

Lightning Detection and Imaging Based on VHF Radar Interferometry

Wenjie Yin ¹, Weizheng Jin ^{1,*} , Chen Zhou ¹ , Yi Liu ¹, Qiong Tang ¹, Moran Liu ¹, Guanyi Chen ¹ and Zhengyu Zhao ^{1,2}

¹ Department of Space Physics, School of Electronic Information, Wuhan University, Wuhan 430072, China; windsoryin@whu.edu.cn (W.Y.); chenzhou@whu.edu.cn (C.Z.); liuyiwuhan@whu.edu.cn (Y.L.); qiongtang@whu.edu.cn (Q.T.); MoranLiu@whu.edu.cn (M.L.); chenguanyi@whu.edu.cn (G.C.); zhaozy@whu.edu.cn (Z.Z.)

² Institute of Space Science and Applied Technology, Harbin Institute of Technology, Shenzhen 518000, China

* Correspondence: jwz@whu.edu.cn

Abstract: In this study, detection and three-dimensional (3D) imaging of lightning plasma channels are presented using radar interferometry. Experiments were carried out in Leshan, China with a 48.2 MHz VHF radar configured with an interferometric antenna array. The typical characteristics of lightning echoes are studied in the form of amplitude, phase, and doppler spectra derived from the raw in-phase/quadrature (I/Q) data. In addition, the 3D structure of lightning channels is reconstructed using the interferometry technique. The localization results of lightning are verified with the locating results of lightning detection networks operating at VLF ranges, which indicate the feasibility of using VHF radar for lightning mapping. The interpretation of the observational results is complicated by the dendric structure of lightning channel and the overlap between passive electromagnetic radiations and return echoes. Nevertheless, some parts of the characteristics of lightning are still evident. The observational result of return echoes shows good consistency with the overdense assumption of lightning channels. The transition from the overdense channel to the underdense channel in the form of amplitude and phase is clearly observed. This technique is very promising to reveal the typical characteristics of lightning return echoes and structure of lightning propagation processes.

Keywords: VHF lightning radar interferometer; 3D lightning imaging; lightning



Citation: Yin, W.; Jin, W.; Zhou, C.; Liu, Y.; Tang, Q.; Liu, M.; Chen, G.; Zhao, Z. Lightning Detection and Imaging Based on VHF Radar Interferometry. *Remote Sens.* **2021**, *13*, 2065. <https://doi.org/10.3390/rs13112065>

Academic Editor: Stefano Dietrich

Received: 24 April 2021

Accepted: 19 May 2021

Published: 24 May 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Lightning is an electrical discharge naturally occurring between charge regions of opposite polarities inside thunderclouds or between clouds and the ground, accompanying electromagnetic radiations over a wide range of frequencies during the formation of hot ionized plasma channels and visible luminous flashes [1,2]. To protect human life and assets from damage caused by the massive amount of energy released by lightning, lightning detection and localization methods and studies of lightning characteristics are of great significance [2–5].

Radar, photographic instruments such as high-speed video camera, acoustic array, passive spheric detection system, and electrostatic field sensor are the common instruments for the study of lightning.

A high speed video camera (HSV) is the most direct way to study the lightning discharge channels by filming luminous lightning channels operating at high frame rates up to 30 Kfps [6–10]. Important information of lightning properties, e.g., the speed of leader propagation and the two-dimensional (2D) structure of lightning channels, can be derived based on the experiment using HSV and electrostatic field sensor [7,10]. Moreover, the configuration of HSV and transmission grating can be implemented to set up the spectral recording system in order to measure the temperature and radius of lightning channel [8].

The acoustic arrays mainly detect acoustic waves of frequencies ranging from a few to hundreds of hertz. An acoustic wave is the decay of the strong shock wave that forms when the channel expands thermodynamically at a very high temperature and pressure during multistage processes of lightning discharges [11]. The location of lightning channels can be determined by the cross-correlation analysis of signals received by acoustic arrays [11–13].

Passive spheric detection systems employ networks of radiation-field sensors to detect and locate the lightning, which measure electromagnetic radiation fields emitted during multistage processes of lightning discharges in broadband frequency ranges from very-low frequency (VLF) through ultra-high frequency (UHF) [4,14]. Very-high-frequency (VHF) and VLF/low-frequency (LF) systems are distinguished based on the different frequency ranges of operation, pulse rates, and amplitudes in the RF spectrum [4]. In the VHF band, lightning mapping systems are commonly carried out using the interferometry (ITF) and time of arrival (TOA) technique or time difference of arrival technique (TDOA) [15–23]. Compared with the TOA and TDOA locating system, the ITF system can locate both isolated pulses and continuous emissions with a higher time resolution [22,23]. VHF emissions can be modeled as point sources considering that VHF signals are pulses of short duration and line-of-sight propagation. Thus, the azimuth-elevation 2D direction of lightning channels can be obtained using the ITF system [18,19,23]. The 3D structure of lightning channels can be obtained using two separated broadband interferometers or by combining other detection methods such as HSV and acoustic arrays [9,24]. However, the line-of-sight propagation of VHF radiation sets limits on the detection range of VHF systems [4]. In VLF detection, radiated pulses can propagate along the surface of earth or in the earth-ionosphere waveguide which can be utilized to locate lightning channels from a long distance [5,14,25–27]. Magnetic direction-finders (MDF), TOA, and TDOA techniques are widely used in VLF/LF systems. Krider et al. developed an improved MDF system for locating cloud-to-ground (CG) lightning within a range of ~500 km [28,29]. IMPACT algorithm applied by the US national lightning detection network (NLDN) can utilize information from any combination of MDF, TOA or combined (MDF/TOA) sensors. What is more, the VLF/LF radiation field propagation can provide the information of the lightning return stroke current based on the theoretical model developed by Uman et al., which is of use to evaluate the electrical impact of lightning events [30–32].

The above methods depend on the optical, acoustic, and electromagnetic properties of lightning, respectively. A radar is also a powerful way for the lightning detection and elucidating properties of lightning plasma channels [33–35]. The radar system transmits electromagnetic pulses and receives return echoes reflected by ionized lightning channels. Radar lightning studies have been conducted since the 1950s [36–38]. Extensive studies of lightning radar echoes of various wavelengths took off since the 1970s [39–42]. Proctor et al. used a radar at wavelengths of 5.5, 50, and 111 cm to study the lightning [41]. Based on vertically pointing 10-cm doppler radar observations, Mazur et al. inferred the properties of lightning channel using the evolution of amplitude and position of the spectral peaks [42]. Meanwhile, the theoretical calculation was made with the progress of practical experiments. For example, Dawson presented a review of previous work of lightning radar echoes and calculated the radar cross section (RCS) of the lightning channel for two cases of underdense and overdense plasma based on previous meteor trail researches [34]. Furthermore, Mazur et al. improved Dawson's results by calculating the RCS of a finite plasma cylinder at an oblique incidence angle [43]. In 1990, Williams et al. summarized the previous work done with a radar of different wavelengths and concluded that the wavelength dependence of lightning echoes is variable possibly due to the precipitation masking effect and longer wavelength such as the VHF band, which can be used to greatly reduce the effect of masking [35]. Röttger et al. tapped the potential of the StratoTropospheric (ST) radar operating at the VHF band to record lightning return echoes during the evolution of deep convection into the thunderstorm [44]. Petitdidier et al. configured the VHF and UHF vertical narrow beam ST radar with electrostatic field sensors to carry out a simultaneous detection of VHF radiation from lightning discharges

and the vertical localization of the thermalized ionized lightning flash channels above the radar [45].

