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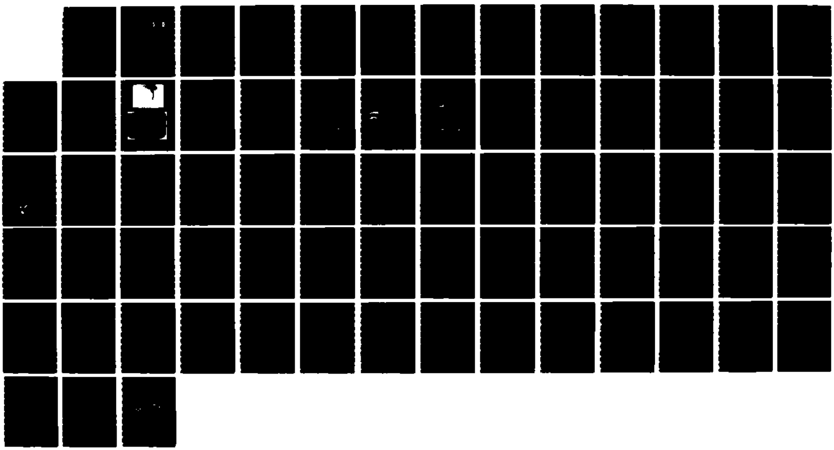

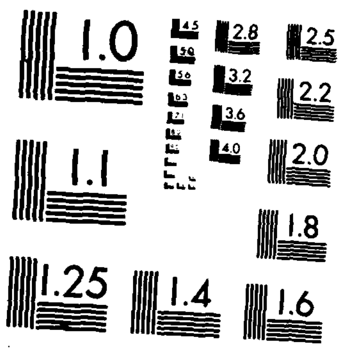

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AIRBORNE LIGHTNING RF DIRECTION FINDING:
A FEASIBILITY STUDY

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November 1985

Final Report
January 1983 to December 1984

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"This technical report has been reviewed and is approved for publication"

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The feasibility of using the RF radiation from lightning, specifically in the VHF range, for locating and avoiding lightning from an aircraft platform is examined from three perspectives. The phenomenological considerations explore the unique characteristics of the VHF radiation from lightning together with arguments for its use in an airborne detection system. The propagation considerations point out the relevant factors which must be considered for VHF radio propagation when both the source and the receiver are located above ground. The third consideration is the technological problems likely to be encountered when placing a direction finding system on the airborne platform.

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19. ABSTRACT (con't)

The current understanding of VHF radiation from lightning is still very limited. As the radiation comes from sources located at aircraft altitudes, there would be a better indication of aircraft hazard than would be obtained by locating the point where lightning contacts ground as is obtained by VLF systems. Propagation considerations require much care, especially in dealing with the signal which is reflected from the ground. Essentially two signals are located a reflected and a direct signal. Range determination by using the reflected wave direction of arrival is shown to be feasible with resolution of about 5 km for ranges less than about 60 km but degrades severely at longer ranges.

Technological considerations do not appear to be major. Rather the phenomenological and propagation problems are significant and must be examined further to utilize this technique for airborne lightning detection and avoidance.

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I. Introduction

In a recent survey, Parker and Kasemir (1980) address the need for reliable and inexpensive airborne lightning warning and avoidance systems. They survey a number of techniques currently in use for lightning research and their potential suitability for aircraft systems. Among those techniques considered for warning of distant storms were a number of sferics detectors. "Sferic" has been used to cover all aspects of lightning RF radiation, though its usage usually is limited to the lower frequency (<10 MHz) radiation. While this radiation is more energetic than the higher frequency (HF and VHF) radiation, recent advances in our understanding of the VHF radiation from lightning suggest that it might be feasible to use the VHF radiation in the development of an airborne warning system.

The present study was undertaken to assess the feasibility of developing an airborne lightning warning system which detects the location of VHF radiation from lightning. Initially a prototype device was also to have been constructed, so the study focused on particular target aircraft which were to be available for testing the prototype. When funding for the prototype was cancelled, the study shifted to an examination of a generic system for any aircraft.

The phenomenological characteristics of VHF radiation from lightning provide definite advantages for an airborne system. These characteristics are examined in section II. First, relevant results from studies of the more familiar optical, acoustic and electrical emanations from lightning are discussed. The unique characteristics of the VHF radiation are then presented with arguments for their use with an airborne system. Section II concludes with a presentation of VHF lightning parameters which would be relevant to the design of an airborne system.

The other factors which must be considered for the feasibility are presented in two categories. Section III considers factors associated with the propagation of the VHF lightning radiation from its source to the aircraft. Such factors as signal strengths, dynamic range, interference and reflections are considered. Section IV considers the technological aspects of a system at the aircraft itself. The suitability for aircraft placement of existing ground techniques is examined for both azimuth and range determinations. Each of these determinations presents technical problems which must be addressed for a system. It is shown that much flexibility exists in the choice of parameters for azimuth determination. The available possibilities for range determination are not as promising.

The target performance for this study of an airborne system was left open to our determination. We set a desired range of coverage at $\sim$150 km. For a craft near the speed of sound this translates to a time frame of roughly 10 minutes. Angular coverage is discussed in the section on azimuth determination. Nothing was provided to indicate whether this system would be used in friendly territory only with possible ground support or whether it would be intended for use during combat. It was also not stated whether or not the system must be purely passive. In the conclusion some of these issues will be addressed in light of what we believe can be done with an airborne RF lightning detector.

II. Phenomenological Considerations

A. General Considerations

Lightning has been defined as a transient, high-current electric discharge whose path length is generally measured in kilometers (Uman, 1969). The most common occurrence of lightning, and the only of interest for this report, is that associated with thunderstorms. Such lightning is usually distinguished between that which takes place entirely within the cloud (intracloud or cloud discharges) and that which comes in contact with the ground (cloud-to-ground or ground discharges). This distinction is somewhat misleading in that all discharges have significant activity within the cloud. Furthermore, many discharges, especially those from mature and complex storms, appear as hybrids or combinations of cloud and ground discharges.

Although the most frequently occurring form of lightning is that within the cloud, the greater part of the lightning literature concerns the ground discharge, especially return strokes. (An entire discharge is usually referred to as a flash, lasting about a half-second; the highly luminous components of discharges from ground to cloud are referred to as strokes, or return strokes, lasting on the order of milliseconds.) These distinctions are important because the incloud processes are obviously of most importance from the standpoint of an airborne platform. Unfortunately much of the work on airborne systems has also concentrated on the return strokes (e.g. Rustan et al, 1983). Although they are connected in the overall structure of the flash, the intent of this discussion on lightning phenomenology is to emphasize what is known about what is happening in the cloud where an aircraft would be located as opposed to the point where a discharge contacts the ground.

Significant advances have been made on the understanding of incloud processes within the last few years. Unfortunately much work remains to be done before a complete picture will emerge.

Optical and photographic techniques which were very successful in the determination of processes occurring in ground discharges have been of little use in studying cloud discharges, for obvious reasons. During a cloud discharge a continuous low luminosity is seen with several relatively bright pulses of less than 1 ms duration superimposed. Any spatial structure can not be determined due to scattering.

Other techniques which have been successful in determining incloud processes are: acoustic reconstruction of lightning channels; analysis of the radar returns from lightning channels within the cloud; modelling of charge transfers from the analysis of charges in the electric field at numerous ground stations; and analysis of the VHF radiation from lightning to determine the location of sources and their movement. With the exception of some earlier electric field studies, real progress using these techniques has occurred only within the last ten years. All studies using these techniques have involved a small number of flashes. Usually little documentation has been available on the thunderstorm environment producing the flashes. It is still somewhat premature to draw general conclusions about incloud lightning processes and their connection to and range of variability with respect to the thunderstorm environment. Nevertheless, the following results from these techniques provide the phenomenological background from which the feasibility of an airborne platform is discussed.

1. Acoustic Reconstruction. Detailed analyses using the acoustic technique of Few (1970) have been presented by Teer (1970) and MacGorman (1978). In this technique, the direction of arrival of a thunder impulse at an array of microphones is determined by the propagation time between microphones, measured to an accuracy of 1 ms using cross-correlation analysis. The acoustic ray defined by this direction is then retraced through the atmosphere to its source. Range to the source is determined from the propagation time between occurrence of the lightning, determined by an electric field change meter, and arrival of the thunder impulse at the array. Source locations are computed from all processes in a lightning flash that produce thunder at the array. However, since acoustic propagation time is long compared to the duration of lightning, the acoustic analysis cannot separate the structure of individual processes in a flash, but integrates the structure from all processes.

The reconstructed lightning structure was shown to be predominantly horizontal, usually much larger than any vertical extent. In addition the flashes for the 10-25 minute intervals of study tended to occur in one or two layers at altitudes above the 0^{0} isotherm. In some storms the horizontal extent of the flashes increased as the storm progressed from a typical 10-15 km to greater than 20 km. The increase was attributed to the growth of new, electrically active cells near the previous activity. It should be noted that these studies were conducted in large, usually mature thunderstorms. The question of whether all lightning from all phases of a thunderstorm is predominantly horizontal remains open.

2. Radar Observations. Radar studies of lightning have not been concerned so much with locating lightning within the storm structure as with determining the actual properties of the lightning channel. Mazur and Rust (1983) present some data concerning lightning propagation using VHF and L band radars. They separate lightning flashes from squall line storms in Oklahoma into two categories: one with echoes having projected lengths onto a horizontal plane of <20 km and another with lengths of >20 km. These lengths are determined from the maximum extent of radar return from the ionized channel along the radar beam direction. Their study shows that the largest lightning density tends to be near the leading edge of the precipitation cores in developing cells. As a cell in the squall line develops, the total lightning density increases. Long discharges develop, but the shorter ones predominate. In contrast, as the cell dissipates, short flashes diminish or cease and the long flashes dominate the activity. It must be emphasized that these results were mainly from a single Oklahoma squall line system.

3. Electric Field Change Studies. Modern observations of the lectric field change produced lightning (Krehbiel, et al., 1979; Krehbiel, 1981) have contributed greatly to our understanding of incloud lightning processes. Measurements are made of the electric field change at a number of ground stations separated by a few kilometers each. These are then fit to a particular model of charge change which would give the measured electric field changes. Models have ranged from a simple point charge model involving four parameters - location x, y, z, and magnitude, Q - to recent work (Liu and Krehbiel, 1984) involving an advancing streamer model with seven unknown parameters. By having more measurements than unknown parameters, the goodness of the fit between data and model can be examined using chi-squared methods. The results of the streamer

model indicate that the initial electric field change of the intracloud flashes was produced by upward motion of negative charge in the cloud. The apparent height of initiation was between 7.3 and 8.3 km MSL for three flashes in a small storm and 10 km for an energetic flash in a large storm. These altitudes correspond to environmental temperatures of -17 to -24°C and - 38°C, respectively. After initiation the streamers progressed upward with a speed on the order of 10^5 m/s or greater. In all cases the charge transfer at the beginning of the flash was vertical or nearly vertical. These results pertain to the intial 15-30 ms of the discharge; after that time the development could not be determined with the models used. Comparisons with VHF radiation analysis (Proctor, 1976, 1981) has led to the conclusion that lightning begin near the negative charge region of a thunderstorm with negative streamer propagation.

Most of the discharges from studies discussed previously and from the Proctor studies were horizontally oriented. Liu and Krehbiel attribute discrepancies to the fact that other studies were from mature or dissipating storms, whereas the flashes from their study occurred in growing cells. Krehbiel (1981) has also shown several extensive horizontal discharges from a dissipating storm system.

Krehbiel et al (1984b) present a study of the initial fifteen flashes in a small Florida storm. The electric field change models are compared with radar observations of precipitation development and velocities in the storm and with locations of VHF sources determined by the KSC-LDAR system. Figure 1 shows a plot of the average height of the negative and positive charge centers (dipole model) and VHF radiation sources for the fifteen flashes. The upper, positive charge centers of the intracloud lightning are located above 15-20 dBZ reflectivity in the top of the cloud and increased in altitude as the storm grew vertically, at the same rate (~ 8 m/s) in both cases. The negative charge centers remained at approximately constant elevation, at temperatures between -10 and -15°C. Two cloud to ground (CG) flashes removed negative charge from essentially the same altitude and volume of the storm as intracloud (IC) flashes before and after them, though the VHF sources indicate that the CG discharges extended downward and the IC flashes extended upward in the cloud.

B. VHF Lightning Phenomenology.

In order to utilize the VHF radiation from lighting in a location system, one must know both the temporal and spatial characteristics of that radiation. The temporal characteristics are important because of differing phenomenology with time during a flash and because the temporal characteristics set the design parameters for the system. The spatial characteristics are important for two reasons. First, the sources must not disrupt the measurement of their location. This could happen if there were numerous widely spaced sources radiating during a single observation period (ie "simultaneous" sources) or if the source positions moved significantly more than an angular resolution element during the observation interval. Second, the VHF sources must be correlated with other lightning and thunderstorm phenomena in order to understand and interpret the significance of their location. Published studies using the ground based techniques of a hyperbolic system (Proctor, 1981,1983) and an interferometric system (Warwick et al, 1979; Hayenga and Warwick, 1981; Hayenga, 1984) provide observations from which we can infer characteristics of the spatial structure of the VHF radiating sources, and the relation of the sources to other lightning and thunderstorm phenomena.

These observations should not be considered comprehensive. Much work remains to be done in this area.

1. Temporal Structure of VHF Radiation. In a study associated with this feasibility study, Rhodes (1985) analyzed some properties of lightning radiation. We present his analysis of one flash to show how VHF radiation evolves in time and how it is related to other lightning phenomena. Lightning was observed with microsecond resolution at four RF frequencies; 34, 368, 1414, 2275 Mhz. Supplemental measurements were made of the electric field change and the optical radiation. A video camera also captured pictures of the flashes.

The flash presented here is representative of the flashes studied. However, the number of flashes studied was too small to make an adequate assessment of the range of variability of the parameters discussed.

The flash occurred at 16 hours, 19 minutes, 23 seconds on September 18, 1982, in an isolated

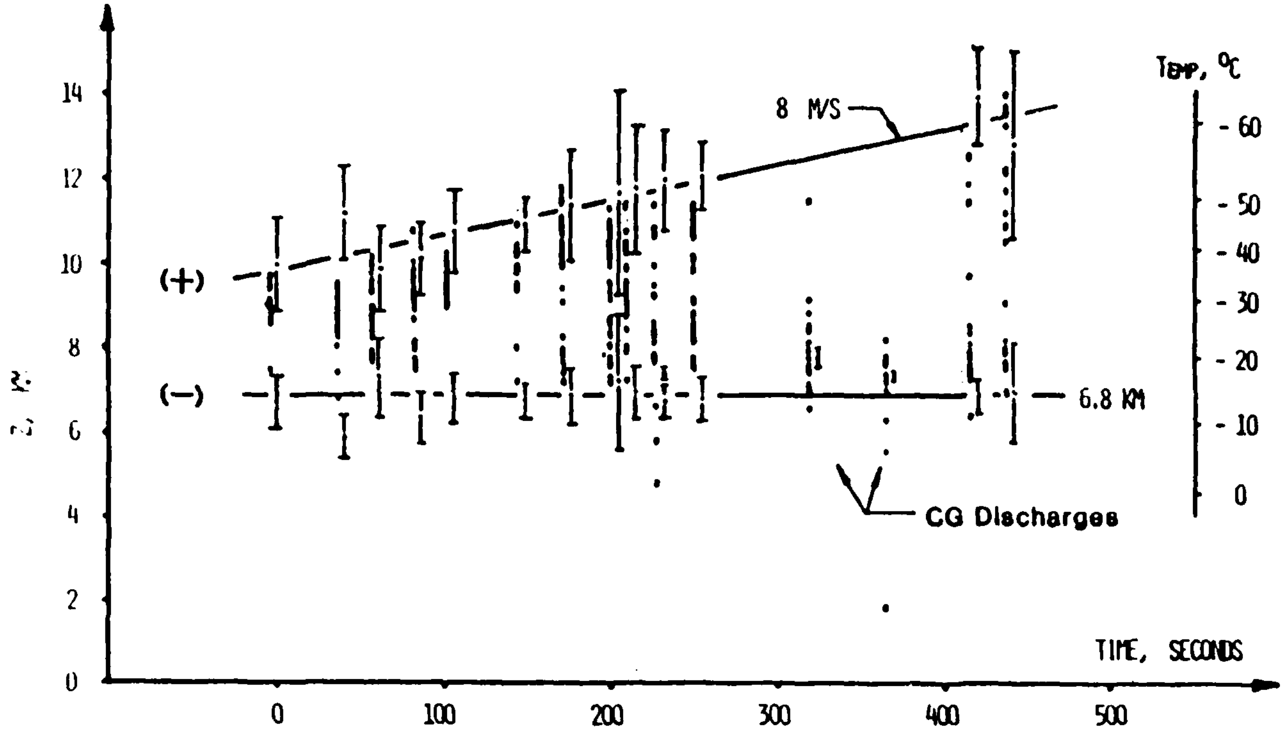


Figure 1. Average height of lightning charge centers (bars) and VHF radiation sources (dots) for the first 15 lightning discharges in a storm at KSC. The negative charge region remains fixed in elevation whereas the positive charge region moves upward at 8 m/s as the storm grows. (From Krehbiel et al, 1984b.)

thunderstorm south of Socorro. Figure 2 shows two frames from the video recording of this flash. The time insertion unit was incorrectly set ten seconds fast. The time to thunder indicates that the ground channels were about 2 to 3 km from the observation van.

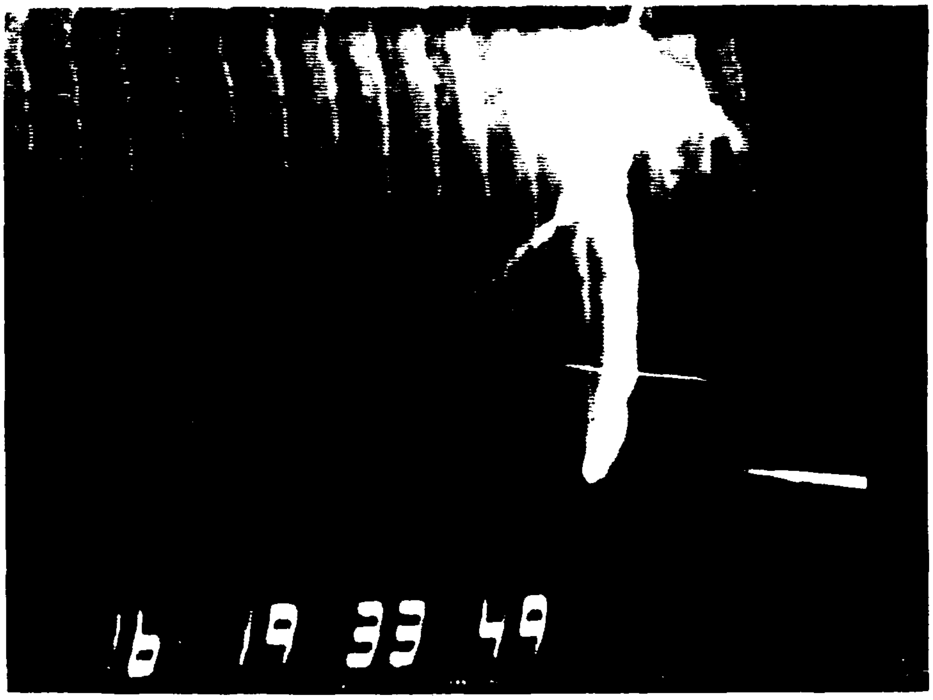
Figure 3 presents an overview of the flash. The received RF powers, optical signal, and electric field measurements are plotted as a function of time with millisecond resolution. The various parts of the flash are labelled. The flash begins with a preliminary breakdown in the cloud. This in most easily seen in the RF records although the 1414 and 2275 Mhz records don't show much radiation; probably due to antenna directionality. Closer examination of the radiation during the preliminary breakdown phase shows that it consists of pulses or groups of pulses of a few microseconds separated by 10 to 100 microseconds. The bursts become more dense with time.

