SESSION 9

Sferics

N72-25383

SFERICS

E. T. Pierce
Stanford Research Institute, Menlo Park, California

ABSTRACT

The properties of sferics--the electric and magnetic fields generated by electrified clouds and lightning flashes--are briefly surveyed, the source disturbance and the influence of propagation being examined. Methods of observing sferics and their meteorological implications are discussed. It is concluded that close observations of electrostatic and radiation fields are very informative, respectively, upon the charge distribution and spark processes in a cloud; that ground-level sferics stations can accurately locate the positions of individual lightning flashes and furnish valuable knowledge on the properties of the discharges; but that satellite measurements only provide general information on the level of thundery activity over large geographical regions. It is recommended that simultaneous investigations of sferics and other--possibly associated--meteorological phenomena be encouraged and that immediate consideration be given to the establishment of a National Sferics Facility; this would consist of a network of ground stations capable of locating every lightning flash in the U.S.A. as it occurs.

1. INTRODUCTION

In meteorology "sferics" studies are usually considered to involve investigations of the electromagnetic signals radiated by distant lightning flashes, and to have as their prime objective the location of the positions of the flashes. Most of this review will be concerned with such studies. However,* some attention will also be given to observations of the electrical field-changes generated by close lightning, and to investigations of the fields accompanying electrified clouds but not directly associated with lightning occurrence.

*In accordance with the request of Professor David Atlas, Chairman, Panel on Remote Atmospheric Probing.

It is usual to define the electric moment M of an electrified cloud by $M = 2\,\Sigma\, qh$ where the summation involves every elementary charge q, at altitude h, associated with the cloud. If the net electrification of the cloud can be represented by a point charge Q at a height H then the vertical electrostatic field, E_s, produced at the surface of the earth by the cloud is given by

$$E_s = \frac{1}{4\pi\varepsilon_o}\,\frac{2QH}{(H^2 + D^2)^{3/2}} = \frac{1}{4\pi\varepsilon_o}\,\frac{M}{(H^2 + D^2)^{3/2}} \approx \frac{1}{4\pi\varepsilon_o}\left(\frac{M}{D^3}\right) \quad \text{for } H \ll D \tag{1}$$

where D is the distance along the ground from below the cloud to the point of observation, and ε_o is the permittivity of free space. When either Q or H are changing rapidly then--in addition to the electrostatic component E_s--the electric field, E_t, at time t has appreciable induction (E_I) and electromagnetic radiation (E_R) components. An approximate representation is

$$E_t = E_s + E_I + E_R = \frac{1}{4\pi\varepsilon_o}\left\{\frac{M_t}{D^3} + \frac{dM_t/dt}{cD^2} + \frac{d^2M/dt^2}{c^2D}\right\} \tag{2}$$

where c is the velocity of light, and retarded values at time (t - D/c) are used for M_t. Equation (2) is a useful guide to general behavior but is of limited applicability. It involves implicitly the assumption that D is appreciably greater than the dimensions of the cloud. Also if λ is the wavelength of any electromagnetic radiation described by Eq. (2) then λ should considerably exceed the length of the radiating channel involved; in practice this implies that the validity of Eq. (2) decreases rapidly for λ less than about 10 km (frequency greater than 30 kHz). Equation (2) applies to an infinite vacuum half-space above a perfectly conducting ground; it will thus be increasingly modified with increasing distance by the finite electrical properties of the earth and the effect of the ionosphere. The ionosphere has the influence-very important in sferics studies--of channelling radio signals at some frequencies around the earth.

It is instructive to note that if M_t is assumed to alter at a frequency f then the three terms in Eq. (2) are equal in magnitude when $D = c/2\pi f$. Thus at 10 k Hz, E_R will dominate in Eq. (2) for D greater than about 5 km; at 100 Hz on the other hand E_s will still be the largest component for $D \leq 450$ km.

Sferics signals are naturally emitted from electrified clouds and are therefore in themselves meteorological information.* A received sferics signal consists of the original source disturbance subsequently modified during propagation. Close to the origin the propagational effects will be slight; the source characteristics are relatively uncontaminated, and since these characteristics are complicated a variety of observational techniques must be employed if they are to be accurately defined. Propagation tends to eliminate or to smooth out many of the source characteristics so that as distance increases sferics become more uniform and so--in consequence--do the techniques for their observation. Some of the source effects are preserved to very great distances, but with others their identification becomes difficult if the length of the propagation "filter" is large.

*This is not always appreciated by meteorologists.

For the above reasons it is convenient to consider separately close and distant sferics observations, and to divide the latter category into ground-based and satellite measurements. However, before these topics are discussed, it is appropriate to present some established and relevant background information.

2. BACKGROUND INFORMATION

2.1 Thunderstorm Behavior

The characteristics of thunderstorms relevant in sferics studies have been reviewed by Dennis (1964) and--more briefly--by Pierce (1967a). Most theories of thunderstorm electrification envisage a time of some 10 to 30 minutes as elapsing between the onset of unusual electrification in a developing thundercloud and the occurrence of the first lightning discharge. This development time is in agreement with electrical observations. The electrification develops in active cells; each has a diameter of perhaps 6 km but the most intense activity is often more concentrated. A cell has a typical lifetime of some 30 minutes; during this time the flashing rate within the cell varies from under one per minute to a maximum which is usually less than 10 per minute but which can be as high as 50 per minute. An average flashing rate is about 3 per minute.

Electrically active cells may occur anywhere within a complex having a diameter of some 30 to 40 km. The complex essentially defines the thunderstorm extent. Within the complex the flashing rate does not differ greatly from that for a single cell since it is rare for more than two cells to be active simultaneously. In most synoptic circumstances complexes are separated by about a hundred kilometers; sometimes they are disposed along a frontal system thus producing a line storm situation which may persist for a day or more.

During the build-up period prior to the first lightning flash only minor sparks--by definition--occur within the cloud. Thus the transient E_I and E_R fields (Eq. 2) will be small, but the semi-permanent E_S field can be large.

2.2 Lightning Flashes

A thundercloud normally contains a net positive charge in its upper portions while the base of the cloud is negatively charged. These are two common types of lightning discharge--the flash to ground and the intracloud discharge. The former usually removes negative charge to earth, while the intracloud flash tends to neutralize the overall electrification of the cloud either by upward movement of the lower negative charge or by downward motion of the upper positive charge.

The electrical effects accompanying a lightning discharge are of considerable duration. For both flashes to earth and intracloud discharges, the average duration exceeds 0.25 s. During most of this time leader processes are occurring. These involve the advance of a charge-carrying channel by a series of comparatively minor sparks which occur in rapid succession. The most intense of these minor sparks are the well-known "steps"; these are often present during the advance, from the base of the cloud to the earth, of the leader-streamer which initiates the flash to ground. Usually--and particularly for streamer processes within a cloud--it is difficult to distinguish the electrical signal associated with each small spark involved in advancing the streamer; it is only the aggregate electrostatic effect or the radiated electromagnetic "noise" that can easily be recognized.

