Correlated Measurements of UHF Radar Signatures, RF Radiation, and Electric Field Changes from Lightning

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ABSTRACT

During Storm Hazards - 82, simultaneous measurements were made of radar echoes, fast and slow field changes and RF radiation from lightning near the Wallops Flight Facility. RF radiation and radar echoes were also obtained during periods when the NASA F106 research aircraft was struck by lightning. These data are presently being used to better understand the electrical processes which occur during strikes to the aircraft. Preliminary conclusions based on data obtained in 1982 verify that the events recorded aboard the aircraft occurred during lightning but also indicate that they occur with surprising frequency very early in the flash.

DURING THE SUMMER, 1982, simultaneous measurements of radar echoes and electromagnetic radiation from lightning were made at the Wallops Flight Facility (WFF), Wallops Island, Virginia. These measurements were part of the Storm Hazards experiment. The electromagnetic fields were measured with fast and slow field change systems and also with radio receivers tuned to several frequencies between 3 and 300 MHz, and the radar measurements were made using the very high resolution UHF radar maintained at the Wallops Flight Facility. Measurements were made to support flight experiments with the NASA F106 research aircraft, and data were collected during several storms during which the aircraft was struck by lightning. Data were also obtained during local thunderstorms not perturbed by the aircraft. The objective of these measurements were to aid in the interpretation of data collected by the F106 and also to learn more about the physics of lightning.

During the Storm Hazards experiment in 1982, electromagnetic radiation was obtained during 45 "strikes" to the aircraft and correlated radiation and radar echoes were obtained for more than 30 events. These cases indicate that the data obtained by the aircraft occurred during lightning discharges and that the events recorded on the aircraft tend to occur quite early in the flash.

INSTRUMENTATION

The electric field change systems employed in these measurements are broad bandwidth devices designed to record changes that occur in the electric field at the ground during a lightning flash. They were based on a design by Krider [1]* and consisted of flat plate antennas followed by an integrator which compensates for the capacitive response of the antenna and also provides gain [1,2]. The integration time constant is chosen to be long compared to the time scale of events of interest. Two systems, similar except for the time constant, were used. The time constant for the "slow" electric field change system was about 1 second and about 1 millisecond for the "fast" field change system. The slow electric field change system has a frequency response from near d.c. to a few kilohertz and measures the quasi-static electric fields at the ground due to changes in charge in the cloud [2]. The fast electric field change system has a frequency response from near a kilohertz to several MHz and is designed to record radiation from the sharp transients that occur during lightning events such as return strokes and stepped leaders. The signal from this system normally is recorded with a high-speed digital sample and hold device (Biomation Model 8100 waveform recorder) capable of sampling at selectable rates up to 10^8 samples/second and storing 2000 samples per record.

At frequencies above a few MHz, radiation was monitored using d.c. coupled A.M. radio receivers. Measurements at 3 MHz and 30 MHz were made using a fixed tuned receiver developed for lightning research at the Georgia Institute of Technology [3]. These receivers were used with vertical whip antennas mounted on the ground. At frequencies between 30 MHz and 300 MHz the radiation from lightning was recorded using commercially available radio receivers (Watkins Johnson models WJ-997 and WJ 8730) which were modified to provide d.c. coupled output. Disk-cone antennas were used at these frequencies. These receiving systems were designed to operate at a bandwidth of 300 kHz.

The electronics for both the RF receivers and the electric field change systems were housed in the Spandar Radar Facility at the Wallops Flight Facility and the antennas were mounted a few hundred feet from the building on the flat grassy lawn between Spandar and the UHF radar. A pair of flat plate antennas were also mounted on the roof of the Spandar Facility and were generally used to obtain fast field changes.

The radar used in these studies to detect the ionized channels created by lightning discharges is a UHF radar which operates at 430 MHz and has an antenna 60 feet in diameter. The radar transmits a pulse 1 μs long once every 3 ms. The antenna beam at this frequency is about 2.5 degrees wide and the range resolution with this pulse is 150 meters. At 100 km this radar scatters from a resolution volume about 4 km high, 4 km wide and 150 meters deep (range). The radar could be slaved to a C-band tracking radar which followed the aircraft during flights. Thus, the aircraft could be continually kept in the resolution volume of the radar as it moved through the storm which allowed the radar to see lightning channels which developed near the aircraft.