The preliminary breakdown leads into the stepped leader as the incloud streamer turns toward ground. The apparent increase in RF power is due to the integration of many short pulses, now more numerous than in the preliminary breakdown. The stepped leader stops abruptly at the first return stroke, indicated by the large amplitude electric field change, the cessation of RF radiation and the large optical signal. This first return stroke is shown in Figure 2a.

The interstroke period shows mostly isolated bursts of RF radiation, lasting a few hundred microseconds each. Some of these have associated optical pulses and electric field signals. Such electric field signals have been named K changes.

This flash is somewhat different in that the second return stroke occurs in what was a branch of the first return stroke channel, as shown in Figure 2b. About 2 milliseconds after this return stroke a return stroke occurs in the original channel, probably initiated by the stroke in the branch.

During the times around the return stroke the RF radiation consists of continuous radiation lasting tens to hundreds of microseconds. This radiation is not due to the return strokes since it usually initiates before the stroke. The radiation may continue through the time of the stroke. Figure 4 shows data near the time of the second stroke with higher time resolution. Since this was a new channel to ground, stepped leader radiation can also be seen in the first



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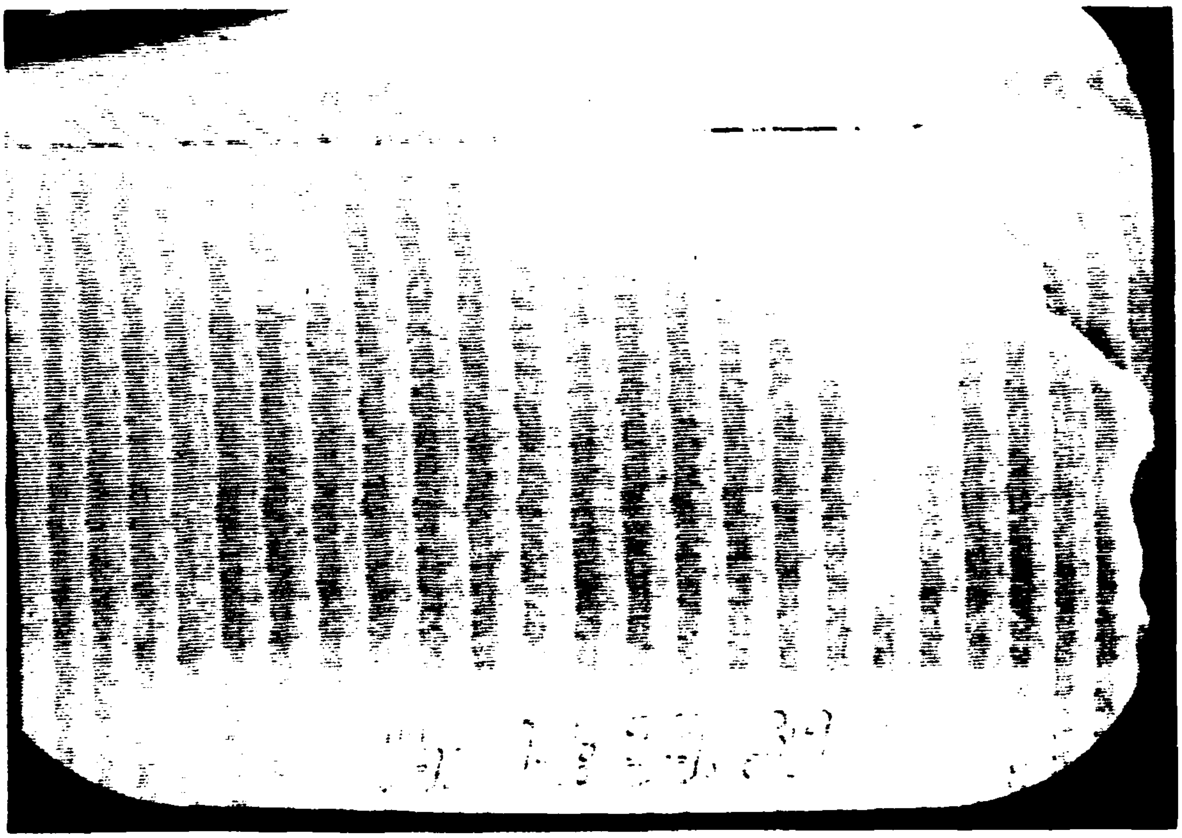


(B)

FIGURE 2. VIDEO PICTURES OF THE SECOND AND THIRD RETURN STROKES OF FLASH 161923. THE TIME INSERTION UNIT WAS INCORRECTLY SET 10 SECONDS FAST.

part of this record.

The video recording showed that the third return stroke also occurred in the branch channel. The expanded time plot for this return stroke in Figure 5 shows a combination of short impulsive radiation (~ a few μs) and quasi-continuous radiation (~ 50 to a few hundred μs).

The last thirty milliseconds of radiation from this flash (cf. figure 2) are from an incloud streamer. The characteristics of this radiation are similar to stepped leader radiation.

These Socorro studies basically agree with French studies by Le Boulch et al (1984) and South African studies by Proctor (1981).

From these studies it has been concluded that lightning RF radiation is of two fundamental types. The first consists of impulses lasting a microsecond or less which come in groups lasting on the order of 20-50 μs. Such groups are separated by intervals of the same order of magnitude in which last from a few milliseconds to several tens of milliseconds. The second type of radiation is of higher amplitude and consists of essentially continuous radiation for periods from tens of microseconds up to one millisecond and occurs in isolation during the flash.

Figure 6 shows measured pulse durations for the flash previously presented at four different frequencies. The durations were determined from the time interval the detected signal was above a specified threshold, indicated on the figure. The values, in dBm, are received power at receiver input, neglecting antenna gain and source polarization and distance. Only the first fifteen time bins contained data, making a statistical analysis rather difficult. A scattering of pulse duration from 50 to 400 microseconds was measured, indicative of the second type of radiation. There is not a significant variation in pulse widths as a function either of frequency or threshold level other than the clear indication that lightning radiated strength declines at shorter wavelengths.

2. VHF Spectrum of Lightning. Published reviews of measurements of the spectrum of VHF radiation from lightning are similar to that shown in Figure 7 from Oh (1969). The spectrum falls off at 1/f or greater with increasing frequency. Usually the only attempt to accomodate the temporal structure of the radiation is by normalization of the various receiver bandwidths

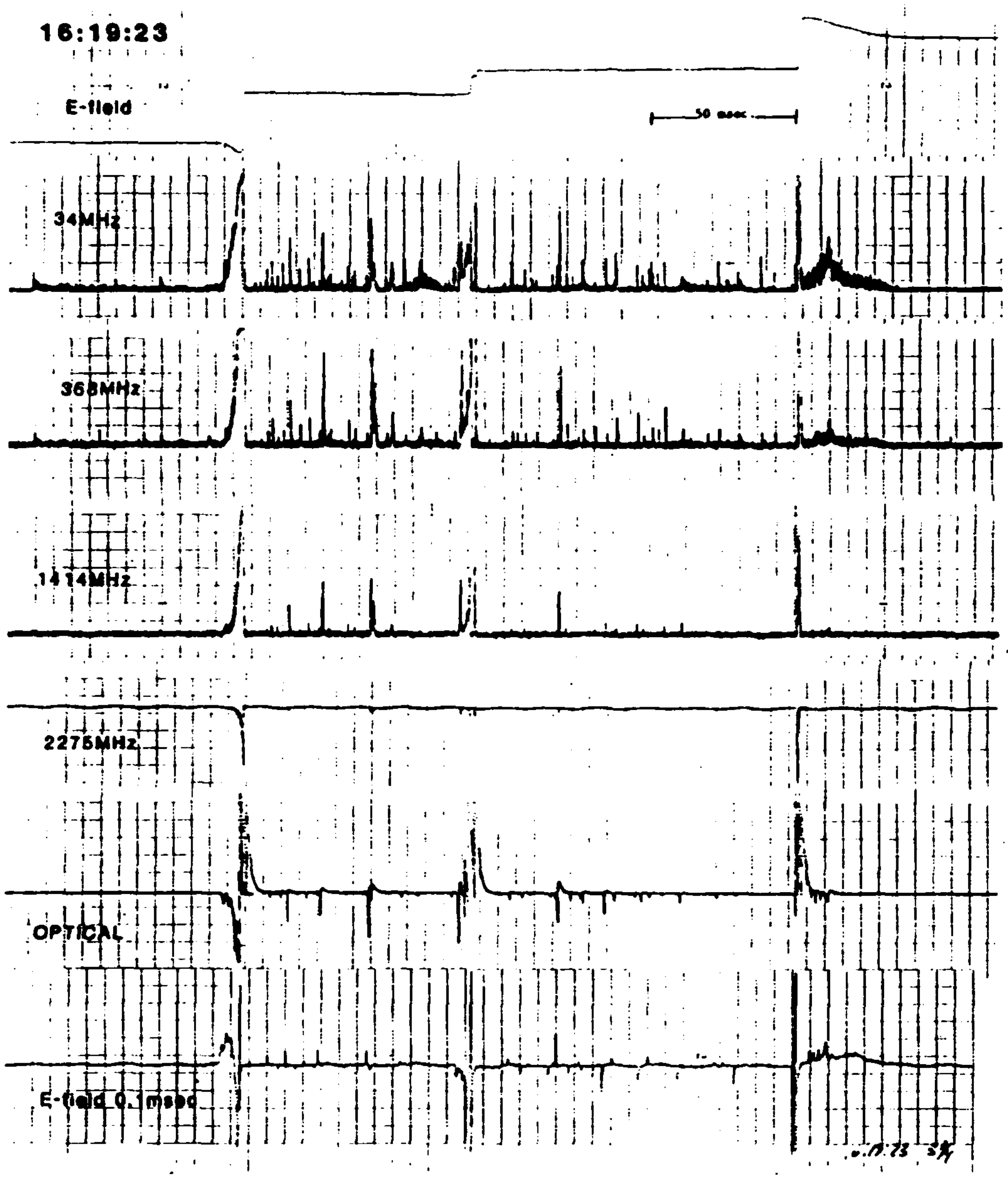


Figure 3. Overview of flash 161923. The electric field change, optical signal and detected outputs from four receivers are plotted. The 2275 MHz signal is inverted. The preliminary breakdown begins the flash, leading into the stepped leader, shown by the dip in the electric field and strong RF radiation. The large discontinuities in the electric field are due to return strokes. (From Rhodes 1985.)

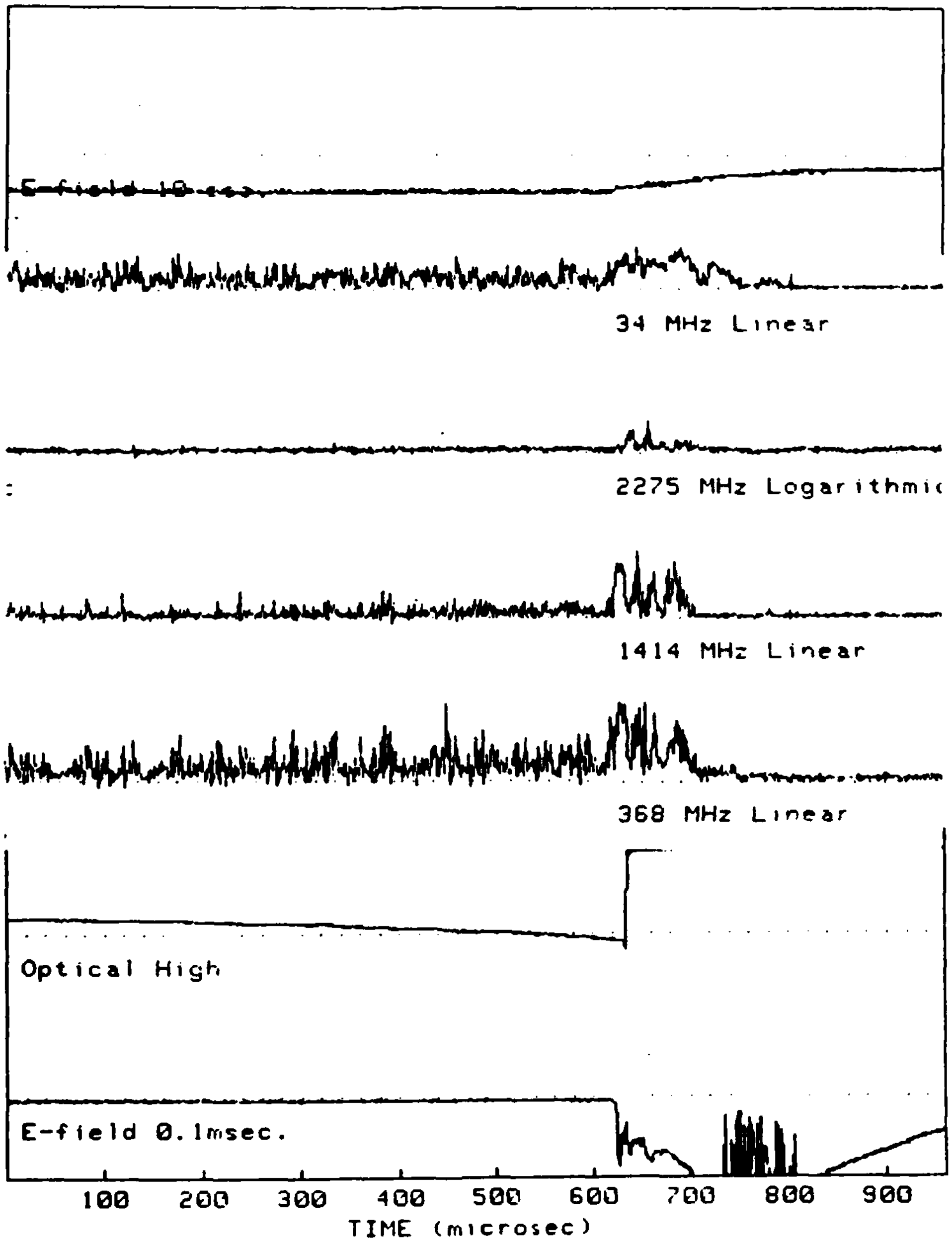


Figure 4. Higher resolution plot of the time around the second return stroke of flash 161923. Stepped leader radiation leading to the return stroke can be seen in the 34 and 368 MHz channels. The optical signal saturated at the return stroke. (From Rhodes, 1985.)

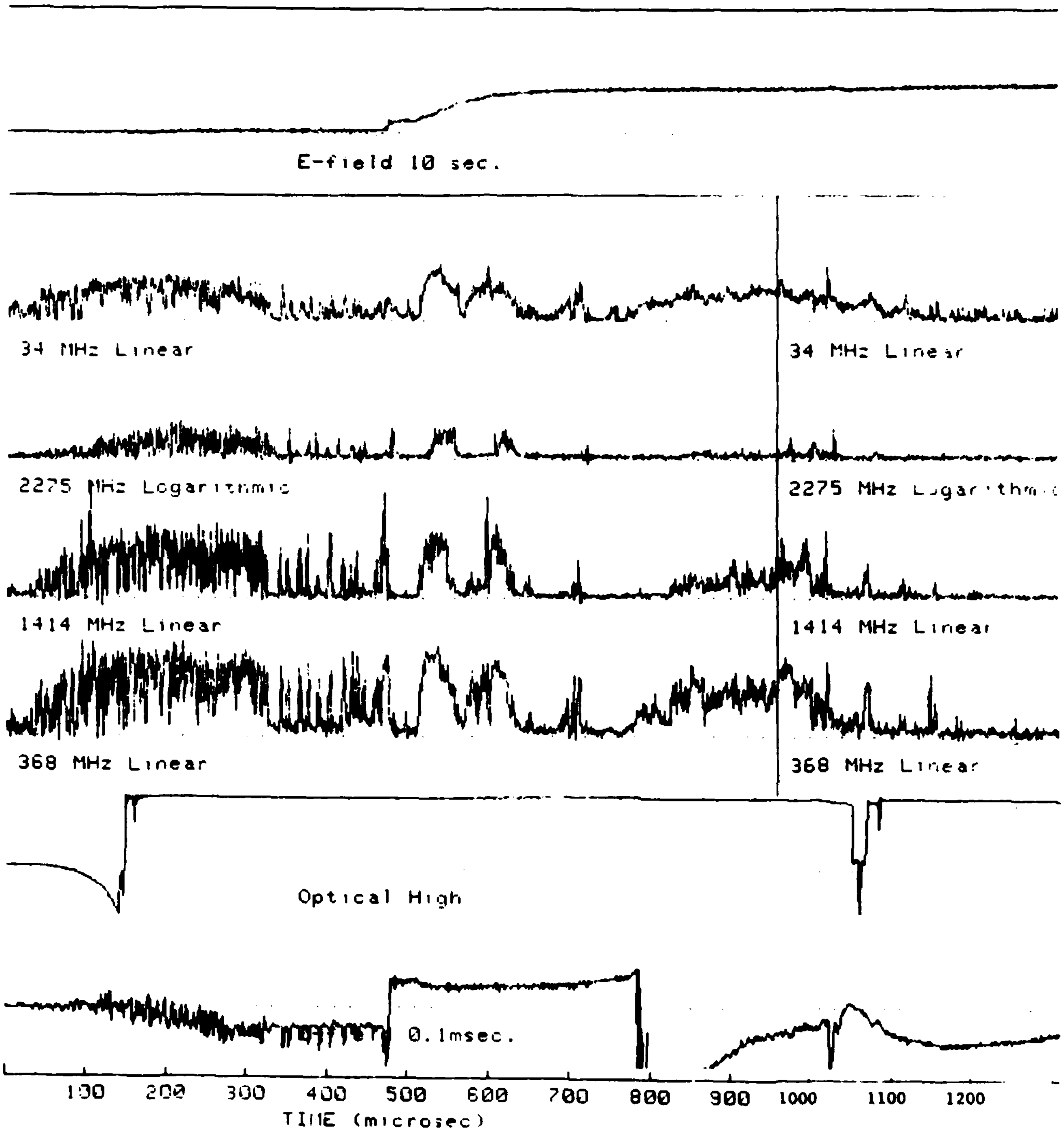


Figure 5. Higher resolution plot of the time around the third return stroke of 161923. Both the short, impulsive radiation and the longer continuous radiation can be seen. (From Rhodes, 1985.)

