentioned conceptual idea should be kept in the reader's mind for the understanding of the latter part of this section.

Lightning Mapping Array (LMA) is principally based on TOA techniques. The NMIMT team deployed several VHF antennas with a receiving frequency of 60 MHz, and developed the portable LDAR [15]. The schematic diagram is presented in figure 5. As we may imagine from the title of the reference, LMA is accomplished by using GPS for the time synchronization between several antennas, to image three-dimensional mapping for lightning discharges. However, as described in a previous section, the one-to-one identification of detected VHF pulses at several sites is difficult, even if a received VHF impulse is isolated. Thus, the NMIMT conducted the enormous calculation for all physically possible combinations, in order to have the three-dimensional location of VHF pulses when they started the LMA project. The recent increase in computer capability and speed dramatically reduces the elapsed time necessary to locate VHF pulses. They introduce the cross correlation and an appropriate time window for data analysis to improve the LMA function, and LMA could be a quasi-operational system for lightning monitoring at this moment.

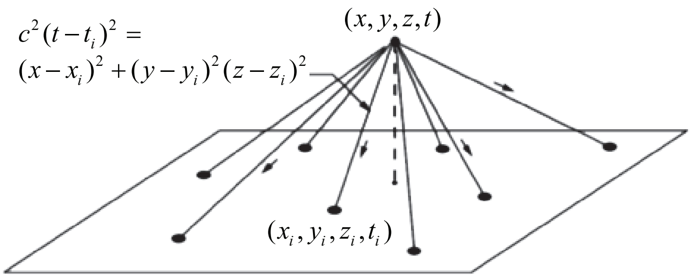


Figure 5 - Basic TOA technique. Measurements of the arrival times ti at N4 locations are used to determine the location and time of the source event *(x, y, z, t)*. (adapted from [16])

In late 1990s and early 2000s LMA showed many interesting observations by archived data analysis. One of the most important discoveries by LMA was the existence of an inverse charge distribution in a super cell thundercloud, as shown in figure 6. The NMIMT LMA found horizontally propagating lightning over a few tens of kilometers, and this lightning reached the ground at more than two locations (figure 7). The multi-point lightning strike over such a long distance presented in figure 7 may be a new subject to investigate and its physical interpretation is still controversial. The possible interpretation for "the bolt from the blue" is also presented and a variety of observations are shown on their website. On the other hand, LMA is still weak in regard to imaging for rapid progression phenomena such as a recoil streamer. VHF bursts associated with the K process cannot be imaged. Lojou [19] presented a detailed discussion of the advantages and disadvantages of TOA and Interferometry. Moreover, [20] suggested the necessity of calibration from the aspect of altitude for locations estimated by TOA because of the curvature of the earth.

The Osaka University group has been engaged in the VHF broadband digital interferometer (BDITF) [21]. The Osaka group's BDITF records a VHF pulse with a broadband frequency range between 30 to 100 MHz. As described in § "Time of Arrival", BDITF is principally similar to a very-shot-baseline TOA. However, the recent digital electronics allow a completely different and sophisticated system to be achieved as a quasi-real time system [22]. It must be noted that BDITF does not deal at all with the time difference between received VHF pulses. The phase difference for Fourier components with common time window is calculated. BDITF can estimate the azimuth and elevation of a VHF pulse incidence angle relative to the position of a BDITF unit, as has been done by the original very-short-baseline TOA system. Because of its broadband signal, a fringe ambiguity can be easily eliminated from the lower Fourier component through to the higher one successively. Schematic diagrams of antenna alignment and the fringe ambiguity elimination procedure are given in figures 8 and 9 respectively. For a recorded VHF pulse, each pair of VHF antennas estimates the incidence angles relative to its base-line (ϕ_1, ϕ_2 in figure 8) based on broadband digital interferometry. Finally, the BDITF allows the arrival angle (α: azimuth, β: elevation) of the VHF pulse to be obtained from the following equations:

