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Frontal and non-frontal characteristics of mid-latitude spread-F structures

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The experimental evidence for frontal and non-frontal structures associated with mid-latitude spread-F occurrence is presented and discussed. The evidence suggests that on most occasions frontal travelling ionospheric disturbances (TIDs) are primarily responsible for the recorded spread-F traces. However, at times non-frontal movements are detected due possibly to interference effects from TIDs travelling in different directions, or from the influence of small-scale structures which are also present at these times. At other times large-scale non-frontal "tongues" of ionization (of which the occurrence rate is somewhat uncertain) have also been detected when spread-F traces are observed.

1 Introduction

The early work on large-scale structures associated with mid-latitude spread-F was recently reviewed by Bowman[1]. One of these early papers published several decades ago[2] presented results of an extensive investigation of these structures. This early investigation used recordings of virtual range versus time (i.e., *h't* plots) at a fixed frequency of 2.28 MHz. Recordings were made at three stations spaced from each other by distances of approximately 100 km. The *h't* recordings from these three stations were used to calculate the speeds and directions of travel of ionospheric disturbances associated with the mid-latitude spread-F phenomenon. Furthermore a frequency of 2.28 MHz is reflected near the base of the nighttime F2 layer so that retardation effects are minimal. Thus the virtual ranges at this frequency are a good indication of the true ranges of the recorded signals.

McNicol *et al.*[2] recognized that the primary components of mid-latitude spread-F were traces which were "satellites" of the main trace which on most occasions moved towards or away from the main trace at rates expected for uniform horizontal movements of the reflecting surfaces. In this paper these extra traces will be called "duplicate" traces since on an ionogram they are seen as duplicates of the main traces but at ranges in excess of the main traces. These duplicate traces (either as single traces or a series of traces at different ranges) were seen sometimes to advance towards the main trace, coalesce with it and then move

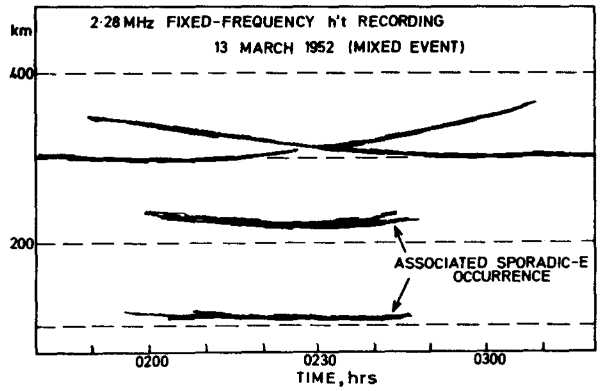

Fig. 1 – Example of a mixed spread-F event recorded at fixed frequency (after McNicol *et al.*[2])

away as Fig. 1 illustrates for a single duplicate trace. These were called "mixed" events. At other times the duplicate traces were found only to move away ("diverging" events) or only to move towards ("converging" events) the main trace, as Fig. 2 illustrates for a single diverging duplicate trace shown on ionograms. Although the coalescing with the main trace of the mixed, diverging and converging traces is suggestive of or at least consistent with the spread-F structures being frontal, there was a small percentage of recordings which suggested the presence of non-frontal structures. For 3 per cent of the time when duplicate traces were recorded, these extra traces did not join the main trace but remained more or less parallel with it during their lifetime. These particular (parallel) events suggest that the traces

