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THUNDERSTORM OBSERVATIONS FROM SPACE SHUTTLE

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16. ABSTRACT

This report covers the results of the Nighttime/Daytime Optical Survey of Lightning (NOSL) experiments done on the STS-2 and STS-4 flights. During these two flights of the Space Shuttle Columbia, the astronaut teams of J. Engle and R. Truly, and K. Mattingly II and H. Hartsfield took motion pictures of thunderstorms with a 16 mm cine camera. Film taken during daylight showed interesting thunderstorm cloud formations, where individual frames taken tens of seconds apart, when viewed as stereo pairs, provided information on the three-dimensional structure of the cloud systems. Film taken at night showed clouds illuminated by lightning with discharges that propagated horizontally at speeds of up to 10^5 m/sec^{-1} and extended for distances on the order of 60 km or more.

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Thunderstorm Observations from Space Shuttle

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ABSTRACT

During the second and fourth flights of the Space Shuttle Columbia, the astronaut teams of J. Engle and R. Truly, and K. Mattingly II and H. Hartsfield took motion pictures of thunderstorms with a 16 mm cine camera. Film taken during the day showed interesting thunderstorm cloud formations. Individual frames taken tens of seconds apart when viewed as stereo pairs provided information on the three-dimensional structure of the cloud systems. Film taken at night showed clouds illuminated by lightning with discharges that propagated horizontally at speeds up to 10^5 m sec^{-1} and extended for distances of the order of 60 km or more.

INTRODUCTION

Data from unmanned instruments flown in the space program have already made significant contributions to the understanding of atmospheric electricity. Orbiting satellites have provided new information on the frequency of lightning discharges as a function of the time of day, year, and location on the earth's surface (Sparrow and Ney, 1971; Turman, 1978; Radio Research Laboratories, Japan, 1981; Orville, 1981). The Pioneer and Voyager programs have revealed that lightning discharges are not peculiar to our atmosphere, but also occur on Venus and Jupiter (Taylor, et al., 1979; Cook, et al., 1979; Ksanfomaliti, 1980; Scarf, et al., 1980).

It is evident from eyewitness accounts of astronauts (Cooper, 1976) that the view from an orbiting satellite gives a new perspective on the details of lightning discharges. Here is an example: "Looking down through moonlit clouds, Conrad could see hundreds of grass fires surrounding what he took to be villages in Africa. On all sides, lightning illuminated patches of thunderheads. He thought of his return from the moon in November of 1969, when from a distance of twenty-five thousand miles he had seen lightning flashes ripping up the entire nighttime side of the earth" (Cooper, 1976).

Here is another description by astronaut Gibson of lightning he saw over the Andes, "We've just been coming over, in the past five minutes, an extensive area of thunderstorms.....There seems to be some sort of a collective organization to the lightning strikes which occur over a wide area. When one goes off, two or three may go off simultaneously, or that one may turn out to trigger a whole lot of other ones all over a very wide area--five hundred thousand square miles, perhaps. The lightning flashes then will go off, numerous ones--ten, twenty, forty, fifty. It'd be calm again for about 1 to 2 seconds, then we'd get another period of--oh, maybe three, four, five maybe up to seven seconds or so of lightning going off in all locations. And it subsides; period of calm; then cycle through that again. A few things which impressed me here: One is the fact that they could go off simultaneously or near simultaneously over a large distance--sympathetic lightning bolts, if you will, analogous to sympathetic flares on the sun. And that we do get periods of calm between periods of very high activity. Some sort of collective phenomenon appears to be at work."

These observations, though surprising, are not entirely unexpected. It has been recognized from ground based radar and visual observations that lightning discharges can on occasion extend over distances as great as 100 km or more (Ligda, 1956; and Brook and Vonnegut, 1960). Furthermore, it has often been noted that lightning sometimes seems to occur almost simultaneously at locations that are separated by many kilometers (Mazur, 1982). However, these observations are greatly extended by the astronaut reports quoted above and others, such as that of Weitz (Vonnegut, 1979), who saw discharges two or three hundred km long over Africa. The new view from a satellite suggests that lightning events can be so extensive and highly organized that they deserve to be considered as a mesoscale meteorological phenomenon.

The foregoing descriptions raise interesting questions concerning the speed of propagation of long horizontal discharges and the temporal relationships between the occurrence of widely separated lightning events. In order to obtain quantitative data concerning these processes and to explore the potentialities of thunderstorm studies from low altitude orbiting satellites, it was proposed to the National Aeronatics and Space Administration that astronauts carry out further lightning observations during the early flights of the Space Shuttle program. Arrangements were made for a small, crew-operated experiment, which was called Night-time/Daytime Optical Survey of Lightning (NOSL). It was flown on the second flight of the Space Shuttle (STS-2) as part of the OSTA-1 payload (Taranik and Settle, 1981; Settle and Taranik, 1982) and on the fourth flight (STS-4). The experimental design and the results that were obtained are as follows.

OBSERVATIONAL EQUIPMENT

A hand-held cine camera was chosen as the primary device to be used by the astronauts for recording thunderstorms. Its purpose was to obtain permanent, quantitative photographic records of lightning events and the cloud systems producing them. Daytime motion pictures provide valuable records of the cloud structures in convective cloud systems. It is not to be expected, however, that photographs of thunderstorms by day could reveal lightning against the bright background of clouds illuminated by sunlight. Pictures obtained at night provide a record of the geometry, areal extent, rate of propagation, and duration of lightning discharges that can be used to make analyses of the mechanism and rate of growth of the dielectric breakdown process. If there is sufficient illumination from lightning or from moonlight, photographs at night can also give information on the character and extent of the cloud systems that are producing the lightning.

To supplement the records obtained on the photographic film, a photocell optical detection system was attached to the camera so that it viewed the same scene. This device, which consists of a Fresnel lens that forms an image on a photocell, converts optical transients produced by lightning into electric signals that are recorded on magnetic tape. The system is capable of recording lightning even against the bright background of a sunlit cloud because it responds only to the time rate of change of illumination and not to its unvarying component. It therefore readily records the optical impulses of lightning either by day or by night. Furthermore, in contrast to the cine camera whose shutter is open only 40 percent of the time during its operation, the photocell provides a continuous record of lightning activity. It has been found in observations from the ground and from aircraft that such optical pulses provide information on the occurrence of lightning and on characteristics of the electrical discharge (Griffiths and Vonnegut, 1975; Vonnegut and Passarelli, 1978; Brook, et al., 1980).

Initially it was planned to use a commercial super-8 mm sound cine camera. This provided a convenient, self-contained package capable not only of taking motion pictures, but also of recording the photocell data on the magnetic sound track of the film. However, because this camera had not been qualified for operation in the environment of the cabin of the Space Shuttle, a 16 mm data acquisition camera that had previously been space qualified was used instead. The 16 mm camera had no sound recording capability. Therefore, to fill this requirement, the pulses from the photocell optical system were recorded on one channel of a SONY stereo cassette tape recorder that had been space qualified and used in Skylab program. To synchronize the recorded impulses on the tape recorder with the 16 mm camera film, a synchronization signal from the camera shutter pulses was recorded on the other channel. The recorder was arranged so that before and after operating the camera, the astronauts could enter data on the time and place of the thunderstorm situation being photographed through a microphone attached to the camera and photocell assembly. The apparatus is shown in Figure 1.

