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A SURVEY OF HIGH FREQUENCY EFFECTS DUE TO LIGHTNING

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A SURVEY OF HIGH FREQUENCY EFFECTS DUE TO LIGHTNING

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Abstract

This review describes the electromagnetic fields produced by natural lightning processes in the frequency range 300 kHz to 1 GHz, which is of interest in determining lightning test procedures for advanced aircraft designs. The form of the current pulses deduced from the observations is considered and compared with theoretical models. The need for further observations is discussed.

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INTRODUCTION

Present aircraft lightning tests are specified in terms of current flowing in the aircraft. Direct and indirect effects are studied by discharging capacitors, inductors, battery banks or pulsed motor generators into a circuit containing the aircraft or the component under test. The waveforms of the voltage and current pulses are specified (Phillpott 1977, SAE AE4L Committee, 1978) but the highest frequencies called for are approximately 300 kHz. This is implicit in the tests of indirect effects which require peak currents of 100 kA and peak rates of rise of 100 kA/μs.

Much higher frequencies are present in the electromagnetic fields created by a thunderstorm. These have never been properly explained in terms of a coherent picture of the total event. Frequencies above 1 MHz are important in assessing the risk to airborne electronic systems which now comprise computers, navigation aids, communications and weapons control and will include in the future flight control systems. The danger is increased by the greater use of composite materials which have much less screening effect than metal against electromagnetic fields.

The testing of aircraft at high frequencies is complicated by the presence of high-frequency transients in the slower current pulses now produced by laboratory generators. The spectrum of these transients is usually not known, and their existence often ignored. It is essential that they be eliminated or controlled, and that test results be interpreted in terms of the transient waveforms actually employed in the test.

Higher frequencies are not necessarily most prominent at the time when the peak current flows. During the breakdown process and the advance of the leader much pulsed electromagnetic radiation appears, and its amplitude in some frequency bands actually falls during the return stroke. These transients are not included in present test requirements. The highest frequencies present in the return stroke current pulse and in subsequent restrikes, which would appear as fine structures in the current waveform, are not represented in present tests either.

Future test techniques will need to include properly designed current feed systems to reproduce the electrical resonances which exist in aircraft. This implies proper terminations which give equivalent voltage and current resonances in the airframe to those which appear in flight.

This survey attempts to summarise the present state on knowledge in this field, and is a first step towards developing test specifications for the indirect effects of lightning. We concentrate on high frequency electromagnetic radiation (above 300 kHz) and fast time-resolved observations, together with the corresponding theories. Results reflect the advances in experimental techniques, giving recent work prominence in what is necessarily a selective review.

No attempt has been made to estimate the potential danger of reported effects. The results of the airborne lightning studies forming part of the Thunderstorm Research International Programme (TRIP) studied in Florida in 1976, 1977 and 1978 demonstrate that significant high frequency electric and magnetic fields can appear within an aircraft, even at some distance from a flash. The coupling of electromagnetic fields into aircraft and airborne electronic systems is not discussed in this survey.

It is assumed that the reader is familiar with present testing methods. The current and voltage waveforms used to represent the effects of a lightning flash are based on the cloud-to-ground return stroke parameters, and these will not be discussed here. The report by Phillpott (1977), the USA equivalent produced by the AE4L Committee of the Society of Automotive Engineers (1978) and the proceedings of the conference held at ONERA as a brief for the NATO Air Electrical Working Party on lightning test procedures (1978) may be consulted.

Similarly the details of the return stroke current pulses observed in natural lightning flashes to ground will not be discussed. Descriptions are given in standard references (Uman 1969, Golde 1977a). It should be noted, however, that cloud-to-cloud, intra-cloud, and cloud-to-air discharges are much more common than ground flashes. When charge centres are produced in a thundercloud discharges between centres of opposite polarity involve the movement of probing streamers or leaders - the nomenclature is not consistent - as do discharges to ground. It is worthwhile to define here some of the terms used in the literature to describe events during lightning discharges apart from the return stroke.

The cloud discharges can be initiated by leaders of either polarity, and these are apparently not stepped but continuous for about 250 ms. Then the luminosity fades for 10 - 100 ms and a series of short, bright flashes about 1 ms long appear. These are called 'recoil streamers' or 'K processes' for historical reasons, and produce fast E-field pulses (K-changes). Similar phenomena appear between strikes during a flash to ground, presumably because of activity in the cloud. An extreme form of recoil streamer is the dart leader seen after a return stroke. The recoil then goes from cloud to ground. The existence of stepped recoil streamers analogous to dart-stepped leaders has been proposed.

Between restrikes during a flash to ground streamers moving in the cloud produce small slow E-field changes as well as the fast K-changes. The whole process is called a junction or J-process. It also appears during cloud discharge, again with K-changes superimposed.

The main body of the review uses these terms, as the literature on natural lightning does. In Section I we describe first the radiation associated with the different phases of the ground flash and the cloud discharge. Measurements are of necessity made at some kilometres distance usually, but distortion during propagation is important. Source characteristics are deduced where possible. Some recent airborne investigations are included.

The modelling of lightning phenomena which has been developed in recent years is reported in Section II with special reference to high frequency phenomena. Most theoretical work has been on return stroke problems.

Section III summarises the results and conclusions of the review.

I. OBSERVATIONS OF HIGH FREQUENCY RADIATION FROM THE LIGHTNING DISCHARGE

1.1 General

Signals detected by a radio receiver aerial in general depend upon both the source frequency spectrum and the characteristics of the propagating medium. Propagation effects are not considered here. Nearby flashes, usually within direct line of sight (d = 1 - 30 km), are often termed 'close' lightning but it is the 'far' or 'radiation' field (see Section 2.1) that is mainly recorded in such measurements. Beyond a certain minimum range such fields scale inversely with distance, but it is not possible to estimate fields very close to the lightning channel in this way. A distance of 1 - 10 km from the flash is the normal limit to simple scaling.

A lightning flash is made up of a number of different components, and generates a complex electromagnetic signature. The structure of the electromagnetic radiation from lightning varies with frequency and time as schematically illustrated in Figure 1 (Cianos, Oetzel and Pierce 1972: Nanevicz 1978).

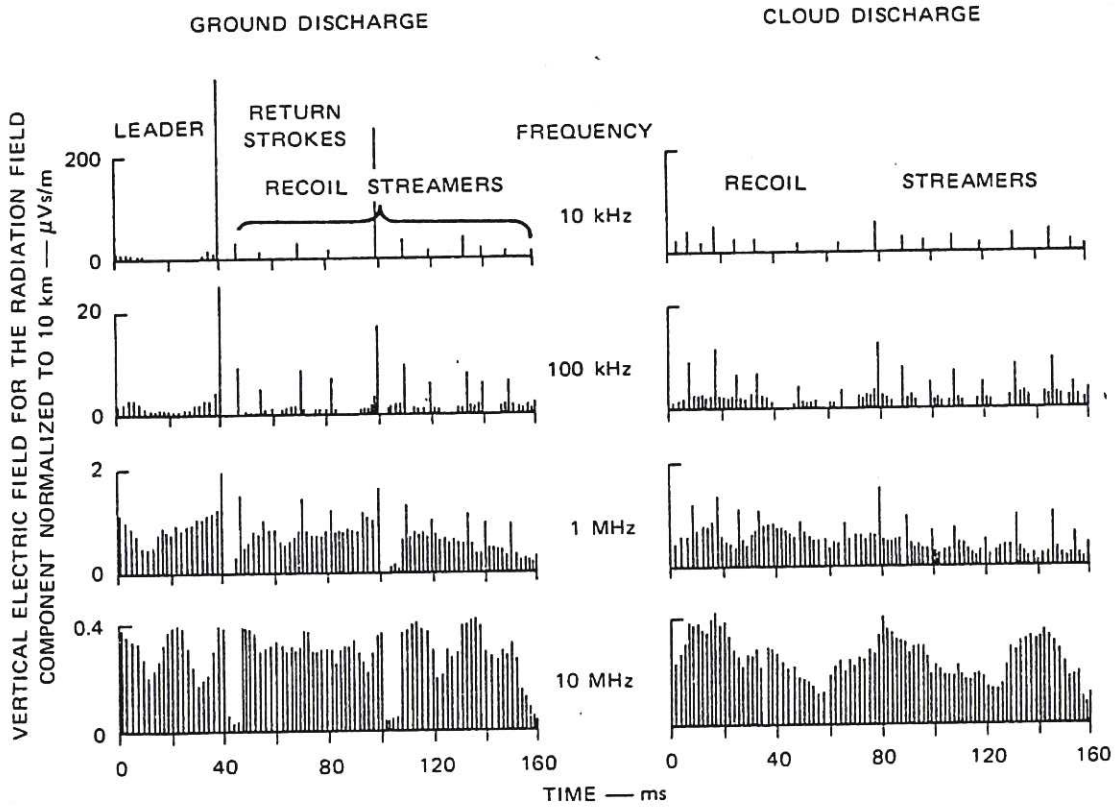

Fig.1 Schematic description of the structure of the fields radiated by lightning as a function of time and frequency (10km distance).

At very low frequencies, VLF (3 - 30 kHz), the pulses are discrete and are generated principally by the return stroke and/or recoil streamers (K-changes). As the frequency increases, the number of pulses per flash also increases, with a maximum of about 10^4 per discharge for frequencies between 30 and 100 MHz (VHF): the disturbance accompanying the flash is then quasi-continuous. These pulses appear to be associated with the initial leader, including its steps, and also with the electrical-breakdown processes accompanying probing leaders moving within the cloud. These probing leaders can occur, for a flash to earth, between return strokes or after the final stroke: for an intracloud discharge their presence is possible at almost any stage of the discharge. It is interesting to note that the signals at HF and VHF associated with return strokes and K changes are not strong, and are indeed partly 'quenched' following the occurrence of return strokes and K changes. It is believed that this quenching is due to a temporary absence of probing leaders. As frequency is further increased beyond the VHF range, there is a sharp decrease in the number of pulses until at centimetric wavelengths ($\sim$ GHz) the pulses are again well separated and associated with the macroscopic features of the return strokes.

This large variation in pulse emission rate with frequency makes the comparison of results obtained with different bandwidths difficult. Where the receiver response to a pulse has decayed before the arrival of another pulse, the output amplitude scales linearly with the receiver bandwidth B. If pulses are much more rapid, they are not properly resolved, and output amplitude is proportional to $B^{\frac{1}{2}}$ (Heydt, 1972, Pierce 1977).

We shall now discuss the discharge to ground in more detail.

1.2 Breakdown

Before a lightning discharge can propagate to ground or between cloud charge centres, breakdown must occur in one location and draw on charge over a wide volume. Lathan and Stromberg (1977) discuss the various mechanisms that have been suggested; colliding raindrops can produce corona, and so can single ice particles near melting.

Although theories of breakdown are far from complete, various observations of r.f. emissions from breakdown processes have been made. Work by Malan (1958) indicates the presence of radio emission at 12 MHz throughout the time preceding the first return stroke. Radiation pulses are also observed at frequencies down to 100 kHz, the peak amplitude of which is up to 20% of the return stroke pulse at that frequency. In observations at 420 and 850 MHz, Brook and Kitagawa (1964) state that the principal source of radiation appears to be with the development of streamers during both initial and subsequent breakdown events.