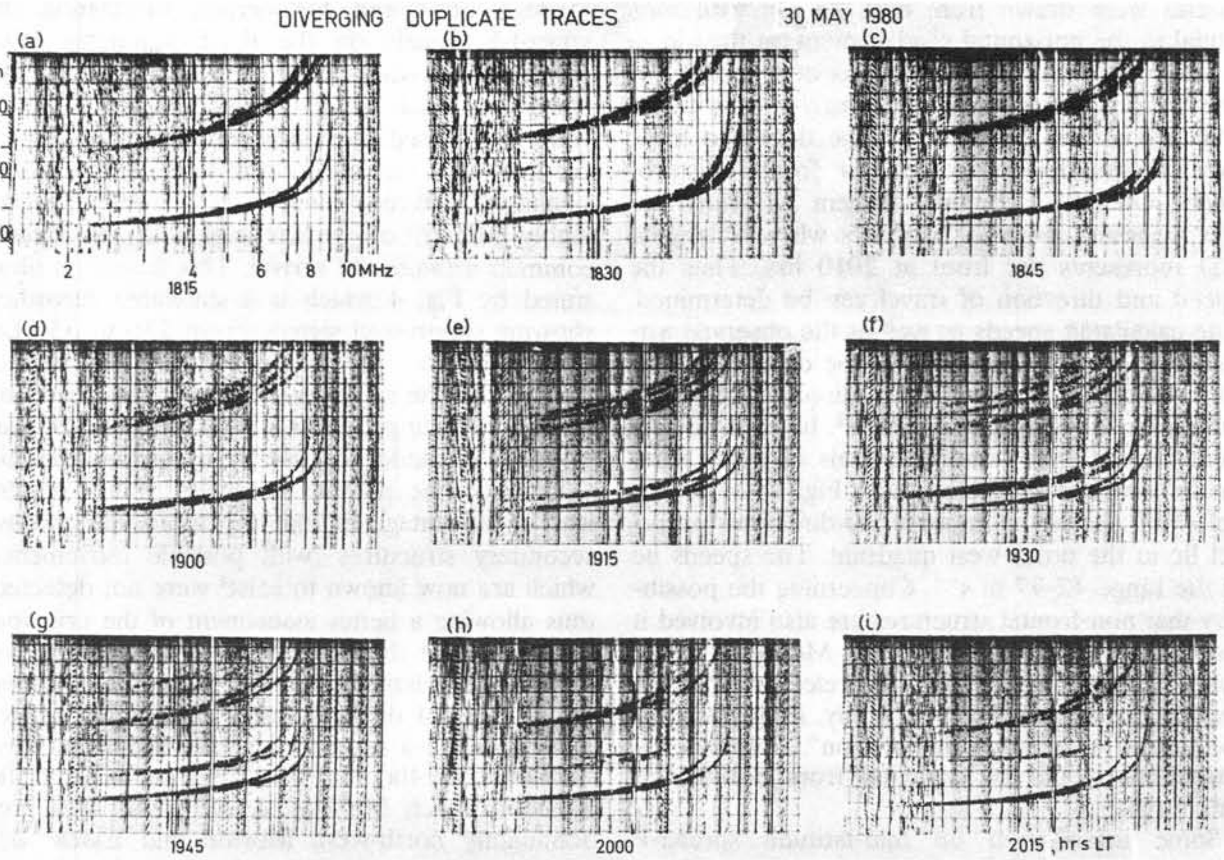

Fig. 2 – Example of diverging duplicate spread-F traces as observed on ionograms recorded at Brisbane on 30 May 1980

are produced by reflections from non-frontal structures which if moving will not necessarily pass overhead at the recording site.

The present paper reviews and discusses the existing evidence (including some hitherto unpublished results) for both frontal and non-frontal structures associated with the mid-latitude spread-F phenomenon. Recordings are considered for Brisbane (27.5°S, 153.0°E, dip 57°). In addition, results are presented for Bribie Island, Buderim and Toowoomba. These stations are located 60, 95 and 95 km from Brisbane at azimuths (relative to geographic north) of 010°,000° and 270° respectively.