In this paper, we investigate the characteristics of lightning return echoes and reconstruct the 3D structure of lightning channels using the VHF radar with interferometric antenna configuration in Leshan, China. The structure of the paper is as follows. The radar equation of the lightning channel, the principle of radar interferometry, and the echo selection criteria are described in Section 2. In Section 3, typical characteristics of lightning echoes are studied in the form of amplitude, phase, and doppler records. In addition, the 3D structure of lightning channels is reconstructed and verified with the locating results provided by the VLF system.

2. Materials and Methods

2.1. Radar Equation of the Lightning Induced Plasma Channel

The radar equation reveals the relation between the characteristics of radar, target, and received signal. The performance of lightning radar can be assessed by examining the radar equation of the lightning plasma channel. The reflection properties of lightning plasma channels depend on many variables, such as the distribution of electron density, the geometry of channels, and the polarization of electromagnetic wave. First, it is important to determine the property of lightning plasma channels.

According to the analysis of William [35], the temperature plays an important role in determining the plasma frequency. Based on the research carried out by Li et al. [46], the temperature of lightning channel is derived to be 6140.8–10,424 K. Uman and Voshall derived the temperature of the lightning channel after cooling for a different radius of the channel [33]. In the operation of VHF radar, it is reasonable to assume that the lightning plasma channel is overdense at an initial temperature and the channel gradually expands thermodynamically to become underdense with the lapse of time.

The radar equation of lightning echoes has been deduced by Tseng based on the presumption that the ionized plasma channel is an infinitely long cylinder with the radius much smaller than the wavelength of incident wave and the main contribution to the RCS is from echoes within the first Fresnel zones of the plasma channel [47]. The result of this theoretical deduction is similar to that of high-density meteor trail by Sugar and only considers the case of the norm incident [48].

Combining previous researches done by Dawson and Mazur [34,35,43], we ignore the complicated geometry of lightning channels and assume it is a long cylinder. From what has been discussed before, the lightning channel can be taken as an overdense channel for the electromagnetic wave of wavelength of 6.22 m. Then, the lightning channel can be approximated as a perfect conductor. Therefore, RCS is only dependent on the ratio of channel radius, the incident angle, and the polarization.

Considering the basic power transfer equation

$$P_R = \left[\frac{P_T G_T G_R \lambda^2}{(4\pi)^3 R^4} \sigma \right] \quad (1)$$

where P_R and P_T are the received and transmitted powers, G_R and G_T present the received and transmitted antenna gain, λ is the radar wavelength, and R is the range, σ means the radar cross section.

Considering linear polarization, the radar cross section is different for transverse and parallel scattering when $2\pi a/\lambda \ll 1$ (a is the radius of lightning channel, λ is the wavelength) [34].

$$\begin{cases} \sigma_{\perp} = 8R\pi^5 a^4 / \lambda^3 \\ \sigma_{\parallel} = \frac{2R\lambda}{\pi |1 - j(2/\pi) \ln(\gamma ka/2)|^2} \end{cases} \quad (2)$$

where γ equals to 1.782, k is the wave number of radar.

The effect of circular polarization wave is distributed equally between two linear polarization components. Mazur introduced the linear to the circular polarization ratio of

RCS to estimate the polarization effect and found that the expected ratio for a randomly oriented overdense plasma cylinder is 1.5 [49]. Therefore, the RCS of circular polarization can be approximated with the ratio.

The radar equation for VHF radar proves that valid data can be obtained and used to analyze the characteristics of lightning.

2.2. Radar Interferometry

With the configuration of closely spaced antennas, the phase difference of incident electromagnetic pulses between neighboring array units can be utilized to determine the azimuth and elevation angles of the target [4,50].

Figure 1 shows the basic geometry of a perpendicular crossed baseline phase interferometer. The lightning plasma channel reflects electromagnetic pulses emitted by the transmitter, which can be considered as a radiation source. One can derive the angle of arrival (AOA) of incident wave based on the arrival-time difference information using the interferometric array. Thus, the two-dimensional location of lightning channels can be estimated [50–52].

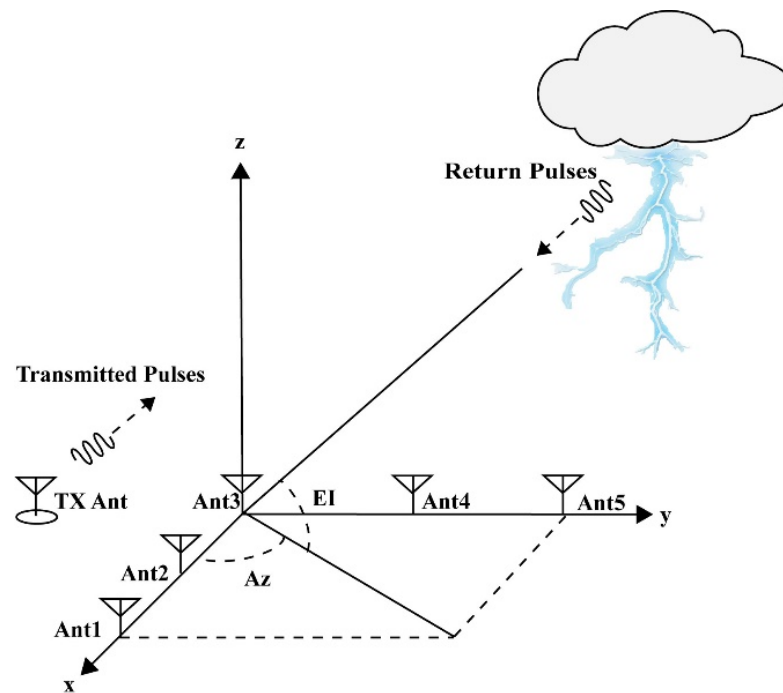


Figure 1. The configuration of interferometric VHF radar for lightning detection and imaging.

For simplicity, we consider a radiation source in the x-y quadrant. Let α be the azimuth angle and θ be the elevation angle, which are shortened as Az and EI in Figure 1. In this geometry, we can obtain the relations between the phase difference and angle of arrival as follows:

$$\theta = \arctan\left(\frac{\varphi_{34}}{\varphi_{32}}\right) \quad (3)$$

$$\alpha = \arcsin\frac{\sqrt{\varphi_{32}^2 + \varphi_{34}^2}}{2\pi d/\lambda} \quad (4)$$

where φ_{ij} is the measured phase difference of signal on Ant j relative to Ant i ; d is the antenna space and λ is the wavelength.

With the convenience of pulse radar, the range can be easily calculated by the echo return time within the unaliased range. The 3D location of lightning channels can be determined with the information given above.

However, the use of interferometry has its inherent problems. When the space between two antennas is smaller than a half of wavelength, the unambiguous AOA can be determined with a possible error of AOA measurement and the mutual coupling between the closely spaced antenna [50,52]. On the opposite, a longer baseline with higher accuracy will lead to fringe ambiguity [50,52].

To avoid the annoying problem, the “L” configured array with five elements and optimized algorithm for solving fringe ambiguity is applied. Each side of the L array was spaced in a straight line creating two baselines, $d_1 = 5\lambda/2$ and $d_2 = 9\lambda/2$, in order to solve the fringe ambiguity. The method using the rotation of phase differences, labeling the phase lines and rounding value of phase difference is performed to determine the unambiguous AOA [50].

2.3. Lightning Echo Selection Criteria

Radar echoes from lightning channels have distinctive characteristics. VHF radar echoes are composed of two types of signal components. One type is passive radio emissions, and another type is received radar signals backscattered by ionized lightning plasma channels [41,45,47]. During the breakdown and ionization processes, there are strong emissions radiated in a wide range of frequencies, which manifest in the form of burst of pulses or isolated pulses observed in all range gates at a time scale of milliseconds. One needs to keep in mind that five receivers work constantly until the next time the transmitter sends pulses and electromagnetic emissions are radiated continuously during multistage processes of lightning discharges. Therefore, electromagnetic emissions in the form of pulses can be seen in all range gates. For backscattered signals of the transmitted pulses, the amplitude of signal rises rapidly out of the background noise and lasts for hundreds of milliseconds [40–42,44].