Iwata and Kanada (1967) published a frequency spectrum of the breakdown phase, reproduced here in Figure 2. The amplitude falls with increasing frequency, and is about one third of that of the return stroke at 100 kHz, becoming comparable in the range 1 - 30 MHz. The amplitudes are scaled to a distance of 10 km. The figure shows observations made by these authors at later phases of the discharge also. These are discussed in the following sections. The theoretical curve was deduced by Arnold and Pierce (1964) for the leader phase (Section 1.4).

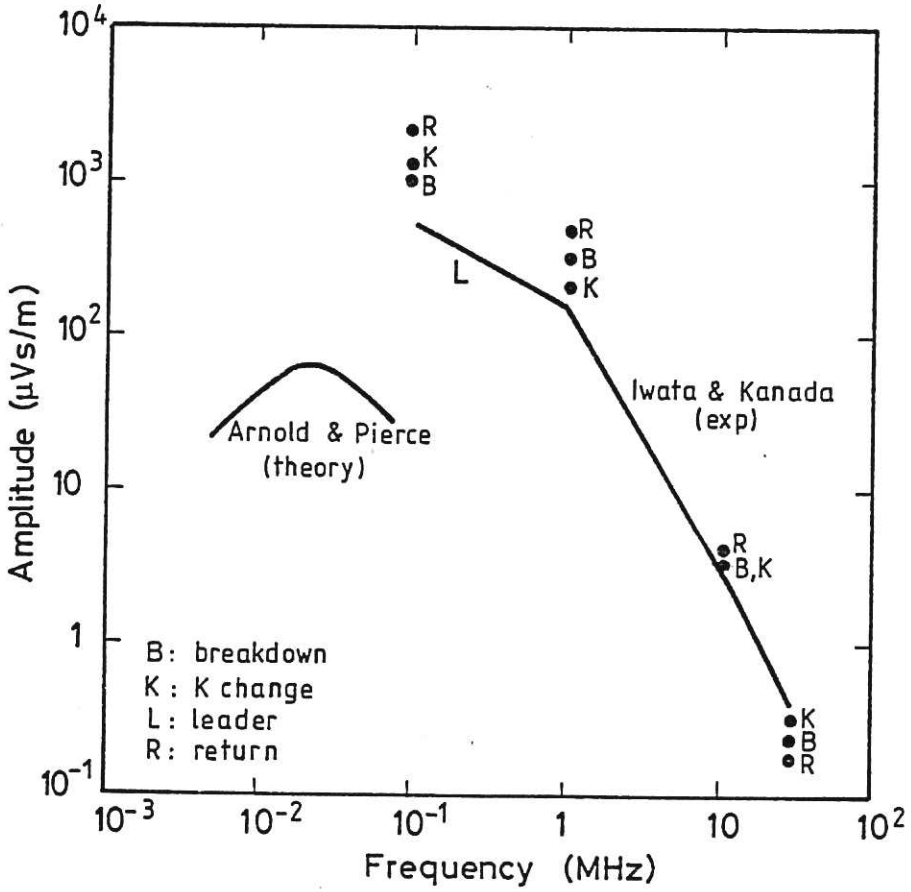

Fig.2 Spectrum of lightning phases, 10km from source.

1.3 Intermediate

Short leaders propagate away from the breakdown event, tapping other charge pockets, for about 10 ms. During this time numerous pulses are emitted at MHz frequencies, comparable in amplitude with those during the initial breakdown. Large pulses at lower frequencies are absent (Malan 1958, Oetzel and Pierce 1969). This phase also occurs between strokes (Section 1.6) and in intracloud discharges (Section 1.9).

1.4 Stepped Leader

When sufficient charge has been accumulated, the field at some streamer tip will be high enough for a further breakdown, forming a conducting channel to ground. This 'leader' phase lasts for about 20 ms, and is characterised by the rapid breakdown of steps of about 50 m, followed by a pause of about 30 - 50 μs. The leader tip propagates at a velocity of $1 \times 10^5 - 8 \times 10^5$ ms^{-1} (Berger and Vogelsanger 1966, Berger 1977). This behaviour is reflected in the associated radio emissions.

Norinder (1951) observed radiation from leader steps, and estimated the peak amplitude frequency to be 30 kHz: field strengths were of order 20 Vm^{-1} at 10 km, measured broadband. Norinder and Knudsen (1957) recorded low frequency radiation pulses from leader steps and found that about one third of all pulses had 15% of the return stroke pulse amplitude. Leader current risetimes were estimated by Hodges (1954) from the ratio R of pulse heights from leader steps and the return stroke, using earlier figures for return stroke currents and risetimes. Similar current propagation velocities were assumed for both processes, and

$$\left.\frac{dI}{dt}\right|_{leader} = R \left.\frac{dI}{dt}\right|_{return}$$

Hodges describes two types of leader, with characteristic current risetimes of 0.6 and 2.6 kA/μs.

Clarence and Malan (1957) point out that for much of the time the leader is a poor radiator at frequencies below 100 kHz, despite the long conducting path. They report similar low frequency pulses to those above when bright

steps appear, and at higher frequencies almost continuous pulse emission of comparable amplitude to other discharge phases.

A frequency spectrum for a train of leader steps was deduced by Arnold and Pierce (1964), with a peak amplitude of order $70\mu Vsm^{-1}$ at 10 km and a frequency of 10 kHz. This is shown in Figure 2, together with the observations by Iwata and Kanada (1967) at higher frequencies mentioned in Section 1.2. The current pulse shape assumed in the model of Arnold and Pierce is probably in error, as shown by later work (Krider and Radda 1975).

Takagi and Takeuti (1963) and Brook and Kitagawa (1964) observed strong radiation pulses in the frequency range 10 - 850 MHz due to leader processes. The pulse durations are much less than the intervals between steps, possibly indicating that VHF radiation here is due to the formation of channel steps.

Submicrosecond resolution of leader pulse trains preceding pulses due to nearby return strokes (from discharges within 10 km) was reported by Krider and Radda (1975) and Krider, Weidman and Noggle (1977). They used a broadband aerial system with a 0.15 μs risetime. The 10 - 90% risetimes of individual step waveforms are frequently less than 0.3 μs, with a typical width at half maximum of 0.4 - 0.5 μs. These are upper limits, because the aerial bandwidth restricts the range of risetimes observable. Pulse amplitudes increase just before the return stroke, reaching about 10% of the return stroke amplitude. These observations are valuable in demonstrating the high frequency content of leader pulses. Peak step currents in the range 2 - 8 kA and rates of rise close to the ground of 6 - 24 kA/μs were estimated. Early measurements clearly had very insufficient bandwidth, and even this detecting sytem is barely adequate: fine structure would not be recorded. Figure 4 of Section 1.5 illustrates their results.

1.5 Return Stroke

The leader reaches ground, or connects with an upward leader from ground, and a conducting channel is formed between the cloud charge and the induced ground charge. The powerful current surge which propagate up the channel is known as the return stroke, and has been extensively studied.

The work of Malan (1958) was developed by Horner and Bradley (1964). Takagi and Takeuti (1963), Iwata and Kanada (1967), and many others to give a fairly comprehensive understanding of the frequency spectrum of the return stroke radiation. It is usually larger than all other components up to 10 MHz, variable and often insignificant in the VHF band, but is again detectable at microwave frequencies (Oetzel and Pierce, 1969). The radiation pricipally consists of a single large pulse at frequencies up to 10 MHz, with peak amplitude at about 5 kHz. The peak received signal amplitude, normalised to a 1 kHz bandwidth and 10 km distance, for all signals radiated by lightning, is shown in Figure 3, reproduced from Cianos and Pierce (1972). Points in the range 1 kHz - 10 MHz are return stroke measurements. When comparing observations at using different bandwidths, the pulse rate (or more generally the temporal structure of the signal) must be properly taken into account (Section 1.1).

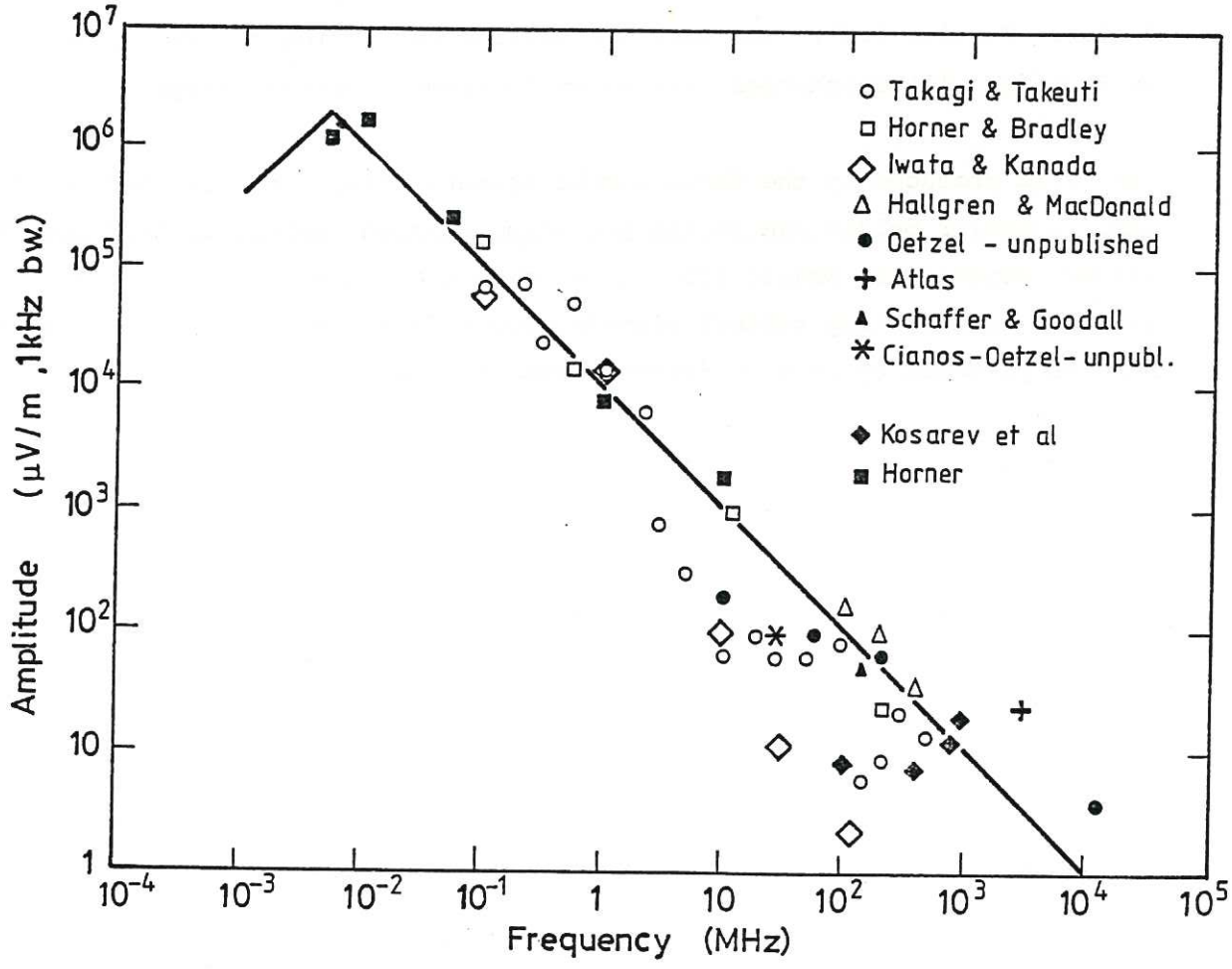

Fig.3 Spectrum of total lightning flash 10km distance.