Data from all instruments were recorded on a strip chart recorder and also on analogue magnetic tape using an Ampex model PR-2200 instrumentation tape recorder. The data recorded on tape included the signals from the fast and slow field change systems, the output from the radio receivers, and the video output from the radar. In addition, to obtain more bandwidth, the fast field changes were recorded digitally using a Biomation 8100 waveform recorder. The waveform recorder was operated in its pretrigger mode in which the memory stores data before and after the triggering

*Numbers in parentheses designate References at end of paper.

signal, and the system was set to trigger when the input exceeded a preset threshold. When the waveform recorder was triggered, a pulse was sent to the magnetic tape and strip chart to aid in correlating these events with the other data. After a trigger digital data stored in the Biomation memory were dumped rapidly into a buffer and the waveform recorder was re-armed. The time required to complete this cycle was less than 2 ms and up to 10 of the 2000 word memory units could be stored in the buffer. Once the buffer was full, or the lightning flash ended, the buffer was transferred to digital tape. An internal clock kept track of the time between triggers and allowed the time between events to be determined with an accuracy of better than 10 μs. The radar data were recorded on magnetic tape and on the strip chart, but for purposes of processing, it was also recorded on a modified video cassette recorder with about 500 kHz bandwidth. The radar video was recorded on the cassette for each pulse plus the time code and a reference pulse which was used when playing the data back for display on an oscilloscope. The data to be presented here were obtained by making video TV images from the oscilloscope display. In doing so, 30 radar pulses were averaged to form one video frame.

DATA

Figures 1-3 show data collected during a lightning flash which occurred at about (23 hrs 17 min 27 sec) on August 17, 1982, during a storm close to the Wallops Flight Facility. Figure 1 is a strip chart summary of all the data collected for this flash. It shows radiation at 3, 30, and 139 MHz, the fast and slow field changes, the pulses from the digital waveform recorder and the raw radar data. The slow field change for this flash consists of a series of abrupt downward steps typical of cloud-to-ground flashes [2]. Three steps can be seen on close examination, suggesting a cloud-to-ground flash with three return strokes. This is corroborated by the fast field change system which produced three distinct pulses. The RF radiation is quite strong at each frequency during this flash with peaks clearly evident during the return stroke phase of the flash, although strong radiation peaks also occur before and after this portion of the flash. Although strong RF radiation during return strokes is to be expected [4], it is not uncommon to find strong RF radiation in other portions of the flash [5], and in fact, there is evidence to suggest that the strongest RF radiation is associated with intra-cloud processes and not return strokes [6].

As mentioned above, the fast field changes were also recorded using the Biomation waveform recorder and digital interface described in the preceding sections. The waveform recorder was set to trigger on large negative pulses for this experiment and to take data at a rate of .05 μs/sample. The waveform recorder was triggered four times during this flash. Three of these coincide with the pulses recorded on the strip chart from the fast field change system. The other event appears to have occurred early, before the first return stroke. The waveforms recorded during these four triggers are shown in Figure 2. The Biomation recorded 100 μs of data each time it triggered (2000 samples x .05 μs/sample). These data were plotted on a strip chart from the digital tape to obtain Figure 2. Although the amplitude in V/m is not accurately known for these radiation fields, the relative amplitude between events is correctly displayed in the figure. Also, although the time is only correct to the synchronization accuracy of the time code generator (about 50 μs), the relative time between events is accurate to better than 10 μs. The first event in Figure 2 (23 hrs 17 min 26.841 sec) is a sequence of regular pulses typical of radiation from stepped leaders preceding first return strokes [1,7]. The same periodic train of pulses can also be seen preceding the second event in Figure 2 (23 hrs 17 min 26.890 sec). This second event has a shape which is typical of radiation from first return strokes [8,9,10,11]. It possesses an initial ramp-like portion followed by a sharp rise to peak and then an irregular decay back toward zero which is typical of first return strokes. The third event (23 hrs 17 min 26.946 sec) is something of a surprise because it also has the characteristics of a first return stroke, whereas one would have expected to have seen a waveform more like the last one. As will be shown below, the radar data during the early phase of this flash indicates ionized channels in two different locations and developing about 60 ms apart, suggesting that in this flash the second return stroke may not have followed the path of the previous stroke but ionized its own channel. The last event is small but has a shape commonly encountered in subsequent return strokes [8,11].

