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LIGHTNING STUDIES USING VHF WAVEFORM DATA

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ABSTRACT

Several atmospheric electricity studies were begun utilizing VHF lightning data obtained with the Lightning Detection and Ranging System (LDAR) at KSC. The LDAR system uses differences in the time of arrival of electromagnetic noise generated by the lightning process to seven antennas to calculate very accurate three dimensional locations of lightning. New software was developed to obtain the source location of multiple, simultaneous, and spatially separated lightning signatures. Three studies were begun this summer utilizing this data and are: (1) VHF observations of simultaneous lightning, (2) ground-based VHF observations of TIPPs, and (3) properties of intracloud recoil streamers. The principle result of each of these studies are: (1) lightning commonly occurs in well separated (2-50 km) regions simultaneously, (2) large amplitude pairs of VHF pulses are commonly observed on the ground but had not been previously identified due to the large number of signals usually observed in the VHF noise of close lightning, and (3) that VHF Q-noise and pulse signatures associated with K-changes within intracloud lightning propagate at velocities of $>10^8$ m/s. The interim results of these three studies are reviewed in this brief report. The results of these studies will be submitted to *Geophysical Research Letters* and the *Journal of Geophysical Research.*

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Mark B. Moldwin, Brent M. Goode, and Carl L. Lennon

1. INTRODUCTION

Kennedy Space Center (KSC), the 45th Space Command at Cape Canaveral Air Station (CCAS), and the National Weather Service (NWS) in Melbourne operate extensive and sophisticated meteorological and atmospheric physics instrumentation and systems to help support the launch activities at KSC (the shuttle) and CCAS (unmanned rockets). One of these systems is the Lightning Detection and Ranging (LDAR) system developed at KSC [1]. This system is used operationally to assist in making lightning warnings and advisories at KSC and CCAS areas. The system uses differences in the time of arrivals (DTOA) at seven stations of VHF (66 MHz) electromagnetic radiation generated in the lightning process. The DTOAs are converted to the three-dimensional location of the source of the radio noise [2, 3]. This method is demonstrated in Figure 1. The radio source is assumed to be a point source that radiates isotropically. The radio signal then propagates out in a spherical pattern intercepting the different stations at different times. By knowing the relative locations of the 6 remote sites compared to the central site, six time differences can be determined. Any combination of three stations ideally would give you the (X, Y, Z) location of the source, however due to uncertainties in the timing, some combinations of sites give better results due to an effect known as the geometric dilution of precision (GDOPs) [4]. We have tested several algorithms to determine the best estimate of the source location using the 20 combinations of four stations possible with a seven antenna array. We found that a method similar to the one utilized by the LDAR system [5] works the best. The new system has been termed "TIPPs" since it was designed to study trans-ionspheric pulse pairs [6]. However, in our effort to study TIPPs we found that the system is also able to study several other phenomena as well. Therefore this report is divided into four sections. The first three sections describe the initial results from three studies and the fourth section summarizes some of the calibration results. The final results of these studies will be submitted to the *Journal of Geophysical Research* and reprints will be given to the NASA/ASEE office when available. In this report only very brief summaries of the later two science projects are presented.

2. VHF OBSERVATIONS OF SIMULTANEOUS (SYMPATHETIC?) LIGHTNING

2.1 Introduction

Visual observations from space of thunderstorms have shown that lightning flashes often occur simultaneously (to the eye) from well-separated regions and that the onset of one flash often appears to precipitate or trigger others over a wide area [7]. The latter phenomena has been termed "sympathetic" or "associated" lightning [8]. Mazur, using VHF radar, defined "associated" lightning as a sequence of echoes from lightning separated by at least 1 km and separated by less than 200 ms in time. He demonstrated for events that occur within 200 ms of one another that the probability that the events are independent and randomly occurring is very small.

The question that arises from such observations is what is the cause of the association between sympathetic lightning flashes. We utilized the Lightning Detection and Ranging (LDAR) system at KSC to determine the locations of VHF lightning signals during one severe winter storm that passed over the LDAR system on 30 April, 1996. We found that within our 200 μs window 42% (41 of 98 records) of our triggered events contained a lightning signal located at least 2 km from the trigger event. Of course the second VHF signal maybe due to a continuation of the same flash since it is common to observe multiple VHF signals within a 200 μs window [e.g., 3].