If an advancing charge-carrying leader encounters a concentration of charge of opposite sign, there is a rapid recoil surge of current backwards along the advancing channel. The electrical and luminous effects produced by such surges are readily identified. In the case of intracloud discharges, the phenomena accompanying the sudden surges are described as K changes. These are pronounced but far more intense effects accompany the return-strokes of the flash to ground. In an earth discharge, the initial leader-channel carries negative charge downward from the cloud. When contact with the ground is made a very intense upward surge of luminosity towards the cloud occurs; this is a return-stroke. There may be several return-strokes contained within a flash to earth. During the intervals between return-strokes it is believed that leader streamers carrying positive charge probe into the cloud from the upper part of the channel energized by the return-stroke. If such a positive leader encounters a medium sized concentration of negative charge within the cloud, there is a recoil streamer giving a K change. Occasionally the recoil may be sufficiently intense to extend as far as the ground; in these instances the recoil streamer is known as a dart leader. In its passage, the dart leader recharges the original channel negatively, so that when the dart reaches the earth the conditions are suitable for another return-stroke to surge upwards. It is noteworthy that K changes are present both for intracloud discharges and for flashes to earth (between return-strokes or after the final return-stroke). On the other hand true return-strokes only occur for the discharge to earth, since it is solely in this case that one extremity of the spark is a large homogeneous, good, electrical conductor.

Equation (2) shows that at close distances and extremely low frequencies the field-change is dominated by the electrostatic component. However for D greater than some 15 km and frequencies exceeding 3 kHz, it is the radiated field that is important. The structure of the electromagnetic radiation due to a single discharge shows interesting variations with frequency; these are illustrated in Fig. 1. [Pierce (1967b)]. At VLF (3-30 kHz) the pulses are discrete and are generated principally by return-strokes or recoil streamers (K-changes). As frequency increases so does the number of pulses per flash to reach a maximum of about 10^4 per discharge at a frequency in the VHF range (30-300 MHz); the disturbance accompanying the flash is then quasi-continuous. With a further increase in frequency there is a sharp decrease in the number of pulses, until at centimetric wavelengths (radar-GHz) the pulses are again well separated and associated with macroscopic features such as return-strokes. Peak pulse amplitudes are reached, for a flash to earth, at about 5 kHz. With increasing frequency up to at least 10^4 MHz there is a general decrease in amplitude which approximately follows an inverse frequency dependency; however over substantial sections of the spectrum between 10 kHz and 10^4 MHz there are probably appreciable deviations from this simple law. Figures 2 and 3 which are taken from a recent review by Oetzel and Pierce (1968) illustrate the amplitude variation with frequency of the radio emission from close lightning. The results--which represent information from several sources--have been normalized to a distance of 10 km. Figure 2 represents the amplitude spectrum, S(f), while Fig. 3 is the peak amplitude, e_p, for a receiver of bandwidth of 1 kHz. The relation between S(f) and e_p is complicated; however,

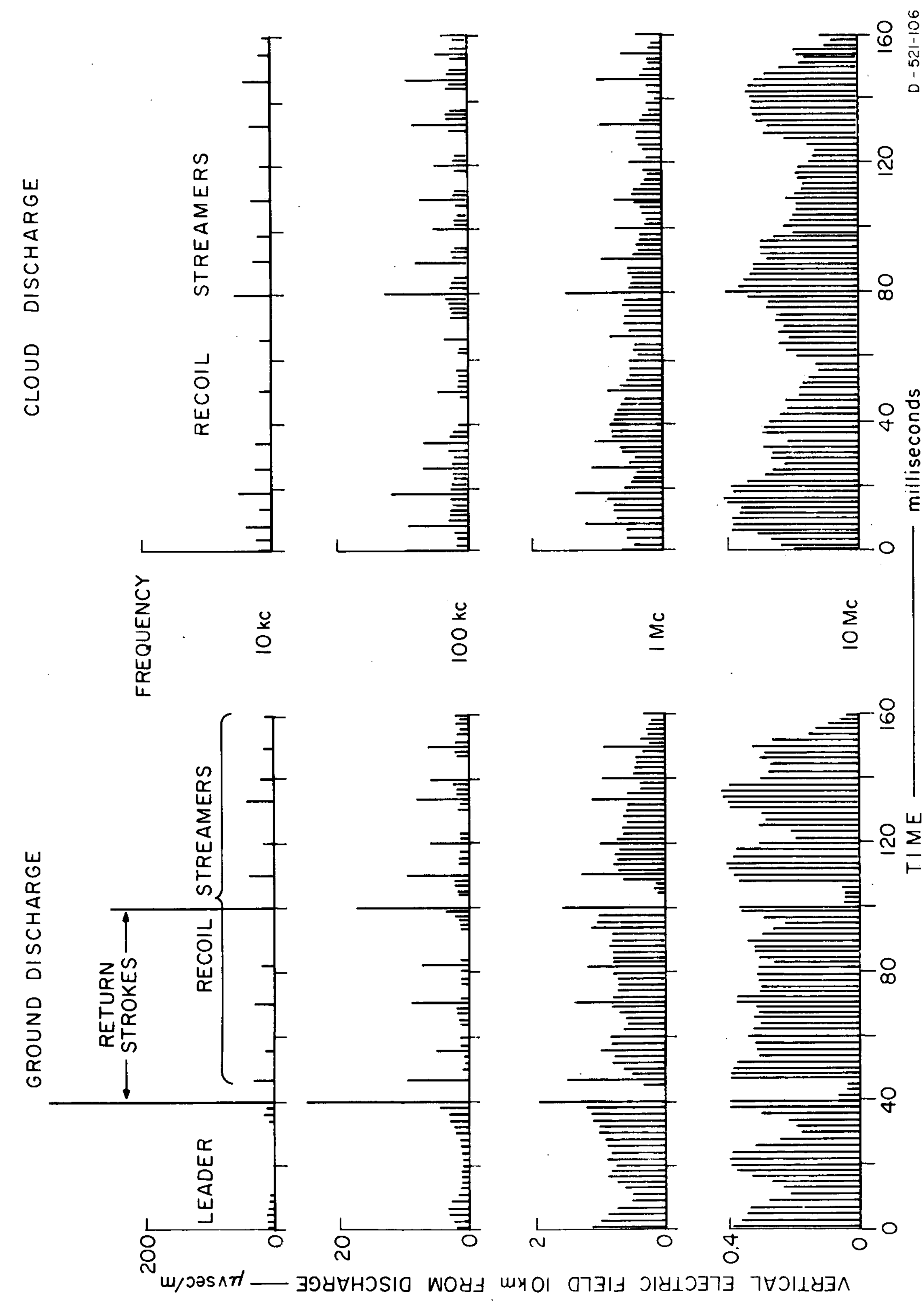

Figure 1. Response of Narrow Band Receivers to a Close Lightning Flash.