The straight line, on the log graph,

$$E = \frac{10^4}{f(\text{Hz})} \qquad \text{Vm}^{-1} \text{ in 1 kHz bandwidth}$$

is an empirical approximation to both the return stroke and other data, in the range 5 kHz - 1 GHz. This gives an average value: the amplitude generally obeys a log-normal distribution within 7 db (Horner 1964).

The main E-field pulse produced by the return stroke has a 10 - 90% risetime of 1 - 6 μs, measured broadband (Fisher and Uman, 1972). The pulse shape is too complex to be described adequately by this single risetime, however. Sub-microsecond resolution of the pulse radiation just prior to and during the development of the first and subsequent return strokes was obtained by Weidman and Krider (1978), using the technique developed for their work with leaders (Section 1.4). The work was carried out during the TRIP programmes in Florida. All discharges were shown to lower negative charge.

The field produced by the first stroke appears after a regular series of samll unipolar pulses due to the preceding stepped leader, as described by Krider, Weidman and Noggle (1977). Weidman and Krider give a series of sketches illustrating typical signals from a first return stroke and subsequent strokes preceded by dart or dart-stepped leaders (Figure 4).

All strokes show a front portion F that is concave in form and rises slowly. For the first return stroke this front lasts about 5 μs and rises to about half the peak value. In subsequent strokes the concave portion lasts only about 1 μs, and after a dart leader rises only to about one quarter of the peak value. A dart-stepped leader is followed by a return stroke field pulse similar to that of a first stroke. Following the initial slow rise a fast transition R to the peak appears, with a smaller secondary peak α and a train of subsidiary broader maxima a, b, c, following (cf inset, Fig. 10, Sect. 2.3).

Histograms of the 10 - 90% rise times for the fast field transitions only show some values below 0.2 μs, so that the aerial response time (0.15 μs) is a limiting factor. The actual rise times are less than 0.1 μs on occasion, and fine structure may be present which the system could not reproduce.

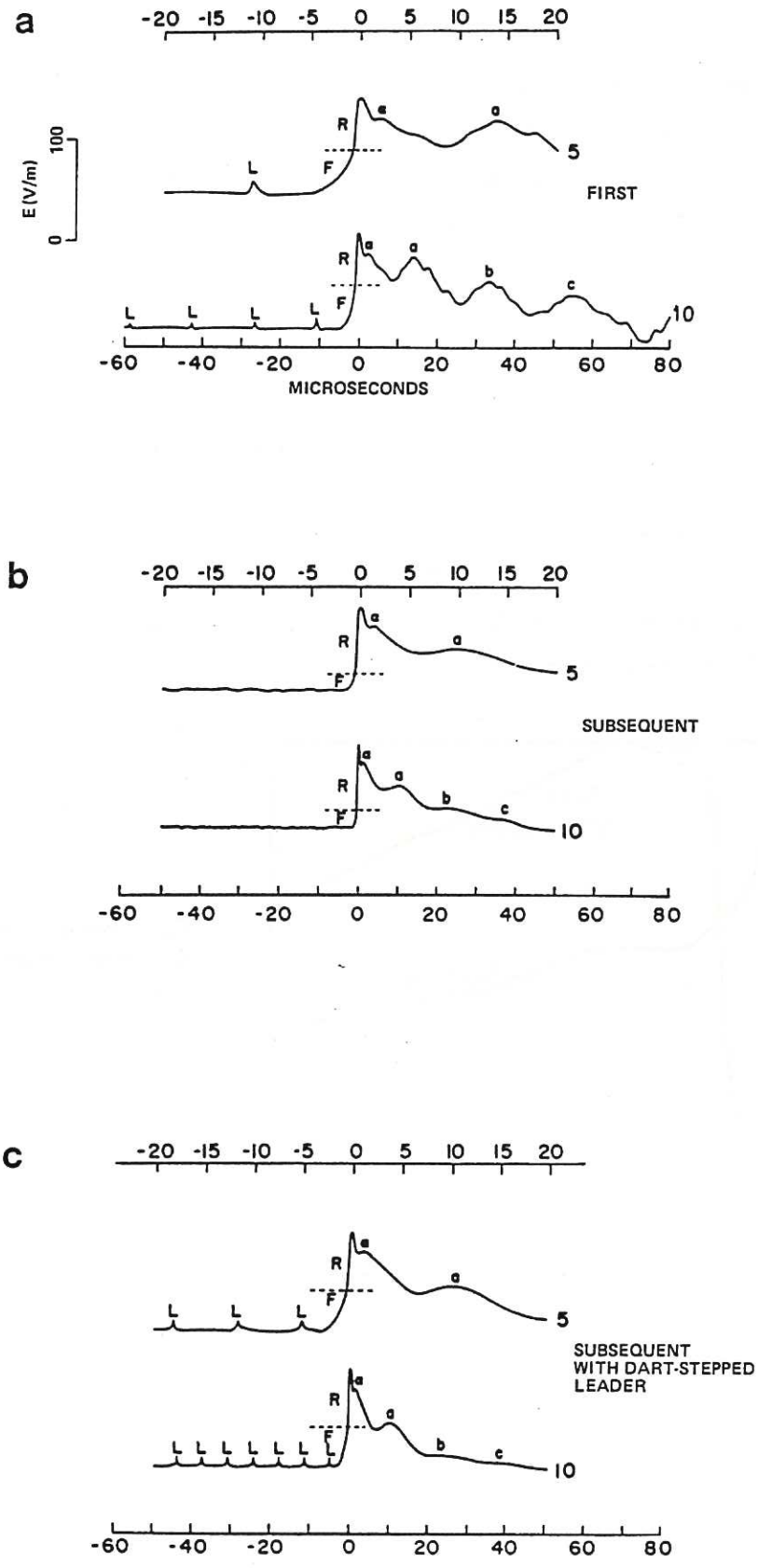

Fig.4 Sketches illustrating radiation fields produced by (a) first return stroke, (b) subsequent return stroke after a dart leader, (c) subsequent stroke after dart-stepped leader. Amplitudes as at 10km distance. The traces, shown at 5μs and 10μs per division, coincide at the centre zero.

The measurements were made at distances of 10 - 30 km. Normalised to 10 km the slow front and the fast transition both have mean amplitudes of about 50 Vm^{-1} for first strokes and subsequent strokes preceded by dart-stepped leaders. Subsequent strokes preceded by dart leaders have a similar mean value for the fast transition, but smaller slow front amplitudes. Since these measurements were made over water the distortion is likely to be less than over land (Wait 1957: Johler et al. 1956: Uman et al. 1975).

The two-stage rise is reminiscent of the current waveform in the return stroke. Berger et al. (1975) presented the average behaviour of first return strokes and restrikes as shown in Figure 5. The concave front and fast subsequent rise appear in both pulses, as in the radiated E-field waveforms of Figure 4. Shorter time-scales for both current and E-field profiles appear with restrikes than with first return strokes.

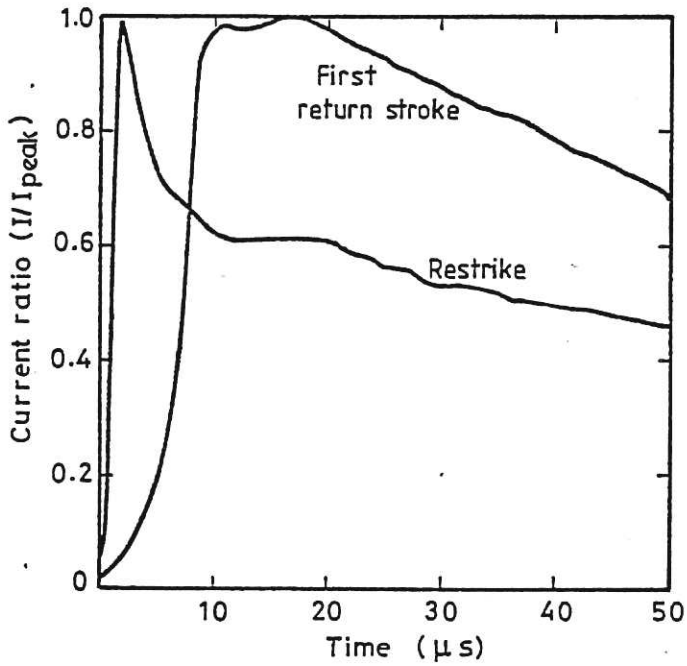

Fig.5 Average waveform of current pulse for first return strokes and restrikes (80 observations).

A quiet period at all frequencies has been observed soon after the start of the return stroke pulse, the length of which depends on receiver sensitivity. Thus Malan (1958) notes a pause of 2 - 15 ms: Horner and Bradley (1964) give about 8 - 20 ms, both near 10 MHz. With greater sensitivity shorter delays between the start of the E-field pulse due to the return stroke, as measured broadband at low frequency, and the onset of weak HF and VHF radiation, have been observed. The time-lag is of interest in determining the spatial origin of radiation. Brook and Kitagawa (1964) measured a delay of 60 - 100 μs at 420 and 850 MHz, while Takagi (1969), who worked at 60 - 420 MHz,

reported a bimodal distribution of time delays, peaking at both 10 and 50 μs. Le Vine and Krider (1977) support the view of a shorter delay of order 20 μs, but also observe radiation at later times. The conflicting observations are possibly due to the difficulty in defining the onset of radiation and to variation in receiver sensitivity. Using a return stroke current wavefront velocity of 10^8 ms^{-1}, 20 μs delay would imply radiation from the main current channel, possibly at branching points, while 60 - 100 μs suggests radiation from cloud height streamer processes.

Taylor (1978) employed fast logic circuits and a wide-band receiving system covering 20 - 80 MHz to determine the direction of individual VHF electromagnetic pulses from lightning discharges during TRIP 76 experiments in Florida. He observed signals from the main channel of cloud-to-ground strokes and from branches above this within the cloud. The horizontal extent of nearly every discharge studied far exceeded its vertical extent. This agrees well with the work of Teer and Few (1974) who reported an average ratio of horizontal extent to vertical extent of about 3:1 for intracloud discharges near Tucson, Arizona. The velocity of the discharge progression was measured at speeds up to 1.4×10^5 m/s.

The parameters of the return stroke current pulse may be estimated from the rise-times reported above for the components of the return stroke pulse radiation. If the concave slow front is produced by the upward streamer from ground, then this must have a length greater than 100 m and carry a peak current of 10 kA or more on the Bruce-Golde model (Section 2.3), according to Weidman and Krider. This length is greater than normally accepted values (Golde 1977). The fast field transition requires a mean rate of rise of 35 - 40 kA/μs at least. If the upward streamer meets the downward leader at several tens of metres above ground, the upward and downward propagation of the current fronts would halve this value. The latest re-evaluation of Berger's data by Anderson and Eriksson (1979) shows a mean value for the peak rate of rise of current of 24 kA/μs for first strokes and 30 kA/μs for subsequent strokes. These values are comparable with those deduced by Weidman and Krider (1978).