However, since we know the location of the source of the VHF noise and the time-delay between the arrival of the signals to the LDAR system, we can estimate a velocity of propagation if the two sources are related. Typical VHF propagation velocities observed for intra-cloud step leaders are several times 10^5 m/s. Therefore by examining the apparent propagation velocity we can attempt to discriminate between observing two parts of the same flash and two separated flashes. Though we cannot uniquely determine the source mechanism of sympathetic lightning, we can restrain the possible causes. Mazur [8] hypothesized that associated lightning maybe caused by the interdependence of electric fields between neighboring electrically active cells (EACs) in a multicell thunderstorm. Specifically it was thought that the collapse of an electric dipole in one of the neighboring EACs due to a lightning flash would cause an electric field pulse which could trigger a neighboring cell. This study can test this hypothesis by examining whether an electromagnetic pulse has the time to propagate between spatially separated EACs.

2.2 Observations and Methodology

LDAR is a passive array of seven antennas that detect VHF pulses at 66 MHz with a bandwidth of 6 MHz. The antennas are sensitive to both horizontally and vertically polarized signals and are separated from 7 to 10 km from a central site (See Figure 1). The system and its performance are described in [4], [5] and [1] and therefore details of its operation are not given here. Though the hardware used in this study is the LDAR system, a new revised data management and new software routines are used. These software changes allow us to analyze the VHF waveform data in 200 μs windows with a sampling rate of 50 ns. The new software also aides in the selection of the "correct" pulses observed at the different stations hence alleviating one of the major disadvantages of long-baseline VHF time-of-arrival systems [9]. This disadvantage, namely the difficulty in identifying VHF pulses from two or more simultaneous separated sources because the pulses can arrive in a different order at each receiver, is alleviated by having the computer help pick the correct peaks depending on an initial "best guess." This semi-automated routine allows one to calculate the 3-Dimensional locations of virtually all the identifiable pulses within one 200 μs window. This is the first system with this capability and allows us to determine the locations of multiple VHF signals separated by only a few microseconds.

Though our sampling rate is 20 MHz (50 ns time resolution), we use a "zero-stuffing" technique [e.g., 10] to increase our effective time resolution to approximately 6 ns. This is accomplished by interpolation using packing in the frequency domain. The total uncertainty in our timing is however approximately 30 ns due to errors in such factors as the speed of the VHF propagation in air, transmission line delays, noise, bandwidth, the geometry of the antenna array with respect to the position of the source (Geometric Dilution of Precision or GDOPs) and quantizing. The main contributor to the error is the uncertainty in calculating the transmission line delays (or K-factors). We use a lightning simulator located at a known source near the central site to determine the K-factors for each of the six remote sites. Due to noise in the signals and quantizing the exact timing of the calibration signal has an uncertainty which is typically 10-15 ns. Due to having an array of 7 antennas we effectively have 20 configurations of 4 antennas to do ranging. This almost virtually assures us of having a combination with good GDOPs to complete our calculations. The lightning simulator allows us to remove any bias or systematic errors from our analysis so we are left with only the random errors outlined above. The system is triggered when a signal is received at the central site that has an amplitude above a preset level. This level was set fairly high, so the pulses triggered were probably large intracloud pulses emitted during the initial or active phase [11, and 12] and have been associated with first streamers within the cloud [3] (though some of the signals move at very high speeds which have been associated with return stroke recoil streamers). Data are saved to disk 5 μs prior to the trigger event and 195 μs after. Due to the spacing of the array, many more than one signal can fall within this 200 μs window. Since we save the waveform data we can inspect each record and determine the individual peaks which correspond to a single event as observed at each station. This gives us 6 time delays from the 6 pairs of stations (each remote site compared to the arrival at the central site). From this we have 6 equations and three unknowns. Therefore any 3 equations (or combination of three sites) gives us a solution of X,Y, Z for the source. However, due to the errors in timing and to the GDOPs, not all combinations necessarily give a good solution. We calculate the lightning location for each of the 20 combinations of three equations and filter out the sites with bad GDOPs. The algorithm used is similar to the LDAR algorithm [4] except that we initially utilize all 20 combinations whereas LDAR uses the 2 combinations that have the best overall GDOPs if their solutions agree within 5%.

