Correlated One Site Three Dimensions VHF Broadband Digital Interferometer algorithm and Phased Array Radar (PAR) Observations

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Abstract. Broadband radio interferometers have been developed to locate the sources of VHF/UHF radiation from lightning discharges in three spatial dimensions (3D) and time. In a previous work, a VHF broadband digital interferometer has been used to estimate the 3D lightning location from only one site. In order to study the accuracy of this algorithm, a cross check of one site 3D VHF broadband digital interferometer with Phased Array Radar (PAR) system will be introduced in this paper. In August 18, 2012, VHF pulses from lightning flashes have been recorded by VHF digital broadband interferometer LIB site located in Nara, Japan. On the same day the precipitation profile has been recorded using Phased Array RADAR (PAR) located in Osaka University. The 3D locations of four flashes are compared with the PAR horizontal and Range-Height Indicator RHI scan images. This comparison introduced a good correlation between 3D VHF broadband digital interferometer algorithm and the precipitation profiles recorded by PAR.

Key words: lightning location, one site 3D location, VHF broadband interferometer, Phased Array RADAR (PAR).

1. Introduction

The technique of broadband interferometer has been designed and manufactured by Osaka University’s lightning research group [R Mardiana and Z Kawasaki, 2000; Shao et al., 1996; T o Ushio et al., 1997]. Mardiana et al. (2000) have developed the technique independently and, then used it, for the first time, to reconstruct lightning in two-spatial dimensions and time. The technique of interferometer is based on measurement of phase differences of a certain signal frequencies received by different antennas. These phase differences are directly related to the incident angles of the signals and are used to calculate the angular locations of the sources in azimuth and elevation. [R Mardiana and Z I Kawasaki, 2000] presented the dependency of lightning source mapping on Fourier spectra and proposed a weighted averaging method rather than the arithmetic-averaging method, which was used to calculate the incident angles, to improve the mapping. [Redy MARDIANA et al., 2001] have used the broadband interferometer techniques to reconstruct lightning discharge channels in two dimensions and in time sequence.

[R Mardiana et al., 2002] have developed the broadband radio interferometers to locate the sources of VHF/UHF radiation from lightning discharges in three spatial dimensions (3D) and time. They used two different sites to locate these VHF/ UHF sources. [Morimoto et al., 2005] proved that VHF broadband digital interferometry can be used to give information on positive charge distribution inside thunderclouds as well as its capability to visualize the negative leader progressions. [T Ushio et al., 2011] have deployed the interferometer system on the GLIMS (Global Lightning and sprite MeasurementS) mission in the International Space Station to detect and locate the VHF impulses emitted by lightning from space. [Akita et al., 2012] have used the VHF broadband digital interferometer and the E-field change on the ground to estimate the amount of charge removed by individual lightning flashes in thunderclouds.
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[Lotfy S. Elbaghdady et al., 2013] described the utilization of VHF broadband digital interferometer technique to estimate the location of VHF radiations from lightning discharges in three spatial dimensions (3D) and time from only one site. The site consists of three VHF broadband antennas and a GPS receiver. The authors just presented one site 3D lightning location system using VHF digital interferometer without studying the accuracy of their algorithm.

This paper will study the accuracy of the one site 3D lightning location system using VHF digital interferometer by showing up the projection views of VHF pulses sources, for the lightning flashes happened in August 18, 2012, with the vertical and horizontal scan Phased Array Radar (PAR) images for the precipitation profile of the same day.

This paper starts with an introduction of VHF interferometry and its applications. This includes a brief review of the principle of broadband interferometry and the method to determine the source location in two spatial dimensions (azimuth and elevation). Then, a brief review of the one site 3D algorithm and its application on four flashes discharged on August 18, 2012. Finally the projection of the VHF sources with the vertical and horizontal scan of PAR images is introduced.