An illustrative example of the differences between two types of signals is shown in Figure 2. The amplitudes of received lightning return echoes for multiple range gates ranging from 12.6 to 17.6 km at the interval of 1 km are placed in order. In addition, the amplitude for the range gate at 27.6 km is placed at the top of the panel to explain further that electromagnetic emissions occur in all range gates. For convenience, two different types of signals are marked with rectangles of different colors in Figure 2. Signals inside the green rectangle represent waveforms of backscattered signals, while red rectangles represent typical waveforms of electromagnetic emissions from lightning discharges. It can be noticed that echoes in all range gates are preceded by a short duration of pulses due to the breakdown process, which can be used as an indicator for the beginning of the lightning event. The intensity of backscattered signals is stronger than that of passive electromagnetic emissions. What is more, the occurrences of return pulses can only be observed at several continuous range gates.

After identifying differences between two types of signals, we can proceed to the echo selection procedure. Our goal is to discriminate lightning echoes from the interference of spikes and other non-lightning noises and to find the starting and ending time of lightning echoes for further signal processing.

Following two basic signal processing principles, effective lightning echoes can be discriminated from background noise and non-lightning echoes. First, the beginning of a lightning event can be set by means of detecting the passive electromagnetic emissions in all range gates [47]. Then, the starting and ending time can be extracted based on the steep rise in amplitude and the lasting time. Second, the cross-correlation of signals received at five receiver channels can be employed to exclude the interference of spikes and other non-lightning noises due to the uncorrelation of noise signals [47,53].

Considering the physical continuity of lightning channels, the isolated points will be rejected in the procedure of 3D reconstruction of lightning [9].

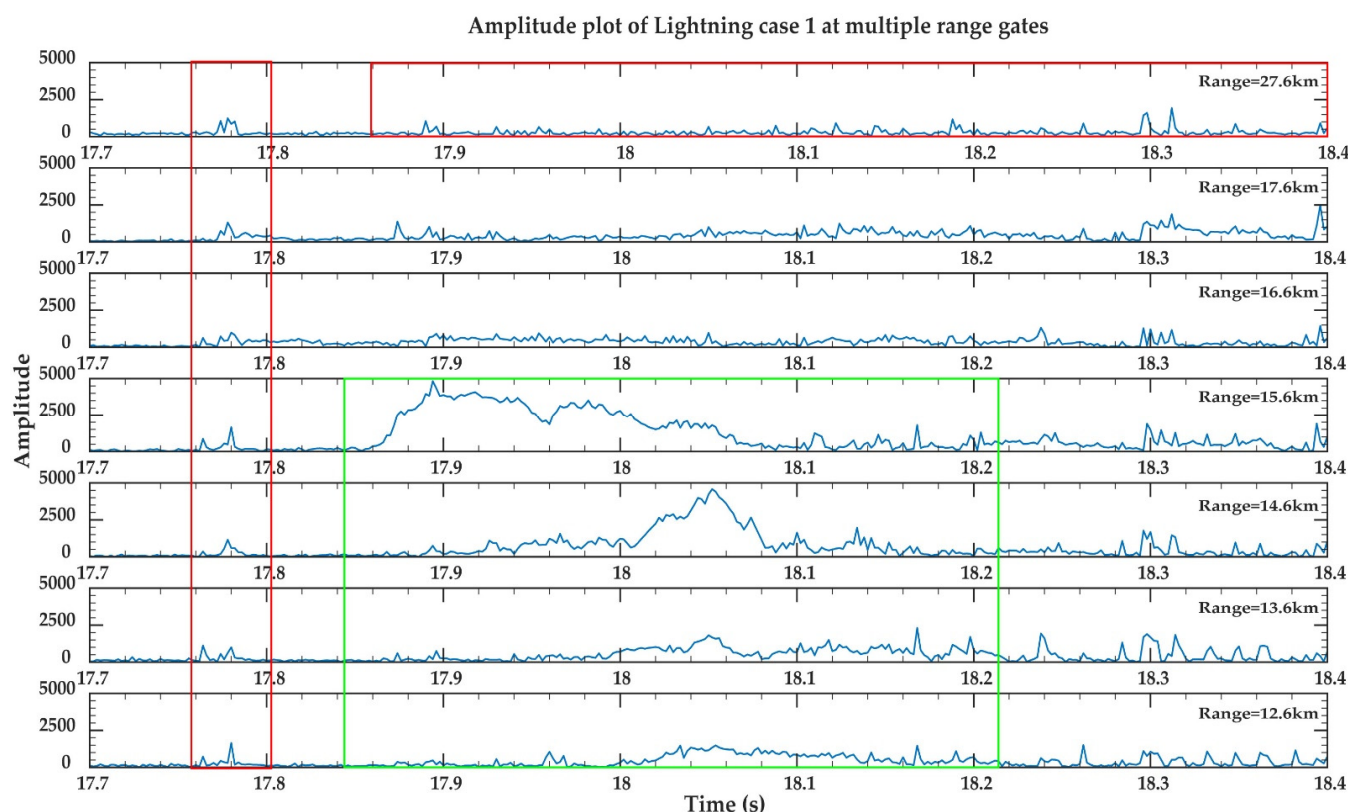


Figure 2. Amplitude of received lightning return echoes for multiple range gates ranging from 12.6 to 17.6 km at the interval of 1 km. The amplitude plot at a range gate 27.6 km is placed at the top for further explanation.

2.4. Experiment Setup

The experiments were done with the Leshan VHF radar, which operates at 48.2 MHz with one transmitting antenna and five receiving antennas (See Figure 3 for details). The antenna pattern of transmitting and receiving antennas are circular polarized (CP) cross-dipole, which consist of two dipoles placed perpendicularly and fed 90 degrees out of the phase to form circular polarization. The transmitter (24 kW peak power) sends pulses with a 2 μ s duration at a pulse repetition frequency (PRF) of 4000 Hz. The return echoes are received by five antennas, i.e., the interferometric system which is applied for solving the unambiguous AOA. The five antennas are configured in the L array. Each side of the L array is spaced in a straight line creating two baselines, $d_1 = 5\lambda/2$ and $d_2 = 9\lambda/2$, in order to solve the fringe ambiguity. Then, complex digital samples with a 14-bit dynamic range are taken at 313 gates between 1.2 and 32.4 km range. For PRF of 4000 Hz, coherent integrations of 8 are done, yielding the time resolution of 2 ms. The raw data of I/Q signal of five receiver channels are saved to a file for further signal processing. The detailed radar optional parameters are shown in Table 1.

Table 1. Leshan VHF radar operational parameter.

Parameter	Value
Wavelength	6.22 m
Transmitter peak power	24 kW
Sensitivity of receiver	−120 dBm
Pulse repetition frequency	4000 Hz
Signal coding type	Gaussian modulated monopulse
Range resolution	300 m
Time resolution	2 ms



Figure 3. Photography of Leshan VHF radar antenna array.

3. Results

With the aid of the meteorological product of Institute of Electrical Engineering of the Chinese Academy of Sciences (IEE, CAS), we can promptly get the information of the weather status in Leshan, which makes it easy to catch lightning events accompanied by strong convective weather. On 11 August 2020, a series of lightning events were successfully observed by the VHF radar. Two characteristic lightning events have been analyzed and the results are shown below.

3.1. The Lightning Experiment: Case 1

Figure 4 presents the range-time-intensity (RTI) plot of the received signal. The magnitude of the signal is color coded in arbitrary units. It can be seen from Figure 4 that a strong echo lasting for 600 ms can be noticed which can be verified to be the lightning echo. The ranges of the signal block expand from 7 to 18 km. It is reckoned to be scattering from the ionized thermalized plasma channel.