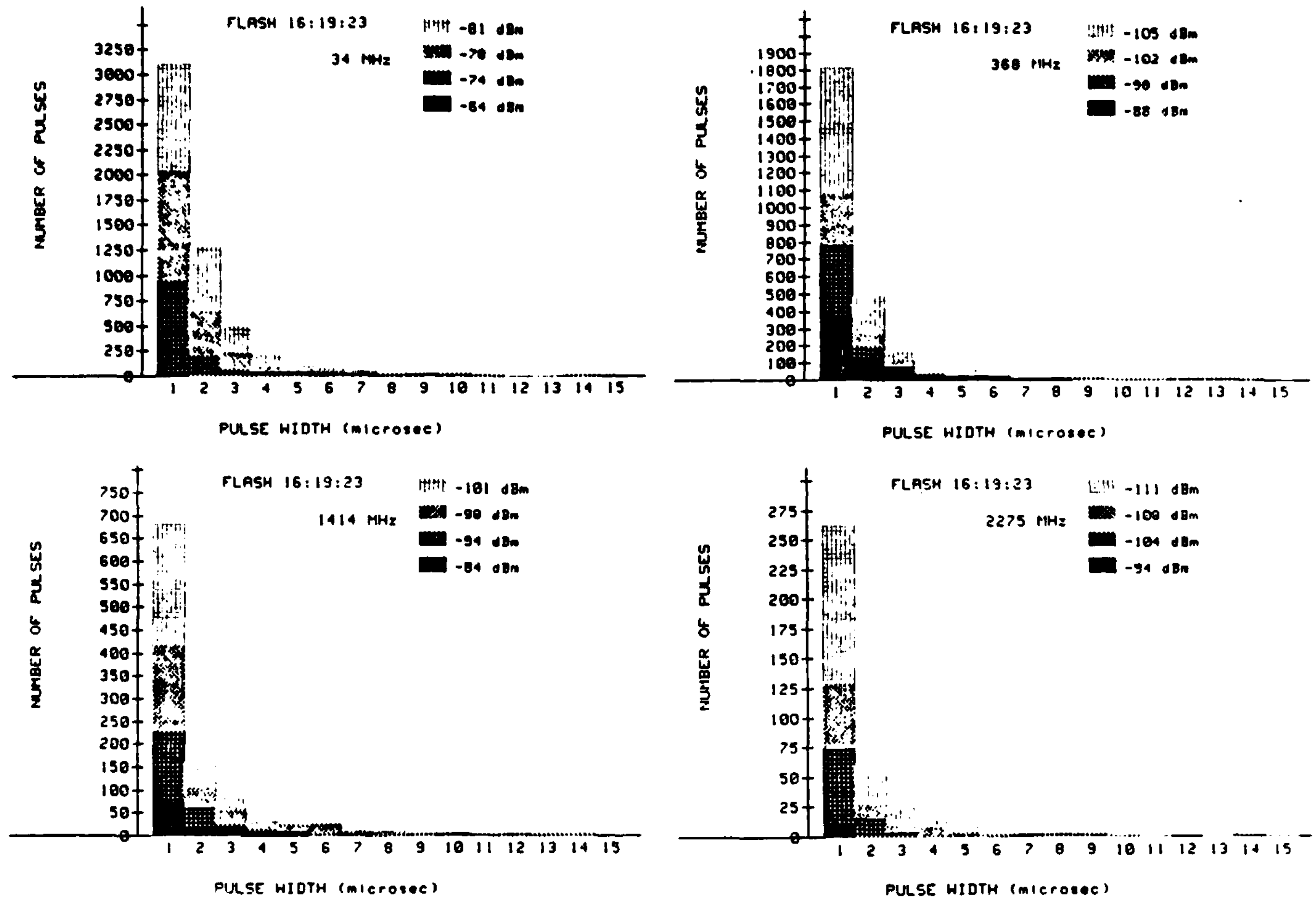


Figure 6. Histograms of the duration of pulses for radiation at four different frequencies. Durations were determined from the time the detected output stayed above the given signal level threshold. The 1 microsecond bin contains all pulses less than one microsecond in duration.

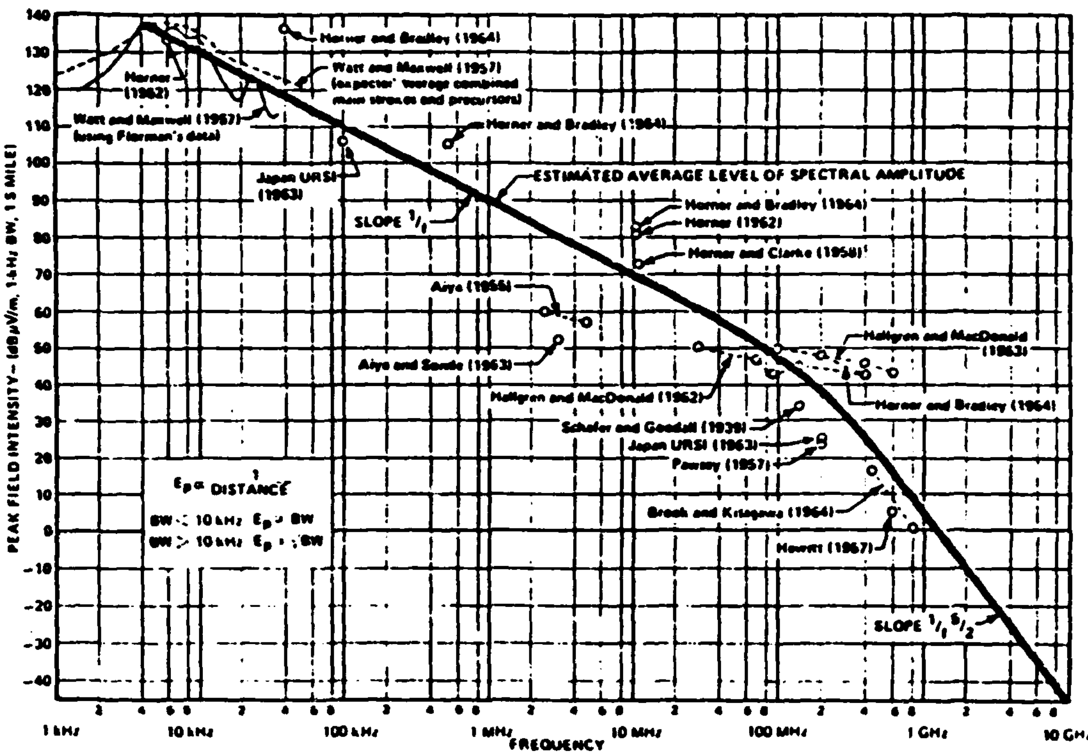


Figure 7. Plot of the spectrum of lightning radiation derived by Oh(1969) from various observations. As pointed out in the text this plot is somewhat misleading.

which are sufficiently narrow to integrate much of the signal. In the spectrum shown in Figure 7 the points from Brook and Kitagawa (1964) and Hewitt (1957) are the dominant points defining the slope of the spectrum. However, the levels used are not received powers but actually the minimum detectable signal characteristics of their receivers. Because the spectrum of lightning at VHF is so poorly specified in the existing literature, we attempted a new set of measurements in the experiment by Rhodes (1985) quoted previously. Although attempts were made at estimating the received power spectrum of the various phases of the lightning flash, the results were of limited value. Large uncertainties in the receiver calibrations and antenna gains together with a lack of knowledge concerning source locations and polarization made accurate estimates of power levels impossible.

It is clear that there are still no reliable measurements of the power spectrum of lightning at VHF frequencies. These measurements are somewhat difficult and expensive to perform. However, when design parameters are discussed in Section III, we will show that a functional system could be designed without these measurements. The fine-tuning of such parameters could be accomplished during the testing of a prototype system.

3. Locations and Movement of VHF Sources. It is important to have some understanding of the locations and movement of the sources of VHF radiation from lightning for two reasons. First, there may be characteristics of their locations which could be utilized to reduce the complexity or increase the performance of the location system. If, for example, all the sources from the flash, or a recognizable portion of it, occurred at the same altitude, the need for measuring elevation angles could be reduced. Second, the sources should not move sufficiently far or fast as to confuse the measurement of their position. In order to obtain an accurate location determination we will need to average over a number of impulses spaced in time. This incoherent average will increase the location accuracy as the square root of the number of impulses averaged, assuming all impulses originate in nearly the same place. If they don't, the location accuracy will not go up as the square root and may even decline.

VHF radiating lightning sources have been located by three different techniques, all based on time differences of arrival between spatially separated antennas. The hyperbolic system uses antennas separated by kilometers. Equal time differences of arrival are situated on hyperbolic surfaces, the intersections of which provide the source location. By using antennas spaced meters apart, the hyperbolic surfaces become cones (i.e., direction cosines), simplifying the computational geometry. Each of these time-difference-of-arrival systems requires recognizable amplitude structure in order to make a measurement. The interferometric method eliminates the need for recognizable amplitude structures by measuring the phase difference between signals at the spaced antennas.

Two hyperbolic systems have been used for VHF lightning studies, the Lightning Detection and Ranging (LDAR) system at KSC and a system built by Proctor in South Africa. The LDAR had provided a few data points per flash in real time allowing for an overview of many flashes in a storm whereas the South African system has been used to provide high detail of a few flashes. Detailed analysis of the LDAR data (Rustan, 1979) has been discredited (Krehbiel et al, 1984a).

Figure 8a shows LDAR data from an entire storm showing height as a function of time. Individual flashes cannot be resolved. The LDAR sources were produced primarily by intracloud discharges and tended to be biased toward the upper or positive end of the discharge. Most of the sources were above 8 km (MSL) altitude and below 12 km (MSL) altitude. The upward sloping radiation patterns were correlated with the occurence of intracloud lightning in individual, growing convective cells. This can be seen in Figure 8b which is a plan view of the radiation sources in during a ten minute interval. Three cells are evident.

Very few points shown in Figure 8a are from channels to ground. This is in agreement with the temporal data presented in the last section in which the channel to ground radiated only during a small portion of the overall VHF radiation.

A consistent feature which emerges from the analysis of a few more storms is the 8 km (MSL) threshold for the LDAR points. Cells did not produce lightning until significant radar echoes extended to 8 km altitude in the cloud and the negative charge center for the lightning appear to remain fixed at a constant altitude (about 7 km, or -15 degrees C) as the cell grew (cf Figure

1). Although we can set a lower threshold for the predominant VHF radiation, a spread (in elevation) of four to six kilometers still exists.

In the previous section two types of VHF radiation were noted. Proctor (1981), using a hyperbolic system, and Hayenga and Warwick (1981), using an interferometric system, have determined propagation speeds for the two types.

The radiation from the short impulsive radiation extends at about 10^5 m/s. Figure 9 shows this drifting motion of numerous sources. The diameter of the drifting region is on the order of 600 meters. Note the horizontal motion of the preliminary breakdown from 0–30 ms and the downward motion of the stepped leader at 30–44 ms.

The longer duration radiation has been labeled Q noise by Proctor and fast bursts by Hayenga. During the few hundred microseconds of radiation these bursts travel at speeds of about 2.5×10^7 m/s, two orders of magnitude faster than the short impulsive sources. Such a burst is shown in Figure 10. Some care must be exercised in determining the speed since it involves differentiating noisy data. The point-to-point length of the path shown is 17 km, yielding a speed of 6×10^7 m/s. Along the smooth drawn in path, representing the general motion, the length is $\sim$6 km giving a speed of 2×10^7 m/s, which we consider more representative.

C. Summary

The results from these studies which are relevant to the feasibility of an airborne system can be summarized as follows:

1. Lightning appears to begin with a negative streamer near the negatively-charged region of the storm. This region is around 0°–15°C temperature. Its actual altitude appears to be storm-dependent. During this phase VHF sources radiation comes in short pulses whose sources move at 10^5 m/s.

2. Ground discharges appear to move downward from this region. The more common intracloud discharges appear to move upward from this region.

3. During many phases of storms lightning may have extensive horizontal extent within the cloud or storm system.

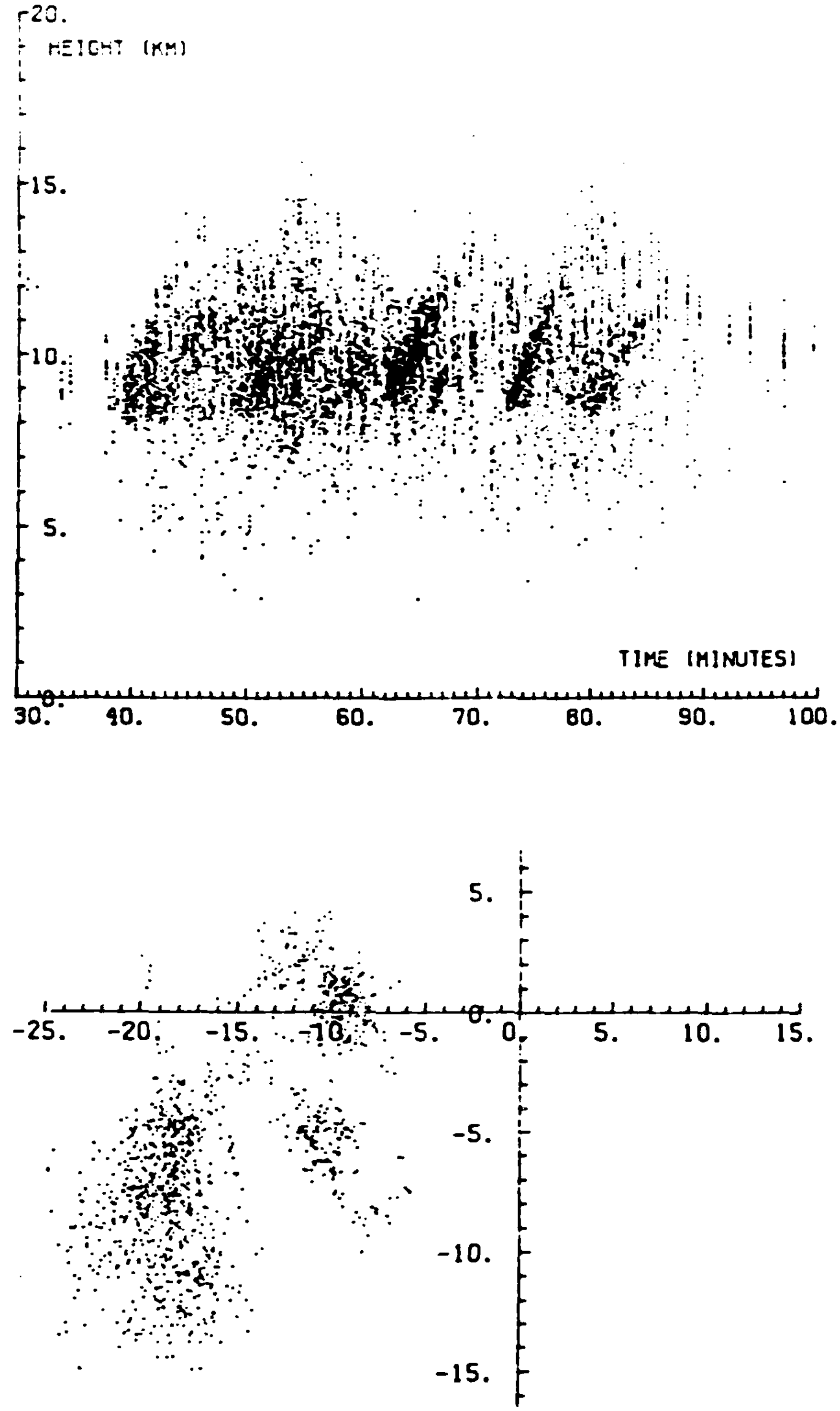


Figure 8. VHF radiation source data for a storm at KSC from the real-time LDAR system. a) Time height plot showing upward trends of points with cell growth. Note that most points lie between 8 and 12 km MSL. b) Plan view of ten minutes of data showing the points grouped in cells. (From Krehbiel et al, 1984a.)

4. VHF radiation also has bursts of hundreds of microseconds duration whose sources move at speeds in excess of 10^7 m/s.

5. Most VHF sources are at elevations >8 km MSL with a spread of some 4 kilometers. It must be emphasized that these results are still new and not yet comprehensive. It is not at all clear what relation lightning activity at a given point in time may have with that 10 minutes later, for example. It can be concluded that the negatively-charged region may remain intact. However, the entire region encompassed by lightning may change dramatically over such an interval, increasing (or even decreasing) by kilometers in both horizontal and vertical extent. If it were necessary to fly a craft within 2-5 km of an active lightning region it would be necessary to monitor the activity on approach rather than rely on data which would become quickly outdated.

While the results presented give some indication of where lightning is occurring within a storm, there is no data to indicate where it will <u>not</u> occur. Neither is there enough data from these studies to develop statistics concerning the probability of a strike to a craft as function of temperature or possibly elevation. Studies by NASA using an F106B (eg. Fisher and Plumer, 1983) may be more helpful in this regard.

A very important aspect which emerges from the phenomenological considerations is the need to detect all discharges, not just the return strokes of ground discharges. Many storms show long intervals with very active incloud flashes and very few ground strokes. No good correlation exists between the location of ground strokes and incloud activity. Aside from the possible errors in actual operation of the Stormscope instrument presented by Parker and Kasemir (1982), phenomenological considerations indicate that the Stormscope would not adequately detect the extent of lightning activity within the cloud and might have a low probability of detection for some storms.

The Stormscope uses the vertically-polarized 50 kHz radiation from lightning. Such radiation comes primarily from return strokes. Any cloud radiation would not follow the model used for range detection which is based on return storkes. It is fortuitous that the errors in the system lead to a larger than actually detected region of avoidance providing a conservative

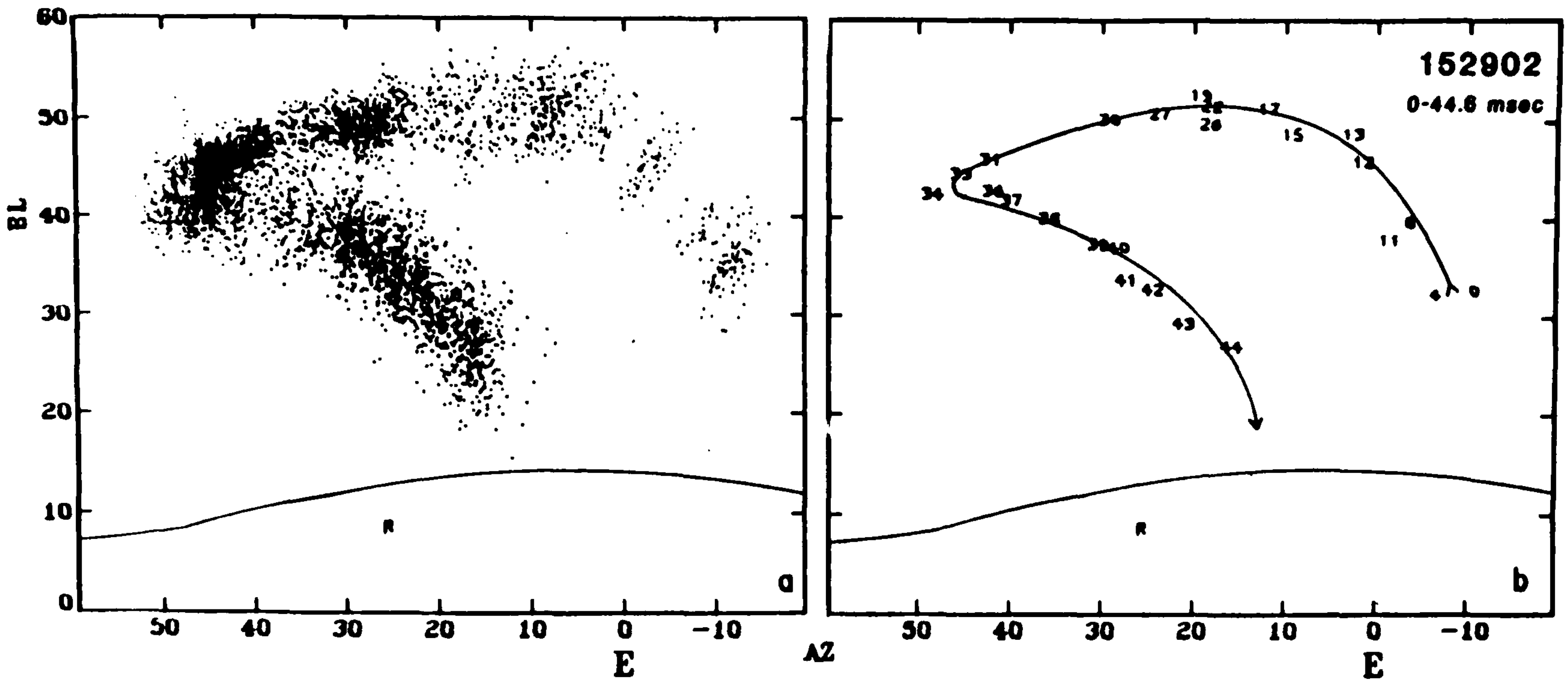


Figure 9. Plot of VHF sources from the first 44 msec of a flash determined with an interferometer system. a) All data points showing a spread of about 600 meters in the points. b) Millisecond averages of the points showing motion of $2x10^5$ m/s. (From Hayenga and Warwick, 1981.)

