General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

THE FEASIBILITY OF INFLIGHT MEASUREMENT OF
LIGHTNING STRIKE PARAMETERS

K. E. Crouch and J. A. Plumer

LIGHTNING TECHNOLOGIES, INC.
Pittsfield, MA 01201

TABLE OF CONTENTS

TABLE OF CONTENTS - continued

THE FEASIBILITY OF INFLIGHT MEASUREMENT
OF LIGHTNING STRIKE PARAMETERS

K.E. CROUCH AND J.A. PLUMER

LIGHTNING TECHNOLOGIES, INC.

SUMMARY

The appearance of non-metallic structural materials and microelectronics in aircraft design has resulted in a need for better knowledge of hazardous environments such as lightning and the effects these environments have on the aircraft. This feasibility study was performed to determine the lightning parameters in the greatest need of clarification and the performance requirements of equipment necessary to sense and record these parameters on an instrumented flight research aircraft. It was found that electric field rate of change, lightning currents, and induced voltages in aircraft wiring are the parameters of greatest importance. Flat-plate electric field sensors and resistive current shunts are proposed for the electric field and current sensors, to provide direct measurements of these parameters. Six bit analog-to-digital signal conversion at a 5 nanosecond sampling rate, short-term storage of 8.5×10^5 bits and long term storage of 5×10^7 bits of electric field, current and induced voltage data on the airplane are proposed, with readout and further analysis to be accomplished on the ground. A NASA F-106B was found to be suitable for use as the research aircraft because it has a minimum number of possible lightning attachment points, space for the necessary instrumentation, and appears to meet operational requirements. Safety considerations are also presented.

INTRODUCTION

There is an increasing need being voiced (reference 1) among many sectors of the aviation industry and government agencies for a better understanding of the electrical properties of thunderstorms and flight safety.

The requirement for a better understanding of the electrical properties, and, in particular of lightning, stems primarily from the increasing reliance upon solid-state microelectronics to perform flight-critical functions, and the replacement of conventional metallic structural materials with non-metallic composites. The next generation of aircraft are being designed to make widespread use of these new technologies, to achieve improved performance and energy-efficiency goals, but microelectronics are very sensitive to harsh electromagnetic environments such as produced by lightning, and most composite materials are unable to conduct lightning-like currents without incurring severe loss of strength. Whereas a large amount of data exists on lightning currents that reach the ground, very little information exists concerning the electrical characteristics of lightning at flight altitudes, and there are reasons to suspect significant differences.

Aircraft which are struck by lightning in flight, for example, nearly always become part of the conductive channel between one charge center and the other. The manner in which this takes place was formerly thought to be rather unimportant, but recent evidence indicates that the charging currents which flow when the lightning leader first comes in contact with the aircraft may rise fast enough to induce significant voltages in the aircraft's electrical wiring. There is no information presently available on the magnitude of these pre-breakdown currents which flow on an aircraft or the voltages they actually induce. To fill this gap, a flight research program is being planned by NASA, in which an instrumented aircraft will be flown through thunderstorm regions with the intent of being struck by lightning. On-board equipment will sense and record the electrical characteristics of the strikes received.

Before plans for this flight research can be completed and the instrumentation designed, objectives must be clearly established and prioritized in terms of their importance to improved understanding of lightning and its effects on flight safety. This feasibility study was conducted, therefore, to identify the electrical parameters in greatest need of clarification, determine the feasibility of sensing and storing this data, define the instrumentation performance requirements necessary to do so, and recommend thunderstorm flight paths for acquiring strikes. Consideration was also given to the kind of aircraft best suited for use in this research. This report presents the results of this study and the recommendations which resulted from it.

2

THE NEED FOR BETTER DATA

Aircraft structural and electrical systems are designed and tested to lightning criteria which are presently based on ground observations of natural lightning. As new aircraft are being designed using state-of-the-art technologies such as microelectronics and advanced composite structural materials, questions have arisen as to the validity of these tests. Whereas the lightning environment has caused comparatively few serious problems to date, it is likely to become a more serious problem to future aircraft if positive steps are not taken to learn more about lightning effects for these new systems.

Tests to measure levels of induced voltages in aircraft wiring resulted from research conducted in 1970 (reference 2) into coupling mechanisms and test techniques (reference 3) developed to investigate these mechanisms. These tests are conducted using simulated lightning current waveshapes at reduced current amplitudes of 200 amperes. The results are then linearly extrapolated to 200,000 amperes. The accuracy of the results depends upon the validity of extrapolation and the degree to which important lightning waveform parameters are represented in the test. This aspect has been a cause for concern since some induced voltages do not show an apparent relationship to the return-stroke current that is simulated during the test, as shown in figure 1.

(a) Waveform of lightning current and magnetic flux.

(b) Induced voltage
$$e = \frac{d\varphi}{d\tau} + i_L R_S$$
= clear relationship.

(c) Induced voltage
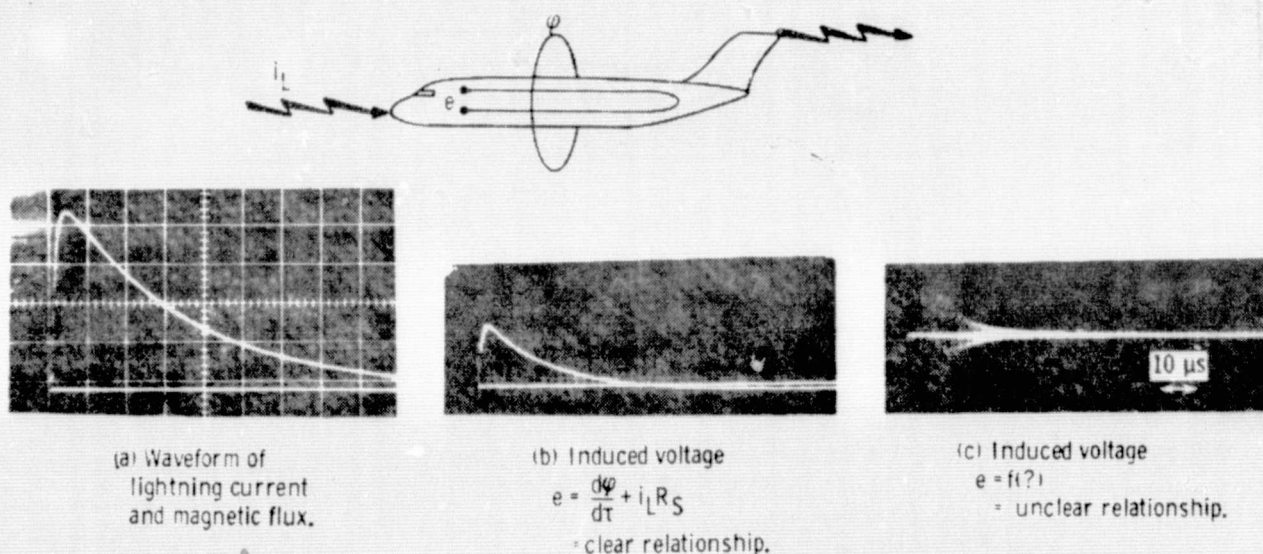$e = f(?)$
= unclear relationship.

Figure 1 - Relationships between Lightning Current and Induced Voltages.

Frequently the "unclear" induced voltages have the highest amplitudes, and when extrapolated linearly to a 200,000 ampere stroke, voltages of over 1,000 volts are predicted. Such voltages seem alarmingly high to the designer of 5-volt electronic logic

3

systems, and to the airframe manufacturer concerned with minimizing cost and weight. Thus, the validity of the test, the extrapolation, and the 200,000 ampere full-scale level are all being questioned.

Previous Attempts

Nearly all of the large amount of data that now exists (reference 4) on lightning stroke waveforms and amplitudes have been obtained from measurements made at instrumented probes on the ground, where the lightning currents enter the earth.

An attempt to measure lightning stroke currents at flight altitudes was made during the period 1965-7 as part of the Rough Rider program (reference 5). About 50 strikes were obtained during this 3-year flight research program, and peak currents ranging in amplitude from several hundred amperes to 22 kiloamperes were recorded. The amplitudes and waveforms may be indicative of cloud-to-cloud or intracloud strokes (or branches thereof) that occur within clouds at the 15,000'-30,000' altitude range where cloud penetrations were made. No attempt was made to measure lightning currents at lower altitudes beneath the cloud bases.

Several attempts have been made to obtain some of these parameters from far-field measurements of radiated electric and magnetic fields. The results are subject to controversy due to uncertainty over the validity of the algorithms used in the derivations.

Some improvement in knowledge of the aircraft-lightning interaction is being obtained from lightning strike reporting projects being carried out with several US airlines (reference 6) and operators of corporate-type general aviation aircraft (reference 7). These projects, which depend on pilot reports, are providing information on the synoptic weather and flight conditions in which strikes to aircraft occur, and, to the extent the operators can identify them, the strike attachment points on the aircraft. This information is particularly important with respect to general aviation aircraft for which very little data have yet been gathered.

Lightning Strike Phases and Parameters

A lightning *flash* consists of a large number of electrical events that occur within a total lifetime of up to one second, yet some of the most important events of which the flash is comprised may transpire in less than a microsecond, and the moments at which these short-duration events occur are not predictable. This implies that a chart 10,000 meters long would be required to display a complete lightning flash if one microsecond per centimeter of

4

time resolution were desired, and if a one kiloampere per centimeter amplitude sensitivity were desired the chart would have to be 2 meters wide. Since these requirements are highly impractical, the measurement system must be planned to select and record only the most important events in a complete flash, and to display these parameters in a practical manner. Thus, the first task in this feasibility study concentrated on defining each of the various lightning parameters that may occur within a flash, and then prioritizing them in terms of their importance to design of lightning protection and achievement of a safe aircraft.

Figure 2 shows the four phases of a lightning strike to an aircraft, together with the electrical events expected to occur within each phase. The time scales of the longer duration events have been compressed. The range of time durations and magnitudes expected of the electrical events associated with each phase are also given, and the probable effects that these events produce in the aircraft are listed.

Pre-breakdown Phase - The pre-breakdown phase begins when the leader propagates toward the aircraft. As the leader approaches, the electric field between it and the aircraft intensifies, especially about aircraft extremities with small radii of curvature. When the ionization potential of air is reached, bursts of corona and streamers will form at these extremities, and displacement currents to feed these streamers flow on the airframe. The electric field at the aircraft increases, and additional streamers and displacement currents occur as the leader continues to advance in steps toward the aircraft. The magnitude of these streamer currents is likely to be small but their rates of change may be high enough to induce voltages in the aircraft's electrical wiring. Eventually, a streamer from the aircraft meets the oncoming leader, and attachment to the aircraft is established.

Leader Phase - The leader phase begins when the leader becomes attached to the aircraft, and ends when the leader reaches the earth (or other center of opposite charge) and initiates the first return stroke. Since the leader propagates at about 10^5 m/s, it would require a time, t, of:

$$t = \frac{1 \times 10^3 m}{1 \times 10^5 m/s} = 1 \times 10^{-2} \text{ sec.} \tag{1}$$

$$t = 10 \text{ milliseconds}$$

for the leader to travel each kilometer. During this time bursts of charge to feed the propagating leader will flow down the leader and through the aircraft. As this happens the electrical potential of the aircraft will change, but the magnitude of these events is not known. It is possible that this is a comparatively quiet phase in the development of the flash.

5

PRE-BREAKDOWN PHASE   LEADER PHASE
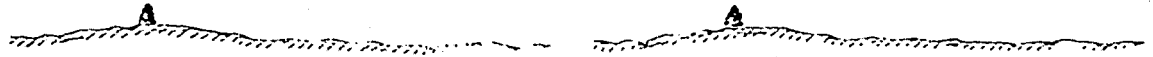
Electric Current in the Aircraft

1-30 ms   1 ms
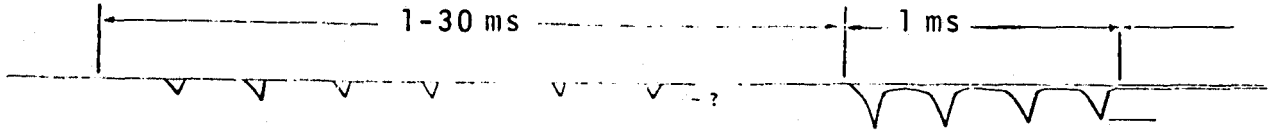
Electric Field at the Aircraft
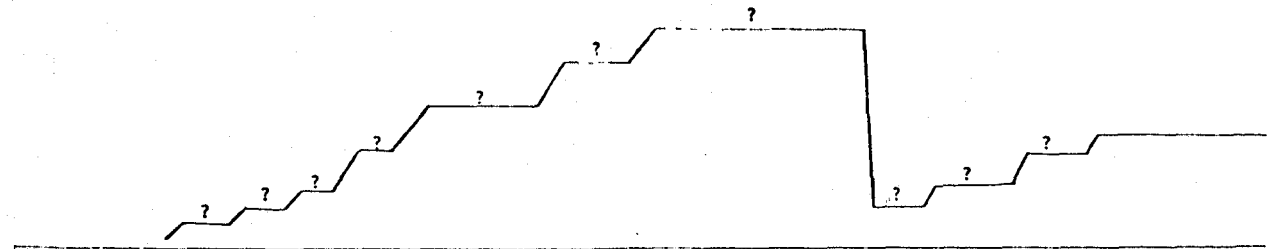
Effects in the Aircraft

• Induced Voltages in Electrical Circuits

• Dielectric Breakdown of Nonconducting Materials

• Induced Voltages

PRE-BREAKDOWN AND LEADER PHASES

Events	Time Scale (seconds)	Magnitudes
Aircraft Exterior		
Electric (E) Field	10^{-7} to 10^{-5}	10^3 to 10^5 V/cm
Magnetic (H) Field	10^{-5} to 10^{-3}	1 to 10^2 A/cm
Streamer Current	10^5 to 10^{-4}	10^1 to 10^3 A
Electromagnetic Wave Reflections	10^{-8} to 10^{-6}	10^2 to 10^4 V or A/cm
Charge	10^{-6} to 10^{-4}	1 to 10 coulombs
Aircraft Interior		
Cabin E-Field	10^{-6} to 10^{-4}	10^1 to 10^3 V/cm
H-Field	10^{-5} to 10^{-3}	10^{-2} to 10^2 A/cm
Typical Cable Harness Voltage	10^{-7} to 10^{-4}	10^1 to 10^4 volts

Figure 2 - Lightning Flash Phases, Effects and Parameters

6

RETURN STROKE PHASE   **CONTINUING CURRENT AND RESTRIKE PHASES**

1-30 ms ———— 1-10 10-100μs ←———— 10-200 ms ————→
μs

0.2 to 1kA

10 to 150 kA

5.75 kA
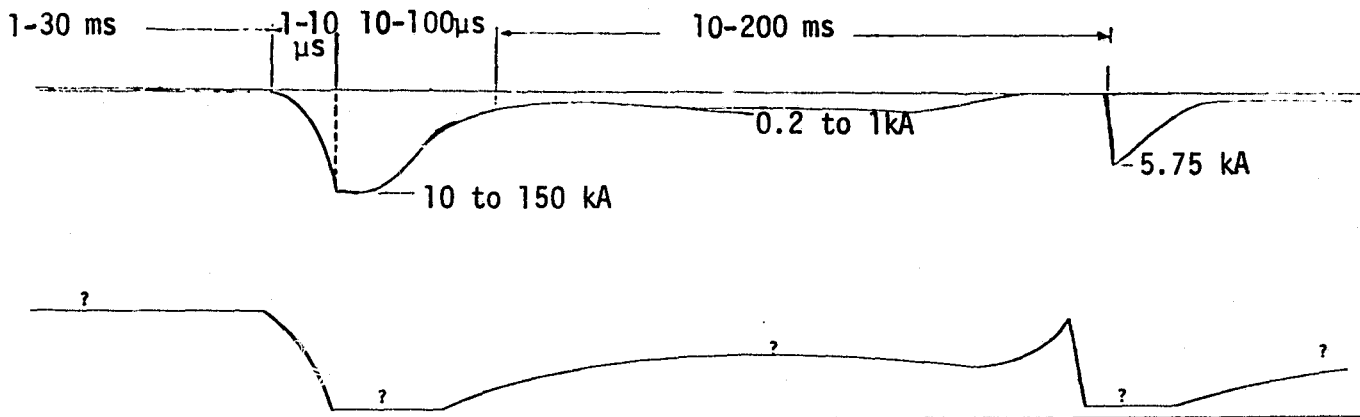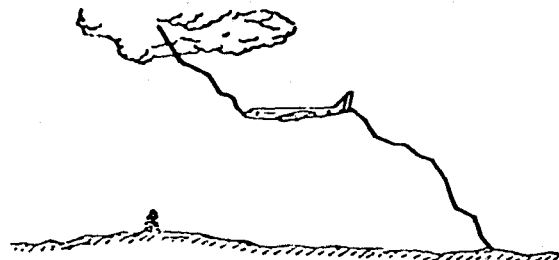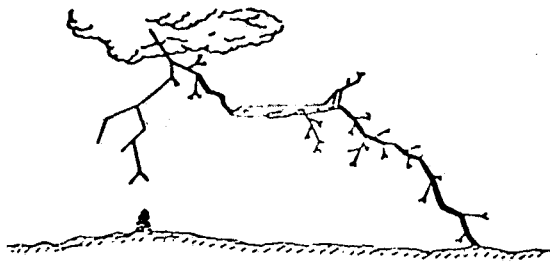
| ● Induced Voltages | ● Physical Damage Melting of Metals | ● Induced Voltages |
| ● Physical Damage: Thermal Blast | | ● Physical Damage: Thermal Blast |

RETURN STROKE AND CONTINUING CURRENT PHASES

Events	Time Scale (seconds)	
Aircraft Exterior		
Electric (E) Field	10^{-7} to 10^{-5}	10^2 to 10^4 V/cm
Magnetic (H) Field	10^{-4} to 10^{-2}	10^1 to 10^2 A/cm
Stroke Current	10^{-5} to 10^{-3}	10^3 to 10^5 A
di/dt	10^{-6} to 10^{-3}	10^2 to 10^5 A/s
Continuing Currents	10^{-2} to 1	10 to 10^3 A
Charge	10^{-4} to 10^{-2}	1 to 100 coulombs
Aircraft Interior		
Cabin		
E-Field	10^{-5} to 10^{-2}	10^1 to 10^3 V/cm
H-Field	10^{-4} to 1	10^{-2} to 10^2 A/cm
Typical Cable Harness Voltage	10^{-6} to 10^{-2}	10^1 to 10^4 volts

Figure 2 - Lightning Flash Phases, Effects and Parameters (concluded).

Return Stroke Phase - When the leader reaches its ultimate destination at a center of opposite charge, recombination of this opposite charge with that contained in the leader forms the *return stroke*, which begins at the ground and travels upward toward the cloud at a velocity approximately one third the speed of light. At the ground, return stroke currents of over 200,000 amperes have occasionally been measured, and currents of at least 20,000 amperes occur 50% of the time. Since the aircraft has become part of the conducting path formed by the leader, the return stroke current passes through it on its way to the cloud. The duration of the return stroke is short as compared with the leader phase, but the current amplitude is much higher. Return strokes may cause physical damage to structures, and induce surge voltages in electrical systems. Figure 2 shows typical rise and fall times associated with a return stroke.

Continuing Current and Restrike Phase - After the return stroke has discharged the leader, the charge that remains within the original cloud charge center may flow along the conductive channel to earth. The *continuing current* that results rarely exceeds 1,000 amperes, but may persist for a comparatively long time until the 100 (or so) coulombs of charge is drained from the original center. The continuing currents are capable of melting holes in aluminum skins if permitted to dwell long enough at one place, such as a trailing edge, but their rate of change is not sufficient to cause induced voltages in electrical systems. Most periods of continuing current flow persist for 200 milliseconds or less, but there may be several such periods within a single flash.

If other charge centers are present in the same cloud, they may discharge via the ionized channel formed by the original leader. The process is somewhat the same, with the channel now being charged by a *dart leader* from the cloud. Since an ionized channel already exists, the dart leader reaches the earth much quicker than the original stepped leader. The return stroke, called a *restrike* which then occurs does not often reach as high an amplitude as the first return stroke, but may have a faster rate of rise. The restrike current, of course, also passes through the aircraft.

One restrike is shown on figure 2, but in actuality there may be several more, separated again by periods of continuing current flow. All of the foregoing phases comprise the lightning *flash*. When the final restrike and/or continuing current has passed, the ionized channel re-combines and extinguishes, and the flash dies. The lifetime of most lightning flashes is less than one second, although some have been observed for more than one second.

Of course, the aircraft is in motion during the life-time of the flash, causing the relatively stationary channel to extend aft along the fuselage from the initial point of attachment.

8

An aircraft flying at an altitude of 3 kilometers and moving at 100 m/s, for example, would travel a distance, d, of:

$$d = (100 \text{ m/s})(3 \text{ km})(10 \times 10^{-3} \text{ s/km altitude}) \qquad (2)$$

$$d = 3 \text{ meters}$$

assuming the leader propagation time of 10 milliseconds per kilometer of altitude as derived from equation 1. If the initial attachment point is at a trailing edge, the flash will simply extend itself and hang on to this point for its entire duration. An instrumented probe at a trailing edge would therefore see all of the components of the flash.

But if an initial attachment point is at a forward extremity such as the nose or a propeller, the flash will extend over other surfaces of the aircraft and may re-attach to successive spots along these surfaces. Thus, an instrumented probe that does not extend well forward of the rest of the aircraft may not receive all of the electrical events of the flash.

Time and Magnitude Ranges - The time and magnitude ranges within which each of the electrical parameters shown on figure 2 are likely to fall are tabulated at the bottom of figure 2. Many of these parameters, of course, are not well known and the ranges presented are only estimates.

Clearly, measurement and recording of all of the parameters shown within each phase of the lightning flash of figure 2 would be a very formidable task, well beyond practical limitations of space, weight and cost. Thus, the first task of this feasibility study concentrated on identification of the most important parameters to be measured. These are discussed in the following section.

PARAMETERS TO BE MEASURED

A study of figure 2 shows that there are four electrical
parameters that could be measured. These include electric fields,
magnetic fields, currents, and induced voltages. Measurement of
any one of these parameters presents a formidable challenge, how-
ever, since the magnitudes and rates of change that must be re-
corded cover a very wide range. Instrumentation to record these
parameters through all phases of a lightning flash must be capable
of measuring a quantity such as electric field, for example, in a
one-second period with magnitudes ranging from 2 to 2×10^4 V/cm
and changes in magnitudes occurring within 10^{-6} seconds. The
instrumentation must acquire enough data points during the flash
to insure that the high rates of change are accurately recorded.
The data storage capacity thus required to accommodate all of the
above parameters is likely to be prohibitive. Thus, each parame-
ter was assessed with respect to its importance to improved under-
standing of lightning effects on aircraft, and the electrical
parameters were prioritized in order of their importance in
Table I, together with the amplitude ranges and bandwidths be-
lieved to be required for each.

TABLE I - PRIORIT_ED LIST OF PARAMETERS

Priority	Parameters	Range	Bandwidth* Requirement
1	Electric Fields external to the aircraft	30 to 30,000 V/cm	DC to 40 MHz
2	Current, including intense streamer, continuing and return currents	3 to 300,000A $(2 \times 10^6 A^2 \text{-s})$	DC to 40 MHz ($i \times t = 200$)
3	Induced Voltages in aircraft wiring coincident with item 2	100 to 10,000 V	DC to 40 MHz
4	Magnetic Fields(B) outside the air- craft, coincident with item 2	1 to 1000 A/cm	DC to 50 MHz
5	Electric and Mag- netic Fields (B) inside the air- craft, coincident with item 2	0.1 to 1000 V/cm 0.01 to 10 A/cm	DC to 50 MHz

*Bandwidth x rise time (10%-90%) = 0.35

10

The rationale for selection of each of the foregoing parameters is presented in the following paragraphs.

Electric Field Change

The electric field and how it changes is important during the leader phase of the lightning flash in determining where lightning will strike the aircraft and whether it will puncture dielectric components. As yet, no measurements of this parameter have been made. The electric field change criteria now in use for design and test purposes have been derived by analytical means from other parameters and are subject to some controversy.

At the beginning of lightning-flash formation, when a stepped-leader propagates outward from a cloud charge center, the ultimate destination of the flash is at an opposite charge center in another cloud or on the ground. The difference of potential which exists between the stepped-leader and the opposite charge center(s) establishes an electric field between them, represented by imaginary equipotential surfaces. The electric field intensity, expressed in kilovolts per meter, is greatest where equipotential surfaces are closest together. Because the direction of electrostatic force is normal to the equipotentials and strongest where they are closest together, the leader is most likely to progress toward the most intense field regions.

If an aircraft happens to be in the neighborhood, it will assume the electrical potential of its location. Since the aircraft is a thick conductor and all of it is at this same potential it will compress adjacent equipotentials and increase the electric field intensity in the vicinity itself. If the aircraft is within several tens or hundreds of meters from the leader, this increased field intensity in between may be sufficient to attract the leader toward the aircraft. As this happens, the intervening field will become even more intense.

The highest electric fields will occur around extremities such as the nose and wing tips, and sometimes smaller protrusions such as antennas or probes, and the direction of these fields will always be normal to the extremity surface. When the field adjacent to these extremities is increased to about 30 kV/cm, the air will ionize and electrical sparks called *streamers* will form, extending towards the oncoming leader. Several of these streamers usually occur simultaneously from several extremities of the aircraft. One of these streamers will meet the nearest branch of the advancing leader and form a continuous spark from the cloud charge center to the aircraft. The electric field about this extremity of the aircraft then collapses and the leader proceeds onward to its final destination from another extremity.

11

Since fiberglass and most other non-metallic materials have no electrical conductivity the electric field passes directly through them, causing streamers to originate from objects inside as well as outside of such structures, as shown in figure 3. What then happens may be viewed as a race between streamers propagating from conducting objects inside and outside of the nonconducting structures

RADOME
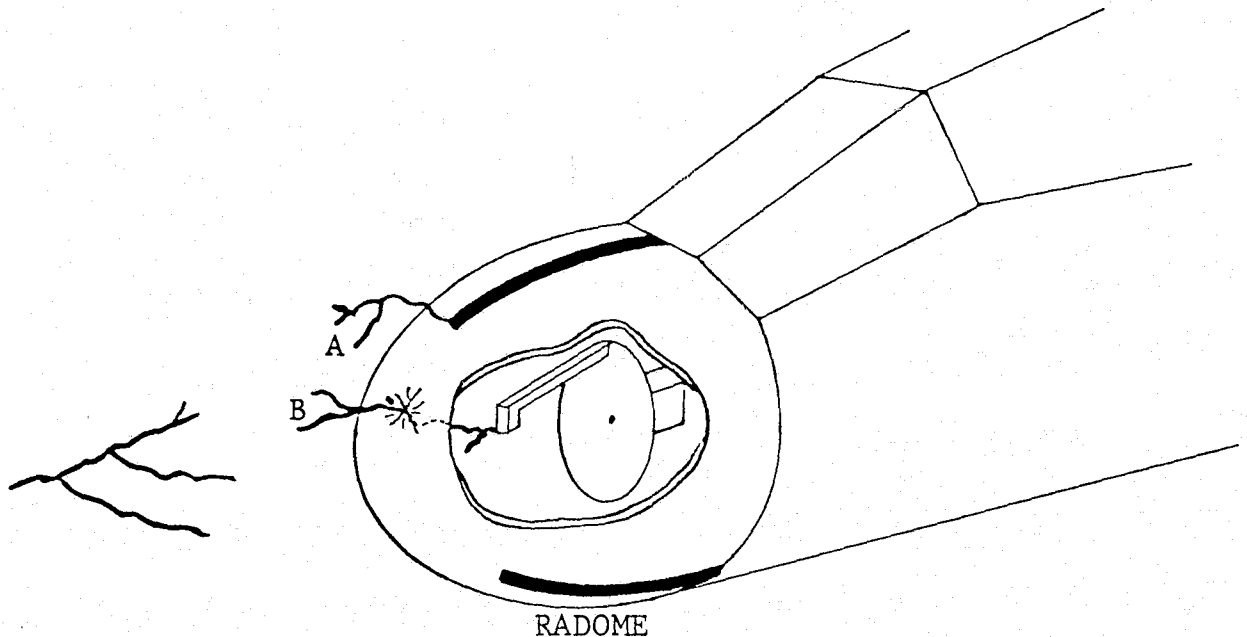
Figure 3 - Streamer Formation on Non-conducting Structures.

Both the voltage withstand capability of the non-metallic skin and the distances along alternate breakdown paths are important in establishing whether puncture or external flashover will occur. A higher intensity electric field is necessary to permit the internal streamer to puncture the fiberglass wall and contact the leader than would be necessary merely to draw the external streamer through the air in the same period of time. Thus the change or *rate-of-rise* of the electric field is important.

The importance of rate of rise can be further explained by comparing the breakdown *timelag* characteristics of solids and air. All insulating materials, whether solids or gases, break down according to a timelag curve of the shape shown in figure 4. Timelag effect means simply this: the shorter the time for which a voltage is applied across a given insulation, the higher the voltage must be to cause breakdown; and conversely, the longer the time, the lower the voltage necessary to cause breakdown. There is, of course, a voltage level below which breakdown will not occur at all. Most solids show a flatter timelag characteristic than do air or surface flashover paths, as illustrated in figure 4.

