J Geophys (1983) 52:158–166

Journal of Geophysics

A Technique for Studying Density Gradients and Motions of Plasmaspheric Irregularities*

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Abstract. Terrestrial myriametric radiation (TMR) is received by spacecraft in the magnetospheric cavity beyond the plasmasphere. There is now general agreement that the radiation emanates mainly from the plasmapause and a technique is under development which allows information on the source regions to be extracted. The method is based on the theory that the radiation has passed through a radio window, this being one mechanism for producing TMR which is receiving considerable attention at present. With accurate direction-finding measurements in which wave polarisation effects must be considered, it is shown how the radial and local-time positions of the TMR sources can possibly be determined, thereby allowing the tracking of plasmapause irregularities and regions of detached plasma which move around from the night side. If additional information is available such as an estimate from banded emissions of the source gyro-frequency, it is shown how it may also be possible to determine the latitudinal positions of sources.

Key words: Terrestrial myriametric radiation – Non-thermal continuum – Remote sensing – Plasmapause – Radio window – Direction finding – Wave polarisation

Introduction

Terrestrial myriametric radiation (TMR), also called non-thermal continuum, is electromagnetic radiation in the frequency range 10–100 kHz (Gurnett, 1975). Its free-space wavelength is of the order of 10^4 m; hence the adoption of the term myriametric (Jones, 1980).

There is evidence that TMR is produced in the left-hand ordinary (*L–O*) mode (Gurnett and Shaw, 1973; Jones, 1980; Okuda et al. 1982; Kurth, 1982) although Etcheto et al. (1982) have reported the observation of what appears to be a predominantly right-hand extraordinary (*R–X*) continuum event on the ISEE spacecraft.

It is becoming well established that the main source of TMR lies in upper hybrid waves at the plasmapause, with a possible secondary source at the morning magnetosheath. Gurnett (1975) noted the close association between continuum radiation and intense bands of electrostatic

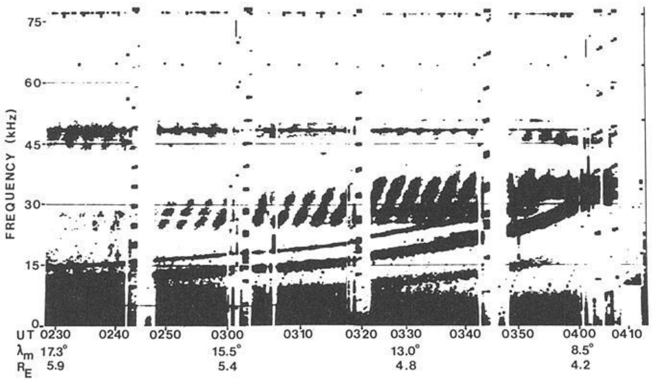

Fig. 1. Wave spectrogram from GEOS 1 showing spin-modulated TMR observed on 4 March 1978

noise observed near the electron plasma frequency at the plasmapause. Kurth et al. (1979a; b) showed an example of intense upper hybrid waves near $4.3\,R_E$ at 5–6 h LT that were apparently causing emission in the TMR frequency band. Further evidence that the two types of emission are intimately linked has been presented by Jones (1980; 1981a; b; 1982), Kurth et al. (1981) and Kurth (1982). Since the most intense electrostatic emissions, at least during relatively quiet geomagnetic conditions, appear to be very tightly confined to the geomagnetic equator (Gough et al., 1979), it has been reasonable to suppose initially that the most intense TMR, such as that which can be observed by spacecraft at relatively large distances from a plasmapause source, also emanates from the magnetic equatorial plane.

Two examples of TMR recorded by the wave experiment (Jones, 1978) on the GEOS 1 and 2 spacecraft are shown in Figs. 1 and 2 respectively. These examples were selected to illustrate the different types of TMR which can be observed. Many other examples have appeared in the literature which further illustrate the wide variety of TMR which can exist (Kurth et al., 1981; Jones, 1982; Gough, 1982; Kurth, 1982; Etcheto et al., 1982).

In Fig. 1, the striated emissions seen in two relatively wide bands are TMR, the stronger straddling ~30 kHz and the weaker lying just above 45 kHz. The narrow line at ~48 kHz is instrumental and should be ignored. The striations are indicative of spin-modulation of the wave electric field received by the 40 m tip-to-tip dipole antenna and lead to the conclusion that the source region is relatively compact. The inclination of the striations is due to the

* Based on a paper given at the Symposium on Plasma and Energetic Particles in the Magnetosphere, EGS Meeting, 23–27 August 1982, Leeds, U.K.