2. VHF Broadband Interferometry

A broadband DITF is a system used 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. The simplest radio interferometer consists of two separate antennas. A Fast Fourier Transform (FFT) is applied to calculate Fourier components of the received EM pulse. Then compute the phase difference of each Fourier component between the two antennas as a function of the incident angle of the EM pulse against the baseline. Employing a couple of antennas as a two-element array of a broadband interferometer enables estimation of the incident angle [Morimoto et al., 2004]:

\[ \phi_m = \cos^{-1} \left( \frac{c \theta_m}{2\pi f_mD} \right) \]  

where, \( \theta_m \) is the phase difference of Fourier component \( f_m \). After calculating the incident angles for all Fourier components, the arithmetic mean value (\( \phi \)) is adopted to be the incident angle of the signal.

A radio interferometer as a two-element array gives the location of an EM source in one-dimension, namely the angle of incidence. Two pairs of antennas and two independent baselines are essential for two-dimensional (2D) mapping in azimuth and elevation format. Three antennas can be used to get the azimuth and elevation angles. They are equipped at three apexes of a level isosceles right-angled triangle as shown in Fig.1.

Fig. 1, Antenna arrangement of perpendicular baselines interferometer for two-dimensional mapping. The antennas 1 and 2 form the first baseline, and the antennas 1 and 3 form the second baseline [Morimoto et al., 2005].
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. Using the angle of incidence $\phi_1$ and $\phi_2$ against to each baseline, the direction of an EM source can be estimated as azimuth ($\alpha$) and elevation ($\beta$) by the following equations.

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

$$\beta = \cos^{-1}\left(\frac{\cos \phi_1}{\cos \phi}\right) = \cos^{-1}\left(\frac{\cos \phi_2}{\sin \phi}\right)$$

3. One Site 3D Algorithm

[Lotfy S. Elbaghdady et al., 2013] proposed a one site 3D lightning location system using VHF broadband interferometer. The algorithm is divided into five steps:

1. Reading the 2D data location, azimuth and elevation, obtained from the analysis of VHF interferometer as explained above.

2. Categorizing the 2D data into several leaders. The stepped leader moves into steps towards the ground and it may be branched into different branches. The pulses that are radiated from one branch are supposed to be very close to each other in time and space location. To investigate this situation, some constraints have been used in the algorithm. First, the time difference between every two pulses is assumed to be less than 1 msec. second, the azimuth difference between every two pulses is assumed to be less than 5° and finally, the elevation difference between every two pulses is assumed to be less than 5°. After applying these constraints, only the closed pulses are grouped together and the scattered ones are discarded.

3. Calculating the distance from the origin to the sources of each leader. The algorithm uses the following equation to calculate the distance between each pulse and the observation site as explained in more details by [Lotfy S. Elbaghdady et al., 2013]:

$$r = \frac{v \times \Delta t}{\sqrt{\Delta \alpha^2 + \Delta \beta^2}}$$

where $r$ is the distance between the observation site and the pulse location, $\Delta \alpha$ is the azimuth angle difference, $\Delta \beta$ is the elevation angle difference, $\Delta t$ is the time difference between the two pulses and $v$ is the leader progression. According to many researches and literatures investigated the stepped leader velocity, the average stepped leader speed is assumed to be $2 \times 10^5$ m/s, which is the value used in the algorithm.

4. Approximating the calculated distances of sources of each leader by a linear function. The algorithm assumed that the variance of distance is linear and calculates the time series of the variance distance of each group. The algorithm calculates the distance of each pulse using time windows with weighted average method as proposed by [Lotfy S. Elbaghdady et al., 2013]. Then the algorithm applies the least squares method on each group to implement it by a formula. To apply the least squares method on each group, let $t$ represents the time values of the pulses inside the group while $R$ represents the distance values of the pulses inside the group. The algorithm is designed to implement each group by a linear equation as follows:

$$R = a_0 + a_1 t$$

where $a_0$ and $a_1$ are the coefficients of the linear equation.
The 3D locations are calculated by applying the approximated linear function of each group on its 2D data. The algorithm is designed to apply these linear approximations on the corresponding 2D data groups as follows:

\[ R_i = a_0 + a_1 t_i \]  