Figure 3 is a sequence of photographs showing the radar signal received during this flash. Each photograph represents the average of 30 radar returns. They are photographs of the video (TV) frames made from an oscilloscope display of the data on the cassette recorder. The vertical axis is intensity of the scattered signal (power) and the horizontal axis is distance in kilometers. The first frame

(23 hrs 17 min 26.87 sec) shows the radar return prior to the beginning of the lightning flash. The second frame shows the radar return just after the flash has begun (i.e., the first evidence of an echo appears). The spike to the right of center in the photograph is from the lightning channel. One frame (photograph) was made every 30 ms and the times on the figures indicate the time when the data was recorded to within about 30 ms. The frames shown have been selected from a great many to illustrate the stages that the echo went through in the course of this flash. There were several frames of data between the first photograph (23 hrs 17 min 26.87 sec) and the second (23 hrs 17 min 26.94 sec) shown here. The echo was first discernable at about (23 hrs 17 min 26.90 sec) but the photograph shown here (two frames later) was chosen for display because it shows the echo more clearly. About two frames (60 ms) after the first echo appears, a second echo appeared in a different location and is shown in its fully mature form in the frame made at (23 hrs 17 min 27.05 sec). The fast field changes also indicate about 60 ms between the first two return strokes (Figure 2). This second echo persists for several tenths of a second broadening and changing shape somewhat, whereas the first echo disappears quite soon after it appeared. Toward the end of the flash, a third echo (illustrated by the frame at 23 hrs 17 min 27.33 sec) appeared. It occurs well after the return stroke phase of this flash is over and coincides well with the large burst of RF radiation evident in Figure 1 in the late stages of the flash. This third echo is short-lived, and has disappeared by about (23 hrs 17 min 27.43 sec). All evidence of ionized channels eventually ends at (23 hrs 17 min 27.60 sec) about 640 ms after the flash began. This duration corresponds well with the duration of the flash as determined from the record of RF radiation in Figure 1. After the flash is over, the radar return again has the form shown in the first frame in Figure 3.

The combination of radar echoes, RF radiation, and electric field changes paint a clearer picture of this flash than either set of data could provide alone. This flash appears to have been a cloud-to-ground discharge with three return strokes, the first two following their own (different) paths, and the third being a subsequent stroke most likely following the path of the second return stroke. In addition, toward the end of this flash, what appears to be a strong intra-cloud event took place somewhat displaced from either return stroke.

The summer of 1982 was the first time that coordinated measurements of UHF radar echoes and radiation fields from lightning had been tried at WFF, and all instrumentation problems weren't solved until late in the summer. However, several good examples were obtained during storms on August 11 and August 17 which are now being analyzed. One objective of this analysis is to compare cloud-to-ground and intra-cloud flashes to see if quantitative differences in their echo structure can be identified and we hope to report results of these studies in the near future.

DATA COORDINATED WITH AIRCRAFT

During the summer of 1982, data was also collected during storms penetrated by the NASA F106 research aircraft. Unfortunately, most of these storms were too far from the Wallops Flight Facility to obtain slow electric field changes, and equipment problems with one system or the other prevented simultaneous records of fast field changes and radar echoes to be obtained at times when the aircraft was struck by lightning. However, simultaneous records of RF radiation and radar echoes were obtained on several flights and yielded good data on occasions when the aircraft reported a "strike". This data is described below.