12

Electric
Field
kV/m

A

Fast Rate of Rise

Slow Rate of Rise

B

Puncture of Solid

Flashover through Air
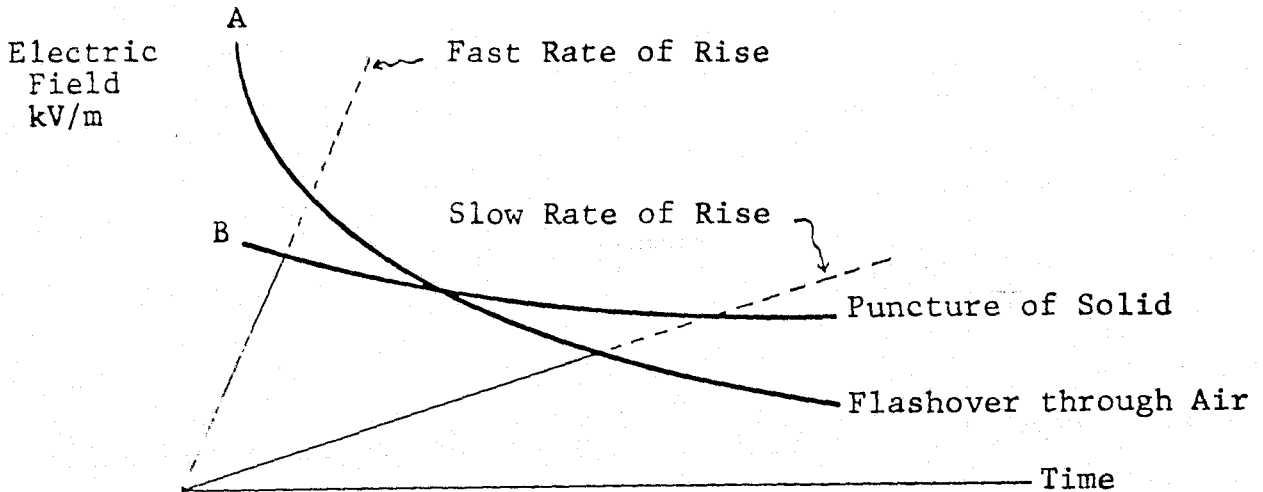
Time

Figure 4 - Electric Field Rate-of-Rise vs. Breakdown.

The significance of electric field rate of rise now becomes
evident. Because the timelag curve for the alternate paths cross
each other, there can be rates of rise that will intersect either
timelag curve, as shown in figure 4, where both "fast" and a "slow"
voltage waveform are superimposed on the breakdown timelag curves.

From figure 4 it is evident that the faster rising fields are
more severe in terms of increased probability of puncture. Thus,
for design and certification testing, a voltage with the fastest
rate of rise expected from a natural lightning leader is desirable
but no measurements have as yet been made of the actual fields pro-
duced by lightning. Plumer (reference 8) has reasoned that if the
leader advances about 2×10^5 m/s, it would require an average of
5 µs for the leader to travel a distance of 1 m. Since about 500 kV
are required to break down a 1 m air gap in 5 µs, the electric field
rate of rise might be the following

$$\frac{dV}{dt} = \frac{500\ 000\ V}{5 \times 10^{-6} s} = 100\ kV/\mu s \qquad (3)$$

and further reasons that if the breakdown of a single step of the
leader is itself a series of smaller steps and pauses, it is likely
that the rate of voltage rise across segments only a few meters out
from the aircraft might be faster than the average, and suggests
that a rate of 1,000 kV/µs be used for design and test purposes.

13

James and Phillpott (reference 9) reason that the electric field rate of rise at the aircraft surface is determined by the time of 1,000 µs (or so) that it takes the leader to progress acoss the entire last step, in which case the rate of electric field rise would be much less than that suggested by Plumer. The question of what electric field parameters are appropriate is of increasing importance for design and certification test purposes as nonconductive materials are gaining increasing use in aircraft.

An example of an E-field measurement is shown in the oscillogram of figure 5 where an E-field is applied during a typical high voltage test of a protective diverter on an aircraft radome. The figure illustrates the rise and collapse of the electric field around the radome as the leater approaches and a streamer reaches out to meet it. In this laboratory test the advancing leader at position A is represented by a test electrode, and the field is generated by a marx-type high voltage generator not shown in the figure. The field in the oscillogram is rising at 2,000 kV/µs.

In Summary -

1. The electric field parameter of interest is:
    A. the electric field rate of change at the surface of typical aircraft surfaces immediately prior to lightning attachment

2. This parameter is important in design and certification testing to:
    A. determine if lightning may puncture a non-metallic component such as a fiberglass radome, wing tip or fin cap; or a polycarbonate resin component such as a windshield or canopy in a lightning strike zone.
    B. to verify the adequacy of protective diverters or other measures to prevent punctures of non-metallic components in a lightning strike zone.
    C. to determine the detailed attachment points on metallic or composite surfaces in a lightning strike zone for the purpose of:
        1) establishing the boundaries of lightning strike zones on aircraft surfaces
        2) establishing skin thickness or other protection requirements

The electric field parameters have been placed in top priority because no measurements of this parameter have yet ever been made, and due to the importance of this parameter to lightning protection design.

Electric Field
Equipotential Lines

A

Radome

B

Radome

C
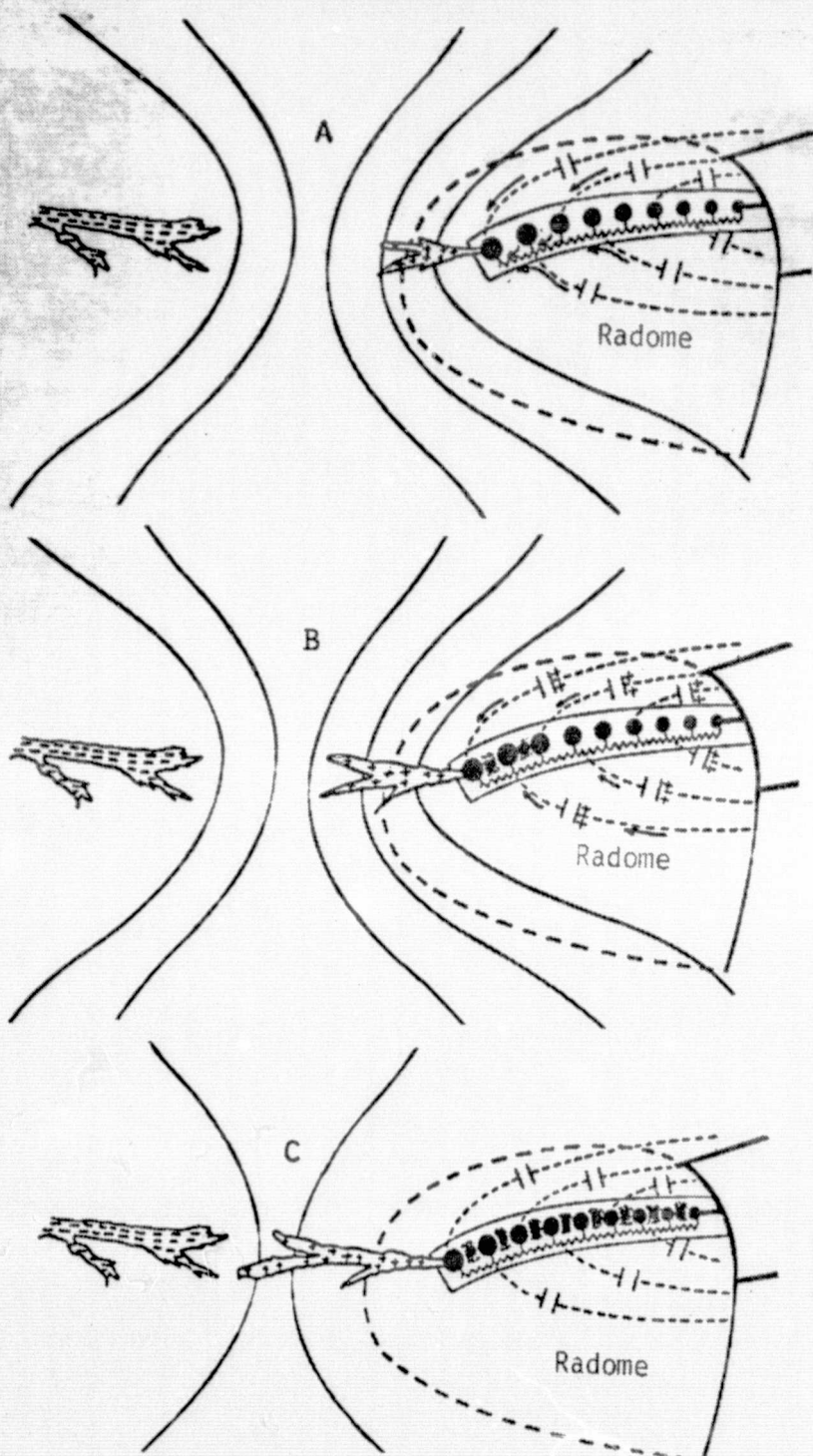
Radome

Example Shown: Electric Field around
a segmented diverter protecting a
radome.

Electric Fields

A

B

C

0.5µs/div   1mV/m/div
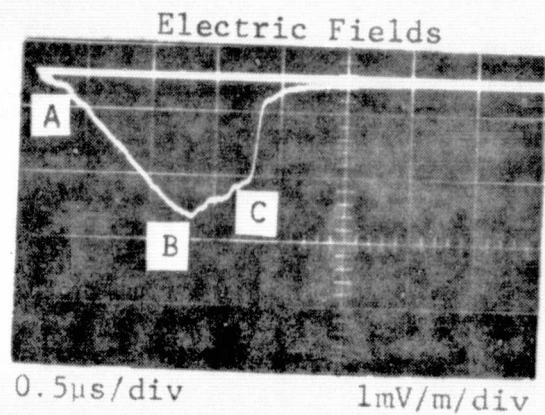
Figure 5 - Example of Electric Field Data Needed.

Currents

The lightning flash currents and their rates of change are responsible for most of the direct and indirect effects that occur to the aircraft. The direct effects include structural damage such as metal erosion, magnetic pinch, and blast damage to structures and fuel ignition from melt through of skins or sparking among structural elements in contact with fuel vapors. The indirect effects include induced voltages in electrical wiring caused by structural resistances and changing magnetic fields passing through structural apertures or diffusing through metallic skins.

Present aircraft lightning design tests are based on ground measured lightning characteristics, i.e. peak amplitude, rate of change and action integral (ability to deliver energy) of the flash, which start with the first return stroke. Leader or pre-breakdown currents are not considered.

As mentioned earlier, the statistical distribution of current amplitudes and other parameters may not be the same at flight altitudes as they are at the ground. Also, the streamer and leader currents which occur during the prebreakdown and leader phases may be important. Very little data exists on the magnitudes and waveforms of streamer and leader currents, even as experienced on the ground. It is recognized that the amplitude of these currents cannot approach that of return strokes or even continuing currents, but their rates of rise may be sufficient to induce significant voltages in electrical circuits which are exposed to the magnetic fields these currents produce. Therefore, particular emphasis should be placed on acquiring data on the streamer and leader currents.

Figure 6 shows an oscillogram of an actual lightning return stroke recorded by Berger (reference 10). The oscillogram, which was recorded on the ground, is of a stroke which resulted from an upward-propagating leader, and thus did not appear until the leader had reached the cloud, about 11.6 milliseconds after the leader began. A similar situation is likely to result at the instrumented aircraft. Thus a period of several milliseconds may elapse between the streamer/leader phase currents and the arrival of the return stroke. The instrumentation system will have to be designed to respond to and record these important currents and avoid recording of less significant events in between.

The charge conveyed by a flash, most of which is contained in continuing currents which follow the return stroke, is also of interest since the amount of metal eroded away at attachment points has been found, in the laboratory, to be related to this parameter. The peak amplitude and waveform of the continuing current are of less importance, however, and an inordinate amount of data sampling and storage capacity may be required to obtain this information.

16
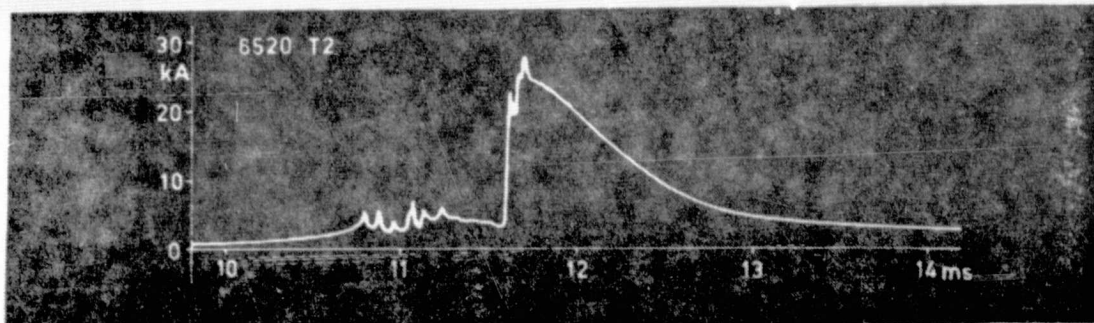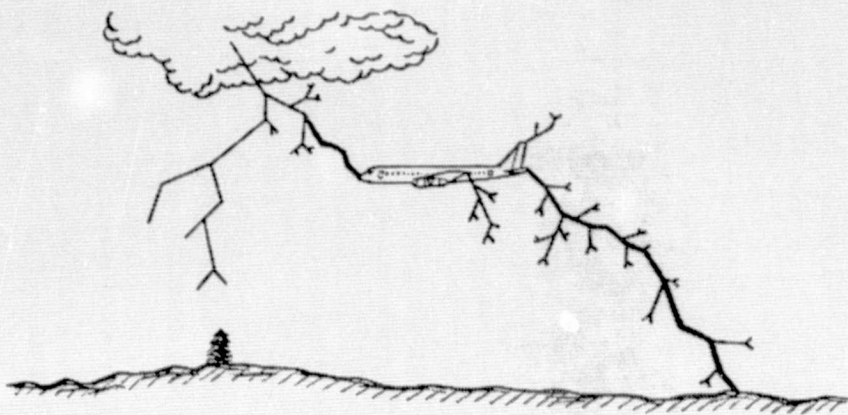
Figure 6 - Example of a Return Stroke Current.
(from Reference 10)

17

On the other hand, a relatively simple integrating circuit can acquire the total charge transferred by this current and record it as one number. Figure 7 shows oscillograms of a typical laboratory-generated continuing current and the value of its time integral. It is the final amplitude of the time-integral trace that is of interest.

In Summary - The lightning current parameters of prime interest are:

1.   The amplitudes and waveforms of the <u>streamer</u> currents that occur during the pre-breakdown phase.

2.   The amplitudes and waveforms of the <u>leader</u> currents that occur during the <u>leader</u> phase.

3.   The amplitude and waveforms of the <u>first return stroke</u> (and of subsequent re-strikes <u>if possible</u>) occurring during the return stroke phase.

4.   The <u>charge</u> and <u>action integral transferred</u> by the <u>flash.</u>

From the above measurements other parameters of importance to design, such as rate of rise and magnetic field intensities, can be derived.

The above current parameters have been listed in second priority due to their importance to safe design, with respect to both direct and indirect effects. They follow electric fields in order of priority because some information on lightning currents is already in existence, whereas no useful data yet exists on the electric field parameters.

Induced Voltages

No measurements have yet been made of voltages induced in aircraft electrical circuits when the aircraft has been struck by lightning in flight, but such voltages are known to exist because interference or burn-out of sensitive electronics sometimes occurs. To date, simulated lightning tests in which reduced-amplitude currents are conducted through the aircraft have been utilized to determine the magnitude of induced voltages. Uncertainty exists, however, concerning the level to which the measured voltages should be extrapolated, or whether the induced voltages should be extrapolated according to return-stroke current at all. Some investigators have suggested, instead, that the maximum induced voltages result from travelling-wave currents that flow initially on the airframe when it is connected to a charge source. This occurs when the laboratory generator is first switched on, or in flight when the

18

Continuing Current

115A/div   20 ms/div

Charge Transfer

4.6 coul/div   20 ms/div
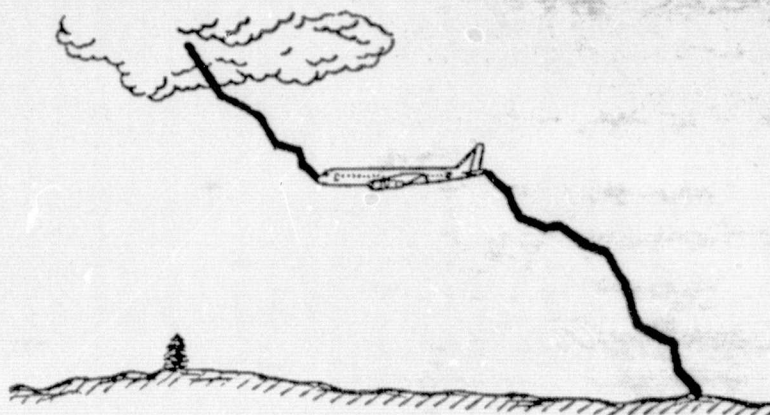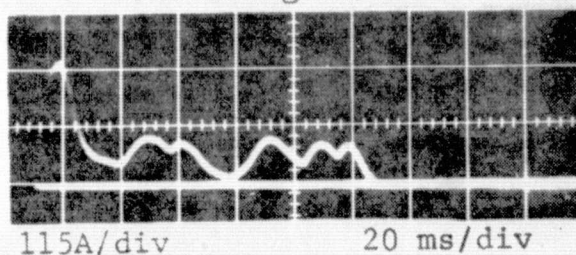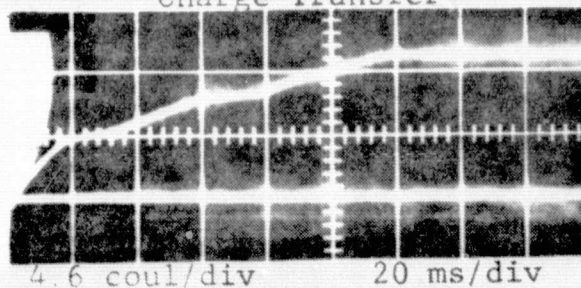
Figure 7 - Example of a Laboratory-generated
Continuing Current and Its Charge
Transfer.

leader first contacts the aircraft. Unfortunately, both the travelling wave currents and the return-stroke currents are initiated at the same time in the laboratory test, making it difficult to distinguish cause and effect relationships. In flight, however, the travelling wave currents produced by leader attachment will occur several milliseconds before the return stroke arrives, and it should be easier to distinguish between voltages induced by each phenomena.

The need, therefore, is for induced voltages to be measured in one or two aircraft circuits, and for these measurements to be correlated in time with the electric field and current measurements so that the appropriate cause-effect relationships can be established. It is not necessary for induced voltages to be measured in a wide variety of electrical circuits (as is usually done during a ground test) because once the most significant cause parameter is established it can be simulated in a laboratory test and applied repeatedly while induced voltages are measured in each circuit of interest.

Figure 8 presents oscillograms of induced voltages measured in a typical electrical circuit within the wing of a fighter-type aircraft subjected to a 40 kiloampere simulated return stroke. Voltages induced by currents of two different waveforms are shown, recorded by fast and slow oscilloscope sweep settings so that high and low frequency events can be resolved. The data is from reference 2.

The slow-sweep oscillograms of figure 8 show voltages that exist for approximately the same duration as the test current, but the fast-sweep oscillograms show a much higher frequency component that reaches a higher amplitude but exists for a shorter period of time. Such components appear in many laboratory measurements, and are the subject of the aforementioned concern.

In Summary - The induced voltage parameters of most importance are the following:

1. The amplitude and waveform of the voltages induced in one or two aircraft electrical circuits during the streamer and leader phases.

2. The amplitude and waveform of the voltages induced in the same circuit(s) as instrumented for (1) during the return stroke.

3. The measurements of (1) and (2) must be accurately correlated in time so that the cause-effect relationships can be established.

The required data are illustrated in figure 9.

Voltages Induced by a
Slow Rising Stroke

Voltages Induced by a
Fast Rising Stroke

Open Circuit Induced Voltage - Complete Wave Forms
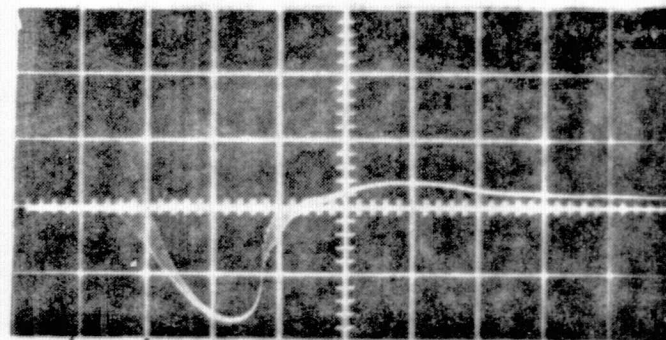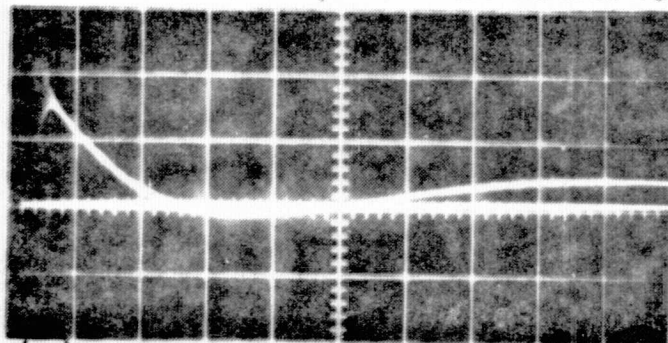
2 volts/Div.   20 µs/Div.   5 volts/Div.   5 µs/Div.

Open Circuit Induced Voltages - Expanded Time Scale Showing High Frequency Oscillations
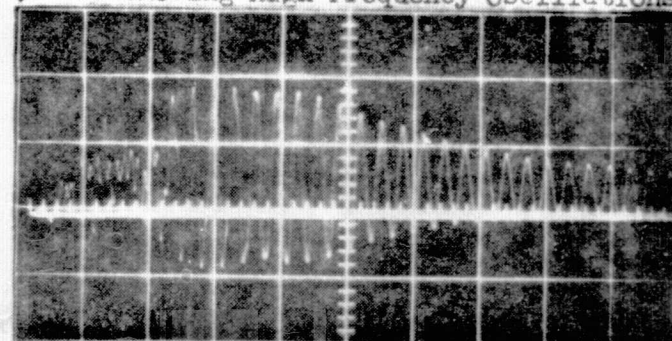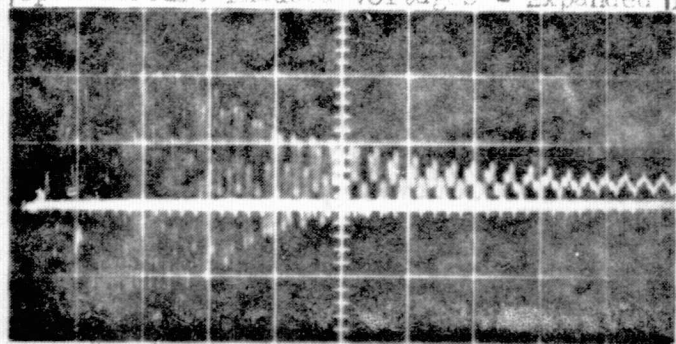
10 volts/Div.   0.5 µs/Div.   20 volts/Div.   0.5 µs/Div.

Figure 8 - Examples of Induced Voltages Measured in a Glide Path
Receiver Antenna Circuit within the Wing of an F-89J
Fighter Aircraft Resulting from 40 kiloampere Slow and
Fast Strokes to the Wing Tip.
(from reference 2)

Streamer and
Leader Phases

Return Stroke
Phase

i_L (peak)

Lightning Currents

$$\frac{di_L}{dt}$$

|←————— 1-30 ms —————→|

Correlation ?   Correlation ?

Induced Response

$v = f(?)$

$v = f(?)$
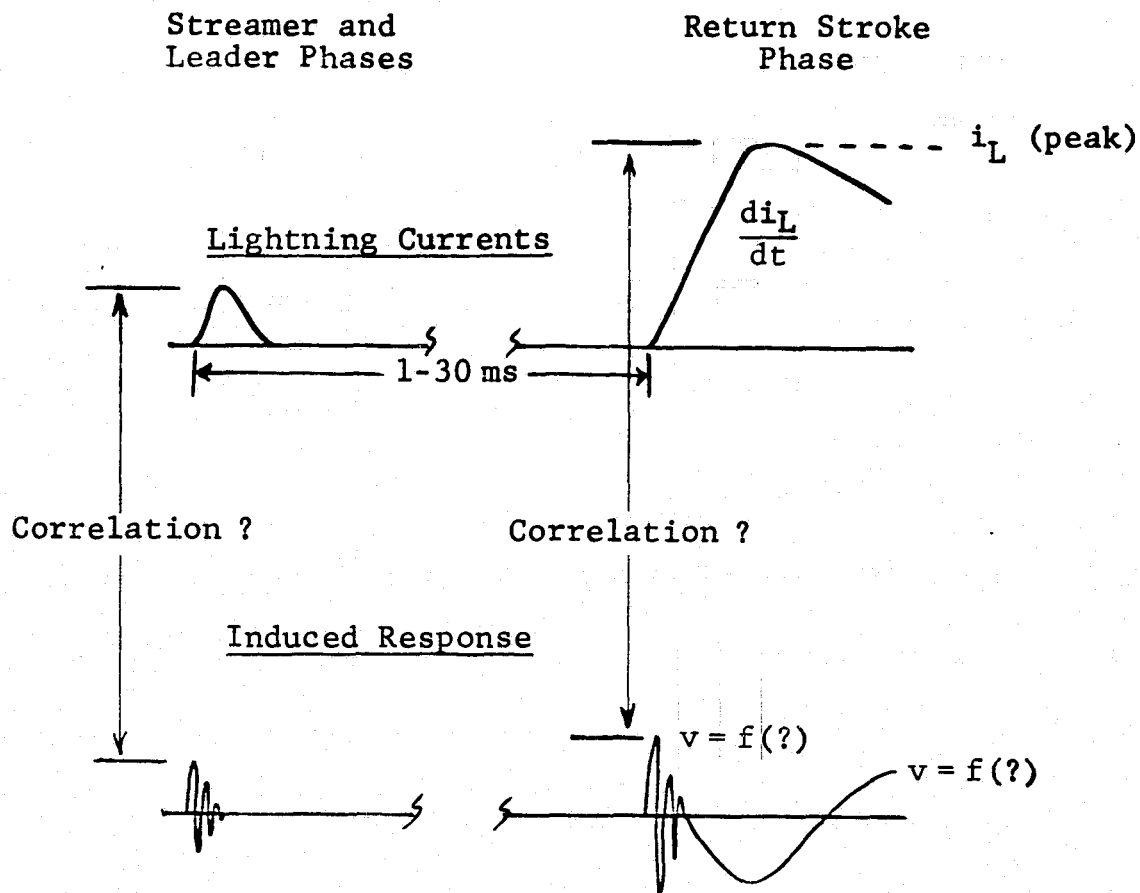
Figure 9 - Required Induced Voltage Data.

Magnetic Fields External to the Aircraft

The magnetic fields that appear immediately external to and within the aircraft while lightning currents flow in the aircraft are also of interest, because these magnetic fields may induce voltage in the aircraft electrical circuits. Since these fields are caused by the lightning currents, they can probably be reproduced on the ground if simulated lightning currents representative of the currents measured in flight are driven through the airframe. Thus the measurement of magnetic fields has been given fourth priority.

The magnetic field very near (1-5 cm) the surface of an aircraft that has been struck by lightning, for example, will be a function of the lightning current density near the point of interest. At greater distances (1-10 meters), the magnetic field intensity will be a function of the total lightning current and the distance to the electrical center of the structure.

The average magnetic intensity at the surface of an aircraft will be given by equation 4 where r is the average radius of the fuselage. Wherever an opening exists in the aircraft structure the magnetic field at the surface can leak inside and link internal wiring. Depending on the size and shape of the aperture, the amplitude of the internal field may be reduced by a factor of 10 to 1000 from the external field.

$$H = I/2\pi r \hspace{4cm} (4)$$

where:

H = Magnetic field intensity (A/m)

I = Total current (A)

r = Radial distance to centroid of the fuselage (m)

The magnetic field present at an aircraft due to lightning flashes that pass near to the aircraft but do not contact it will also be governed by equation 4 with r now equal to the distance from the flash to the aircraft. For a flash to miss an aircraft, it will probably have to be 50 meters or more away. If the maximum radius of an aircraft is assumed to be 5 meters, the magnetic intensity due to a nearby flash would never exceed 10% of that due to direct strike currents in the aircraft. A direct strike can therefore be assumed always to create higher magnetic fields at the aircraft than a nearby flash.

The waveforms of the magnetic fields external to the aircraft will be very nearly the same as those of the lightning currents that produce them. The magnetic field produced by the return stroke, then, will appear similar to the current waveform shown on figure 6.

In Summary-The magnetic fields external to the aircraft during the leader and return stroke phases are the parameters of interest, but since these fields are directly related to the lightning currents, measurement of the currents (given higher priority) will provide the data necessary to reconstruct the magnetic fields either by analysis or by tests on the ground. Therefore, unless the external magnetic fields can be measured in flight without encumbering the acquisition of higher priority data, it is not recommended that exterior magnetic fields be measured.

Internal Electric and Magnetic Fields

Electric and magnetic fields inside the aircraft are functions of external electric and magnetic fields and of the lightning currents flowing in the airframe. These fields, in turn, induce voltages in the aircraft's electrical circuits. The internal fields are dependent on airframe geometry and may vary much more widely from

one aircraft to another, and from place to place inside a single aircraft, than the lightning current that produces them. Since the induced voltages which result from the fields, and the lightning currents which produce the fields are recommended for measurement, measurement of the internal E and H fields is not recommended.

Other Parameters

There are many other parameters which are associated with a lightning flash, such as radiated electromagnetic fields, K-changes, light intensities and blast pressures, and these parameters are of interest to a further understanding of natural lightning phenomena itself. Some of these parameters are not, however, very important to the design of a safe aircraft, and others can be determined from laboratory simulations or by ground-based instrumentation. Since measurement of the three parameters given highest priority represents a formidable task by itself, it is recommended that attention be limited to these parameters only, at least until satisfactory flight data on them have been obtained.

Direct vs Derived Measurements

Electric fields external to the aircraft, lightning currents in the airframe, and the voltages these currents induce in an aircraft electrical circuit are considered to be most important for the reasons outlined in the foregoing paragraphs. Several important aspects apply to each of these parameters.

1. The foregoing assessment disclosed no situation in which a nearby flash might result in more severe parameters at the aircraft than would a flash which directly contacts the aircraft.

2. All parameters except the return stroke and continuing current are influenced by the geometry and construction of the aircraft.