1.6 Junction Processes

After the return stroke has reached the cloud, further breakdown may follow as a result of ground potential appearing at the top of the channel, tapping other charge centres. During this 'junction' phase, the radiating events are primarily K changes (recoil streamers) which occur when a probing leader encounters a pocket of charge of opposite polarity. The ensuing current surge resembles that produced by a dart leader to ground, with typical current, charge and channel length of 1.4 kA, 1.4 C and 1 km respectively. The associated radiation pulse typically has a duration of less than 1 msec (Brook and Ogawa, 1977) and its frequency spectrum peaks near 8 kHz (Arnold and Pierce, 1964): the amplitude is about an order of magnitude lower than the return stroke at 10 kHz, becoming comparable at 100 kHz and above (Pierce, 1974). The junction process lasts for 50 - 100 ms and contains about 3 - 10 K-changes.

HF radiation from probing leaders is almost continuous during the time after the quiet period noted above and is of similar amplitude to other phases of the discharge. Radiation at VHF is almost all associated with K-changes (Brook and Kitagawa, 1964). This phase of the ground discharge closely resembles the 'active' and the 'final' stages of the cloud discharge (see Section 1.9).

1.7 Dart Leader

A recoil streamer becomes a dart leader (velocity 10^6 - 2 x 10^7 ms^{-1}) if it propagates to ground along the channel of an earlier return stroke. Brook and Kitagawa (1964), Krider et al, (1977) Le Vine and Krider (1977) and Weidman and Krider (1978) report observations of radiation from dart leaders and dart-stepped leaders. Pulses from dart-stepped leaders are similar to those from stepped leaders, but with a shorter mean interval between steps (6 - 8 μs as opposed to about 16 μs for the latter, see Figure 4 above). Brook and Kitagawa (1964) cite the dart leader as one of the strongest sources of VHF radiation and report that emission ceases for between 50 - 150 μs before the subsequent return strokes. Takagi (1969) finds that VHF radiation continues through the whole return stroke in about one-third of the cases considered. Le Vine and Krider (1977) give a similar mixture of results.

It is not certain, therefore, whether the leader tip or processes within the cloud are mainly responsible for radiation at VHF.

1.8 Subsequent Return Strokes

It is well known that in general subsequent strokes are less intense than the first and rates of current rise are greater. Radiation waveforms partly reflect this: a mean of 3 μs for the 10 - 90% risetime is reported, only 20% less than that of the first return stroke pulse (Fisher and Uman, 1972). However, Uman et al. (1973) deduce typical current risetimes of 0.5 - 5 μs for all strokes from the radiation field. Later measurements by Krider, Weidman and Noggle (1977) show that the pulse front is complex, having a slow, concave initial rise with a fast rise to peak following. Subsequent strikes show definitely faster time-scales (see Figure 4 of Section 1.5).

An average (worldwide) of about four return strokes occurs in a single flash to ground, although flashes with ten or more strokes are not uncommon (Kitagawa et al.1962). A junction phase will precede each stroke. After the final return stroke radio emission decays in a period very similar to the junction phase.

1.9 Cloud Discharge

This is a necessary precursor to cloud-to-ground lightning and may also occur without any ground stroke following. The electric and magnetic fields produced by the different types of cloud discharges (cloud-to-cloud, intracloud and cloud-to-air discharges) can be very complex (Brook and Ogawa 1977). Broadband measurements covering the frequency range from about 1 to 100 kHz show that these fields contain intermittent bursts of pulses with highly variable amplitudes and duration, (Norinder and Knudsen, 1957: Kitagawa and Brook, 1960). The pattern of pulse activity can be broadly classified into three periods: the initial, the active, and the final stages, characterised by different pulse amplitudes and repetition frequencies (Kitagawa and Brook, 1960).

The initial portion is characterised by irregular pulses at intervals of 0.1 - 1 ms, lasting for 100 - 300 ms. This contrasts with the breakdown

preceding a leader to ground, where pulse intervals are 20 - 100 μs over a period of 10 - 50 ms, and suggests that there are quite different breakdown mechanisms. A very active phase of strong and irregular pulses follows, lasting about 200 ms and finally a J-change which is very similar to the J process in a ground discharge. The sequence is described in the Introduction and in Section 1.6 (see also Brook and Ogawa, 1977).

Krider et al. (1975) have resolved quite regular sequencies of fast, small pulses lasting 100 - 400 μs during an intracloud discharge: magnitudes were of the order 5 Vm^{-1} at 10 km, measured broadband, and the waveforms are almost unipolar. The pulse width is typically 0.75 μs and the time interval between pulses is about 5 μs. The pulse risetime can be very short, down to their aerial limit of 0.15 μs, which suggests a significant content at high frequencies. The pulse train closely resembles that from a dart-stepped leader (Figure 4).

The frequency spectrum of a complete cloud discharge resembles that of a ground discharge above 100 kHz. At lower frequencies cloud discharge radio emission is weaker since K-changes are generally less severe events than return strokes. Malan (1958) compares these spectra (Figure 6).

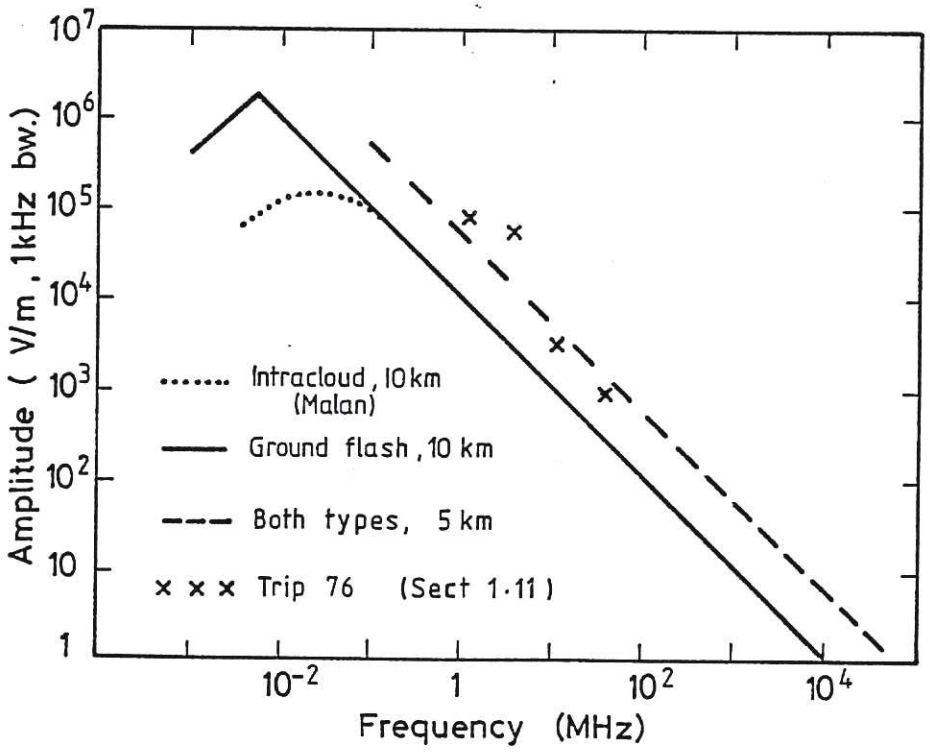

Fig.6 Spectra of intracloud and ground flashes.

Broadband measurements of the large-amplitude fast E-fields produced by the intracloud portion of cloud-to-ground flashes and isolated ground discharges have recently been published (Weidman and Krider, 1979). The time-resolution is sufficient to resolve the structure of the individual pulses, using the technique of Krider et al. (1977) for intracloud discharges and Weidman and Krider, (1978) for stepped leaders. This also was done as part of the 1976, 1977 and 1978 TRIP programmes at the Kennedy Space Center, Florida.

The basic waveform is bipolar, with several faster unipolar pulses superimposed on the initial half-cycle. If negative charge is lowered the pulse is considered positive and the sign of the first half-cycle defines the sign of the whole pulse. The third trace of Figure 7 shows a negative bipolar pulse.

Positive pulses usually occur 10 - 100 ms before a first return stroke. Negative pulses, where the sign of the entire bipolar signal is reversed, also appear. Their characteristics are similar to those of positive pulses, but more variable and with more prominent unipolar fast pulses. Sometimes only a single negative fast pulse is seen, and this type usually forms the first signals detected from developing storms. Usually negative pulses occur in intracloud discharges and no return stroke follows.

The mean time intervals between the fast unipolar pulses are about 8 μs for positive and 15 μs for negative waveforms, similar to the regular intracloud pulses reported by Krider et al. (1975) and the stepped leader fields analysed by Krider et al. (1977). The fast rise times (down to the aerial limit of 0.15 μs) and pulse widths (about 5 μs) are also reminiscent of the pulse trains studied earlier (Sections 1.4 and 1.5).

This data is not likely to be distorted by propagation and is assumed to be produced by the radiation term in the general field equations (Uman et al. 1975). The shape of the bipolar pulses contrasts sharply with the smooth, almost unipolar pulses produced by return strokes (Weidman and Krider 1978). The fast unipolar pulses are similar to those due to stepped and dart-stepped leaders near the ground (Krider, Weidman and Noggle (1977)) which are sketched in Figure 4.

Weidman and Krider (1978) suggest that the discharge channel is formed by a stepped leader of some kind, and that a current surge follows the establishment of the channel and gives the bipolar pulse, as Uman and McLain (1970)

proposed. Le Vine, Krider and Weidman (1979) state that recoil streamers in abruptly-terminated tortuous channels could also produce the observed complex pulse. These authors found that each E-field pulse was associated with a simultaneous burst of RF radiation over frequencies from 3 - 300 MHz.

Figure 7 shows an example of their results: an upward excursion represents a negative signal, so the E-field pulses are typical of intracloud discharges. Pulses preceding a ground stroke are roughly similar in character, but of opposite sign. Trains of pulses, unipolar or bipolar, usually are of one sign throughout.

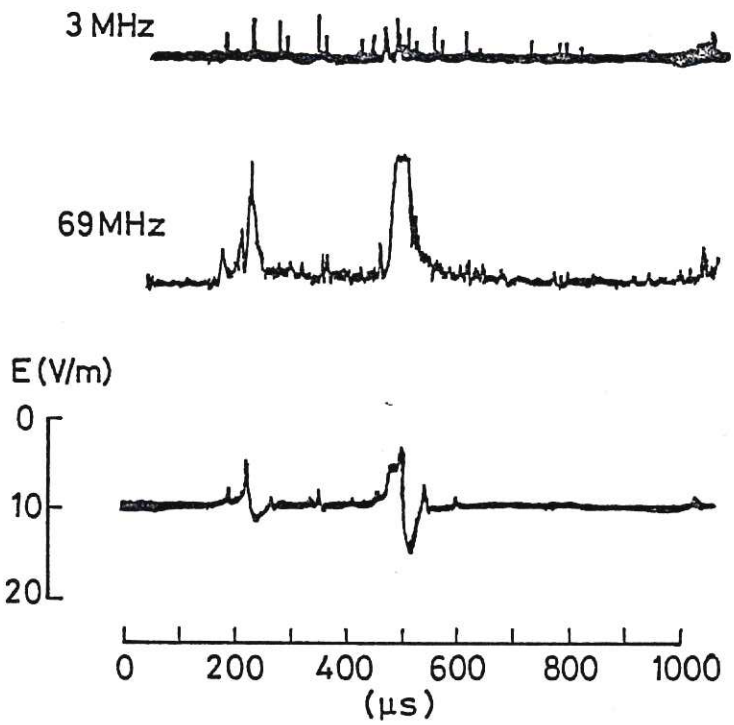

Fig.7 Example of RF and fast E-field pulse during intracloud discharge.