(6)

where \(R_i\) is the distance between the pulse and the origin and \(t_i\) is the arrival time of the pulse. Cartesian coordinates \((X, Y, Z)\) of the pulse source are calculated using the azimuth, and elevation angles and distance \(R_i\) of each pulse as follows:

\[ X_i = R_i \times \cos(\alpha_i) \times \cos(\beta_i) \]

\[ Y_i = R_i \times \cos(\alpha_i) \times \sin(\beta_i) \]

\[ Z_i = R_i \times \sin(\beta_i) \]  

(7)

4. Data and Analysis

On Saturday August 18, 2012, lots of lightning flashes were discharged starting from 05:53 GMT and ended around 10:40 GMT in Osaka, Japan. All these flashes were recorded using one site called LIB located in Nara, Japan. This site is consisting of three broadband VHF circular flat plate antennas having a diameter of 30 cm and a GPS receiver. The received signal is first intercepted by a band-pass filter and then amplified. The signal is then transmitted through a coaxial cable to three-channel ADC synchronized with the signals from the other two antennas, and then stored in a personal computer (PC).

To complement the analysis of one site 3D algorithm, a phased array radar (PAR) was deployed at Osaka University, Japan, located at 30.6 km to the North-West of the LIB site. Fig. 2 shows the locations of PAR and LIB sites. The phased array radar (PAR) is a 1-D array antenna (horizontal polarization) consisting of 128 elements. Precipitation at several elevation angles is simultaneously observed. The PAR operated at 9.43 GHz and covered a range of 60 Km radius, consequently it covers the LIB site location. It operated at 0-90° elevation angle Range-Height Indicator (RHI). It records the precipitation profiles every 30 s per volume scan.

Fig. 2, Distance between LIB site which located in NARA and PAR site which located in Osaka University is 30.6 km.
The one site 3D VHF digital interferometer algorithm is applied on all recorded flashes, about 1699 flashes, of lightning discharges occurred on that day. Due to the difficulty of analyzing all flashes here in this paper, only four of them will be discussed.

A. Flash 2012.08.18_05:53:24 GMT

During the beginning of the storm, a cloud-to-ground flash was initiated at 05:53:24 GMT. One site 3D algorithm is applied on this flash and gave 3D locations of the VHF pulses radiated as shown in Fig. 3.

![Fig. 3](image)

Fig. 3, Four projections of VHF sources locations for the flash that initiated at 05:53:24 GMT. 1) at top, an easting versus altitude plot (view looking due to north), 2) at center left, an easting versus northing plot (plan view), 3) at center right, an altitude versus northing plot (view looking due to west), 4) at bottom, an altitude versus to time plot. The source span 160 ms in time, and are color coded according to the key at the top right which is depended on time.

The first pulse of this flash was radiated at time 569.4 ms at x = -6.92 km from the observation site location toward the west, y = 7.5 km toward the north and at altitude 5.83 km as indicated by arrows in Fig. 3. This flash was composed of four branches or leaders, the initial breakdown moved in a random manner around the initiation point then one leader went toward east and another one went toward west. After approximately 60 ms from the initiation time, another branch started going down toward ground east-south direction from the initiation point and terminated at an altitude around 3 km then a forth branch started going around the initiation point toward the east-north and terminated at altitude around 6 km.