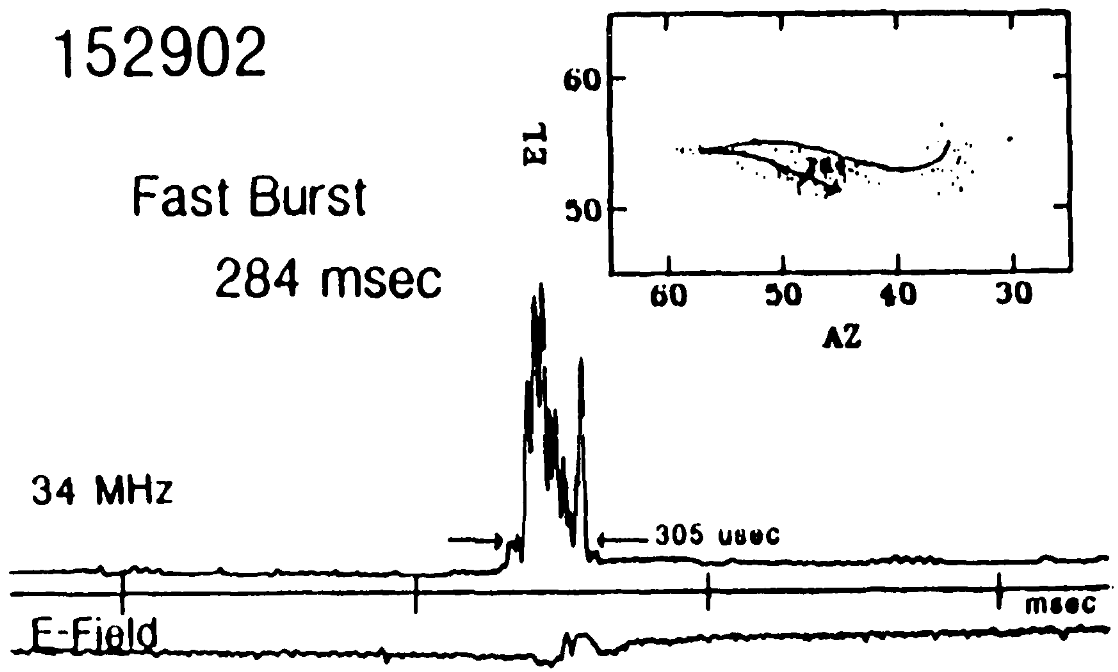


Figure 10. VHF power, electric field change, and source positions for a fast burst. The radiation was continuous for 305 microseconds. The sources progressed along the drawn in path at a speed in excess of 10^7 m/s. (From Hayenga, 1984.)

warning of severe weather as indicated by Baum and Seymour (1979). A more reliable system should detect the incloud hazard as it develops in the path of the craft. The survey of the VHF phenomenology of lightning shows why it is the preferred activity to detect.

III. Propagation Considerations

A. General Considerations

The RF signal from a lightning source can be treated as any other signal in terms of propagation to the aircraft, with a few notable exceptions. Most of the fundamental work on propagation at the frequencies of interest was performed many years ago as reported by Kerr (1951) and Reed and Russell (1953). It is not the intention to rehash any of that work here, but rather to present aspects of it which are relevant to this study and refer the reader to those texts for more details.

A single propagation path consisting of a direct path and a ground reflection path between the lightning source and the aircraft is assumed for this study. This path is shown in Figure 11. he distance between the source and the craft ranges from 10 to 150 km, the aircraft altitude varies from 5000 ft to 30,000 ft above ground and the lightning source varies from 2 to 10 km above ground. A plane geometry (flat earth) is also suitable for this study although corrections might be needed in a prototype phase to account for spherical geometry.

Appendix I shows the elevation angle of arrival for sources within the selected geometry. Plots were made for each aircraft altitude from 5000 ft to 30,000 ft in 5000 ft increments. On each plot the elevation angle of arrival for the direct and ground reflected waves is plotted as a function of range from 10 to 150 km for lightning sources at 2, 4, 6, 8, and 10 km above ground. The range of elevation angles plotted is $\pm$ 20°. These plots demonstrate why the reflected wave must be considered. At higher aircraft altitudes direct waves are received at the same angles at which reflected waves are received when the plane is at lower altitude. The possibly of having a directional antenna which is steered as a function of aircraft altitude was not considered as it would unduly complicate the system.

Anomalous propagation such as ducting, troposcatter, diffraction, or multiple reflections in not considered. Any such propagation would cause an incorrect position determination and would degrade the performance of the system. Most anomalous propagation would affect the apparent elevation of sources with the exception of multiple reflections (such as from moutainsides) which

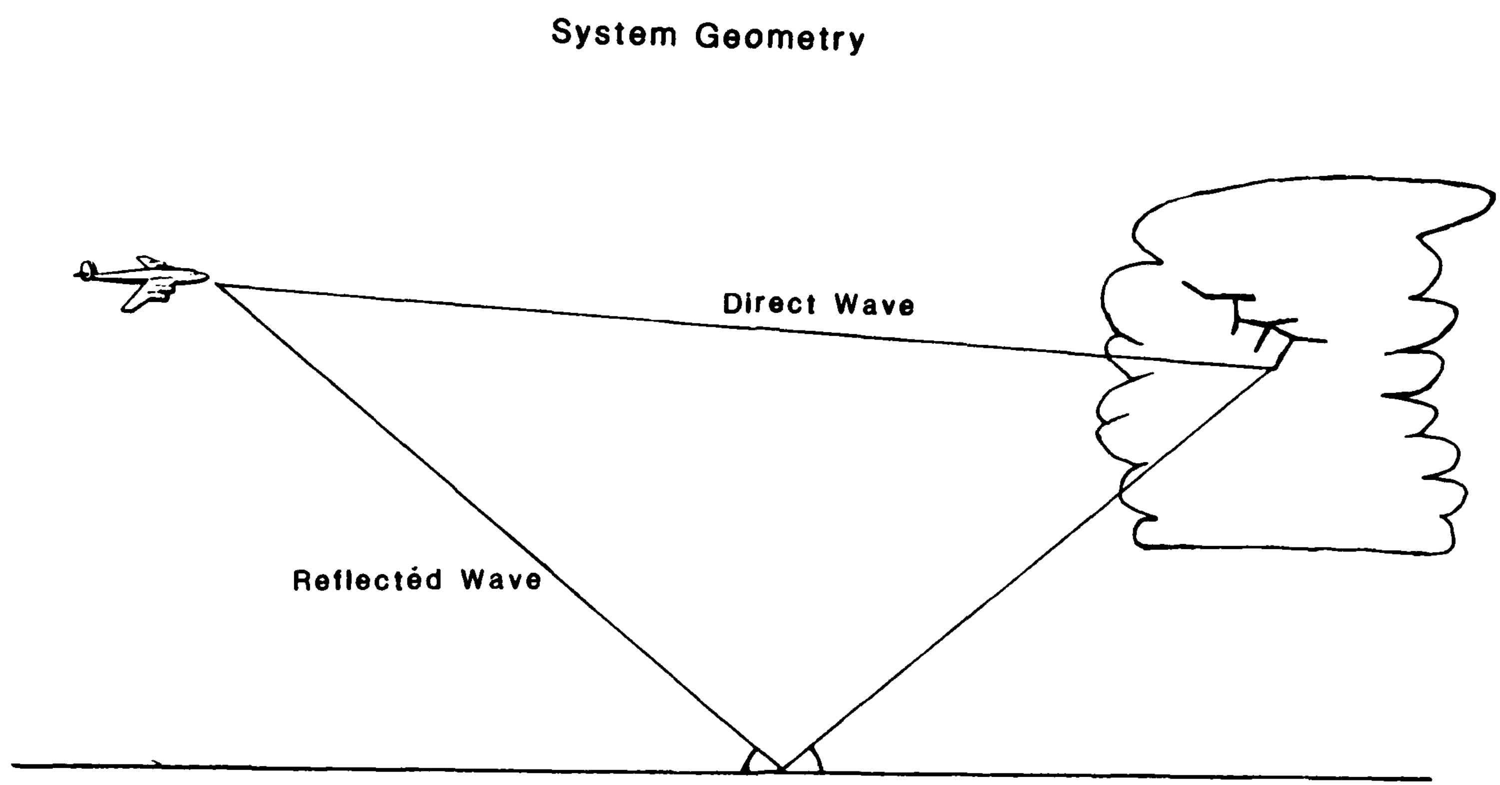


Figure 11. System geometry assumed for this study. It is assumed two waves will be received at the aircraft; a direct wave, and a specularly reflected ground wave. Parameters for the system are discussed in the text.

would affect azimuth determination. This propagation is difficult to characterize with respect to the general operation of this system and should be left for the prototype stage in order to assess the impact on performance with actual data.

Using the assumed propagation path together with the phenomenological considerations of the preceeding sections it is possible to parameterize the operating frequency, required minimum detection level and dynamic range required of the system. The effects of the ground reflection path can also be assessed. Most of this material can be found in standard references (Kerr, 1951; Reed and Russel, 1953; and Erst, 1984) with only a few significant differences.

The most important difference to consider is that the reference texts generally deal with CW signals, i.e. signals of duration long compared to the time for propagation; whereas lightning radiation is very impulsive. Instead of interference lobe structures, the designer of this system must consider multiple pulses from various regions of space with duration and duty cycle such that they may or may not be received simultaneously at the aircraft.

Appendix II shows plots of the difference in path length between direct and reflected path for the geometries of interest. Path difference and equivalent time of arrival difference are plotted as a function of range for the same parameters of aircraft elevation, range, and source height used in the plots in Appendix I. A comparison of the time differences shown and the pulse durations and intervals between pulses given in the previous section shows that the system will receive a combination of isolated pulses from either the direct of reflected waves or simultaneous radiation from both sources with the direct wave radiation starting before the simultaneous radiation and reflected wave continuing on afterward. Any location system must be able to handle any of these situations in order to perform reliably.

B. System Design Parameters

The three design parameters to consider in this section are operating frequency, receiver sensitivity or minimum detectable signal (MDS), and dynamic range of the system. Since these parameters will be interdependent in this system we will consider them together.

The expected signal strength at the receiving antenna will allow a determination of the necessary sensitivity of the system. Only the direct path will be considered initially. The power received, RP, is given by

$$RP = ERP - PL,$$

where ERP is the effective radiated power of the source and PL is the path loss, all measured in dB. Assuming the reference standard of an isotropic receiving antenna, the path loss is given as (Erst, 1984)

$$PL = 92.45 + 20 \log f + 20 \log d,$$

where d is the path length in kilometers and f is the frequency in GHz.

Over the path lengths of interest, from 10 km to 150 km, the path loss varies by 23.5 dB. The data from Rhodes (1985) indicate a variation in lightning signals of less than 40 dB. We can conclude that a 60 dB dynamic range should be adequate for the lightning system. A 60 dB dynamic range is easily achieved with standard receiver design techniques.

The variation in path loss as a function of frequency is 20 dB from 30 MHz to 300 MHz. In the absence of good spectral information the choice of operating frequency in difficult to specify, but a change of about 20 dB in expected ERP from 30 MHz to 300 MHz is reasonable. A system at 30 MHz would need to be about 40 dB less sensitive than one at 300 MHz. In a later section, the need for a higher frequency of operation in order to reduce antenna array sizes is stressed as a trade-off with the push toward lower frequencies to reduce requirements on system sensitivity. In a prototype system design, it is likely that neither factor will define the operating frequency. Any system considered in this report will require a bandwidth of one megahertz or greater, thus making the system susceptable to interference, from both transmitters on the ground and from other systems on the craft. Freeing the system from interference would be the strongest factor influencing the selection of operating frequency. It should be noted that increasing the frequency will require a lower MDS in order to receive lightning at the greater distances, thus again increasing susceptability to interference.

As in the choice of operating frequency it is difficult to determine the required minimum detectable signal (MDS) for this system without accurate information on the effective radiated power from lightning. We can make some estimate from the work of Rhodes (1985). His system at 34 MHz had an MDS of -85 dBm while the system at 368 MHz had an MDS of -100 dBm. Both received lightning signals out to at least 20 km. In order to receive lightning out to a direct line of sight path of 150 km would require an additonal 17.5 dB of sensitivity, or a - 102.5 dBm MDS at 30 MHz and -117.5 dBm MDS at 300 MHz. Assuming a 1 MHz bandwidth, the 30 MHz system could have a noise figure up to 11.5 dB whereas a 300 MHz system would be unattainable without very complicated electronics. From these estimates, it can be concluded that the operating frequency may need to be kept below 100 MHz to avoid system complexities in achieving a reasonable MDS to receive lightning signals out to 150 km. Better definition of these parameters would have to be done empirically during a prototype stage.

During the prototype phase the effect of ground reflections could also be assessed. While there is considerable discussion of reflections in the literature (Reed and Russell, 1953; Kerr, 1951), the effects from the ground on an impulsive, rapidly moving source are not clear. While the losses on reflection may be sufficient to put the reflected signal below detectable levels, there are reasons why it may be desireable to detect the ground reflection (of Section III-C).

IV. Technological Considerations

A. General Considerations

In the previous two sections we have examined the nature of the VHF lightning signal as it originates at the source and the effects of propagation to the aircraft. This section examines the detection of that signal and the processing of the signal to provide information on its location. The determination of location is discussed as two separate determinations, azimuth and range. The azimuth determination covers both bearing and elevation above or below that of the craft. Range determination covers finding the distance between the source and craft.

The discussion of location determinations is made from a systems point of view. Parameters such as accuracy, angular coverage, etc. are discussed without reference to particular hardware implementations. Effects such as errors from hardware are more appropriate for a prototype development phase.

B. Azimuth Determination

1. Expected Resolution. In general, direction finding (DF) systems fit in two broad categories. The first involves comparisons of signal amplitudes received with known antenna patterns to determine the direction of arrival which would produce those amplitudes. The crossed loop direction finder (CRDF) such as Stormscope is a simple example of such a system. To our knowledge no antenna pattern systems have been used at VHF for lightning location, although there are current examples of such systems at VHF being used in military applications. For satisfactory operation a high degree of antenna pattern accuracy is required, along with predictable source polarizations. Carter (1957) has shown that this type of direction finding is not feasible for aircraft implemenation at HF, especially on propeller craft. Most reasons given are also applicable at VHF and for those reasons and the lack of good polarization characteristics of VHF lightning radiation, such systems were not considered feasible.

The second broad category of DF systems involves the correlation of signals received at spatially separated antennas. Systems correlating the amplitudes are usually termed Time-Difference-of-Arrival (TDA or TOA) systems. Those using a phase correlation are interferometers.

Both TOA and interferometric systems have been used for lightning location at VHF frequencies and have been proposed for aircraft implementation (Parker and Kasemir, 1982, Section V. A & B). In their discussion, Parker and Kasemir present the expected bearing errors for the two systems, although the example parameters are not nearly optimum.

For a time of arrival system the angular error ($\Delta\theta$) is related to the time resolution for a given pulse (Δt) approximately by

$$\Delta\theta^{\circ} \sim \frac{60c\ \Delta t}{\alpha}$$

where c is the speed of light and d is the baseline dimension (antenna separation). Note that this is independent of operating frequency. The two ways to decrease angular errors are by increasing d, which is difficult to do in an aircraft system, or to decrease Δt, that is increase the time resolution. Time resolution can be increased by an increase in system bandwidth. This will lead to increased interference from non-lightning noise. Moreover, the pulse rise time will be the limiting factor in determining time resolution. The lightning signal must contain short rise-time pulses of sufficient energy to be received up to 150 km away by a system with sufficient bandwidth to not reduce that rise-time. It is not clear that such pulses occur within lightning radiation with any regularity. The severity of required pulse shape and the susceptibility to interference are sufficient to limit the feasibility of TOA systems for azimuth determination.

The accuracy of angle determination in an interferometric system depends in four parameters of the system; operating wavelength, λ; baseline, d; system bandwidth, B; and the integration or averaging time interval, τ, assuming a signal is present during the entire averaging period. The expected phase measurement error, in degrees, is

$$\Delta\delta^{\circ} \sim \frac{90}{2\pi}\,\frac{\lambda}{d}\,\frac{1}{\sqrt{2B}^{\,1}}\ ,$$

as derived by Hayenga (1979). Angular errors are of the same order, but are dependent on actual direction of arrival as shown by Jacobs and Ralston (1981).

The four parameters for determining the accuracy of angular measurement for an interferometric system are not only interrelated but also are related to many other aspects of system design, such as angular coverage, system complexity and system size. Much flexibility exists in the definition of a system by trading-off various aspects of the system. Before indicating choices for any particular system we will spell out the various trade-offs possible with these parameters.

In the previous sections, we presented phenomenological and propagational reasons for using a lower frequency of operation for a location system. For an inteferometric system, longer λ requires that the baseline, d also be increased in order to maintain the same accuracy and requires that antenna size increase to maintain system sensitivity. Both impact the size of the system require a trade-off with aircraft size.

For a system receiving a hemisphere with a baseline longer than $\lambda/2$, the phase measurement will be ambiguous, since phase is only measured modulo 2. Jacobs and Ralston (1981) discuss methods for resolving this ambiguity by adding antennas. Ambiguity resolution roughly double the complexity of a system, so initially we will consider only a system with $\lambda/2$ baseline length. At 30 MHZ, this would mean a baseline of 5 meters, reasonable for placement on most aircraft wings. Below 30 MHZ, aircraft interactions become important (Carter, 1957).

With the limitation to a $\lambda/2$ baseline, the error equation now is dependant on the inverse square root of the product of B and τ. Precision is increased by maximizing the Bτ product. Hayenga (1979) and Richard and Auffray (1985) have shown that B must be no more that one tenth the operating frequency to maintain signal coherency, and ideally should be less. In the VHF band, B would range from 3 Mhz at 30 Mhz to 30 Mhz at 300 Mhz. However, it is certain that for a system to operate in the general environment throughout which an aircraft would fly interference from non-lightning sources will limit B much further. It is more feasible to consider 1 Mhz as a maximum reliable bandwidth. Choice of bandwidth and operating frequency will have to be chosen carefully during prototype development to avoid interference.

With the assumed 1 Mhz bandwidth and $\lambda/2$ baseline the error equation is dependent only on τ.

Representative values of $\Delta\theta$ for various values of τ are:

τ	$\Delta\theta$
1 μs	21°
10 μs	6.5°
100 μs	2.1°
1 ms	$.65^{\circ}$

At 150 km (worst case) range, the 2.1° resolution obtained with a 100μs averaging interval corresponds to a region 5.5 km across. Phenomenological considerations have been presented earlier showing the need to monitor regions of activity as the craft approaches to note any evolution in the lightning producing regions. By the time the craft is within 50 km of the lightning activity the 2.1° resolution now corresponds to a region less than 2 km across. This is less than a tolerable distance for avoidance of lightning within clouds. It is safe to conclude then that a reliable 2° resolution in azimuth is sufficient for the operation of this system and would be attainable with a 100 μs averaging time. However, the error equation is only valid if all sources occurring within an averaging interval, τ, arrive from the same angle $\pm\Delta\theta$. Multiple (simultaneous) sources or *rapidly-moving sources will invalidate the equation.* In research implementations τ, has been kept very short (~1-2 μs) in order to avoid these problems. Since an airborne system does not need such high time resolution, we can use other methods to deal with potential problems from multiple or moving sources.

The short, impulsive radiation whose sources move at $\sim 10^5$ m/s will not present a major problem. The speed represents only a movement of 10 meters in 100 microseconds, with the spread of sources around this motion an order of magnitude larger. An average of these points will locate the proper region of space. Since the duty cycle during these periods of radiation is about 20% (Hayenga and Warwick, 1981), the actual interval of averaging would be on the order of 500 microseconds. The occurence of the pulses could be determined with an amplitude threshold criteria, but this would not be necessary as the phase measurements of the noise are random and would cancel in the average.