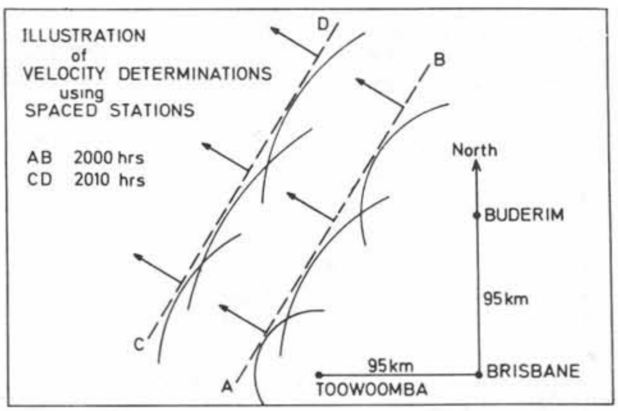

Fig. 3 – Diagram illustrating method used by McNicol *et al.*[2] to calculate speeds and directions of travel of spread-F TIDs

2 Results

2.1 Evidence for frontal structures

The analysis by McNicol *et al.*[2] was comprehensive as many events were considered. The duplicate traces which were classified as parallel, convergent, divergent or mixed were recorded in the ratios 1:8:20:6. Thus it can be seen that traces which merged with or moved away from the main trace were 34 times more likely than traces which were parallel. Furthermore the most dominant type was the diverging trace.

Another aspect of the investigation by McNicol *et al.*[2] was that it provided strong support for the concept that frontal structures were primarily involved. Fig. 3 illustrates the use of the three spaced stations (Brisbane, Buderim and Toowoomba) to determine the speed and direction of travel of disturbances. At a particular time arcs of circles were drawn from each station with radii equal to the horizontal displacement (in the ionosphere) of the calculated positions of reflection for the duplicate traces. As illustrated it was found that a common tangent could be drawn to these arcs as would be expected for frontal disturbances. On Fig. 3 common tangent AB illustrates the suggested front at 2000 hrs whereas tangent CD represents the front at 2010 hrs. Thus the speed and direction of travel can be determined. The calculated speeds as well as the observed azimuths of travel were found to be consistent with the values determined from direction-of-arrival measurements made at Brisbane[2]. In all 87 determinations of speed and directions of travel were made using the spaced stations. Fig. 18 of McNicol *et al.*[2] shows that most of the directions of travel lie in the north-west quadrant. The speeds lie in the range 42-97 m s^{-1}. Concerning the possibility that non-frontal structures are also involved it seems important to note what McNicol *et al.*[2] state, referring to the arcs of circles drawn from the three stations, "There is rarely, if any, any indication of a common intersection". Common intersections would be expected from non-frontal structures.

Some information on mid-latitude spread-F structures was obtained by using a system of rotating loops[3]. The system rotated continually through 360° and for certain orientation the spread-F signals on the fixed frequency (3.84 MHz) *h't* recordings were suppressed, indicating a specific azimuth of arrival for the traces which were suppressed. A consistent feature of the recordings was that at any one time all the spread signals at different ranges (and therefore presumably different off-vertical angles) had essentially common azimuths of arrival. This feature is illustrated by Fig. 4 which is a simulated recording showing suppressed signals (from 250 to 350 km range) all with a common azimuth of 310° east of true north. The identification of discrete traces on spread recordings which would otherwise appear diffuse was made possible by using a swept-gain technique. The relative simplicity of this system was an advantage in that the more complicated secondary structures (with possible movements) which are now known to exist[4] were not detected, thus allowing a better assessment of the principal structures and their movements. It is difficult to explain the relatively constant azimuths-of-arrival for a series of discrete traces at different ranges other than by a series of parallel fronts, as illustrated by Fig. 4(a) and (b), all moving in a specific direction which McNicol *et al.*[2] found was predominantly north-west. Morton and Essex[5] detected nighttime travelling ionospheric disturbances (TIDs) travelling in north-west directions