Our objective in this initial study was to examine times when the instrumentation on the aircraft was triggered to see if, in fact, these events corresponded to the occurrence of lightning and to see if this lightning was in any way unusual. The trigger times of the modified Biomation waveform recorder aboard the aircraft were selected as the definition of the event. Then the records of RF radiation and radar echoes were examined at these times. Figure 4 is an example of radiation received at 3 MHz during flight #34 on July 30, 1983. About 40 seconds of data is shown near (19 hrs 55 min 28.75 sec) when the aircraft reported a Biomation trigger. The trigger occurred at the very beginning of the strong flash shown in the middle of the figure. The fact that the aircraft trigger occurred early in the flash was typical of the RF data collected during 1982 [12]. Figure 5 is a histogram made from 45 events which correlated with RF radiation at WFF. It shows the location of the aircraft events measured from the beginning of the flash and plotted as a percentage of the duration of the flash. The beginning and duration were determined from the RF radiation at 3 MHz. It is clear from the figure that the Biomation triggers tended to occur early on the flash. It was most probable to find the aircraft event in the first 10-20% of the flash and the mean was about 29%.

The UHF radar was also operating on July 30 and recorded an echo during the event shown in Figure 4. The first four frames of radar data for this flash are shown in Figure 6. The sharp pulse in the first frame (19 hrs 55 min

19.7 sec) is the radar return scattered from the aircraft just before the flash began. In the second frame (19 hrs 55 min 29.8 sec) the outline of an echo from lightning can be seen superimposed on the return from the aircraft. This echo becomes more distinct and grows in amplitude and spatially in the succeeding frames. The interesting feature of the radar echo is that it appears to begin right at the location of the aircraft. This was not always the case as is evident in Figure 7 which shows the first four frames of the radar return during flight #37 on August 6, 1982, during an event at about near (19 hrs 50 min 04 sec). In this case, the radar indicates a channel which developed several kilometers from the aircraft and then grew in spatial extent to eventually include the resolution volume in which the aircraft was located. Of more than 35 events recorded during the summer of 1982, (i.e. aircraft events during which there were both RF radiation and radar echoes) less than 10% were nearby flashes of the form shown in Figure 7. The overwhelming majority had echo patterns such as that shown in Figure 6.

A final example of data recorded during the aircraft flights is shown in Figures 8 and 9 for a flash recorded at about (22 hrs 34 min 48 sec) on August 9, 1982, during flight #40. The aircraft recorded an event at (22 hrs 34 min 47.86 sec) and Figure 8 shows the RF data at 3 MHz and 30 MHz recorded at this time as well as the unprocessed radar video signal. This example was obtained from magnetic tape by playing the data back at slow tape speed to obtain very high time resolution. This was done with most events to clearly show the detail of the radiation signal. The radar echo began at about (22 hrs 34 min 47.67 sec) for this flash and persisted for about 550 ms until about (22 hrs 34 min 48.22 sec). The beginning of the echo is apparently associated with the large pulse of RF radiation occurring in the center of the flash. On several occasions, the beginning of the radar echo was associated with large pulses in the RF radiation. This flash is somewhat unusual in that the radar echo and aircraft event occur in the middle of the flash. It is also unusual in that the duration of the RF radiation is quite long, about 1.5 seconds. There is a strong possibility that this is not one flash, but rather two overlapping flashes (the RF system is omni-directional and therefore receives radiation from all storms within range of the system at the same time). For example, in 18 cases of good quality, high time resolution data studied so far, the RF signal divided naturally into two quite distinct classes: flashes whose duration was less than one second (the average was .67 sec), and those whose duration was greater than one second (average = 1.85 seconds). Most examples (67%) were in the first category. The length of the flashes in the second category strongly suggests overlapping flashes. The interesting feature of these two classes is that in every one of the former (short flashes) the radar echo and aircraft event occurred right at the very beginning of the flash, on the average within 70 ms of the first noticeable RF radiation. In the second class (very long flashes) the radar echo and aircraft event occurred on the average 0.60 seconds from the beginning of the RF radiation. The implication is that the events recorded aboard the aircraft occur toward the beginning of the flash with even more frequency than indicated in Figure 5. This is so because the histogram was obtained using all flashes, including those of the second class, and these may very well have been overlapping flashes with the aircraft event actually occurring at the beginning of one them.

CONCLUSION

The combination of radar echoes from lightning channels and the electric field changes and radiation at radio frequencies from the flash promise to offer improved insight into the structure of lightning. These data are presently being used to help understand the lightning which occurs during strikes to the NASA F106 research aircraft as part of Storm Hazards. Preliminary conclusions based on data obtained during 1982 verify that the events recorded on the airplane occurred during lightning flashes, but also indicates that they occur with surprising frequency very early in the flash.