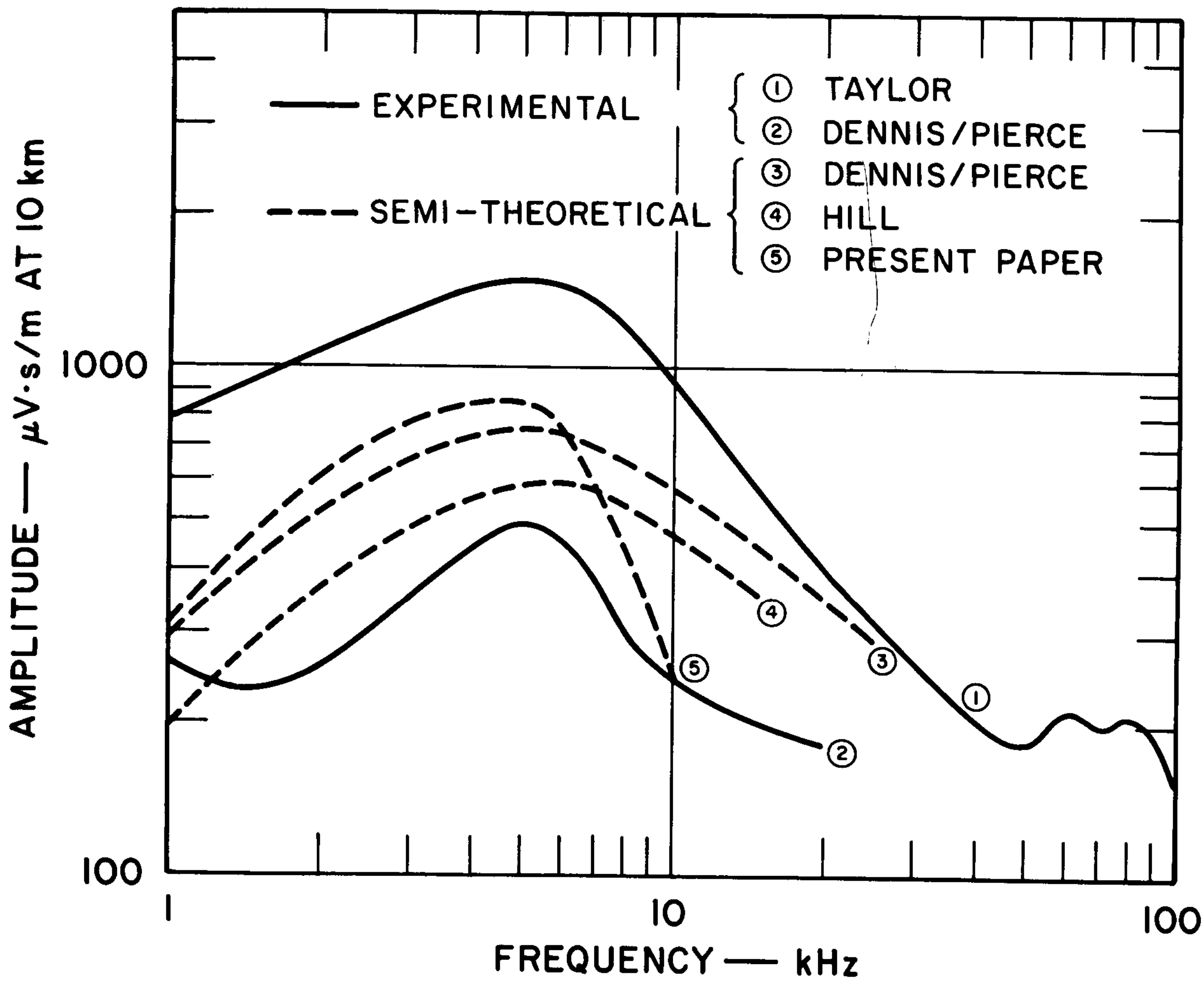

Figure 2. Amplitude Spectra of Return-Stroke Pulses.

Fig. 2 can be appoximately interconnected to Fig. 3 if the ordinate scale of Fig. 2 is multiplied by 10^3. Note that Fig. 2 represents the spectrum of the return-stroke pulse; at 5 kHz this exceeds the spectrum of a K change pulse by more than an order of magnitude, but at 100 kHz the two spectra are much more comparable.

The behavior of the radio emissions from close lightning may be summarized by stating that a multitude of subsidiary sparks of many different types is involved: the larger the current peak in a given type of spark, the longer the energized channel, the lower the frequency at which peak signal is radiated, and the less frequent the occurrence of the particular kind of spark. High current channels tend to be orientated vertically (especially the return-stroke); minor subsidiary discharges are, however, much more randomly disposed.

2.3 Propagation Effects

If sferics signals are to reach ground receivers at great distances from the thunderstorms generating the sferics then the propagation must be almost entirely by ionospherically reflected rays. This implies a restriction to frequencies below the HF bank (3-30 MHz). At HF and MF (0.3-3 MHz) there are very considerable temporal variations in long distance radio propogation and losses are always substantial; at still lower frequencies, however, there are two frequency ranges, of especial importance in sferics studies, at which propagation conditions are relatively stable and attenuation is minimal.

For frequencies below about 100 kHz radio signals travel between the earth and the lower ionosphere as in a quasi-waveguide. The variation in signal strength E (mv/m) with distance D, can often be approximated when D is large by the equation

$$E \approx \frac{300}{h} \left\{ \frac{P\,\lambda}{a \sin (D/a)} \right\}^{\frac{1}{2}} \exp(-\alpha_f D) \tag{3}$$

In Eq. (3), λ is the wavelength involved, a is the radius of the earth, h the effective width (earth-ionosphere) of the guide, P the radiated power from the flash (kW). The attenuation coefficient α_f depends principally on frequency, f, but is also affected by the electrical characteristics of the earth and lower ionosphere; by the temporal changes that occur in the ionosphere; and by the orientation of the propagation path with respect to the geomagnetic field. Usually α_f has two pronounced minima which occur in the frequency range of 10 to 30 kHz and at frequencies below about 300 Hz; this behavior is illustrated in Fig. 4b. If the source disturbance has the spectrum shown in Fig. 4a, (for a typical return-stroke pulse), then the frequency-selective propagational attenuation tends to remove components at frequencies above 30 kHz and between 300 Hz and 10 kHz. Thus the sferic received from a distant lightning flash tends to consist of distinct VLF and extremely low frequency (ELF) signals The propagation is dispersive with the VLF signal traveling the more rapidly; thus a sferic as recorded using a broad-band system (Fig. 4c) consists of a VLF oscillation succeeded by an ELF perturbation (sometimes known as the "slow tail").

With the advent of satellites sferics propogation through the ionosphere has obviously become of importance. Radio signals can penetrate the ionosphere if their frequency exceeds the ionospheric critical frequency f_c;

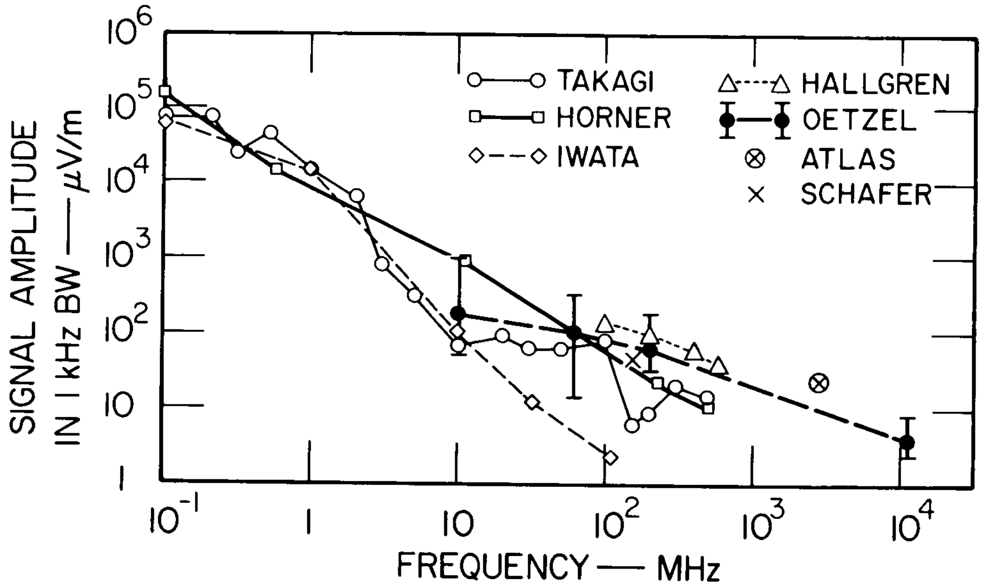

Figure 3. Peak Amplitude of Radiation from Lightning, 0.1 MHz to 10^4 MHz. Data have been normalized to 1 kHz bandwidth and 10 km range.