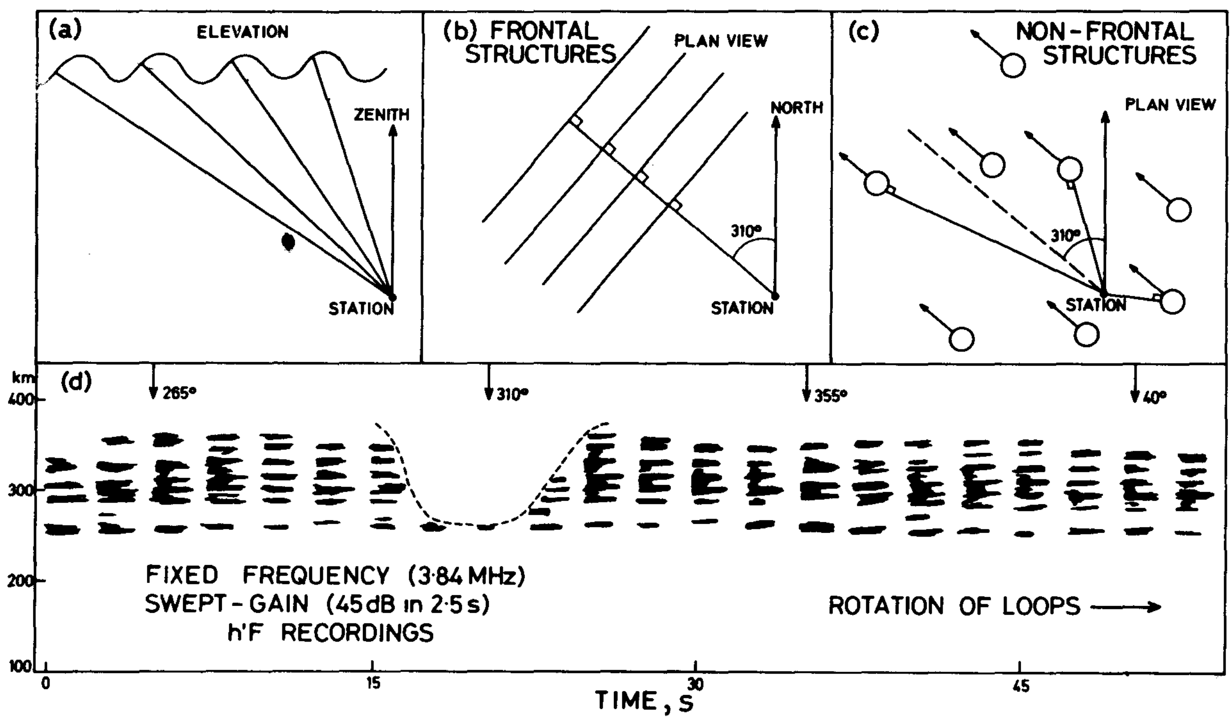

Fig. 4 – (a) Elevation view and (b) plan view of suggested frontal structures; (c) plan view of non-frontal structures; and (d) simulated rotating-loops recording showing azimuths-of-arrival of around 310° (after Bowman[3])

for somewhat higher (Southern Hemisphere) latitudes. Thus common azimuths for traces at all ranges can be expected for frontal structures as illustrated. However, for non-frontal structures moving either in a common direction [Fig. 4(c)] or in random directions, the azimuth measurements on them should be scattered over many angles. Results similar to these sunspot-maximum results by Bowman[3] were reported by Clarke[6] for a sunspot-minimum period. In addition extensive direction of arrival measurements on spread-F signals by Clarke[7] led him to state "An analysis of directional ionograms showing resolved spread-F (satellite) traces indicates that the causal irregularities are frontal with horizontal wavelengths of around 65 km".

Monro[8] (see also Fig. 1 of Bowman and Monro[9]) was able to make direction-of-arrival measurements at closely-spaced time intervals of a single duplicate trace as it approached and later moved away from the main trace for an event similar to the "mixed" event illustrated by Fig. 1. A fixed frequency of 2.28 MHz was used. These direction-of-arrival measurements are reproduced in Fig. 5. Although the reflection positions on the advancing structure as well as the receding structure are shown to change azimuth continually in a somewhat random fashion, nevertheless it seems obvious that the disturbance responsible for these traces passes overhead (moving in a north-west direction) and is therefore probably frontal in nature. However, the quasi-random movements of the azimuth are suggestive of non-frontal movements over intervals of time of the order of 10 min. For example from 2023 to 2055 hrs the movement is apparently to the north-east (see line AB) while from 2055 to 2115 hrs the movement is more westerly (line BC) than the overall direction of movement to the north-west. These random movements are probably associated with the small-scale segmentations of the duplicate traces on range-spread ionograms reported by Bowman[4]. Events of this kind involving only one duplicate trace at a time represent the simplest form of the spread-F phenomenon. For events involving several duplicate traces, particularly if they are overlapping as represented by unresolved spread-F, the random motions might be expected to be even more severe.