All of the lightning echoes show the same pattern of development in which strong lightning echoes are preceded by a sudden increase of the amplitude level in all range gates, which could be emitted by the breakdown and ionization process. The burst of magnitude in all range gates lasting 10 ms or longer occurs at the time interval of dozens of milliseconds. This phenomenon can be attributed to discharges of the lightning channel along with the emission of VHF radiation.

In Figure 5, the amplitude and phase of return signal are calculated from the selected time series of I/Q signal in the range of 15.5 km. The phase of the signal is unwrapped within two red line regions to show a clear variation of the phase. In the lowest panel, there are 11 doppler spectra windows. The doppler spectra windows are numbered in the right corner of the subpanel. Each subpanel is calculated using 32 data points of the selected raw complex signal. The time resolution of data points can be calculated combining the PRF

and coherent times as described before in Section 2.4. Three panels are aligned together to dig further into the characteristics of lightning echoes in different aspects as the function of time.

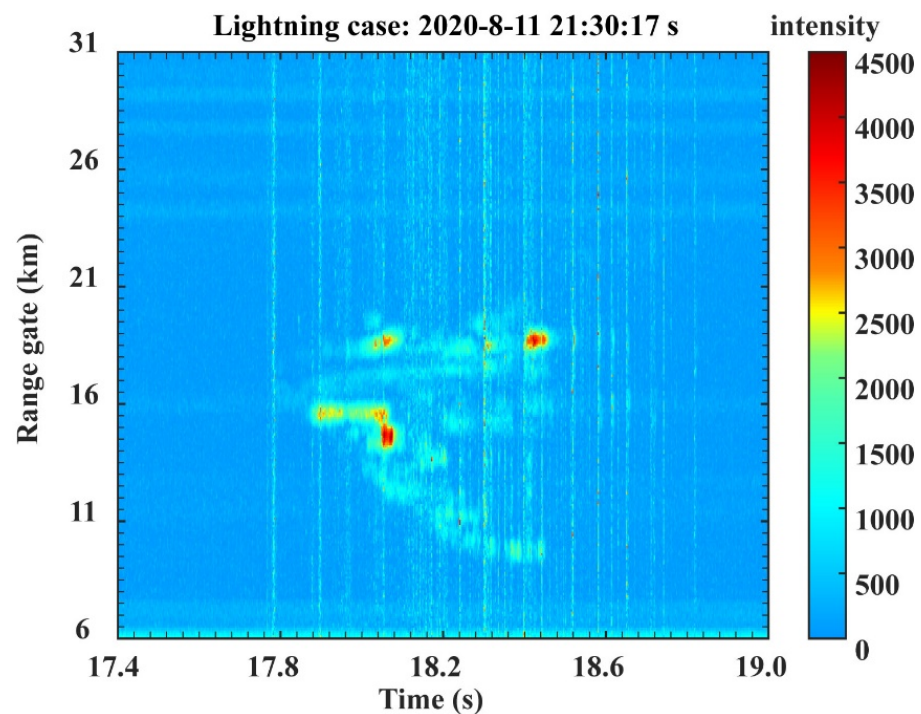


Figure 4. RTI plot of the received lightning echo.

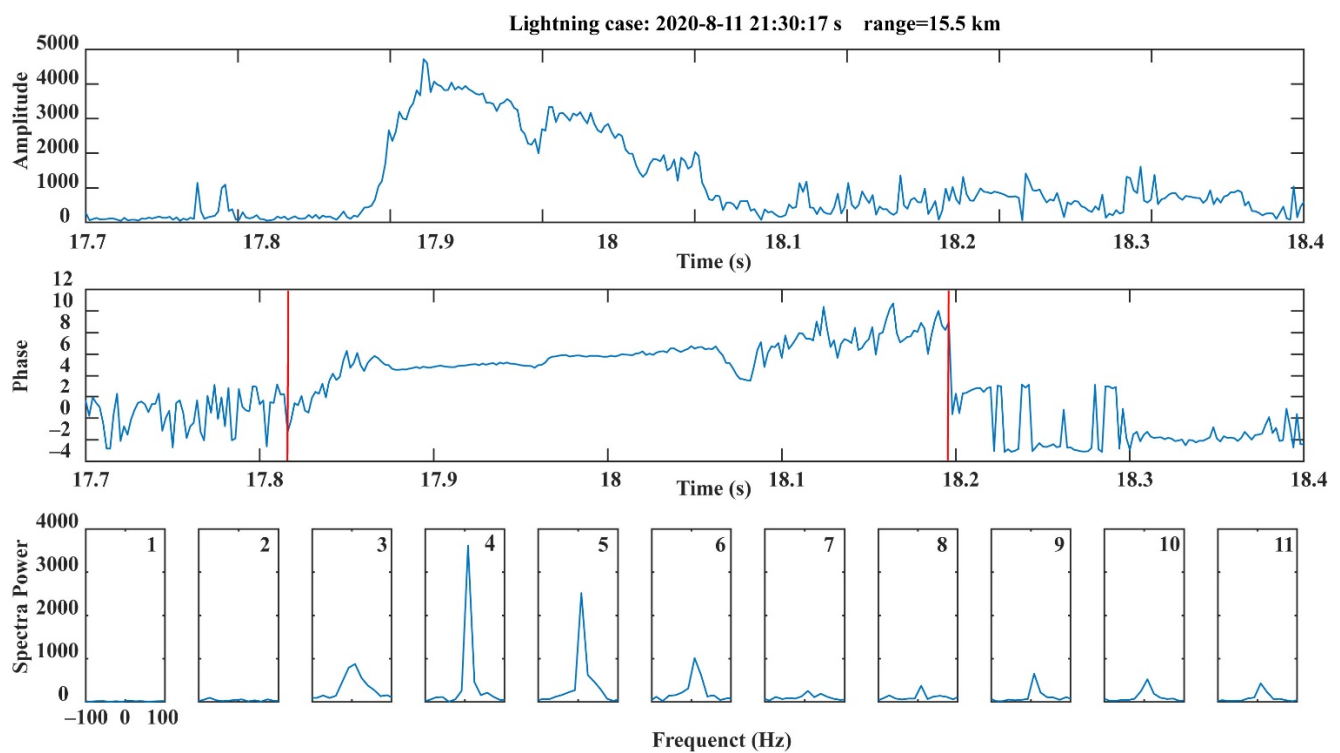


Figure 5. Amplitude, phase, and doppler spectra of I/Q raw data. The doppler spectra windows are numbered in the right corner of the subpanel. Each subpanel is calculated using 32 data points of the selected raw complex signal.

What makes the analysis more complicated is that the radar echoes we received are the sum of consistent passive electromagnetic emissions and return echoes backscattered by ionized channels, which can only be received at some certain range gates. The passive emissions are filled with the whole range gates due to the continuing process of lightning discharges.

The amplitude of the return echo rises abruptly out of the noise and reaches quasi-saturation which is due to the characteristics of the overdense lightning channel. There are three temporary valleys of amplitude on the saturation stage along with corresponding changes of the phase, which might indicate that branches of the lightning channel result in a change of the scattering center [44].

The overall performance of amplitude accords with an overdense channel being modeled as a metallic cylinder that expands with time [48,54]. The decay of amplitude is exponential, which is consistent with the assumption that the ionized channel becomes underdense with the lapse of time. It means that the transmitted electromagnetic wave can penetrate the lightning channel and the backscattered signal is the sum of scattering from individual electrons [34,35,43].

The result of 3D imaging of the lightning channel is shown in Figure 6. Based on the interferometry method described above, AOAs and corresponding ranges can be calculated to obtain the three-dimensional location of the target point.