The 16 mm camera and tape recorder system had two disadvantages. It was somewhat more unwieldy than the originally proposed 8 mm equipment, and analysis of the data required synchronization of the magnetic tape with the camera film. However, the 16 mm camera did have the advantage that it provided significantly better photographic images than were possible with the smaller super-8 format.

A reflex zoom lens having an aperture ranging from f/2.0 to f/16 and focal lengths ranging from 17 to 85 mm was used with the 16 mm camera. This provided a field of view ranging from 32^{o} X 24^{o} to 6^{o} X $4\text{-}1/2^{o}$, giving the crew the capability of photographing large-scale cloud systems or lightning discharges such as those described by previous astronauts or providing a more detailed view of smaller individual thunderstorms. The film used, QX824, similar to Ektachrome ASA64, was exposed at 24 frames per second. Daylight exposure was 1/500 sec at f/8, and at night 1/60 sec at f/2.

The fie'd of view of the photocell optical system was fixed at approximately 6^{o} and corresponded to that of the zoom lens in the telephoto position. The photocell therefore covered the entire field of view of the camera when the zoom lens was in the telephoto setting and only the central region of the field of view when it was in the wide angle setting.

A diffraction grating was provided by Richard E. Orville of the State University of New York at Albany to obtain spectral information on lightning discharges taking place on the dark side of the earth. The two-dimensional diffraction grating made with holographic techniques and having 500 lines per mm could be mounted in front of the camera lens at night or removed for daylight photography.

OPERATIONAL PROCEDURES

It is difficult to forecast when and where thunderstorms will occur during the flight of the Space Shuttle. Therefore, it was planned that the astronauts would take data with the equipment when thunderstorm and lightning targets of opportunity presented themselves, providing that this would not interfere with their scheduled activities. The only time in the crew activity plan specifically allotted for the thunderstorm observation experiment was 20 minutes at the beginning of the flight to unstow and assemble the apparatus and a similar period near the end of the flight to restow it before landing.

If an astronaut were free to spend his time observing atmospheric phenomena, there is little doubt that he could see and evaluate thunderstorm and lightning activity in far greater detail than is possible for someone using the data normally available to meteorologists on the ground. However, since both astronauts were heavily involved with other activities and could not keep looking out of the window, provision was made to notify them when they would pass over regions of strong convective activity that had the potential to produce lightning. During the course of the flight, a NOSL experiment team in the Payloads Operations Control Center with the help of the meteorological group at the Johnson Space Center, the atmospheric science team at Marshall Space Flight Center using the McIDAS (Man-computer Interactive Data Access System) system, and the USAF Global Weather Central group at Offutt Air Force Base in Omaha, Nebraska, monitored weather situations over the globe. When it appeared there might be time available in the crew's schedule to take pictures, they were notified of possible targets of opportunity through Space Shuttle Communicator (CAP COM) approximately one orbit (90 min) before the vehicle would be in a position for them to take data.

If one of the astronauts were available and a suitable target presented itself, he would first start the tape recorder, indicate the time, position, and character of the target through the microphone, and then turn on the camera. In daylight he would begin photography using the wide-angle lens setting to show the overall meteorological situation. He could then, if he desired, change to a normal or to a telephoto setting to show details of the thunderstorm's cloud structure.

Photography of lightning at night from the Space Shuttle was more difficult. It is impossible to predict when and where the lightning will occur, and there are no fixed lights or landmarks that can be used to position the camera. With a telephoto or even a normal lens, which have rather small fields of view, the chances of securing photographs are small unless the lightning is frequent or extends over a large area. As a consequence, all nocturnal lightning photography was carried out by using the wide angle setting of the lens and pointing the camera in the general direction of the most recent flashes. For some sequences, the astronaut would also place the grating on the lens to provide spectra.

To mark the end of each nocturnal photographic sequence, he would point the camera at a modulated light, such as a cathode ray tube on the instrument panel. This also provided a signal on the tape recording useful in synchronizing it with the film. Photography was continued so long as a suitable target was in the field of view, usually for a period of one or two minutes.

DAYTIME OBSERVATIONS

On the sunlit side of the earth, astronauts on both the second and the fourth flight of the Space Shuttle succeeded in obtaining beautiful photographs of convective storm systems. These pictures, taken through the full range of the zoom lens, show details that are much smaller than those resolvable from a geostationary satellite. The cloud structure is revealed in greatest detail when the sun approaches the horizon and casts shadows of the convective elements. It had been hoped it might be possible to follow convective motions through detailed examination of the photographs. However, this was not the case. Because any cloud scene can be photographed for only a minute or two and because the view of the clouds is constantly changing as the result of vehicle motion, it is difficult to identify small cloud features that can be used to establish convective motions.

The successive frames of the 16 mm camera showing the cloud structure as seen from different positions in space can be utilized for stereo viewing. When frames separated by 5 or 10 seconds are viewed as stereo pairs, they provide a three-dimensional view of the cloud structure that reveals details not apparent in the single frames. Although the orientation of the camera is not accurately known, it would be possible by photogrammetric analysis to secure semiquantitative data on the three-dimensional structure of the clouds. Daylight photographs of interesting storm cloud systems, such as that illustrated in Figure 2, were taken covering a two 2-minute interval during STS-2 in November 1981. During this brief period no pulses attributable to lightning were identified.

On STS-4, June 27-July 4, 1982, a total of 10.5 minutes of film was exposed during daylight, mostly of large storm systems 1,000 km or more from the spacecraft and a few smaller thunderstorms lying nearer. Only one pulse clearly identifiable as lightning because of its shape was recorded from the photocell optical system. This pulse is illustrated in Figure 3, and the cloud system that produced it in Figure 4.

NIGHTTIME OBSERVATIONS

The majority of the nocturnal lightning events can be readily recognized on the 16 mm photographic film. These are the bright areas, undoubtedly clouds illuminated by lightning, that repeatedly appear in about the same position on successive frames. The first pictures of lightning from the Space Shuttle were taken by astronaut Truly during the second Space Shuttle flight. As the Columbia passed over South Africa on 13 November 1981 at 20:18 GMT on orbit 20, he photographed several lightning discharges that were occurring at the rate of a few flashes per minute in a thunderstorm some distance away from the Space Shuttle's track. The images on the film were small, only about 0.1 mm in size.

The lightning events photographed by astronauts Mattingly and Hartsfield during the fourth flight of the Space Shuttle were larger in size and lasted for a longer time. The illuminated areas on the frames of the film were sometimes as big as 5 mm and continued to appear for as many as 40 frames of the film, corresponding to a time interval of almost 2 sec. This storm over the southern portion of Brazil, which was photographed on 28 June 1982 at 23:18-23:21 GMT on orbit 22 and on 29 June at 00:52-00:58 GMT on orbit 23 is illustrated in the McIDAS picture shown in Figure 5. Superimposed on this photograph are the tracks of the Columbia during orbits

22 and 23. The first 9 frames of one of the more spectacular of these lightning events, which initially developed into a Y-shaped pattern, is illustrated in Figure 6.

When a luminous area appears only on a single frame, as is sometimes the case, it is often quite small, no more than a few tenths of a millimeter in size. Then it is often difficult to be sure whether the small, bright area indicates lightning or whether it is one of the defects that occasionally can be found on the photographic film.

It is to be expected that images of stars, fires, or lights on the ground would sometimes appear, but none has yet been observed on film taken during the Space Shuttle flights. Mattingly and Hartsfield commented on impressive displays of electric lights in cities they saw at night over South America, but they took no photographs at this time.