Pulses from any cloud discharge process show a large pulse-to-pulse variation in radiation frequency spectrum (Oetzel and Pierce, 1969: Nanevicz et al. 1976). Adequate modelling of the cloud discharge will evidently require statistical data on the distribution of current pulse heights and shapes, such as that attempted by Nakai (1977) for ground discharge radiation.

It should be noted that this data refers to summer air mass thunderstorms in Florida. Data on other types of storms is needed.

1.10 Other Forms of Discharge

In the above descriptions, no distinction has been made between the various kinds of cloud or ground discharge. Intracloud, cloud-to-cloud and cloud-to-air discharges have not been treated individually: they are commonly held to be similar. Moreover, we have only described the advance of a leader from a negative cloud charge towards ground and the subsequent return stroke lowering negative charge to ground, since this is believed to be most common ground flash. Positive cloud-to-ground flashes are known, and it is known also that discharges can be initiated by upward leaders from tall structures on the ground (Berger 1977, Golde 1977c, Anderson and Eriksson 1979).

1.11 Measurements made in Aircraft

High frequencies were first investigated by an instrumented aircraft flown in the vicinity of thunder-storm cells around Florida, U.S.A. during 1976 - 1978 as part of the Thunderstorm Research International Programme (Bly and Nanevicz 1977: Nanevicz, Adamo and Bly 1977: Nanevicz 1978).

The aims were to study lightning phenomena from an aircraft and to investigate the interaction between aircraft and a thunderstorm environment. Signals received by modified h.f. aerial and by a cabin wire which ran along part of the fuselage interior were analysed and recorded in the 1976 flights. Other instrumented wires in different parts of the aircraft were added in 1977. Either a multichannel spectrum analyser centred on 1, 3, 10 and 30 MHz (20 kHz bandwidth) or a transient-digitiser (500 MHz bandwidth) processed the 1976 data. An additional digitiser was employed later. The unperturbed electrostatic field was determined by using four or five separate measurements on different parts of the aircraft together with data obtained from scale model tests. A high 'Q' 10 kHz tuned circuit coupled directly to the aerial monitored the occurrence of low frequency signals; these derive mainly from return stroke and recoil streamers.

During 1977 multiple thunderstorm cells were active simultaneously to an unusual extent, so that it was difficult to fly the aircraft close to one individual cell. The value of the additional equipment was restricted by the sparse data collected.

A nearby strike in 1976 produced records as shown in Figure 8. The aircraft was at an altitude of 11 km under an anvil, in heavy hail.

Substantial signals were induced in the cabin wire, the largest in the 10 MHz channel. An earlier pulse on the 10 kHz antenna did not produce strong signals on any other record. The E-field change associated with this earlier strike was comparable with that for the stroke of Figure 8 (15 kV/m).

No information is available to determine how near the lightning events were. Distances larger than 50 m would imply that radiation fields would dominate signals received at frequencies of 1 MHz and above. The storm cells were several kilometres in horizontal extent so the discharge could have been as much as 5 km away. In this case it is interesting to compare the signals recorded in the aircraft with data obtained from ground-based measurements of other storms. In Figure 6, Section 1.9, the TRIP signals at 1, 3, 10, and 30 MHz (from Figure 8) scaled linearly to a 1 kHz bandwidth (since the pulses are well resolved), but at unknown distance, are shown with the empirical frequency spectrum discussed in Section 1.5 (Figure 3). The TRIP data resembles that of a cloud or ground flash at 5 km distance.

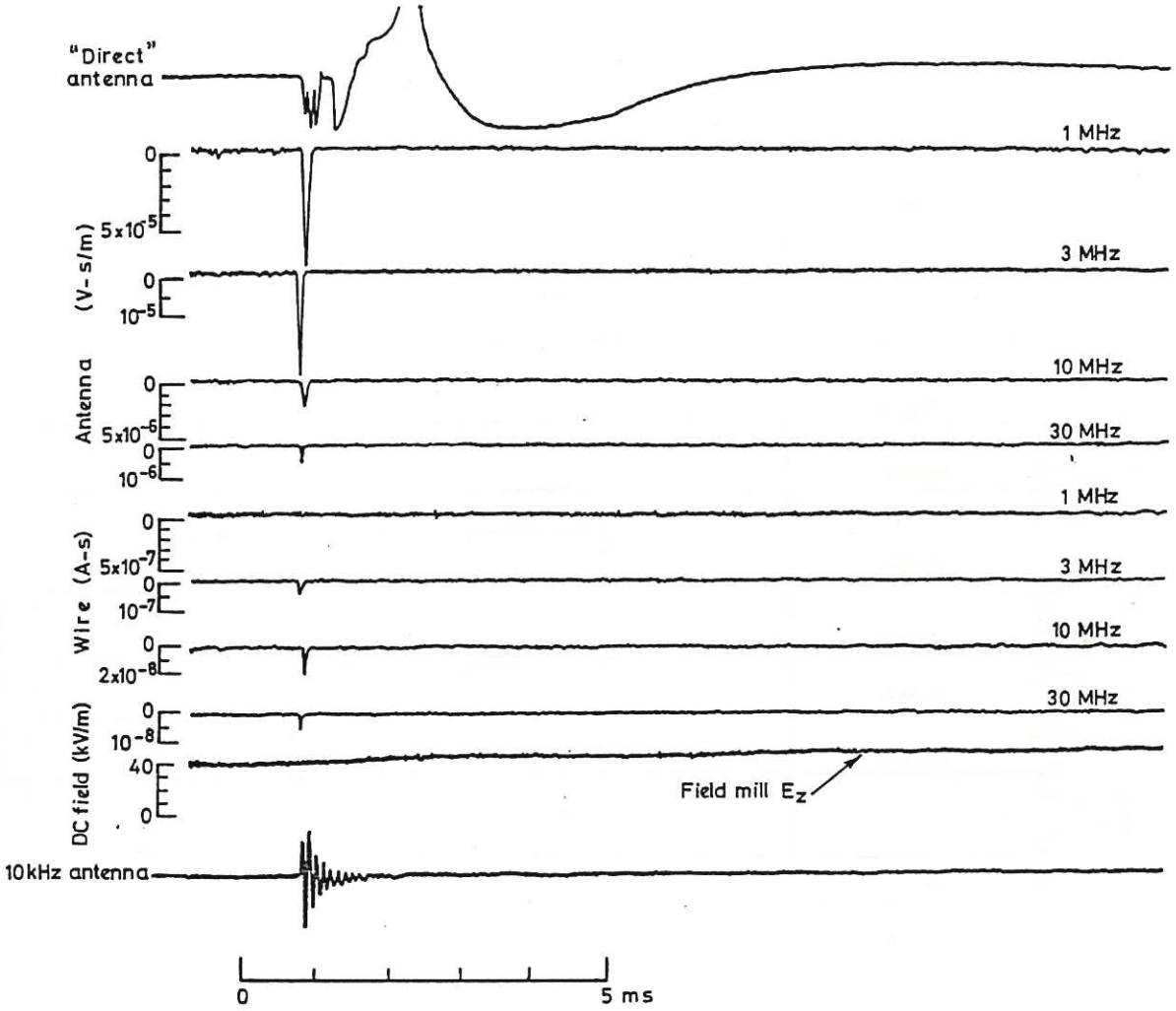

Fig.8 Detail of TRIP record for nearby lightning strike.

The observed spectrum varied from stroke to stroke, with the maximum signal in the cabin wire equivalent to that produced by a fast-rising current step of about 0.5 A. The dipole aerial recorded signals up to about 50 μVsm^{-1} in the 1 MHz band and about 3 μVsm^{-1} in the 10 MHz band. These are considerably larger than the expected signals at 10 km distance from a lightning stroke (see Figures 1 and 4).

Direct strikes to the aircraft gave similar results. Figure 9 shows a typical set of output data.

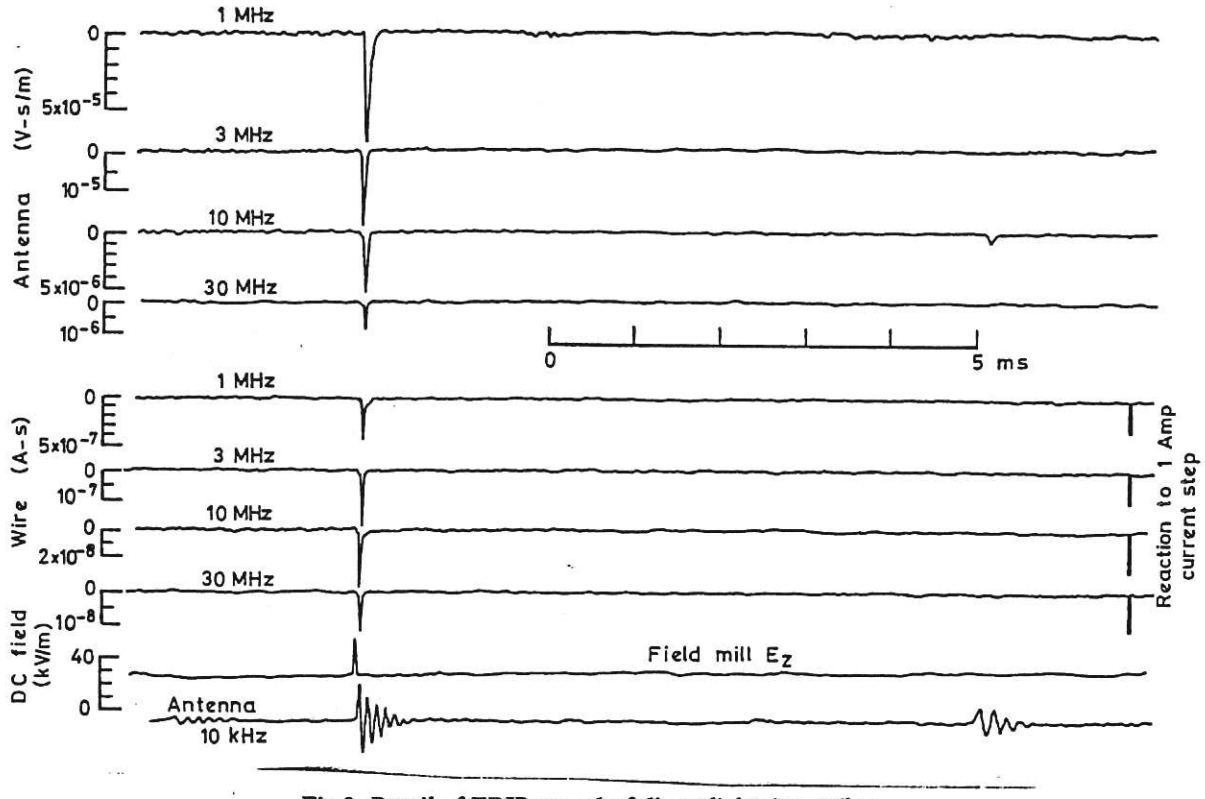

Fig.9 Detail of TRIP record of direct lightning strike.