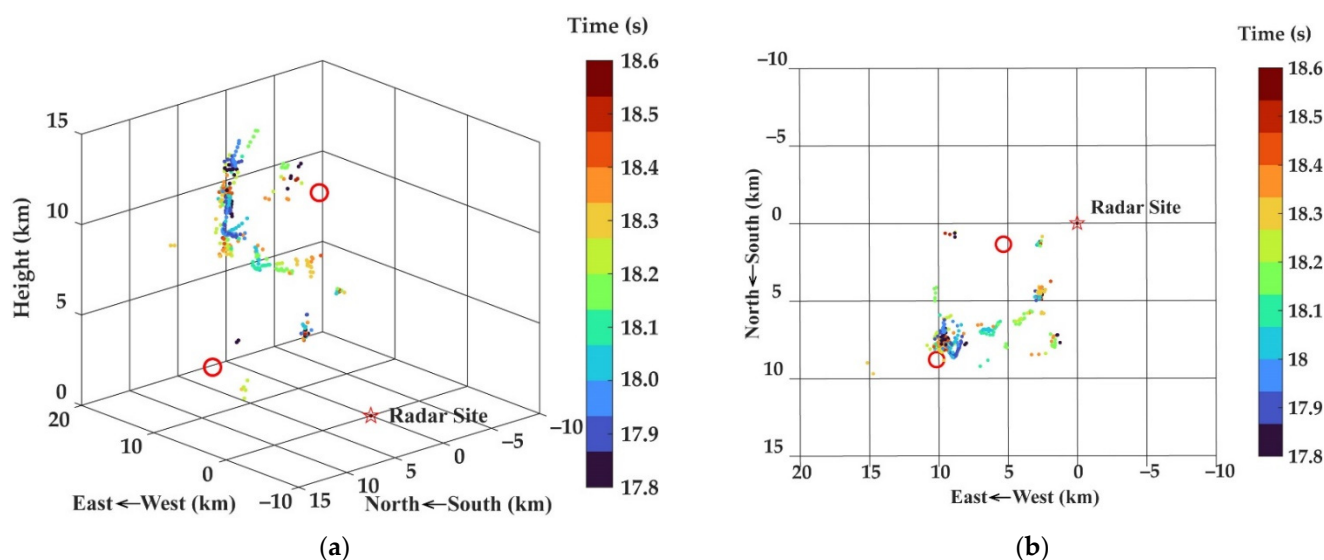


Figure 6. The 3D reconstruction and 2D project of the lightning channel. (a) The 3D locating result of the lightning channel, two VLF locating results (shown as two red circles), and the radar site (marked as a pentagram); (b) the projection of the 3D locating result at the top view.

The spatial structure of the lightning channel can be clearly seen in the x-y-z plane. The labels of x-y plane are substituted with East<-West and North<-South. The radar station is marked as a red pentagram. The location of lightning channels reported by the VLF lightning detection system occurring at the same time are chosen for comparison. The detailed data format of the VLF locating system offered by IEECAS is listed at the end of the section in Table 2. The latitude and longitude information along with the height are used to form a red round ball in the 3D result. However, the VLF locating results only have a point which may not fit well with the fine 3D structure of the VHF result. To the convenience of observation, the 2D result of the project of x-y plane is depicted in Figure 6b. The location of the VLF lightning detection system in the 2D plane are within a small distance, but the height is not in well agreement with results of the VHF system in the 3D view. The deviation between two results is reasonable since the VLF lightning mapping

are performed with multiple stations from a long distance, which might lead to possible locating errors.

Table 2. VLF data records of two lightning cases.

Latitude	Longitude	Time (LT)	Height (Km)	Lightning Type
29.712	103.870	2020-8-11T 21:38:29	1.13	IC
29.605	103.851	2020-8-11T21:30:17	2.584	IC
29.579	103.809	2020-8-11T21:30:17	11.759	IC

3.2. The lightning Experiment: Case 2

In Figure 7, the RTI of the lightning shows that return echoes do not follow the occurrence of the first passive emission signal after a short time interval. It is rare that the enhanced return echoes appear at the end of the event. The possible reason for this phenomenon is that the ionized lightning channel exists after the initial passive radiation. However, the backscattering RCS of the lightning channel at that time is small possibly due to the orientation angle of the lightning channel.

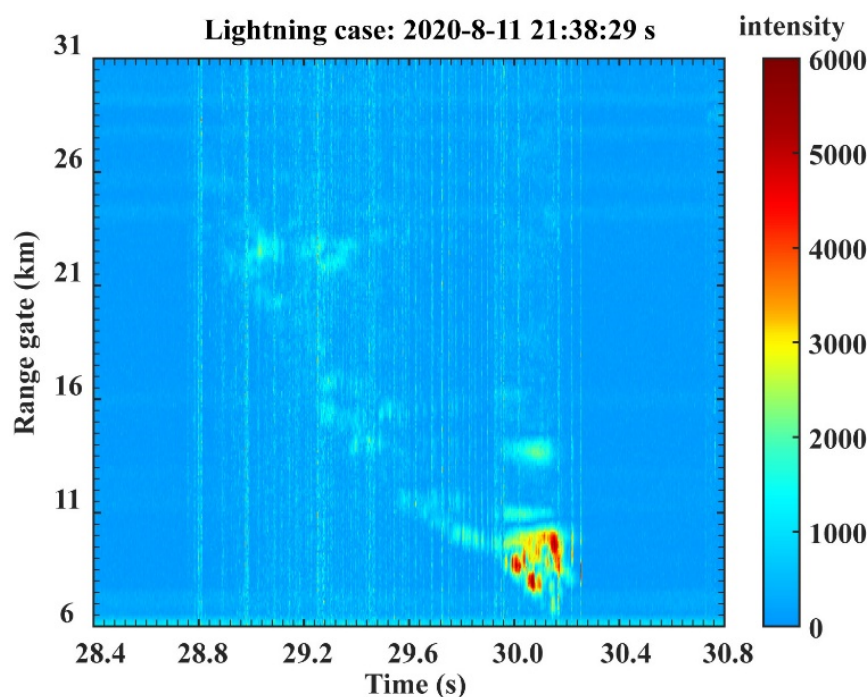


Figure 7. RTI plot of the received lightning echo.

In Figure 8, the amplitude plot has two obvious peaks lasting several hundreds of milliseconds along with the corresponding peaks in doppler spectra. There are a few bursts of pulses overlapped with the return echoes adding a further complication to the interpretation of the signal. If annoying spikes are ignored, it can be clearly seen that the second one reaches saturation for 200 ms and decays exponentially, which is in well accordance with the hypothesis that lightning echoes are scattering from the overdense plasma channel and the channel gradually becomes underdense with the lapse of time. The phase plot shows a typical performance of an overdense plasma channel [54]. It is also supported by the 3D structure of the lightning channel in Figure 9. The lightning channel forms a long cylinder parallel to the ground. It finally passes through the radar main beam transversely, which explains the clear plot of the second enhanced signal part in the amplitude.