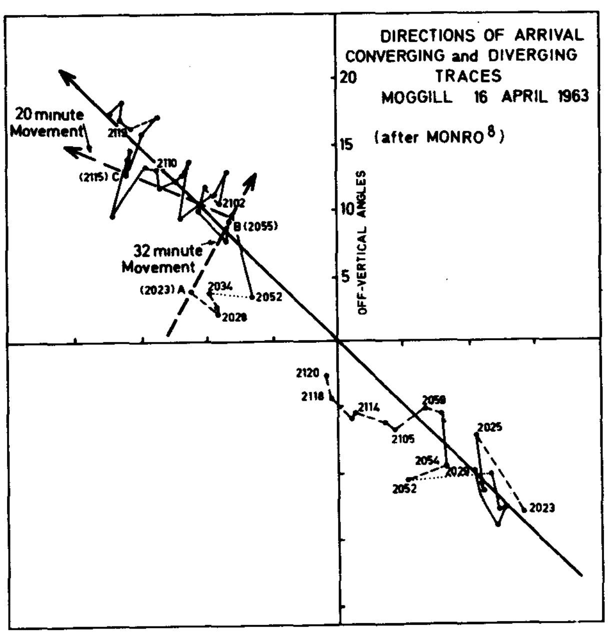

Fig. 5 – Directions-of-arrival of duplicate traces (at closely spaced time intervals) for a mixed spread-F event on 16 Apr. 1963 (after Monro[8])

Finally, the discovery of wavetrains in the isoionic contours at times of spread-F occurrence (see Fig. 3 of Bowman[10], and Fig. 6 of Bowman and Monro[9]) is consistent with an association between frontal travelling ionospheric disturbances (TIDs) and spread-F.

2.2 Evidence for non-frontal structures

Despite what seems to be convincing evidence for frontal structures being associated with the mid-latitude spread-F phenomenon, other measurements have been made showing that at times what appear to be non-frontal movements also occur. The frequency of occurrence of these non-frontal structures is at present uncertain. However, mention has already been made of extra traces on *h't* recordings which do not join the main trace during their lifetime. This behaviour, which occurs for a small percentage (3 per cent) of the time when extra traces are recorded, is consistent with reflections occurring from non-frontal structures.

Although, as mentioned earlier, Clarke[7] concluded that spread-F structures were frontal, he did report one occasion when direction-of-arrival measurements suggested a non-frontal structure. Fig. 6 is a reproduction of his Fig. 7-17 showing the movements of two duplicate traces as observed from directional information on ionograms. Clarke[7] labelled these traces as satellite A and satellite B. The structures responsible for these two duplicate traces were each tracked for approximately one hour. Since the closest approach to the observing station of the satellite A structure is about 200 km, it seems likely that this is a non-frontal irregularity. Of satellite B Clarke[7]