$$\alpha = \tan^{-1}\frac{\cos\phi_2}{\cos\phi_1}$$

$$\beta = \cos^{-1}\frac{\cos\phi_1}{\cos\alpha}$$

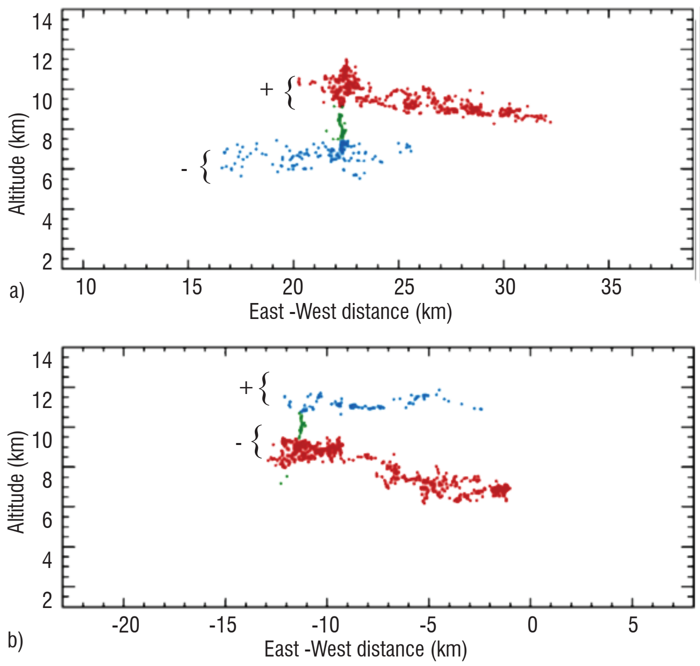


Figure 6 - Classification of the lightning radiation sources mapped by the LMA, in terms of the parent storm charge for the (a) normal-polarity and (b) inverted-polarity cloud flashes, respectively. The red dots indicate inferred positive charge in the storm, the blue dots indicate negative storm charge and the green dots connecting the two charge regions are not applicable to the inferred charge structure of the storm. (adapted from [17]).

The full details of the location technique are available in [24].

The BDITF has a disadvantage and some advantages over LMA. The disadvantage is the need to triangulate for three-dimensional mapping. Moreover, even if the time synchronization among BDITF units is perfect, the lines-of-site from two or three interferometer units hardly intersect each other and this is why LMA can be superior to BDITF in this regard. NMIMT used to be engaged in BDITF [25], but they have changed their focus to a TOA system.

The advantages of BDITF are the availability of VHF burst pulse location, easy real-time operation for lightning monitoring and the freedom of antenna alignment, etc... [23]. Figure 10 shows the two-dimensional location of a cloud-to-ground stroke in azimuth and elevation format, obtained at most one second after the lightning strike. [25] were able to reveal the mechanism of a cloud discharge K process thanks to the advantage of VHF pulse burst imaging. The Osaka Group showed one of the possible interpretations for long propagating lightning channels, by combining BDITF and dual polarized RADAR observations [25]. According to their understanding, a negative breakdown progression is prevented from descending toward the ground by a positively charged layer and it propagates horizontally for a distance of over 15 kilometers. This interpretation is consistent with the well-known common sense obtained through many-years-field-observations.