A typical set of waveform data from this storm is shown in Figure 2. The seven panels show from bottom to top the signal from the central site (site 0) to site 6. Notice the sequence of distinct pulses that arrive at the different stations at different times. We use this time delay information and the known locations of the 7 sites to determine the 3-dimensional (X,Y,Z) location of the VHF noise source. For sources within approximately 15 km of the central site the accuracy is within 1% in X, and Y and 2% in Z. For events that occur within the baseline of the array, the uncertainty is on the order of 10s of meters.

For the interval shown in Figure 2 twelve pulses have been identified and their locations and absolute time differences determined. The locations are giving in Table 1. Note that pulses K and L are located 11.47 km apart while pulse pair H and I were located coincidentally in space (within the errors). The two pairs (KL) and (HI) are examples of two types of multiple signals we typically see in our 200 μs window. Pair KL is an example of apparently separate lightning flashes while HI are examples of multiple signals from the same flash as reported by [3, 5, 13]. We also occasionally trigger on Q-noise which [3, 14] attributes to recoil streamers preceding K-changes in intracloud lightning flashes. The properties of Q-noise is examined separately and is described in section 4.

2.3 Main Result

We examined the major amplitude pulses observed in ninety-eight 200 μs records obtained during the 30 April, 1996, winter thunderstorm. For each set of pulses observed at all 7 sites we calculated its 3-dimensional location relative to the central observing site, the relative time delay between it and any subsequent pulses, the amplitude, the absolute time of the pulse, and the apparent propagation velocity between each possible combination of pulse pairs. On average we identified 2.31 VHF lightning discharges per record. As seen in Figure 2 however, it should be noted that there is often many other pulses observed that were not identified due to changing amplitude of the signal between stations, proximity to other pulses, presence of Q-noise, or having the signal arrive prior to opening or after the closing of the 200 μs window.

Figure 3 shows a histogram of the number of 200 μs records that contained 1, 2, 3, or more separate lightning signals within the record. Most records contained multiple signals but from the same source, though 42% of the records contained signals coming from well separated sources.

We have found that it is common to observe multiple lightning discharge VHF signals from well separated (2-50 km) sources within several 10s of μs of each other. We present these results as evidence of simultaneous lightning in a winter multicell thunderstorm. The natural question that arises from these observations is if these lightning discharges are dependent or independent of one another. Mazur [8] demonstrated that the interdependence hypothesis fails for lightning flashes that begin within about 200 ms of each other and are separated by at least 1 km to the 5% confidence level. Because of our non-continuous records we cannot uniquely determine the start of the lightning flash (i.e., we don't know if we triggered at the first pulse of the flash or somewhere in the middle). Therefore we cannot directly extend Mazur's results to our data. However we do demonstrate that multiple flashes do often occur simultaneously in time over extended distances.

The next question that arises is if they are dependent, what is the mechanism of their relationship? We suggest two possibilities; (1) as suggested by [8], an EMP is launched from one EAC to another changing the electric field configuration in such a way as to trigger the second lightning discharge, and (2) a extra-terrestrial source such as a cosmic ray shower passing through two widely separated EACs generating new ionization trails which leads to lightning discharges.

3. GROUND OBSERVATIONS OF TIPPs

TIPPs were originally observed from space using a broadband VHF radio receiver on the Alexis satellite [6]. They are characterized by a pair of dispersed (in frequency) signals separated from one another by 4 to 100 μs (with a median of 50 μs). Their VHF source power is estimated to be considerably stronger than typical lightning discharges (about 100 kW compared to the 1-1000 W for typical lightning). Though the source mechanism of the signals could not be determined it was suggested they came from thunderstorms and perhaps were related to sprites, jets, elves, or terrestrial gamma-ray bursts observed in the upper atmosphere. In observations of close lightning (within 15 km) there are multitude of pulses and Q noise trains within a 200 μs window (see Figure 2). However, as the thunderstorm moves away from the LDAR system the number of pulses (particularly Q noise pulses) rapidly diminish. This suggests that Q noise maybe an electrostatic process that falls off as the inverse cube of the distance. This is in contrast to EM radiation signals whose fields fall off as 1/R. (However, this fall off with distance may be due to the inherent relative weakness of Q-noise compared to pulses). For lightning far away from the system several examples of large amplitude, pulse pair signals have been observed. The characteristics of the pulse pairs such as pulse duration, and inter-pulse timing are identical for those found for TIPPs. However, a distribution of the source power of these signals show that they are considerably weaker than those estimated for TIPPs. Despite this difference, we suggest that TIPPs are just radio observations of very energetic pulse paired lightning. The open question that remains is what lightning process occurs in pairs?