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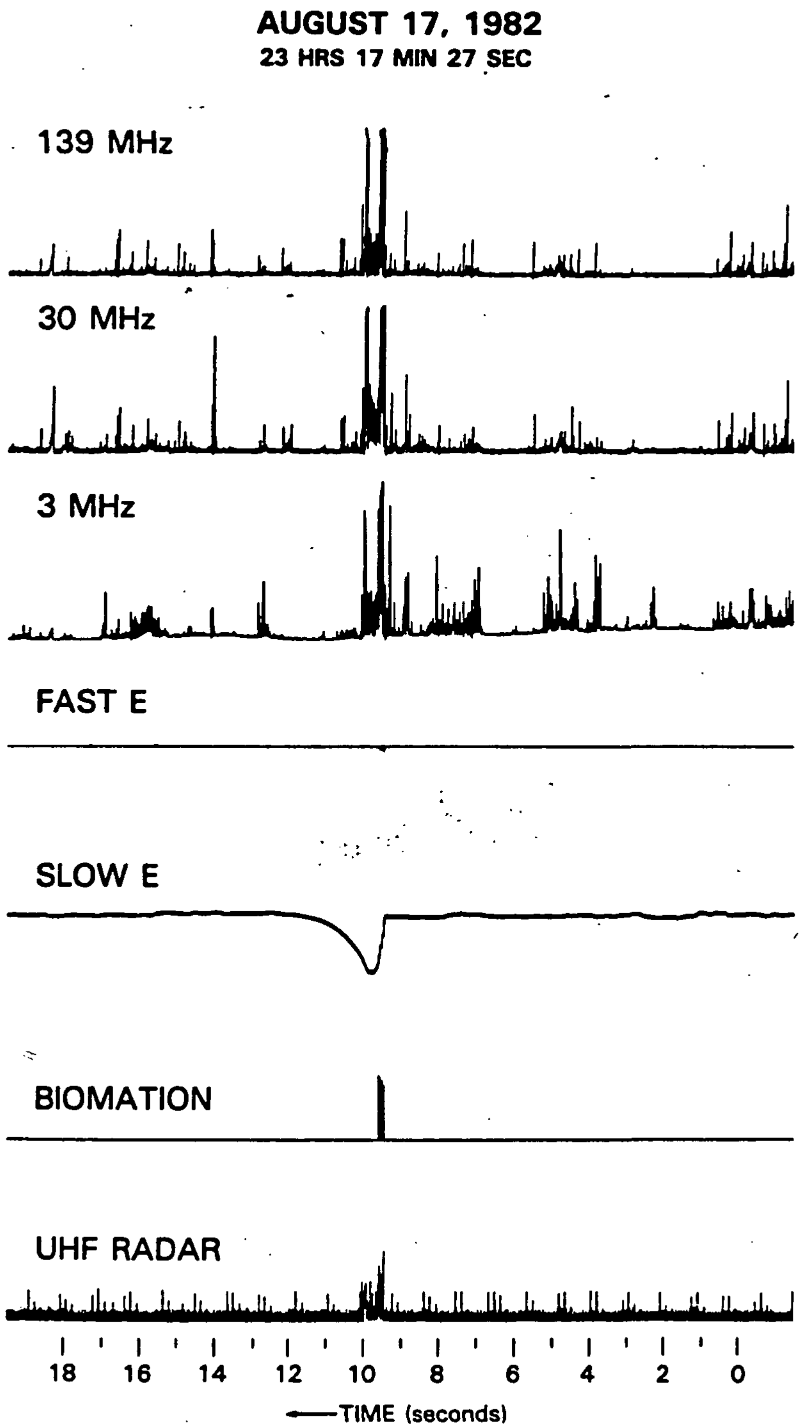

Fig. 1 - Strip chart record showing data collected on August 17, 1982, at about (28 hrs 17 min 27 sec) during a storm close to the Wallops Flight Facility, Wallops Island, VA