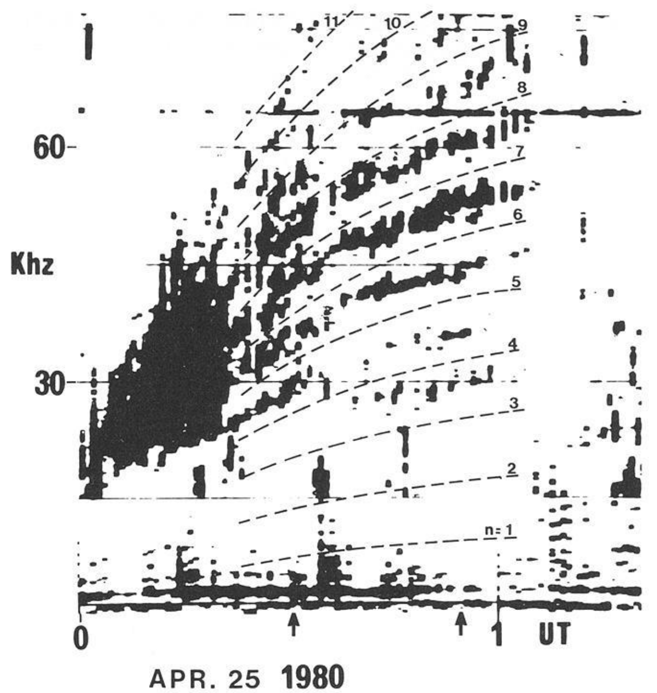

Fig. 2. Wave spectrogram from GEOS 2 showing multi-banded TMR observed on 25 April 1980. The arrows on the ordinate are at 0033 UT and 0057 UT (see text)

beat between the sweep period (22s) of the on-board frequency analyser and the spin period (6s) of the spacecraft. It is clear that the spin modulation contains information on the direction of the source. In the past, source directions have been determined from the spin modulation without any consideration being given to the effect of wave polarisation (Gurnett, 1975; Kurth et al., 1981; Gough, 1982; Etcheto et al., 1982), but it has been shown that this approach can introduce large errors (Lecacheux et al., 1979; Manning and Fainberg, 1980; Jones, 1982).

Attention is drawn to other characteristics of TMR visible in Fig. 1. The frequency and bandwidth of the lower band varies as the spacecraft moves, whereas for the upper band the parameters remain fairly constant. The spin modulation of the lower band varies between unity (no spin modulation) and a figure of ~ 4, depending on the time and on the frequency. Thus, since it is the power that is being displayed in the Figure, the electric field modulation lies between 1 and 2.

The manner in which the various items of information contained in Fig. 1 can be used for remote sensing of the plasmapause requires a brief discussion of what has been proposed as a source mechanism of TMR. This is given in the next section and is followed by a detailed discussion of possible source positions of the TMR shown in Figs. 1 and 2. The main thrust of the paper is firstly to draw attention to the problems of direction-finding and secondly to show how the work of Jones (1982), which assumed sources confined to the magnetic equatorial plane, can be generalised to allow remote sensing of non-equatorial sources.

TMR Generation Mechanism

Barbosa (1982) has recently presented a good review of the characteristics of TMR and has considered the three leading theories which have been proposed for its production. The synchrotron mechanism proposed by Frankel (1973) apparently falls short of the required power level by a factor of 10^2–10^3. The linear theory of Jones (1976a; b) which invokes UHR/Z mode to L–O mode conversion is also too inefficient by a factor of 10^2, although Barbosa adds that if some efficiency-saving mechanism can be found, this theory could achieve a paramount position and be universally accepted. The third theory, non-linear wave-coupling suggested by Melrose (1981), can achieve the required efficiency, but, again according to Barbosa, it lacks credibility because of the ad hoc nature of its assumptions and the lack of observations of the requisite ingredients (low frequency waves cospatial with upper hybrid noise). Lembege and Jones (1982) have considered the ray paths relevant to the linear theory and have suggested an efficiency-saving mechanism. On the basis of this, and of Barbosa's comments, it is suggested that the linear theory and its possible implications for remote sensing of TMR sources deserves a more thorough investigation.