3. The electric field of interest is that which is immediately adjacent to aircraft conducting surfaces and conducting parts with non-conducting surfaces. Since there can be no component of an electric field tangential to a conducting object, this field must always be normal to such parts, and it is not the same electric field as would exist in the same spot if the aircraft were not present.

Accordingly, it is recommended that the measurements be limited to those that result from a direct lightning strike to the aircraft.

SENSING DEVICES

The reasons for designation of the external electric field, lightning currents, and induced voltages as the parameters of greatest interest were presented in the previous section. In this section, the requirements for sensors necessary to measure these parameters are discussed, and sensing devices capable of meeting these requirements are described.

To assure that the sensors recommended are feasible, a general review of sensor technology was conducted (references 11-15), and discussions were held with several sensor manufacturers. Consideration of sensors has also been guided by the principle that it is best to measure the parameters of interest directly. That is, if electric field change is of interest, it is then better to measure electric field change itself rather than to measure magnetic field change, determine the transfer impedance, and calculate electric field change. For some parameters, measurements cannot be made directly and indirect methods must be used, but for the parameters listed previously. Direct measurement of the three given highest priority are quite practical.

An important requirement of all sensors and recording equipment is adequate *response time* or *bandwidth*. Response time is the time required for the sensor to respond to an abrupt stimulus and is the time required for a system to respond from the 10% level to 90% of the amplitude of a step-function input signal. Bandwidth is the ability of the sensor to respond faithfully to signals with a wide range of frequencies.

Since many sensors respond with ease to low-frequency signals down to DC, in practical terms the bandwidth indicates the highest useable frequency. Bandwidth is universally presented in terms of the "3 dB down" response. This 3 dB down (from mid-range) response is the 1/2 power point (1/2 of actual power delivered) and means the system is passing only 70.7% of the signal being sensed at that frequency. In the discussion that follows, the system risetime, t_r, and bandwidth, BW, are related by the customary relationship:

$$t_r \times BW = 0.35 \tag{5}$$

where,

$$t_r = 10\%\text{-}90\% \text{ risetime (sec)}$$

$$BW = 3 \text{ dB down bandwidth (sec}^{-1})$$

Electric Field Change Sensors

As discussed in the first section, analysis indicates that the electric field surrounding an aircraft just prior to a strike may rise at a rate of up to 10^{12} volts per second. At field intensities of 3×10^4 V/cm, the air at the surface of an aircraft

25

will most certainly have ionized and become conductive. Ioniza-
tion of the air will result in a cloud of ions or electrons near
the aircraft which will cover the electric field sensor and dis-
tort its output. From this point on, the data is of less interest.
A 10^{12} V/s field change will reach 3×10^{4} V/cm in 3×10^{-8} s. To
accurately reproduce a signal whose risetime is 3×10^{-8} seconds
the sensor and recording system should have a risetime 1/5 that of
the signal to be measured, or in this case, 6×10^{-9} seconds.

Heretofore, most airborne electric field measurements have
been made with a device called a *field mill*, pictured in figure
10. The field mill, sometimes called a *generating voltmeter*, has
been utilized to measure the static (DC) electric field at the
surface of an aircraft when it is near a thunderstorm cell. Since
the DC field can induce no current to flow on a sensing element,
a set of grounded vanes are rotated in front of flat sensing
plates to apply a changing field to the sensing plates, thereby
producing an AC signal voltage, proportional to the intensity of
the incident DC field and the velocity of the rotating vanes. The
response time of a field mill is typically greater than 15 micro-
seconds, however, so it can not be used to measure electric field
changes occurring in shorter times. For these measurements an
electric field *change* sensor is used. Basically, this sensor
operates the same as field mill except that the rotating vane is
removed and only the isolated sensing element remains. The iso-
lated sensor is connected to electronic amplifiers which maintain
the sensor at the same potential as the adjacent structure. The
current that flows off the sensing element is proportional to the
electric field change. Because the sensor is a conducting plate it
can be contoured and inserted directly in the skin of an aircraft
extremity, isolated from the surrounding skin by a small amount of
electrical insulation. A possible configuration is illustrated in
figure 11.

Electric field change sensors have been used very successfully
in measurements of electric field behavior preceding the breakdown
of long air gaps in high voltage laboratories.

Isolated plate sensors of the type pictured in figure 11,
smooth and flush with the aircraft surface and being held at air-
craft skin potential by the electronics, are not susceptible to
unrealistic interference from corona or precipitation static charge.
This is in contrast to whip or blade-type electric field sensors
which act as a corona point when the aircraft becomes electrified
due to precipitation static charging or presence in a thunderstorm
cross-field.

Current Sensors

Two basic means of sensing lightning current exist. The first
and oldest is by use of a non-inductive resistive shunt. The sec-
ond method is by use of a wide-band current transformer.

26

Peak Voltage
Detector
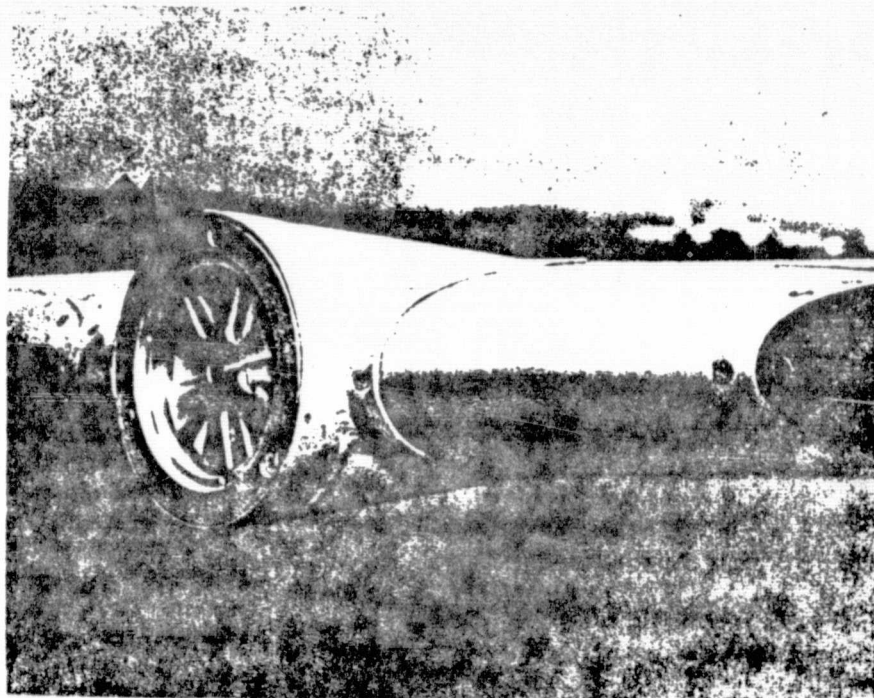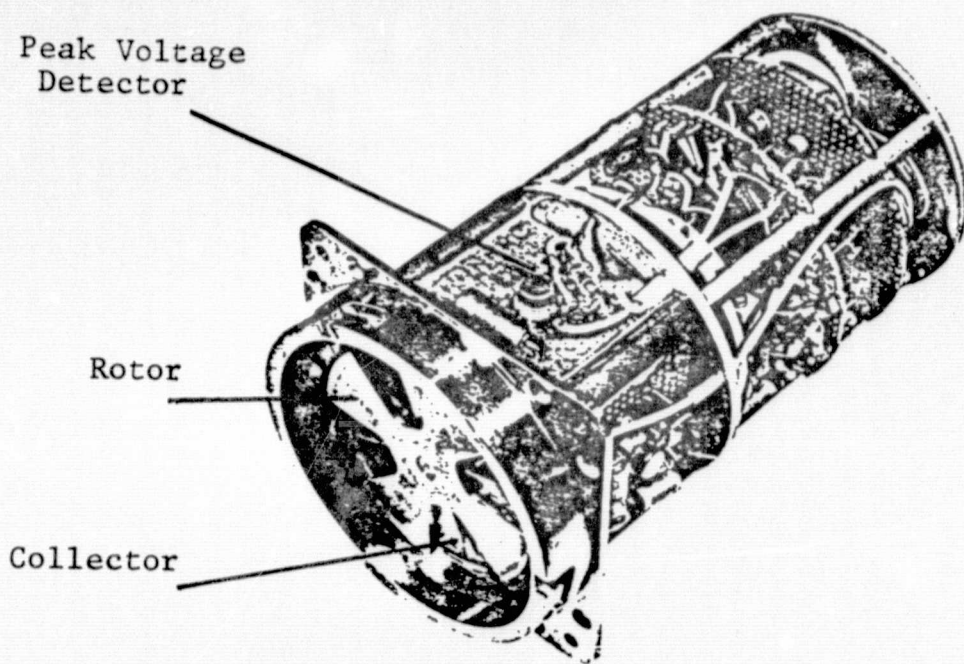
Rotor

Collector

Figure 10 - Field Mill for Measuring Electric Fields.

27

Peak voltage detector

Rotor

Collector

Virtual earth amplifier

T.R.69218

Fig.7. The field mill showing rotor and collector

Fig.7

Fig.8

T.R.69218

Virtual earth amplifier output

Output to recorder or meters

Input for aircraft 400Hz three phase supply

Power supply circuits

Polarity sensing circuit

Logarithmic amplifier

Reference generator

Drive motor

Earthing brushes

ORIGINAL PAGE IS OF POOR QUALITY
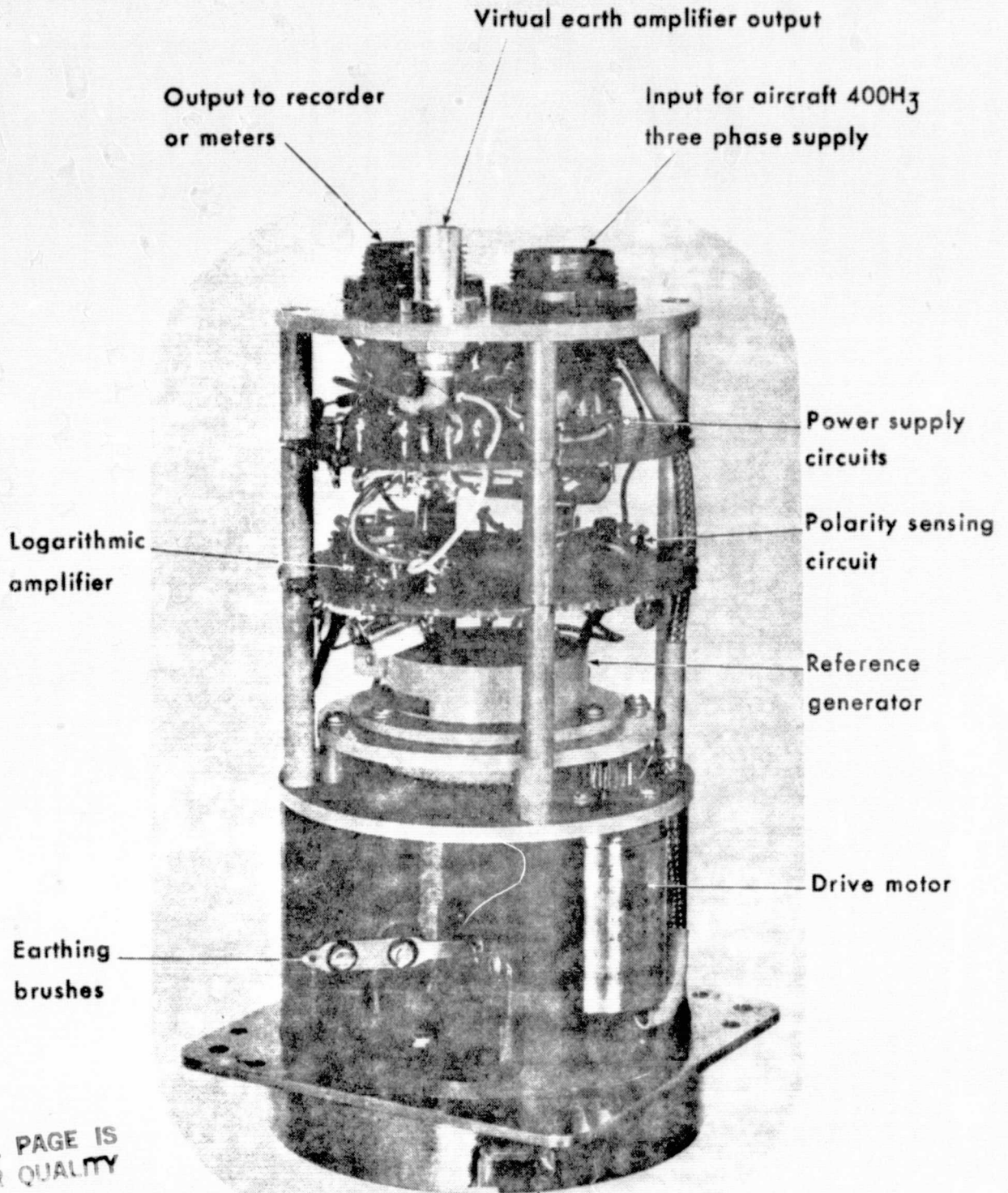
Fig.8. The field mill showing reference generator and drive motor

**Flat Plate
E-Field Sensor**

E-Field

Vertical
Fin

$$i_{out} = C\frac{de}{dt}$$

Figure 11 - E-Field Change Sensor Mounted on
a Vertical Fin.

Resistive Shunts - A resistive shunt is a non-inductive resistor which produces a voltage identical in waveform and proportional in amplitude to the lightning current passing through it. Inductive effects are eliminated by utilizing a coaxial construction so that the magnetic flux is external to the resistor and the output voltage is proportional to the shunt resistance only. The response time of a properly constructed shunt is typically several tens of nanoseconds and is limited only by the time required for current to diffuse into the resistive element.

28

To produce reasonable signal voltages throughout the 3-to-300,000 ampere range of possible current amplitudes of Table I, a shunt resistance of 10 milliohms may be utilized. This would provide signal voltages between 30 millivolts and 3 kilovolts. Appropriate signal conditioning, of course, will have to be provided to accommodate even this range of voltages. Requirements and limitations associated with this signal conditioning are discussed in a subsequent section.

Another consideration in the sizing of a shunt is its thermal capacity, as it must contain sufficient material to dissipate the heat generated within it by the lightning current. Assuming that action integrals which have been measured at the ground terminus of a flash are not exceeded farther up the channel, an airborne shunt resistor must be designed to withstand an action integral of $2 \times 10^6 A^2$-s. At 10 milliohms, this would result in an energy dissipation, E, of

$$E = \text{(action integral)(shunt resistance)} \qquad (6)$$
$$= (2 \times 10^6 \ A^2\text{-s})(0.01\Omega)$$
$$= 20 \times 10^3 \ \text{Joules}$$

Discussions with shunt manufacturers disclose that temperature rises of up to 100°C are permissible, that 1000 grams of the specialized resistance metal will be required, and that this material must be formed into a sheet not exceeding 0.102 mm thickness if a shunt risetime of 10 nanoseconds is to be maintained. One of these manufacturers indicated that a shunt meeting the above requirements and packaged for airborne application could be built at a cost of about $500. The circuit and approximate dimensions of such a shunt are shown on figure 12.

Current Transformers - A wide-band current transformer (CT) is another means of measuring lightning current. This device employs magnetic coupling between the current being measured and the measurement circuit. CT's are desirable for some applications because no direct connection is necessary between the current-carrying conductor and the measurement circuit. The main disadvantage of a CT is its inability to reproduce unidirectional current of long duration. When a long duration (i.e. several seconds) square-wave of current is measured by a CT, the energy available to drive current through a measurement resistor across the secondary winding of the CT must be supplied by allowing the core flux to increase. As the core flux increases the secondary current then decreases simultaneously and the signal voltage appearing at the secondary decreases. In current transformer specification this behavior is called *droop* and is rated in percent unit time. To reduce droop, more turns are added to the secondary winding and larger cores are used, both of which degrade the transformer response time. All CT's exhibit some degree of droop.

RESISTIVE SHUNT

R = 0.01 ohm

20×10^3 Joules

IN   **OUT**

Lightning
   Current,

i_L

Up to 300 kA

$2 \times 10^6 \, ^@ \, Amp^2$-sec

$e_{out} = i_L R$

≤ 2 kV

60-90 cm

10-15 cm
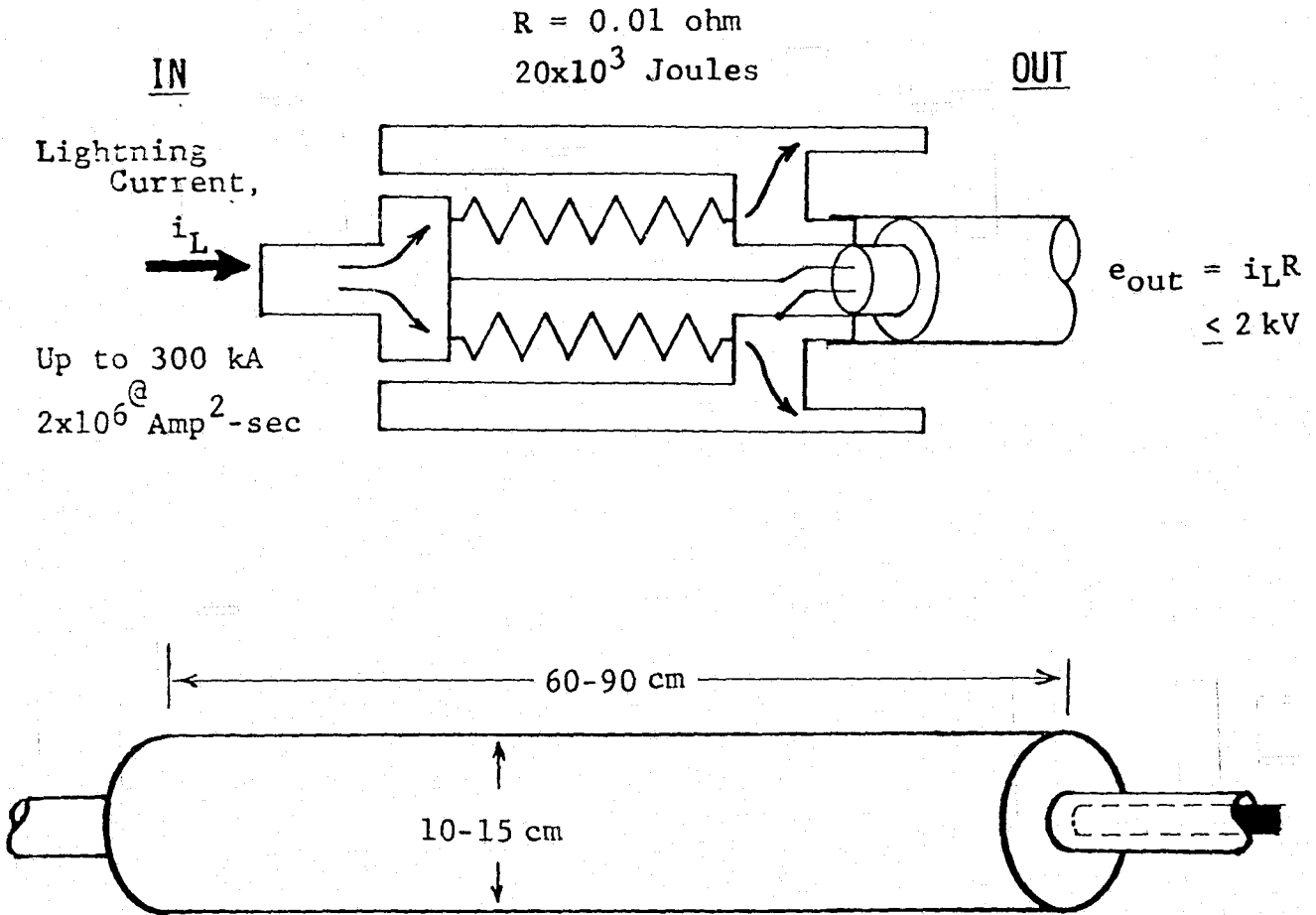
Figure 12 - Configuration of a Resistive Shunt
for Measuring Lightning Currents.

From discussions with CT manufacturers it was learned that a CT with droop as low as 0.03% per millisecond is currently available. However, if such a transformer were utilized to measure a continuing current of 200 amperes lasting for one second, the secondary voltage would be low by an amount equivalent to 60 amps at the end of one second. If a 100 kA occurred *after* the one-second continuing current the 60-amp error would be insignificant and this stroke would be measured correctly. But if instead the continuing current dropped to 100 amperes the indication of this current would be in error by 60%.

30

Some of these problems might be resolved by using active feed-back electronics to maintain "zero flux" in the current transformer core. However, the system becomes much more complicated and since it is no longer a passive system; drift, stability and range become troublesome.

Rogowski Coils - Another sensor, called a Rogowski coil, was investigated as a possible current-sensing device since it can be constructed in various geometrical shapes, does not require an iron core and could, in theory at least, be wrapped around a large structural member such as an empennage or pylon. Unfortunately, Rogowski coils sense only changes in current and thus have very poor low frequency response. Active circuitry would again be required to interpret this sensor's output.

Summary of Current Sensors - When compared to the resistive shunt, the disadvantages of both the current transformer and the Rogowski coil far outweigh the advantages of either device. The simplicity and reliability of a properly constructed resistive shunt make it the best sensor for measuring lightning currents.

Induced Voltages

The induced voltages in aircraft wiring have two basic sources; the voltage drop, called the IR component, along the air-craft structure due to lightning current in the airframe, and the changing magnetic flux also produced by lightning currents in the airframe.

The IR component is related directly to the lightning flash current but may be delayed in time somewhat due to current diffusion through the aircraft skin.

Magnetic fields are introduced into the aircraft interior in two ways. One is by direct penetration of external magnetic flux through apertures in the aircraft structure. These apertures range in size from the small cracks around access doors to the large openings provided by windshields or canopies. Magnetic fields associated with the lightning current in the aircraft "leak" through these apertures and couple circuits inside.

When lightning currents first enter an aircraft most of the current is in the outer portion of the skins, and except for that which leaks through apertures, the magnetic fields associated with this current remain outside the airframe. After several 10's of microseconds, however, the current will have *diffused* through-out the skin and some of it, together with its magnetic field, will appear on the inner surfaces. The magnetic fields that enter through apertures are frequently referred to as *aperture fields* and those that appear via the diffusion process as *diffusion fields*.

31

The diffusion process in a typical aircraft structure with 0.1 cm (0.04 in.) skins will reduce the rate of change of the diffusion fields by about two orders of magnitude with respect to that of the exterior field and the aperture fields. Thus, the voltages induced by diffusion fields are correspondingly lower.

Induced voltage tests have been conducted on several aircraft using scaled-down, simulated lightning currents as described earlier. The IR and magnetic components of the induced voltages measured during these tests have often been found to be separated in time, with the magnetic component occurring first. The magnitudes of these two components vary widely among different circuits and different aircraft, and are a function of structural design, wiring practices and aperture sizes and locations. Aircraft electrical circuits which use the airframe for return can exhibit IR components with magnitudes equal to or greater than the magnetic components. In other circuits, which use an independent return, the magnetic component usually predominates.

The magnetic component of induced voltage usually has a frequency content not exceeding 50 MHz and a duration of less than 10 microseconds. The IR component of the induced voltage will typically contain frequencies up to 100 kHz and have durations as long as the lightning stroke itself (10^{-3} sec.).

Some investigators have doubts about the projected full-scale magnitudes of the magnetic component of induced voltages that have been measured during the scaled-down tests. The primary bases for these doubts has been the observation that the magnetic component of induced voltage occurs at the time of test generator switching and does not appear to be directly related to test current rate of change. When highly oscillatory test currents are applied, the magnetic component of induced voltage appears at the start of the applied current wave but not at subsequent zero crossing even though a high di/dt is present at these times as well.

These questions can be answered during the inflight measurement program if the voltages induced in one or two of the aircraft's electrical circuits are measured and recorded at the same time and with the same resolution as the lightning current.

As a sensor, two wires, one in the aircraft wing and one in the fuselage should be monitored. The far-end of each wire should be connected to airframe structure and the near ends connected together and terminated to the airframe in their estimated surge impedance, which is typically 50 ohms. This will allow a significant voltage to be measured regardless of whether the lightning strike current flows in the wing, as from a wing tip-to-wing tip strike, or in the fuselage, as in a nose-to-tail strike, and it will require that only one signal be recorded.

DATA PROCESSING

The most formidable task in the design of the instrumentation system to measure the parameters described earlier will be design of the data storage, processing and recording system. This system must discriminate between wanted and unwanted parameters, record those that are required with sufficient resolution to provide the information required, and enable read-out in a practical fashion. If not, the essential facts may be lost among an overwhelming quantity of numerical data.

For example, if one lightning current data channel of 50 MHz bandwidth were to be displayed on an oscillographic strip chart (neglecting for the moment the problem of displaying 4 orders of current magnitude on the vertical scale) the signal must be recorded at rates between 10 and 100 nanoseconds (ns) per division. Choosing divisions one centimeter long to represent 50 ns, a one-second flash would require about 125 miles of chart paper.

The marked advances made in digital signal processing and memory technology during the past decade provide the means to accomplish this objective and this is the reason that a significant improvement can be made in the quality and quantity of lightning data to be obtained as compared with that obtained during the rough-rider program of the 1960's.

This portion of the feasibility study therefore concentrated on determining what amount of data could be stored and processed to the degree of resolution desired with presently available technology. This task also included definition of the data processing system requirements.

The equipment necessary to completely process the data may be extensive and if attempted in flight, may impose excessive weight and space requirements. Accordingly, it appears practical to have some processing accomplished with ground-based equipment, after the data-gathering flight is complete. Figure 13 shows a logical division.

In-Flight Data Recording

The data generated by the sensors in the aircraft can be stored in either analog form or in digital form. Analog recording systems are a well-established technology with many years of experience. Magnetic tapes or photographic chart papers are examples of analog storage techniques and large quantities of data can be stored on these media, but the information is limited in frequency response to 5 MHz or less. Analog recording of higher frequency data can be accomplished by photographic records of oscilloscope displays; however, these analog records are always of very limited time durations, usually about 25 times the reciprocal of the

highest frequency of interest (i.e. 500 ns for a 50 MHz signal).
Consequently, analog recording systems either lack the frequency
response or the duration that would be desirable for this project.

```
┌──────────┐      ┌──────────┐      ┌──────────┐      ┌──────────┐
│          │      │          │      │Analog to │      │          │
│  Sensor  │─────>│  Signal  │────>│ Digital  │────>│   Data   │────>
│          │      │Compression│     │Conversion│      │ Storage  │
│          │      │          │      │          │      │          │
└──────────┘      └──────────┘      └──────────┘      └──────────┘
```
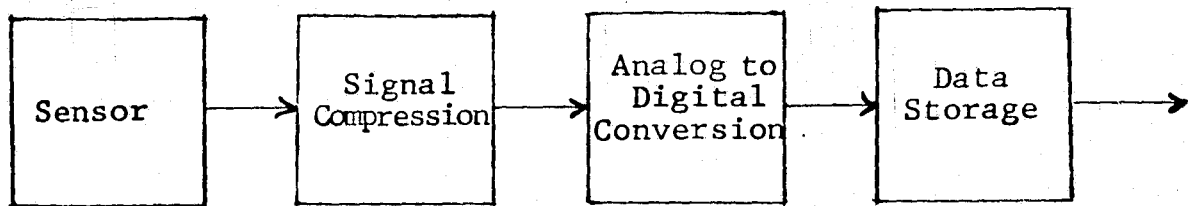
In-Flight Data Operations

Ground Data Operations

```
          ┌──────────┐      ┌──────────┐      ┌──────────┐
          │          │      │Processed │      │Interpre- │
    >────>│   Data   │────>│   Data   │────>│  tation  │
          │Processing│      │ Display  │      │          │
          │          │      │          │      │          │
          └──────────┘      └──────────┘      └──────────┘
```
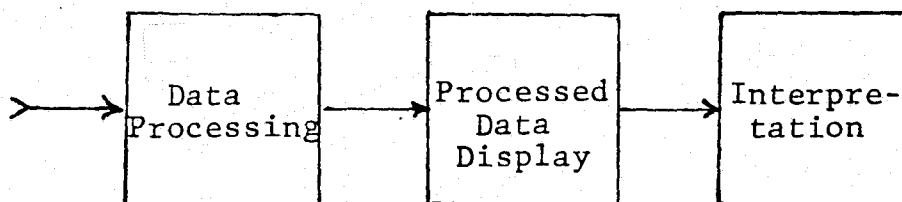
Figure 13 - In-Flight and Ground Data Processing.

New high speed analog to digital (A/D) converters are avail-
able that will handle frequencies of approximately 100 MHz. Basi-
cally, an A/D converter samples the amplitude of an analog signal at
a point in time and represents the amplitude as a coded digital
binary word. Two types of converters are available, the *successive
approximation* type and the *flash* type. Successive approximation
converters are the oldest and are relatively slow. The flash con-
verters, however, have very high conversion speeds made possible by
advances in Large Scale Integration (LSI) technology.