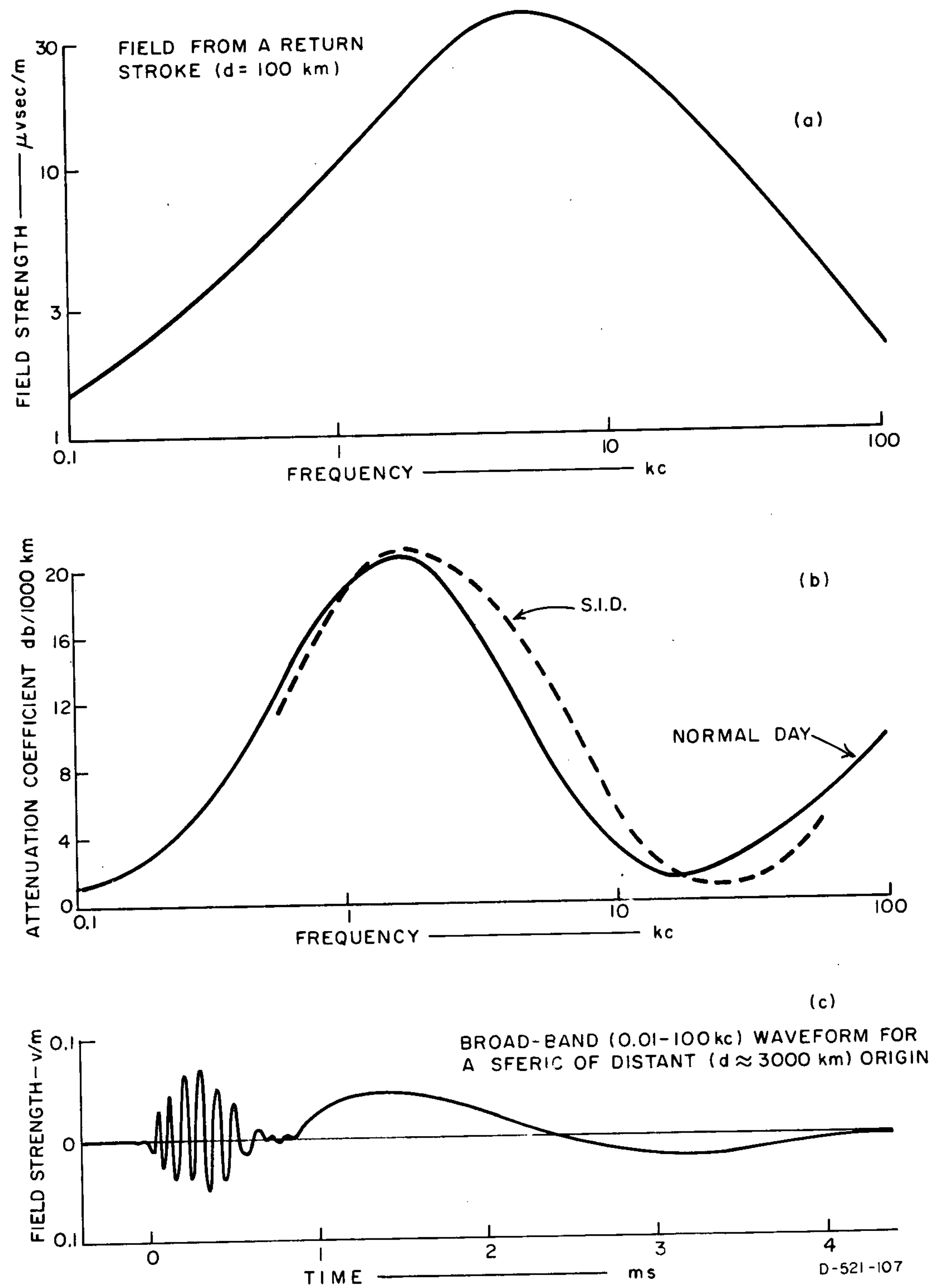

Figure 4. Illustrating some Factors in the Formation of a Sferic.

f_c is normally a few megahertz. Penetration is also possible for some frequencies less than f_c by means of the whistler mode. In this mode of propagation the signals travel in a guided fashion along geomagnetic field lines. Whistler mode propagation is particularly effective at VLF. The main propagation is along the earth-ionosphere waveguide but there is a continual leakage from the upper boundary of the guide into the whistler mode.

At frequencies exceeding f_c where penetration of the ionosphere is possible the attenuating and other effects of the ionosphere decrease in magnitude as f increases. However, it is likely that f must be more than 100 MHz at least before the influence of the ionosphere can be ignored and the propagation considered as line-of-sight. When f is not much greater than f_c (say $4f_c > f > f_c$) the ionosphere acts in an interesting way to limit the ground area from which sferics signals can be received in an overhead satellite. For oblique upward radio propagation with an angle of incident ϕ upon the ionosphere penetration occurs if f is greater than f_c sec. It follows that a satellite at height x will be receiving signals from an area A_f below given approximately by

$$A_f = \pi x^2\left(\left(\frac{f}{f_c}\right)^2 - 1\right) \tag{4}$$

3. SFERICS OBSERVATIONS OF CLOSE LIGHTNING

The techniques [Chalmers (1967)] for studying the electric and magnetic signals generated by a nearby lightning flash are so diverse and specialized that their description must inevitably deal in generalities if it is not to be intolerably prolix. When a thunderstorm is close the difficulties imposed by the unpredictability, in position and time, of lightning occurrence are most pronounced: the relative size of the electrostatic, induction, and radiation field components changes very rapidly with distance and with the frequency band at which observations are being made: the time resolution required ranges from much less than a microsecond for certain features of the discharge (e.g. the return-stroke pulse), to perhaps a second if the overall effects of flashes and thunderstorms are being investigated: while the dynamic recording range must be large embracing, for instance, currents of from tens of amperes (in leader stages) to well over 10^4 A (return-strokes).

A common practice among investigators of close lightning is to employ broad-band equipment which either extends in frequency response from a fraction of a cycle per second to an upper cutoff at a few kHz, or responds to a higher frequency range (possibly 3-300 kHz). With the former frequency coverage the recorded fields and field-changes essentially represent the electrostatic component and can therefore be interpreted in terms of charge magnitudes and locations: however, if the higher frequency range is selected, the signals are dominantly transient radiated fields and their examination is thus primarily informative upon spark characteristics (especially when individual pulses such as those due to K processes or return-strokes can be identified). Simultaneous recording using two broad-band but separated frequency ranges can be particularly instructive [Kitagawa and Brook (1960)].

At frequencies exceeding perhaps 1 MHz noise interference usually precludes wide band recording except at certain ideal sites. Narrow band experiments give useful but restricted information.

Much valuable knowledge regarding thundercloud electrification can be derived from observations of the field variations occurring during the course of a storm but not generated by or coincident with lightning. This fact is apparent in the pioneer electrostatic field measurements of C. T. R. Wilson. It has long been realized that as the electrostatic fields grow during the developmental stage of a thunderstorm magnitudes will be attained at which points at the surface of the earth will break into corona; corona and micro-sparking can also occur for drops within the cloud. Such minute discharges generate radio emissions [Pierce (1962)]; these have been experimentally detected, at frequencies of some tens of megahertz, from thunderclouds several minutes before the first lightning flash, [Zonge and Evans (1966)] and even from shower clouds which never develop into thunderstorms [Sartor (1964)].

In sferics studies of close lightning, there are many modern ways of improving basic techniques. Appropriate antenna arrays can be employed at the higher frequencies, while the use of broad-band tape recorders is especially profitable in that it enables sferics signals to be processed at leisure in several ways long after the occurrence of the thunderstorm. Simultaneous measurements at several ground stations have some advantages; these can be extended to the height dimension with aircraft, balloons, or rockets. However, the complexities of interpretation are sometimes such that more is lost by multi-station work than is gained; this is particularly so if redundant information is being obtained.