Following the observation by Gurnett (1975) that continuum radiation seemed to be closely associated with intense bands of electrostatic noise observed near the electron plasma frequency at the plasmapause, Jones (1976a) provided the first theory relating the continuum to upper hybrid waves. This is the linear theory which invoked the generation of Z-mode waves by the Cerenkov mechanism, and the subsequent propagation of the waves in a density gradient so as to access a radio window which exists where the wave frequency equals the plasma frequency f_{pe}. Z-mode waves have since been observed in the generation regions of TMR (Jones, 1982; Kurth, 1982) and the Cerenkov mechanism is undoubtedly the source of some continuum. However, the observation of more intense, banded TMR, whose frequency spacing satisfies the relation $f \approx (n+\frac{1}{2}) f_{ce} \approx f_{UHR}$ where f_{ce} is the electron cyclotron frequency and $f_{UHR} = (f_{pe}^2 + f_{ce}^2)^{\frac{1}{2}}$, has led to the conclusion that electrostatic upper-hybrid waves play the most important role. Since these electrostatic waves lie on the same dispersion branch as the Z-mode radiation (Oya, 1971), it was suggested by Jones (1980) that their propagation in the density gradient at the plasmapause will naturally convert them into Z-mode waves, with mode conversion to the L–O mode again occurring at the radio window. In parallel, it was becoming evident that the most intense electrostatic (e.s.) emissions were located at the magnetic equator (Gough et al., 1979) and this would allow the best access by energy in the e.s. waves to the radio window via the Z-mode. Lembege and Jones (1982) have shown detailed ray paths of the electrostatic and electromagnetic waves at the magnetic equatorial plasmapause and have commented on the characteristics required of the source e.s. waves if the window theory is to be sufficiently efficient. Their suggestion requires additional observations and theoretical work, which are beyond the scope of this present paper, but a brief summary of the proposal will be given here since, as stated by Barbosa, this factor is crucial if the linear theory is to be elevated to a paramount position.

Figure 3 is a three-dimensional representation which endeavours to portray simultaneously both refractive index space and 'real' space. The elements of the latter are the magnetic field vector B_0, the magnetic equator lying perpendicular to B_0, and the plasmapause shown as the cross-hatched surface which, for clarity, has been limited to one

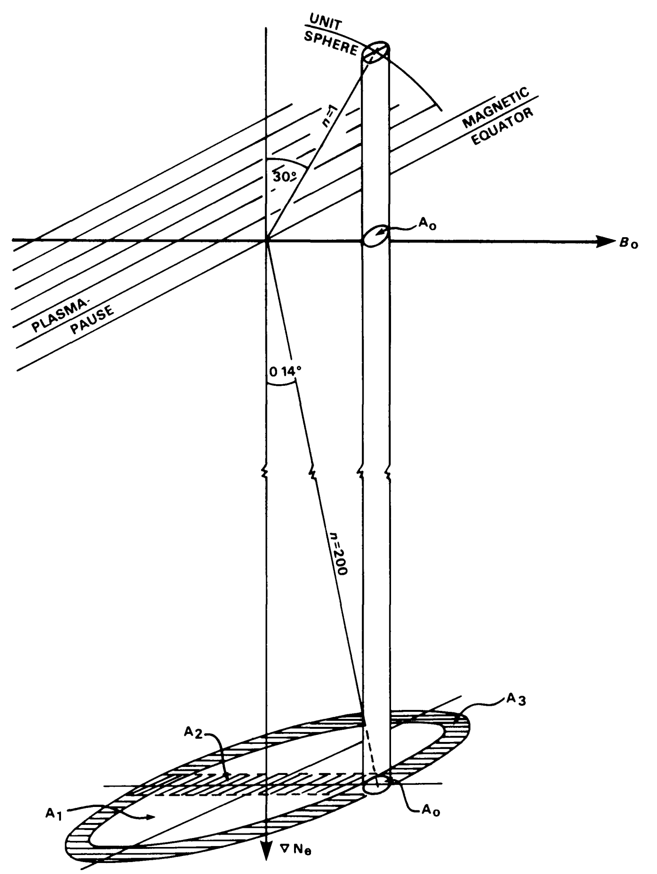

Fig. 3. Three-dimensional sketch of refractive index space overlaid on the magnetic equatorial plasmapause. A_0 is the radio window which, when projected into the electrostatic wave domain, is compared with the areas A_{1-3}