Even when the camera is looking directly down at the closest part of the earth from its operating altitude, 260 km for STS-2 and 300 km for STS-4, the film and optical system with the wide-angle lens is incapable of resolving structures that are much smaller than several hundred meters. It appears that with the wide angle lens the camera will generally be incapable of resolving lightning channels, even when they are not obscured by clouds.

No clearly recognizable photocell optical signatures of lightning were recorded during the nighttime photography of lightning. This is not surprising, because few, if any, of the discharges occurred in the narrow 6^{o} field of view of the photocell in the center of the 32^{o} field of view of the wide angle camera lens. In future observations, it is suggested that the field of view of the photocell be increased to match that of the wide angle lens. This will increase the chances of recording the optical signatures of lightning by more than twenty fold.

Although the diffraction grating was used for some of the nighttime lightning photography carried out during STS-2 and STS-4, no lightning spectra were observed. Apparently none of the lightning discharges was of sufficient brightness to produce a spectrum with the lens and film system that was used.

There is wide variation in the appearance of the lightning images on the film. The discharges photographed on STS-2 were white. On STS-4 the colors ranged from orange or yellow to almost white for the brightly illuminated areas, while the color changed to deep red in the case of the more faint images. A few bright, white images were also observed on STS-4, but these appeared only on isolated single frames. Because none of them was associated with an illuminated area in a similar location on an adjacent frame, it is difficult to know whether or not they were the result of lightning. It is conceivable that these very small, very bright dots that were occasionally observed were the images of brief single lightning flashes taking place very near the upper part of the cloud, or in the clear air above it.

Caution must be exercised in the interpretation of the brightness and extent of the images on the film. Not only does the brightness, and hence the extent, of the images depend on the brightness, duration, and depth of the lightning in the cloud, but it also depends on other factors. With the 24 per second framing rate of the camera, the shutter is open for approximately 16 msec and then closed for the 26 msec interval during which the film is being transported. The brightness of the image on the film will depend greatly on the period in the lightning event during which the shutter is open. The brightness of the flash will be greatly attenuated if the shutter opens just as the electric discharge is ending. Individual lightning discharge events are often short in comparison with the 26 msec interval during which the shutter is closed. As a consequence, it is probable that a significant fraction of the lightning events taking place in the field of view of the camera are not recorded on the film.

There is uncertainty in establishing the dimensions of the images on the lightning photographs. Because the camera was held by hand, and because no features such as the limb of the earth are visible, the orientation and angle of view of the camera with respect to the earth are not known. All that can be done in analyzing the pictures is to establish a minimum scale for the photographs on the assumption that the camera is looking directly downward. If this were the case, then the scale of distance would be correct in both dimensions. The camera will probably seldom be looking vertically down. As a consequence, the scale will differ in both dimensions of the photographs, and distances may be underestimated by a factor of as much as two or more.

The feature of primary interest in the photographs that were taken at night is the development of lightning events that can be seen progressing frame by frame over rather surprisingly large areas. In the pictures taken thus far the resolution of the photographs is apparently insufficient to permit study of the lightning channel and the cloud structure, the other features that would be of great interest. The brightness of the discharges varies greatly from one frame to

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another. The faint ones are just barely visible. It is therefore quite difficult to construct a photographic montage illustrating the development of luminous areas in a succession that may involve as many as several dozen frames. We have, therefore, found that the most satisfactory way of presenting the data in these lightning episodes is to project the film on a piece of paper one frame at a time, and to outline the maximum extent of each luminous area with a pen or pencil. By this method a condensed view showing the time of occurrence and the location of each of the luminosities can be presented on a single figure.

The sequences of lightning activity taken during STS-2 over Africa are illustrated in this way in Figure 7. Those taken during STS-4 over Southern Brazil are shown in Figures 8 and 9. Episodes C through G were taken on 28 June at 23:20 GMT, and H and I the next day one orbit later at 00:57 GMT. The first luminous area to appear is designated with a 0. Each successive area that develops in the lightning event is given a number showing how many milliseconds intervened after the first area appeared. Because no information is available on when the luminosity occurred during the 16 millisecond exposure of each frame of the film, there is an uncertainty in the assigned times of + 8 msec.

It must be recognized that the indicated boundaries of the areas are based on subjective judgments of their maximum extent. The line of demarkation between the exposed area and the unexposed film is, of course, not sharp, so that the areas indicated are, to some extent, approximations. Undoubtedly, there are many lightning events that remain undetected because the luminosity they produced was below the threshold of detection.

In lightning events in which the illuminated area is clearly recognizable from one frame to the next, such as that illustrated in Figure 9I, there is little ambiguity in ascertaining the growth or progression of the luminous area.

In other cases in which no repetitive pattern can be clearly perceived, such as that shown in Figure 9G, there is a further problem in interpreting the data. Changes in the position of the luminous area from one frame to another can be produced by other causes than the progression of the lightning discharge. Rapid changes of orientation of the hand-held camera with respect to the vehicle, changes in the orientation of the vehicle, and motions of the vehicle with respect to the thunderstorm, can all produce a displacement of the luminous areas on the film.

Examination of pictures of cloud features taken from the Space Shuttle during daylight shows that camera movements at a rate of one tenth of a radian or more per second can sometimes occur. Should such motions take place during lightning photography, they would produce apparent motions of the order of 30 km sec^{-1} or more. The speed of the Space Shuttle is 8 km sec^{-1}; therefore, the uncertainties in the measurements of lightning propagation arising from these causes could possibly be of the order of several tens of km sec^{-1}.

DISCUSSION

Close inspection of the larger and brighter illuminated areas in the nocturnal photographs shows fine structures on the scale of about 10 km that probably are cumuliform cloud tops similar to those shown in detailed photographs taken from U-2 aircraft (Brook, et al., 1983). With photographic equipment of greater resolving power, it should be possible to see some structure in the overshooting cloud tops but not the detail evident at much closer range from the U-2 aircraft.

The orange and red coloration of the lightning photographs taken over southern Brazil poses some unresolved problems. Although the lower intensity images on the 16 mm film are clearly orange to red in color, astronaut Mattingly, who took the pictures, remembers that the lightning appeared to him to be white. Conceivably this difference might be explained if the response of the film were biased toward the red at low exposures, but this appears unlikely. According to a representative of the film manufacturer, the color response of this film should remain faithful even at low exposures. Furthermore, tests conducted by one of the authors (BV), in which a white incandescent bulb was photographed over a range of exposures extending to the limit of the film's sensitivity, failed to show any enhancement of the red. These apparently irreconcilable facts may perhaps be explained on the basis of the difficulty that undoubtedly exists in making subjective judgments concerning the color of instantaneous lightning flashes with little or nothing to compare them with. Possibly Mattingly's recollections are primarily of the whitish brighter flashes, while more faint reddish flashes escaped his attention. Another possibility is that the red coloration may have arisen somehow from the treatment or the processing of the film.

The red coloration of the fainter images may in fact be real, for red and other colors are described in some lightning observations from the ground (McGinley, et al, 1982). It might be explained on the basis that the shorter wavelengths of the light are attenuated as they pass through increasing depths of the cloud. Such selective transmission of the longer wavelengths might be expected if the cloud were contaminated with aerosol particles produced by fires, dust storms, or volcanic eruptions. It may be possible to resolve these uncertainties about the color of the lightning when a larger sample of lightning photographs taken from satellites has been accumulated.