A phased array radar (PAR) image horizontal scan at the time of the flash is shown in Fig. 4. This horizontal scan image is showing the precipitation profile for 30 s starting from 05:53:06 to 05:53:36.
As shown in Fig. 4, all the VHF pulses are located at the edge of the cloud in the north-west direction of LIB observation site and in the south-east direction of PAR site. In order to see the height cross section of the pulses with the cloud, the azimuth angle of each pulse must be taken into consideration. It is difficult to show the all pulses in one cross section due to the wide range of azimuth angles of all pulses in the aspect of the cross section angle. So the analysis will study the initial breakdown pulses to show their altitude cross section with the cloud height. For more information, the LIB observation site is located at azimuth angle 122º from the north of PAR site. The first pulse has an azimuth angle 120º from the north of PAR site. Fig. 5 shows the cross section of initial pulses and the range height indicator (RHI) scan at phase angle 120º. To show more pulses in the image, the pulses lay in a range of 5º around the angle 120º is added to the image. As shown in Fig. 5, the first pulse is located at height 5.83 km, indicated by the arrow, and at the edge of the cloud.
In this cloud-to-ground flash, one site 3D algorithm showed the initial breakdown process and succeeded to image the lightning discharge channel in three spatial dimensions. Furthermore, it showed the branches of the stepped leader and their directions in 3D. Cross check with the PAR horizontal scan image gave a good accuracy to the capability of the one site 3D algorithm in the estimation of horizontal axes (X, Y) of the pulses. Also, cross check with the PAR RHI scan image increases the capability of the algorithm in the estimation of the vertical axis (Z).

B. Flash 2012.08.18_05:58:33 GMT

The flash is an intracloud discharge, and was initiated at 05:58:33 GMT. One site 3D algorithm is applied on this flash and gave 3D locations of the VHF pulses radiated as shown in Fig. 6.

![Fig. 6](image)

Fig. 6, Four projections of VHF sources locations for the flash that initiated at 05:58:33 GMT. The source span 400 ms in time, and are color coded according to the key at the top right which is depended on time.

The first pulse is initiated at time 59.62 ms at x = -13.69 km from the site location toward the west, y = -5.63 km toward the south and at altitude 10.56 km as indicated by arrows in Fig. 6. It is noticed from the figure that all pulses are located in south-west direction of the LIB observation site. The initial breakdown started moving from the initial point toward the east-north direction taking around 6 km toward east and 3 km toward north; also it took around 5 km down toward the base of the cloud. After 80 ms from the initiation time one leader is went up and moved in semi horizontal line toward the east direction as shown in the top plot. At time 333.2 ms, a leader started to propagate at the same ionized channel and moved almost 2 km toward east.
A phased array radar (PAR) image horizontal scan at the time of the flash is shown in Fig. 7. This horizontal scan image is showing the precipitation profile for 30 s starting from 05:58:06 to 05:58:36.

As shown in Fig. 7, all the VHF pulses are located in a high reflectivity region of the cloud in the south-west direction of LIB observation site and in the south-east direction of PAR site. To see the initial breakdown cross section with RHI scan image of the PAR, the azimuth angle of the first pulse is taken into consideration which is equal to 152º. Fig. 8 shows the phased array radar RHI scan at angle 152º and a plot of pulses that lay in the range of 5º around this angle. As shown in Fig. 8, the first pulse is located at an edge of the high reflectivity region and at height 10.56 km as indicated by the arrow.

Fig. 7, Phased array radar (PAR) horizontal scan image, recorded at time from 05:58:06-05:58:36 GMT, covers LIB site location area which indicated by the red circle.

Fig. 8, Phased array radar RHI scan of the radar reflectivity factor (in dBz) taken at 05:58:06 to 05:58:36 GMT at 152º from north of PAR site location. The first pulses are located at an edge of high reflectivity region of the cloud, pulses in range of 5º around 152º are also shown in this image.
In this flash, the one site 3D VHF broadband digital interferometer images the propagation channel of the flash. It also showed the propagation of last leader in the same ionized channel that constructed by the first leaders. Also, the comparison with PAR horizontal and RHI scan images showed how the 3D VHF digital interferometer algorithm introduced a good horizontal estimation of all pulses and a good altitude estimation of the initial pulses of the flash respectively.

C. Flash 2012.08.18_05:59:28 GMT
This flash is a cloud-to-cloud flash which initiated at 05:59:28 GMT. One site 3D algorithm is applied on this flash and gave 3D locations of the VHF pulses radiated as shown in Fig. 9.