It is evident from the preceding paragraphs that observations of the signals from close lightning is rarely a routine matter, and that the optimum techniques to be used largely depend upon the primary objectives of the individual experimenter. Perhaps the only simple instrument by which useful data on some electrical characteristics of local thunderstorms can be routinely obtained is a lightning-flash counter. These instruments count whenever the incoming signal produced by a lightning discharge exceeds a certain threshold E_T; E_T can be statistically related to an effective counter range R. Counters must never be regarded as precise instruments but they can yield valuable information, especially if counters of identical design are employed under similar circumstances at different geographical locations. Horner (1967), for example, has demonstrated how counter results can establish the diurnal variation of lightning activity, and can be used to refine and to replace the common meteorological statistic of the thunderstorm day.

4. SFERICS OBSERVATIONS OF DISTANT LIGHTNING

4.1 Ground-Based Techniques

An atmospheric received at a ground station from a distant thunderstorm consists predominantly of VLF and ELF components (Fig. 4c). Methods-- of various levels of refinement--for recording such atmospherics are well established. In meteorology, networks of VLF sferics ground stations have been very extensively and profitably used [Horner (1964)] to determine the position of the original lightning discharge responsible for an atmospheric incident over the network, and thus to track thunderstorms. The flash is located by analysis, either of times of arrival, or of bearings recorded, for the incoming sferic at each network station.

Considerable efforts have been made to develop methods whereby the origin of a sferic can be established from a single station. The approach is usually to combine a bearing observation with the measurement of some distance-dependent characteristic of the incoming atmospheric. The techniques of Frisius, Heydt, and Volland [see for example Volland (1965)] are especially sophisticated; using these techniques the distribution of amplitudes and group time delays for incoming atmospherics can be recorded as a function of azimuth and frequency, and the information then analyzed to give thunderstorm positions. Even with this refined approach, however, the accuracy of the results obtained is much less than that achieved by a multi-station fixing network.

Studies of the characteristics of VLF sferics that have traveled a long distance tend to be more informative on radio propagation at VLF than on the source disturbance. However, some meteorological data can be obtained. Most VLF sferics can be identified as originating in return-strokes or K streamers, and sferics measurements such as amplitude and phase spectra can be analyzed, after allowing for the propagational modifications, to yield estimates of the form and magnitude of the current surges in the corresponding source pulses. Information on the relative magnitudes and time separations of the individual return strokes and K processes in discharges is fairly easily obtainable, and this information can be applied to determine whether a sequence of VLF sferics was generated by an intracloud discharge or by a flash to earth.

Investigations of sferics at ELF ("slow tails") have been surprisingly neglected in recent years; there are present signs, however, of a revived interest [Hughes (1967)]. Bearing information can be obtained just as effectively at ELF as at VLF. Furthermore, since propogation at ELF depends less on variations in ground conductivity, path orientation with respect to the geomagnetic field, and temporal changes in the ionosphere, than does VLF propagation, it is easier to allow for the propagational modifications when attempting to extrapolate back to source properties.

There are two specialized aspects of sferics studies which merit at least passing mention. Several stations at various locations in the world monitor radio noise at selected frequencies [ITU (1964)]. The results from the radio-noise stations can be used to determine crudely the temporal variations in position and strength for the main global thundery areas. Similar approximate information can be deduced from investigations of the Schumann resonances. These resonances of the earth-ionosphere cavity, which occur at frequencies of about 8, 14, 20, 26 Hz and upward, are excited by lightning flashes. The strengths of the resonances at a given station are related to the rate of occurrence (activity) of the discharges, and their locations with respect to the observing point.

4.2 Satellite Techniques

Sferic measurements in satellites have great apparent attractions but a little consideration soon reveals their very real limitations. The radio signals that contain most information about the lightning source are those at the lower frequencies (especially in the VLF band); it is these frequencies that are most influenced by the propogation through the ionosphere, so that much of the source information is lost. For signals at frequencies (above) perhaps 100 MHz), that are relatively unaffected in their passage through the ionosphere, the original radiation is of low amplitude (Fig. 3), and contains only crude information on the lightning flash.

The flashing characteristics of a cell impose severe restrictions on the effectiveness of the surveillance of individual thunderstorms by low-altitude (say 1000 km) sferics satellites. For such satellites the orbital speed is about 7 km/s; thus with an antenna system resolving a cloud area comparable with that of a thunderstorm cell the area is only monitored for about a second. Since the interval between flashes is typically 20s, one second is a time quite insufficient for a cloud to be identified as thundery or not.

High altitude--stationary would be 37,000 km -- orbits, in conjunction with elaborate antenna scanning systems might enable fairly small areas of the earth's surface to be examined. However, at 37,000 km sferics signals must be identified within a framework of strong background noise. There may be advantages in using optical ($H\alpha$) sensors but the discussion of these is beyond the scope of this report.

Summarizing, sferics satellites seem incapable of yielding useful information on individual lightning flashes or thunderstorms. They can monitor large areas (diameter ca 1000 km), and hence determine approximately the degree of thundery activity within these areas. Thus the main potential use of sferics satellites is in improving our knowledge of temporal variations in the strengths and positions of the main global thunderstorm regions.

Sferics sensors in satellites might operate either at VLF, HF, or VHF. At VLF the source radiation is strong, but propagation is by the whistler mode so that the received sferic penetrates the ionosphere along the geomagnetic field line through the satellite position; before entry into the ionosphere the sferic propagates, from the originating lightning discharge, below the ionosphere in the earth-ionosphere quasi-waveguide. This complicated path entails difficulties in identifying the location of the lightning flash generating the sferic. The geomagnetic path control has some remarkable implications; for example, a satellite 1000 km above the equator would tend to receive VLF signals from equatorial thunderstorms via a path below the ionosphere as far as a latitude of 20° N or S, and then through the ionosphere along the appropriate field line.

At HF the sferics signals received in satellites above the ionosphere are well above the ambient background in strength. The ionosphere itself defines the area upon the surface of earth that is being monitored (Eq. 4). If several narrow-band receivers tuned to various frequencies within the HF band are employed then the recorded noise can be associated with different areas and the value of the results enhanced. A multi-frequency experiment of this kind, presently being carried on the Ariel III satellite, is already yielding useful data [Bent (1968)]. One aspect of HF sferics sensors is that the results are equally revealing upon the characteristics of the ionosphere as upon those of the thundery activity beneath. Indeed, if the latter information is to be deduced then the ionospheric effects must first be reliably estimated.

The main drawback to using sensors at frequencies (> say 100 MHz) essentially unaffected by passage through the ionosphere is the low ratio of sferics signal to other noise. This other noise can be of cosmic, solar, terrestrial (thermal) or manmade (including receiver) origin. Pierce (1967a) has estimated that for a satellite at an altitude of 1000 km the signal/noise ratio deteriorates from about 10/1 at 100 MHz to perhaps 2/1 at 600 MHz; this decrease is principally due to the drop in the lightning signal as frequency increases (Fig. 3). If the satellite altitude becomes greater the signal/noise ratio becomes less; this is because, at best the sferics signal varies inversely with distance (Eq. 2), while several noise sources (cosmic, solar, receiver) are independent of distance.

It is perhaps appropriate in this section to query whether sferics satellites are really necessary since the information they can supply is possibly being already obtained by other satellite experiments. For example, there are indications that large-scale thunderstorms with massive convection can be identified from cloud-photographing satellites. This identification might become more positive, if comparisons were made between the cloud photographs and the considerable amount of sferics data that has already been obtained in satellites (Lofti, Ogo, Alouette, Ariel, etc.). Certainly this comparison should be performed before elaborate schemes for specialized sferics satellites are considered.