The lightning sequences illustrated in Figures 7, 8, and 9 seem to have been formed in a similar way. Apparently under the influence of strong electrical stresses building up in the storm, dielectric breakdown of the air is initiated at some point and then spreads in various directions to produce the patterns shown in these figures.

It is possible to make estimates of the speeds of growth of the illuminated cloud pattern. If it is assumed that the displacements of the bright areas from frame to frame arise entirely from the progression of the luminous region through the cloud and that effects from the movements of the camera or the vehicle can be neglected, the results are as shown in Table 1. It must be remembered that because of the uncertainty in the scale of the figures, these estimates may be considerably less than the actual speed.

Table 1

Speeds of Growth of Illuminated Cloud Patterns

Lightning Sequences	A	B	C	D	E	F	G	H	I
Max Speed 10^5 $msec^{-1}$	1.2	0.4	0.7	20	0.8	3.0	2.0	0.7	2.0

In sequence I where the initial luminous area persisted for almost half a second and served as a fixed reference, it is clear that camera motions are having negligible influence on the estimate of the speed of growth. In other cases, camera motions may be playing a significant role. In sequence B, there is such a similarity in the sizes and shapes of the four images it is possible that the displacements are entirely the result of camera motion and that they may in fact be of the same cloud illuminated by repeated strokes.

Inspection of Table 1 shows that, with the exception of sequence D, the propagation speeds range from 0.4 to 2 X 10^5 $msec^{-1}$. These values are similar to the value of 5-8 X 10^4 $msec^{-1}$ that follows from Paul Weitz's statement about the flash he saw in Africa: "It went 100 to 150 km in a couple of seconds, but this is only an estimate." (Vonnegut, 1979). Within the limits of experimental error, these values are in agreement with the speeds based on optical observations of the stepped leader (Uman, 1969) and on VHF measurements of lightning (Rustan, et al., 1980; Proctor, 1981, and Hayenga and Warwick, 1981).

The lightning event illustrated in sequence D is unusual in that not one, but two, luminous areas, which are separated by a distance of 82 km, appear on the initial frame. A possible explanation for this situation is that a breakdown process first occurred in one of the locations and then spread to the other. In this event the minimum value for the speed of connection between the two areas is 20 X 10^5 $msec^{-1}$, the value shown in the table. The speed is so large it appears likely that the phenomenon taking place is different from that in the other 8 lightning events.

The sudden initiation of lightning at almost the same time in two widely separated places that is shown in sequence D suggests a phenomenon similar to that which has previously been observed by astronauts. For example, Gibson said in his description (Cooper, 1976) that the lightning "could go off simultaneously, or near simultaneously, over a large distance....". Truly, in his debriefing, described two separated areas of frequent lightning in the Amazon Basin that appeared "to be talking to each other". Aside from a high speed ionization process communicating between the two areas, there are several other possible explanations for the nearly simultaneous discharges. Perhaps one of the discharges may be triggered by electric field changes or electromagnetic radiation produced by the other discharge. Possibly both discharges are being triggered by a third discharge not in the field of view of the camera. Conceivably, electrons precipitated by VLF radiation from one discharge (Vampola, 1977) are capable of triggering other discharges some distance away. It must also be recognized that these simultaneous occurrences may be unrelated coincidences that occur entirely by chance.

Analysis of further and more numerous observations will permit it to be determined whether such separate lightning occurrences are related. If a sympathetic relationship is found, it will be of interest to see over what distances it can be observed.

The Y-shaped lightning discharge shown in the photographs in Figure 6 and in the upper left-hand corner of the patterns shown in sequence I is of particular interest. The initial bright area in the first frame remains visible for almost a half-second, thus providing a fiducial point from which growth can be reckoned. This part of the discharge continues to be as bright or brighter than any other portion of the discharge during the entire period that the Y-shaped pattern is visible. The persistence of this initial bright area suggests that it may be the position of an initial cloud-to-ground lightning stroke and that successive strokes extending to greater distances are continuously funneling charge into this initial plasma that is connected to the ground. This discharge is in many ways similar to the lightning event described by Workman, et al. (1960). If our interpretation is correct, this kind of photographic sequence provides a means for distinguishing between cloud-to-ground and intracloud discharges.

Although, as is shown in Table 1, there is some consistency in the maximum rates at which the patterns grow, there is a puzzling, very wide variation not only in the speed, but in the direction of the pattern's development. Some patterns, such as the upper portion of sequence C, show an orderly progression of the luminous area, but often this is absent. It is difficult to understand what is taking place in the sequence illustrated in Figure 6. Why is it, after the development of the curved segment up to d, that in e an arm begins to extend itself at right angles? If these patterns represent the spread of a dielectric breakdown process, why doesn't the arm form at once? Why does it delay until the segment reaches its maximum development shown in Figure d? Why does the direction of development rapidly change, sometimes by 180° in a brief period of time? The manner in which these patterns develop suggests that a release of electrical energy in one portion of the cloud is increasing the electrical stresses in other parts of the cloud, thus triggering the development of a new breakdown process.

The maximum span of the discharges observed thus far, about 100 km in Sequences C and I, is considerably smaller than the figure of 200 or 300 km estimated by Weitz. The maximum area encompassing a discharge, about 5,000 square km in sequence I, is much smaller too than the figure of a million square kilometers estimated by Gibson. However, these differences are not surprising. The observations reported here were of a winter thunderstorm, in itself an unusual event, of only modest electrical activity. There can be little doubt that space observations of lightning provide the opportunity for interesting scientific discoveries and that in future space observations more intense storms will be photographed that will exhibit lightning events even larger than those witnessed by astronauts in the past. It is worth noting that the lightning activity in the Amazon Basin astronaut Truly reported prior to the time the camera was unstowed on STS-2 was comparable in size to that reported by Gibson and Weitz.

CONCLUSIONS

It is encouraging to find that even this brief and modest effort to photograph lightning from the Space Shuttle has yielded interesting results. It provided data showing that lightning events spread horizontally at speeds up to 10^5 m sec^{-1} and can, in some cases, grow into discharge patterns that extend for 60 km or more. Because the data sample is small, comprising only a few dozen lightning flashes, it is difficult in some cases to draw firm conclusions. The first frame of one lightning sequence shows that discharges originated at two points 80 km apart in a 42 msec time interval. It is unclear whether the two events are related or whether they occurred by chance.

The results show that the Space Shuttle is particularly well suited for obtaining data on mesoscale lightning discharges that are too large to be photographed from a high altitude airplane or too distant to be resolved from a geostationary satellite.

Continued photography of thunderstorm cloud formations and lightning by astronauts should be encouraged. There is no substitute for their demonstrated ability to recognize, and take pictures of interesting cloud structures and electrical discharges and to utilize the most appropriate focal length of lens and exposure. In the past astronauts have accumulated fascinating and useful photographs valuable to geologists, oceanographers and meteorologists. It should be possible to extend these activities on future flights to include, when feasible, the photography of lightning at night. All of the conventional film and video cameras routinely carried on every flight can readily be used for this purpose.

A time exposure photograph of airglow taken by astronaut Valery Ryumin from Salyut 6 (Koutchmy and Nikol'skij, 1983) shows interesting lightning events similar to those reported here. It is to be anticipated that through further international cooperation it will eventually be possible to accumulate a wide diversity of photographs of lightning phenomena as observed from space.

