NIGHT-TIME SFERIC PROPAGATION AT FREQUENCIES BELOW 10 kHz

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Summary

Results of a study at Brisbane of individual night-time sferics of known origin are described. A propagation attenuation minimum was observed in the 3–6 kHz range. The geographic distribution of sferic types was also examined. Apparent propagation asymmetries were observed, since sferics were detected at greater ranges to the west than to the east at 10 kHz, whilst the number of tweek-sferics arising from the east was about four times that arising from the west. Comparison with European studies suggest that these asymmetries are general. These results are then interpreted in terms of an ionospheric reflection coefficient which is a function of the effective angle of incidence of the wave on the ionosphere and of orientation with respect to the Earth's magnetic field within the ionosphere.

I. Introduction

The location of the origin of lightning discharge sferics by radio direction finding enables studies of source and propagation effects. Below 10 kHz, sferics are the principal means of investigating v.l.f. propagation characteristics, owing to the absence of transmitters at these frequencies. Previous studies, particularly those made in conjunction with the British Meteorological Office C.R.D.F. Network (operating at 10 kHz) summarized by Hepburn (1958) and Croom (1964), have shown the following:

1. The type of source discharge, e.g. cloud-to-cloud or cloud-to-ground, may be deduced by inspecting the waveforms.
2. Waveforms arising from the cloud-to-ground discharge appear to show a regular variation in appearance with both the distance and direction of the source relative to the receiver.
3. By considering the spectral content of the waveforms as a function of distance, the variation of the propagation attenuation can be deduced as a function of frequency.

The waveguide theory of v.l.f. propagation (Budden 1961; Wait 1962) has gained acceptance in recent years, but little has been done to apply it below 10 kHz to the earlier experimental sferic results, which must find their interpretation in the waveguide mode theory. Thus, in this theory, the earth–ionosphere system may be considered as making up a waveguide in which a lightning discharge acts as an impulsive Hertzian dipole source exciting the possible transmission modes of the waveguide. If the reflection coefficient R of both earth and ionosphere is approximated as $R = +1$, then, for vertically polarized excitation and reception, the resulting TM modal components consist, as in simple microwaveguide theory, of a zero-order

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modal component travelling with the free-space group velocity C and higher-order modal components, each of which may be considered as made up to two crossing self-consistent waves. The angle of incidence of these waves on the guide walls decreases with frequency to zero angle at the cutoff frequency (f_c) of the mode, and the mode becomes evanescent below this frequency. There is a corresponding decrease in the group velocity with decreasing frequency from the free-space value at high frequencies to zero at f_c. The cutoff frequency is given by $f_c = cn/2h$, where c is the free-space velocity, n the modal order number, and h the height of the waveguide. For an earth–ionospheric height of 90 km (e.g. at night) the first-order mode cutoff frequency is about $1 \cdot 7$ kHz. Below this frequency only the zero-order mode will propagate, whilst at 4 kHz, for instance, zero-, first-, and second-order components are present, each with its characteristic group velocity.

At night such behaviour is indeed observed, and the sferic form resulting from the propagation dispersion in the waveguide is known as a "tweek", so named by Burton and Boardman (1933) because of the distinctive musical sound when heard in a loudspeaker. Plate 1 shows frequency–time plots (sonagrams) of such sferics made with a Kay-Electric "Sonagraph". The retardation of the modal component frequencies corresponding to acute angles of incidence is clearly seen. However, whilst the tweek-sferic is commonly heard at night, not all night-time sferics show such dispersed components. It is of interest, therefore, to ascertain the conditions necessary for a tweek to arise.

The present paper describes the results of a study of individual night-time sferics whose origin had been found with the aid of the sferics C.R.D.F. network operated by the Commonwealth Bureau of Meteorology. In particular, the occurrence of the tweek-sferic is examined and an interpretation of its spatial occurrence made in terms of waveguide mode theory.