5. METEOROLOGICAL INFORMATION POTENTIALLY OBTAINABLE FROM SFERICS.

Sferic observations can furnish direct information on the electrical characteristics of individual lightning flashes, and on the temporal changes in the level of electrical activity for single thunderstorms or for thundery regions. They can also be used to locate the positions of active storm centers. Non-electrical meteorological information can be deduced from sferics results, but the validity of such deductions is often questionable since the degree of association between electrical and other meteorological phenomena is seldom well established, and may indeed in many instances be very slight.

Three classes of sferics observations have been identified in the preceding text. Of these, satellite measurements seem primarily capable only of improving our climatological knowledge of the main global thundery regions. However, such information, which essentially establishes the spatial and temporal variations of thunderstorm activity, has important basic and applied implications. In the former category, the most obvious use is in improving our definition of the qualities of the global thunderstorm generator controlling the universal aspects of atmospheric electricity. Again, in the basic field, accurate knowledge of thunderstorm climatology may assist our understanding of the general atmospheric circulation and of the distribution of atmospheric contaminants since it is possible that the large convective clouds of intense thunderstorms play a vital role in exchanges between the troposphere and the stratosphere. Practical applications of satellite sferics measurements tend to be non-meteorological; two such applications are in improving the estimation of atmospheric noise interference to radio communication, and in establishing approximately the optimum degree of lightning protection required for electrical power transmission lines to be located in remote areas of the world.

Ground-level sferics techniques can locate the positions of individual lightning flashes and therefore of active thunderstorms, while the examination of incoming sferics is informative upon the electrical characteristics of the flashes in storms. Radio noise and Schumann resonance measurements give information on the locations and strengths of active thundery areas, comparable in refinement with that obtained by satellite techniques; however, a VLF sferics network yields incomparably more accurate fixes. This improved location precision enables VLF sferics data to be applied in ways for which cruder results would be unsuitable. Among these uses are the selection of optimum safe routing for aircraft, and the estimation of forest fire hazards after lightning strikes. A standard VLF sferics network with station separations of the order of 1000 km can continuously locate lightning flashes, and record the waveforms (for example) of the corresponding sferics, over a region with a dimension of several thousand kilometers. The pulses within the individual sferics can be usually recognized as due to return-strokes or K processes; consequently, an identification with intracloud or cloud-ground discharges can be established. Detailed examination of the time separations and structure of the pulses yields some estimate of the currents and charges involved in the sferic (flash). Flashing-rates can obviously be derived for individual thunderstorms, and lead to estimates of the violence of the storm; this in turn is possibly related to such specialized meteorological phenomena as the occurrence of unusual hydrometeors (large hail). It is especially interesting to note that thunderstorms containing active tornadoes could perhaps be identified by distant sferics measurements, since tornadoes appear to produce very high flashing rates and to possess an unusual spectral distribution, in the VLF and LF bands, of the sferic source disturbance [see for example Jones (1965)].

Observations of close thunderstorms are naturally more informative on thunderstorm characteristics than are measurements at a distance. All the knowledge that can be deduced from records of distant VLF sferics, and more, can be determined from short range observations of radiation fields. This VLF information is enhanced by measurements of the electromagnetic radiation at other radio frequencies which propagate relatively poorly so that the signals are readily detectable only close to the source. Observations of radiation fields over a very wide frequency range are necessary in order to build up a complete picture of all the spark processes associated with lightning. At short distances ionospheric influences are unimportant; it is thus possible by employing suitable antenna arrangements to determine the polarization and hence the orientation of a large discharge channel. Electrostatic fields are only dominant (Eq. 2) when D is small. Records of such fields are by far the most direct way of estimating the magnitudes and heights of the charges in a thundercloud and the manner in which the electrical activity varies with time; this includes the growth phase before the first lightning flash. The radio emissions during the growth phase are potentially informative on the development of micro-discharges (for example between water-drops) within the cloud; however, these emissions are very weak and therefore difficult to study, while their identification with specific processes involving cloud constituents is not yet definitely established. Indeed the latter deficiency applies very generally; little is known of the association, if any, between electrical characteristics and other thunderstorm information such as height, rainfall-rates, updrafts, et cetera.

6. DISCUSSION AND SUGGESTIONS FOR FUTURE WORK

There are many facets of sferics that have been thoroughly investigated;

there are others that have been extensively studied but still merit further examination; while some aspects have been relatively neglected. This section will discuss the extent of our knowledge, and indicate how any deficiencies might be remedied. Specific recommendations, which appear to deserve priority in action, are listed in the following section.

Sferics satellites and their meteorological uses are a presently fashionable topic. Any system for the reception of sferics in a satellite must examine the nature of the disturbance generated at the source; the modification of the signals during their propagation to the satellite; the background noise above which the sferics must be identified; the technical aspects of the reception in the satellite; and the limitations imposed on the obtainable information by satellite orbits and thunderstorm characteristics. All these aspects need to be considered to comparable degrees in the design of a sferics satellite system. It is disturbing to find systems described that treat one specific aspect with extreme sophistication, while accepting crude idealized models for the other aspects; indeed papers have appeared demonstrating that the authors, if they had been aware of the true physical picture for these other aspects, would have realized that their sophisticated approach in one respect was quite inapplicable! Much knowledge is now available upon all the problems connected with sferics satellites; the difficulty is to ensure that all this information--and not merely a biased selection--is employed. There is perhaps only one obvious investigation which could provide a valuable supplement to existing knowledge regarding sferics satellites; this is a comparison of radio noise data already taken in satellites with low-level cloud and thunderstorm information.

Turning to ground level observations of distant sferics, the techniques of location using VLF signals and a network of stations have become standardized; so also have methods--often very sophisticated--for recording waveforms and other characteristics of the individual sferics [Grubb (1967)]. The problems of extending location coverage to a very large geographical area by interlinking sferics networks are organizational rather than technical and scientific. The ELF frequency band apparently offers some advantages for position location and other investigation of sferics of distant origin; more observational results at these frequencies are needed. Extensive work has shown that establishment of thunderstorm position from a single sferics station cannot be done easily with any accuracy [Horner (1964)]; it seems futile to pursue any further the simple techniques so far considered in this connection. Sophisticated methods [Volland (1965)] may eventually enable single station location to be achieved; however, it should be decided whether very complicated equipment at one station is any real improvement over several much simpler instruments placed at a few stations within a network, particularly when it is considered that the automation of such a network is not difficult. Any deductions regarding thunderstorm climatology that can be obtained from radio noise or Schumann resonance measurements are likely to be crude; thus there is little reason--from a meteorological point-of-view--to encourage research in these fields.