Because of the many demands that are made on astronauts' time, it is unlikely that they will be free to photograph more than a small fraction of the thunderstorms and lightning displays that will be visible from their orbiting spacecraft. It appears feasible to enhance the rate of data acquisition by installation of equipment in the payload bay of the Space Shuttle that will automatically photograph lightning. Such equipment triggered by lightning signals picked up by a photocell could automatically take photographs of clouds and lightning and record the accompanying optical transients.

The results thus far from a brief preliminary program of lightning observations conducted from the Space Shuttle show that a satellite in low orbit provides unique opportunities for the study of lightning activity on the mesometeorological scale. The data that has been obtained will be of value in the development of lightning detecting instrumentation that can be used on a satellite in geostationary orbit. Data from this vantage point will doubtless provide a new and revealing picture of lightning activity on a global scale.

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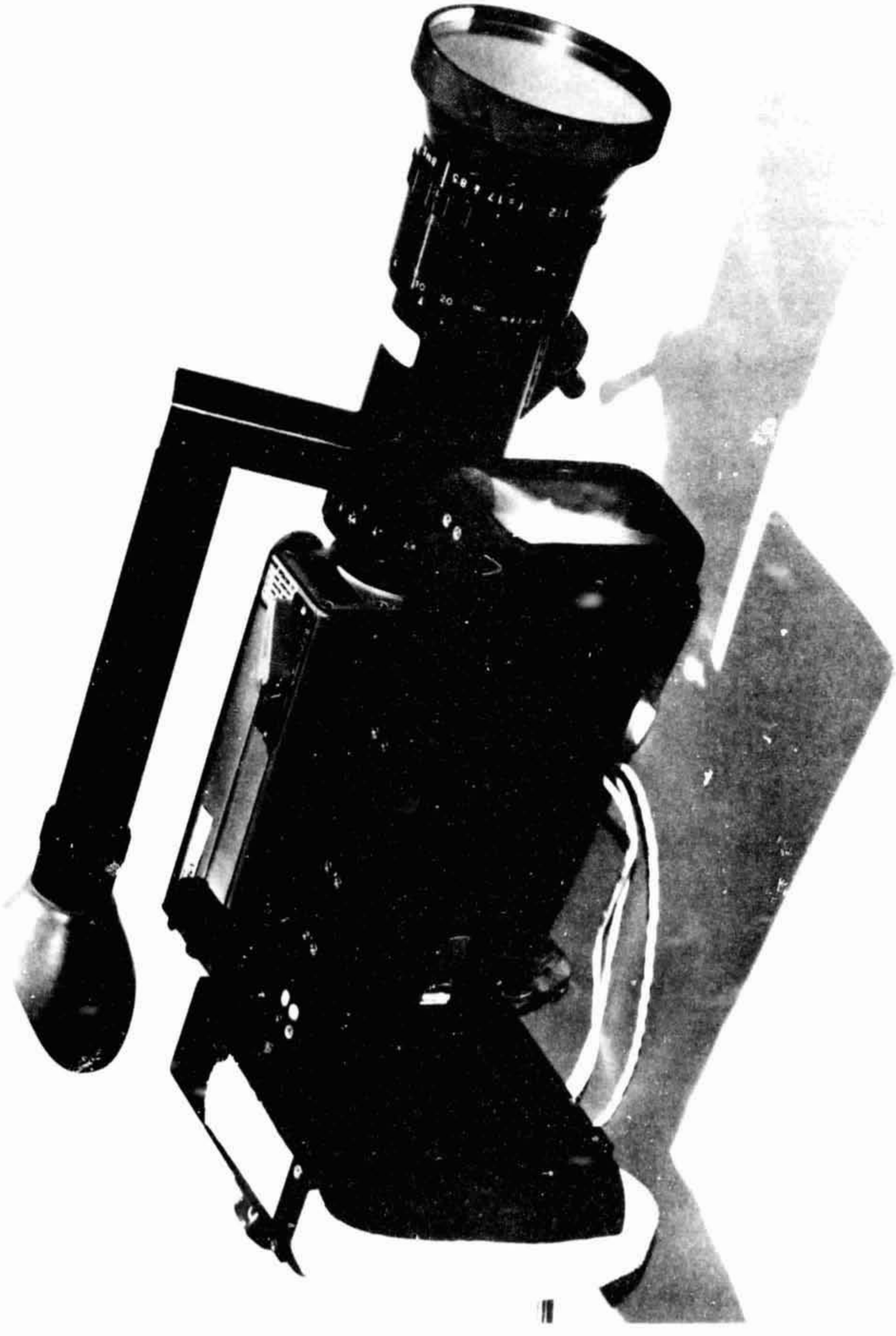

Figure 1: Instrumentation package comprising 16 mm motion picture camera and photocell sensor.

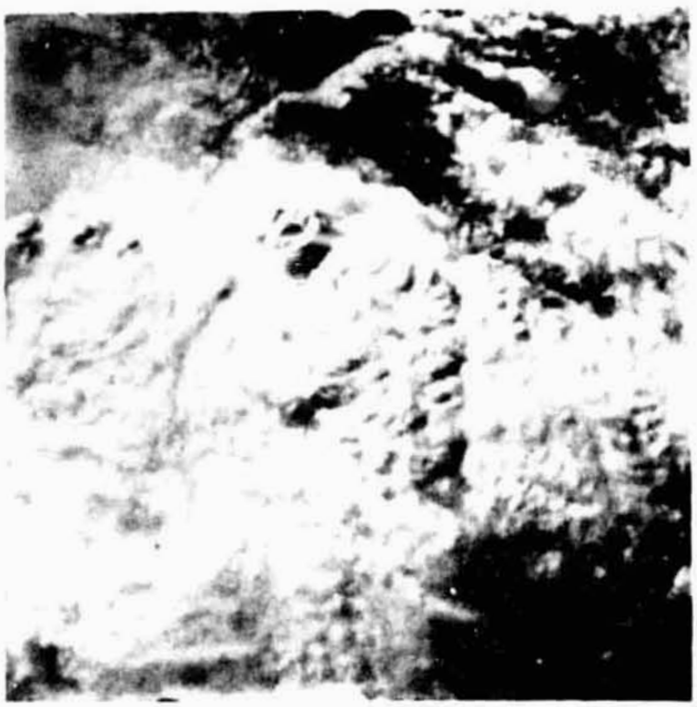

Figure 2: Thunderstorm cloud system photographed by astronaut Truly during STS-2 November 1981.