The effect of a 1A current step in the wire is shown on the right-hand side. This direct strike (at an altitude of about 11 km once more) is likely to be an intracloud event. The responses are similar to those of Figure 7, showing that nearby strikes and direct strikes create similar hazards to aircraft at frequencies of 1 MHz and above. No damage to any airborne electronics occurred, though some structural damage resulted.

Generally, low-frequency impulses appeared without accompanying high-frequency noise about as often as both appeared together. High frequencies never appeared alone. The noise signals from the complete stroke lasted up to 0.3 s in all. Recoil streamers and return strokes are the main cause of low-frequency radiation, and these observations suggest that they can give rise to significant high-frequency emission too. The work of Krider and his co-workers reported in Sections 1.4 and 1.5 also indicates that the fast-rising front of unipolar pulses and the fast-rising section of the return stroke pulse could create frequencies above 1 MHz.

The flight data showed evidence of streamering from the aircraft, and electrostatic charging by precipitation. The noise amplitudes on the cabin wire due to streamering were not much less than those due to lightning.

1.12 Summary of Observations

(a) Scope of Report

Measurements of the E- and B-fields due to a lightning flash are made either by measuring RF radiation in various frequency bands or by recording the magnitude of the total field changes. This report deals mainly with the E-field values obtained in both ways: the B-fields are consistent with these.

Slow E-field changes occur in times of order 0.1 s during the whole flash, with fast changes superimposed. We do not discuss the slow changes. The rise-time of the fast E-field pulses is of order 5 μs or less, and their duration 100 μs of less. The spectrum of the RF radiation emitted peaks at about 5 kHz and extends beyond 10 GHz in frequency. We are concerned with frequencies above 300 kHz.

(b) RF Radiation

The radiated field intensity due to lightning is inversely proportional to the distance from the flash if that distance is greater than 10 km approximately. This scaling holds for individual sources of radiation down to distances of 500 m for frequencies above 100 kHz if the sources are much less than 500 m in extent. Since the radiation from a travelling current pulse behaves as if

emitted from the ends of a straight conducting channel, or from bends in a tortuous channel, the sources are likely to be small compared to 500 m. They may be distributed over distances of several kilometres.

Amplitude spectra for the RF radiation emitted at a frequency of f Hz ($f > 10^5$) from a ground flash are approximately represented (see Figure 3) by the expression

$$E = \frac{10^4}{f} \quad \text{V/m for 1 kHz bandwidth}$$

at a distance of 10 km. Above 300 kHz a cloud flash behaves similarly. The scaling of E with bandwidth B depends on the pulse repetition rate. As an approximation for an extremely low rate $E \propto B$: for very high rates $E \propto B^{\frac{1}{2}}$.

Some features of the RF radiation spectrum emitted during the initial breakdown phase and the leader development are described in Figure 2. The mechanism of the radiation is still under investigation.

Below 300 kHz single RF pulses appear, associated with a return stroke (about 4 per flash) or a K-change (about 40 per flash). Above 300 kHz the number of pulses per flash increases. Pulses are emitted during the breakdown processes associated with the movement of leaders in the cloud, recoil streamers (perhaps propagating along twisted channels) and leaders to ground. The average rate of pulse emission rises from 2×10^3 s^{-1} at 3 MHz to a maximum near 10^4 s^{-1} at 300 MHz. Above 10 MHz and in the VHF band (to 300 MHz) dart leaders and recoil streamers (K-changes) are the strongest sources of radiation. Above 300 MHz the pulse emission rate continues to fall and return strokes become more important again. At 10 GHz few pulses appear, each being associated with a return stroke.

The observed rate of emission depends upon receiver characteristics, and the variation between discharges is large. Cloud flashes produce somewhat more pulses than ground flashes.

(c) Fast E-Field Changes

The amplitude of these pulses from a return stroke 10 km distant is typically 50 V/m log-normal distribution. When the signals are expressed relative to the median value in dB the deviation is about 7 dB. Pulses lowering negative charge are defined as positive pulses by the observers.

The pulse shape is initially concave, rising slowly for about 5 μs when the source is the first return stroke and for about 1 μs with subsequent strokes. The final rise to the peak is very fast, occurring in a time of order 0.1 μs or less. The decay time is approximately 50 μs for the first stroke and 20 μs for subsequent strokes, but the pulse shape is complex. Several subsidiary maxima appear after the main peak (see Figure 4).

First return strokes are preceded by a stepped leader, and the pulsed currents of this leader generate a train of unipolar E-field pulses. Their rise times are less than 1 μs, and typically about 0.3 μs: the lower limit is not known. The pulse width is 0.5 μs and the amplitudes increase just before the return stroke, reaching 10 V/m (10 km distance). Subsequent return strokes may be preceded by a dart-stepped leader, which produces a similar train of fast E-field pulses: dart leaders yield no such train, but the fast part of the return stroke pulse following these leaders is typically 80 V/m in amplitude.

In contrast to the unipolar form of the pulses produced by return strokes and leaders to ground, the basic wave shape of large pulses from a cloud process is bipolar. The initial half-cycle is usually positive if the event is a precursor to a ground flash, and usually negative if an isolated cloud discharge is developing (see Figure 7). Several faster, nearly unipolar pulses of the same sign as the first half cycle may be superimposed upon it or precede it. These pulses have about half the amplitude of the main bipolar pulse. A typical amplitude for the main pulse is about 20 V/m at 10 km distance, and the total duration is about 50 μs with approximately equal positive and negative sections. The time intervals between the fast unipolar pulses superimposed on the first half cycle are approximately 8 μs for positive and 15 μs for negative waveforms. Their rise times are less than 0.2 μs, widths about 1 μs and amplitudes about 10 V/m. They resemble the pulses produced by stepped leaders to ground.

Quite regular sequences of fast, approximately unipolar pulses similar to those just described may appear without the bipolar pulse at times, in intracloud discharges. A single sequence may last 100 - 400 μs.

(d) Relation between E-field Pulses and RF Radiation

During large intracloud events the RF radiation and fast E-field pulse are nearly simultaneous, reaching a maximum usually in the initial negative half-cycle. In contrast, the RF radiation during first return strokes in Florida storms reaches a maximum 10 - 30 μs after the start of the E-field pulse. During subsequent return strokes the delay is between 200 and 600 μs. Obviously different mechanisms obtain for the two types of discharge, but these have not been described in detail.

(e) Parameters of the Current Pulse

From observations of the radiation patterns it is deduced that the rates of current rise in a leader step lie in the range of 0.6 - 2.6 kA/μs or 6 - 24kA/μs according to different authors. The current amplitudes lie between 2 - 8 kA. In return strokes the mean rate of rise is estimated to be 35 - 40 kA/μs, comparable with the values measured directly.

II. MODELS OF THE LIGHTNING DISCHARGE

2.1 The Dipole Field Approximation

We now consider the methods by which fields at arbitrarily close distances to the lightning discharge may be investigated. Although different techniques and models have been employed by various authors to describe the time and spatial variation of currents in the lightning discharge, all rely on the dipole approximation to calculate the associated electric and magnetic fields.

The vertical electric field $E(t,d)$ and horizontal magnetic flux density $B_\phi(t,d)$ at a time t and distance d from a channel length $\ell(t)$ carrying a current $I(t)$ is described to a good approximation by the variation in the current moment $M(t) = 2I(t)\ell(t)$, according to

$$E(t + \frac{d}{c},d) = \frac{1}{4\pi\varepsilon_o}\left[\int_o^t \frac{M(\tau)d\tau}{d^3} + \frac{M(t)}{cd^2} + \frac{1}{c^2 d}\frac{dM(t)}{dt}\right] \qquad (1)$$

$$B_\phi(t + \frac{d}{c},d) = \frac{\mu_o c}{4\pi}\left[\frac{M(t)}{cd^2} + \frac{1}{c^2 d}\frac{dM(t)}{dt}\right] \qquad (2)$$

where $c = (\mu_o \varepsilon_o)^{-\frac{1}{2}}$, the velocity of light in free space: (Uman 1969). Note that the fields depend on currents at earlier times, allowing for propagation delay. Electric and magnetic field wave shapes are clearly identical except at very short distances. The equations are valid provided both

$$d >> \ell$$

and $$\tfrac{1}{2}\lambda >> \ell \text{ or } f << \frac{c}{2\ell}$$

where f and λ are the frequency and wavelength of an emitted disturbance. These restrictions permit the radiating channel to be considered as a small coherent element, giving the simple forms (1) and (2). The three terms in the electric field equation are known as the electrostatic, induction, and radiation fields respectively, and are equal at a distance $d_o = c/2\pi f_o$. For $d >> d_o$ and $f \geq f_o$ or $f >> f_o$ and $d \geq d_o$ the radiation or 'far' field term dominates. For a return stroke channel of length 2 km or more, equations

(1) and (2) will only be valid for distances above 20 km. To obtain fields close to the channel, it is necessary to perform an integral summing radiation from elements along the whole length. This approach is desirable to include the variation of current along the channel.

Fields due to short sparks would be more readily described by the basic equations, but this has hardly been attempted: attention has centred almost entirely on the return stroke.

2.2 Empirical Representation of Current Waveforms

One of the earliest and most widely used empirical approximations to the return stroke current waveform at ground is due to Bruce and Golde (1941):

$$I(t) = I_o \, (\exp(-\alpha t) - \exp(-\beta t)).$$

This has been extended to include continuing currents after the main pulses:

$$I(t) = I_o \, (\exp(-at) - \exp(-\beta t) + I_1 \, (\exp(-\delta t) - \exp(-\varepsilon t)).$$

Typical values of the constants are (Pierce 1978):

$$\alpha = 2 \times 10^4 \ s^{-1} \qquad \beta = 2 \times 10^6 \ s^{-1}$$

$$I_o = 10 \ kA \qquad I_1 = 2 \ kA$$

$$\delta = 10^3 \ s^{-1} \qquad \varepsilon = 10^4 \ s^{-1},$$

and the current wavefront propagates with a velocity given by

$$v(t) = v_o \exp(-\gamma t)$$

where $v_o = 10^8 \ ms^{-1}$ $\qquad \gamma = 3 \times 10^4 \ s^{-1}$

Dennis and Pierce (1964) included the variation of channel current with height, which removed the assumption that charge was transferred instantaneously from ground to the current wavefront. Only the far fields were calculated, and these are in good agreement with experimental data at low

frequencies. Other authors (e.g. Iwata 1970) make changes to the details of this model, without substantial improvements. Surprisingly, near fields have not been calculated from this current waveform, although the work involved is not arduous. Transmission line models of the return stroke are much more commonly used to give information on the near field, because this direct physical description provides more insight than an empirical approach.

The Bruce-Golde waveform can also be criticised for its poor representation of the initial rise to peak current. Currents measured at ground show an initial concave rise (see section 1.5) rounding only near the peak current, while the double exponential form commences at maximum slope and has a convex rise to peak: the high frequency content of these will be different.

The far field radiation from K-changes, which has also been modelled in this way (Arnold and Pierce 1964, Cianos and Pierce 1972, Pierce 1977) is in fair agreement with experimental data for the low frequency amplitude spectrum.