The operation of A/D converters and the differences between
the operation of successive approximation and flash converters can
best by understood by following the step by step operations. Fig-
ure 14 is a small time interval of an analog signal, a portion of
the current waveform pictured in figure 9. Figure 15 shows the same
waveform samples at equal intervals of (5 x 10^{-9} seconds). An A/D
converter will take a sample, and decide if the voltage is higher
than 1/2 of full scale. If it is greater than 1/2 scale, a binary

34
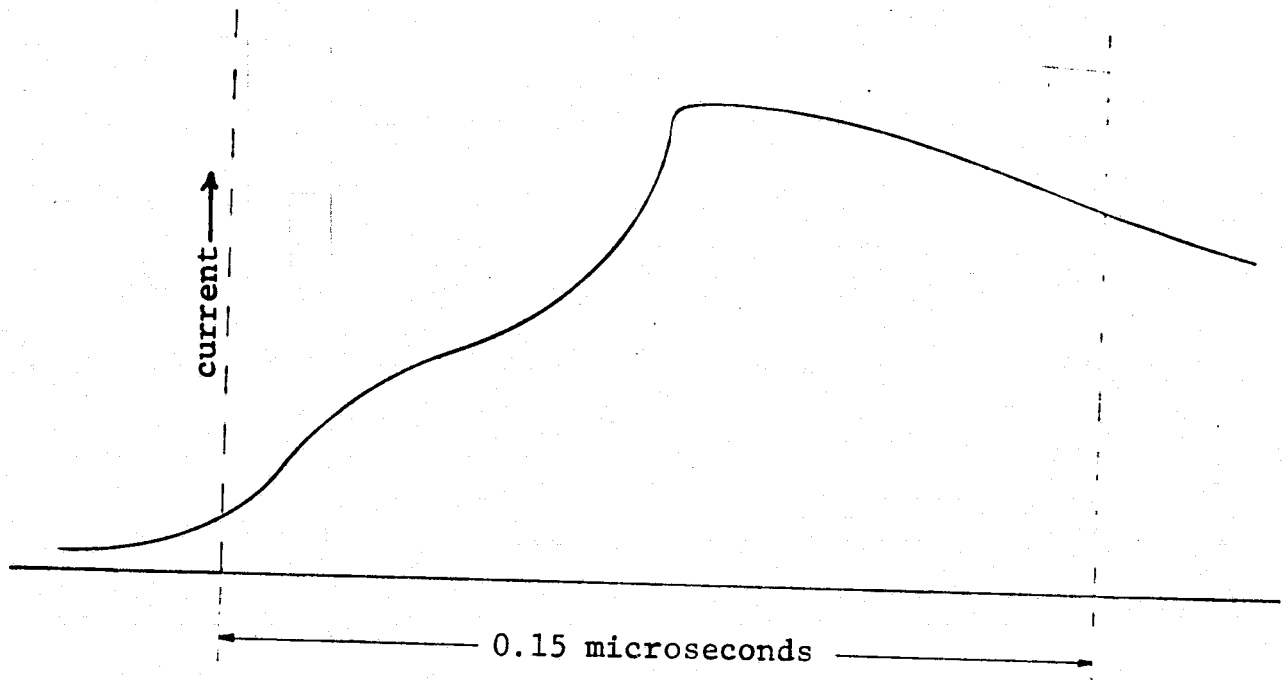
Figure 14 - A Portion of a Lightning Stroke Current.

Figure 15 - Voltage Samples of the Lightning
Current Amplitude.

one is recorded, but if it is less, a zero is recorded. The binary one or zero represent the first and most significant bit of the binary word. After resolving the first bit, the second bit is determined. If the first bit is a one, a voltage equal to one half of full scale is subtracted from the sample, if zero, no voltage is subtracted. Now the process is repeated to determine if the remaining sample is greater or less than one quarter of full scale. Again a 1 or a 0 is generated as the 2nd bit. Appropriate subtra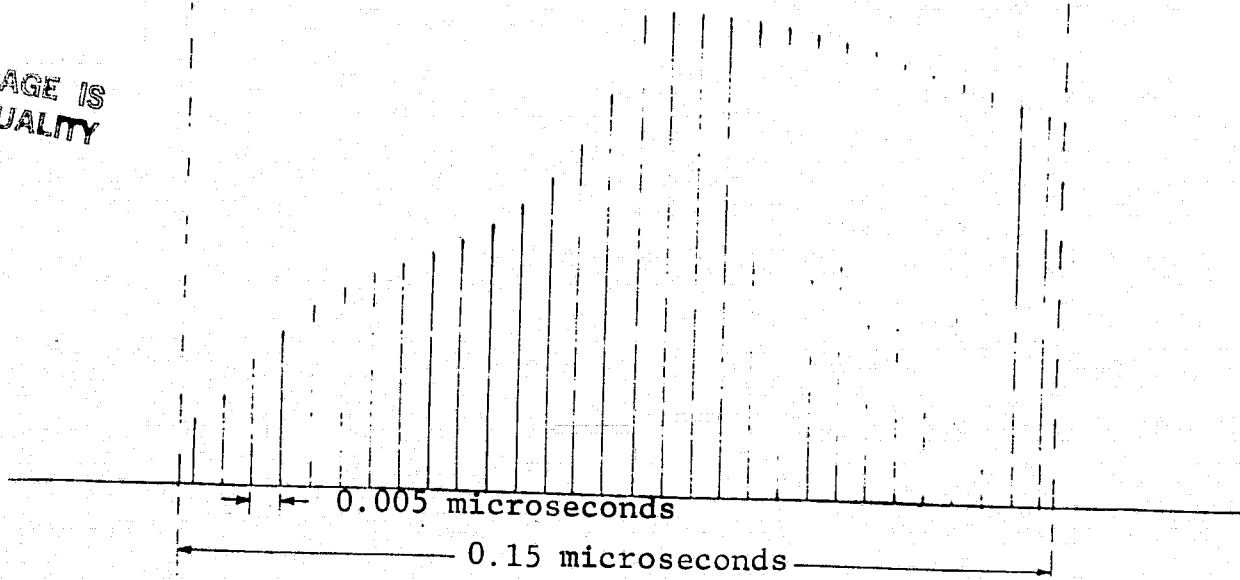ctions are accomplished and the third bit is generated. This process continues until the last bit, called the least significant bit (LSB) has been generated. The number of bits generated depends on the design of the particular A/D converter being used. A/D converters are available that will generate anywhere from 3 to 15 bits for each sample. The greater the number of bits, the more accurate the amplitude of the sample.

The successive approximation A/D converter generates the bits by completing the above operations in series. Thus the more bits being generated, the longer the conversion time required. Typically a 6-bit converter will require 10 to 15 microseconds to complete the conversion because of the many steps required. Figure 16 shows the comparison voltage levels of a 3 bit A/D converter.

In the flash A/D converter, a set of parallel voltage comparators are biased a voltage equivalent to the least significant bit apart. The output of the voltage comparators are sent to a decoder whose output is the binary digital word representing the sample amplitude. Thus only two steps are required to digitize the samples. The disadvantage of the flash method is that a large number of comparators are required. For a 6-bit converter, 63 comparators are required to monitor the appropriate levels. Circuits containing the large numbers of components necessary for 63 comparators were not feasible before the recent advances in LSI technology, but flash A/D converters with 5 nanosecond sample intervals are now available.

It can be shown using information theory that if a signal is sampled at a rate that just exceeds two times its highest frequency component, the signal can be completely reconstructed from the samples, but practical limitations in the construction of filters necessitate sampling rates of 4 to 5 times the highest frequency in order to accurately reproduce a signal. Thus a 50 MHz signal would require a minimum 200 MHz sample rate.

These high sampling rates will, of course, create many binary words which must be stored in solid-state memories.

Manufacturers of digital waveform recorders often use a first in, first out (FIFO) solid-state memory for storing this data.

36

```
FULL SCALE
        3RD BIT
        2ND BIT
        3RD BIT
        1ST BIT
        3RD BIT
        2ND BIT
        3RD BIT
```

|←————————— 0.15 microseconds ————————→|
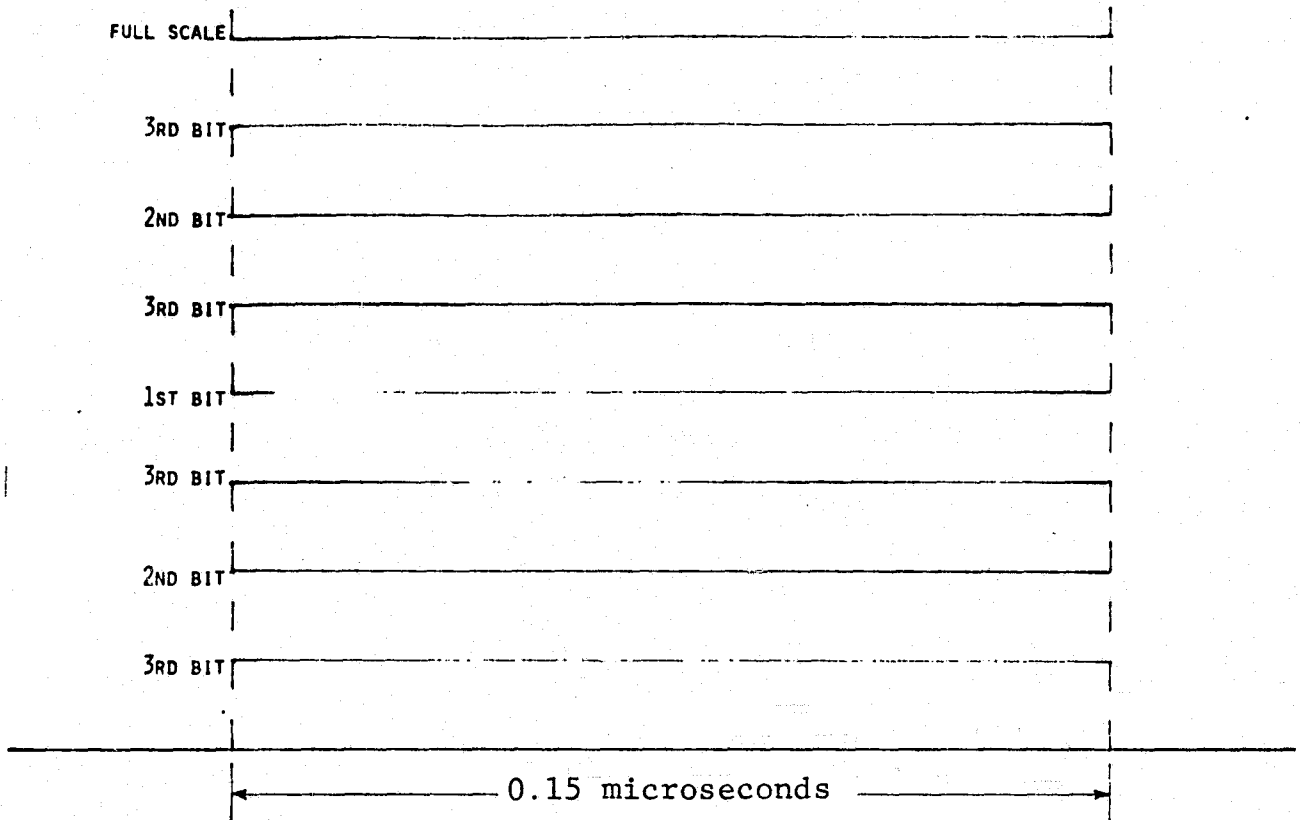
Figure 16 - Comparison Voltage Levels
of a 3-Bit A/D Converter.

In such a memory, as each new data word is placed in the memory,
it moves the previous word over one slot. The chain continues un-
til all memory slots are full. After the memory is full, each new
word causes a previous word to be lost. If a word is stored every
5×10^{-9} sec, and the memory has slots for 1000 words, 5×10^{-6} sec.
of information can be stored in the memory. When a decision is
made to stop entering new data the previous 1000 words of data are
stored and useable. This feature allows "pretrigger" viewing of
the data, since, when a decision is made to record the data, a
memory full of data stored prior to the trigger time is already
stored and can be saved. This can be contrasted to other record-
ing systems such as the simple oscilloscope, in which the data that
can be recorded is only that which appears after the decision to
record has been made.

Commercial digital waveform recorders (flash A/D converters
with a memory) are presently available. Present memory capability
is 1000 words or about 5 microseconds at 5 nanosecond sampling in-
tervals. The memories on these commercial systems have been ex-
panded to capacities of 1.3×10^{5} words which would allow storage of

37

up to 200 microseconds of data at 5 nanosecond sampling rates.
Further expansions may be possible at a later date but do not
appear feasible at the present time.

Magnitude Scaling - The discussion thus far has dealt with
the risetime and frequency requirements to insure that no abrupt
changes or oscillatory signals are lost by the recording equip-
ment, and this discussion is applicable to the E-field and light-
ning current parameters as well as the induced voltage signals.
As discussed earlier, lightning current data throughout a range
of 3 to 4 orders of magnitude in amplitude are of interest. If
this data is recorded on a linear scale, values of less than 10%
of full scale may not be accurate. It would be possible to use
4 parallel systems having full scale values of 30, 300, 3000, and
30,000 amperes with the lower 3 inputs protected against the
overvoltages impressed upon them, but this approach would require
a large amount of equipment. It should be used only if no other
alternative can be found.

Signal compression is another approach. Logarithmic ampli-
fiers are commercially available with good dynamic range through-
out 5 decades at an accuracy of $\pm$ 1%. However at low level inputs,
frequency response is very bad; typically 100 to 1000 Hz. The
poor response results from 1st decade operating currents ranging
between 1 and 10×10^{-9} amperes. Charging any stray capacitance
with such low level currents requires excessive time and results
in the slow response.

Amplitude compression in Project Rough Rider was achieved
with a compression circuit consisting of tunnel diodes paralleled
in reverse directions. However, no data on the frequency response
of this scheme was reported, so the tunnel diode approach should
be evaluated in the laboratory to determine its low level frequency
response.

Another alternative would be to construct a flash A/D con-
verter with logarithmic comparator levels. An example of such
levels for a 3 bit comparator covering 4 orders of magnitude is
shown in figure 17 and figure 18 shows the digit words correspond-
ing to such an A/D conversion. With only 3 bits covering such a
wide range, the data would be almost useless, however if 6 bit
levels were used, such as shown in figure 19, the conversion would
be much more accurate.

Discussions with various digital equipment manufacturers re-
veal that although no theoretical problem exists with logarithmic
flash A/D conversion, a practical signal to noise (S/N) problem may
exist. Low level white noise exists in all systems and is genera-
ted by the components making up that system.

38

FULL SCALE

3RD BIT

2ND BIT

1ST BIT

|← ——————— 0.15 microseconds ————— →|
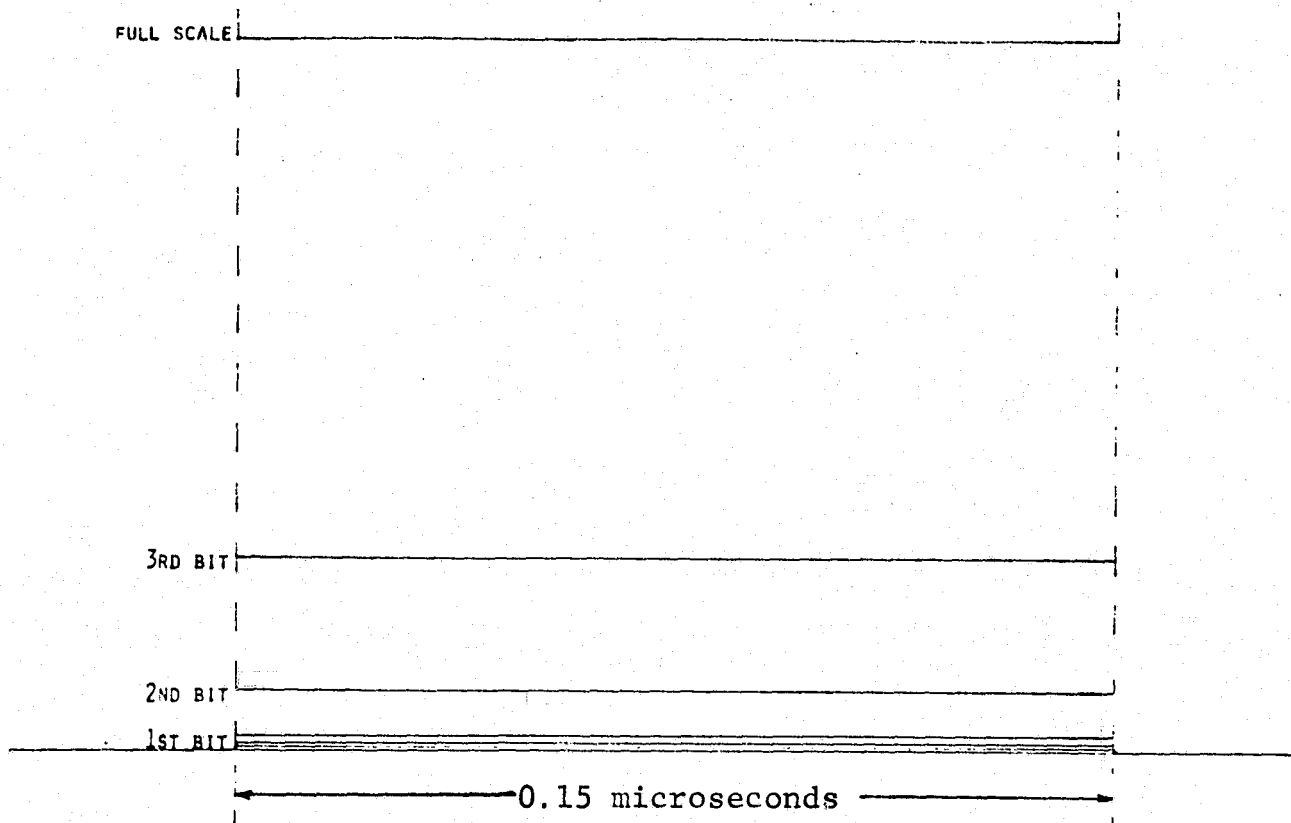
Figure 17 - Logarithmic, 3 Bit, Parallel A/D Converter Levels.

LSB   0   0   0   1   1   1   1   1   1   1   1   1   1   1

       1   1   1   1   1   1   1   1   1   1   1   1   1   1

MSB   1   1   1   1   1   1   1   1   1   1   1   1   1   1

|→| |← 0.010 microseconds
|←————— 0.15 microseconds ————→|
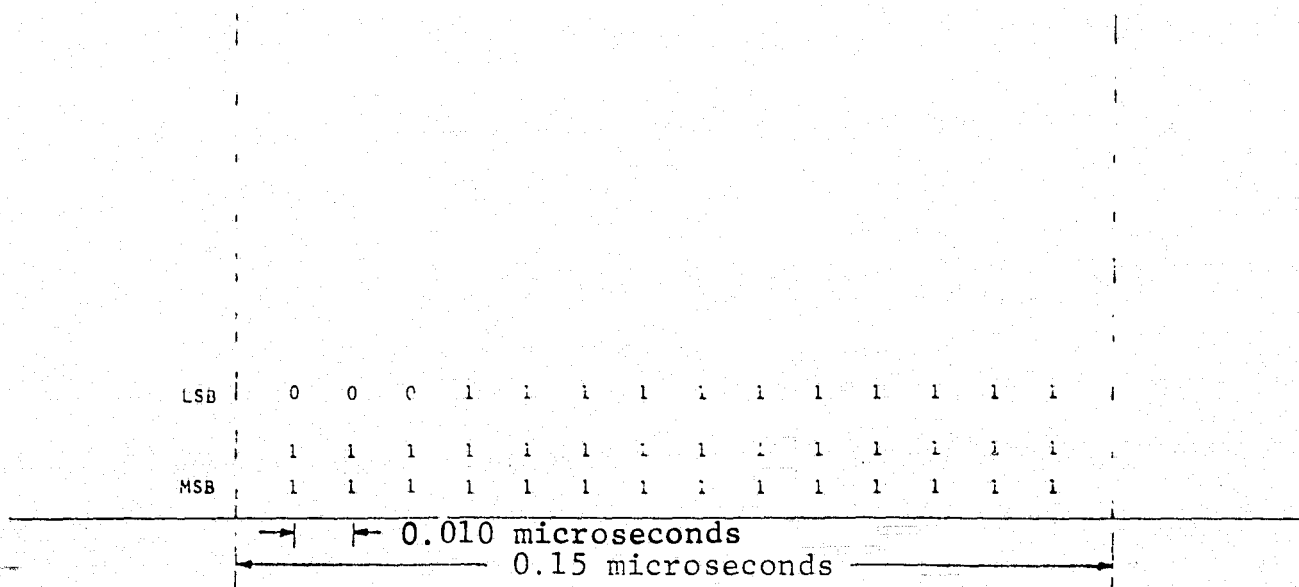
Figure 18 - Binary Output of a Logarithmic 3 Bit
A/D Converter as a Function of Time.
(1/2 of the Binary Words Omitted)

39

FULL SCALE

6TH BIT

5TH BIT

6TH BIT

4TH BIT

6TH BIT

5TH BIT

6TH BIT

3RD BIT

6th BIT
5th BIT
6th BIT
5th ;;
6th ;;
2nd BIT

47 OTHER
LEVELS

|←————————— 0.15 microseconds ——————————→|
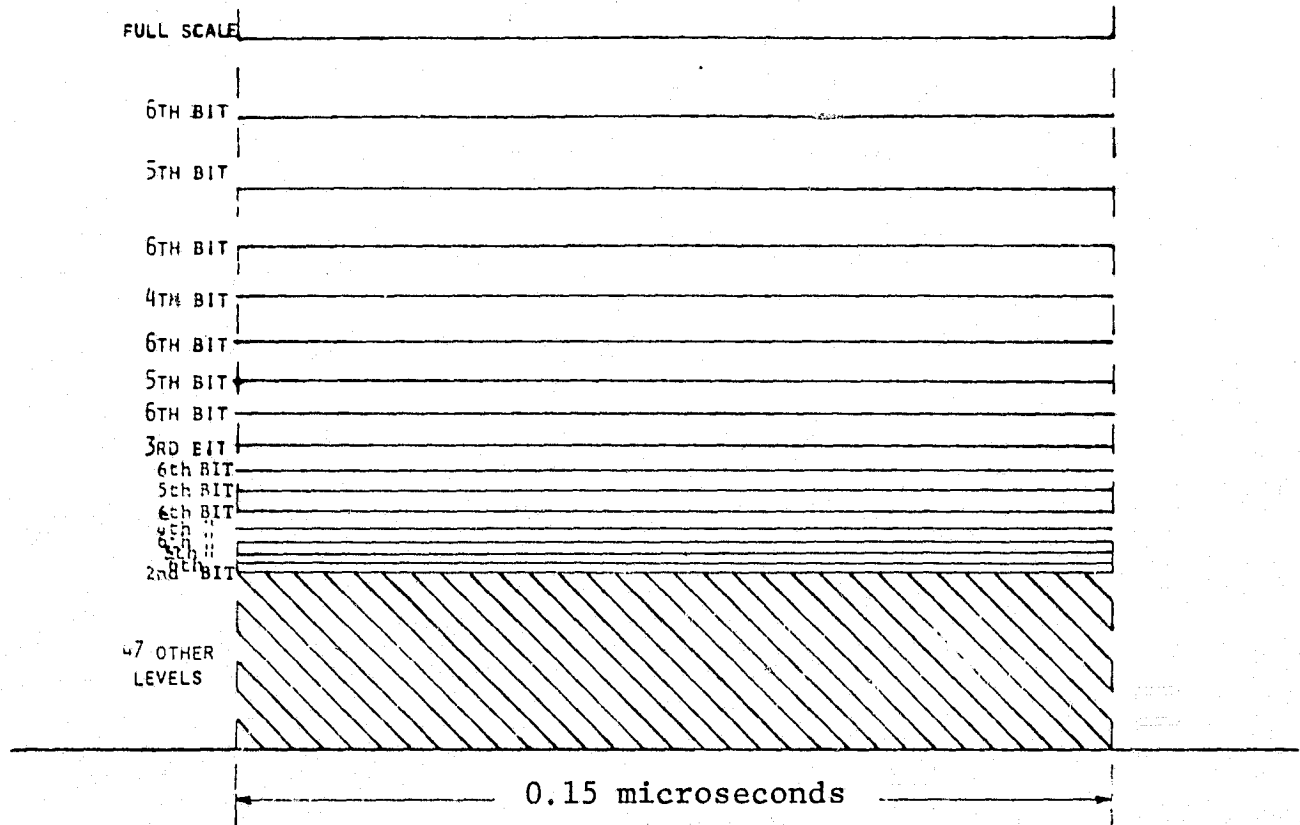
Figure 19 - Logarithmic 6 Bit Parallel
A/D Converter Levels.

For example, the noise voltage, e_n, generated by a resistor
is given by: (reference 16)

$$e_n = \sqrt{4KTR(\Delta f)} \quad \text{(volts rms)} \tag{7}$$

$$K = \text{Boltsman Constant} = 1.38 \times 10^{-23}$$

$$T = \text{temperature (°Kelvin)}$$

$$R = \text{resistance (ohms)}$$

$$\Delta f = \text{band width (Hertz)}$$

By equation (7) a 10 megohm resistor in a 50 MHz bandwidth
system at 25°C exhibits a noise level of approximately 3×10^{-3}
volts. A 50 ohm resistor will exhibit noise of approximately
6×10^{-5} volts. Since active system components usually exhibit
noise levels higher than resistors, a high impedance circuit such
as the electric field change sensor could exhibit noise levels of
5-to-50 millivolts. Low impedance circuits such as the current
sensors, could exhibit noise levels of from 50 microvolts to 0.5
millivolts.

40

Full scale input voltage for most solid-state circuits is 10 volts. This would provide a range of 4 decades for a low impedance circuit and 2 decades for a high impedance circuit. The resistance ladder for biasing the 63 flash comparators would have to be fairly high impedance and would therefore probably restrict operations to no more than 2 or 3 decades of input range. It therefore appears at the present time that if 4 decades of signal are desired, 2 parallel recording systems must be utilized, with each covering 2 decades.

Electric Field Change Data Recording - At electric field intensities of 3×10^4 V/cm, the air at the surface of an inflight aircraft will have ionized and become conductive. A breakdown of the air will result in a cloud of ions (electrons) near the aircraft which will cover the electric field sensor and after this its output data will no longer be useful. If 10^{12} V/s electric field changes actually occur, the field will reach 3×10^4 V/cm in only 3×10^{-8}s. To accurately reproduce a pulse with a rise time of 3×10^{-8} seconds the system should have a rise time 1/5 that of the pulse to be measured. The system rise time should then be 6×10^{-9}s.

The system bandwidth required to accurately reproduce a 6×10^{-9}s rise time is approximately 60 MHz (58.33 MHz exactly). However, the information lost by using a 50 MHz bandwidth would be very small. Using an A/D converter which samples the signal every 5×10^{-9} seconds will preserve the data available.

Since the electric field change sensor will not produce accurate data after the aircraft has encountered a lightning leader, the A/D waveform recorder can be "pretriggered" to record the interval just prior to leader attachment. The trigger signal can be provided from one of the current sensors, and set so that a signal representing 3 to 30 amperes will provide a trigger pulse. Since the air around the electric field sensor will have ionized just before triggering occurs, measurement of the field change from 100 V/cm to 10,000 V/cm (2 decades) should be sufficient to obtain the required data, requiring only a single channel recorder.

After the data has been stored in the high speed digital memory associated with the waveform recorder, it can be transferred at lower bit rates into a mass storage medium such as a floppy disk or magnetic tape system. Once the transfer is complete, the recording system will be ready to accept data from another inflight strike. A block diagram of the electric field change sensor and data recording system is shown in figure 20.

Lightning Current Data Recording - Measurements of lightning flash currents in tall grounded objects, such as buildings or towers on mountain tops, have shown that low level currents for comparatively long duration often precede the high amplitude, short duration return stroke. These long duration (10^{-2} to 10^{-1} s)

low level (10^1 to 10^3 A) currents are associated with upward reaching leaders that originate at the structure.
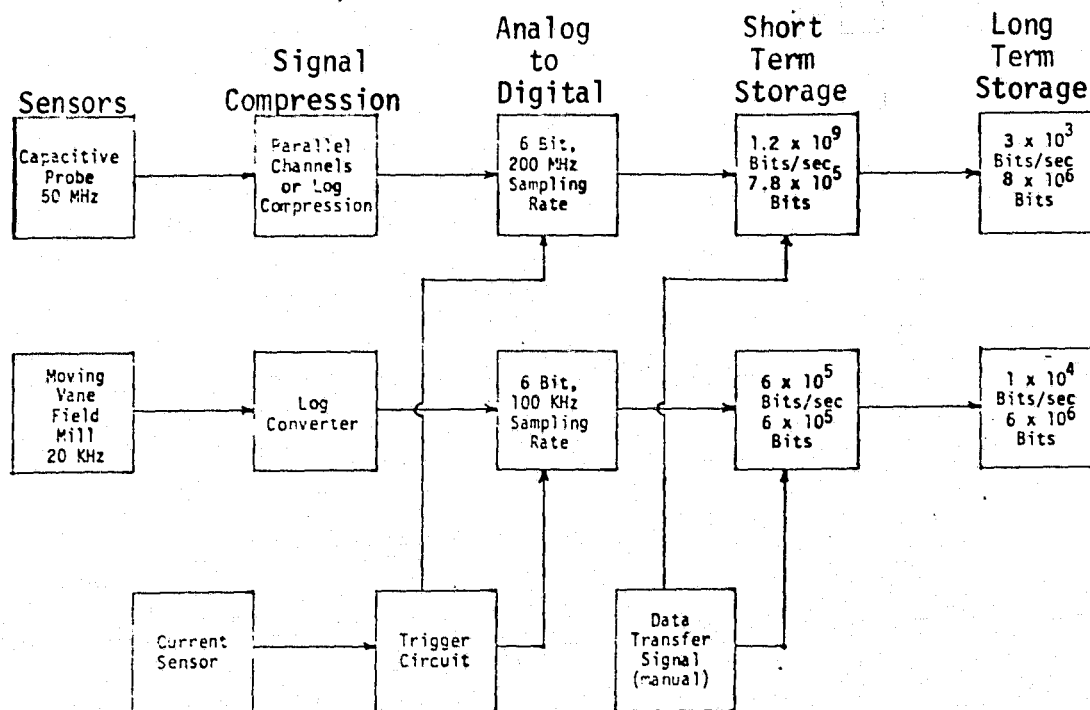
Figure 20 - Candidate Electric Field Data Handling System. (Aircraft Portion)

As previously discussed, an aircraft will also encounter streamer and leader currents prior to the arrival of the first return stroke. The duration of the leader currents will depend on the aircraft position in the developing leader and will probably vary from 1×10^{-4} to 1×10^{-1} seconds.

Measured return stroke durations vary from about 10^{-5} to 10^{-3} seconds and the highest current rate of rise (di/dt) has usually been observed near the peak of the stroke current.

Ground observations of lightning flashes have recorded di/dt's of 80 to 100 kA/μs. If these current rates of rise are assumed for current changes of only 10 kiloamperes or more, a measurement rise time of 100 ns is required. Study of the current measuring shunts discussed earlier has indicated that shunts with rise times of 10 nanoseconds are possible. A 10 ns rise time shunt will accurately measure 50 ns rise time current pulses and will be sufficient for this project.