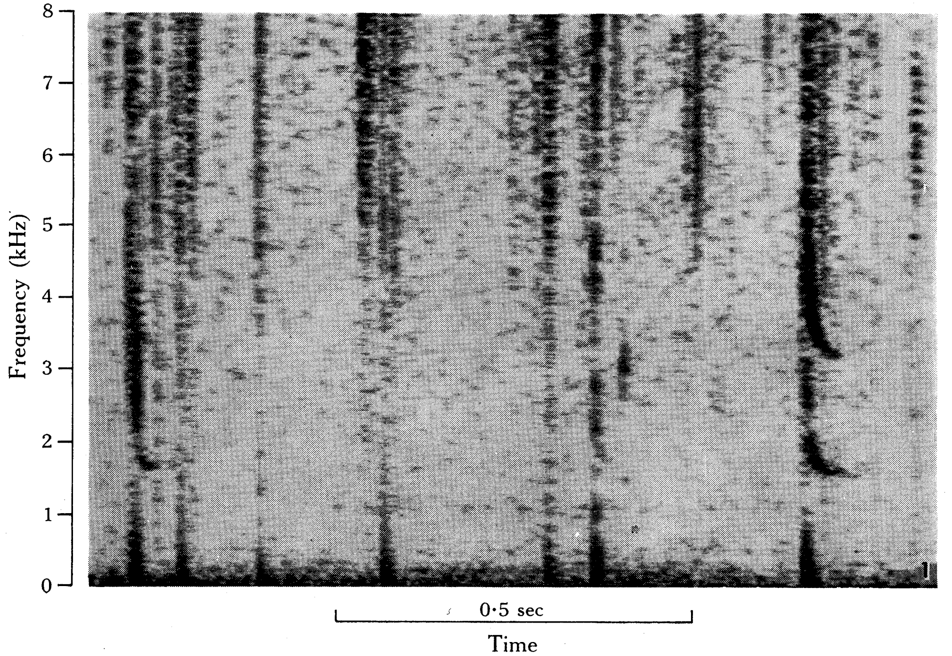
II. Experimental Method

The Commonwealth Bureau of Meteorology operates a C.R.D.F. sferic location network from Brisbane, other stations in the net being located at Charleville, Townsville, and Cloncurry. The direction finding is done at a frequency of 10 kHz. Arrangements were made so that sferics recorded at the Samford field site with comparatively wide band equipment could be identified with sferics located by the C.R.D.F. network.

Sferics were received at Samford with a top-loaded vertical wire aerial feeding a low-pass filter and preamplifier. The main amplifier and recording tape decks were located some 100 yd distant. The received signal strengths ranged from a few up to hundreds of millivolts per metre, depending on storm distance. The total system response on replay was flat to 3 dB from 1 to 7 kHz, and was 10 dB down at $0 \cdot 5$ and 10 kHz.

A Kay-Electric "Sonagraph" analyser was used to obtain the frequency spectra of received sferics. In order to relate the sferics to the waveform studies of other authors, waveforms were examined on a restricted scale and compared principally with the description and examples of Hepburn (1958). The comparatively narrow bandwidth of the recording system resulted in some waveform distortion but not sufficient to prevent identification of the main sferic types.