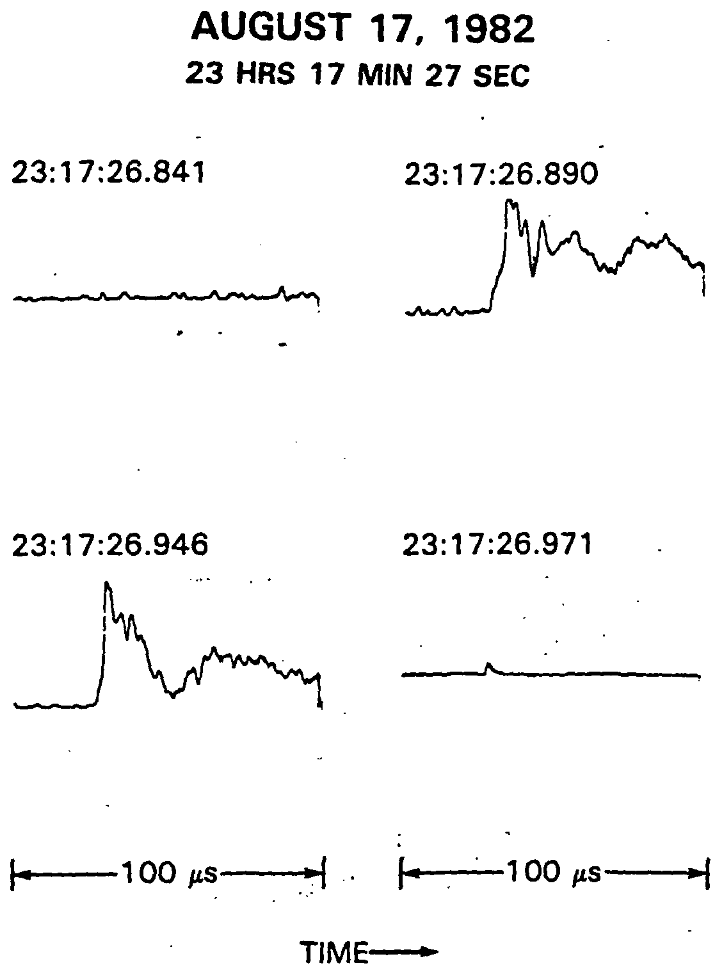

Fig. 2 - Fast electric field changes recorded on the Biomation waveform recorder on August 17, 1982 during the lightning flash shown in Figure 1. The Biomation sampling rate was .05 μs/sample

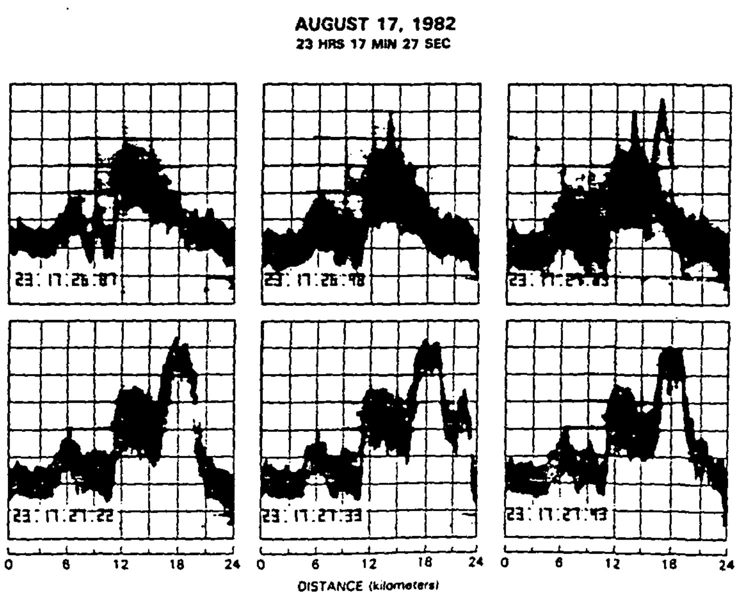

Fig. 3 - Representative frames showing UHF radar data obtained on August 17, 1982, for the flash shown in Figure 1