The fast-moving ($\sim 10^7$ m/s) sources of radiation would cover 1 km in the 100 microsecond averaging time. A single data point at the average position would represent this motion and might be misleading for nearby sources. The 1 km source extent would cover more than the assumed 2^0 resolution for sources closer than 28 km away.

Multiple sources would occur for two reasons. First, there is the possibility of radiation occurring in different parts of the sky during the 100 microsecond averaging time (or 500 microseconds if the duty cycle is considered). Second, the ground wave and direct wave sources will combine to form three distinct sources; the direct wave alone, the ground wave alone, and the superposition of the two sources. With a simple interferometer, it is not possible to determine from a phase measurement the multiple sources giving that phase measurement. However, it is possible to determine the phase measurement which will result from a given distribution of sources. The details are presented in the Appendix to Hayenga and Warwick (1981). It is shown that for two sources of small separation ($<10^0$), the result of these sources is a single source location between the two. If we allow small deviations in source position but reject large deviations, the correct region of lightning occurence can be identified.

It appears feasible to overcome potential problems from moving or multiple sources in the following manner. Tests run on a TMS 320 evaluation board and experience with the new generation ground-based interferometer (Hayenga, 1983) have shown that it is possible to process interferometer (Hayenga, 1983) have shown that it is possible to process interferometer data in a pipe-lined fashion in less than 5 microseconds per location. Assume we process every 10 microseconds of data. The expected error is 6.5^0 per data point. If we store some 50 data points (ie 500 microseconds of data) we can perform a Random Sample Consensus (RANSAC) as described by Fischler and Bolles (1981) to determine the subset of those data points which came from the same region of space. The algorithm eliminates data points far away from an average of the data. Most averaging techniques rely on the assumption (smoothing assumption) that the maximum expected deviation of any datum from an assumed model is a direct function of the size of the data set and that there will always be enough good data to smooth out gross deviations. As this may not hold for moving or multiple sources, the RANSAC algorithm is well suited to this application. The algorithm has three unspecified parameters; the error tolerance used to determine whether or not a point should be accepted, the number of subsets which must be tried, and the threshold value for the number of compatible point necessary to imply that the solution is valid. We can set the first at 10^0 as determined from the expected error for a 10 microsecond average. The third parameter should be greater than 10 to ensure that the equivalent 100 microsecond average is obtained. The second parameter would have to be determined at prototype stage by the available processing power and actual prototype tests on data to indicate performance.

In summary, a single, half wavelength interferometer system should provide angular resolution of 2^0 with a time resolution of about one half millisecond. For a typical flash of one half second we would have one thousand data points. From consideration of the duty cycle for radiation given by Hayenga and Warwick (1981) and Rhoded (1985) we expect some 20 to 100 to pass the consensus algorithm as valid data to be passed on for display.

2. Configuration and Angular Coverage. Possible interferometer configurations and the resultant angular coverage are very difficult to specify in any general fashion. Allowable antenna type and location points will vary considerably from one aircraft to another. The site errors and potential shadowing from the craft will then also be craft-dependent. A horizontal baseline for azimuthal coverage is easier to find on a craft than is a vertical baseline for elevation coverage. For the sake of this feasibility study we present the simplest configuration, discuss the coverage and errors that result and suggest additions which could enhance performance.

We assume a source can arrive from any azimuth but will be limited to about + 20^0 in elevation during normal operation as shown in Appendix I. The simplest configuration would be two antennas separated by one-half wavelength located on the leading edge of the wings of the craft, thus limiting the patterns to the forward direction (Johnson and Jasik, 1984, chapter 37). This configuration would not be capable of elevation angle determination.

Figure 12 shows lines of constant phase measurement for the forwad 180^0 in azimuth and $\pm 20^0$ in elevation. The measured phase equals the product of the sine of the azimuth angle and the

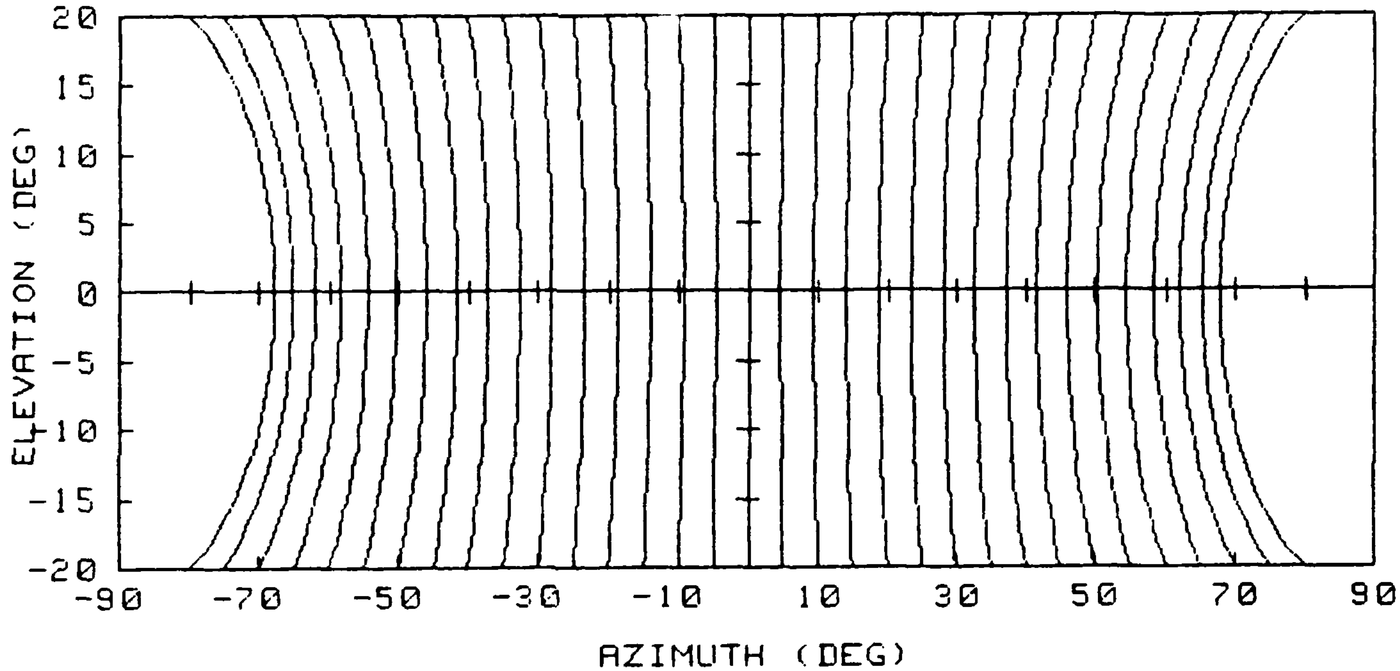


Figure 12. Plot of lines of constant phase difference versus azimuth and elevation angle for an interferometer with a horizontal baseline. If only the single baseline is used, sources occurring at large elevation and azimuth angles will not be located at the proper azimuth. The error is given by the difference between the actual azimuth and the intersection of the constant phase line for the source with the 0° elevation line.

cosine of the elevation angle (Hayenga and Warwick, 1981). Sources not at 0° azimuth with respect to the aircraft would lead to an error in azimuth determination. For example, consider a source at -60° azimuth at 60 km range, 8 km above ground received by a craft at 15000 ft. From Appendix I, the direct wave would arrive at $+4^{\circ}$ el and the ground wave at -12° el. Figure shows the sources and the possible source azimuth determinations which would be made from each wave and the the combined wave. The direct wave would be located at 57.6°, the ground wave at 57.9°, and combined wave at 58.7°. The errors due to geometry in this example are only slightly larger than the expected system errors. At azimuth angles less than + 60° the errors decrease. For the same configuration except on azimuth of 80° the sources are fixed at 70°, 74°, 76.5°; and the errors are now significant.

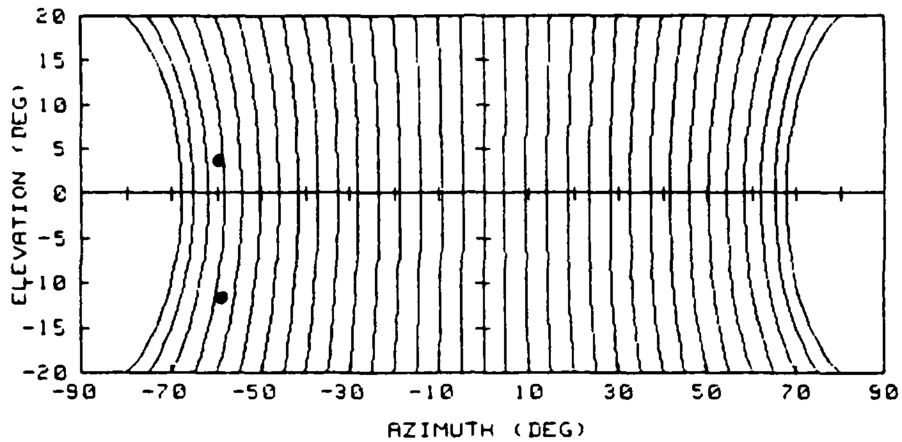
It should be noted from Figures 12 and 13 that the largest geometry errors occur at large azimuth and elevation angles. In other words errors increase outward from the flight path. The larger errors at the edges of the geometry would not be as critical as if they had occurred near the flight path.

In summary, a single horizontal base line should be capable of providing azimuth angles within the 2° expected error of the system over $\pm$ 60° in azimuth from the flight path. This anticipates that potential site errors can be reduced to the same level during prototype development. Consideration of a crossed baseline (i.e., vertical) for elevation determination can be done from the previous discussion by rotating the diagrams by 90°.

C. Range Determination.

In their survey, Parker and Kasemir (1980) suggest that two interferometers placed at the wingtips of an aircraft might be used to determine range by triangulation. If r is the spacing of the two systems, to first order the angular resolution needed to triangulate at range R is given by the angle that r subtends at range R. In degrees the angular resolution, $\Delta\phi$, for triangulation is approximately

$$\Delta\phi = 5.73 \frac{r}{R} .$$



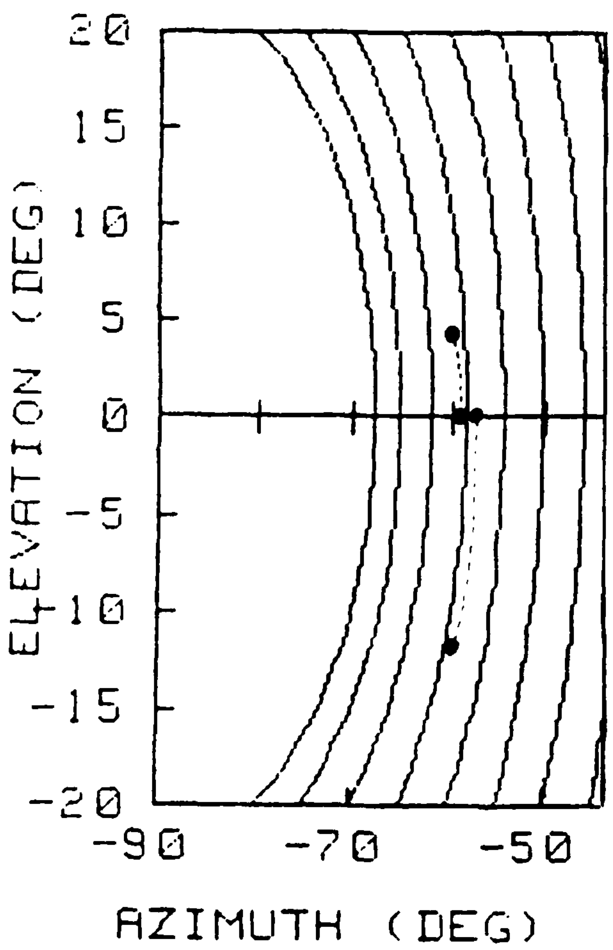


Figure 13. Illustration of azimuth error for direct and reflected wave from a source at 60° azimuth. Actual values of the errors are given in the text.

It is easy to show that triangulation is not feasible. If we assume a moderate-sized craft with $r = 30$ meters, the 2^0 angular resolution quoted in the previous azimuth determination section would allow ranging to 1 km. To range to 150 km would require an angular resolution of $.01^0$. This is clearly not feasible by any method known to the author.

In the phenomenology section we presented results from studies of radar returns from lightning. By scaling the antenna size from those studies down to size suitable from aircraft and than scaling up the required transmitted power to accomodate the reduction in antenna gain and keeping all other factors constant, a radar of 1-10 megawatts pulse power would be required to see lightning channels out to 150 km. We can conclude that radar is not feasible for ranging on lightning.

A method for range determination using the RF radiation from lightning which might be feasible uses the path length difference in propagation of the direct and reflected waves from the source. This path difference appears at the aircraft as a time difference between the direct and reflected waves which would be identical signals except for changes upon reflection of the reflected wave. *Studies presented by Reed and Russell* (1953) *showed little change in pulse* shapes between direct and reflected signals. Markson (personal communication, 1985) is studying the effects of reflection on lightning signals.

Appendix II shows plots of the path difference and time delay between the waves for the system geometry. The difference is a function of source height, source range, and aircraft altitude. Since the aircraft altitude is known, range determination involves measurement of the time delay and source height or elevation angle seen at the craft.

Measurement of the time delay is very straightforward. The impulsive lightning signal above would not have a strong autocorrelation over the one to forty microseconds of the the delay times given. If we perform an auto-correlation on the received signal which consists of the direct and ground reflected signals, we can expect the strongest autocorrelation peak to occur at the path delay. In effect, the direct and ground-reflected signals are being cross-correlated. The implementation of the autocorrelation could be done with analog, digital, or hybrid technology in the prototype stage. As this is a rapidly advancing technology, it would be premature to suggest a technology. From the plots we conclude that a resolution of about 200 ns in the first 10 microseconds and 1 microsecond from 10 to 40 microseconds would be sufficient for the correlator.

This range determination method critically depends on the height of the source. For example consider a measured delay of 2 microseconds when the aircraft is at 15,000 ft. At the extremes, this could be due to a source 2 km above ground at 30 km or a source 10 km above ground at 150 km as shown in Figure A-II-3. Using terrain information and the phenomenological consideration that VHF lightning sources occur mostly from 8-12 km MSL we might reduce the height spread to four kilometers, say 4-8 km above ground. The possible range to the source is now from 60 to 120 km. Figure I-A-3 shows very little change in elevation angle of arrival for sources from 4 to 8 km above ground in the range from 60 to 120 km. It does not appear feasible to determine range at long distances by this method since there is no accurate estimate of the elevation angle of arrival.

At closer range, where accurate range is more important, the situation is much better. As the plots in Appendix I demonstrate the elevation angles of arrival for various sources heights spread out at shorter ranges. This allows a better estimate of source height for a given angular resolution of the elevation angle of arrival. As noted in the previous section, a sourc. will usually appear at three elevations, from the direct, reflected, and combined waves. These estimates of source height together with the time delay would be sufficient to devlop an estimate of the source range. For example, consider a measured time delay of 9 microseconds with the aircraft at 15,000 ft. Source heights and range vary from a 4 km high source at 15 km range to a 10 km high soruce at 30 km range (Appendix II Figures). The 10 km high source direct wave would arrive at + 11° elevation whereas the 4 km high direct wave would arrive a -3° elevation, a difference easily measured (Appendix I Figures).

The above examples illustrate that the ground reflection technique is feasible for close ranges (<~60 km) but not very accurate at longer ranges. If the technique is implemented in a prototype design a complete error analysis would be necessary.

It is implicit that this technique requires the measurement of elevation angles of arrival using a vertically oriented interferometer baseline. We would recommend this for a prototype stage. However, research on the location of VHF sources from lightning indicate that all flashes may originate near the negative charge layer which has also been tied to the environmental temperature. If these indications can be verified by further basic research, it would be feasible to make a range determination using only the initial few milliseconds of a flash and an assumed height. This could eliminate the need for the vertical baseline and its attendant doubling of system complexity.

In summary, the ground reflection technique for range determination falls off in accuracy at increasing range. The technique is untested in that no actual data of lightning radiation received at an aircraft with reflected and direct waves exists. Tests should be performed on the effect of reflection on lightning signals in the lower VHF range and the correlation with the direct wave as a first step in prototype development.

V. Conclusions

The feasibility of an airborne lightning location system using the VHF radiation from lightning has been examined in this report in three areas. From the phenomenological standpoint we have shown that our current understanding of the VHF radiation from lightning is still very limited but appears promising for a detection system. We have shown that there is little established connection between lightning location and other potential weather hazards from thunderstorms such as turbulence or hail. Further basic research on thunderstorms must be performed before we can use lightning location as an indicator for other hazards. The phenomenical considerations of source size, movement and variability in extent from flash to flash are basic limitations to any system. No new information can be gained by a more technically advanced system.

There are significant potential problems which must be considered as the lightning signal propagates to the aircraft. The system must be considered as a complete link including source characteristics, propagation, and receiver design. Again, the lack of basic research on VHF lightning characteristics limits the information available for system design somewhat, requiring some empirical work at a prototype stage.

From the technical standpoint we have shown that an interferometric system operating in the 30-100 MHz range with 1 MHz bandwidth is feasible for locating lightning in the range from 10 to 150 km. Angular coverage of $\pm 60^0$ with 2^0 resolution appears feasible with a single baseline of one half wavelength. A second baseline would resolve elevation if desired. Range determination by ground reflection is feasible with resolution ~5 km for ranges less than ~60 km but degrades severely at longer ranges. The technical considerations are tied to our current phenomenological understanding. It should be stressed that current constraints are not technical, but phenomenological.

Hardware specific problems were not addressed. These include antenna type and size and possible siting errors on the craft. It is assumed that these can be specified sufficiently well in a prototype to not degrade the given performance expectations. Tolerances of components in the interferometer were not addressed. From our experience with the construction of a ground station these will not be a problem in the airborne system.

VI. Recommendations.

Two recommendations emerge readily from this study. First, the study was limited by our current understanding of the VHF radiation from lightning. Although significant advances have been made, more remains to be done, especially in areas of relating the sources of this radiation to the thunderstorm environment. Not only would such continued research help further define the possibilities of an airborne system, such research would also aid in the testing of an airborne system. We anticipate difficulty in testing a system which detects a still somewhat unknown phenomena in the sense of sorting out technical problems from phenomenological variations.

The second recommendation concerns the construction of the prototype unit. We do not consider theoretical considerations sufficient to determine fully the feasibility of an airborne system. We have attempted to address these aspects which affect operation of this system, but can obviously make no claim about having seen every possible problem. The construction and testing of a prototype system could more accurately address a number of areas which were only addressed as possible problems or areas needing more work.

Specifically, we recommend a prototype crossed baseline interferometer system with one half wavelength baselines operating in the region from 30–100 MHz which has tolerable interference levels. This would allow assessment of azimuth and elevation determinations.

We suggest a bandwidth of 1 MHz with integration by the methods discussed of half millisecond intervals. We also recommend studies on the ground reflected waves from lightning as seen from an airborne receiver as first test of the ranging method described. As a second step a correlating receiver would be integrated with the interferometer with appropriate pro-cessing to determine range from elevation and time delay information. We also stress the need to study carefully the means by which the performance of such a prototype system would be evaluated.

Appendix 1

Elevation Angles in System Geometry

This appendix contains six plots of the angle of arrival in elevation of sources within the system geometry. The software used to generate the plots is also listed. For the system geometry we assumed the distance to the lightning source would range from 10 km to 150 km. Source heights were assumed to range from 2 km to 10 km above ground with the plots showing source heights in two kilometer increments. Each plot is for a fixed aircraft altitude ranging from 5000 ft above ground to 30,000 ft in 5000 ft increments.