4. 3-D MAPPING OF VERY FAST INTRACLOUD RECOIL STREAMERS

Recoil streamers associated with ground return strokes have been found to have the highest propagation velocity of any lightning phenomena typically exceeding one-third the speed of light [9]. The TIPPs system offers the first 3 dimensional velocity information of these events since earlier estimates were made photographically or with interferometers which could only make 2D measurements. We found that recoil streamers travel at approximately 2 x 10^8 m/s and travel several kilometers at a time with no marked stepping. This phenomena has been observed by [3] using a VHF DTOA system and [15] using VHF interferometric techniques. However, the former identified this phenomena with Q-noise trains. We found that this phenomena has both Q-noise and pulse waveforms. In addition, we observed Q-noise pulses of <10 μs duration whereas in a histogram of 310 Q-noise durations [3] demonstrated that he found none of that short a duration (though in one of his examples he presents a 7 μs long Q-noise burst). We were able to map the propagation of several of these recoil streamers over many kilometers and found that the apparent velocity between pulses remained fairly constant along a single path.

5. CALIBRATION AND PROGRAMMING

This section describes the miscellaneous tasks that were completed. The WVWSSTRXYZL program was commented and debugged. The jitter (a measure of the uncertainty) was changed to the standard deviation of the X, Y, and Z values for the different antenna combinations used in the solution. A Grid Search/Linear Least Squares algorithm was developed and compared to the "LDAR" method. It was found that the LDAR solutions were equal to this more computationally intensive method using calibration data. New K-factors were determined and are listed in the WVWSSTRXYZL program. A calibration power curve for Site 0 was made to determine the absolute electric field amplitudes for the TIPPs study. It was found that the relationship between counts and power followed the following linear relation

$$\text{dB(above a microvolt)} = (\text{count} + 426.71)/72.165 \quad (1)$$

The antenna response pattern changes with elevation angle and was estimated to follow the following linear relationship from 30 to 0 degrees

$$\text{dB} = [30\text{-elevation angle}] \times (0.40) \quad (2)$$

or 11.87 dB fall off from 30 to 0 degrees. The antenna response is from 0-1 dBi from 90 to 30 degrees.

6. ACKNOWLEDGMENTS

I would like to thank Carl Lennon for being an excellent mentor, colleague, and host. The LDAR system he has developed has made and will continue to make important contributions to the field of lightning studies. Brent Goode has been an excellent summer research assistant and I look forward to working with him on completing the studies next fall. The KSC NASA/ASEE staff have made the summer faculty fellowship program a intellectually rewarding experience and I wish them continued success.

7. REFERENCES

[1] Lennon, C. L., LDAR-A new lightning detection and ranging system, *EOS*, AGU, 56(12), 991, 1975.
[2] Oetzel and Pierce, VHF technique for locating lightning, *Radio Sci., 4,* 199, 1969.
[3] Proctor, D. E., VHF radio pictures of cloud flashes, *J. Geophys. Res., 86,* 4041-4171, 1981.
[4] Poehler, H.A., An accuracy analysis of the LDAR system, NASA Technical Report FEC-7146, 1977.
[5] Maier, L., C. Lennon, T. Britt, and S. Schaefer, Lightning detection and ranging (LDAR) system performance analysis, Proc. Intn'l. Conf. Cloud Phys., Dallas, TX, paper 8.9, Amer. Meteorol. Soc., Boston, MA., 1995.
[6] Massey, R.S., and D.N. Holden, Phenomenology of Trans-Ionospheric Pulse Pairs, *J. Geophys. Res.,* 1995.
[7] Vonnegut, B., O.H. Vaughan, Jr., M. Brook and P. Krehbiel, Mesoscale observations of lightning from Space Shuttle, NASA Technical Memorandum 86451, 1984.
[8] Mazur, V., Associated lightning discharges, *Geophys. Res. Lett., 9,* 1227-1230, 1982.
[9] Uman, M. A., *The Lightning Discharge,* Academic Press, New York, 1987.
[10] Bracewell, R.N., The Fourier Transform and its Application, McGraw-Hill, New York, 1986.
[11] Kitagawa, N., and M. Brook, A comparison of intracloud and cloud-to-ground lightning discharges, *J. Geophys. Res., 65,* 1189-1201, 1960.
[12] Weidman, C.D., and E.P. Krider, The radiation field wave forms produced by intracloud lightning discharge processes, *J. Geophys. Res., 84,* 3159-3164, 1979.