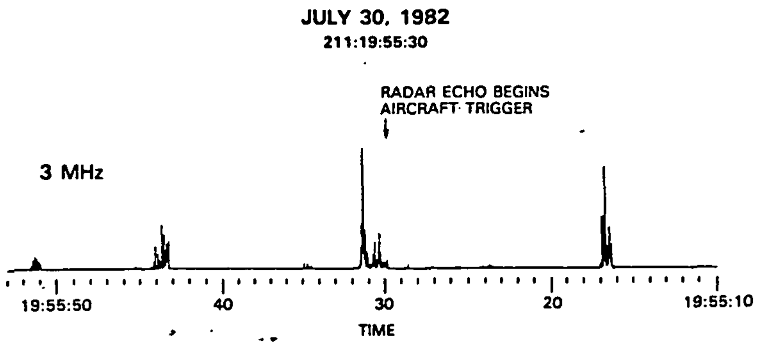

Fig. 4 - A strip chart record of radiation at 3 MHz recorded on July 30, 1983, during flight #34. The aircraft recorded an event at (19 hrs 55 min 29.75 sec)

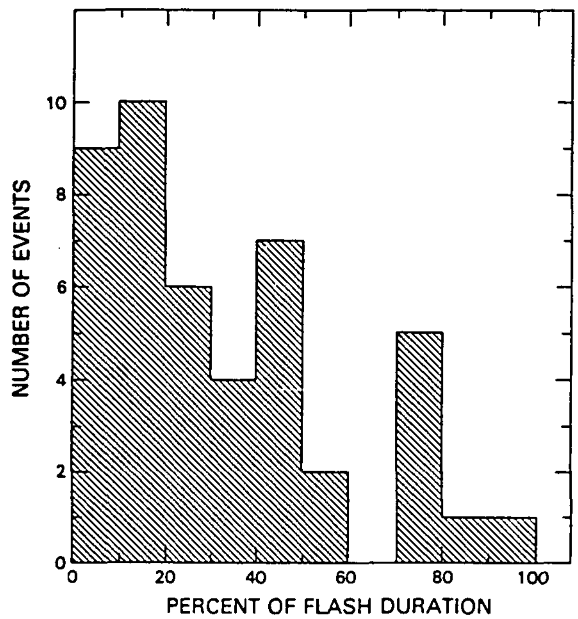

Fig. 5 - Histogram showing the occurrence of events recorded aboard the aircraft measured from the beginning of the lightning flash and plotted as a percentage of the duration of the flash. Flash duration was determined from records of RF radiation at 3 MHz

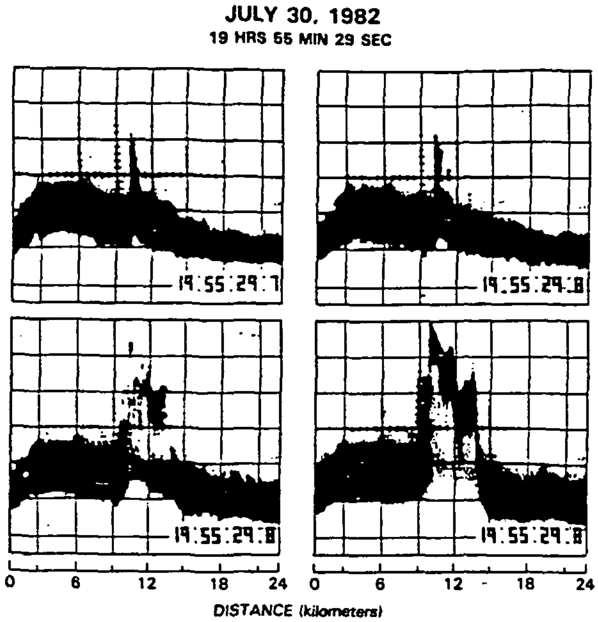

Fig. 6 - The first four frames of UHF radar data at the beginning of the flash on July 30, 1982, shown in Figure 4