STS-4/NOSL OPTICAL (DAY) PULSE

DATA TAKE # 16

TAPE 1242

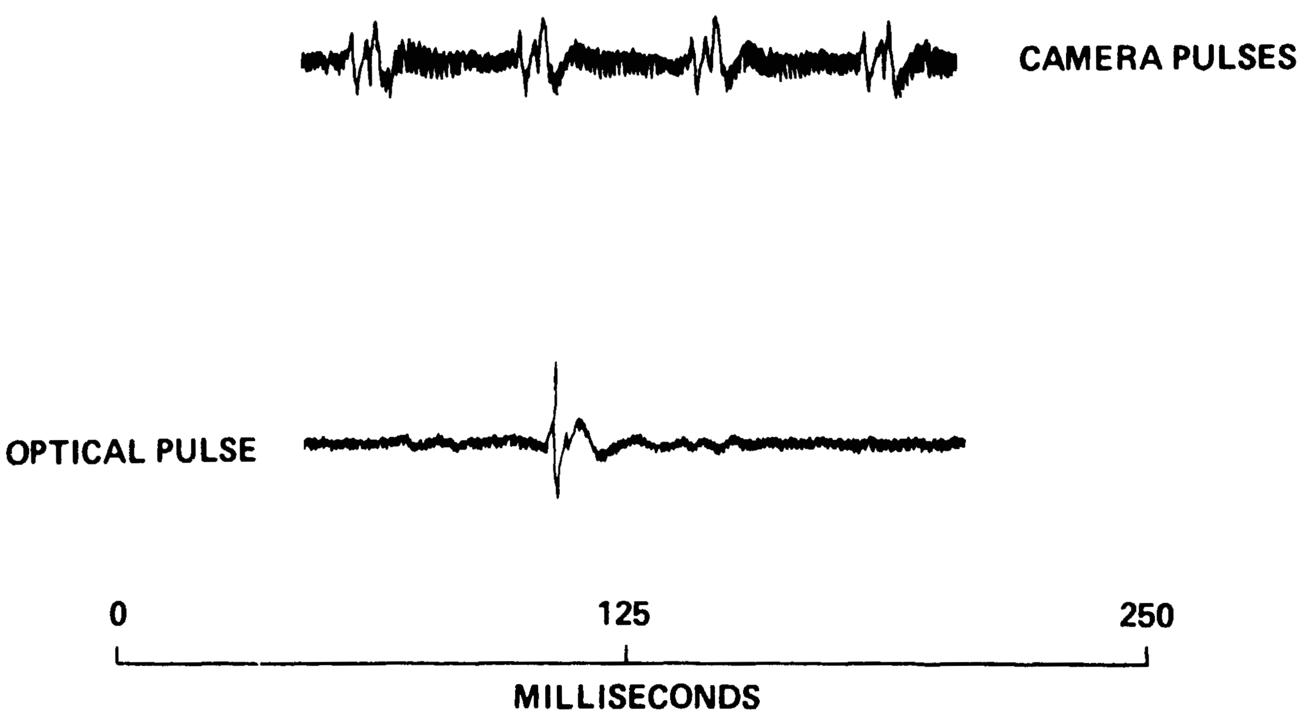

Figure 3: Optical pulse characteristic of lightning recorded during STS-4, July 1982.

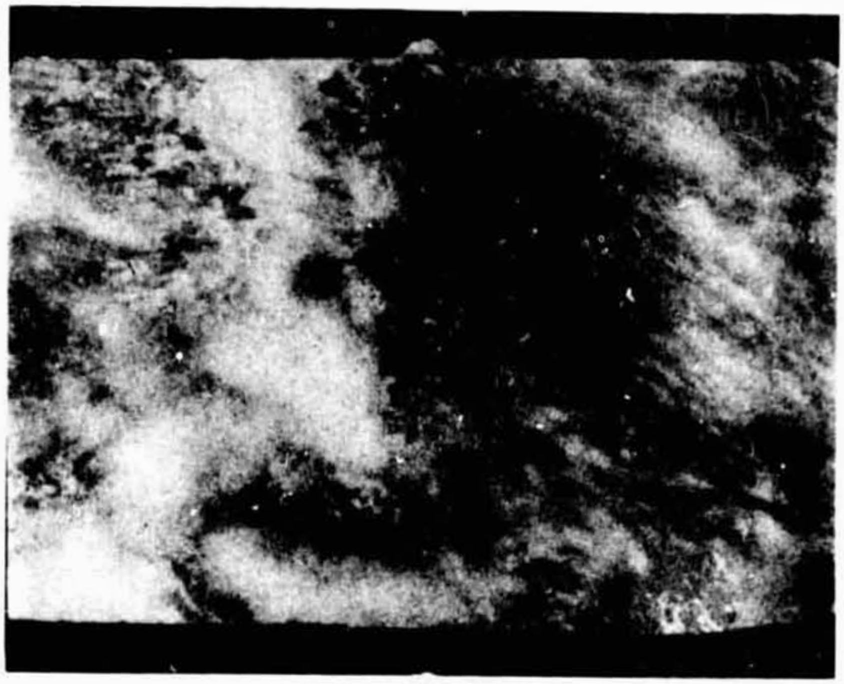

Figure 4: Cloud system that produced optical pulse shown in Figure 3.

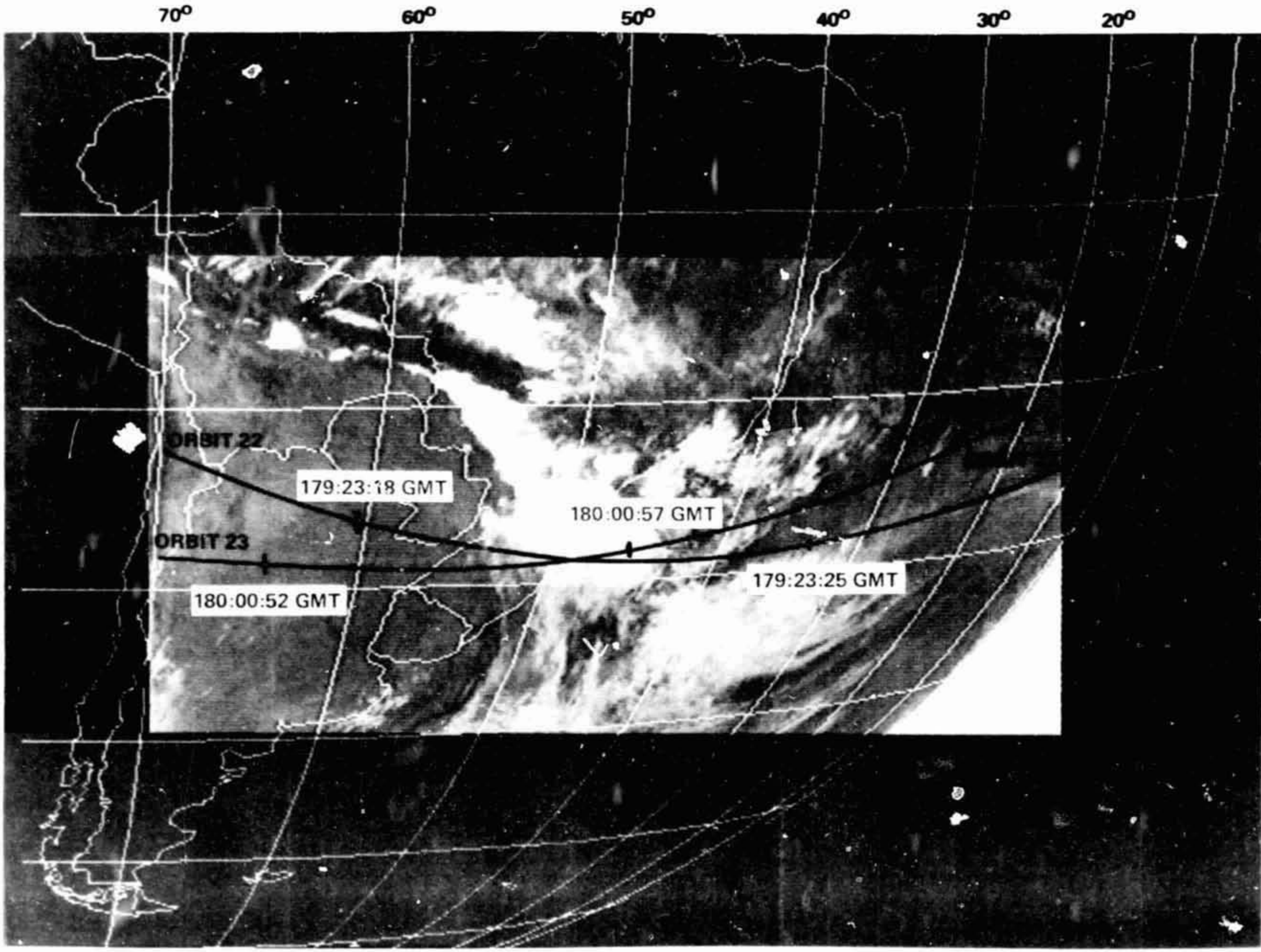

Figure 5: McIDAS image showing the storm over southern Brazil that produced the lightning events photographed during orbits 22 and 23.