Assume a propagation velocity

$$V(t) = V_1 \exp(-kt) + V_2 \exp(-mt)$$

with $V_1 = 2 \times 10^7$ ms $^{-1}$, $V_2 = 10^6$ ms^{-1}, $k = 4 \times 10^4$ s^{-1} and $m = 2 \times 10^3$ s^{-1}

and a current variation

$$I(t)/I_o = \left[\exp(-at) - \exp(-bt)\right] + \frac{1}{3}\left[(\exp(-dt) - \exp(-et)\right]$$

where I_o = 15kA, $a = 5 \times 10^4$ s^{-1}, $b = 2 \times 10^5$ s^{-1}, $d = 5 \times 10^3$ s^{-1}

and $e = 2 \times 10^4$ s^{-1}

This analysis yields K-pulses of about 3 Vm^{-1} at a distance of 10km (Pierce 1974). The high frequency spectrum is not well described.

2.3 Radiation from the Return Stroke

The return stroke has been fairly well described by the discharge of a line initially charged by the leader and suddenly terminated at ground. The channel and ground plane are treated as the two conductors. Useful observations of far field return stroke pulse risetimes have been made by Uman and co-workers, who then fit the propagation velocity and peak current of a transmission line model waveform to reproduce the far field behaviour.

Near fields are subsequently calculated from this model. (McLain and Uman 1971, Uman 1972, Uman and McLain 1969, 1972, Uman et al 1973). Currents so obtained are more sharply peaked than those observed directly (Berger et al 1975, Golde 1977, Berger 1978). The radiation field at one point does not give a unique solution for the current waveform, and further the electric field at distances under 10km calculated in this way displays features which are not observed experimentally (Uman, Brantley et al 1975). Figure 10 shows their calculated fields at 1km distance (curve U). The inset shows the E-field and B-field pulses observed at about 2km distance.

An improvement in modelling the near field waveform is due to Price and Pierce (1977), who consider the channel as an initially charged transmission line which is suddenly terminated by its characteristic impedance at ground. The resulting disturbance which propagates up the channel is subject to resistive losses. The far field obtained in this way is similar to that of Uman, but the near field now follows that observed quite closely after the initial rise, as shown in figure 10 for a stroke 1km away (curve P & P). There is scope for extending this work to include the first sharp change in electric field when the current surge just begins. Its omission means that the high frequency content is very poorly simulated (see also section 2.5). The step rise is accompanied by a peak in natural lightning pulses.

We present also a diagram from Pierce (1975) which models the frequency spectrum of electric and magnetic fields at 300m distance from severe ground and intracloud discharges (figure 11). Details of this work are lacking, but it is likely that a transmission line model was employed. Values at high frequencies are not unreasonable by comparison with far field radiation amplitudes (compare figure 3).

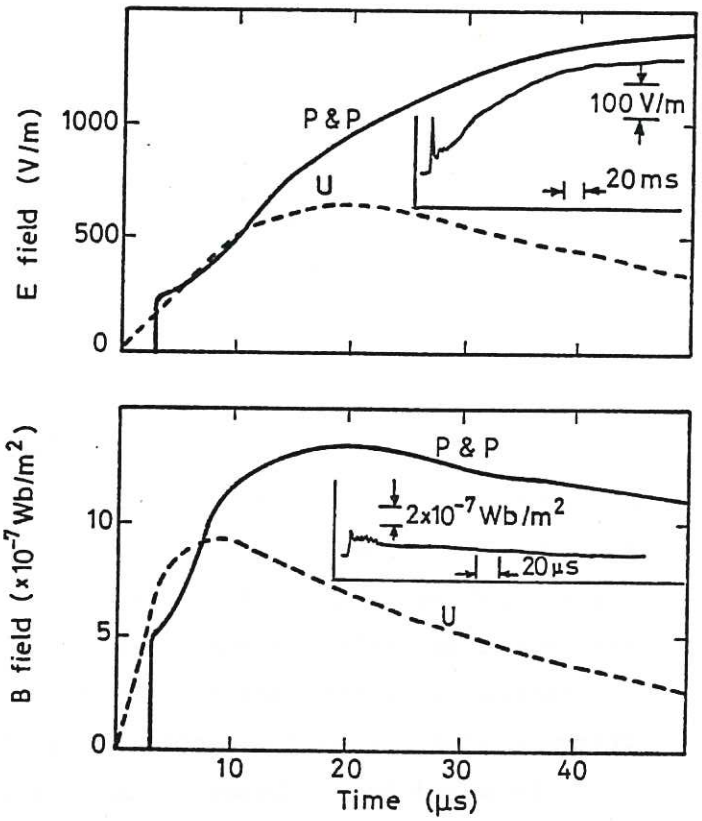

Fig.10 Electric and magnetic field pulses at 1 km distance from a return stroke, computed from models by Uman et al (U) and by Price and Pierce (P&P). Inset: observed E-field and B-field, pulse at about 2 km distance (Uman et al).

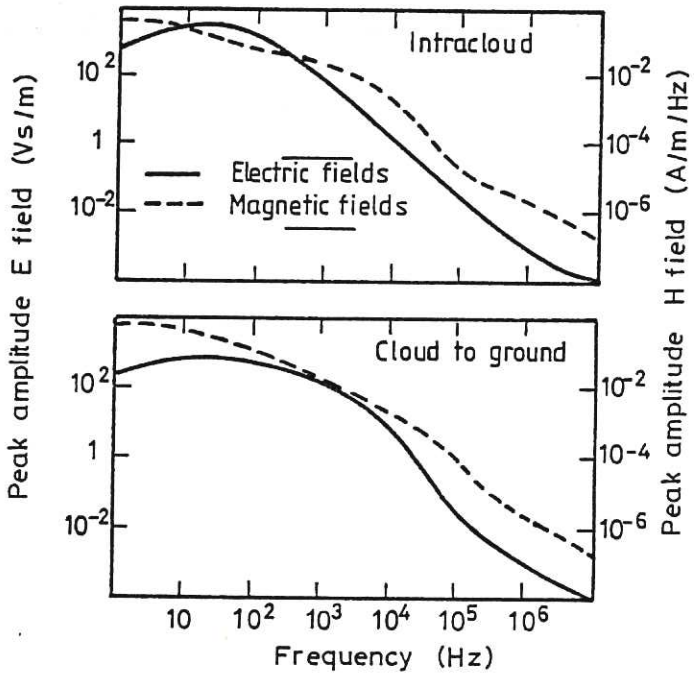

Fig.11 Frequency spectrum at 300 m distance from intracloud and ground strokes, according to a model used by Pierce.

Liese and Taylor (1977) have used a transmission-line model to analyse spherics but their interest was largely in effects at greater distances (over 50km). They point out that horizontal or near-horizontal sections of radiating channels must be considered.

It is well-known that a conducting filament carrying a travelling current pulse radiates as if the fields emanated from the ends of the filament (see for example Schelkunmoff 1952). Uman, McLain and Krider (1975) used this result without taking into account the tortuous nature of the return stroke channel. In a real strike radiation will appear from every point where the channel changes direction. Le Vine and Meneghini (1978) included this effect and found that the electric field changes observed can be better accounted for as a function of time. The spectrum radiated is also better described (Le Vine 1978: Oetzel and Pierce 1969: Horner 1964). Le Vine, Kinder and Weidman (1979) state that time delays between the onset of the fast electric field and the radiation pulse of about 20μs can be obtained theoretically if the tortuous nature of the channel is recognised and a change in the scale of the tortuosity of the channel is assumed to occur near the cloud base. Longer delays of 60-100μs imply radiation from sources within the cloud (see section 1.9).

2.4 The Current Pulse in the Return Stroke

Related work has been reported by Prinz (1977), Kim et al (1977) and Little (1978). The complete leader from cloud to ground is approximated by an L-C-R ladder circuit of 8-10 loops in the last two papers. Prinz (1977) considered a still simpler version, in which the cloud capacitance stored all the charge, and the leader was represented by inductive and resistive elements only. Even this model gave rough agreement with observed action integrals. Kim et al (1977) neglected cloud charge storage, and inserted constant values of L and C per metre for the channel to make the pulse propagation speed $u = (LC)^{-\frac{1}{2}} = 10^8\ ms^{-1}$. That model was used to describe transients in an aircraft suffering a direct stroke.

Little (1978) extended this work, including both cloud capacitance and a variable geometry, with the height above ground that the circuit is completed as a parameter. This models the effect of an upward leader meeting a downward leader, which is assumed to be at cloud potential. The values of

L and C are calculated numerically from the potential distribution when the circuit is almost completed, and are taken to be constant with time. Good, but not fully consistent behaviour of the current pulse at ground level is derived.

Although the model is not yet accurate enough to describe the electromagnetic field near the return stroke, it does provide a means of deducing the current pulse at altitude from that known at ground level. An important result is that if the leaders join near the ground the peak current is reduced by a factor of 3-5 and the maximum value of di/dt is lowered by about two orders of magnitude in propagating up the channel.

For negative strokes, where usually the initial leader progresses downward from the cloud and joins an upward leader at a short distance above ground (see Section 1) this implies that the parameters measured at ground are the most severe found anywhere along the channel. For positive strokes, where the initial leader moves upward from the ground to meet a short answering leader from the cloud at a great altitude, the parameters measured at ground are not the most severe. Transmission line theory predicts that smoother pulses with slower rise times and fall times should appear. This is in accord with measurements of the general differences in the current pulse shapes for negative and positive strokes. The highest values of di/dt and I appear at the junction point, and the transmission line functions as a low-pass lossy filter to reduce the high-frequency content of the pulse as it progresses along the channel. This description applies both to positive and negative discharges.

The model of Kim et al (1977) has been used by Quinn (1979) as the basis for a numerical solution which gives the current pulse at various altitudes along a lightning channel.

A significant advance in modelling has been the introduction of a time-varying resistance into the channel. Strawe (1979) computed this directly from the physics of the arc channel, assuming that all variables are only dependent on radius and time. A large number (200) of elements were used to represent the channel. A lengthy computer programme employing Braginskii's idealisation (1958) of the problem with constant conductivity gives current pulses that fall by a factor of two to four as they move up the channel. The rate of rise of current is reduced by one-to-two orders of magnitude. These results are similar to those of Little (1978) described above. Little (1979)

also introduced into his model a cruder empirical representation of the time-varying resistance and divided the channel into only a small number of elements (8). His conclusions were broadly unchanged. He estimated the effect on an aircraft placed in the channel, and found oscillations near the expected half-wave resonance frequency, whose amplitude was of order 1kA at ground level when the peak current in the channel was 200kA. The voltage along the aircraft was consistent with the assumed value of its inductance. At the top of the channel the amplitude of the oscillating current was reduced to a negligible value.

The transmission line models usually assume that the downward leader meets the upward leader close to the ground. For this case the close-to-ground stroke parameters measured at ground level must be significantly reduced when the threat to aircraft in flight is being considered. The degree of protection required may not be affected greatly, but the probability of damage is greatly modified if the flight pattern is normally well above (say) 12,000 feet. If the leader from the ground is very long, as in positive discharges, the junction point is several kilometres above ground and the greatest threat to aircraft will then occur at this altitude.