A flat-earth geometry was assumed for this study and the direct and specularly reflected waves are shown. In actual design a spherical earth must be used. These plots also have no corrections for refraction or anomalous propagation. Such factors must also be treated completely in actual system design. The effects would not significantly affect conclusions derived from these figures.

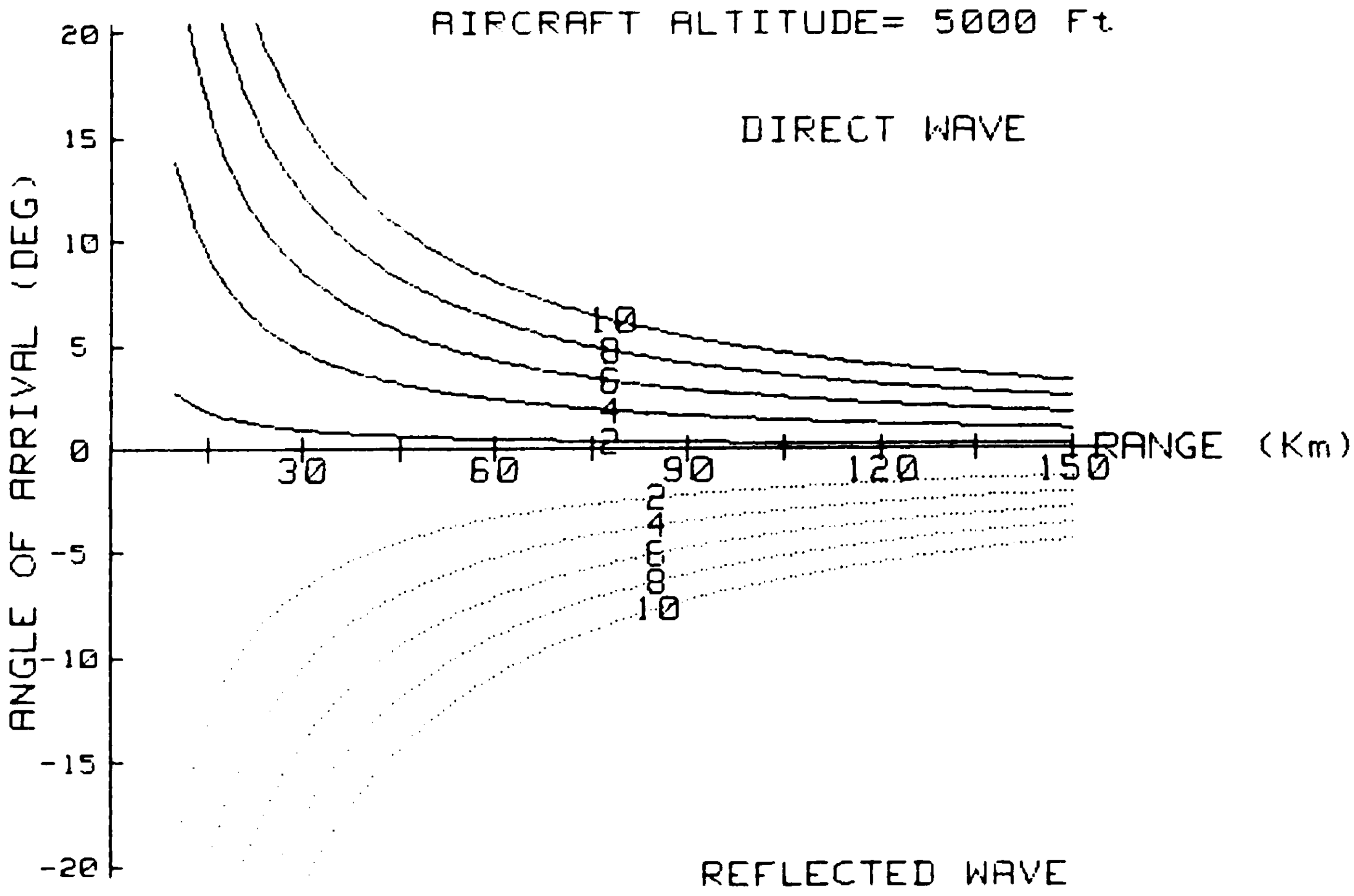


Figure I-A.1. Elevation angles of arrival for sources with craft at 5000 ft.

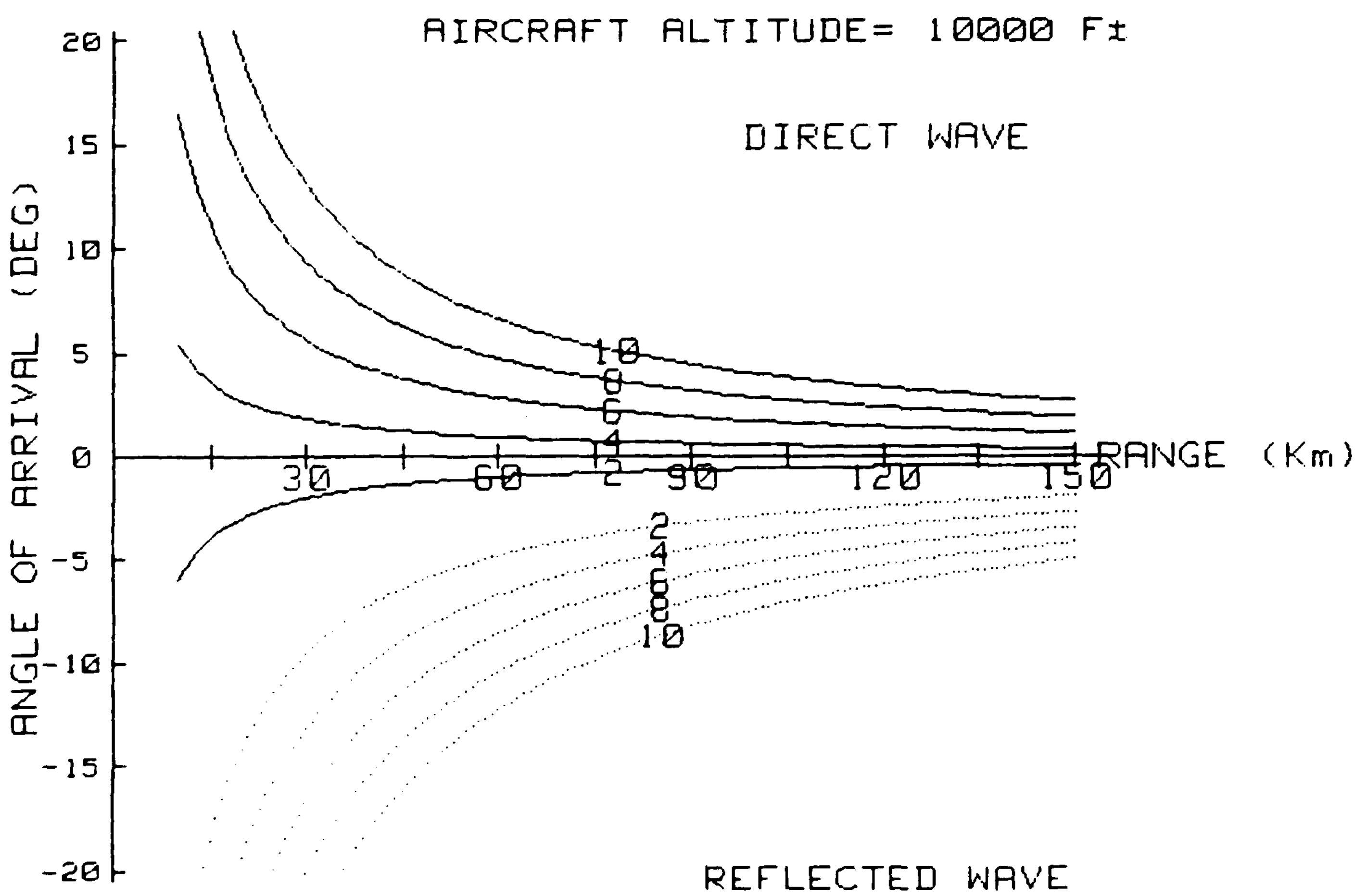


Figure I-A.2. Elevation angles of arrival for sources with craft at 10,000 ft.

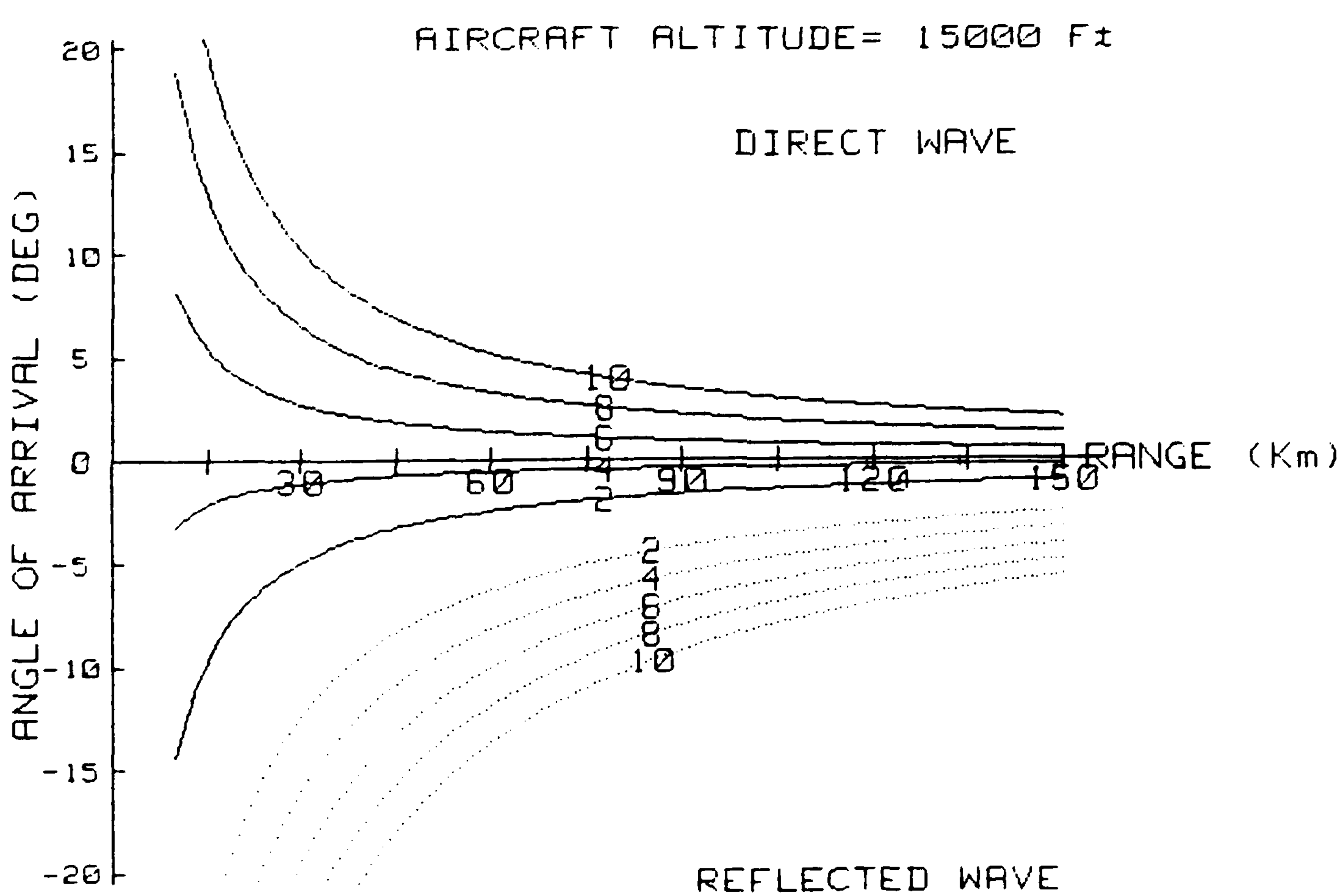


Figure I-A.3. Elevation angles of arrival for sources with craft at 15,000 ft.

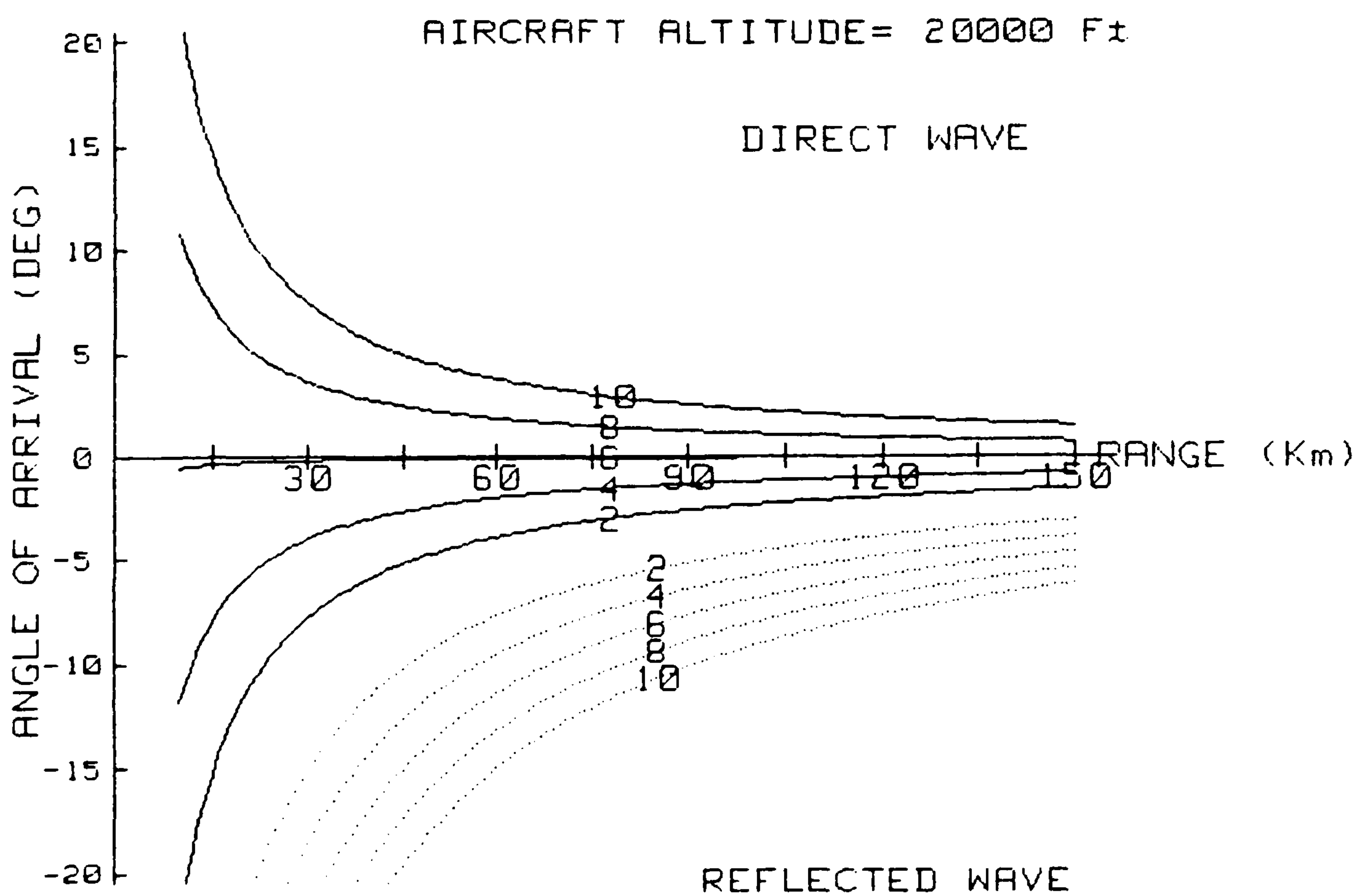


Figure I-A.4. Elevation angles of arrival for sources with craft at 20,000 ft.

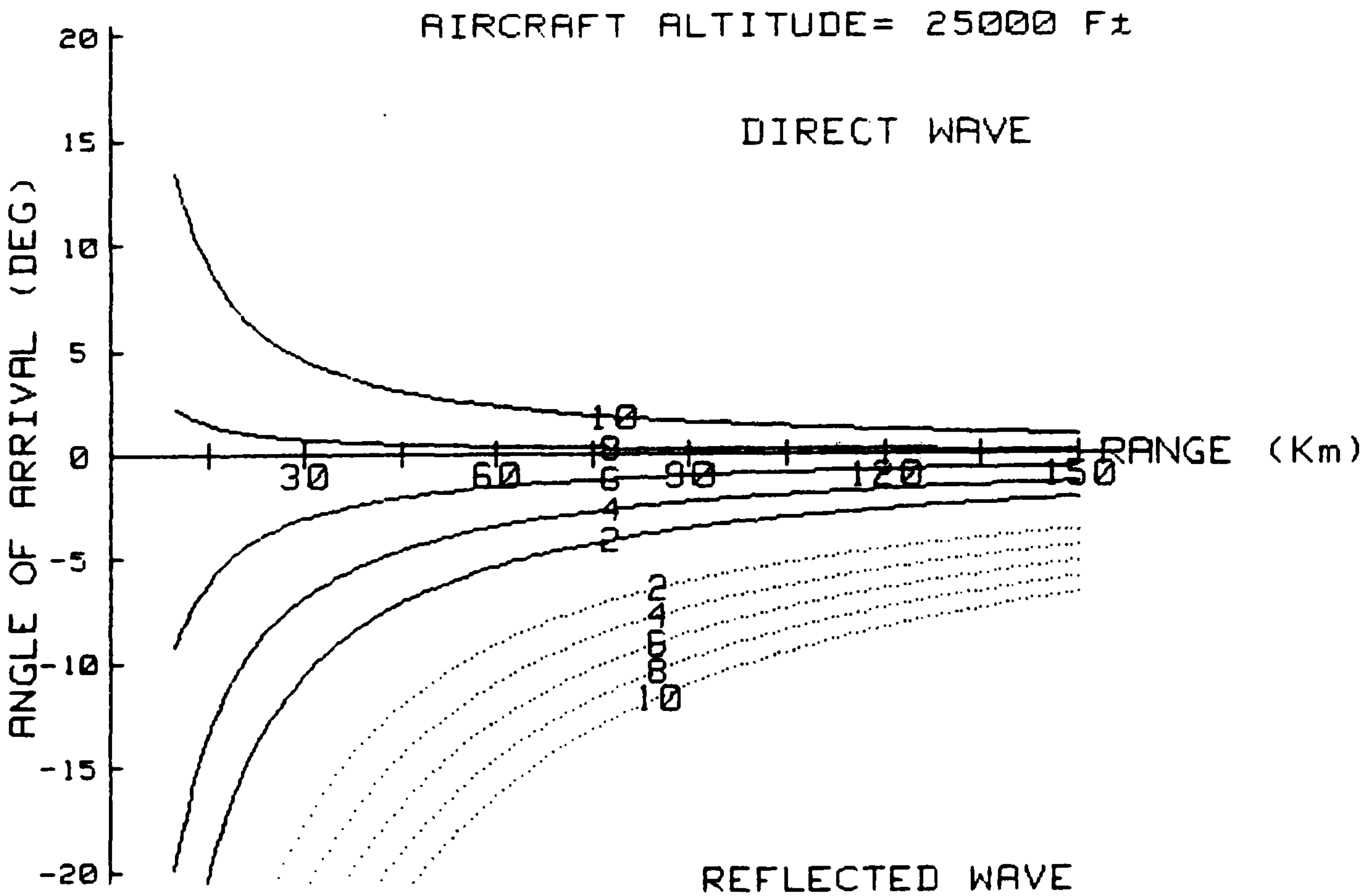


Figure I-A.5. Elevation angles of arrival for sources with craft at 25,000 ft.