The system bandwidth corresponding to a 10 ns rise time is 35 MHz so a digital sampling rate of 175 MHz is required. If a 200 MHz sampling frequency is selected, a sample must be taken every 5 nanoseconds. A digital memory of 1.3×10^5 words would then store 650 microseconds of data.

Because of the nature of the lightning flash currents, 1 ms of data is not sufficient, and, as discussed earlier, digitization of the entire waveform is not practical. Selective recording of only the most important characteristics of current flow is therefore necessary.

The lightning current characteristics believed to be the most important are:

1. Peak Current (I_p, A) - induced voltages and
                              magnetic force effects

2. Rate of Current Change (di/dt) - induced voltages

3. Action Integral ($\int i^2 dt$, A^2-s) - heating of conductors,
                              explosive damage

4. Charge Transfer (coulombs, Q) - erosion of metals

The action integral and charge relate to the entire flash and are obtained by integrating current and the square of current with time.

The current waveform, and in particular the wavefront where the highest rate of change is expected to occur, may not be recordable in its entirety if its duration is long, but the occurrence of the fast rate-of-rise phenomena can probably be detected by the appearance of high induced voltages (also being measured) at the same time. Since the magnetically induced voltages are directly related to di/dt, the induced voltage signal may be used to trigger the current waveform monitoring equipment. The duration (window) of current waveform data recorded will not have to be very long. To cause induced voltages of more than 100 volts, the di/dt can be estimated to be greater than 10^9 A. At this rate, a peak current of 20 kA (the average of lightning stroke peak currents measured on the ground) will be attained in 20 μs. Digitized waveform data of 20 μs *may* be sufficient to capture all di/dt data contained in a single stroke of the flash, and 200 μs will certainly be adequate.

Peak current occurs only once during a flash. This and the charge transfer and action integral can be captured by analog circuits which monitor the entire flash waveform and perform the required algebraic functions. The output of each circuit would be a single DC voltage. These voltages can be stored digitally on command as one word and the systems reset to record new data.

Analog multipliers, necessary to obtain the action integral, are now available with a 5 MHz bandwidth. Multipliers with wider bandwidths would be desirable but the error produced by a 5 MHz device over a *one-second* time period would be acceptable.

Signal compression can be used for the peak holding circuit (peak current) but cannot be used for the integrated quantities since there is no way to take the antilog of the independent variable after integration.

To obtain the several decade coverage needed for charge and action integral, several parallel circuits must be used, with each set for different full-scale magnitudes. Circuits to calculate charge and action integral are not commercially available but have been built for laboratory purposes.

To sum up, integrating and peak detecting circuits can be used to record all lightning flash current data with the exception of rate of change. Since rate of change is closely related to induced voltage levels, induced voltage levels can be used to trigger current waveform digitizing equipment to obtain waveform data for periods of 200 microseconds. A candidate current-measuring system is shown on figure 21.
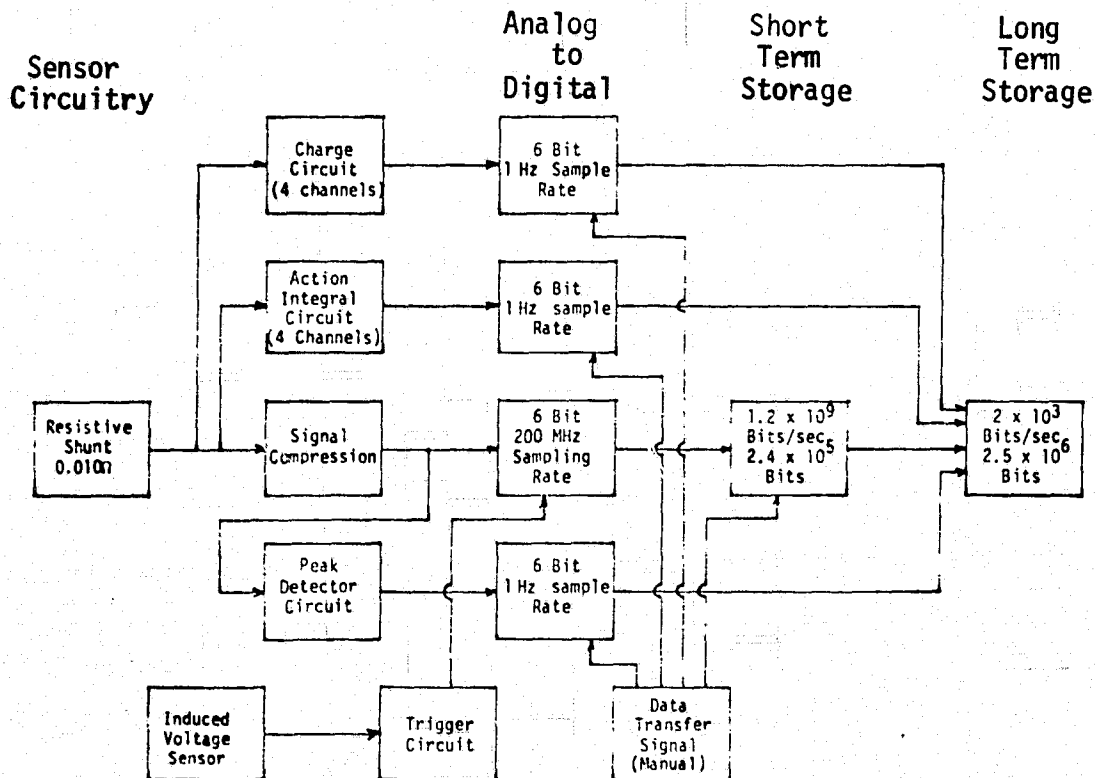

Figure 21 - Candidate Current Data Handling System.
(Aircraft Portion only)

Induced Voltages - Induced voltages in aircraft electrical circuits have two basic sources, including the voltage rise along the aircraft structure due to lightning current in the aircraft (known as IR voltages); and the changing magnetic flux also produced by lightning currents in the airframe.

As discussed earlier, the IR voltages are related directly to the lightning flash current but may be delayed in time somewhat due to current diffusion through the aircraft skin, and magnetic fields enter the aircraft through apertures and by current diffusion through its skins. The magnetic fields cannot immediately penetrate conductive skins because of eddy currents induced in the skins, but as the eddy currents die out magnetic fields appear inside the structure.

The diffusion process in a typical aircraft structure with 0.1 cm (0.040") skins will reduce the magnetic field rate of change of interior fields by two orders of magnitude with respect to exterior field rates of change. The voltages induced by diffusion magnetic fields are correspondingly lower.

The measurement system for induced voltages must therefore have similar characteristics as that for the lightning current. As a sensor, two wires, one in the aircraft wing and one in the fuselage should be monitored. The far end of each wire should be connected to airframe structure and the near ends tied together and terminated to airframe with their surge impedance, which typically is 50 ohms.

Most avionics in present aircraft that are connected to harness wiring can withstand transient voltages of up to 100 volts but only a few can survive pulses of greater than 1,000 volts. Therefore, as a starting point, the recording system can be set to trigger the system at 150 volt levels with full scale capabilities of 1,000 volts. If magnitudes of greater than 1,000 volts consistently appear, thought may be given to increasing the amplitude range. The candidate system for measuring induced voltage is shown in Figure 22.
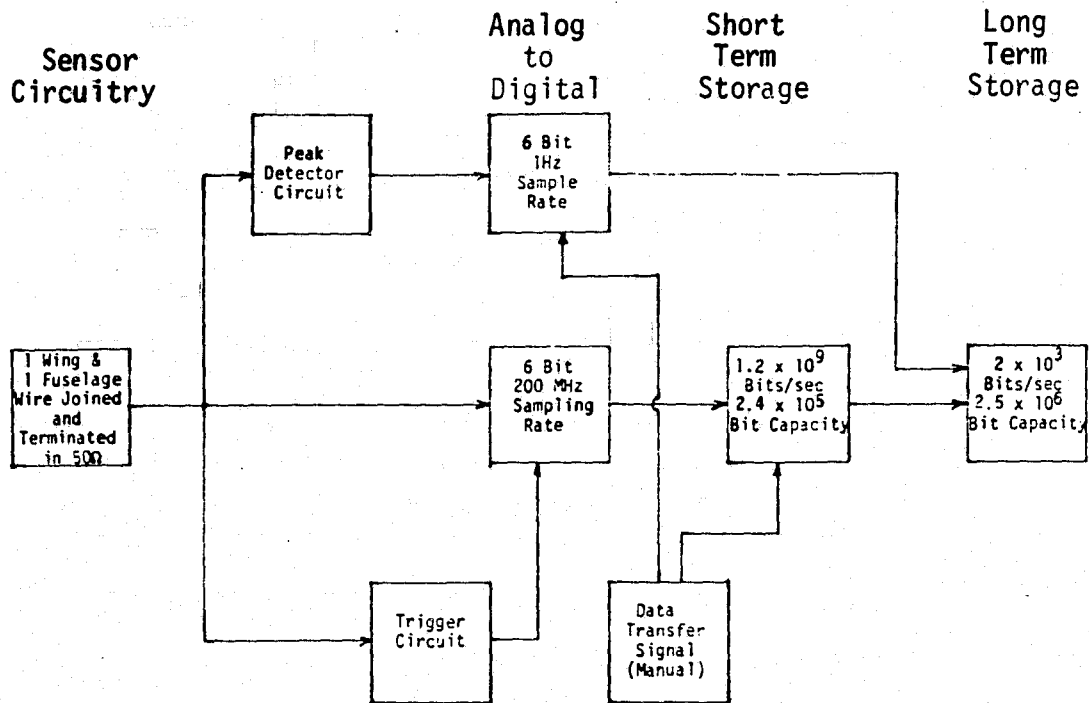
Figure 22 - Candidate Induced Voltage Data Handling System.
(Aircraft Portion only)

46

SYSTEM CONSIDERATIONS

Data sampling rates, response times and memory requirements of the instrumentation necessary to measure each of the three lightning parameters given highest priority were discussed in the preceding section. Considerations related to instrument system integration, performance tradeoffs, electromagnetic interference, noise, and calibration of this instrumentation are now discussed.

Complete System Requirements

Number of Channels Required - The discussions in the last section outlined the data processing system requirements as viewed from the lightning parameter input data characteristics. Measurement system bandwidths and A/D sampling rates were determined by the signals expected from each of the sensors. From an overall system point of view, it is desirable to use identical equipment in all parallel systems to simplify interface and maintenance requirements.

A review of the data processing requirements developed in the previous section shows that 50 MHz would be adequate *system* bandwidth for all systems except the moving-vane field mill which should remain at 20 kHz.

The 50 MHz (3dB down) bandwidth signal can be captured at a 200 MHz sampling rate. If a 6 bit A/D converter is used, then 1.2×10^9 bits per second are generated and if 100 μs of data is to be stored, the high speed, short term memory capacity must be 1.2×10^5 bits or 2×10^4 words of 6 bits each.

Since the field mill data will be of little value after the leader phase is complete, the field mill will be used to capture ambient electric field data prior to the strike.

Now the digital storage requirement for the field mill drops by 1×10^2 to 6×10^3 bits, or one thousand 6 bit words.

As will be discussed in the following section, the research aircraft to be utilized in this program should have as few initial lightning attachment points as possible. Ideally it should have no more than four. If this were possible, instrumentation at three of the four attachment points would (theoretically) measure every stroke that hits the aircraft. If the research aircraft selected has five or more initial attachment points, additional instrument channels would be required to insure that all strokes are captured.

Assuming that three measurement points on the aircraft are sufficient, ten individual data channels will be required, as shown in Table II.

47

TABLE II - Instrumentation Channels Required if Four
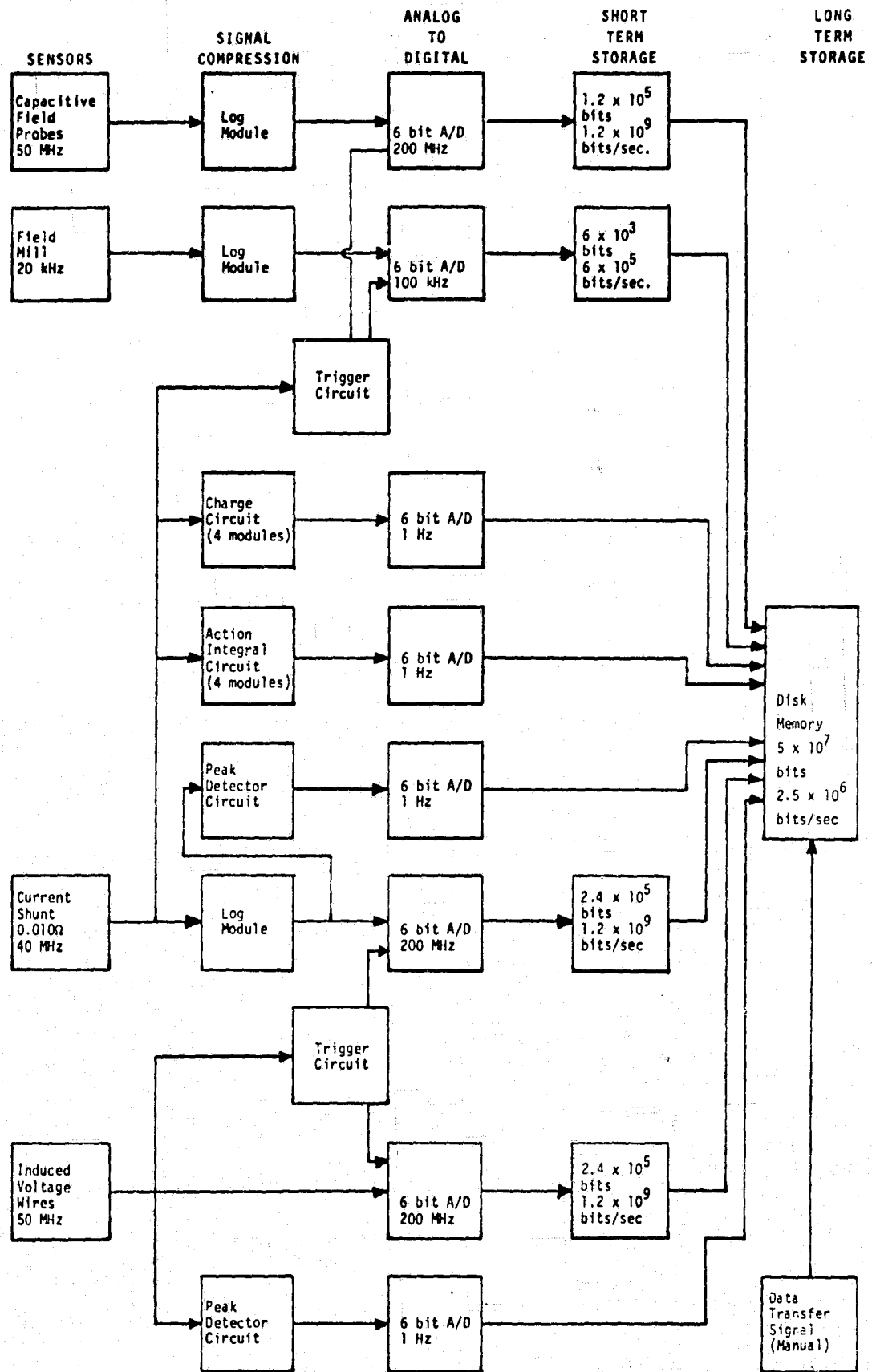Initial Attachment Points Are Present

Parameter	No. of Channels	Number of Information Bits Required
Fast electric field changes	3	$3(1.2 \times 10^5)$
Ambient electric fields	3	$3(6 \times 10^3)$
Current	3	$3(2.4 \times 10^5)$
Induced Voltage	1	(2.4×10^5)
Totals	10	$\sim 14 \times 10^5$ bits

With the addition of the peak detector and integrated analog data with appropriate addressing instructions for all data, measurement of one strike will require less than 2×10^6 bits of storage. If a minute or more is allowed for data transfer the input bit rate necessary to transfer the stored data into long term storage is 3.3×10^4 bits per second, which is equivalent to 5.5×10^3 words/sec.

Memory Requirements - Disk and tape memory storage units with capacities of up to 5×10^7 bits and transfer rates of up to 2.5×10^6 bits per second are commercially available.

One long-term memory storage unit with a capacity of 5×10^7 bits and a transfer rate of 3.3×10^4 bits per second could store all the digital data generated by the lightning measurement system for 25 strikes occurring during a single mission.

It appears feasible to use 10 identical A/D converters to digitize the high speed data. All A/D converters would be driven by the same 200 MHz clock signal to allow close correlation between the output data. The field mill A/D would be keyed from the 200 MHz signal but would operate at 1/1000 of the clock frequency. After each strike all stored data should be transferred serially into the long term storage, and the systems should be reset to accept data from a subsequent strike. A block diagram of the entire system is shown in figure 23.

48

SENSORS	SIGNAL COMPRESSION	ANALOG TO DIGITAL	SHORT TERM STORAGE	LONG TERM STORAGE

Capacitive Field Probes 50 MHz

Log Module

6 bit A/D 200 MHz

1.2×10^5 bits
1.2×10^9 bits/sec.

Field Mill 20 kHz

Log Module

6 bit A/D 100 kHz

6×10^3 bits
6×10^5 bits/sec.

Trigger Circuit

Charge Circuit (4 modules)

6 bit A/D 1 Hz

Action Integral Circuit (4 modules)

6 bit A/D 1 Hz

Peak Detector Circuit

6 bit A/D 1 Hz

Current Shunt 0.010Ω 40 MHz

Log Module

6 bit A/D 200 MHz

2.4×10^5 bits
1.2×10^9 bits/sec

Trigger Circuit

Induced Voltage Wires 50 MHz

6 bit A/D 200 MHz

2.4×10^5 bits
1.2×10^9 bits/sec

Peak Detector Circuit

6 bit A/D 1 Hz

Disk Memory 5×10^7 bits 2.5×10^6 bits/sec

Data Transfer Signal (Manual)

*Represents 3 parallel measurement systems.

Figure 23 - Integrated Candidate Data Recording Systems for In-Flight Measurement of Lightning Parameters.

49

Availability of Commercial Equipment - Present commercially available transient waveform recorders would be capable of handling the required high speed A/D conversions, but each one would have to have its high speed, short term memory increased by a factor of 40.

The field mill A/D converters can be accomplished with unmodified commercial equipment. The necessary recorders will weigh approximately 200 kg (450 lbs) consume 3 kW at 115 V 60 Hz power and require about 0.4 cubic meters of space. One commercially available recorder claims a 500 MHz sample rate, although only 200 MHz is required for the system proposed.

The capability to select different sampling rates higher or lower than that decided upon initially is very desirable, however, since this would allow data to be over a shorter period with higher resolution if this should become desirable; or, conversely to acquire data over a longer period. For example, the entire lightning flash period (1 sec) could be digitized and recorded in a few cases, to determine the number of strokes in the flash. The sampling frequency for a one-second period would be 20 kHz and the reconstructible signal bandwidth in such a case would be 5 to 8 kHz which is adequate for obtaining approximate waveform descriptions of return strokes and intermediate currents.

Electromagnetic Interference Considerations - Most of the electronic circuits required to process and record the lightning data include sophisticated transistor-transistor logic (TTL) on large scale integrated (LSI) linear semiconductor devices operating at ± 15 volts. As discussed before, lightning-induced voltages are expected to occur in most of the aircraft's electrical wiring, and these transients may reach as high as 1,000 volts in unshielded circuits. Induced voltages must also be expected to occur in the lightning instrumentation circuits, and unless adequate protection is provided, these voltages could severely upset the data collected or even cause component failures.

The input data signal from the current probes can reach a peak value as high as 2,000 volts on rare occasions; however, most of the data will be 2 or 3 orders of magnitude lower than this since the highest peak currents are statistically infrequent (5% occurrence levels or less). Most of the time, stroke current signals will range from 0.5 to 5 volts, and during the leader phase signal levels of only 0.01 to 0.1 volts will be of interest. At these levels, errors due to excessive induced voltages could be larger than the signals themselves.

Careful design of the system grounding and shielding can reduce these problems to acceptable levels. The following procedures should be followed when installing the instrumentation:

1. Signal Cables

Signal conductors should be twisted pairs and should be contained within two shields which are electrically insulated from each other as in figure 24.
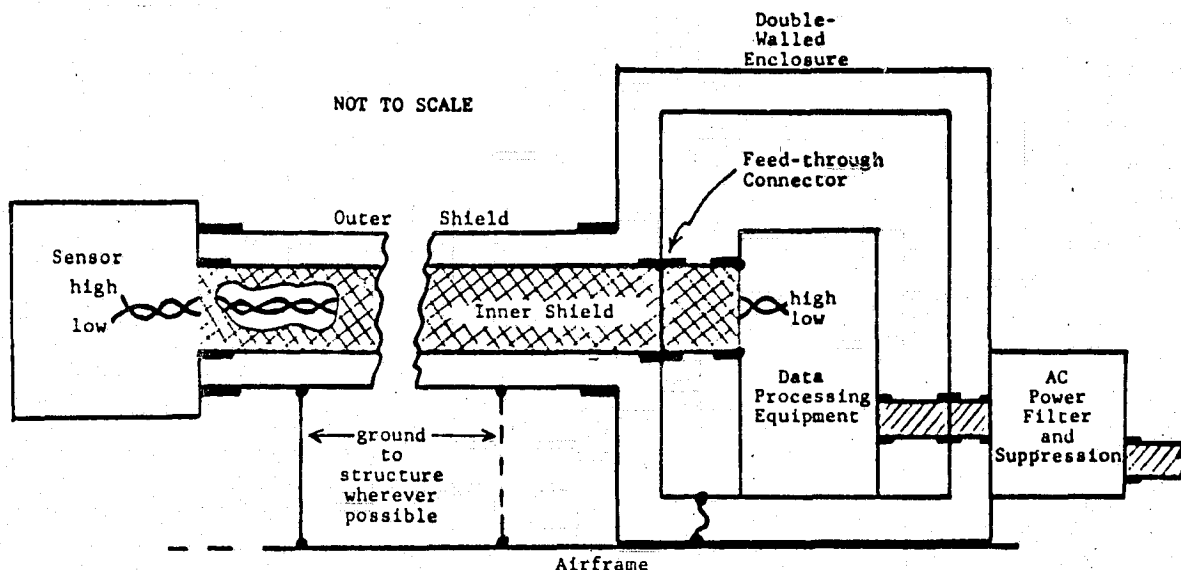

Figure 24 - Shielding of Signal Cables to
Minimize Interference.

The "low" output of the sensor may be grounded at the sensor and also at the data processing equipment. The inner shield may be made of a flexible copper braid. If only one circuit is involved, one of the commercially available twin-axial cables, such as RG-22, may be utilized. This shield should be grounded to the sensor housing and to a feed-through connector at the inner wall of a double-walled equipment enclosure.

Preferably, the outer shield will be a conduit made of soft copper tubing, but if this is impractical a flexible shield of copper braid may be utilized. This shield must also be grounded to the airframe at each end, and wherever it passes close to the airframe (i.e. a rib, bulkhead, etc.) in between. If the cable runs to a current probe, its outer shield (or conduit) must have sufficient cross-sectional area to conduct lightning currents to the airframe. The wall of this conduit should be sufficient to conduct 2.25×10^6 A^2-s of lightning current without a temperature rise of more than 10°C. The cross-sectional areas for various metals required to accomplish this are given in reference 17.

2. Measurement and Data Recording System

The high speed logic in each component of the system must be shielded (a) to prevent upset from external noise sources, and (b) to prevent noise generated by one logic circuit from coupling into other circuits. In some cases, this shielding must be done at the component-module level to insure that no interference results when the entire system is assembled.

The components of the entire data processing and recording system should be contained within one or two double-walled conductive enclosures (a box within a box). One side (probably the bottom) can have contact between the two walls and elsewhere the spacings between inner and outer walls need only be about 1 or 2 millimeters, or more, if practical considerations warrant. Access doors into the shielded enclosures must make 360° electrical contact with overlapped joints. Rubber gaskets and painted surfaces should be avoided.

3. Power and Control Signal Connections

Surge suppression and filtering should be applied to incoming AC power as shown in figure 24. It may be best to perform AC frequency conversions outside of the equipment enclosure to eliminate this source of noise, and bring only 60 hertz power into the enclosure.

External controls and interfaces with other systems in the aircraft should be kept to a minimum, and those that are necessary should utilize twisted shielded pair conductors within double shields as illustrated in figure 24. In addition, filters to impede all but the required signal should be installed in incoming cables.

The foregoing requirements may appear to be conservatively stringent and are; however, such precautions are necessary because millivolt signals are being measured with kiloampere currents present in the aircraft skins. Whenever similar measurements have been undertaken in the laboratory, shielding of this degree has been necessary in order to obtain reliable data.

An example of the installation of a radome-mounted current probe according to the above guidelines is presented in figure 25.

In the example of figure 25, lightning current will enter the probe, flow through the shunt resistance and thence to the airframe via the outer shield or conduit, which must be grounded where it first enters the airframe. This shield should also be grounded wherever it passes near other airframe members on its way to the equipment enclosure.

52

Lightning Current

Probe

NOT
TO
SCALE

$\wedge$
Forward

Top $\rightarrow$

Current
Shunt

i_L i_L

Inner Shield

Radome
(non-conductive)

i_L i_L

Bond to
nearest
Structure

Bond to Equipment Bay

Outer
Shield
Terminates
Here
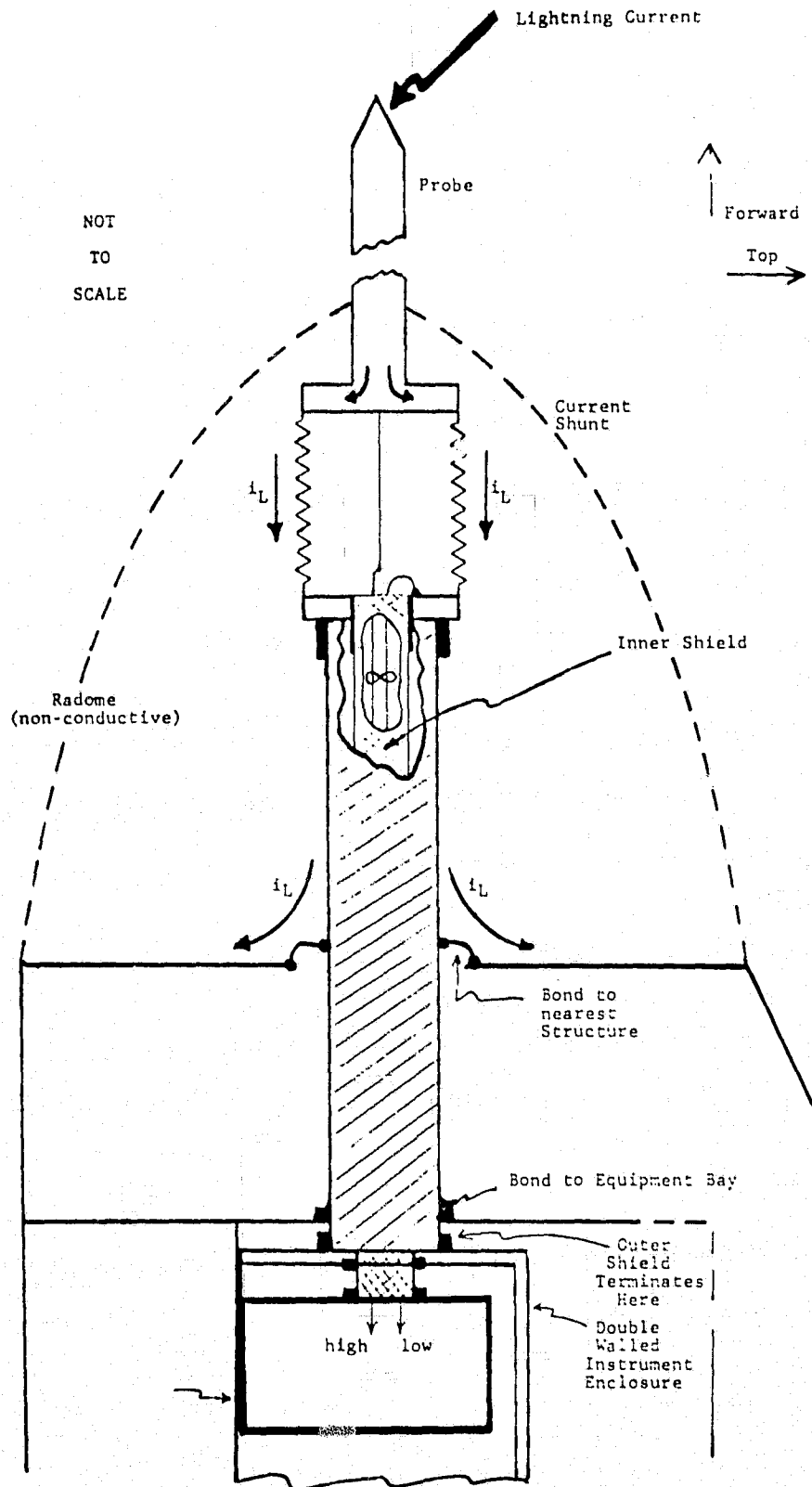
Double
Walled
Instrument
Enclosure

high   low

Figure 25 - Example of Sensor Installation and
Recommended Cable Shielding.

The inner shield should be electrically insulated from the outer shield. It need not be thick enough to conduct lightning currents, as about 99% of these currents will flow on the outer shield. After the installation of the probe and measurement system is complete, the aircraft can be subjected to high voltage and high current simulated lightning tests to calibrate the measurement system and check it for interference immunity. During these tests many other safety and operation checkouts must also be carried out, as discussed in the following sections.

The amount of interference due to induced voltages in the measurement system can be determined by grounding both the high and low conductors at the probe. This will cause all of the induced voltage in the circuit to appear at the data processing equipment, where it can be monitored. By using an external signal to trigger the data handling system, it can be made to record even very small noise and stroke currents to the aircraft. It can then be determined if further shielding is necessary.