NIGHT-TIME SFERIC PROPAGATION



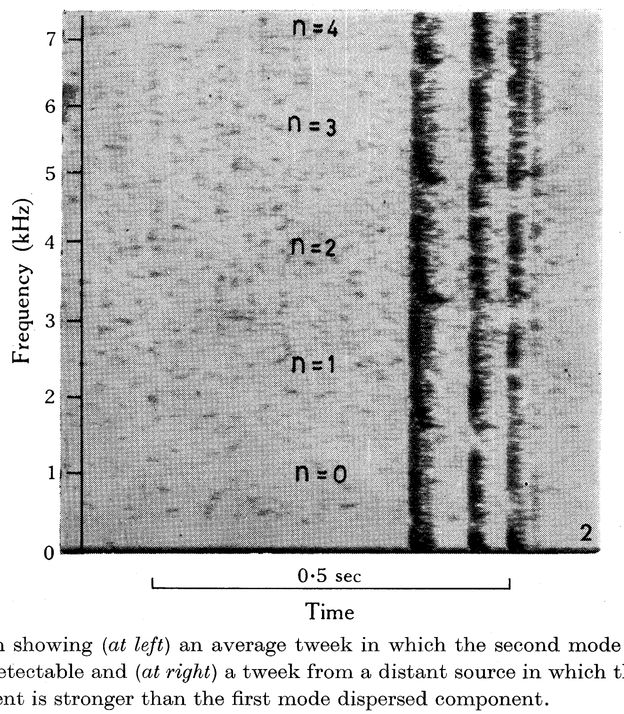


Fig. 1.—Sonagram showing (*at left*) an average tweek in which the second mode dispersed component is barely detectable and (*at right*) a tweek from a distant source in which the second mode dispersed component is stronger than the first mode dispersed component.

Fig. 2.—Sonagram of tweeks arising from a multiple ground return stroke. The first four modal components can be seen near their cutoff frequencies. (Distance 1000 km; bearing 30°.)

NIGHT-TIME SFERIC PROPAGATION

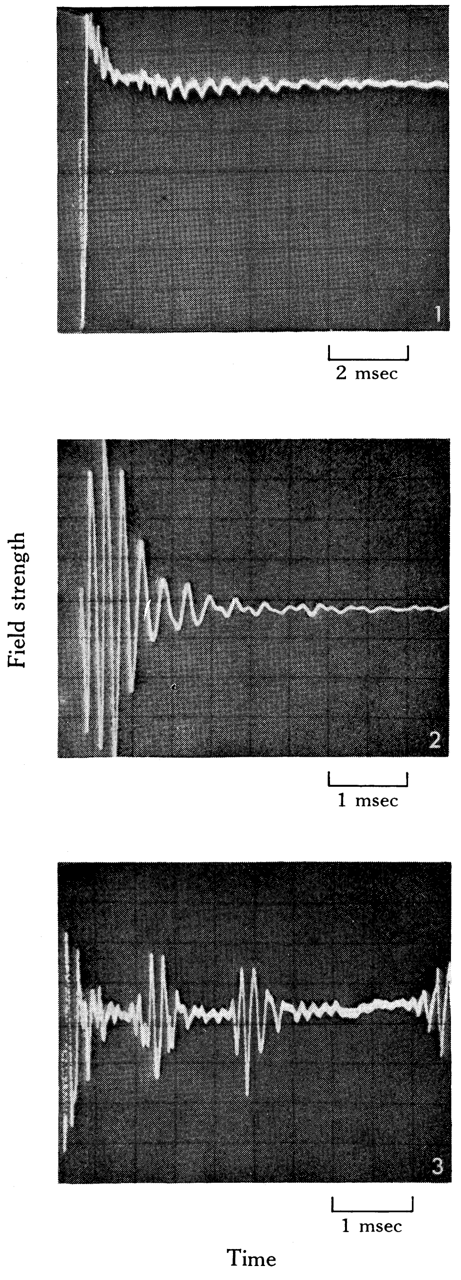


Fig. 1.—Waveform of a typical tweek. (Distance 2200 km; bearing 10°.)

Fig. 2.—Waveform of undispersed ground return stroke of quasi-sinusoid type. (Distance 2500 km; bearing 10°.)

Fig. 3.—Waveform of cloud-to-cloud discharge (cloud dart type). (Distance 2800 km; bearing 310°.)

(Field strength scales are arbitrary, and different.)