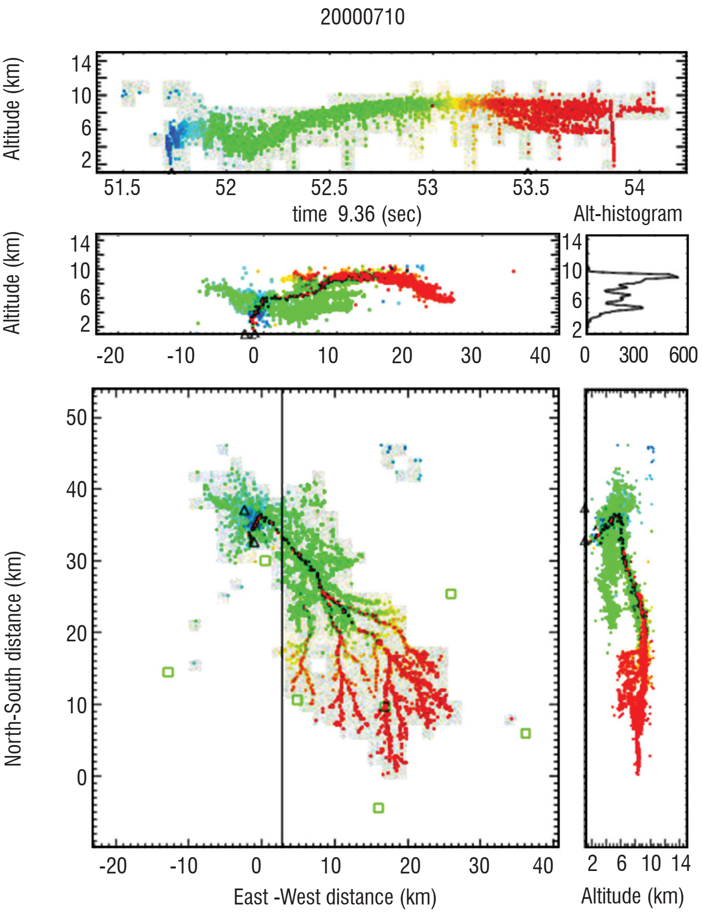


Figure 7 - A normal polarity, negative CG flash (negative charge descending to ground) that had a substantial (>50 km) incloud horizontal extent and a spectacular dendritic structure. The small triangles indicate the -CG strike points, as determined by the NLDN, but provide no indication of the overall size of the discharge (adapted from [18]).

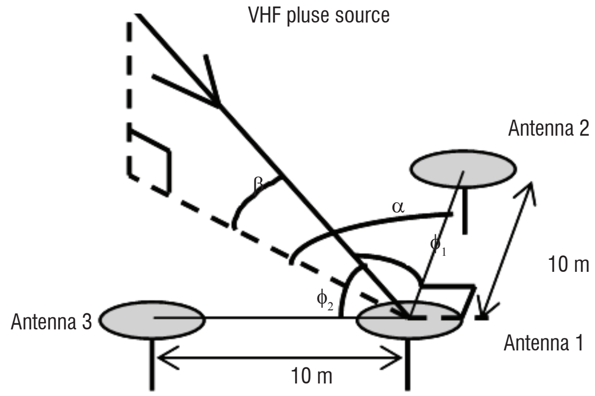


Figure 8 - Antenna arrangement of a perpendicular-baseline-interferometer for 2D mapping. Antennas 1 and 2 form one baseline, and antennas 1 and 3 form the other baseline.

NMIMT and Osaka University have been collaborating to evaluate each other's systems. LMA and BDITF have been installed in New Mexico and simultaneous observations are ongoing. According to the preliminary results, which were presented at the AGU fall meeting in 2011, both systems show an excellent correspondence in terms of the two-dimensional time sequence of mapping in azimuth and elevation, as shown in figure 11. However, as expected in the case of a rapid change like a recoil streamer, BDITF definitely maintains the advantage over LMA. On the other hand, LMA proves to be superior to BDITF for three-dimensional imaging.

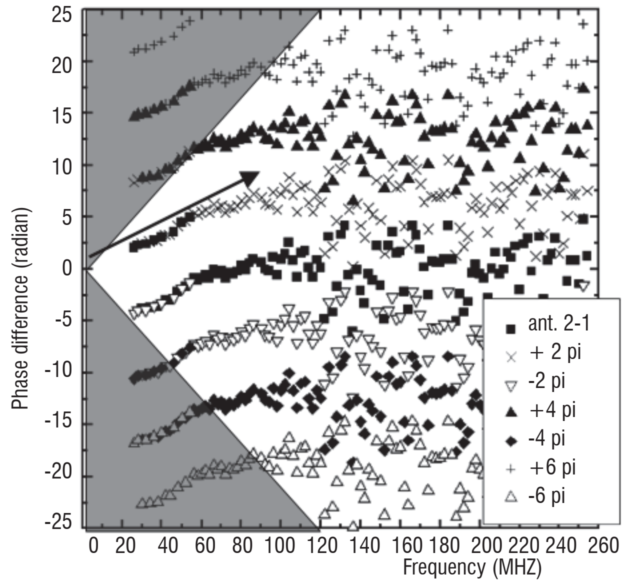
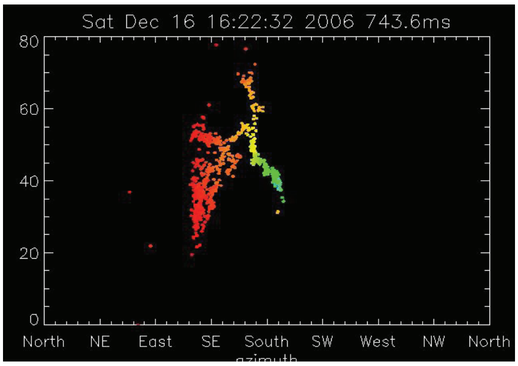