Calibration Considerations

Throughout the feasibility study, considerable emphasis has been placed upon establishment of the required bandwidth and rise time characteristics for the sensors, A/D converters and analog circuits and discussions were held with a number of digital equipment manufacturers to determine what performance is feasible. Unfortunately, manufacturers' criteria of specifying product capability vary from one to another, and tendancy is often to present a product at its very best. This has led in several cases to initial misunderstanding of what performance can actually be attained under conditions different from those specified.

An example of this was evident in the specifications of a high-speed A/D converter. The converter was specified to have an 8 nanosecond, 6 bit rise time and an analog bandwidth of 37 MHz at 0.5 dB down and 80 MHz at 3 dB down. However the maximum sampling rate was reported as 75 MHz which corresponds to one digitized sample every 13 1/3 nanoseconds. At a 75 MHz sampling rate, however, the highest practical reconstructible frequency is between 15 and 25 MHz.

Consequently calibration tests imposing conditions and signal waveforms similar to those expected during use should be applied not only to the final system but to each building block used in the system prior to assembly. For this purpose, the desired information about the response of subsystem components can be obtained by applying step function voltage and/or current pulses to the probes and comparing it with the data recorded by the instrumentation system.

Low impedance, capacitive voltage sources using mercury wetted relay contacts for switching can generate step rise times of less than one nanosecond for test purposes. With such pulses applied to data processing system inputs in place of the sensors, the rise time of the recorded output will be the maximum system rise time response.

Waveforms generated for full scale system calibration will not have subnanosecond rise times but will simulate natural lightning as presently defined for ground environments. A preliminary set of proposed tests to be run on the completed instrumentation system is given in Table III.

TABLE III - Proposed High Voltage and Current
Calibration Tests to be Applied to
the Measurement System after Instal-
lation in the Research Aircraft

Test No.	Waveshape	Polarity	Amplitude	Rate of Change	Remarks
	High voltage tests to be applied at each sensor location, aircraft grounded, hemispherical electrode.				
1	1.2x50 μs	Pos & Neg	10-20 kV/cm	10^{12} V/s	1 meter gap
2	1.2x50 μs	"	Breakdown	10^{12} V/s	0.5 meter gaps
3	1.2x2 μs	"	10-20 kV/cm	10^{12} V/s	Chopped wave
4	500x3000μs	"	10-20 kV/cm	4×10^{9} V/s	1 meter gap
	High current tests to be applied at each sensor location aircraft grounded. One inch rod gap to current probe.				
5	Oscillatory	-	200 kA	-	2×10^{6} A^2-s
6	"		200 kA		System noise checks
7	2 x 50 μs	Pos & Neg	50 kA		Linearity
8	"	"	10 kA		measurements
9	"	"	5 kA		
10	"	"	1 kA		
11	0.5 front	"	1 kA		Step function test

FLIGHT RESEARCH CONDITIONS

The lightning characteristics about which there is greatest need for more information, and the feasibility of acquiring this data with modern data processing and recording electronics have been established and discussed in the preceding sections. In this section, the flight and weather conditions most likely to produce an adequate number of meaningful lightning strikes are discussed as an aid to planning of the research flights. In the section to follow, desirable characteristics of an aircraft with which to perform this research are discussed, together with safety considerations.

Weather Conditions Conducive to Lightning Strikes

One of the best summaries of weather conditions prevailing at the time of lightning strikes to aircraft is that of H.T. Harrison of United Air Lines (reference 18) who documented the synoptic meteorological conditions prevailing for 99 United Air Lines lightning-strike incidents occurring between July 1963 and June 1964. Table IV lists the synoptic type and the percentage of incidents occurring in each type of weather. Examples of the four most predominant synoptic conditions are presented in figure 26(a), (b), (c) and (d) taken from reference 19.

TABLE IV - Synoptic Types Involved with
99 Electrical Discharges
July 1963 to June 1964

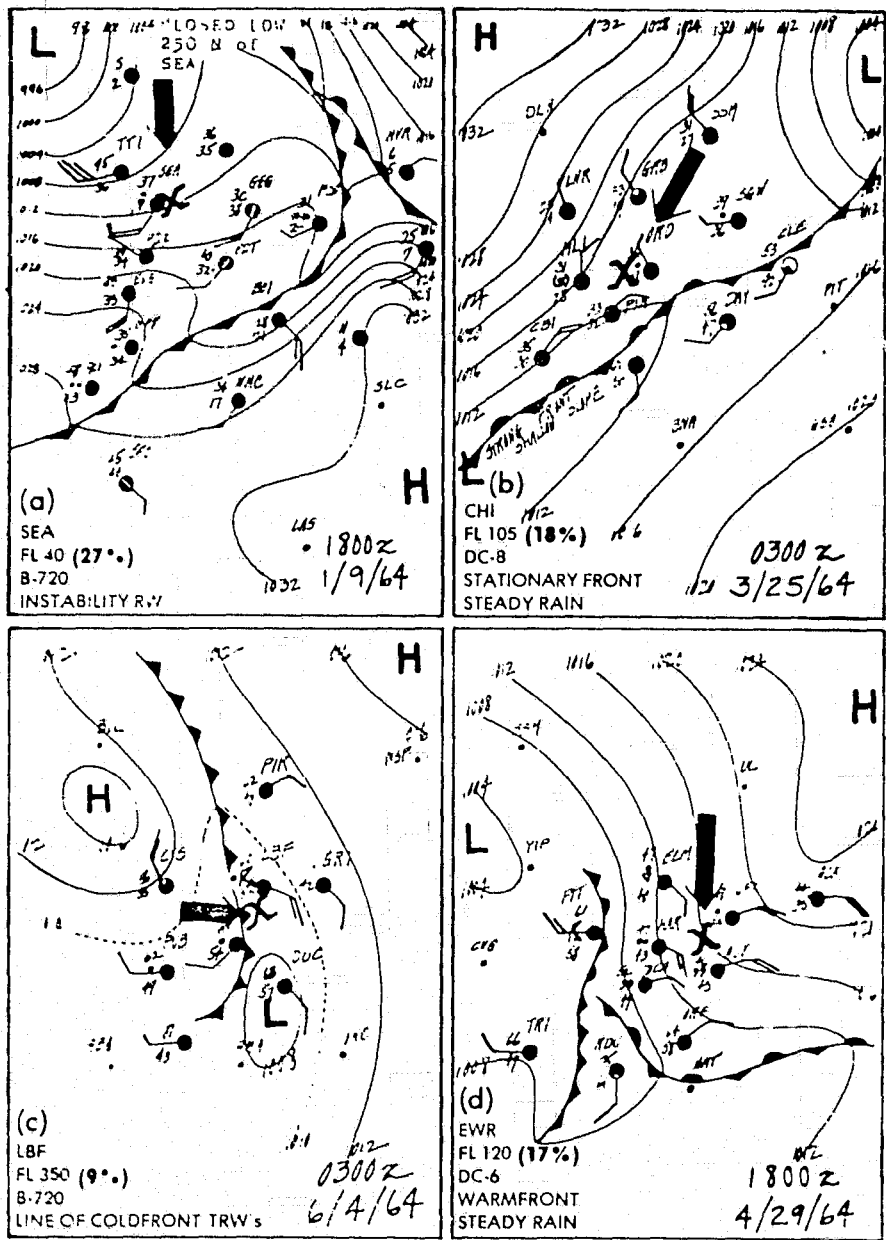| Synoptic type	Percentage
Airmass instability	27
Stationary front	18
Cold front	17
Warm front	9
Squall line or instability line	9
Orographic	6
Cold LOW or filling LOW	5
Warm sector apex	3
Complex or intense LOW	3
Occluded front	1
Pacific surge	1

Figure 26 - Examples of Most Frequent Synoptic
Meteorological Conditions when
Aircraft Have Been Struck. Tip of
Arrow Indicates Position of Aircraft
when Struck.

Table IV and figure 26 give examples of the types of weather conditions within which lightning strikes occur most frequently to aircraft. Not all cold fronts (for example) produce significant amounts of lightning, so the thunderstorm experience records associated with candidate bases of operations should be studied to determine the most fertile locations.

The only parameter related to lightning incidence for which world-wide data accumulated over many years exists is the *thunderstorm day*. This data is accumulated by the World Meteorological Organization and is called the *isokeraunic* level (reference 20). A thunderstorm day is defined as a 24 hour day on which thunder is heard. Thus, the parameter does not give information on the duration or intensity of the storm. For the United States, the isokeraunic level ranges between a low of 5 thunderstorm-days per year along the West Coast, to a high of nearly 100 days on which thunder is heard in central Florida, as shown on the isokeraunic map of figure 27. This parameter is often designated as T_y.
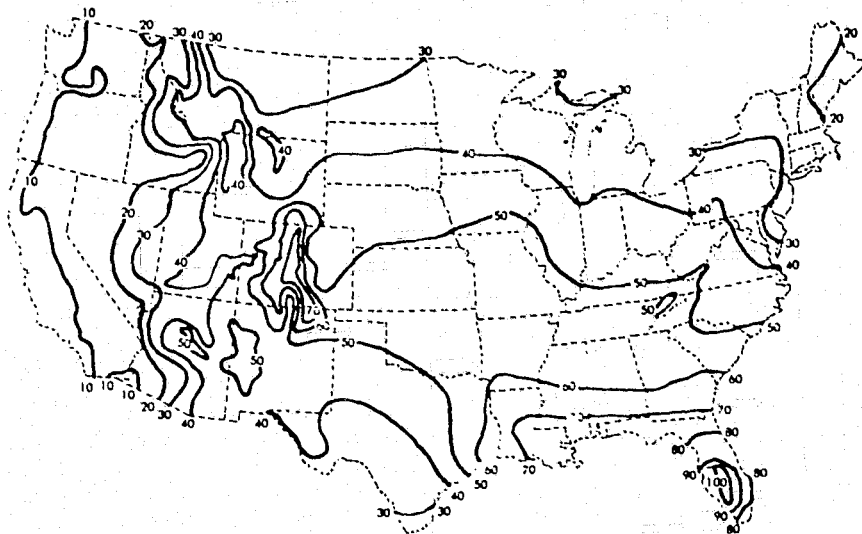

Figure 27 - Thunderstorm Days (isokeraunic level) within the Continental United States.

The mean area covered by a typical thunderstorm has been estimated (reference 21) to be 500 km^2 so the observation of a thunderstorm day should correspond also to a thundery area of (at least) 500 km^2.

Most observers agree that the average rate of lightning flashing in a thunderstorm cell is about 3 flashes per minute, and that the lifetime of a single cell is about one to three hours.

Therefore, if it is assumed that one thunderstorm cell lasting for one hour and covering an area 500 km^2 is present on a thunderstorm day, then the number of flashes, F, per observed thunderstorm day would be:

F = (3 flashes per minute)(60 minutes per hour)(1 to 3 hours)   (8)

   = 180 to 540 flashes per 500 km^2 per thunderstorm day.

This is an estimate of the number of flashes to be expected during a one to three hour period of each storm.

Assuming that the area covered by this observation is 500 km^2, then the number of flashes occurring over each square kilometer of area would be:

$$\sigma y = \frac{180}{500} \text{ km}^2 \text{ to } \frac{540}{500} \text{ km}^2 \qquad (9)$$

$$= 0.36 \text{ to } 1.08 \text{ flashes per square kilometer}$$

This situation is shown graphically in figure 28.

It might logically be assumed that flash density, σy, is proportional to the number of yearly thunderstorm days. Actually, however, studies (reference 22) using lightning flash counters which count the bursts of radio interference produced by flashes occurring within a particular range have shown that flash density actually increases more nearly as the square of the number of thunderstorm days occurring in a particular region. This is clearly due to the greater proximity of thunderstorms to one another in the more active regions or at more active times of the year. Thus, it may be more appropriate to consider thunderstorm days per *month*, T_m, as a measure of the lightning activity at various locations.

Two especially thorough analyses of lightning-flash-counter data have been made (reference 23). Pierce has developed the empirical relationship

$$\sigma_m{}^2 = aT_m + a^2 T_m{}^4 \qquad (10)$$

where σ_m is the monthly flash density (flashes km^{-2}), and the empirical constant, a, has the value 3×10^{-2}. This relationship is plotted in figure 29. Note that for months of fairly high activity ($T_m \geq 5$), σ_m is approximately proportional to $T_m{}^2$.
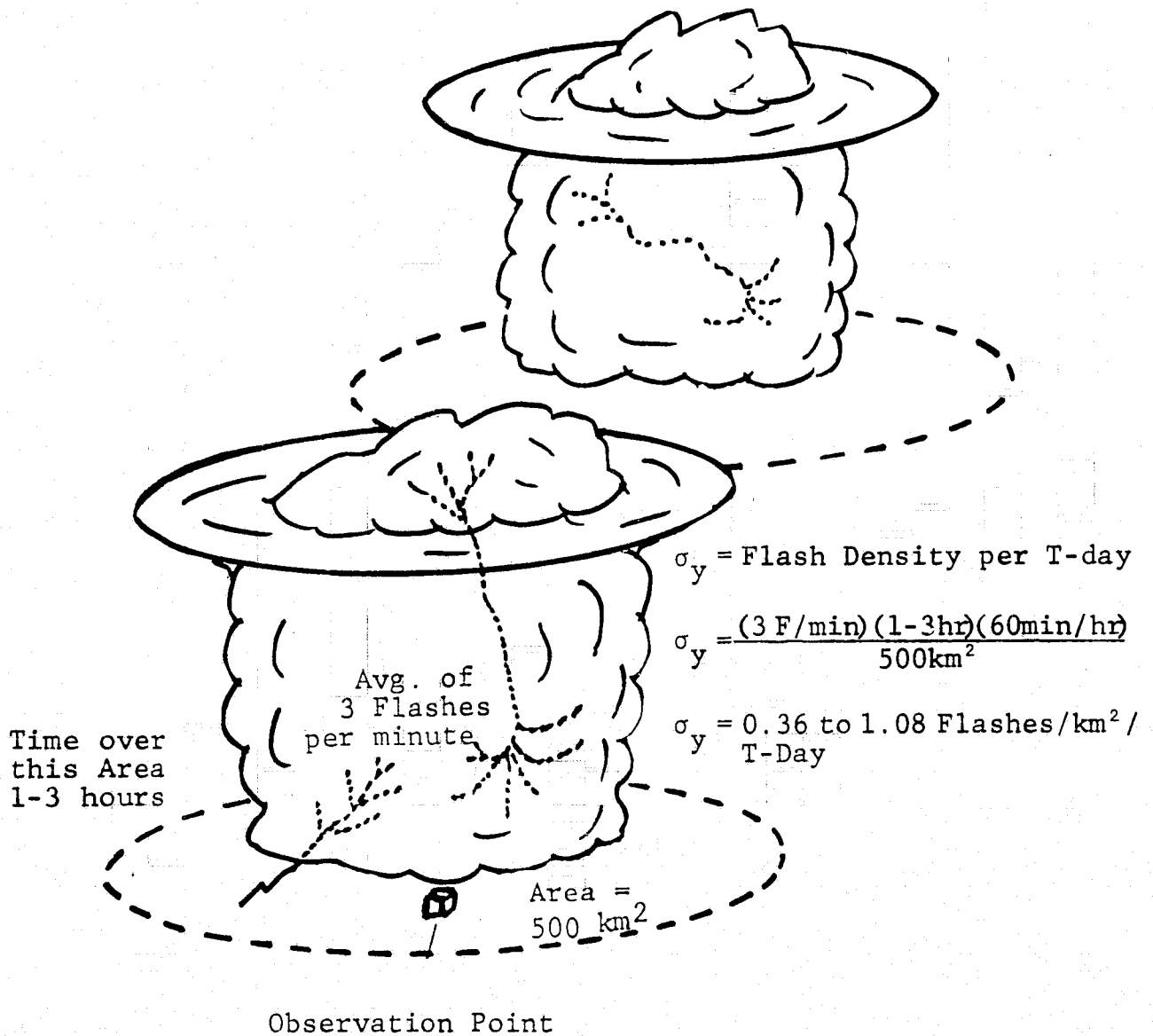
σ_y = Flash Density per T-day

$$\sigma_y = \frac{(3\ F/min)(1\text{-}3hr)(60min/hr)}{500km^2}$$

σ_y = 0.36 to 1.08 Flashes/km²/ T-Day

Time over this Area 1-3 hours

Avg. of 3 Flashes per minute

Area = 500 km²

Observation Point

Figure 28 - Flash Density Related to Thunderstorm Day.

Also plotted on Figure 29 is the relationship

$$\sigma_m = 0.06T_m^{1.5} \tag{11}$$

based on analysis by workers at Westinghouse. Over the most common range $2 \le T_m \le 10$ there is not much difference between the two curves.
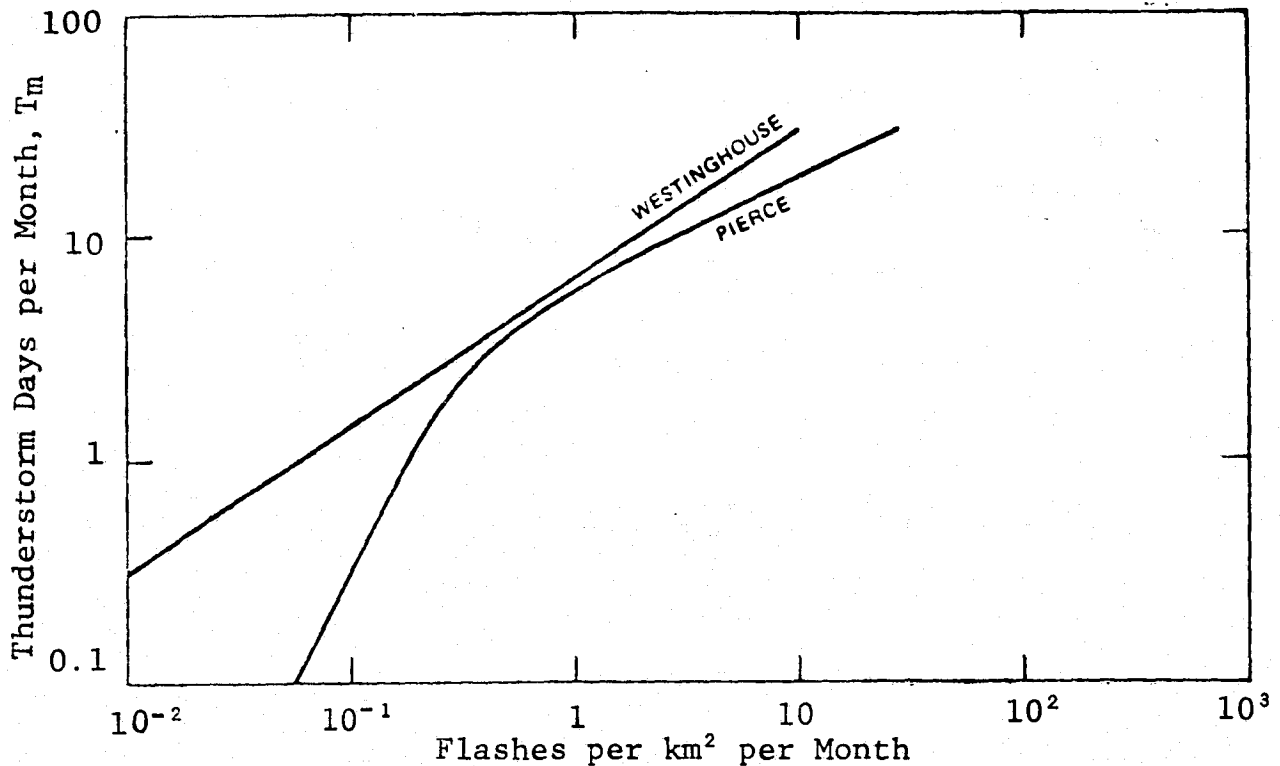
Figure 29 - Relationship between Thunderstorm Days per Month
and Lightning Flash Density.

Equations 10 and 11 do not yield simple relationships be-
tween the *annual* flash densities σ_y and number of thunderstorm
days, T_y, since there is a non-uniform distribution of thunder-
storm activity throughout the year. However, the same relation-
ship can be determined on a whole-year basis by adding up the
values of σ_m calculated by equations (10) or (11) for each month.
This has been done by Pierce (reference 24) for 8 different
observation points in the U.S. and plotted on figure 30 as a
function of T_y. Also plotted on figure 30 are two straight-line
relationships derived from Japanese and European data. For this
study the relation between the isokeraunic level, T_y, and the
flash density will be that shown by the dot and dash line, a
more conservative fit to the Pierce and Westinghouse calculated
points. The relation that describes this line is:

$$\sigma_y = 0.021 \ T_y^{1.6} \tag{12}$$

The flash densities predicted by equations, 10, 11 or 12
and Figures 29 or 30 include both flashes between clouds and
flashes to ground. These equations or figures may be used to
estimate the degree of lightning activity to be expected at
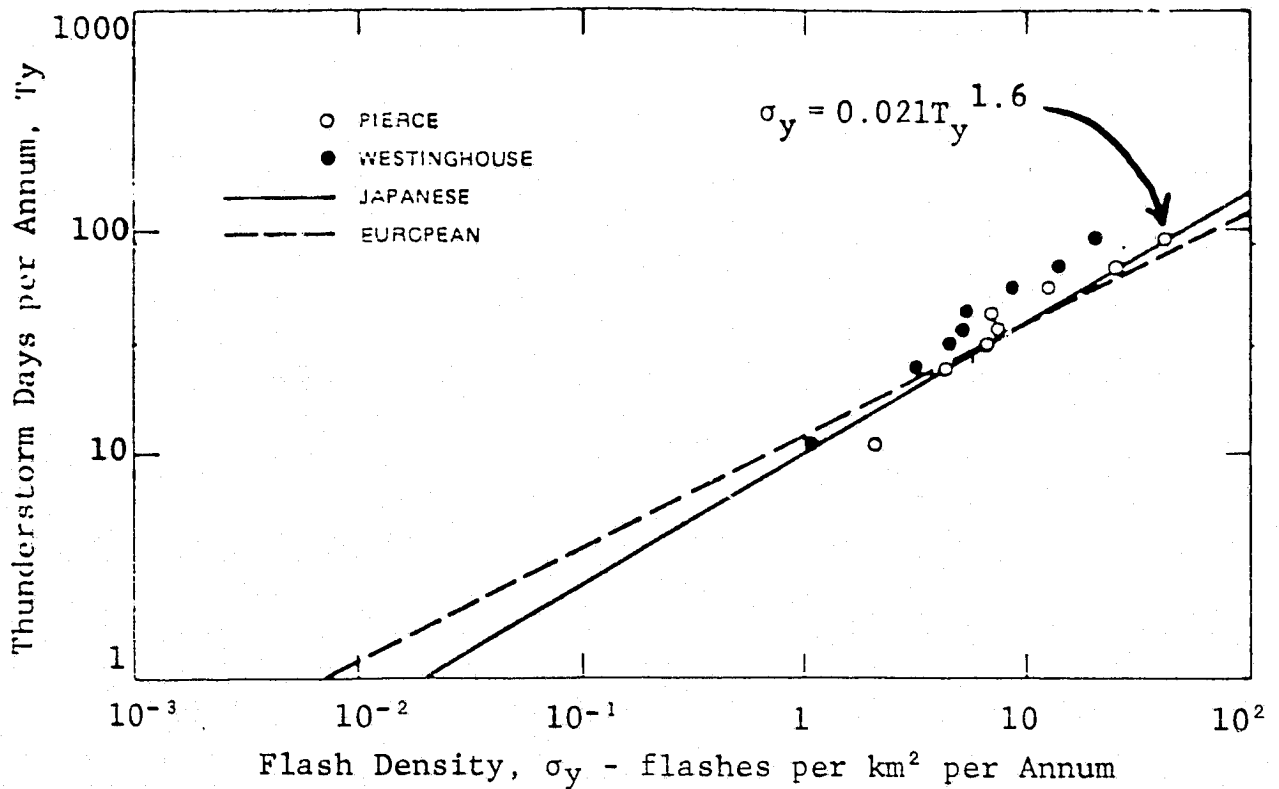possible flight research locations.

Figure 30 - Relationship between Annual Thunderstorm Day (T_y)
and Flash Density (σ_y) Values.

Using equation (12) and the isokeraunic data from reference
20, the number of flashes that can be expected to occur within a
square mile or a square kilometer at several locations under con-
sideration for this flight research have been calculated. The
results are presented in Table V.

TABLE V - Lightning Activity at Possible
Flight Research Location

Locations	Isokeraunic Level	Total Flashes per Year per km²	per mi²
Flagstaff, AZ	35	8.4	21.8
Sacramento, CA	4	0.2	0.5
Kennedy Space Center, FL	88	40.4	104.7
Wichita, KS	54	17.6	45.6
Cape Hatteras, NC	40	10.6	27.4
Oklahoma City, OK	45	12.9	33.5
Tulsa, OK	58	19.9	51.5
Houston, TX	57	19.3	50.0
Port Arthur, TX	72	28.7	74.4
Norfolk, VA	38	9.7	25.1

Flight Altitudes Conducive to Lightning Strikes

Once a geographic region of sufficiently high lightning activity has been decided upon, it is next necessary to consider the flight altitudes at which strikes to the research aircraft are most likely to occur.

Cumulonimbus clouds which produce lightning commonly extend from bases at about 3,000 m (10,000') to altitudes of 10,000 m (30,000'). On occasion, these clouds reach as high as 20,000 m (60,000'). Flashes of lightning have been observed at all altitudes within them. The charge separation process is thought to produce accumulations of negative electrical charge near the base of the cloud and positive charge near the top. This situation produces lightning flashes between these charge centers within the cloud. Other lightning flashes, of course, extend from lower regions of the cloud to the ground, and these are called *cloud-to-ground* flashes. When these occur, charge from other centers within the same cloud, or in nearby clouds, may discharge to earth via the channel formed by an original cloud-to-ground flash. These situations are shown in figure 31.
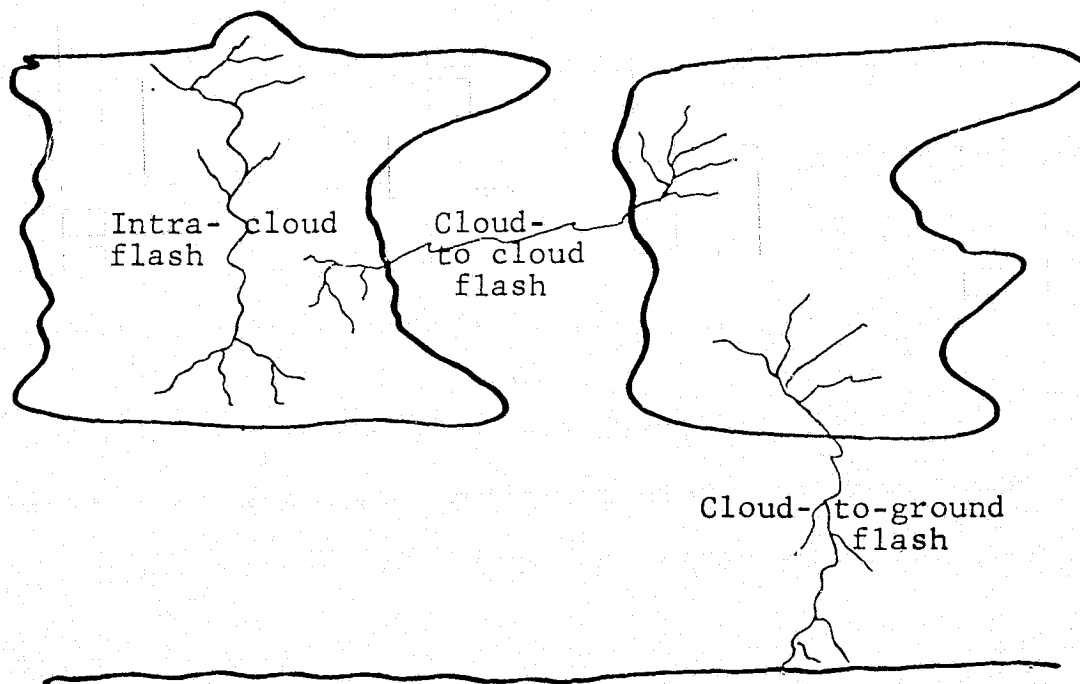

Figure 31 - Possible Types of Lightning Flashes.

Whereas lightning flashes must be expected at all altitudes within or near thunderclouds, study of a large number of pilot reports of in-flight lightning strike incidents shows that most strikes to turbojet aircraft have occurred between 2,000 m (7,000') and 5,000 m (16,000') during approach or climbout phases of the flight, as shown in figure 32. A very few strikes have been reported at higher altitudes during cruise, but the ability to fly over some cloud tops and circumnavigate others reduces the exposure of turbojet aircraft to strikes during cruise.
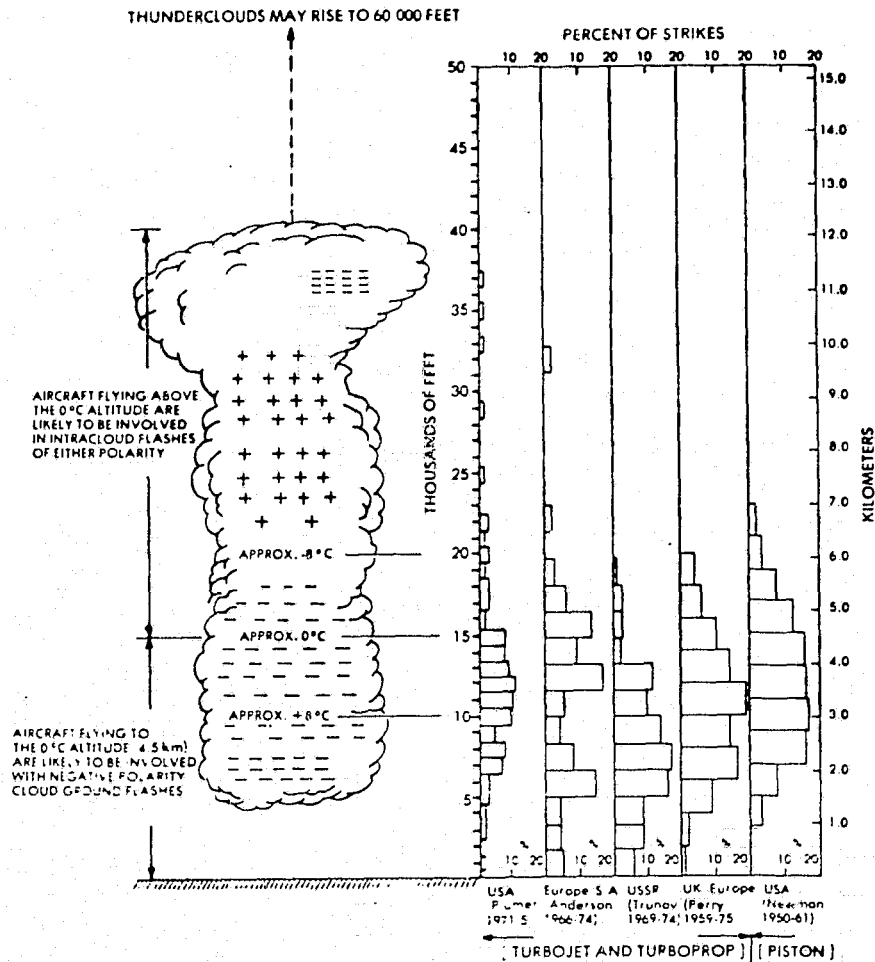
Figure 32 - Aircraft Lightning Strike Incidents vs Flight Altitude.