[13] Rustan, P.L., M.A. Uman, D.G. Childers, and W.H. Beasley, Lightning source locations from VHF radiation data for a flash at Kennedy Space Center, *J. Geophys. Res.*, *85*, 4893-4903, 1980.
[14] Proctor, D. E., R. Uytenbogaardt, and B.M Meredith, VHF radio pictures of lightning flashes to ground, *J. Geophys. Res.*, *93*, 12683-12727, 1988.
[15] Shao, X.M., P.R. Krehbiel, R.J. Thomas, and W. Rison, Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*, 2749, 1995.

Table 1. The locations of the pulses identified in Figure 2.

Event	x (km)	y (km)	z (km)
A	-6.464	8.845	6.905
B	-7.563	9.945	6.034
C	-8.545	8.356	6.746
D	-7.868	7.452	7.666
E	-7.081	5.935	4.460
F	-4.369	6.268	7.483
G	-4.401	6.310	7.650
H	-6.403	8.906	7.935
I	-6.656	9.140	7.132
J	-6.447	8.891	7.033
K	-11.620	15.084	15.188

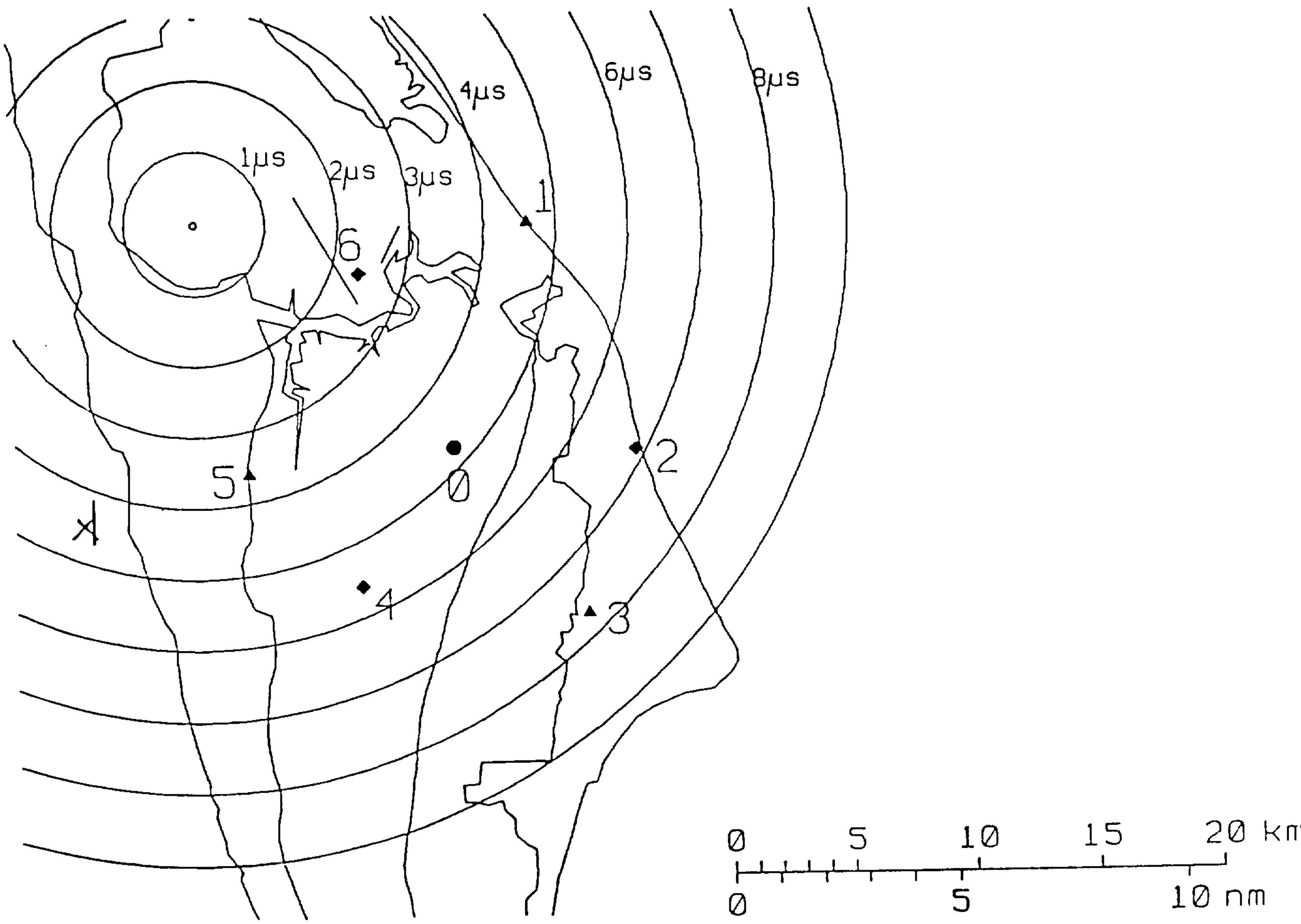

Figure 1. The locations of the seven LDAR sites on KSC and the location of the EMP as it propagates out from a example lightning pulse.

Figure 2. An example LDAR "TIPPs" waveform plot. The plot contains 200 μs of data and shows the data from the central site (bottom) through the 6th remote site.

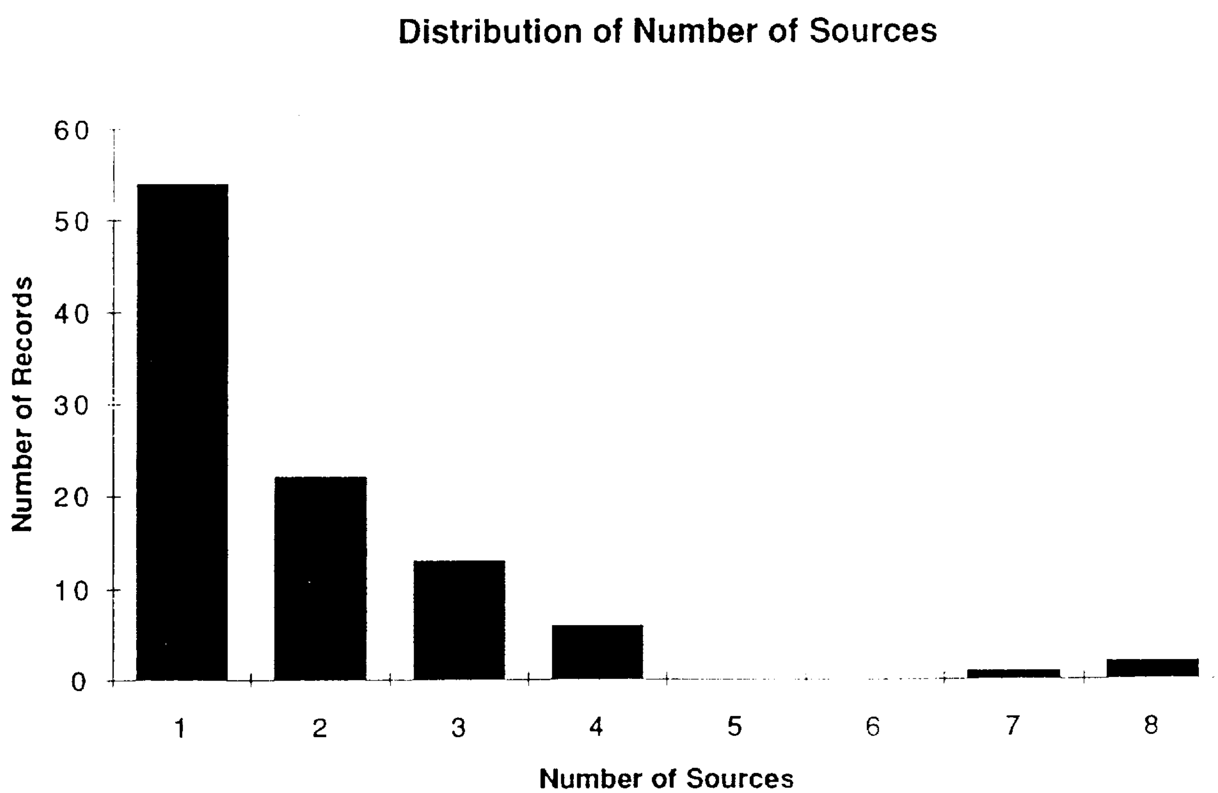

Figure 3. A histogram showing the distribution of records that contained multiple pulses.