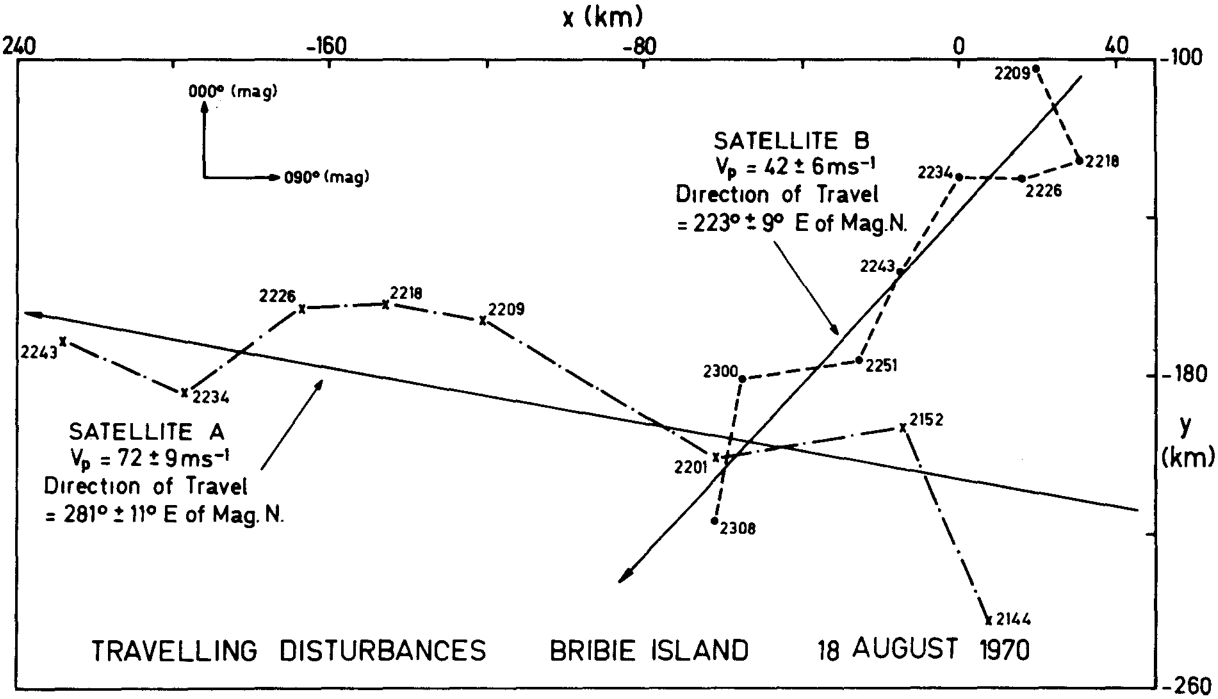

Fig. 6 – Plan positions of the movements of two duplicate traces (labelled Satellite A and Satellite B) on 18 Aug. 1970 (after Clarke[7])

states "A second satellite trace (labelled B) appeared to be coincident with the main trace between 2200 and 2215 hours, thereafter its virtual range increased. Consequently, this trace may represent reflections from a frontal TID". These recordings were made on Bribie Island.

What appears to be the most convincing evidence yet for the existence of non-frontal structures at times of spread-F occurrence comes from the detection of "tongues" of ionization. These consist of isolated enhanced regions of plasma density which extend to significantly low levels below the nighttime F2 layer, at times when spread-F is recorded on ionograms. Airglow measurements in Hawaii[11] record a well-defined structure of this nature for a period of about 2 hr. The airglow measurements clearly indicate a non-frontal structure. In his paper on spread-F, King[12] has made calculations which indicate that this particular tongue extends down from the layer 64 km and passes within 400 km of the recording station.

Bowman and Dunne[13,14] used ionograms to detect tongues of ionization similar to those reported by Van Zant and Peterson[11] who used airglow measurements. Over a two-month period Bowman and Dunne[13] estimated that tongues were present on 34 occasions during a period of 55 hr when spread-F was present. A detailed examination of a "tongue" event (on the night of 31 July/1 Aug. 1981) was made by Bowman and Dunne[14]. The analysis suggests a large tongue of ionization extending down below the base of the layer by approximately 100 km. The duplicate traces produced by this structure resulted from signals coming from different positions on the structure as it moved in a north-west direction. This direction of movement was the same as wavelike frontal structures (which are more regularly associated with spread-F) which apparently were also present. Fig. 7(a) shows the general north-west movement of the "eye" of the tongue while Fig. 7(b) shows the reflection positions at a frequency of 3.5 MHz as the position of reflections moves to different positions on the structure.