Figure 9 - Removing phase ambiguity by the displacement of phase differences θ_{12} with $\theta_{12}\pm2\pi$, $\theta_{12}\pm4\pi$, ... The shaded area is the contradictory area to the 10 m baseline. The series of phase differences follows the arrow.

a)



b)

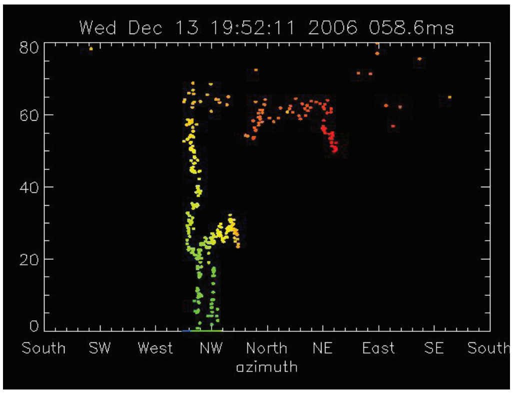


Figure 10 - (a) positive cloud-to-ground flash (b) negative cloud-to-ground flash. A video of two-dimensional VHF source locations of a cloud-to-ground flash in an azimuth and elevation format. In the case of a positive CG, the return stroke and breakdown inside the cloud are located, on the other hand, in the case of a negative CG the leader propagation can be imaged. For both cases we may see the negative breakdown.
(http://www.aerospacelab-journal.org/al5/review-of-the-location-of-VHF-pulses-associated-with-lightning-discharge)

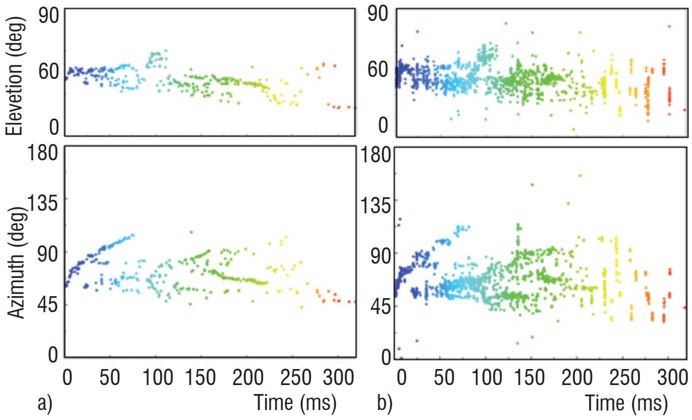


Figure 11 - The 2D mapping for IC flash recorded at 2258:03 UT on the 7th of September 2011 in New Mexico. Data is shown for (a) LMA, (b) BDITF. (adapted from [26])

Conclusions

This review article gives a brief summary of two VHF location system principles that have been developed since the 1970s. Because of recent advanced technology in digital electronics, lightning location systems are able to reveal new phenomena and interpretations, even though they are based on the same principle as in the 1970s or 1980s. For example, though the TOA technique was known originally, LMA contributes much for atmospheric electricians and lightning physicists. The BDITF is also based on the very-short-baseline technique and an operational quasi- nowcasting BDITF system has been developed. Moreover, LMA and BDITF are ultimately and principally equivalent, from the point of view of lightning channel imaging. The author expects that these two systems will be able to contribute to unveil the remaining problems. One of the expectations is the real-time and automatic discrimination between positive and negative breakdowns. Though at the moment discrimination is performed manually, using well trained eyes, an operational real-time system can be expected soon ■

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Acronyms

DITF (Digital InTerFerometer)
LDAR (Lightning Detection And Ranging systems)
LMA (Lightning Mapping Array)
NMIMT (New Mexico Institute of Mining and Technology)
TOA (Time-Of-Arrival)

AUTHOR

Zen Kawasaki (M'72) received the B.S., M.S., and Dr. Eng. degrees in communications engineering from Osaka University, Osaka, Japan, in 1973, 1975,and 1978, respectively. In 1989, he joined the Department of Electrical Engineering, Osaka University, where he is currently a Professor in the Division of Electrical, Electronic and Information Engineering. His research mainly concerns the electromagnetic compatibility and atmospheric electricity. He is a Fellow of the IEE Japan and the President of the International CommissiAtmospheric Electricity (IUGG/IAMAS)