The complexity of actual lightning discharges must be borne in mind when models are employed. Uman et al (1978) report a good example of co-operative study on one storm during TRIP 76.

2.5 Electron Shock Waves in Leaders and Return Strokes

The physics of the initial breakdown process and the transition from a leader to a return stroke channel need considerable further study. At present the time-dependence of the fast-rising sections of the current pulse, and the velocity of the current front, are not well understood. This section considers the importance of shock wave phenomena in these processes.

During the initial breakdown of a gas, and at all times when the conductivity of the gas is changing rapidly, fast-moving waves propagate in the medium. This has been known since the days of J. J. Thomson (1891). Reviews were

given by Fowler (1974, 1976). He with others (Shelton and Fowler 1968, Fowler and Shelton 1974): Sanmann and Fowler 1975): Scott and Fowler 1976) provided a theory based on the fluid dynamics of the electron gas present. During breakdown the electrons are considered as advancing under forces due both to their own pressure and to the electric field present. In this advance more electrons are created by ionisation of the gas present, whether this is previously conducting or not. A shock condition exists at the leading edge between the neutral gas and a region where the electric field E and electron fluid velocity v change rapidly while the gas temperature T and electron density n varies slowly. Behind this region E and v are zero, but T and n are still variable.

This theory leads to the conclusion that in breakdown conditions where the direction of the electric force on the electrons is in the same direction as the wave propagation (proforce waves) the speed of advance is proportional to the electron mobility, and determined directly by E at the leading edge. For breakdown propagation in the opposite direction (antiforce waves) the shock speed is proportional to the electron pressure which in turn is proportional to E. Numerical results agree well for wave speeds above 3×10^6 m/s with experiments on shock tubes and with observations on lightning, both leaders and return strokes. Photoionisation is not thought to be important except at low pressures.

A free-standing linear plasma column of definite diameter is a fair representation of any leader or return stroke channel. Since wall-independent constricted columns are observed in laboratory shock tubes, Fower and Scott (1977) propose the following model for a one-dimensional treatment of a lightning discharge, regarding it as a shock in a cylindrical tube.

Within the cloud two centres of charge of opposite sign are created, separated vertically with the positive charge usually at higher altitude. As these charges grow, the electric field E over large volumes within and around the cloud grows to very high values, and the potential at the cloud base rises. When the value of E becomes great enough that the ionization frequency exceeds the attachment frequency, free electrons (which are everywhere transiently present from cosmic ray action) can amplify their numbers and form avalanches.

As the charge in the vertex of the cloud begins to drive the breakdown wave a reservoir of charge is needed to allow the leader column to grow.

Fowler and Scott suggest that the radial field from the cloud can act by avalanche processes to enhance the ion pair concentration sufficiently to provide electrons in the requisite numbers. It appears then that the space charge residing on the edges of the cloud mass supplies the field and energy for the charge flow, and electron ionization at the cloud face just over the column head will serve as the charge reservoir for the growth of the column.

The proforce leader moves in steps of about 50m towards the ground. From a shock tube standpoint we have a self creating shock tube growing steadily longer, along which successive shocks are launched as the apparatus becomes charged up to permit them. The initial wave hypothesized to exist by Schonland (1938), and named the pilot leader, is a necessary feature. Its nature must be a weak discontinuity proforce shock wave whose velocity should be close to that observed in the laboratory by Wagner (1966) for proforce avalanches. The motive field is the nearly uniform field prevailing between cloud and ground. Launching the shock from the cloud cathode results in a local surplus of positive charge which raises the potential at the column head and chokes off any further supply of electrons. At the same time the lack of field in the column causes all slow electrons left behind the pilot front to attach to oxygen molecules, preventing any electron flow to the tip completely. During this interval the positive charge draws neutralizing charges from the general cloud charge. The neutralizing time constant ε_o/neK_+ (where K_+ = mobility) gives agreement with the observed mean time of 50 μs between rekindling waves (steps). When the potential at the head of the column is restored a new wave can start down the channel using the same initial processes as before. But the waves which succeed the pilot leader have the advantage of delivering whatever charge has accumulated during the interval at cloud potential down a column of fixed diameter. The amount of charge delivered is determined by the time delay which elapses before electron multiplication (rather than attachment) becomes possible along the path of the original pilot leader. The amount of charge is almost invariable at about 0.1 coulomb, and when distributed over the cross sectional area of 5m radius column makes a reduced field of 10^5 V/m-torr which can generate a preionized strong discontinuity shock of 2×10^7 ms^{-1} speed. As long as the rekindling wave is moving down the path pursued by previous rekindling waves it does not need to use any of its charge in bringing the

plasma conductor to a space potential consistent with the cloud above. But when it reaches the new section previously transversed only by the pilot leader, it must begin expending its charge because the pilot leader does not charge its column, being driven by an external field. The loss of charge results in bringing the wave exponentially down to minimum propagating speed. The charge brought down from the cloud is almost always sufficient to move somewhat beyond the path blazed by the pilot leader, but has nearly constant length probably governed by the expression

$$\ell = \frac{\pi a \varepsilon_o}{c_1} \quad \ell n \frac{v}{v_m}$$

where c_1 is the capacitance per unit length of the new conductor, v is the velocity produced by the charge brought down, and v_m is the minimum propagating speed.

When the column reaches a distance above ground slightly longer than one step, it is usual for an antiforce wave (the leader from ground) to leave a sharp point on the ground and move to the column to make the final connection. Again the wave is a shock wave, and it derives its large speed from the fact that its local potential is essentially the same but of opposite sign to that of the end of the column, while its radius is very small because its electron needs are met by a solid electrode. It is, in fact, of the same character as a long spark in the laboratory.

This small radius, fast moving, antiforce wave not only reaches the column, but penetrates it, taking advantage of the large amount of energy stored during formation in the column by radial electron diffusion and attachment. These electrons and the energy which their charge separation represents are easily available to the strong electric fields generated by the return stroke via collisional detachment, so the stroke can proceed from ground to cloud at speeds up to 2×10^8 ms^{-1} driven by a wave field $\sim 10^6$ volts/m-torr.

Restrikes behave like the first return stroke, if the leader is stepped. Dart leaders are very similar to the rekindling waves, in speed and every

other aspect. Their behaviour, however, furnishes one more point of contact with theory. Because the channel is hot following sudden internal implosive discharge forming the return stroke, theory predicts and the experiment confirms that no breakdown wave is possible until it cools. During the interval it will conduct freely any charge supplied at the upper end - the continuing current.

All these processes seem to be describable by a shock theory which uses the fluid dynamics of electrons that multiply by collision processes. This shock-wave model provides a physical basis yet to be exploited for developing a theory of the processes which lead to the appearance of sub-microsecond rise-time in the EM pulses radiating from lightning leaders and return strokes. This offers the best hope of deriving the sources of the HF, VHF and UHF components in the current pulse and in the electric and magnetic fields surrounding lightning discharges of all types.

2.6 Summary

The electric and magnetic fields from a section of the lightning discharge can only be approximated by relatively simple dipole fields if the radiating length is much less than both the distance between observer and channel, and the wavelength concerned. This restricts the dipole approximation to distances greater than around 20km when considering the return stroke, the most studied phase of the discharge.

In modelling the near fields, knowledge of the current waveform in the stroke is vital. Treating the main discharge channel as a transmission line, charged by the leader and discharged by the return stroke, near fields can be calculated (given certain parameters) from ensuing current waveform. Working backwards from the far field to the current waveform and then deducing the near field has been attempted. The best results so far have included resistive losses in the transmission line model. This model is not yet fully developed: the physical basis on which the equivalent L, C and R have been derived has so far been over simplified, because C and R depend strongly on both time and position. Some near field computations have been reported and these show broadband electric and magnetic fields of a few hundred volts per metre and about one micro-tesla respectively.

Improved near field modelling will require the use of a more accurate return stroke current waveform. Current propagation is beginning to be modelled adequately, but it is necessary to include effects due to the tortuous nature of the lightning channel and the existence of horizontal sections of the discharge channel within the cloud. Radiation from branch points and kinks in the channels results in a complex array of sources along the channel below the cloud and within the cloud itself. They form a pattern like that of a branching tree.

The initial current rise is dependent on the details of the breakdown which completes the channel to ground and starts to transform the leader channel into a very high current conductor. The junction of ground and cloud leaders can occur near the cloud or near ground, and at this junction the highest currents and fastest rates of rise of current appear.

Shock wave phenomena in the electron fluid appear to be important in leader propagation and in the return stroke. The continuing current appears when the leader channel is too hot to allow shock waves to propagate ie too hot to support a leader stroke.

III CONCLUSIONS

Electromagnetic disturbances generated by lightning discharges in the frequency range 5kHz - 1GHz have been reviewed, with an emphasis on those effects above 300kHz most relevant to aircraft. Although a good deal is known about radiated fields a long distance from the flash and the currents which flow to ground, much less is known about the environment very close to a discharge channel, particularly at cloud height.

Distant measurements suggest that fields in the frequency range 5kHz - 1MHz are dominated by the largest current surges, return strokes and K-changes. The almost continuous pulsed radiation seen during a flash at frequencies between 1MHz and 100MHz is partly due to the fast-rising fronts of recoil streamers, dart leaders and return strokes, with additional contributions from probing leaders and other processes within the cloud. The relation between these lightning phenomena and the electromagnetic fields generated is complex. Shock waves seem to be involved.

The strongest transients experienced by an aircraft are likely to be those associated with return strokes and K-changes. Nevertheless streamering from the aircraft itself can induce currents in internal wiring comparable with those induced by direct lightning strikes (probably intracloud) or nearby strikes. Both direct strikes and lightning close to the aircraft create similar disturbances in internal wiring, the amplitude of which is by no means negligible. Although peak voltages and currents induced might be significant, the durations of the transients are quite small, and hence the energy deposited is small. It should be possible always to design adequate protection for sensitive circuitry, once the likely hazards have been evaluated.

Models of the near field are sufficiently advanced to allow fair prediction of the form of the electric and magnetic field pulses due to lightning, but the higher frequency transients are not well accounted for. The physics of the breakdown process and the transition from leader to return stroke are not well described. The variation of the current pulse with height is important, and the rise-time is predicted to increase significantly as the pulse propagates along the channel. The fastest rate of rise occurs at the junction of the leaders from cloud and ground.

For negative flashes, the cloud leader propagates almost to ground before the return stroke begins. The parameters measured at ground then represent the peak currents and greatest rate of rise of current appearing in the return stroke. For positive flashes, where a long leader from ground is very probable, ground measurements describe the current pulse after transmission over a great distance. The parameters of the pulse at the junction of the leaders near the cloud will show higher currents and faster rates of rise. In estimating the hazards to aircraft these differences in the interpretation of ground measurements on positive and negative flashes must be taken into account.

Measurements on aircraft carrying appropriate instrumentation would obviously be very valuable. If possible, ground observations supplementing the airborne surveys should be made simultaneously, and such surveys should be carried out on thunderstorms in many parts of the world.

Test techniques for simulating the high frequency effects of lightning in the laboratory also need to be developed. A statistical analysis of lightning current pulses as a function of altitude, using wide-band transient analysis equipment, is needed to provide a reliable base for establishing these test techniques. Similar information on E-field and B-field pulses due to very close strikes is also required so that a complete range of tests can be devised.

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