Five data bases are shown in figure 32. All but that of Newman (1950-61) apply to turbojet aircraft, but Newman's data apply almost exclusively to piston-powered aircraft whose cruise altitude remained below about 6,000 m (20,000'). For this reason, Newman's data show a higher percentage of strikes at these middle altitudes than the turbojet data. From this data it may be concluded that lightning strikes to aircraft are probably at least within the range 2,000 m - 6,000 m with perhaps the highest probability of receiving a strike being between 3,000 m - 4,000 m.

Other Factors Conducive to Lightning Strikes

Pilot reports also show that aircraft are most often "within a cloud" and experiencing some precipitation and turbulence when lightning strikes occur; and the outside air temperature is usually near the freezing point. Figure 33 shows the percentages of times that strikes occurred within clouds, precipitation or when turbulence was encountered in one of the data bases of Figure 32 (reference 25), and figure 34 illustrates the high percentage of strikes that occur near the freezing level (reference 26).
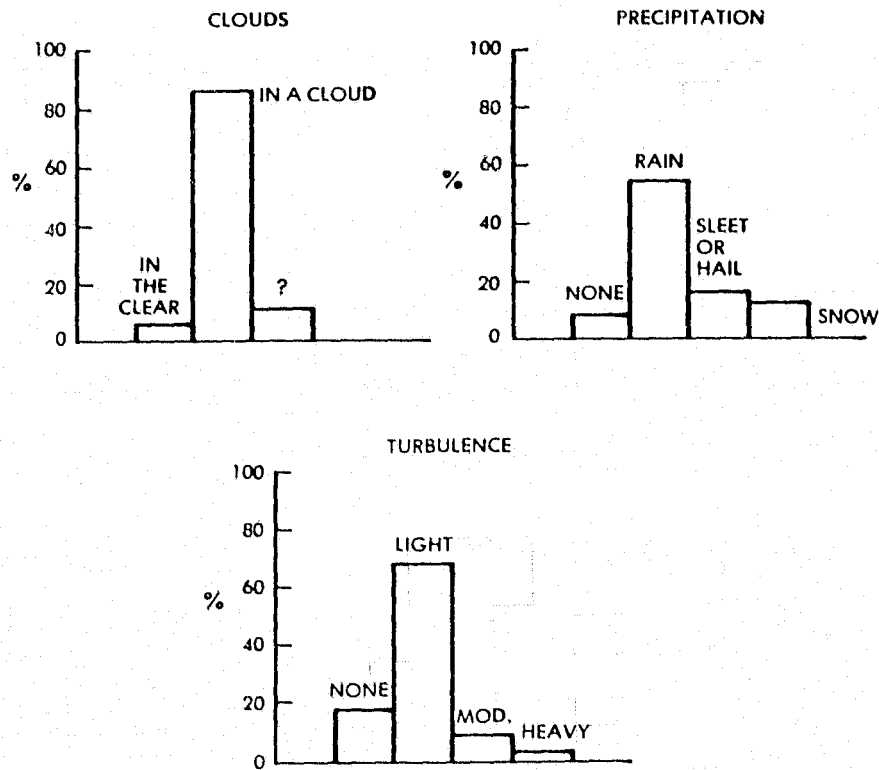

Figure 33 - Environmental Conditions at Time of Strike.

Recommended Flight Conditions to Acquire Strikes

As emphasized before, it is recommended that primary emphasis of this flight research program be placed on acquiring data related to the main channel of the lightning discharge, under conditions similar to those experienced when civil aircraft are struck during "routine" operations. Some of the conditions under which this data may be most easily and safely obtained are now discussed.
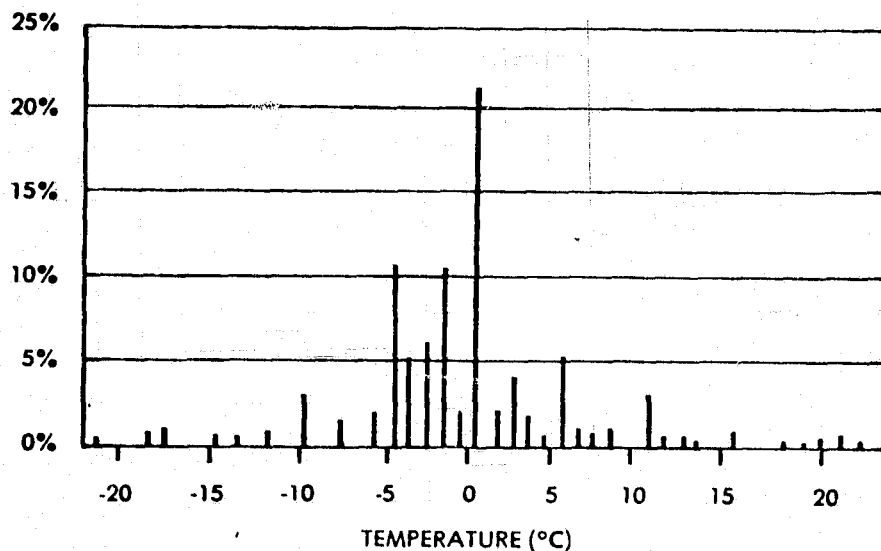
Figure 34 - Outside Air Temperature at
Time of Strike.

General Conditions - Initially, at least, it is probably best
to work with convective, air mass thunderstorms rather than large
frontal storm areas because the thunderclouds may be easier to
identify visually and correlate with air and ground-based radar
returns. Also, more clear-air space may exist between active
clouds than would be the case within an extended frontal area.
During the daytime, the large cumulonimbus clouds formed by con-
vective activity may be visually identifed from a distance, and
the clear-air space surrounding them will be useful for identifi-
cation of aircraft position with respect to the cloud when a
strike occurs, and for photographic purposes when a chase plane
is utilized. More important, clear-air will provide an attitude
reference in the unlikely event the aircraft loses flight instru-
ments or the pilot becomes flash-blinded from a strike.

Daytime flights will be appropriate because of ground-support
availability, but if difficulty is encountered in obtaining strikes,
it will be helpful to fly at night when regions of electrical ac-
tivity can be easily seen and the flight path adjusted accordingly.
Useful information will be obtained on the ability of an aircraft
to trigger a strike, and its ability to divert one to itself. Moon-
lit nights, when the clouds themselves are visible, will be ideal
for this.

In general, it may be better to fly through the fringes of
clouds rather than to make penetrations through their centers. The
reasons for this are as follows:

 • civil aircraft do not often fly directly through cumulo-
   nimbus-type clouds, hence the data obtained may be less
   representative than that obtained when the aircraft is
   alongside a cloud.

66

- there is a lower probability of intercepting the main channel of a flash when inside a cloud, as compared with outside, and

- the rain, icing, hail and turbulence likely to be found inside the cloud will increase the safety hazard.

In this discussion "penetrations" through the cloud center mean flights through areas of precipitation as indicated on weather radar, and the "fringes" refer to the variously cloudy/clear areas surrounding the cores of precipitation. Before the program is complete some penetrations should be made to study the relationship between lightning and gushes of rain, but these flights should not occur until confidence is gained in the reliability of the lightning instrumentation and critical flight instruments under lightning strike conditions.

Specific Conditions and Flight Paths - Based upon consideration of (a) the lightning strike experience data reviewed earlier, and (b) the desirability of measuring representative strikes, a group of eight suggested flight paths has been proposed, as illustrated in figures 35 and 36. These are, of course, not the only paths that should be flown, but they are ones which should be included at the beginning of the program. Other appropriate paths will become evident as the program proceeds. Some important aspects of the eight flight paths illustrated in figures 35 or 36 are as follows:

Interception of the Complete Channel - As illustrated in figure 31 there may be several branches associated with the ends of a lightning flash and the charge and currents in a single branch may be much lower than those in the main channel. Since the multiple charge centers that encourage this branching reside within a cloud, flights should be made beneath the cloud base, alongside the cloud beneath the anvil, and between two clouds as illustrated by paths 1, 2 and 3 on Figure 35. The flights along path 1 should be as close to the cloud base as possible (i.e. at as high an altitude as possible) to provide altitude for recovery in the event of an engine flameout or other problem.

Cloud-to-ground Flashes - Since cloud-to-ground flashes are generally believed to contain the highest charge, current, and current rate-of-rise magnitudes and to cause the most severe damage to aircraft, considerable emphasis should be placed upon obtaining data on this type of flash. Paths 1 (beneath the cloud base) and 6 (through the bottom of the cloud), at altitudes no higher than the -5°C level, are the most likely to intercept these strikes. This will be in contrast to the Project Rough Rider flights of reference (4) which were performed at higher altitudes. In those flights, little data indicative of cloud-to-ground flashes were obtained.
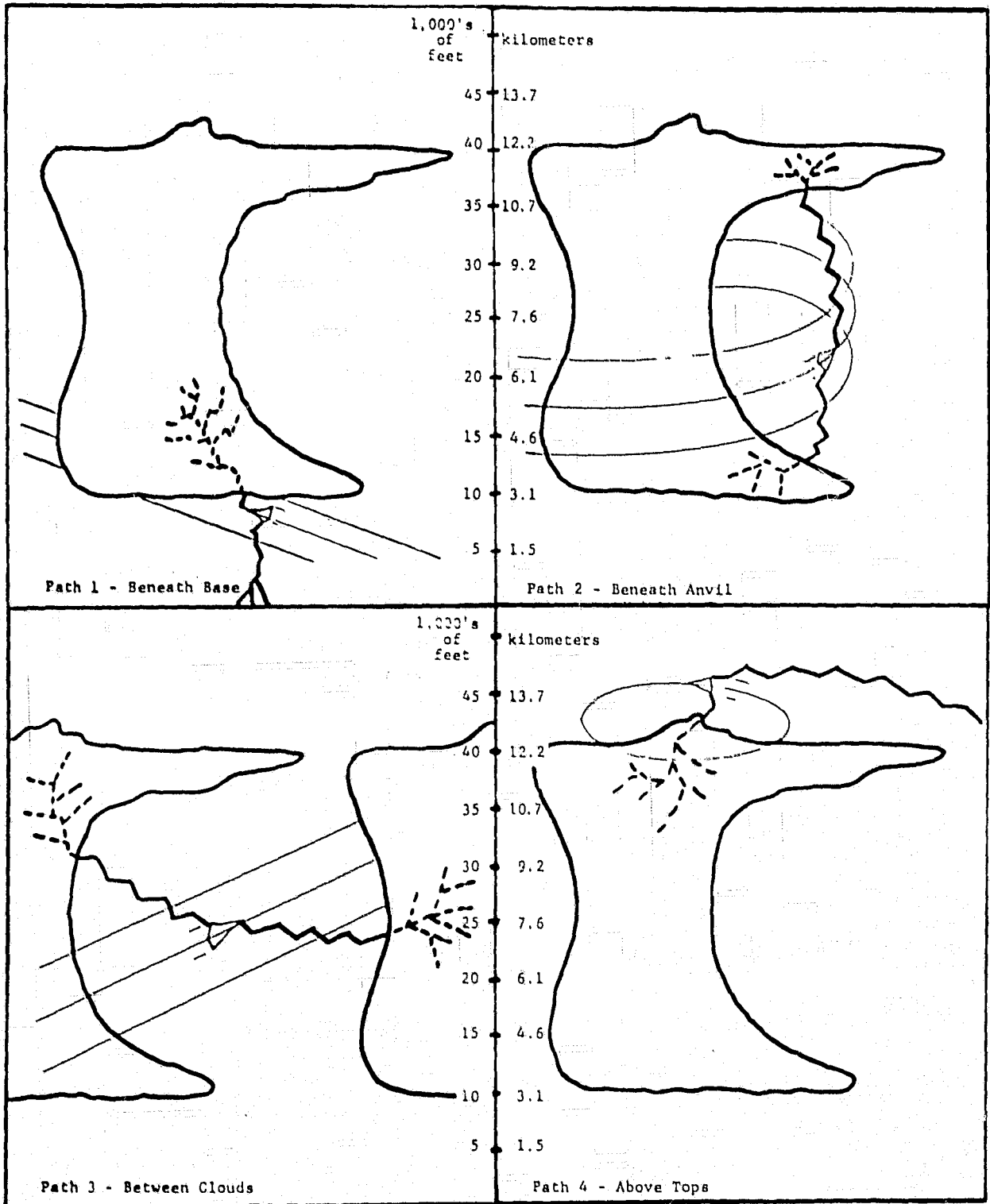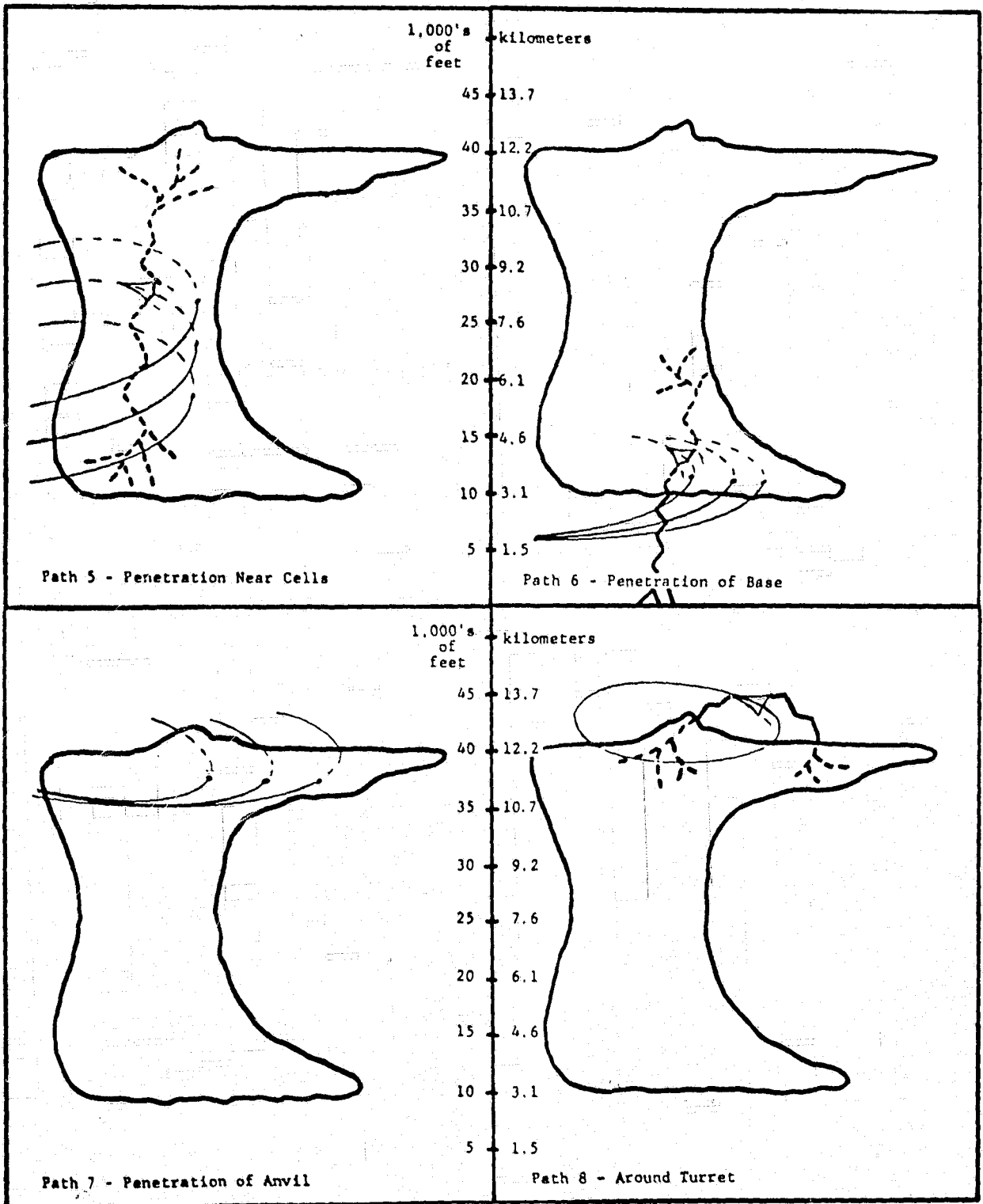
Figure 35 - Recommended Flight Paths.

68

Figure 36 - Recommended Flight Paths.

69

The probability of obtaining a strike during a flight beneath the cloud base will be lower than that applicable to penetrations through charge centers within the cloud where branching is prevalent, but those that are obtained beneath the cloud will have a higher probability of containing all of the components of the flash than strikes contained within the cloud.

Cloud-to-cloud and Intracloud Flashes - The stroke currents in cloud-to-cloud flashes are thought to be lower in peak amplitude and rate of rise than those in cloud-to-ground flashes, but longer in duration. There is very little data in existence on cloud-to-cloud flashes, however, so attempts should be made to capture this type of strike. Flight paths 3 and 5, at altitudes above the freezing level are intended for this purpose. Since path 5 involves penetration of the cloud, it is advisable to fly it after confidence in the aircraft and instrumentation systems has been obtained.

Path 3 goes between two clouds to capture the cloud-to-cloud strikes, representing the relatively common situation in which an aircraft is threading its way among cumulonimbus clouds, and there are frequent reports of strikes to aircraft in this situation.

These flights should be made at higher altitudes (5,000 m - 10,000 m in order to have the greatest probability of acquiring cloud-to-cloud or intracloud flash data.

Other Flight Paths - There are several other flight-path situations which, although not likely to be as "productive" as the aforementioned ones, should nevertheless be included in this flight research program because they are frequently encountered during normal flight operations. These include flights over the cloud tops as in path 4 of figure 35, and flights through the anvil and around the turret as in paths 7 and 8 of figure 36. These situations are encountered frequently by civil aircraft unable to fly over cloud tops at cruise altitudes, and by aircraft unable to circumnavigate anvils which may extend many miles across the line of flight. Lightning strikes have been encountered by aircraft in both situations, and occasionally, strikes at these altitudes produce considerable damage. There is a possibility that some of the strikes obtained during flights along paths 4, 7 and 8 may be positive flashes, conveying positive charge from the cloud to another cloud or to the earth. The stroke currents in positive flashes (which comprise about 10% or so of the total) to earth usually contain higher action integrals than negative strokes, producing a higher degree of physical damage. Data on the characteristics of positive flashes aloft is of interest because lightning certification and test standards presently in use have been based primarily upon the characteristics of negative flashes.

Several of the flight paths described in the foregoing paragraphs are shown on the cloud photograph of figure 37 as a further illustration of what is intended. These flight paths, of course, are offered only as a guide for the purpose of obtaining the lightning data desired. Several of these may prove unproductive, and others will become self evident as the program proceeds, and the flight plans should be adjusted accordingly as the program progresses.
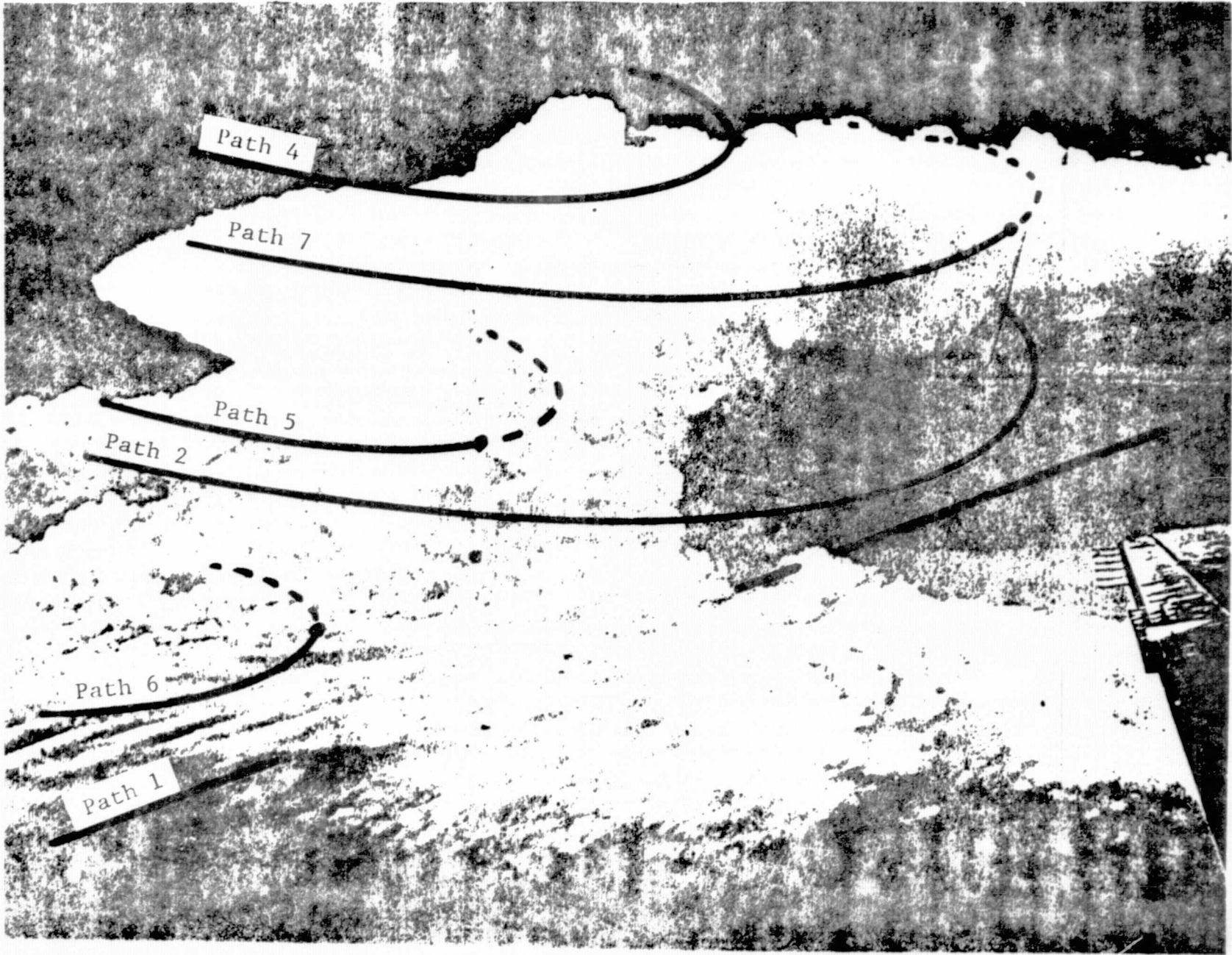
Path 4

Path 7

Path 5

Path 2

Path 6

Path 1
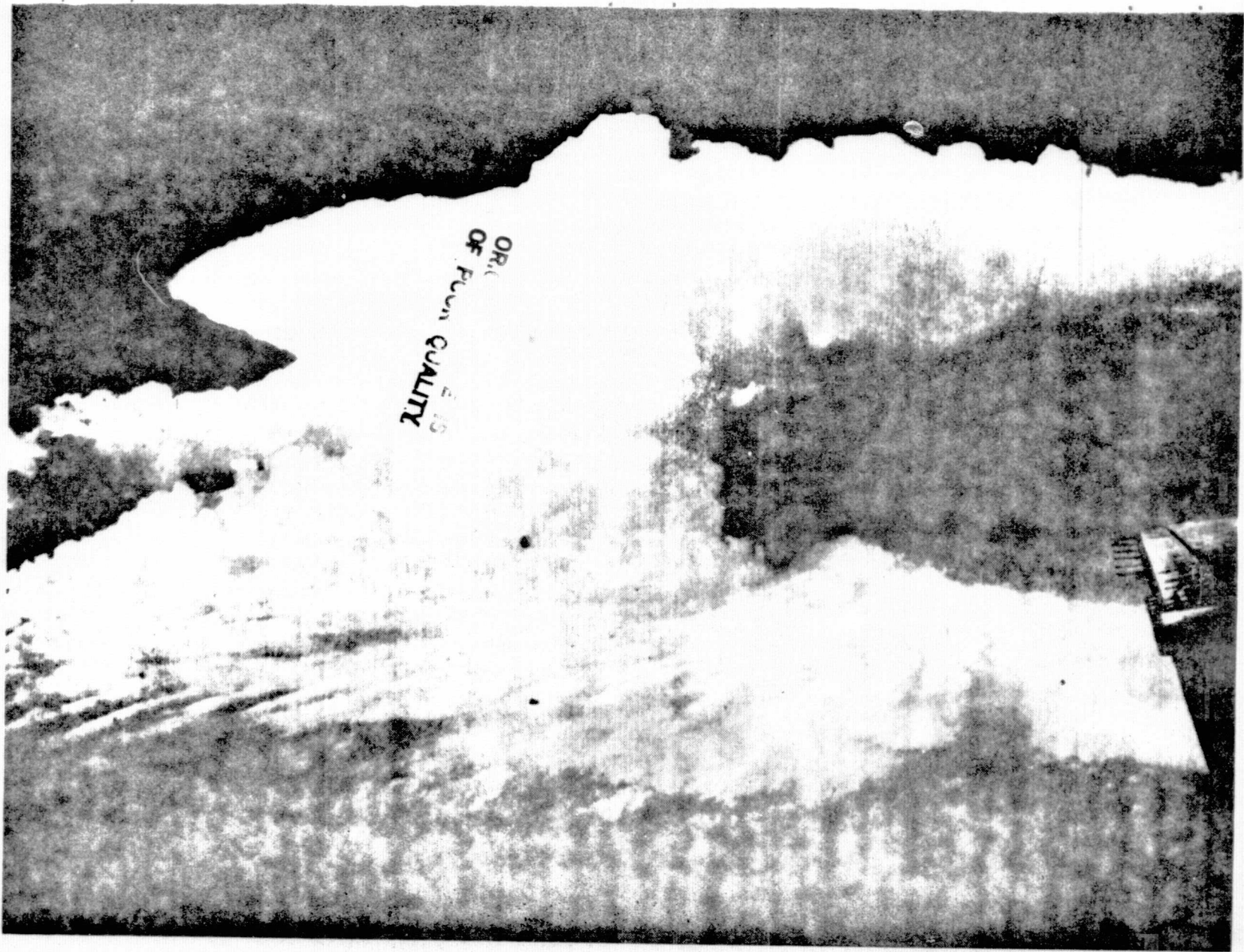
Figure 37 - Examples of Recommended Flight Paths.

FLIGHT RESEARCH AIRCRAFT

The requirements for an aircraft capable of being instrumented with the lightning sensors, carrying the data processing equipment and safely flying the flight paths recommended in the previous sections are summarized in this section. A NASA F-106B aircraft, under consideration for use in this program, was inspected to determine if these requirements appear feasible, and a discussion of findings from this inspection is presented. Using the F-106B as an example, illustrations are provided showing where the lightning sensors should be installed. Finally, safety considerations applicable to any aircraft utilized for thunderstorm research are presented.

Requirements

The requirements for the research aircraft follow directly from the instrumentation and flight-path descriptions developed earlier in the program, and are as follows:

1. <u>All-weather Capability</u> - Since some of the flights will be within clouds, the aircraft must have instrumentation necessary for flight under instrument flight rules (IFR) conditions. It is desirable but not mandatory, that this aircraft have airborne weather-radar for aid in flying the flight-paths desired, and also to enable identification of the aircraft's proximity to cells of precipitation when lightning strikes occur.

The research aircraft should also be equipped with anti-icing devices on its windshield and engine intakes, and at other surfaces where icing may be detrimental to safe flight, and should not be susceptible to excessive hail damage.

2. <u>Turbulence Withstand Capability</u> - Lightning strikes are frequently associated with turbulence. Thus, the research aircraft should be stressed to withstand "moderate to severe" turbulence. The USAF F-100F utilized in the Project Rough Rider storm penetrations of reference 5 had maximum acceleration limits of +6 and -3 g's. A fighter-type aircraft is thus desirable.

3. <u>Small Size to Avoid Premature Strikes</u> - In order that the lightning current amplitude data obtained during the program is a representative sample, it is desirable that the aircraft not be large enough to trigger strikes before the cloud has become fully charged. Wide-body aircraft, for example, appear to trigger strikes; whereas conventional transport and general-aviation aircraft do not show this tendency. A wide-body aircraft, therefore, would be less desirable for this program than one of conventional size.

4. Crew Size - Space for a crew of two is desirable (a) to provide backup in the event the pilot becomes temporarily disabled by flash blindness, and (b) to provide assistance in observing cloud formations, icing, radar patterns, and lightning strike points on the aircraft. The second crewmember can also monitor electric field readings and operate photographic equipment.

5. High Altitude Capability - Several of the recommended flight paths require flights at or above cumulonimbus cloud tops. Thus, capability to fly at least up to 13,000 m (40,000') is desirable.