More recently From and Meehan[15] have presented experimental evidence for the existence of non-frontal structures at times of spread-F occurrence. Their Fig. 5 shows "a scatter plot of the directions of travel of spread-F echoes". In general their directions are not consistent with those expected from frontal structures for which directions of travel should be directed through the position of the recording station as illustrated by Fig. 5. However they do state "the previously reported very strong bias for angles-of-arrival from the north-west at Brisbane is supported".

3 Discussion

Experimental evidence which supports the idea that large-scale structures have a central role to

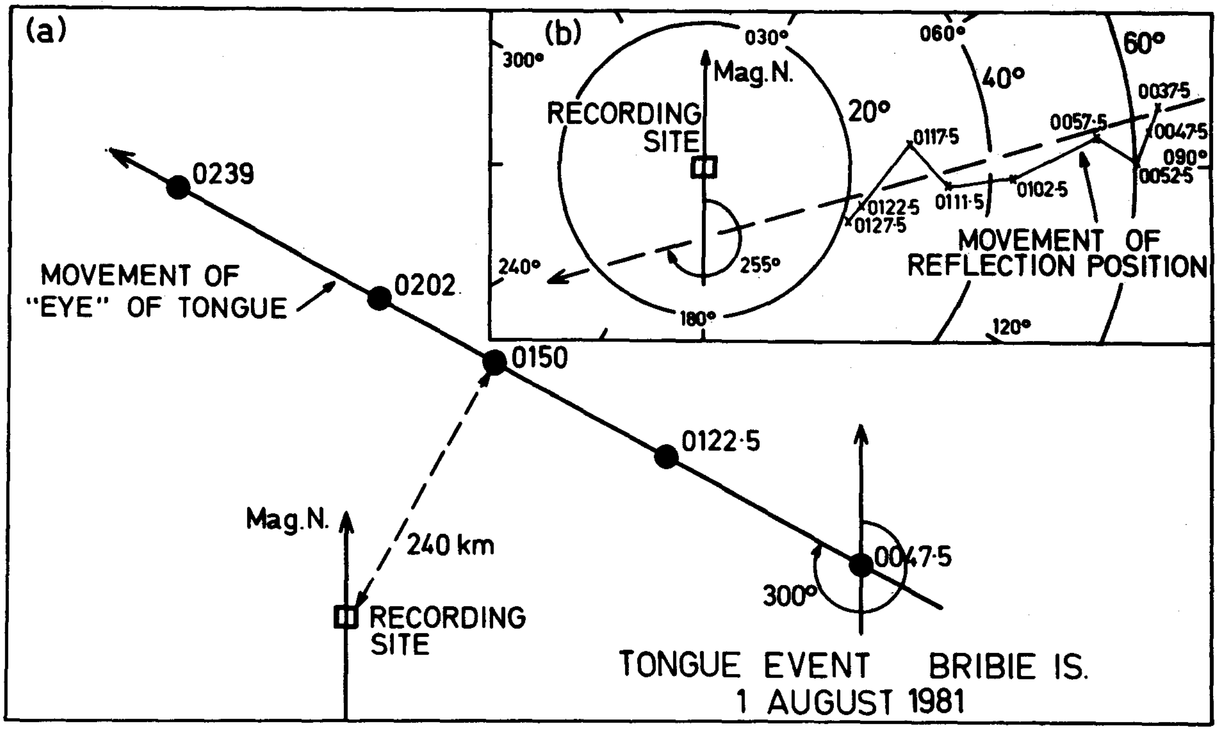

Fig. 7 – For a "tongue" event on 1 Aug. 1981: (a) general movement of the large-scale structure, and (b) movement of the reflecting point as it changes position on the large-scale structure

play in the recording of spread-F traces on ionograms is on the increase, especially so in more recent years[16–18]. Even for equatorial regions Argo and Kelley[19] suggest that atmospheric gravity waves are involved in spread-F occurrence on ionograms (see also Rottger[20]). For a temperate latitude Rastogi[21] states "The temperate latitude spread-F is suggested to arise mostly from the reflection of radio waves from the ripples and undulations in the iso-ionic surfaces in the ionosphere rather than from the scattering of radio waves from plasma instabilities".