III. Experimental Results

(*a*) *Sferic Types*

In the search for possible variations of sferic types with geographic location relative to the receiver the night-time sferics were divided into tweeks and undispersed sferics. An undispersed sferic, in this study, is defined as one in which no dispersed modal components could be distinguished either with the ear or with the Sonagraph. Waveforms were examined and the undispersed sferics thus further divided into undispersed ground return strokes and cloud-to-cloud discharges. Waveforms of a typical tweek, of an undispersed ground return stroke sferic similar to the quasi-sinusoid type of Hepburn, and of a cloud dart discharge sferic are shown in Plate 2. Cloud-to-cloud discharges were rarely identified at ranges greater than 1000 km owing to their relatively small amplitude. Replayed at a speed some 10 to 20 times slower than normal, the cloud discharge sferic characteristically sounded as a broad hiss compared with the sharper thud of the undispersed ground return stroke sferic and the rapidly descending whistle of a tweek.

As will be made clear in Section IV(*c*), large geographic areas existed from which the tweek was characteristically received, suggesting that the occurrence of the dispersed modal components depended on propagation conditions rather than on some unusual source discharge. As might be expected from the low pulse amplitude and multiple nature of the cloud discharge, no tweeks were found to originate from such discharges.

(*b*) *Reflection Height*

The value of f_c for the first-order mode was measured from the sonagrams of 38 tweeks as $1\cdot65\pm0\cdot05$ kHz, corresponding to an effective reflection height, at vertical incidence at this frequency, of 91 ± 3 km (using the formula of Section I). The r.m.s. error quoted reflects the error in measuring the sonagrams rather than any variation in reflection height.

(*c*) *Attenuation*

Day-time sferic waveforms are short and damped, indicating a large departure from the simple $R = +1$ approximation for the ionospheric coefficient. Tweeks were thus not heard in daytime except (as originally reported by Burton and Boardman) when night conditions were sufficiently close to the receiver for tweeks to penetrate the short daytime path of up to about 1000 km.

At night, as previously reported by Outsu (1960), the number of distinguishable dispersed modal components present in a tweek decreased with distance, as might be expected owing to the greater attenuation of higher modes. It was also found that the attenuation of the dispersed component varied with direction relative to the receiver and this is further discussed in Section IV(*d*). Figure 2 of Plate 1 shows a sonagram of a group of tweeks arising from a multiple ground return stroke at 1000 km to the north-east of Brisbane. In the sonagram the first four modal components are resolved near their cutoff frequencies. Characteristically, at 3000 km only the first-order mode dispersed component could be distinguished. However, propagation conditions appeared to vary from night to night, and, occasionally, multiple component tweeks were received from the limit of the normal identification range ($\sim$ 3000 km) and beyond, as evidenced by their small amplitude and great dispersion. On such nights the faint background of distant sferics appeared to consist largely of tweeks. The period of observation was geophysically quiet, and such changes appear to be most likely due to the presence or absence of D-region irregularities, which are known to be prevalent at night (e.g. Gossard and Paulson 1964).

By comparing the relative intensity against frequency of many sferics received over different distances the individual variation in source spectra may be eliminated, giving the variation of the propagation attenuation with frequency. The sonagrams of tweeks received from a variety of distances were thus compared and the relative intensity deduced from the degree of sonagram blackening.

As a further check the spectral composition of selected sferics was also examined using the sectioning facility of the Sonagraph machine. Whilst the method used was crude, the following general conclusions could be drawn.

1. The attenuation of the zero-order modal component where it alone was present (i.e. below 1·65 kHz) increased with frequency and at 1·65 kHz appeared to be some 4 dB per 1000 km greater than that of the modal component sum at 3 kHz.

2. A minimum in propagation attenuation occurred below 8 kHz. The position of the minimum lay between 3 and 6 kHz, where the attenuation appeared to be some 2 dB per 1000 km less than at 8 kHz.