STS-4/NIGHT-TIME DAYTIME OPTICAL SURVEY OF LIGHTNING EXPERIMENT (NOSL)

CLOUD/LIGHTNING FLASH SEQUENCE

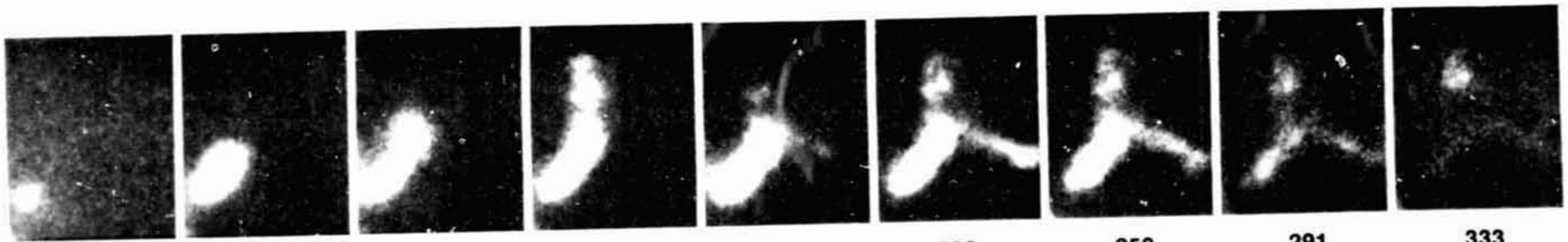

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Figure 6: Images from the first nine frames of 16 mm film showing Y-shaped lightning event over southern Brazil. The dimensions of the Y-shaped pattern are at least 30 X 40 km.

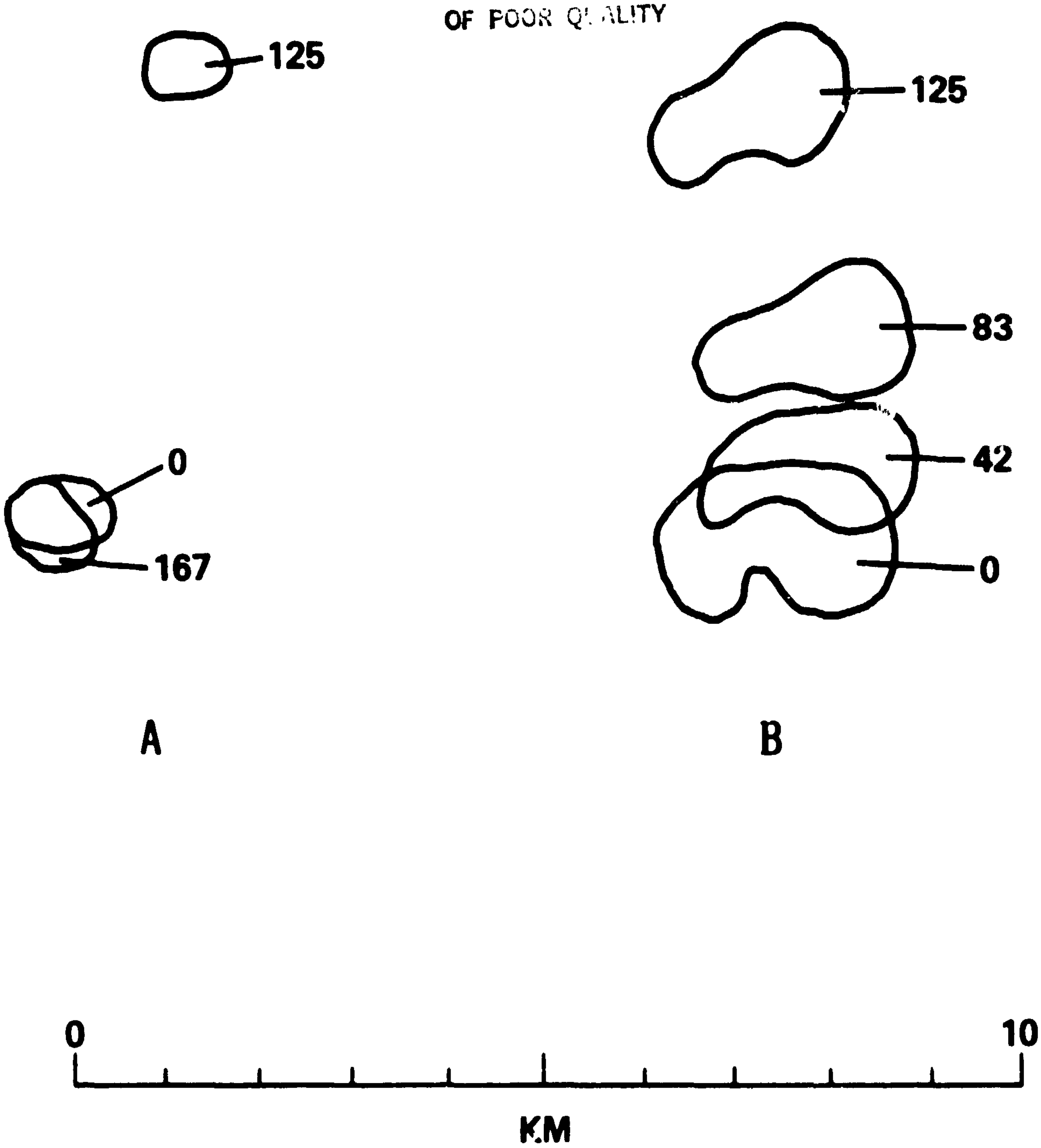

Figure 7: Lightning sequences A and B photographed by Astronaut Truly during STS-2.