In the early days of the recording of spread-F on ionograms, small-scale structures were thought to be involved because of the correlation of radio wave scintillations from artificial earth satellites and extra terrestrial sources with spread-F occurrence[22]. However, although this association continues to be reported, it is now known that large-scale structures are also present at these times as detected by total electron content (TEC) changes or resolved duplicate traces observed on the spread-F ionograms[23,24]. Sinno and Kan[25] reported the recording of "irregular fluctuations of Faraday rotation angle, ... with periods a few minutes up to several tens of minutes .... At the same time, severe intensity scintillation of period usually shorter than one minute occurred".

As far as spread-F is concerned the experimental results suggest (if they are large structures which are being considered) that both frontal and non-frontal structures are associated with its occurrence. As far as the frontal structures are concerned they can be regarded as travelling ionospheric disturbances (TIDs)[9] which it seems likely result from the presence of atmospheric gravity waves. If this is so then the possibility of two or more such TIDs being present at the same time but travelling in different directions should be considered. Evidence for the existence at one time of more than one disturbance was reported by McNicol *et al.*[2] Referring to the fronts which they deduced from the tangents to the arcs drawn from their three stations they state "The simultaneous occurrence ...... of two independently moving tangents is fairly common". This duplication of tangent orientation presumably occurs when measurements are made on two different duplicate traces on the *h't* records. Thus it seems likely that when single events are recorded (see e.g. Figs 1 and 2) other TIDs may be present with amplitudes sufficiently small that they are not detected by the equipment being used. During very disturbed spread-F conditions, no doubt there are several disturbances travelling in different directions contributing to the spread which is ob-

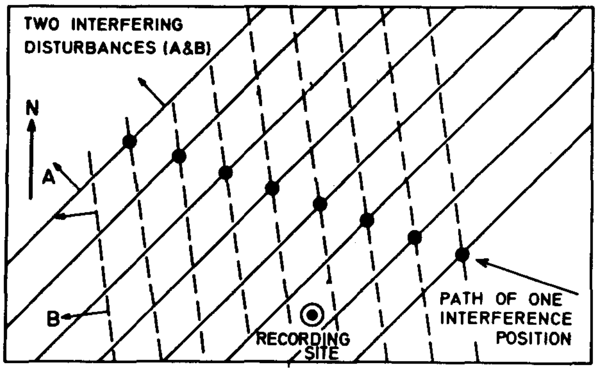

Fig. 8 – Diagrammatic illustration of two interfering wavetrains travelling in different directions

served. Some of the non-frontal movements reported here including the quasi-random movements seen in Fig. 5 may be explained by interference effects caused by the presence of additional TIDs as well as the presence of small-scale structures which are now known to exist at these times[4]. Fig. 8 illustrates diagrammatically at spaced intervals of time the positions of either the crests or the troughs of one cycle of each of two wavetrains (wavetrain A and wavetrain B) travelling in different directions. The straight line of black dots shows one of the movements associated with enhanced crests or troughs due to interference effects between the two wavetrains. If this interference produces a structure (perhaps an enhanced isolated trough region) which can be tracked by HF radio waves, the direction of travel will not necessarily pass through the observing station. Some of the tongue events may be explained in this way. Further investigation of tongue events is needed to discover whether or not this is true. There is some experimental evidence[14] that tongues of ionization occur in association with frontal TIDs.

4 Conclusions

Finally considering all the evidence it seems likely that wavelike frontal structures are primarily responsible for nighttime mid-latitude spread-F conditions although the extent of the role played by tongues of ionization has yet to be determined. The small-scale structures which are also present, as well as the possibility of interference effects from the presence of two or more TIDs, may be responsible for the quasi-random movements[15] which have been reported.

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