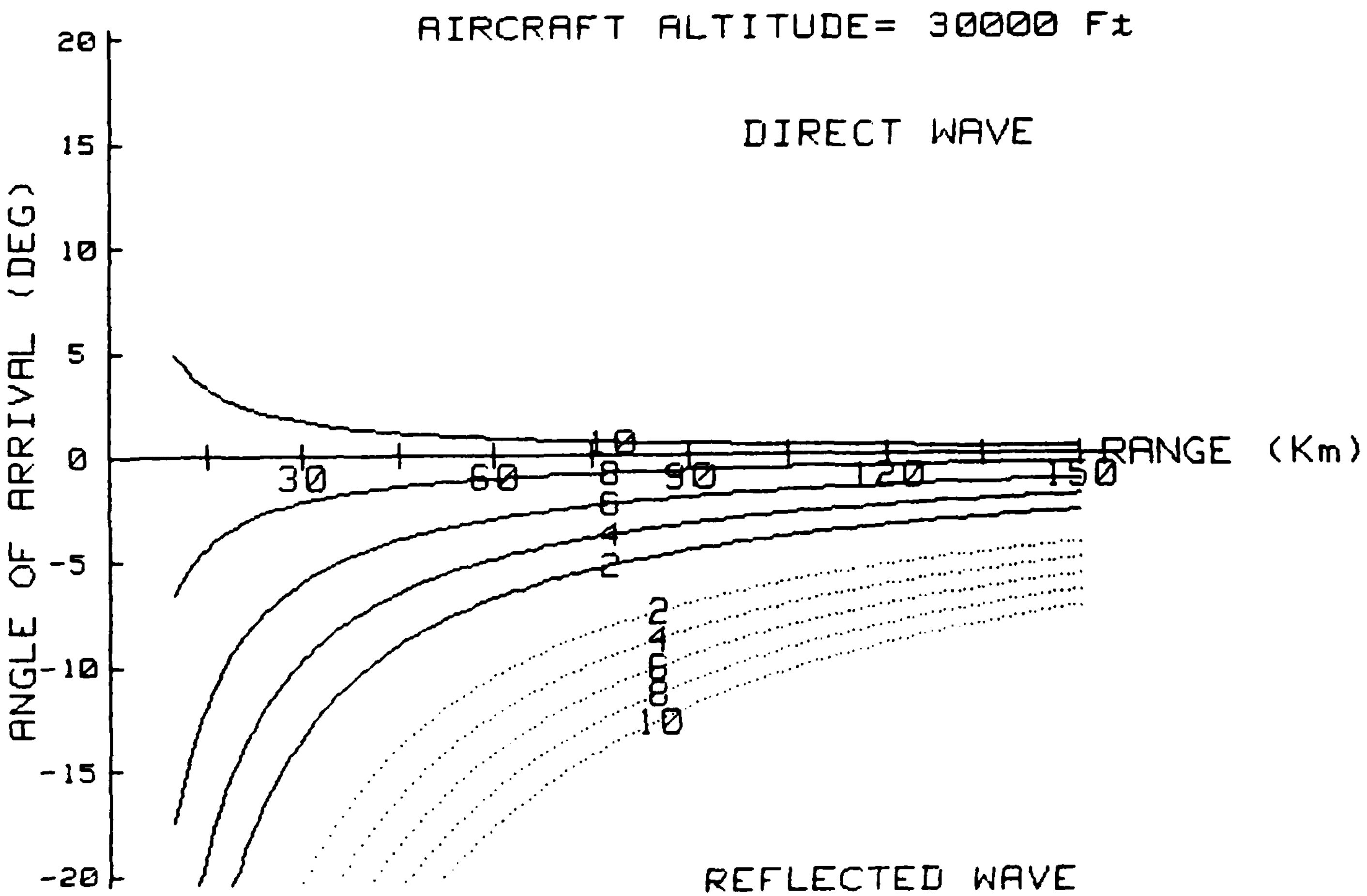


Figure I-A.6. Elevation angles of arrival for sources with craft at 30,000 ft.

```
10     ! PROGRAM BOUNCE
20     ! THIS PROGRAM CALCULATES THE ANGLES OF ARRIVAL OF THE
30     ! DIRECT AND REFLECTED WAVES FROM AN ELEVATED RADIO SOURCE
40     ! TO AN AIRBORNE RECEIVER.
50     ! VERSION 1.02.C. Rhodes..
60     ! GEOPHYSICAL RESEARCH CENTER..
70     !
80       OPTION BASE 1
90       DEG
100      PLOTTER IS 3,"INTERNAL"
110      GRAPHICS ON
120      GCLEAR
130      PRINTER IS CRT
140      PRINT CHR$(12)
150    !
160    !
170    ! THE FOLLOWING LINES OF CODE
180    ! GENERATE AND PLOT THE ANGLES OF
190    ! ARRIVAL FROM THE SOURCE OF THE
200    ! DIRECT AND GROUND-REFLECTED WAVES.
210    !
220 Again:     !
230      GCLEAR
240      INPUT "ENTER AIRCRAFT ALTITUDE IN FEET",Alt
250      H2=Alt*.3048
260      VIEWPORT 10,100,10,90
270      Res$="LOW"
280      INPUT "ENTER Y AXES RESOLUTION DEF=LOW",Res$
290      IF Res$="LOW" THEN
300          WINDOW 0,1.55E+5,-91,91
310          AXES 15000,10,0,0
320          GOSUB Low
330      ELSE
340          WINDOW 0,1.55E+5,-10.5,10.5
350          AXES 15000,1,0,0
360          GOSUB High
370      END IF
380      LINE TYPE 1
390      FOR Y=2 TO 10 STEP 2
400          FOR X=10 TO 150
410              D=X*1000
420              H1=Y*1000
430              Theta=-(ATN((H2-H1)/D))
440              MOVE 0,0
450              PLOT D,Theta,1
460              LORG 5
470              CSIZE 4
480              IF (X MOD 75)=0 THEN LABEL Y
490          NEXT X
500      NEXT Y
510    !
520      LINE TYPE 1
530      FOR Y=2 TO 10 STEP 2
540          FOR X=10 TO 150
```

```
550               H1=Y*1000
560               D=X*1000
570               Phi=ATN((H2+H1)/D)
580               PLOT D,-(Phi),1
590               LORG 5
600               CSIZE 4
610               IF (X MOD 70)=0 THEN LABEL Y
620           NEXT X
630           PENUP
640       NEXT Y
650    !
660       GOSUB X_axes
670       INPUT "ANY FURTHER PLOTS?",Answer$
680       IF UPC$(Answer$)="Y" THEN Again
690       STOP
700 Low:   !
710    !
720    !
730       VIEWPORT 0,120,10,90
740       WINDOW 0,120,-91,91
750       FOR I=-9 TO 9
760           MOVE 7,I*10
770           LORG 5
780           CSIZE 2.5,1
790           LABEL I*10
800       NEXT I
810       MOVE 4,0
820       CSIZE 4
830       LDIR 90
840       LABEL "ANGEL OF ARRIVAL (DEG)"
850       LDIR 0
860       VIEWPORT 10,100,10,90
870       WINDOW 0,1.55E+5,-91,91
880       RETURN
890 High:      !
900    !
910    !
920       VIEWPORT 0,120,10,90
930       WINDOW 0,120,-10.5,10.5
940       FOR I=-10 TO 10
950           MOVE 7,I
960           CSIZE 2.5,1
970           LORG 5
980           LABEL I
990       NEXT I
1000      CSIZE 4
1010      LDIR 90
1020      MOVE 2,0
1030      LABEL "ANGLE OF ARRIVAL (DEG)"
1040      LDIR 0
1050      VIEWPORT 10,100,10,90
1060      WINDOW 0,1.55E+5,-10.5,10.5
1070      RETURN
1080 X_axes:  !
```

```
1090  !
1100  !
1110     VIEWPORT 0,120,0,100
1120     WINDOW 0,120,0,100
1130     MOVE 111,50
1140     CSIZE 3.0
1150     LABEL "RANGE (Km)"
1160     VIEWPORT 10,100,0,100
1170     WINDOW 0,1.55E+5,0,100
1180     FOR X=10 TO 150
1190         I=X*1000
1200         IF (X MOD 30)=0 THEN
1210             MOVE I,48
1220             LABEL X
1230         END IF
1240     NEXT X
1250     VIEWPORT 0,120,0,100
1260     WINDOW 0,120,0,100
1270     MOVE 80,80
1280     LABEL "DIRECT WAVE"
1290     MOVE 80,10
1300     LABEL "REFELCTED WAVE"
1310     MOVE 70,90
1320     CSIZE 4.5
1330     LABEL "AIRCRAFT ALTITUDE=";Alt;"Ft"
1340     RETURN
1350     END
```

Appendix II

Path Differences in System Geometry

This appendix contains twelve plots shown as six figures presenting the path length difference or time delay for reception of a signal in the system geometry propagating directly and propagating by means of a single, specular reflection. The software used to generate the plots is also listed. The system geometry and assumptions are identical to those given in Appendix I. The lower plot in each figure is a plot of the shorter differences (longer range sources) expanded for clarity.

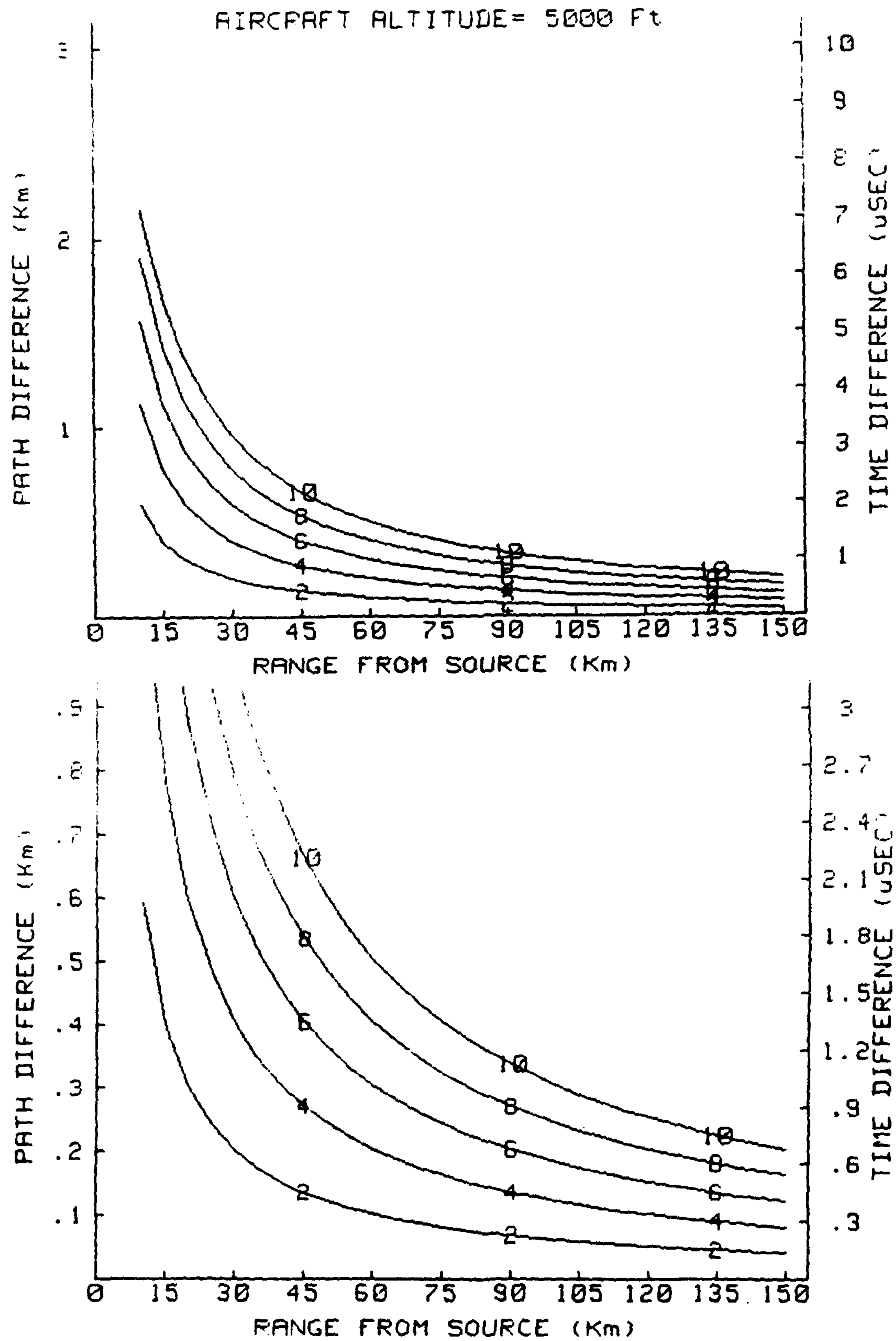


Figure II-A.1. Path difference and time delay for craft at 5000 ft.

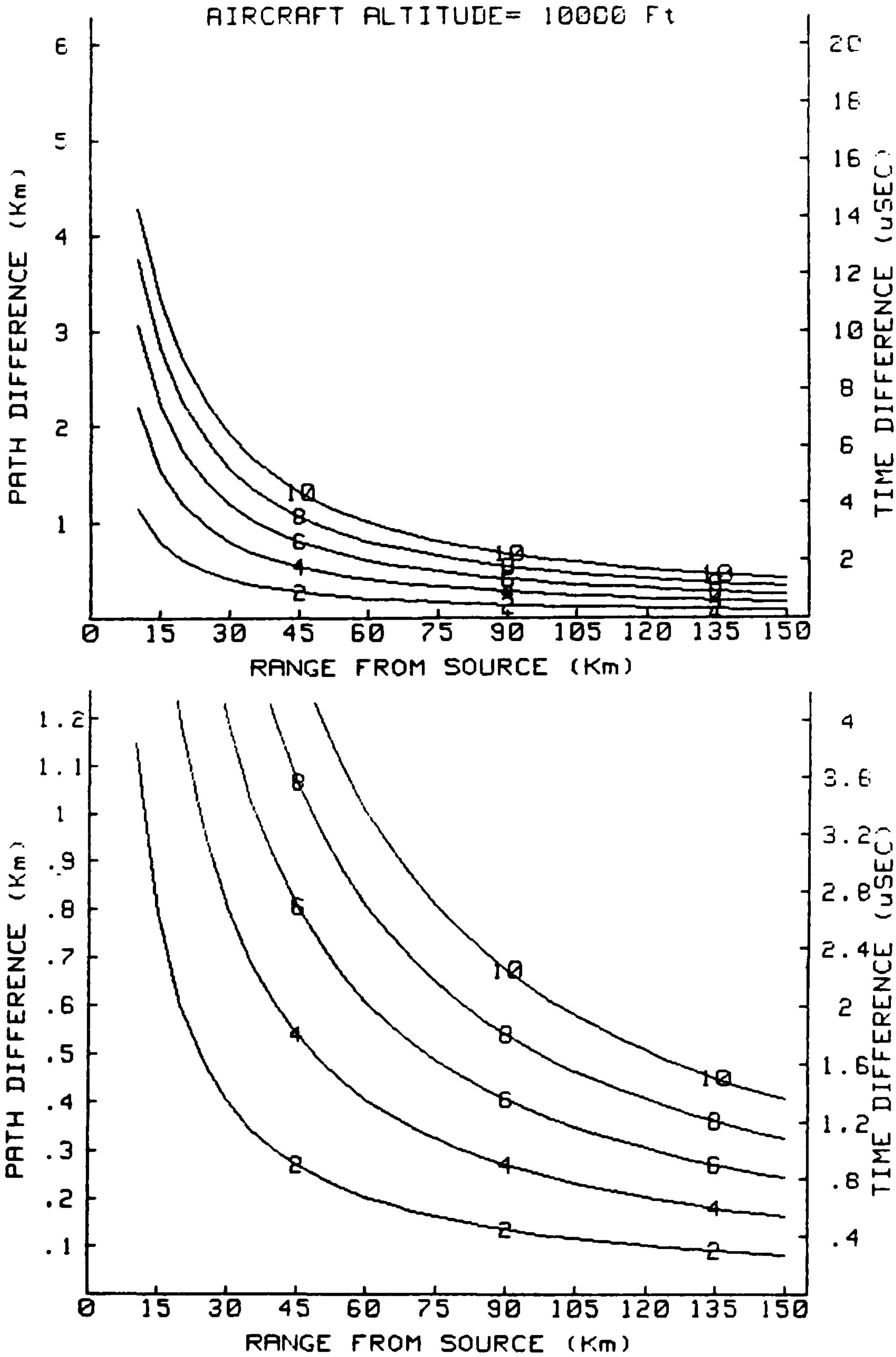


Figure II-A.2. Path difference and time delay for craft at 10,000 ft.

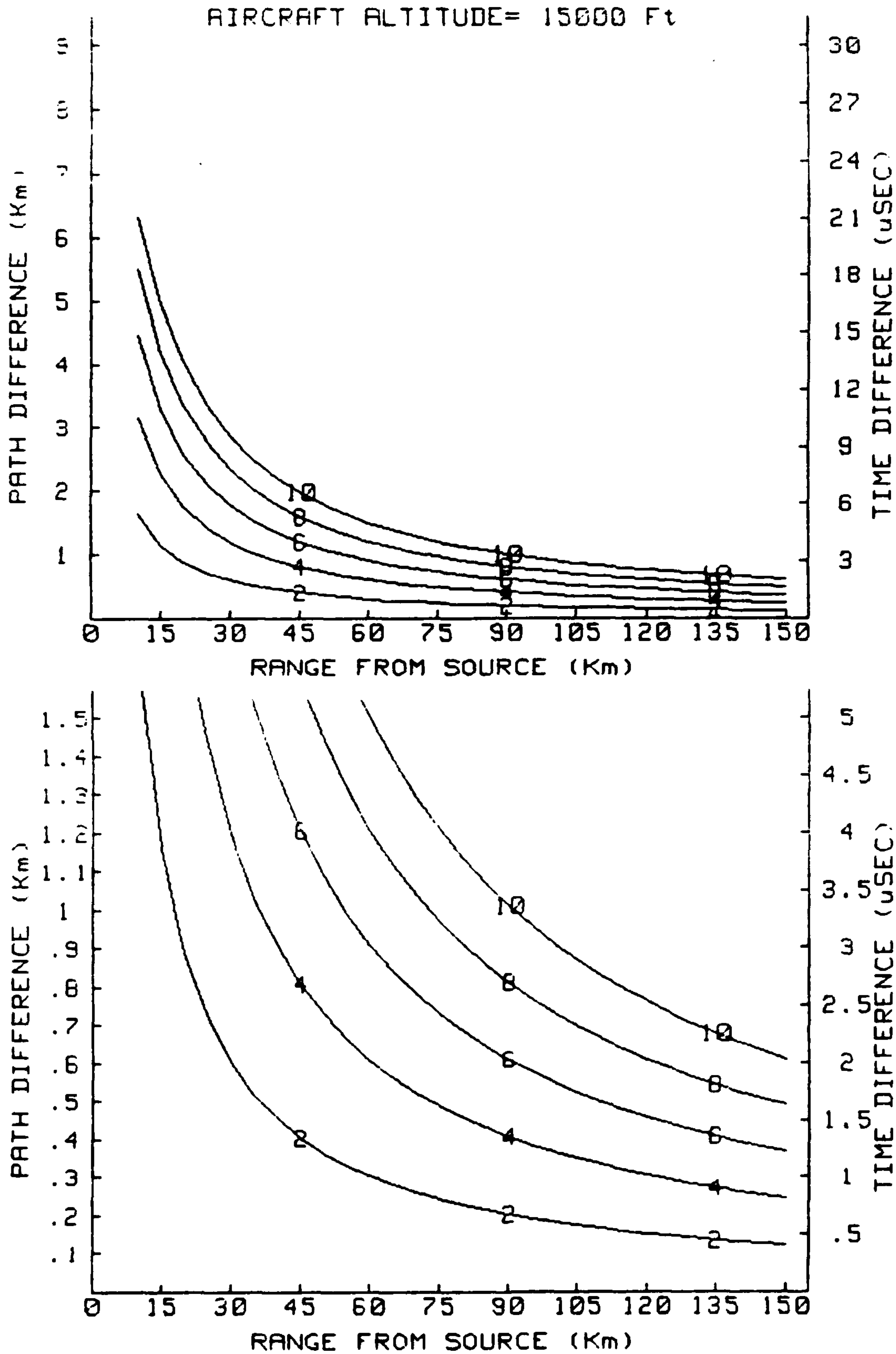


Figure II-A.3. Path difference and time delay for craft at 15,000 ft.