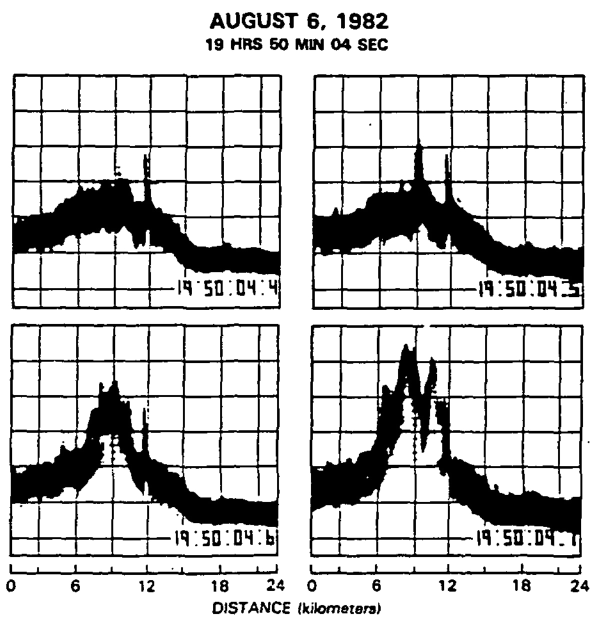

Fig. 7 - The first four frames of UHF radar data for a flash on August 6, 1982, during flight #37 which started near the aircraft and then spread to include it

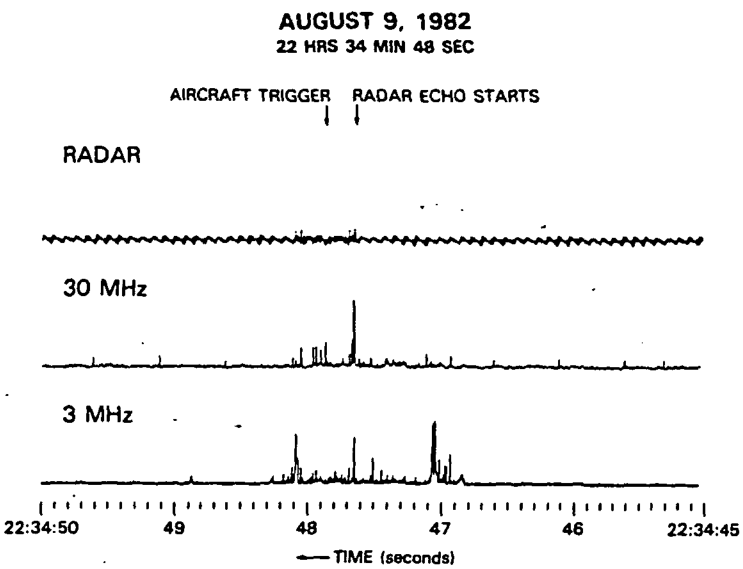

Fig. 8 - Example of RF radiation and UHF radar echo data for a flash on August 9, 1982, during flight #40. The aircraft reported an event at (22 hrs 34 min 47.80 sec). The UHF radar echo began at (22 hrs 34 min 47.66 sec)

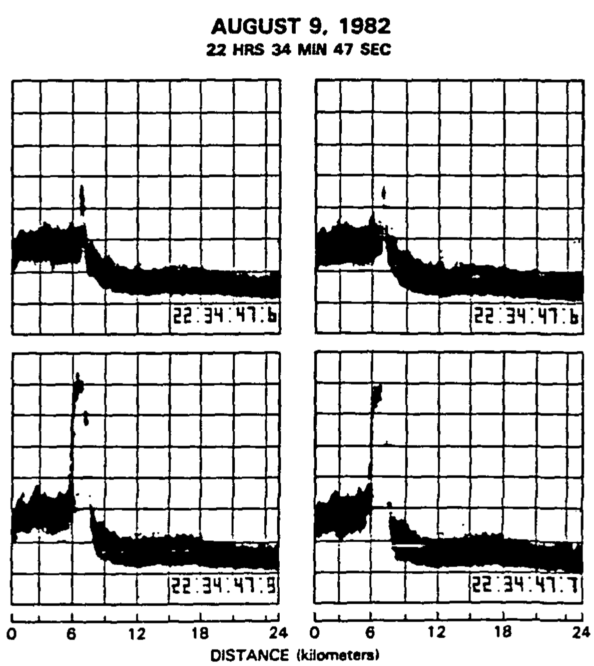

Fig. 9 - The first four frames of processed UHF radar data for the lightning flash on August 9, 1982, shown in Figure 8