There have been many investigations of the field-changes due to close lightning in which either the electrostatic component or the VLF radiation fields have been studied; further work in these areas is unlikely to be very profitable. Lightning research should concentrate primarily upon studies of the electromagnetic fields radiated at frequencies above about 50 kHz; the changes in structure as frequency increases from 50 to 500 kHz, and again between 10 to 200 MHz, deserve special attention. Another frequency range that has been relatively neglected in researches on close lightning is that from 100 Hz to 3 kHz; it is surprising that we are still somewhat uncertain which phases of the lightning flash are involved in the generation of ELF sferics. Measurements of the fields occurring during thunderstorm growth and decline but not directly associated with lightning need more attention; such observations should include data obtained simultaneously for both electrostatic and radiation components. Indeed, simultaneous recordings using well-separated frequency bands are immensely advantageous in lightning research. This is particularly so if one measurement is continuous and the other intermittent; it is pointless, for example, to obtain a triggered high time-resolution record of lightning radiation at VHF, unless the phase of the complete lightning discharge at which the triggered record occurred can be established by comparison with, for instance, a continuous registration of the electrostatic field. Simultaneity of records should not be confined to electrical phenomena; only an inter-comparison of data from electrical and other-notably radar-sensors, can resolve the urgent question of how closely the electrical characteristics of a thundercloud are associated with the other meteorological phenomena of the storm. In this latter connection, and also for some practical reasons, it is often desirable to be able to locate lightning positions at distances of up to about 100 km; over this range conventional VLF methods are relatively ineffective, and while other techniques are promising they still need development. Finally, it is perhaps appropriate to mention that the human observer of thunder and lightning is still in many ways a useful standardized instrument capable of yielding reliable statistical information on the gross electrical characteristics of local thunderstorms; only a simple lightning-flash counter, possibly, can give comparable information as easily and as cheaply.

7. SPECIFIC RECOMMENDATIONS

These recommendations are limited to the items that seem presently of most importance; the previous section has indicated some other areas in which action is desirable but not a matter of urgency.

(a) Immediate consideration should be given to establishing a National Sferics Facility (Nasfa?).* This would locate--in real time--every lightning flash occurring over the continental U.S.A. and adjacent areas; simultaneously the characteristics of the associated sferic would be recorded. There are no technical difficulties involved in achieving the facility by means of a ground network of VLF sferics stations; the received information could be continuously displayed and/or stored at a central master control point. A National Sferics Facility would supplement or partially replace--especially in routine functions--the existing sferics activities of many institutions; these establishments include government departments, universities, non-profit organizations, and industrial laboratories. Existence of the Facility would lead to identification and detailed warning of potentially dangerous meteorological

*Details of a possible practical arrangement for such a Facility are given in the Appendix. This Appendix was submitted as the original input to the Panel on Remote Atmospheric Probing in September 1967. Since the Appendix includes material not appearing in the present review it is being reproduced as a supplement.

situations; the resulting national economic benefits in aviation, public safety, and forestry--to name only a few areas--would be immense.

(b) Every proposal for sferics measurements from satellites should be very carefully scrutinized in order ensure that all relevant factors have been considered. The implementation of any elaborate scheme for sferics satellites should be deferred until existing radio noise data already obtained in satellites has been analyzed and its relation to surface meteorological conditions established.

(c) Observations of close thunderstorms should concentrate on interlinking the various electrical phenomena, and--especially--on relating these phenomena to other meteorological effects. Simultaneous recording using several sensors is to be encouraged; investigations in which only a specialized fine-structure aspect of sferics is being studied should receive little support.

(d) It seems time to replace the meteorological statistic of the thunderstorm day by some more refined and quantitative parameter. A convenient way of achieving this replacement is by the routine use of a simple standardized lightning-flash counter and recorder.

APPENDIX ≠

REMOTE ATMOSPHERIC PROBING TECHNIQUES* SFERICS OBSERVATIONS

1. INTRODUCTION

An atmospheric or more colloquially a "sferic" is the radio disturbance generated by a lightning discharge and modified by propagation influences during its travel towards an observing station. The signal at the lightning source is complicated, since it represents the combined effects of a multiplicity of sparks, all different in character, and occurring over the considerable (approaching a second) duration of the discharge. However, the main features of the radio emissions associated with an individual flash are isolated impulses of large amplitude at frequencies in the VLF band (3-30 kc/s) and below; a transition to a quasi-continuous succession of pulses of less amplitude than those at VLF as frequency increases to HF (3-30 Mc/s); and a gradual reversion to isolated pulses but now of very small amplitude as frequency further increases to UHF (300-3000 Mc/s).

Radio signals at frequencies exceeding about 30 Mc/s follow quasi line-of-sight paths and are therefore of little use for remote probing. Signals in the MF (0.3-3 Mc/s) and HF bands can travel around the earth through ionospheric returns, but the propagation characteristics are very temporally variable especially between day and night. However, radio waves at lower fre-

---

*It is assumed that the probing is only to consider ground-based equipment, and that "remote" implies an equipment location essentially unaffected by the atmospheric conditions being probed.

≠ See footnote on page immediately preceding.

quencies, particularly in the VLF band, propagate well under almost all conditions in the quasi-waveguide formed by the earth and lower ionosphere. Since the source signals at VLF are large discrete pulses and the propagation is good, VLF atmospherics are easily received many thousands of kilometers away from their thunderstorm origin.

In meteorology it is almost tacitly assumed that sferics observations imply measurements in the VLF band; this interpretation will be followed in the ensuing text. The basic meteorological objective of measurements on VLF atmospherics is to locate the thunderstorm sources of the sferics.

2. DESCRIPTION OF TECHNIQUE

Sferics location techniques using a network of stations are well éstablished in theory and have been thoroughly tested in practice. Most commonly each station fixes the direction of the incoming VLF sferic by means of a crossed loop antenna arrangement; triangulation using the directions established respectively at the various network stations then fixed the origin of the sferic. In a rather more accurate technique the times of arrival of the VLF sferic at any pair of network stations are compared; a given difference in the arrival times defines a hyperbola, and the intersection of the hyperbolas fixes the sferic position.

Many techniques for locating areas of sferic activity from a single station have been suggested; none of these have yet reached the stage where they are suitable for routine operation. The most promising approach is probably in further development of the work of Heydt and Volland. In this research the statistical distribution of incoming impulse magnitudes is recorded as a function of azimuth for several selected frequencies in the VLF and LF bands.

3. APPLICATION TO ATMOSPHERIC PROBLEMS

Sferics observations can readily identify the position of a lightning flash at distances of up to a few thousand of kilometers from the locating stations. By definition, if a lightning discharge is fixed then so is a thunderstorm position, while the rate of occurrence of flashes in a specific area is an indicator of the strength of thundery activity in that area. If a thunderstorm region is located then, by association, it is an area of violent atmospheric convection and turbulence within which such unusual hydrometeors as large hailstones are likely to occur.

Sferics techniques are the only way in which ground measurements can establish the positions of distant thunderstorms. Information upon the spatial and temporal variations of thunderstorm activity has both basic and applied implications. Among basic problems are those of the general atmospheric circulation and the vertical distribution of atmospheric contaminants, since it is believed that the large cumulonimbus clouds of intense thunderstorms play a vital role in exchanges between the stratosphere and troposphere. Another fundamental problem is that in atmospheric electricity of the qualities of the global thunderstorm generator.

Among applied areas lightning location information is useful in forestry (fire hazard);in assessing the need for protection of electrical power transmission lines; in aviation by enabling optimum safe routing to be easily selected; in estimating atmospheric noise interference to radio communication; and in other ways. A specially interesting application is the remote location of tornadoes; this can be achieved because tornadoes are identifiable since they seem to produce a very much higher flashing (sferics occurrence) rate than do conventional thunderstorms.

4. FACILITIES

Even within the confines of the U.S.A. there are far too many establishments making sferics measurements of one kind or another for any comprehensive listing to be appropriate in a brief note of this kind. There are certainly--at a conservative estimate--well over fifty establishments recording sferics data. The agencies concerned include government departments (e.g., Air Force, Navy, ESSA); Universities (e.g. Montana State, Oklahoma); non-profit organizations and industry (e.g., SRI and Litton). Unfortunately, there is little standardization of measurements and co-operation between the various active establishments.