(*d*) *Distribution of Sferic Types*

The results discussed were obtained from sferics located on 30 nights at 2035 hr E.S.T. and on 20 nights at 2330 hr E.S.T. between December 1963 and March 1964. Owing to the distribution of storm activity over Australia during the period of observation, an insufficient number of sferics was received beyond 500 km in the southern half of a circle centred at Brisbane for useful conclusions to be reached. In the north-east and north-west quadrants from Brisbane a total of 294 sferics was located. Of these the waveforms of 120, including, in particular, those within 2000 km of Brisbane, were examined. Thirteen cloud-to-cloud discharges were thus identified, leaving 281 ground discharge sferics to be considered. These sferics were divided into tweeks and undispersed sferics (as defined in Section III(*a*)). The sferic distributions for the two observation periods were plotted on maps and examined separately. Since no significant difference was observed in the two time distributions, they have been combined. The scheme of relative occurrence of tweeks as a function of distance for the north-east and north-west quadrants is given in Table 1. Two conclusions may be drawn.

1. Sferics were identified at 10 kHz from greater distances to the west than to the east.

2. The tweek-sferic occurred more commonly in the north-east quadrant than in the north-west quadrant.

The second point is emphasized in the comparison below of the percentages of tweeks in the four northern 45° sectors in the distance range 1500–3500 km centred on Brisbane (195 sferics received).

Bearing (octant)	E.–NE.	NE.–N.	N.–NW.	NW.–W.
Tweeks (%)	100	78	62	26

The tweek percentage is seen to decrease from east to west.

The greater range of sferic identification from the west is to be expected from the well-known east–west v.l.f. propagation asymmetry for oblique angles of incidence. For instance, Watt and Croghan (1964) give west–east attenuation as 2–3 dB per 1000 km less than east–west at 10 kHz. However, the tweek as a waveform received predominantly from the east was the reverse of what might have been expected, and if this is taken as being due to an ionospheric propagation attenuation asymmetry it would imply that for the modal components near the mode cutoff frequency the east–west attenuation was some 3 dB per 1000 km less than the west–east attenuation. Discussion of this matter is reserved for Section IV.

Table 1

PERCENTAGES OF TWEEKS IN 281 GROUND RETURN STROKE SFERICS RECEIVED IN THE NORTH-EAST AND NORTH-WEST QUADRANTS

Quadrant	Distance from Brisbane (km)				
	500–1500	1500–2500	2500–3500	3500–4500	>4500
NE.	100%	78%	92%	—	—
NW.	80%	59%	39%	15%	0%

The cloud discharges located by the C.R.D.F. net lay, in general, close to the stations. At these short ranges they were more frequently located than ground return strokes, as might be expected from the greater production rate of cloud-to-cloud discharges compared with the ground return discharge. The situation was reversed at distances greater than 1000 km owing to the intrinsically greater amplitude of the ground return stroke sferic.

IV. Discussion

In considering the attenuation minima observed below 8 kHz both modal excitation and attenuation factors are important. Between 1000 and 3000 km to the east, rapid attenuation of higher-order modal components was observed in the 5–8 kHz range. The theoretical ratios of modal excitation factors of the zero-order and first four modes that can propagate at 8 kHz are approximately $\frac{1}{2}:1:1:1:1$ (Budden 1961; Wait 1962). Since the attenuation of all higher-order modes is much greater than that of the first-order mode, some seven-ninths of the energy goes into rapidly attenuating modes at this frequency as against one-third at 3 kHz where only the zero- and first-order modes can propagate. Moreover, the least attenuated first-order mode attenuation factor as given by Wait (1957) exhibits a minimum between 8 kHz and the infinite attenuation at the modal cutoff frequency. Both these factors are compatible with the observed attenuation minima. Further, Croom (1964), by analysing waveforms, also found a minimum below 8 kHz.

Croom summarizes the attenuation results derived from sferics by past workers, the most noteworthy feature being the lack of agreement below 10 kHz, indicating the difficulties of interpretation and analysis of sferics in this region. In general, at these frequencies the attenuation coefficient derived by comparing spectra at different distances is, in fact, a summation of several modal attenuation coefficients acting on modal components of different relative strength at the one frequency, and thus the apparent attenuation factor varies with distance. Moreover, it is sometimes overlooked that the group-velocity dispersion results in segregation of the modal component frequencies in different parts of the waveform. A Fourier analysis of only the first few milliseconds of a waveform may indicate an unrealistically large attenuation with distance for frequencies in the 2–5 kHz range, since only the zero- and higher-order modal component amplitudes far from cutoff would be found. Much of the energy at these frequencies would actually lie later in the waveform, particularly so in the tweek, the long dispersed tail of which, though of small amplitude, is not negligible in terms of energy because of its great duration (e.g. tens of milliseconds).