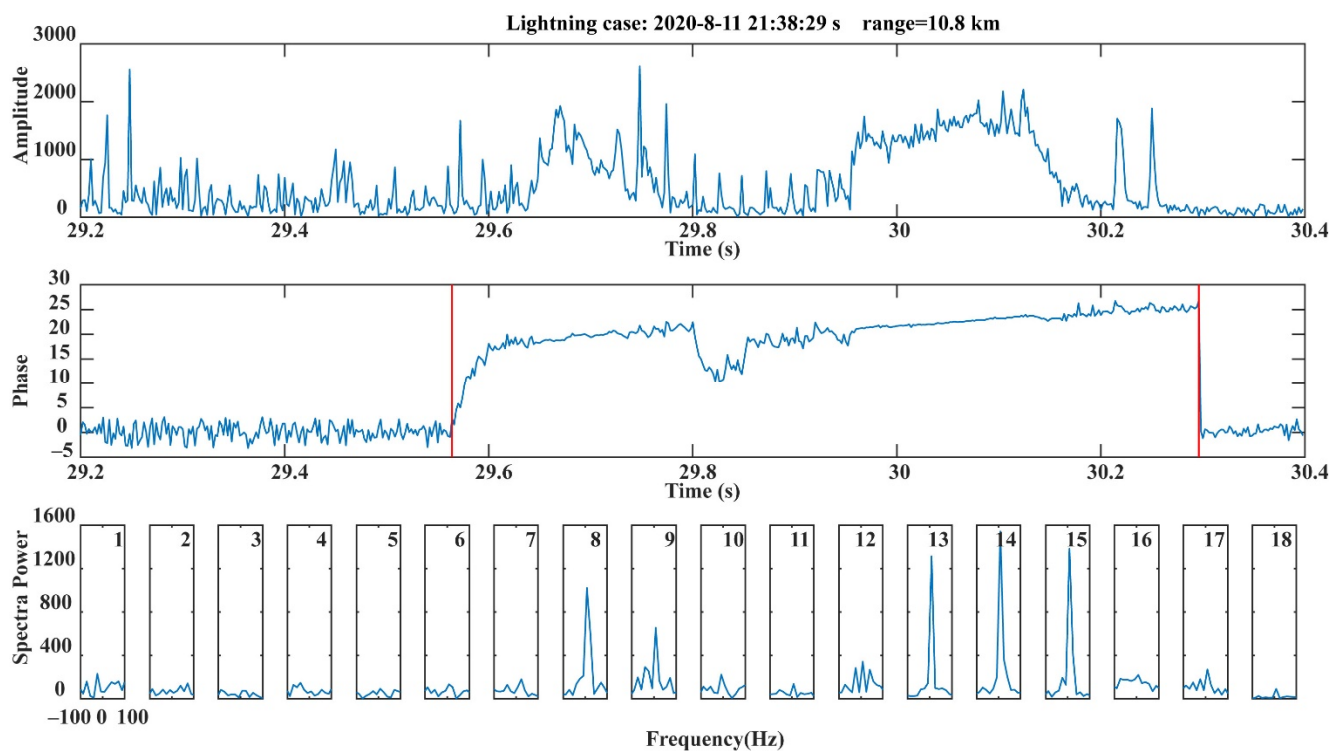


Figure 8. Amplitude, phase, and doppler spectra of I/Q raw data. The doppler spectra windows are numbered in the right corner of the subpanel. Each subpanel is calculated using 32 data points of the selected raw complex signal. The scale of the time axis is the same as in Figure 4, which starts from 29.2 to 30.4 s.

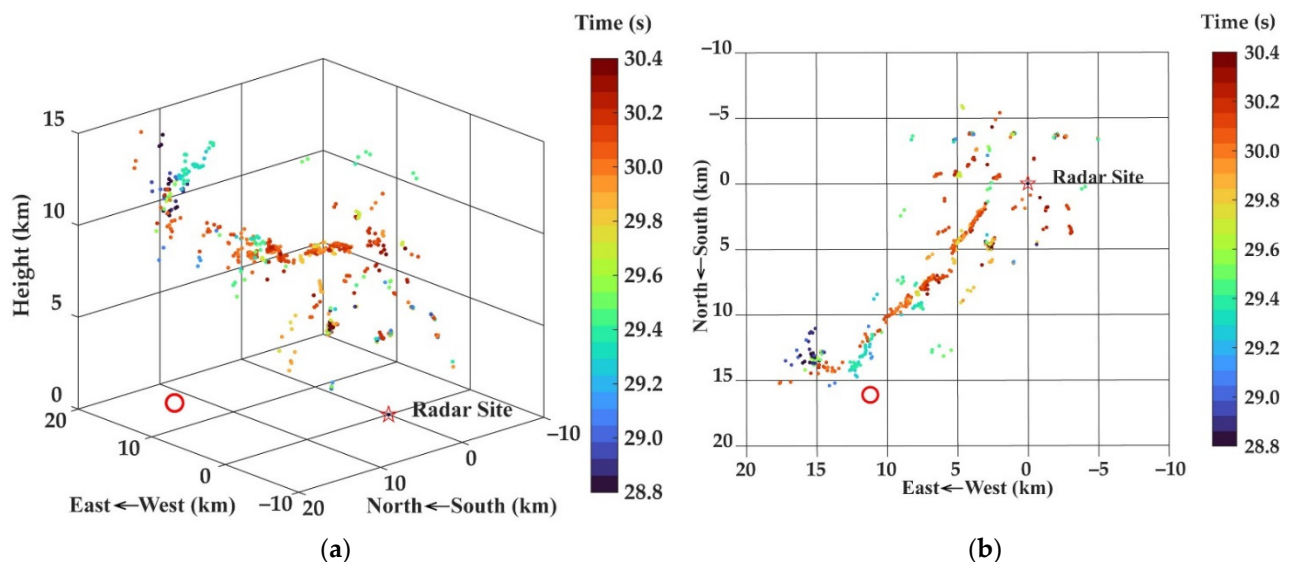


Figure 9. The 3D reconstruction and 2D project of the lightning channel. (a) The 3D locating result of the lightning channel, VLF locating result (shown as two red circles), and the radar site (marked as a pentagram); (b) the projection of the 3D locating result at the top view.

4. Discussion

Based on the VHF radar observation, the characteristics of lightning plasma channels and its return echoes are explored. The intensity of lightning return echoes backscattered by ionized channels are significantly stronger than the background noises and the amplitude of passive electromagnetic emissions produced by the breakdown and ionization processes are also higher than that of noises. These two types of signals also have different features.

The former occurs only at several continuous range gates and often lasts for hundreds of milliseconds, while the latter occurs at all range gates in the form of a short duration of burst pulses. It even adds a further complication to the analysis when two types of signals are overlapped.

The amplitude of the typical lightning return echoes rises abruptly out of noises and reaches saturation for a while before the exponential decay of the amplitude. This observational result supports the overdense assumption which agrees with William's conclusion [35]. The phase of return echoes shows a sharp increase before the peak of the amplitude and stays relatively flat during the quasi-saturation stage. The increase of the phase possibly indicates that the formation of the lightning channel and the wind turbulence might lead to the slow change of the phase in the saturation stage [44].

During the observation, all the results of 3D reconstruction of lightning channels can be classified into the intracloud (IC) flashes. However, this does not mean that there is no cloud-to-ground flash shown as 3D channels connecting to the ground in the observation results. There are long cylinder-shape objects connecting to the ground in the 3D locating result. Yet, those cylinders tend to occur at the same positions almost in every lightning echoes, which could be attributed to the echoes from tall metal buildings such as the transmission line tower or the lightning induced by lightning rods fixed at some places. Therefore, these points are removed from the final results.

Petitdidier used a synchronized VHF and UHF vertical narrow beam radar to receive simultaneous UHF radiation from lightning and the VHF backscattered signal from the thermalized ionized lightning flash channels above the radar [45]. If passive radiations and return echoes received on a radar at the same frequency band can be separated and used to perform a synchronized analysis, it will be promising for the future study of lightning and the lightning mapping technique.

5. Conclusions

The observation made with the Leshan VHF interferometric radar array has successfully recorded echoes of lightning events, in which the correctness is verified with locating results of the VLF detection system offered by IEECAS. Typical features are analyzed in the form of amplitude, phase, and doppler spectra of the raw I/Q data. The results show good consistency with the previous researches carried out by other authors [44,45]. The interpretation of the observational results is complicated by the dendric structure of lightning channels and the overlap between passive electromagnetic emissions and return signals. Nevertheless, some parts of the characteristics of lightning channels are still evident. The transition from the overdense to the underdense channel in the form of amplitude and phase is clearly observed. The 3D reconstruction of ionized lightning plasma channels is performed by means of radar interferometry. The overall correctness of lightning localization can be verified. However, the precision of the location of points in the 3D structure of lightning still need to be examined and further improved.