side of the magnetic equator. The density gradient vector ∇N_e, which is assumed to control wave propagation in cases where $f_{pe} \gg f_{ce}$, points downwards. Thus for simplicity one can define three basic domains – the plasmapause surface, the high density plasmasphere below, and the low density magnetospheric cavity above. The magnetic field and density gradient are two vectors which are also normally displayed in cases where refractive index space is under consideration. Therefore, in Fig. 3, refractive index space has been overlaid on 'real' space for illustrative purposes. In refractive index space for a wave of frequency f the radio window A_0 is a small area whose plane is perpendicular to ∇N_e and which is located on the magnetic field line B_0 at a distance from the origin of $n=[f_{ce}/(f_{pe}+f_{ce})]^{\frac{1}{2}}$ (see Budden, 1961), where $f=f_{pe}$. From Snell's Law, it is clear that if the energy in electrostatic upper hybrid waves, whose refractive index n may be of the order of 200 (Horne, private communication; Lembege and Jones, 1982), are to escape through the window A_0, their wave normals must initially lie approximately within the area A_0 at the end of the refractive index vector $n=200$ shown in Fig. 3. It is thus possible to compare the window area A_0 to certain areas A_1, A_2, A_3 corresponding to hypothetical electrostatic wave distribution functions (WDF). In this way one may endeavour to determine what type of WDF is required in order that the observed conversion efficiencies can be achieved. It should be added that when the wave energy has passed through the window A_0, it will, in 'real' space, propagate away from the plasmapause into the magnetospheric cavity. In refractive index space, as required by Snell's Law, this involves a rotation of the wave normal, from being parallel to B_0 at the window level where $n=[f_{ce}/(f_{pe}+f_{ce})]^{\frac{1}{2}}$ to an angle arctan $(f_{pe}/f_{ce})^{\frac{1}{2}}$ where $n \approx 1$. Alternatively, the radiation can be said to be beamed at an angle $\alpha=\arctan(f_{ce}/f_{pe})^{\frac{1}{2}}$ with respect to the magnetic equatorial plane (Jones, 1982). It is this beaming property of the theory that allows remote sensing of sources by a satellite in the magnetospheric cavity.

The radio window is an area in refractive index space whose dimensions can be calculated (see Budden, 1961; 1980; Jones, 1982). Using a very modest density gradient, the area of the window is found to be rather small, leading to the conclusion that only a restricted cluster of Z-mode wave normals can be converted to L–O mode radiation; it is this which has led to the criticism that the mechanism is perhaps not efficient enough to yield the levels of TMR observed. The approximate area of the window A_0 can be taken from Jones (1982) and is compared with three areas labelled A_1, A_2 and A_3 in Fig. 3, the last being included only for comparison and having, perhaps, little physical significance. The percentage ratios so obtained are $A_0/A_1=0.13\%$, $A_0/A_2=6.4\%$ and $A_0/A_3=0.6\%$. Clearly, if the e.s. waves are gyrotropic, the ratio will be much smaller than the smallest of these. It should be noted, however, that if one is considering the total transfer of energy, the above numbers need to be doubled, due to the presence of the second window which lies in the direction antiparallel to B_0 in Fig. 3. However, it is more probable that a spacecraft will make measurements when in the beam from a single window, unless, of course, it happens to be in the source region.

Few spacecraft measurements of the relative intensity of TMR and its source UHR waves have been made. One requires special conditions for a spacecraft to remain in the TMR beam and also to pass through the source region. Okuda et al. (1982) reported a ratio of between $10^{-2}\%$ and $4.10^{-2}\%$, but the spacecraft may not have been anywhere near the centre of the beam. Kurth (1982) arrives at a value of 3% for another event. It may be premature at this stage, therefore, to compare these sparse and widely differing observed values with those obtained from the hypothetical wave-normal distributions considered in Fig. 3. It should be added, however, that some of the density gradients reported by Kurth (1982) are more than two orders of magnitude larger than those used in the window computations of Jones (1982). Such large gradients would have the effect of greatly increasing the window dimensions. In fact, the gradients encountered by Kurth are so large that it is no longer possible to compute the window dimensions on the basis of the approximate equations of Budden (1980) and it is necessary to resort to full-wave calculations, which will be reported separately.