![Fig. 9. Four projections of VHF sources locations for the flash that initiated at 05:59:28 GMT. The source span 300 ms in time, and are color coded according to the key at the top right which is depended on time.](image)

The first pulse is initiated at time 8151.8 ms at $x = -10.24$ km from the site location toward the west, $y = -4.98$ km toward the south and at altitude 7.34 km as indicated by arrows in Fig. 9. It is noticed from the figure that all pulses are located in south-west direction of the LIB observation site. The initial breakdown started moving from the initial point toward the east-north direction taking around 8 km toward east and 4 km toward north; also it took around 5 km down toward the base of the cloud. Later at time 8266 ms, another leader moved in the same ionized path toward east-north direction. At time 8380 ms and time 8396 ms two leaders at different altitudes are moved in the same ionized path toward the east-north direction as shown in the top and center plots.

A phased array radar (PAR) image horizontal scan at the time of the flash is shown in Fig. 10. This horizontal scan image is showing the precipitation profile for 30 s starting from 05:59:06 to 05:59:36.

As shown in Fig. 10, all the VHF pulses are located in a high reflectivity region of the cloud in the south-west direction of LIB observation site and in the south-east direction of PAR site. To see the initial breakdown cross section with RHI scan image of the PAR, the azimuth angle of the first pulse is taken into consideration which it is equal to 133º. Fig. 11 shows the phased array radar RHI scan at
angle 133° and a plot of pulses that lay in the range of 5° around this angle. As shown in Fig. 11, the first pulse is located at an edge of the high reflectivity region and at height 7.34 km as indicated by the arrow.

Fig. 10, Phased array radar (PAR) horizontal scan image, recorded at time from 05:59:06- 05:59:36 GMT, covers LIB site location area which indicated by the red circle.

Fig. 11, Phased array radar RHI scan of the radar reflectivity factor (in dBz) taken at 05:59:06 to 05:59:36 GMT at 133° from north of PAR site location. The first pulses are located at an edge of high reflectivity region of the cloud, pulses in range of 5° around 133° are also shown in this image.

In this cloud-to-cloud flash, the one site 3D VHF broadband digital interferometer algorithm presented an estimation of the propagation channel in three spatial dimensions. It showed the directions of the leaders inside the cloud. It showed also the leaders that propagated in the same ionized channel where the first leaders passed through. The comparison with PAR horizontal and RHI scan images confirmed the horizontal estimation of pulses and the altitude estimations of the initial pulses.
D. Flash 2012.08.18_07:01:17 GMT
The flash is an intracloud discharge, which was initiated at 07:01:17 GMT. One site 3D algorithm is applied on this flash and gave 3D locations of the VHF pulses radiated as shown in Fig. 12.

![Fig. 12](image_url)

Fig. 12. Four projections of VHF sources locations for the flash that initiated at 07:01:17 GMT. The source span 400 ms in time, and are color coded according to the key at the top right which is depended on time.

The first pulse is initiated at time 1421.2 ms at x = -1.64 km from the site location toward the west, y = 9.35 km toward the north and at altitude 5.30 km as indicated by arrows in Fig. 12. It is noticed from the figure that all the pulses are located in the north direction of the LIB observation site. This flash was composed of many leaders, the initial breakdown started moving horizontally, around 5 km altitude, from the initial point toward the west-south direction taking around 7 km toward west and 4 km toward south. Later, one leader moved to higher altitude toward west-north. Also, there are some leaders moved in the same ionized path through the east-west direction as shown in the top and center plots.

A phased array radar (PAR) image horizontal scan at the time of the flash is shown in Fig. 13. This horizontal scan image is showing the precipitation profile for 30 s starting from 07:01:06 to 07:01:36.