Factors of possible importance in explaining the observed asymmetry in sferic type distribution and detection range are

(i) increased propagation attenuation over land relative to sea;

(ii) a dependence of the amplitude and phase of the ionospheric reflection coefficient on the orientation of the incident wave relative to the Earth's magnetic field;

(iii) a geographic variation in lightning discharge characteristics.

In general, it is not possible to differentiate between these possibilities experimentally for sferics received at only one site. However, results obtained from England, for which the geographic situation was essentially the reverse of that at Brisbane, are available for comparison. The chief English night asymmetry results (Horner and Clarke 1955; Chapman and Pierce 1957; Hepburn 1957, 1958) may be summarized as follows.

1. Sferics (at 10 kHz) were identified at greater distances to the west than to the east.
2. The long train reflection waveform (i.e. tweek) was essentially an eastern waveform.
3. To the west the reflection type of waveform rapidly gave way with distance to the quasi-sinusoid, and the distant long train reflection waveform was not observed.

If these results are compared with those obtained at Brisbane it will be seen that the asymmetries show the same directional dependence, despite the fact that the distribution of land and sea is the opposite in the two locations. This agreement would suggest that the Earth's magnetic field is the chief cause of the observed asymmetry, a possibility previously raised by Hepburn (1957). Thus, attenuation at 10 kHz corresponding to obtuse angles of incidence was less for propagation from the west than from the east, whilst attenuation of the dispersed waveform component corresponding to acute angles of incidence appeared greater from the west than from the east.

The variation of the modulus of the ionospheric reflection coefficient R with angle of incidence allowing for the Earth's magnetic field was calculated by Barber and Crombie (1959) for east–west and west–east vertically polarized wave propagation at the equator, where the asymmetry is a maximum. For obtuse angles of incidence it was found that $|R_{W-E}| > |R_{E-W}|$, as is known experimentally (Crombie 1958; Watt and Croghan 1964). For acute angles of incidence the asymmetry was reversed and $|R_{W-E}| < |R_{E-W}|$. Similar behaviour was found by Field and Tamarkin (1961), though in the ionospheric models used the asymmetry reversal for acute angles of incidence produced a negligible east–west attenuation difference in practical terms. Barber and Crombie also calculated the argument of R, i.e. the phase change on reflection at the ionosphere, for east–west and west–east propagation. It was found that for east–west propagation the phase change on reflection was 360° as for a perfect conductor, whilst for west–east propagation the phase change was 180°. The direction of this asymmetry was confirmed by Field and Tamarkin with more extensive calculations of the variation of the argument of R with angle of incidence.

The tweek as an eastern waveform is compatible with the above asymmetries. For a tweek to arise at all with the observed cutoff frequency implies an ionospheric reflection phase change close to 360°. The observed change in the waveform of the ground return stroke, from a tweek as received from the east, to a short damped waveform as received from the west could be due either to a decrease in the argument of the reflection coefficient or to a marked departure of the phase change on ionospheric reflection from 360° for acute angles of incidence as the propagation direction changes from east–west to west–east. It would seem that, of the two, the variation in the reflection phase would be the most significant, but the theoretical magnitude of these effects is not, as yet, clear.

It is thus suggested that the major asymmetries in sferic waveform distribution as observed at night in low and temperate latitudes are propagation effects produced essentially by an anisotropic ionosphere. It is evident that more theoretical work is needed in finding the effects of v.l.f. ionospheric reflection asymmetries at acute angles of incidence on the characteristics of the propagation modes. Experimentally, more work is required at different sites to confirm that the sferic waveform asymmetries are indeed general.

V. Acknowledgments

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