Before any estimate of the cost of a central sferics remote probing facility can be made, some definition of the function and scope for such a facility must be made. Suppose we arbitrarily consider a facility consisting of a master station situated in the heartland of the U.S.A. with several peripheral sub-stations. Let the function of the facility be to locate all thunderstorms occurring within the continental U.S.A., and a major proportion of those active in the immediately contiguous areas. Furthermore, the information is to be presented at the master station with a time delay of a few minutes at most.

A network comprising a master station in the St. Louis area, with eight sub-stations in the vicinities of Seattle, San Diego, Boulder, Colorado, El Paso, N. Dakota, Florida, Washington, D.C., and Maine, would cover the continental U.S.A. very adequately while also providing a desirable degree of redundancy. A standard sferics direction-finding set costs well under $10,000; installation and addition of an output stage giving a signal, representing the D-F information and/or pulse magnitude, that can be readily applied to a radio or telephone link, is unlikely to cost more than $5,000. It seems likely that the sub-stations could be located at establishments, e.g., colleges, where the equipment would be gladly accepted as an addition to the local research facilities, so that personnel and other charges for maintenance and routine operation would be low; perhaps $1,000 a month per sub-station would be adequate. The sub-station signals must be conveyed to the master station with a delay which is less than a few milliseconds and known with fair accuracy if confusion between separate sferics is to be avoided; a leased telephone line (typical cost $1,250 a month) is a simple and reliable solution. At the master station the technique of combining the incoming information might range from plotting by operatives to an elaborate fully automated display. There would be a balancing between personnel and capital equipment costs; perhaps $40,000 per annum for the former and $80,000 for the latter is a suitable compromise. It is assumed that the master station could be housed at an appropriate establishment without appreciable costs specifically attributable to the sferics work.

Summarizing, the national sferics facility might cost $200,000 to set up initially and $250,000 per annum to operate thereafter. Although the latter figure is substantial, it should be realized that once a national facility is functioning, many other systems presently in operation would be free to concentrate upon specific detailed investigations, and to eliminate some of their more routine functions. The savings from this elimination, and the national economic benefits in--to give only a few areas--aviation, public safety, and forestry, cannot be accurately assessed; however, even the most conservative estimate suggests that they should very considerably exceed $250,000 per annum.

REFERENCES

Bent, R. B., 1968: Investigations of global thunderstorm activity from the Ariel III satellite. Paper prepared for the Fourth International Conference (Tokyo, Japan, May 1968) on Universal Aspects of Atmospheric Electricity.

Chalmers, J. A., 1967: Atmospheric Electricity. New York, Pergamon Press, 515 pp.

Dennis, A. S., 1964: Lightning observations from satellites. Final Report SRI Project 4877, Prepared for National Aeronautics and Space Administration, Contract NAS r49 - (18). Stanford Research Institute, Menlo Park, California, 94025, U.S.A.

Grubb, R. N., 1967: A digital data collection system for transient waveforms in the 1-100 kilohertz band and its application to the study of atmospherics. Paper prepared for the M.F., L.F., and V.L.F. Radio Propagation Conference, November, 1967, IEE, Savoy Place, London.

Horner, F., 1964: Radio noise from thunderstorms. Advances in Radio Research, Vol. 2, New York, Academic Press, 121-215.

, 1967: Analysis of data from lightning-flash counters. Proc. IEE, 114, 916-923.

Hughes, H.G., 1967: Nonreciprocal attenuation rates at ELF from slow tail measurements. J. Geophys. Res., 72, 5383-5388.

International Telecommunication Union, 1964: World distribution and characteristics of atmospheric radio noise. CCIR Report 322, Document X, Plenary Assembly (1963), Geneva.

Jones, H. L. 1965: The tornado pulse generator. Weatherwise, 18, 78-85.

Kitagawa, N. and M. Brook, 1960: A comparison of intracloud and cloud-to-ground lightning discharges. J. Geophys. Res., 65, 1189-1201.

Oetzel, G. N. and Pierce, E. T., 1968: The radio emissions from close lightning. Paper prepared for the Fourth International Conference (Tokyo, Japan, May 1968) on Universal Aspects of Atmospheric Electricity.

Pierce, E. T., 1962: Sources of atmospheric noise in lightning. Radio Noise of Terrestrial Origin, Amsterdam, Elsevier, 55-71.

Pierce, E. T., 1967a: Atmospherics-their characteristics at the source and propagation. Progress in Radio Science 1963-1966, Proceedings XVth General Assembly (Munich 1966), URSI, 987-1039.

, 1967b: Spherics (sferics). Encyclopaedia of Atmospheric Sciences and Astrogeology, New York, Reinhold, 935-939.

Sartor, J. D. 1964: Radio observations of the electromagnetic emission from warm clouds, Science, 143, 948-950.

Volland, H., 1965: Long range detection of thunderstorms. The Controller, 4, 35-36.

Zonge, K. L. and W. H. Evans, 1966: Prestroke radiation from thunderclouds. J. Geophys. Res., 71, 1519-1523.

REFERENCES (FOR APPENDIX)

Heydt, G. and H. Volland, 1965: Long range detection of thunderstorms, The Controller (IFATCA Journal), 4, 2, 35-37.

Pierce, E. T. 1966: The determination by radio methods of global thunderstorm characteristics, Report for the National Academy of Sciences (Committee on Atmospheric Sciences, Panel on Atmospheric Electricity), Stanford Research Institute, Menlo Park, California.

COMMENTS ON THE PAPER BY E. T. PIERCE

Heinz W. Kasemir

Atmospheric Physics and Chemistry Laboratory
ESSA Research Laboratories
Environmental Science Services Administration
Boulder, Colorado

In general I agree with Dr. Pierce's paper therefore I can limit myself to only a few points where I deviate from his opinion or where I think the emphasis should be shifted. My remarks will be to the following topics:

1. Sferics Satellite
2. Sferics ground network
3. Lightning counter
4. Analysis of the electric field of near lightnings

1. Sferics satellite. Even considering the limitations of the satellite such as lack of resolving power to pinpoint an individual storm, the loss of a faithful reproduction of the sferics signal by frequency cutoff by the ionosphere, the one task the satellite can do very well, namely scanning rapidly the large thundery areas of the globe would be an important achievement and worthwhile effort. True that the same result could be obtained by a worldwide sferics network, but the satellite would be independent of international organization of such a network and its political ramifications.

2. Sferics ground network. The establishment of a national sferics network with the capability of recording the location of each lightning discharges in the U. S. A. and in the neighboring countries would be indeed a very rewarding enterprise. Here I would like to shift the emphasis to tornado tracking and short range forecasting. I believe that the tremendous number of lightnings produced by a tornado should be identifiable by a sferics network. A government agency like ESSA with its facilities and know-how could be suggested for establishing and operating such a network.

3. Lightning Counter. I support to the fullest Dr. Pierce's recommendation of the wider use of the lightning stroke counter. This instrument is inexpensive, almost maintenance free, and would lift the much needed thunderstorm statistic from a poor estimate to a measured parameter.

4. Analysis of the electric field of nearby lightnings. I disagree with the statement on page 610 of Dr. Pierce's paper: "There have been many investigations of the field changes due to close lightning in which either the electrostatic component or the VLF radiation fields have been studied; further work in these areas is unlikely to be very profitable '. I think the electrostatic field of a close lightning is one of the best sources of information of the electric structure of the lightning discharge as well as the charge

distribution in the thundercloud. Recording instruments with a frequency range from to about 100 KHz are commercially available and well in the state of the art. The evaluation of the data is handicapped by the lack of an adequate theory. The widely used formulas of the oscillating dipole, referred to at the beginning of Dr. Pierce's paper, are not even sufficient as a first approximation. Therefore much information is still hidden in the electrostatic field records of the nearby lightning discharge.