6. Dual Engine Intakes and Inflight Re-start Capability - Turbo-jet engines are known to be susceptible to flameouts or compressor stalls when inlet air is disrupted by the compression and rarefaction produced by a lightning channel directly in front of the inlet duct. This situation frequently occurs after lightning strikes occur to the nose of an aircraft with fuselage-mounted engines. As the aircraft flies forward, the lightning channel is swept along the fuselage and may appear directly in front of an engine intake before the flash dies out. Aircraft with an engine on each side of the fuselage can expect to have one engine affected, since the flash usually is swept along only one side of the fuselage. Aircraft with a single engine intake in the nose or on the belly can expect to have this single engine flame-out or stall. No reported cases have been found of lightning related flame-outs or stalls in a single-engined aircraft with twin intakes. This is probably because only half of the inlet air to the single engine can be disrupted when a lightning flash is swept along one side of the fuselage.

There may, therefore, be less probability of a lightning-related engine malfunction in a single-engined aircraft with twin intakes as compared with a twin-engined aircraft.

The heavy precipitation that may be encountered during penetrations may also cause flame-outs or stalls, and this, in fact, happened during the Rough Rider F-100F penetrations (reference 27). Thus, effective autoignition and inflight re-start capability should be present on any aircraft utilized for this program.

7. Adequate Lightning Protection - Needless to say, the aircraft selected for this mission must be adquately protected from hazardous lightning effects. This includes the airframe and all of the flight-critical systems, as well as the crew. Flight-critical systems include at least the flight instrumentation, flight controls, electrical system, communication equipment and the fuel system. If an aircraft meeting requirements 1 through 6 is found that does not already have adequate protection, it must then be capable of being adequately protected. A checklist of areas of concern is presented in a later paragraph.

8.   Other Requirements - Requirements 1 through 7 were found to be of prime importance, but there are additional features that are also *desirable*. One of these desirable features is to have the smallest possible number of extremities which may serve as lightning attachment points. This is to reduce the number of necessary sensors and data-processing channels and/or have the highest probability of acquiring data from each strike that the aircraft receives. The nose, wing tips, vertical fins and horizontal stabilizer tips are common lightning attachment points, as are a ventral fin or pylon-mounted stores if present. A "clean" delta-winged aircraft, therefore, would be advantageous from this standpoint.

Another desirable feature is capability to fly at moderate speeds so as to maximize the aircraft's exposure time during penetrations and permit the flash to dwell as long as possible on forward-mounted sensors.

The NASA F-106B Aircraft

A NASA F-106B aircraft is among the aircraft being considered for this program. This aircraft was inspected during this feasibility study to determine if it meets the requirements discussed in the previous paragraph, and identify possible locations for sensors and data-processing equipment.

General Description - The aircraft was inspected at NASA Lewis Research Center and the aircraft is identified as NASA N616NA, Tail No. 72516. The aircraft was manufactured by the Convair Division of General Dynamics Corporation, and is a high-performance, land-based, delta-wing, all-weather interceptor. The F-106B is a dual-place airplane whose original mission is all-weather interception and destruction of attacking hostile airplanes or airborne missiles that operate within the performance capabilities of the airplane. The airplane is equipped with a fully retractable tricycle landing gear and is powered by the Pratt and Whitney J75-P-17 continuous flow gas turbine engine. The aircraft is about 15 meters long and has a 12 meter wing span. The wings are of the full cantilever, stressed skin construction with a delta configuration and 60-degree sweep-back of the leading edge. The right and left wing panels are attached to the fuselage with special high-strength bolts through the main spars and fuselage bulkhead fittings, and by drag angles riveted to the inboard edge of the wing and attached to the fuselage structure by means of screws. Each wing panel is equipped with removable cambered leading edge sections, a cambered wing tip, an elevon, a main landing gear and gear wing fairing, and provisions for the external mounting of droppable fuel tanks.

The tail group consists of a vertical fin and rudder. The fin is equipped with a removable leading edge, a fin tip, and a rudder. The fin loads are carried by four vertical forged spars which are an integral part of the fuselage bulkhead assembly. The rudder is made of aluminum honeycomb core-sandwich type construction with detachable hinge fittings on the leading edge spar.

The fuselage design is of semi-monocoque construction and includes an integral fuel tank, a missile bay, two engine air intake ducts, a main landing gear wheel well, electronic and accessory compartments, and the engine compartment. The fuselage is enclosed by stressed skins made of aluminum, magnesium, and titanium alloys that are attached with flush-head rivets and other types of fasteners.

A photograph of the NASA F-106 is shown in Figure 38, and a diagram of stations and compartments is shown in Figure 39, taken from the aircraft maintenance manual (reference 28).

The fuel system includes nine integral fuel tanks. Four of these tanks are located in each wing and one tank is located in the fuselage as shown in figure 39. Provisions are also incorporated for installing an external jettisonable fuel tank to the underside of each wing. All integral fuel tanks are built as a part of the basic structure of the aircraft. Each tank is provided with large structural access doors.

All fuel tanks are normally closed to atmosphere except during refueling, fuel transferring, and extreme flight maneuvers. The pressure required to force the fuel from one tank to another is obtained from engine bleed air. Air pressure regulators maintain the pressure differential necessary for sequencing fuel flow to the proper tanks, and boost pumps provide motive power to ensure adequate fuel supply to the engine.

Suitability of the NASA F-106B for This Program - The NASA F106B has a number of features that make it suitable for this program. The radome-mounted nose boom presently extends about 1.7 m beyond the radome which is itself about 1.7 m long. If the boom is utilized as a lightning current probe and attached to a current sensor located at its base inside the radome, the flash can hang on to the boom while the aircraft travels at least 3.5 meters before re-attaching to the fuselage. This will permit a time window up to about 10 milliseconds long, enabling a good possibility of capturing the return stroke as well as the pre-breakdown and leader phase currents.

Being a delta-winged aircraft, there are only 4 probable initial attachment points, as follows:

Figure 38 - NASA F-106B

NOTES

IN ESTABLISHING LOCATION OF EQUIPMENT IN THE AIRPLANE, REFERENCES ARE SOME TIMES MADE TO STA. (STATION) BL. (BUTTOCK LINE) AND WL. (WATERLINE). THESE TERMS ARE EXPLAINED AS FOLLOWS: STATIONS ARE MEASURED IN INCHES, EITHER FORE OR AFT FROM STATION 0.000. FOR EXAMPLE, STATION —44.90 IS A POINT 44.90 INCHES FORWARD OF STATION 0.00 WHILE STATION 40.89 IS A POINT 40.89 INCHES AFT OF STATION 0.00.

BL 0.00 REFERS TO THE VERTICAL CENTERLINE OF THE AIRPLANE. ALL DIMENSIONS OUTBOARD ARE MEASURED IN INCHES FROM THIS POINT.

WL 0.00 IS AN ARBITRARILY ESTABLISHED HORIZONTAL PLANE FROM WHICH VERTICAL DIMENSIONS ARE MEASURED IN INCHES. DIMENSIONS BELOW THIS PLANE ARE TERMED MINUS; DIMENSIONS ABOVE ARE TERMED PLUS. FOR EXAMPLE, WL —17.00 IS A POINT 17.00 INCHES BELOW WL 0.00.
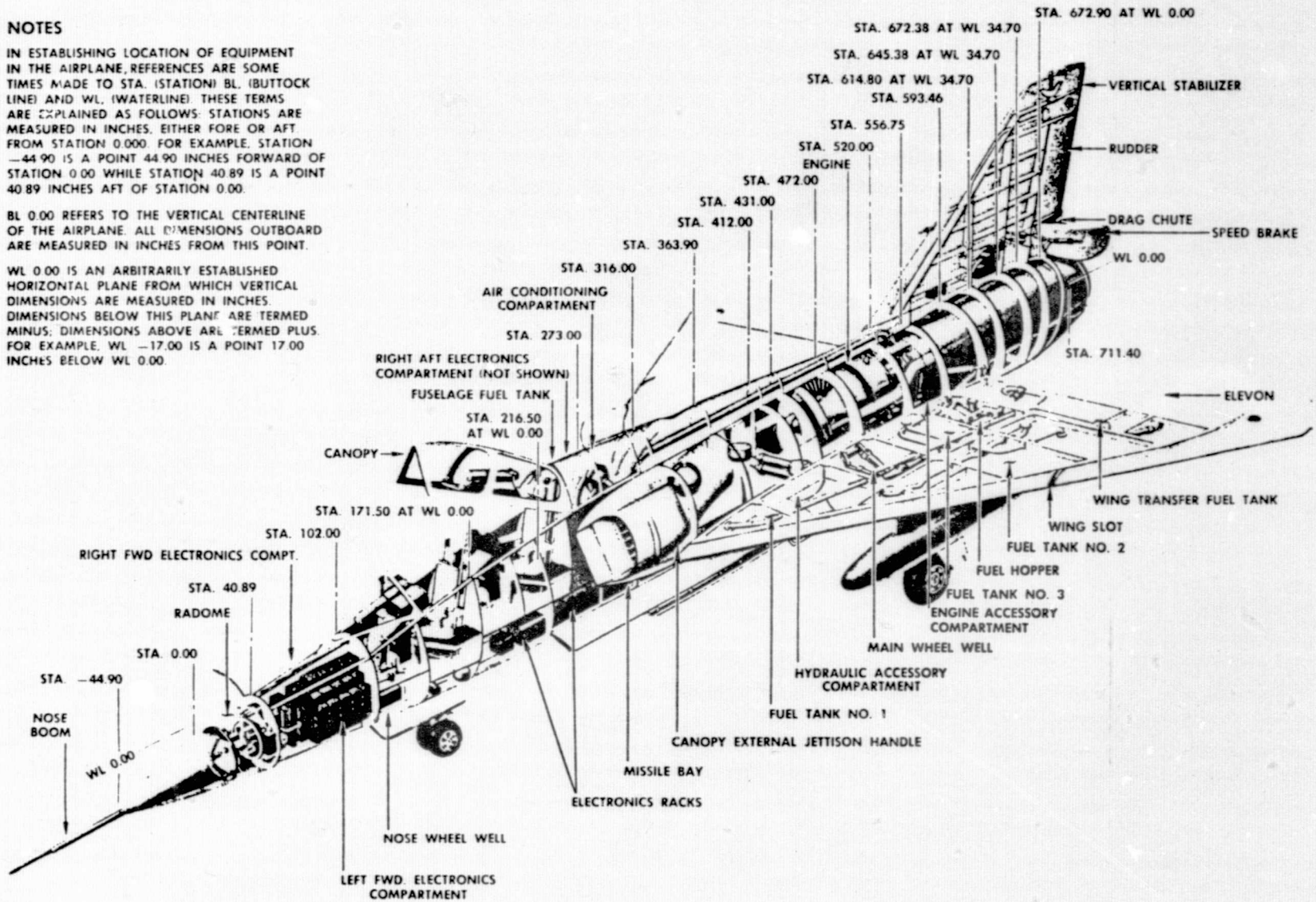

Figure 39 - Stations and Compartments of the F-106B.

- the nose

- the two wing tips

- the vertical fin

    Since two of these attachment points are likely to be in-
volved in each strike, it is necessary to instrument only three
of them to acquire data on all strikes. In addition to the nose
boom, the vertical fin and one of the wing tips could be instru-
mented. Additional suggestions for location of sensors are pre-
sented in a subsequent paragraph.

    The left forward electronics compartment has a useable area
approximately (1.5 m long) x (0.9 m high) x (0.5 m deep) which amounts
to a volume of about 0.68 cubic meters of available space for
data-processing equipment. As discussed earlier, a volume of
about 0.4 cubic meters will be required for this equipment. The
right forward electronic compartment contains the aircraft's navi-
gation and communication equipment and a patch panel used for pre-
vious instrumentation, but a small amount of space is also avail-
able in this compartment for additional equipment if necessary.

    A comparison of the NASA F-106B characteristics with the
eight basic requirements discussed previously is presented in
Table VI.

    Safety Aspects of the NASA F-106B - Several safety-related
aspects of the NASA F-106B make it especially desirable for use in
this flight research program.

There include:

- The windshield and canopy design is very suited for thun-
  storm penetration because of the metal windshield center-
  post and canopy centerline and window frames. These metal
  structures will prevent punctures of the windshield and
  canopy by lightning strikes sweeping past, or by static
  charge accumulations. The metal framework will also mini-
  mize streamering from the crew helmets, and electric shock.

- With the exception of two accidents caused by lightning
  surges entering the radome pitot heater systems, the USAF
  F106 fleet has been free of damaging lightning strike
  effects. A total of 21 lightning strikes to USAF F106's
  have been reported, yet there have been no engine stalls
  or flameouts attributed to weather factors (reference 29)
  including lightning and precipitation.

  The pitot heater problem has been corrected on the USAF
  fleet by the addition of a lightning suppressor and other
  modifications. The NASA F-106B does not have the radome-
  mounted pitot heater system that was the cause of the two

TABLE VI - Candidate Aircraft Characteristics vs Basic Requirements

	Basic Requirements	NASA F-106B	Aircraft A	Aircraft B
1.	"all weather" capability	yes		
2.	turbulence withstand capability	yes		
3.	small size to avoid triggered strikes	yes		
4.	minimum crew of two	yes		
5.	high altitude capability (to 12,000 m)	yes		
6.	Dual engine intakes	yes		
7.	Autoignition and restart capability	yes		
8.	lightning protection	yes- few modifications needed		

Air Force accidents, so the problem and the retrofit are not related to this aircraft.

● The closed, pressurized fuel system of the F-106B reduces the probability of fuel vapor ignition because the vents are normally closed, although the vents are located beneath the wing in a region not likely to be exposed to lightning.

● The aircraft has a large, single engine fed by twin inlets, rendering it highly unlikely that a lightning strike can disrupt enough inlet airflow to cause engine flameouts or compressor stalls.

80

Location of Sensors

Three types of sensors are required to obtain data on the three parameters given highest priority: electric field, rate-of-change, currents and induced voltages. The induced voltage sensor should be a pair of conductors located inside of the aircraft, but the electric field and current sensors must be mounted on the outside of the aircraft at extremities where lightning strikes are probable. Considerations relevant to location of these sensors, again using the NASA F-106B, are as follows:

Electric Field Rate-of-change Sensor - Since this parameter is of interest with respect to puncture of aircraft surfaces, it should be measured with a probe fitted in an aircraft surface at or near an extremity where strikes are likely. On the NASA F-106B, the vertical fin cap is the most appropriate spot. Here the electric field will not be influenced or distorted by protrusions such as the pitot boom on the nose since there are no such protrusions on the vertical fin. The field at the vertical fin is of direct interest because this part of many aircraft is non-metallic and lightning-strike damage is frequent. Also, the field about the vertical fin is likely to be similar to that about the wing tips; another area of interest to lightning protection designers.

Figure 40 shows how the flat-plate electric field sensor, described in an earlier section, can be installed in the vertical fin, together with a current probe to be located there. The field sensor must be mounted flush with the skin, and must not be in an area shielded by the current probe. Approaching leaders will apply the electric field to the sensor prior to eventual leader attachment to the current probe, as shown in the figure. If additional electric field sensors are desired, they should be mounted on the wing tip. Due to the unusual influence of the nose boom, it will not be advisable to mount an electric field sensor on the nose.

Current Sensor - Current sensors should, ideally, be provided at three of the four extremities on the NASA F-106B. The nose, vertical fin, and one of the wing tips are preferred locations. If only two current data channels can be provided, then the wing tip sensor should be omitted, because the wing-tips on the F-106B appear to be the most difficult of the extremities on which to mount sensors. Other criteria for location of the current sensors are that (a) the lightning flash should hang on to the sensor long enough to receive the first return stroke, and (b) that all of the lightning current that flows during this time should pass through the sensor. These criteria are illustrated in figure 41, and a typical installation is pictured in figure 42.

Insulate
for
1 kV

Electric
Field

Electric
field
rate-of-change
sensor

Signal
conditioning

Replaceable
lightning
attachment
plate

Lightning
flash
hangs on
here

Insulate
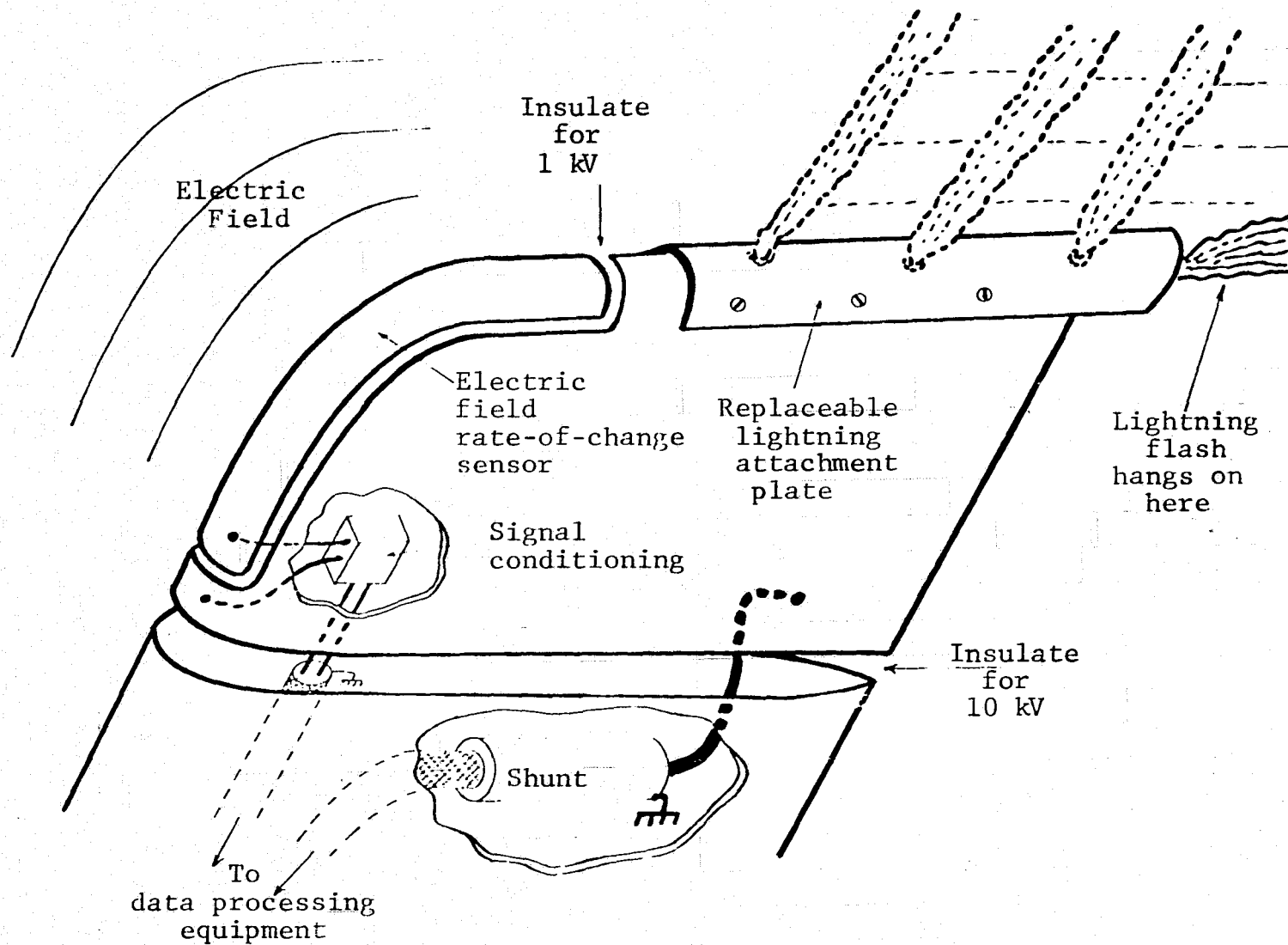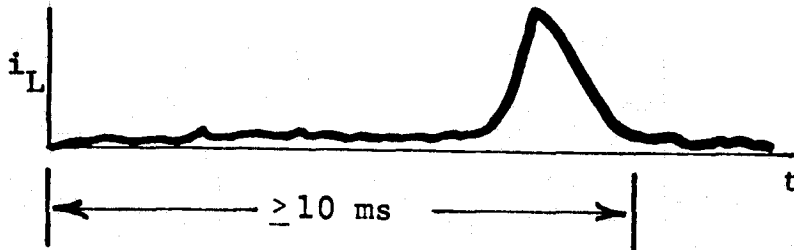for
10 kV

Shunt

To
data processing
equipment

Figure 40 - Installation of Electric Field and
Current Sensor in Vertical Fin

1. The current sensor should be able to receive the first return stroke (at least)

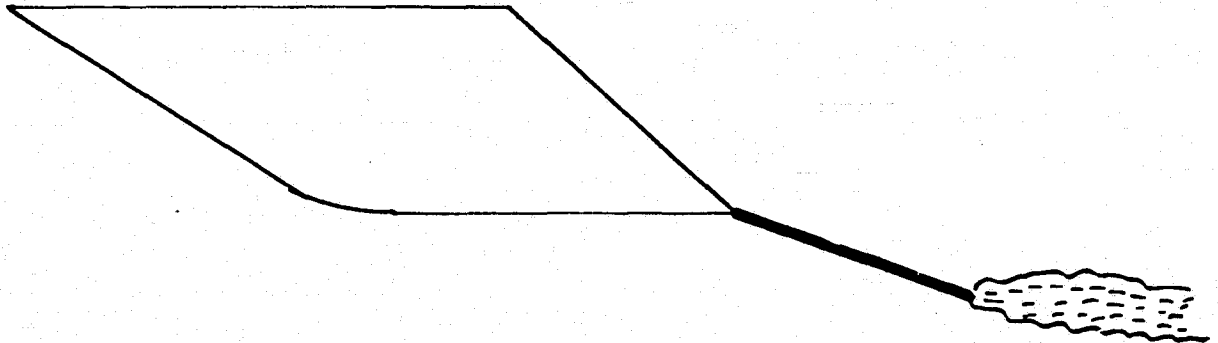2. All current should pass through the sensor

Figure 41 - Criteria for Installation of Current Sensors.

Lightning currents
pass through shunt until
channel reaches fuselage
or canopy

Boom

Shunt

Data Processing
equipment in left
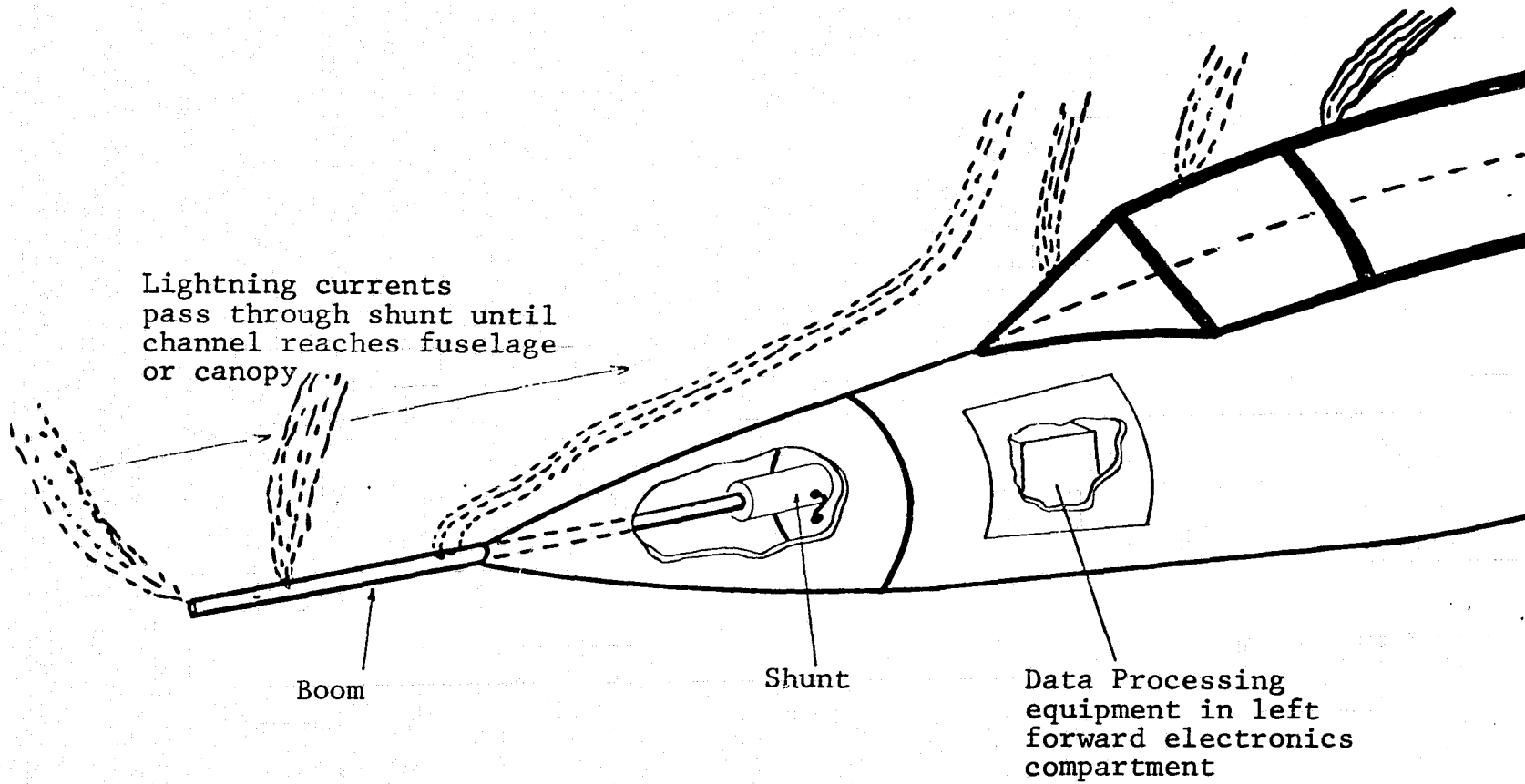forward electronics
compartment

Figure 42 - Typical Installation of a Current
Sensor on a Nose.

Langley Research Center
National Aeronautics and Space Administration
Hampton, Virginia 23665
October 16, 1978

References

1. "Proceedings of the Second Annual Workshop on Meteorological Inputs of Aviation Systems", March 28-30, 1978 at University of Tennessee Space Institute, NASA CP 2057/FAA-RD-78-99.

2. Lloyd, K.J., Plumer, J.A. and Walko, L.C., "Measurements and Analysis of Lightning-Induced Voltages in Aircraft Electrical Circuits", NASA CR-1744, February 1971.

3. Walko, L.C., "A Test Technique for Measuring Lightning-Induced Voltages on Aircraft Electrical Circuits", NASA CR 2348, February 1974.

4. Cianos, N. and Pierce, E.T., "A Ground Lightning Environment for Engineering Usage", Stanford Research Institute Technical Report 1 for McDonnell-Douglas Astronautics Co. under contract to Bell Telephone Laboratories and the U.S. Army Safeguard System Command, August 1972.

5. Petterson, B.J. and Wood, W.R., "Measurements of Lightning Strikes to Aircraft", Final Report No. DS-68-1, Federal Aviation Administration, Aircraft Development Service, Washington, D.C. 20590.

6. Plumer, J.A. and Hourihan, B.I., "Data from the Airlines Lightning Strike Reporting Project", General Electric R&D Report GPR-75-004, March 1975.

7. Plumer, J.A., "Lightning Strike Feedback: More Pilot Reports Needed", Flight Operations Magazine, July 1978, pp. 42-47.

8. Fisher, F.A. and Plumer, J.A., "Lightning Protection of Aircraft", NASA Reference Publication 1008, October 1977, pp. 206-220.

9. James, T.E., and Phillpott, J., "Simulation of Lightning Strikes to Aircraft", Culham Laboratory Report CLM-R111, May 1971, p 34.

10. Berger, Karl, "Development and Properties of Positive Lightning Flashes at Mt. San Salvatore with a Short View to the Problem of Aviation Protection", 1975 Lightning and Static Electricity Conference Proceedings, April 1975.

11. Electromagnetic Pulse Sensor and Simulation Notes, Air Force Weapons Laboratory, Kirtland AFB, N.M.
    Vol. 1, Notes 2, 3, 4, 7, 8, 11, 18, 19, 23 and 25
    Vol. 2, Notes 30, 38, 40, 41, 43
    Vol. 5, Notes 72, 74, 78
    Vol. 6, Notes 80, 86, 91
    Vol. 11, Notes 127, 133

References - continued

12. Miller, E., "1964 Rough Rider Summary of Parameters Recorded, Test Instrumentation, Flight Operations and Aircraft Damage", USAF Aeronautical Systems Division, Technical Report ASD-TR-65-1, April 1965.

13. Roys, G.P., "Airborne Instrumentation System for Measuring Meteorological Phenomena inside Thunderstorms", USAF Aeronautical Systems Division, Technical Report ASD-TDR-63-231 May 1963.

14. Nanevicz, J., Adams, R. and Bly, R., "Airborne Measurement of Electromagnetic Environment near Thunderstorm Cells" (TRIP-76) Stanford Research Institute, March 1977.

15. Cooper, J., "On the High Frequency Response of a Rogowski Coil", Journal of Nuclear Energy, Part C, 1963, Vol. 5, pp 285-289.

16. Schwartz, M., "Information Transmission, Modulation, and Noise", McGraw-Hill Book Company, Inc., New York, N.Y., 1959, p. 213.

17. Fisher and Plumer, "Lightning Protection of Aircraft", p. 193.

18. Harrison, H.T., "UAL Turbojet Experience with Electrical Discharges", UAL Meteorology Circular No. 57, United Air Lines, Chicago, Illinois, January 1965, pp. 27-48.

19. Harrison, H.T., pp. 37, 39, 43, 47.

20. "World Distribution of Thunderstorm Days, Part I", WMO/OMN No. 21, TP 6, World Meteorological Organization, Geneva, Switzerland, 1953.

21. Cianos, N. and Pierce, E.T., p. 6.

22. Cianos, N. and Pierce, E.T., p. 8.

23. Cianos, N. and Pierce, E.T., pp. 9, 10.

24. Cianos, N. and Pierce, E.T., pp. 121-124.

25. Fisher and Plumer, "Lightning Protection of Aircraft", p. 64.

26. Fisher and Plumer,   "   "   "   p. 65.

27. Roys, G.P., "Airborne Instrumentation System for Measuring Meteorological Phenomena Inside Thunderstorms", USAF, Aeronautical Systems Division", p. 46.

References - continued

28. USAF Technical Order T.O. IF-106A-2-5, pp. 1-3.

29. USAF Automated Data, Air Force Inspection and Safety Center, Norton AFB, California.