Author Contributions: Conceptualization, C.Z. and Y.L.; methodology, W.J. and W.Y.; investigation, W.Y., Y.L. and M.L.; data curation, G.C.; writing—original draft preparation, W.Y.; writing—review and editing, W.Y, Q.T., C.Z. and Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (NSFC Nos. 41574146, 41774162, 42074187), Excellent Youth Foundation of Hubei Provincial Natural Science Foundation (No. 2019CFA054), the National Key R&D Program of China (2018YFC1503506), and the foundation of National Key Laboratory of Electromagnetic Environment (6142403180204).

Data Availability Statement: Data sharing is not applicable to this article.

Acknowledgments: We acknowledge the use of VLF data from the Institute of Electrical Engineering of the Chinese Academy of Sciences. The data of Leshan VHF coherent scatter radar are available by contacting Chen Zhou (chenzhou@whu.edu.cn). This work was supported by the National Natural Science Foundation of China (NSFC Nos. 41574146, 41774162, 42074187), Excellent Youth Foundation

of Hubei Provincial Natural Science Foundation (No. 2019CFA054), the National Key R&D Program of China (2018YFC1503506), and the foundation of National Key Laboratory of Electromagnetic Environment (6142403180204).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

List of abbreviations used in the paper.

3D	Three-dimensional
2D	Two-dimensional
I/Q	In-phase/Quadrature
VLF	Very-low-frequency
LF-MF	Low-frequency and medium-frequency
VHF	Very-high-frequency
UHF	Ultra-high-frequency
HSV	High speed video camera
Kfps	Kilo frames per second
ITF	Interferometry
TOA	Time of Arrival
TDOA	Time Difference of Arrival
AOA	Angle of Arrival
IC	Intra cloud
CG	Cloud to ground
RCS	Radar cross section
RTI	Range-time-intensity
PRF	Pulse repetition frequency
CP	Circular polarized
MDF	Magnetic Direction-Finders
NLDN	US National Lightning Detection Network
IEECAS	Institute of Electrical Engineering of the Chinese Academy of Sciences

References

1. Dwyer, J.R.; Uman, M.A. The physics of lightning. *Phys. Rep.* **2014**, *534*, 147–241. [\[CrossRef\]](#)
2. He, J.; Rakov, V.; Wang, D.; Wang, P.K. Lightning physics and effects. *Atmos. Res.* **2013**, *129*, 33. [\[CrossRef\]](#)
3. Maggio, C.R.; Marshall, T.C.; Stolzenburg, M. Estimations of charge transferred and energy released by lightning flashes. *J. Geophys. Res. Atmos.* **2009**, *114*. [\[CrossRef\]](#)
4. Alammari, A.; Alkahtani, A.A.; Ahmad, M.R.; Noman, F.M.; Esa, M.R.M.; Kawasaki, Z.; Tiong, S.K. Lightning Mapping: Techniques, Challenges, and Opportunities. *IEEE Access* **2020**, *8*, 190064–190082. [\[CrossRef\]](#)
5. Cummins, K.L.; Murphy, M.J.; Bardo, E.A.; Hiscox, W.L.; Pyle, R.B.; Pifer, A.E. A combined TOA/MDF Technology Upgrade of the US National Lightning Detection Network. *J. Geophys. Res. Atmos.* **1998**, *103*, 9035–9044. [\[CrossRef\]](#)
6. Hill, J.D.; Uman, M.A.; Jordan, D.M. High-speed video observations of a lightning stepped leader. *J. Geophys. Res. Atmos.* **2011**, *116*. [\[CrossRef\]](#)
7. Karunarathne, S.; Marshall, T.C.; Stolzenburg, M.; Karunarathna, N.; Orville, R.E. Modeling stepped leaders using a time-dependent multipole model and high-speed video data. *J. Geophys. Res. Atmos.* **2015**, *120*, 2419–2436. [\[CrossRef\]](#)
8. An, T.; Yuan, P.; Liu, G.; Cen, J.; Wang, X.; Zhang, M.; An, Y. The radius and temperature distribution along radial direction of lightning plasma channel. *Phys. Plasmas* **2019**, *26*. [\[CrossRef\]](#)
9. Li, Y.; Qiu, S.; Shi, L.; Huang, Z.; Wang, T.; Duan, Y. Three-Dimensional Reconstruction of Cloud-to-Ground Lightning Using High-Speed Video and VHF Broadband Interferometer. *J. Geophys. Res. Atmos.* **2017**, *122*, 13420–13435. [\[CrossRef\]](#)
10. Campos, L.Z.S.; Saba, M.M.F.; Pinto, O., Jr.; Ballarotti, M.G. Waveshapes of continuing currents and properties of M-components in natural negative cloud-to-ground lightning from high-speed video observations. *Atmos. Res.* **2007**, *84*, 302–310. [\[CrossRef\]](#)
11. Dayeh, M.A.; Evans, N.D.; Fuselier, S.A.; Trevino, J.; Ramaekers, J.; Dwyer, J.R.; Lucia, R.; Rassoul, H.K.; Kotovsky, D.A.; Jordan, D.M.; et al. First images of thunder: Acoustic imaging of triggered lightning. *Geophys. Res. Lett.* **2015**, *42*, 6051–6057. [\[CrossRef\]](#)
12. Arechiga, R.O.; Johnson, J.B.; Edens, H.E.; Thomas, R.J.; Rison, W. Acoustic localization of triggered lightning. *J. Geophys. Res. Atmos.* **2011**, *116*. [\[CrossRef\]](#)
13. Depasse, P. Lightning Acoustic Signature. *J. Geophys. Res. Atmos.* **1994**, *99*, 25933–25940. [\[CrossRef\]](#)
14. Cummins, K.L.; Murphy, M.J. An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, with an In-Depth Look at the US NLDN. *IEEE Trans. Electromagn. Compat.* **2009**, *51*, 499–518. [\[CrossRef\]](#)
15. Proctor, D. A Hyperbolic System for Obtaining VHF Radio Pictures of Lightning. *J. Geophys. Res.* **1971**, *76*, 1478–1489. [\[CrossRef\]](#)