As shown in Fig. 13, all the VHF pulses are located in a high reflectivity region of the cloud in the north direction of LIB observation site and in the south-east direction of PAR site. To see the initial breakdown cross section with RHI scan image of the PAR, the azimuth angle of the first pulse, which it is equal to 106º, is considered to be the cross section angle of the phased array radar RHI scan image. Fig. 14 shows the phased array radar RHI scan at angle 106º and a plot of pulses that lay in the range of 5º around this angle. As shown in Fig. 14, the first pulse is located at an edge of the high reflectivity region and at height 5.31 km as indicated by the arrow.

In this intracloud flash, the one site 3D VHF broadband digital interferometer algorithm investigated most of the leaders and showed their directions inside the cloud. It also showed the
propagation paths of these leaders and the propagation channels of the whole flash. Some of them propagated through the same ionized channel and some of them made new channels.

Cross check with PAR horizontal scan confirmed the horizontal estimation of all pulses and propagation channels. Also cross check with RHI scan image showed the capability of 3D VHF broadband digital interferometer algorithm in the altitude estimation of the initial pulses inside the cloud.

Fig. 13. Phased array radar (PAR) horizontal scan image, recorded at time from 07:01:06-07:01:36 GMT, covers LIB site location area which indicated by the red circle. VHF pulses are located in the north direction from LIB site location.

Fig. 14. Phased array radar RHI scan of the radar reflectivity factor (in dBz) taken at 07:01:06 to 07:01:36 GMT at 106º from north of PAR site location. The first pulses are located at an edge of high reflectivity region of the cloud, pulses in range of 5º around 106º are also shown in this image.
5. Discussion and conclusion

In this paper, four of the flashes occurred on August 18, 2012 have been analyzed using one site 3D VHF broadband digital interferometer algorithm that proposed by [Lotfy S. Elbaghdady et al., 2013]. In order to study the accuracy of this algorithm, the analysis of these four flashes are compared with phased array radar horizontal and RHI scan images.

First flash through third flash have small number of pulses in comparison with the fourth flash. These pulses are located in an area around the observation site LIB. This area will be shown in the horizontal scan image as a very small area due to the scale of the horizontal scan image (120 *120 km). Therefore the pulses are seemed to be located on each other in a very small area. Also, the pulses are color coded depending on their time. The colored pulses shown in the horizontal scan images are the pulses that have higher altitudes than other pulses in the same flash, therefore, they drawn on the top of pulses that have lower altitudes. That is why the lower altitude pulses are not shown in the horizontal scan images.

Each pulse in the flash is looking to the PAR location site with certain angle that may be different from other pulses looking to PAR site. Consequently, it is difficult to show all the pulses in one cross section angle with phased array radar RHI scan. Therefore, the RHI scan cross section is taken at the same angles of the initial breakdown pulses (looking toward PAR site angles). Also pulses that lay in a 5° range around the cross section angle are added to each RHI scan image.

The flashes are four different flashes, one of them is Cloud-to-Ground flash and the others are Cloud-to-Cloud flashes. These flashes are analyzed by the one site 3D VHF broadband digital interferometer algorithm and their results are compared with horizontal and RHI scan images of a phased array radar located in Osaka University in order to determine the accuracy of the one site 3D VHF broadband digital interferometer algorithm. From the analysis of the four flashes, these comparisons gave an acceptable accuracy of the one site 3D VHF broadband digital interferometer algorithm. This comparison with PAR horizontal and RHI scan images is a fruitful step in the way to improve the one site 3D VHF broadband digital interferometer algorithm.

From this study, we can say that the one site 3D VHF broadband digital interferometer algorithm is practically acceptable but it is still need to be improved. It needs to be able to distinguish between positive and negative pulses of the discharge. It still needs further improvement to be able to change stepped leader velocity according to positive or negative leaders.

Acknowledgement. This research was supported by the Ministry of Higher Education (MoHE) of Egypt through Ph.D. fellowships. Our sincere thanks to E-JUST University, JICA and Osaka University for guidance and support. We also thank Dr. Tang Wu for supporting us with his PAR software code and his advices.

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(Received December 1, 2013; revised December 23, 2013; accepted December 23, 2013)