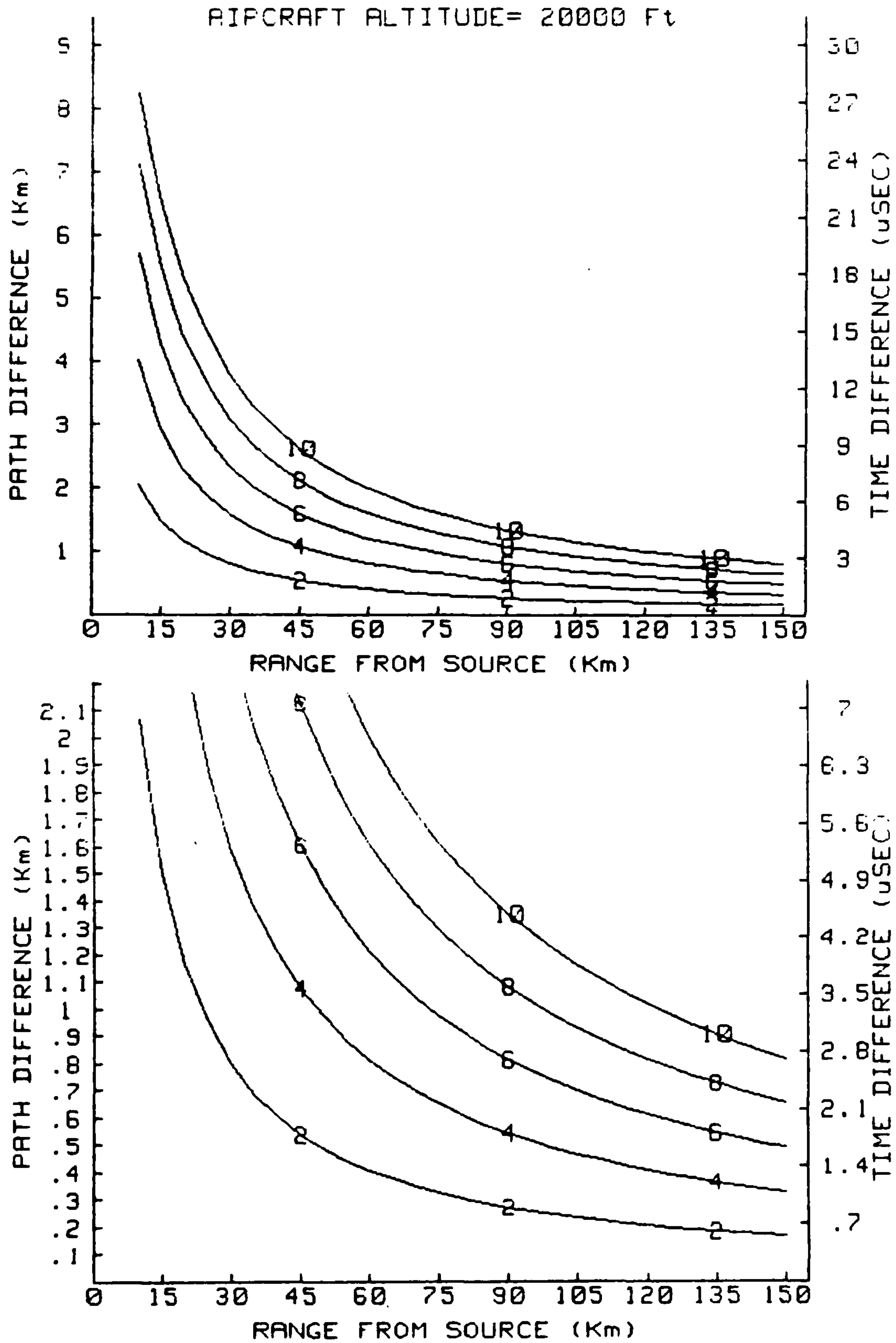


Figure II-A.4. Path difference and the delay for craft at 20,000 ft.

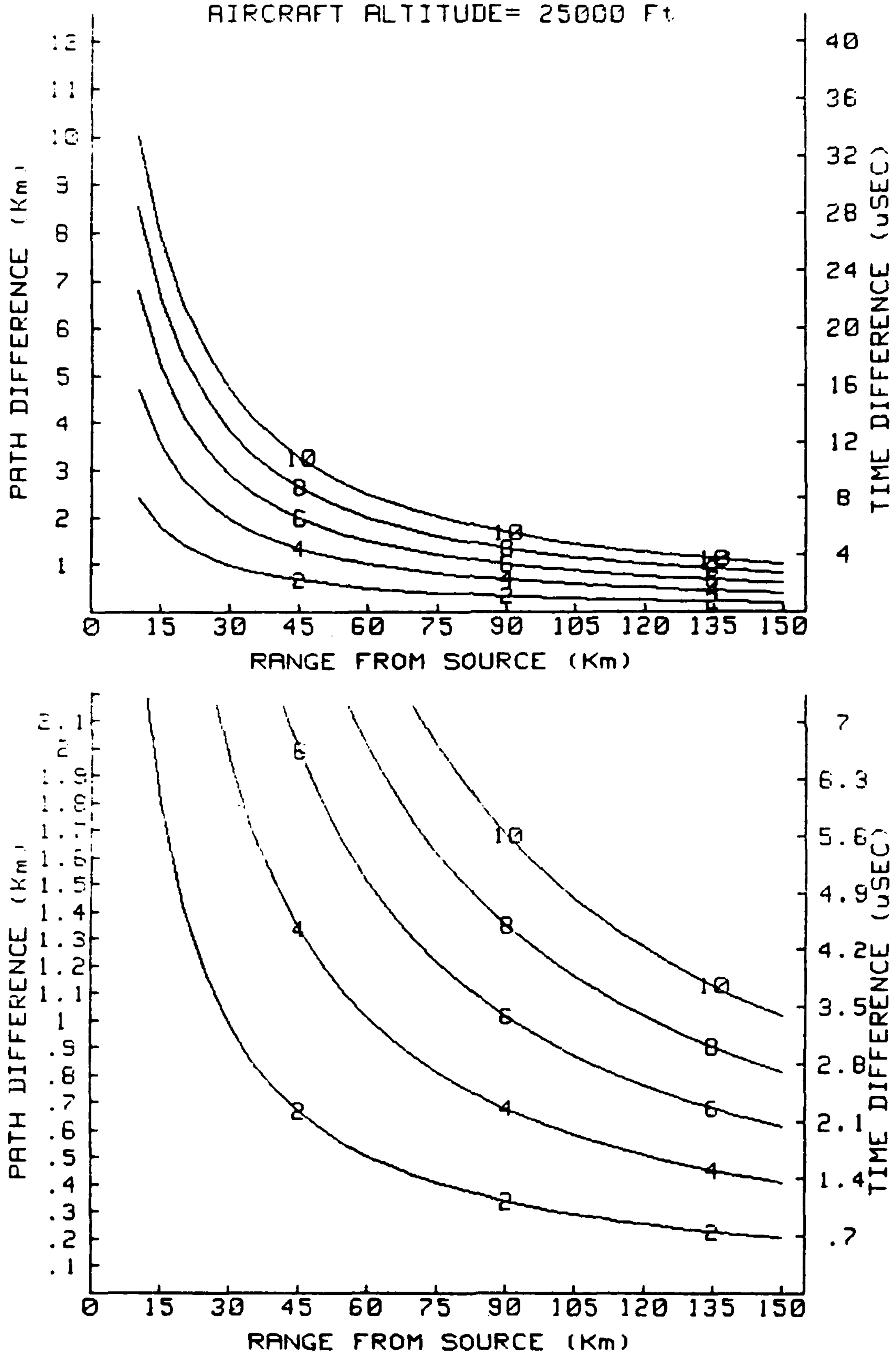


Figure II-A.5. Path difference and the delay for craft at 25,000 ft.

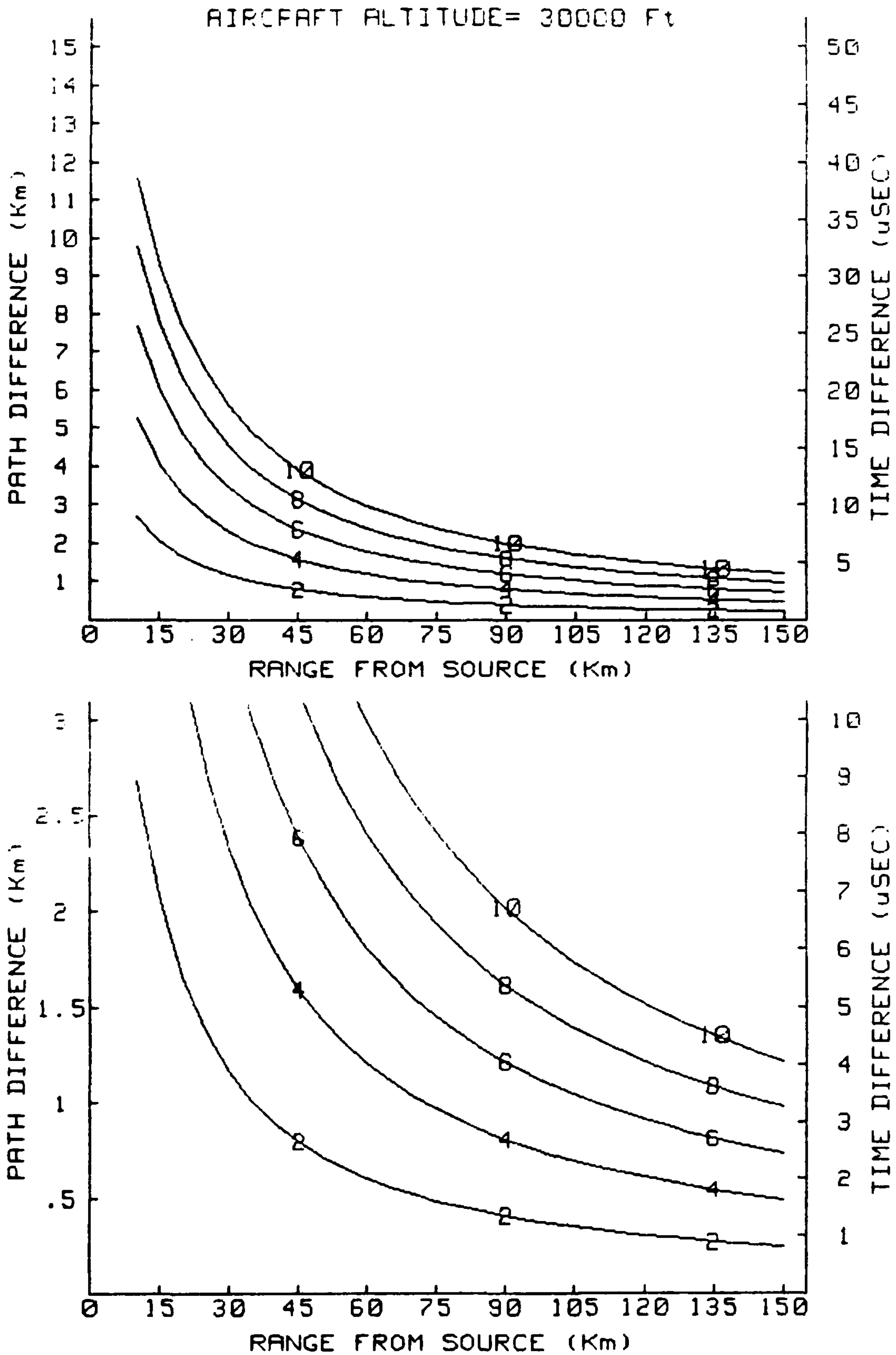


Figure II-A.6. Path difference and time delay for craft at 30,000 ft.

```
10      ! PROGRAM PATH_DIF
20      ! THIS PROGRAM CALCULATES THE DIFFERENCE INPATH LENGTH
30      ! BETWEEN A DIRECT WAVE AND REFLECTED WAVE, OR THE
40      ! PATH DIFFERENCE BETWEEN INCOMING WAVES TO AN AIRBORNE RECEIVER.
50      ! VERSION 1.02.  C.Rhodes..
60      !
70        OPTION BASE 1
80        DIM Path_dif(5,30)
90        PLOTTER IS 3,"INTERNAL"
100       GRAPHICS ON
110       GCLEAR
120     ! THE FOLLOWING LINES OF CODE ARE USED
130     ! TO ENTER THE VARIOUS PARAMETERS FOR
140     ! CALCULATING THE PATH DIFFERENCE
150     ! BETWEEN THE DIRECT AND REFLECTED WAVE.
160     ! THE FLAT EARTH APPROXIMATION IS USED.
170     !
180 Again: !
190       GCLEAR
200       INPUT "ENTER THE RECEIVER ALTITUDE IN FEET",Rcvr_alt
210       Rcvr_alt=Rcvr_alt*.3048!M/Ft
220       Y2=Rcvr_alt
230       FOR Y=2 TO 10 STEP 2!KM
240         FOR X=10 TO 150 STEP 5!KM
250           I=Y/2
260           J=X/5-1
270           Y1=Y*1000
280           X1=X*1000
290           R1=SQR((Y2-Y1)^2+X1*X1)
300           R2=SQR((Y2+Y1)^2+X1*X1)
310           Path_dif(I,J)=R2-R1
320         NEXT X
330       NEXT Y
340       Max_dif=0
350       FOR I=1 TO 5
360         FOR J=1 TO 29
370           Max_dif=MAX(ABS(Path_dif(I,J)),Max_dif)
380         NEXT J
390       NEXT I
400     !
410     ! THE FOLLOWING LINES OF CODE SCALE AND
420     ! PLOT THE RESULTING PATH DIFFERENCES
430     ! VERSUS RANGE FOR THE VARIOUS SOURCE
440     ! ALTITUDES
450     !
460       PRINTER IS CRT
470       PRINT "MAX PATH DIFFERENCE= ";Max_dif
480       INPUT "ENTER Y_SCALE FACTOR",Y_scale
490       PRINT CHR$(12)
500       LINE TYPE 1
510       VIEWPORT 12,110,10,95
520       Y_scale1=Y_scale+(.05*Y_scale)
530       WINDOW 0,1.55E+5,0,Y_scale1
```

```
540    !
550      INPUT "THE Y_AXES TICK RESOLUTION",Ticks
560      AXES 15000,Ticks,0,0
570      Micro_res=(Y_scale/3.E+8)/(1.0E-6)
580      Micro_res1=(Y_scale1/3.0E+8)/(1.0E-6)
590      WINDOW 0,1.55E+5,0,Micro_res1
600      AXES 0,.1*Micro_res,1.55E+5,0
610      WINDOW 0,1.55E+5,0,Y_scale1
620      FOR I=1 TO 5
630          FOR J=1 TO 29
640              LINE TYPE I+4
650              PLOT (J+1)*5*1000,Path_dif(I,J)
660          NEXT J
670          MOVE 0,0
680      NEXT I
690    !
700    ! LABEL THE X-AXES IN Km
710    !
720      LORG 5
730      LDIR 0
740      CSIZE 3.5
750      LINE TYPE 1
760      VIEWPORT 12,110,0,100
770      WINDOW 0,1.55E+5,0,100
780      FOR I=0 TO 10
790          Xx=I*15000
800          Xxx=I*15
810          MOVE Xx,5
820          LABEL USING "DDD";Xxx
830      NEXT I
840      BEEP
850      VIEWPORT 0,120,0,100
860      WINDOW 0,120,0,100
870      MOVE 60,3
880      LABEL "RANGE FROM SOURCE (Km)"
890    !
900    ! LABEL THE Y-AXES IN Km
910    !
920      VIEWPORT 0,120,10,95
930      WINDOW 0,120,0,Y_scale1
940      FOR I=1 TO INT(Y_scale/Ticks)
950          Yy=I*Ticks
960          Yyy=I*Ticks/1000
970          MOVE 7.5,Yy
980          LABEL Yyy
990      NEXT I
1000     LDIR PI/2
1010     VIEWPORT 0,120,0,100
1020     WINDOW 0,120,0,100
1030     MOVE 2.0,50
1040     LABEL "PATH DIFFERENCE (Km)"
1050   !
1060   ! LABEL SECOND Y-AXES IN MICROSECOND
1070   !
```

```
1080     VIEWPORT 0,120,10,95
1090     WINDOW 0,120,0,Micro_res
1100     LDIR 0
1110     FOR I=1 TO 10
1120          Yy=0
1130          Yy=I*(.1*Micro_res)
1140          MOVE 112,Yy
1150          LORG 2
1160          CSIZE 3.0,.6
1170          LABEL USING "D.D";Yy
1180     NEXT I
1190     WINDOW 0,120,0,100
1200     LORG 5
1210     MOVE 119,50
1220     LDIR PI/2
1230     CSIZE 3.5,.7
1240     LABEL "TIME DIFFERENCE (uSEC)"
1250  !
1260  !  GENERATE GRAPH LEGEND
1270  !
1280     LINE TYPE 1
1290     LDIR 0
1300     VIEWPORT 50,90,60,90
1310     FRAME
1320     CSIZE 3.0
1330     VIEWPORT 0,120,0,100
1340     WINDOW 0,120,0,100
1350     MOVE 70,86
1360     LORG 5
1370     LABEL "SOURCE HEIGHT Km"
1380     LORG 1
1390     MOVE 53,80
1400     CSIZE 4.5
1410     LABEL "2Km ="
1420     LABEL "4Km ="
1430     LABEL "6Km ="
1440     LABEL "8Km ="
1450     LABEL "10Km="
1460     FOR I=1 TO 5
1470          MOVE 65,81-(I-1)*4
1480          LINE TYPE I+4
1490          FOR Z=65 TO 89
1500               DRAW Z,81-(I-1)*4
1510          NEXT Z
1520          PENUP
1530     NEXT I
1540  !
1550  !  NOW LABEL THE GRAPH
1560  !
1570     VIEWPORT 0,120,0,100
1580     WINDOW 0,120,0,100
1590     MOVE 60,95
1600     LORG 5
1610     LINE TYPE 1
```

```
1620     LDIR 0
1630     CSIZE 4.0
1640     LABEL "AIRCRAFT ALTITUDE= ";Rcvr_alt;"m "
1650   !
1660   ! THE FOLLOWING LINES OF CODE DEFINE THE
1670   ! PLOTTING DEVICE. IN GENERAL THIS WILL
1680   ! BE THE THINKJET PRINTER AT HP-IB
1690   ! ADDRESS AT 706
1700   !
1710     DUMP DEVICE IS 706,EXPANDED
1720     PRINTER IS 705
1730     INPUT "GENERATE A HARD COPY PLOT?",Answer$
1740     IF UPC$(Answer$)="Y" THEN
1750         FOR I=1 TO 8
1760             PRINT
1770         NEXT I
1780         DUMP GRAPHICS
1790         PRINT CHR$(12)
1800     END IF
1810     PRINTER IS CRT
1820     BEEP
1830     INPUT "ANY FURTHER ALTITUDES?",Answer$
1840     IF UPC$(Answer$)="Y" THEN GOTO Again
1850     STOP
1860     END
```

END

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