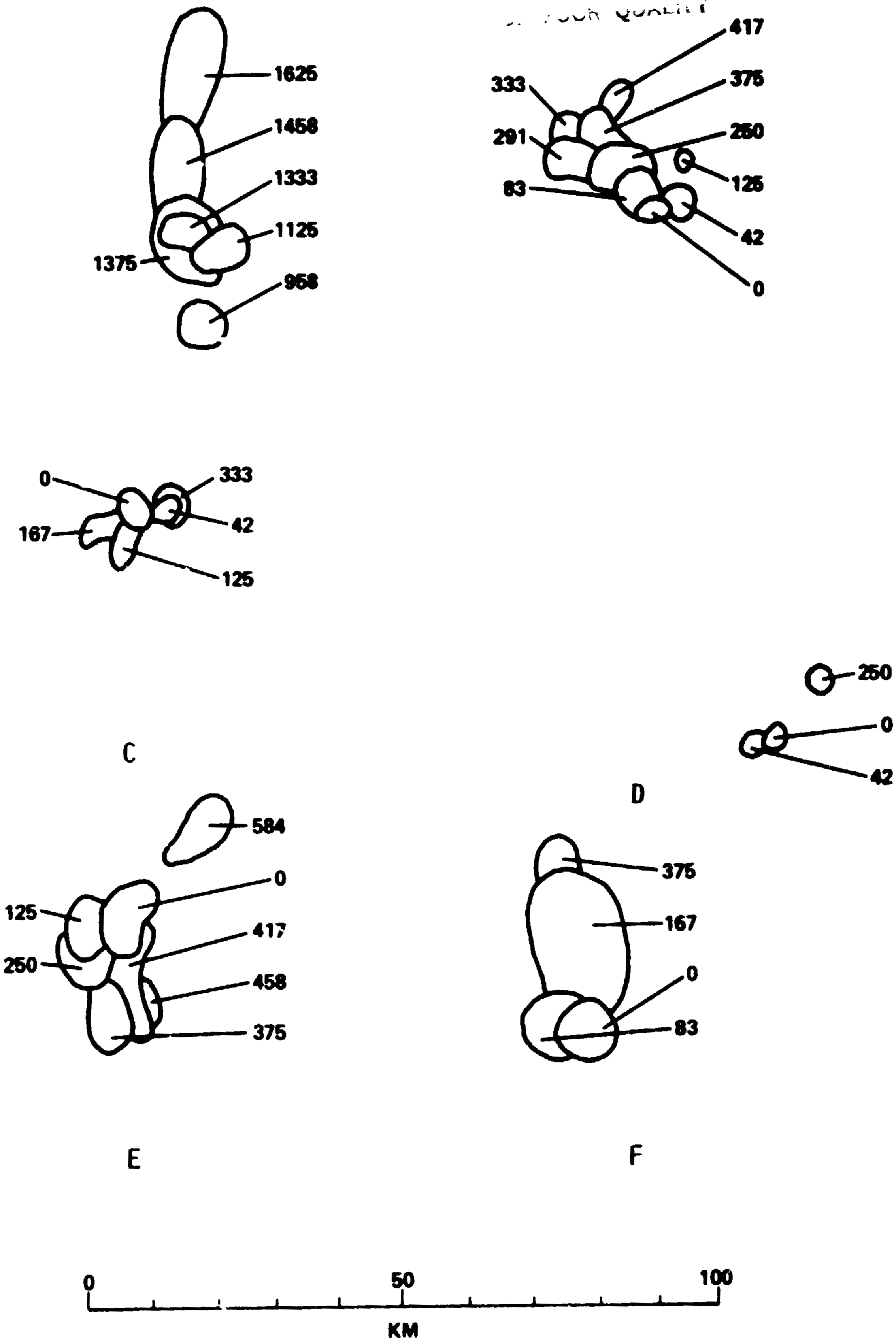

Figure 8: Lightning sequences C-F photographed by astronaut Mattingly during STS-4. D illustrates two simultaneous origins on same frame.

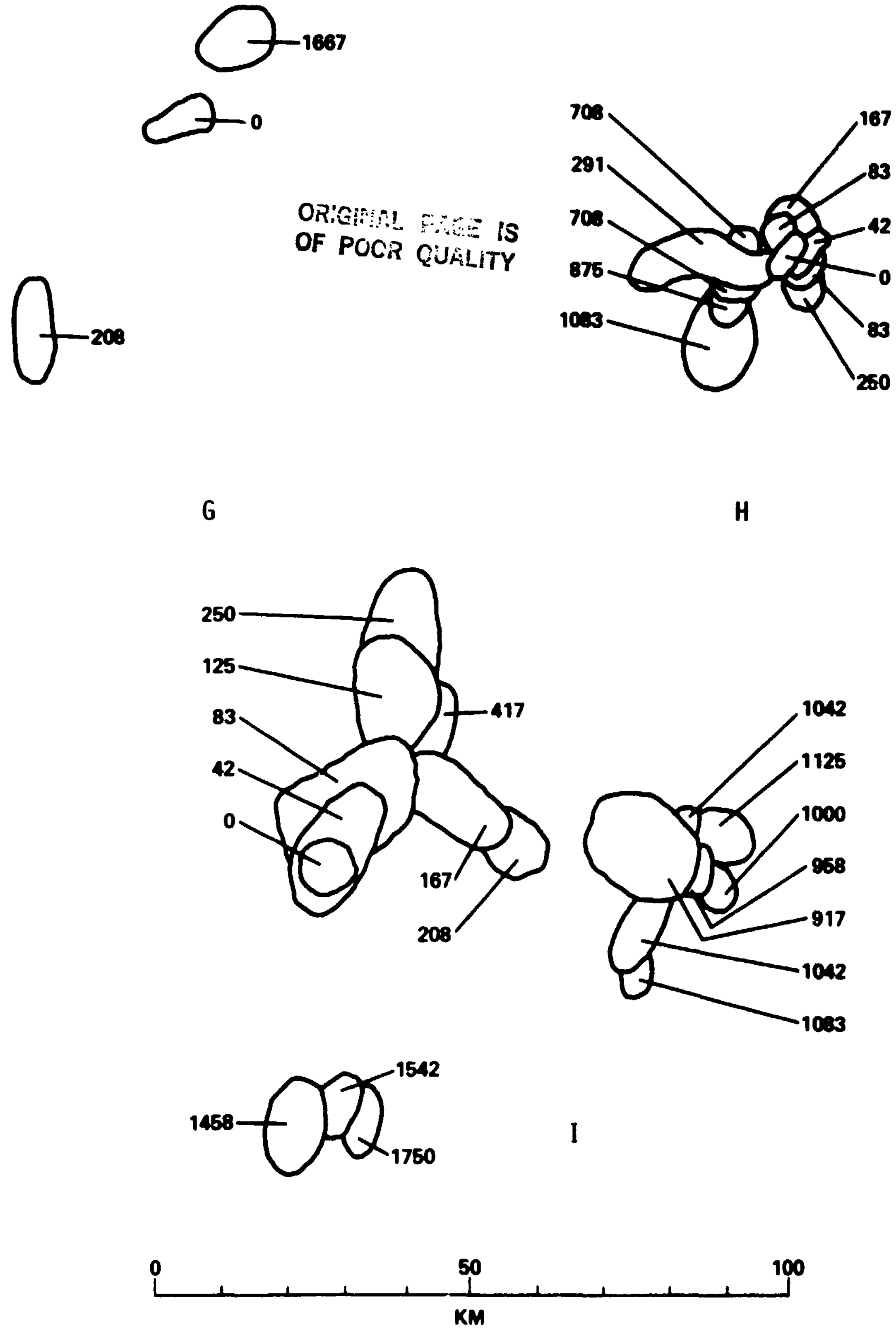

Figure 9: Lightning sequences G-I photographed by astronaut Mattingly during STS-4. I illustrates event shown in Figure 5 and subsequent discharges.

APPROVAL

THUNDERSTORM OBSERVATIONS FROM SPACE SHUTTLE

By

B. Vonnegut, O. H. Vaughan, Jr., and M. Brook

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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