16. Proctor, D.E. VHF Radio Pictures of Cloud Flashes. *J. Geophys. Res. Ocean.* **1981**, *86*, 4041–4071. [[CrossRef](#)]
17. Warwick, J.W.; Hayenga, C.O.; Brosnahan, J.W. Interferometric Directions of Lightning Sources at 34-MHZ. *J. Geophys. Res. Ocean. Atmos.* **1979**, *84*, 2457–2468. [[CrossRef](#)]
18. Rhodes, C.T.; Shao, X.M.; Krehbiel, P.R.; Thomas, R.J.; Hayenga, C.O. Observations of lightning phenomena using radio interferometry. *J. Geophys. Res. Atmos.* **1994**, *99*, 13059–13082. [[CrossRef](#)]
19. Shao, X.-M.; Ho, C.; Bowers, G.; Blaine, W.; Dingus, B. Lightning Interferometry Uncertainty, Beam Steering Interferometry, and Evidence of Lightning Being Ignited by a Cosmic Ray Shower. *J. Geophys. Res. Atmos.* **2020**, *125*. [[CrossRef](#)]
20. Sun, Z.; Qie, X.; Liu, M.; Cao, D.; Wang, D. Lightning VHF radiation location system based on short-baseline TDOA technique—Validation in rocket-triggered lightning. *Atmos. Res.* **2013**, *129*, 58–66. [[CrossRef](#)]
21. Tantisattayakul, T.; Masugata, K.; Kitamura, I.; Kontani, K. Broadband VHF sources locating system using arrival-time differences for mapping of lightning discharge process. *J. Atmos. Sol. Terr. Phys.* **2005**, *67*, 1031–1039. [[CrossRef](#)]
22. Mazur, V.; Williams, E.; Boldi, R.; Maier, L.; Proctor, D.E. Initial comparison of lightning mapping with operational time-of-arrival and interferometric systems. *J. Geophys. Res. Atmos.* **1997**, *102*, 11071–11085. [[CrossRef](#)]
23. Stock, M.G.; Akita, M.; Krehbiel, P.R.; Rison, W.; Edens, H.E.; Kawasaki, Z.; Stanley, M.A. Continuous broadband digital interferometry of lightning using a generalized cross-correlation algorithm. *J. Geophys. Res. Atmos.* **2014**, *119*, 3134–3165. [[CrossRef](#)]
24. Qiu, S.; Zhou, B.-H.; Shi, L.-H. Synchronized observations of cloud-to-ground lightning using VHF broadband interferometer and acoustic arrays. *J. Geophys. Res. Atmos.* **2012**, *117*. [[CrossRef](#)]
25. Lee, A.C.L. Ground Truth Confirmation and Theoretical Limits of an Experimental VLF Arrival Time Difference Lightning Flash Locating System. *Q. J. R. Meteorol. Soc.* **1989**, *115*, 1147–1166. [[CrossRef](#)]
26. Cummins, K.L.; Krider, E.P.; Malone, M.D. The US National Lightning Detection Network (TM) and applications of cloud-to-ground lightning data by electric power utilities. *IEEE Trans. Electromagn. Compat.* **1998**, *40*, 465–480. [[CrossRef](#)]
27. Dowden, R.; Holzworth, R.; Rodger, C.; Lichtenberger, J.; Thomson, N.; Jacobson, A.; Lay, E.; Brundell, J.; Lyons, T.; O’Keefe, S.; et al. World-Wide Lightning Location Using VLF Propagation in the Earth-Ionosphere Waveguide. *Antennas Propag. Mag. IEEE* **2008**, *50*, 40–60. [[CrossRef](#)]
28. Krider, E.; Noggle, R.; Uman, M. A Gated, Wideband Magnetic Direction Finder for Lightning Return Strokes. *J. Appl. Meteorol.* **1976**, *15*. [[CrossRef](#)]
29. Krider, E.; Noggle, R.; Pifer, A.; Vance, D. Lightning Direction-Finding Systems for Forest Fire Detection. *Bull. Am. Meteorol. Soc.* **1980**, *61*, 980–986. [[CrossRef](#)]
30. Thottappillil, R.; Rakov, V.; Uman, M. Distribution of charge along the lightning channel: Relation to remote electric and magnetic fields and to return-stroke models. *J. Geophys. Res.* **1997**, *102*, 6987–7006. [[CrossRef](#)]
31. Rakov, V.; Uman, M. Review and evaluation of lightning return stroke models including some aspects of their application. *Electromagn. Compat. IEEE Trans.* **1998**, *40*, 403–426. [[CrossRef](#)]
32. Nucci, C.A.; Diendorfer, G.; Uman, M.; Rachidi, F.; Ianoz, M. Lightning return stroke current models with specified channel-base current: A review and comparison. *J. Geophys. Res. Atmos.* **1990**, *95*. [[CrossRef](#)]
33. Uman, M.; Voshall, R. Time Interval between Lightning Strokes and Initiation of Dart Leaders. *J. Geophys. Res.* **1968**, *73*. [[CrossRef](#)]
34. Dawson, G. Radar as a Diagnostic Tool for Lightning. *J. Geophys. Res.* **1972**, *77*, 4518–4528. [[CrossRef](#)]
35. Williams, E.; Geotis, S.; Bhattacharya, A. A Radar Study of the Plasma and Geometry of Lightning. *J. Atmos. Sci.* **1989**, *46*, 1173–1185. [[CrossRef](#)]
36. Pawsey, J.L. Radar observations of lightning on 1.5 metres. *J. Atmos. Terr. Phys.* **1957**, *11*, 289–290. [[CrossRef](#)]
37. Browne, I. A Radar Echo from Lightning. *Nature* **1951**, *167*. [[CrossRef](#)]
38. Ligda, M.G.H. The radar observation of lightning. *J. Atmos. Terr. Phys.* **1956**, *9*, 329–346. [[CrossRef](#)]
39. Szymanski, E.W.; Rust, W.D. Preliminary observations of lightning radar echoes and simultaneous electric field changes. *Geophys. Res. Lett.* **1979**, *6*, 527–530. [[CrossRef](#)]
40. Holmes, C.R.; Szymanski, E.W.; Szymanski, S.J.; Moore, C.B. Radar and acoustic study of lightning. *J. Geophys. Res. Ocean.* **1980**, *85*, 7517–7532. [[CrossRef](#)]
41. Proctor, D.E. Radar observations of lightning. *J. Geophys. Res. Ocean.* **1981**, *86*, 12109–12114. [[CrossRef](#)]
42. Mazur, V.; Zrnic, D.S.; Rust, W.D. Lightning channel properties determined with a vertically pointing Doppler radar. *J. Geophys. Res. Ocean.* **1985**, *90*, 6165–6174. [[CrossRef](#)]
43. Mazur, V.; Doviak, R. Radar cross section of a lightning element modeled as a plasma cylinder. *Radio Sci.* **1983**, *18*, 381–390. [[CrossRef](#)]
44. Röttger, J.; Liu, C.H.; Pan, C.J.; Su, S.Y. Characteristics of lightning echoes observed with VHF ST radar. *Radio Sci.* **1995**, *30*, 1085–1097. [[CrossRef](#)]
45. Petitdidier, M.; Laroche, P. Lightning observations with the Strato-Tropospheric UHF and VHF radars at Arecibo, Puerto Rico. *Atmos. Res.* **2005**, *76*, 481–492. [[CrossRef](#)]
46. Li, X.; Zhang, J.; Chen, L.; Xue, Q.; Zhu, R. Measuring Method for Lightning Channel Temperature. *Sci. Rep.* **2016**, *6*. [[CrossRef](#)] [[PubMed](#)]
47. Tseng, T. A Comparative Study of Lightning Detection and Error Analysis between Interferometry Method and Time-Of-Arrival Technique. Master’s Thesis, National Central University, Taoyuan, Taiwan, 2014.

-
48. Sugar, G.R. Radio propagation by reflection from meteor trails. *Proc. IEEE* **1964**, *52*, 116–136. [[CrossRef](#)]
 49. Mazur, V.; Walker, G.B. The Effect of Polarization on Radar Detection of Lightning. *Geophys. Res. Lett.* **1982**, *9*, 1231–1234. [[CrossRef](#)]
 50. Doan, S.V.; Vesely, J.; Janu, P.; Hubacek, P.; Tran, X.L. Optimized algorithm for solving phase interferometer ambiguity. In Proceedings of the 2016 17th International Radar Symposium (IRS), Krakow, Poland, 10–12 May 2016; pp. 1–6.
 51. Hayenga, C.O.; Warwick, J.W. Two-dimensional interferometric positions of VHF lightning sources. *J. Geophys. Res. Ocean.* **1981**, *86*, 7451–7462. [[CrossRef](#)]
 52. Jones, J.; Webster, A.R.; Hocking, W.K. An improved interferometer design for use with meteor radars. *Radio Sci.* **1998**, *33*, 55–65. [[CrossRef](#)]
 53. Hocking, W.K.; Fuller, B.; Vandeppeer, B. Real-time determination of meteor-related parameters utilizing modern digital technology. *J. Atmos. Sol.-Terr. Phys.* **2001**, *63*, 155–169. [[CrossRef](#)]
 54. Elford, W. Radar observations of meteor trails, and their interpretation using Fresnel holography: A new tool in meteor science. *Atmos. Chem. Phys. Discuss.* **2004**, *4*. [[CrossRef](#)]