A question which arises naturally from the foregoing discussion is: are the source e.s. waves gyrotropic, or are they predominantly in the direction of the density gradient? Jones (1980) and Lembege and Jones (1982) suggest that if the basic instability is of a convective nature, the plane containing B_0 and the density gradient is that in which the ray paths have symmetry. Thus, a feedback mechanism can be set up in that plane, whereby energy not escaping as TMR is fed back into the particles in the source region. It is clear that there are a number of unresolved questions concerning the e.s. instability and these also require a separate investigation. Observations are needed of unambiguous sources of TMR in which the gyrotropy or otherwise of the e.s. waves can be further tested; preliminary results indicate that the waves are indeed non-gyrotropic (W. Kurth, private communication). In parallel, it is necessary to consider the theory of the convective instabilities in a density gradient in order to determine which k-vectors will tend to grow preferentially.

Remote Sensing

Sources in Magnetic Equatorial Plane

Details of how the window theory allows TMR to be used for remote sensing of the plasmapause if one assumes that the sources are confined to within $\pm 1°$ in latitude have been reported previously (Jones, 1981b; 1982) and only a very brief summary will be given here. The confinement of the intense e.s. waves to the magnetic equatorial plane is most apparent during quiet magnetic conditions, such as those which correspond to Fig. 1. In such cases, knowing the magnetic coordinates of the spacecraft and assuming the radiation propagates in the magnetospheric cavity from the source to the spacecraft at the angle $\alpha = \arctan\,(f_{ce}/f_{pe})^{\frac{1}{2}}$ with respect to the equatorial plane, it is possible to determine the loci of possible sources in the magnetic equatorial plane. Given additional information, such as the direction of arrival of the radiation, one may then pinpoint the position of the source in radial distance and in local time. Two interpretations of Fig. 1 will be considered. In the first it is assumed that the TMR source lies in a direction radially inwards from the spacecraft; in the second that the source lies nearly perpendicular to that direction. These two extremes will serve to illustrate the importance of determining the azimuth from which the radiation is arriving at the spacecraft. In the former case one can, in theory, determine the density profile in the source region, whereas in the latter it is shown how it may also be possible to detect motion of the source region.

If it is assumed that the source of the TMR in Fig. 1 lies radially inwards from the satellite, the plasma frequency profile obtained by remote sensing is shown in Fig. 4 (see Jones, 1982). The frequency change with time of the lower TMR band in Fig. 1 is due to the spacecraft's orbit being such that it encounters beams of different frequencies as it moves. In contrast, the upper frequency band in Fig. 1 is relatively stationary indicating that GEOS 1 remained within the beam during the time shown. Examples of the TMR ray paths for this event are given in Fig. 8 of Jones (1982).

Gough (1982) has published the directions of electric field minima detected by the spinning dipole on GEOS-1 for this event and these are found to lie within 20° of the radial direction. At first sight, this seems to imply that the source was indeed approximately radially inwards from the satellite. Unfortunately, however, Gough did not consider the effects of wave polarisation on his measurements and hence, as Jones (1982) has shown, the difference between the spin modulation nulls and the direction of the source may differ by up to $\pi/2$ if the radiation is in the L–O mode. At this stage, therefore, it is of interest not to limit the discussion to the radial direction, but to discuss the more general case which is depicted in Fig. 5.

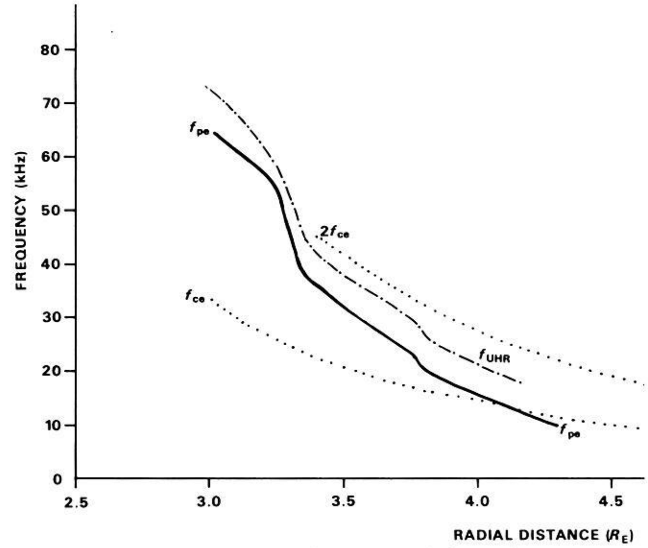

Fig. 4. Plasma frequency profile obtained from the spectrogram in Fig. 1 by remote sensing, assuming that the TMR emanates from a source located at the magnetic equatorial plane radially inwards from the satellite

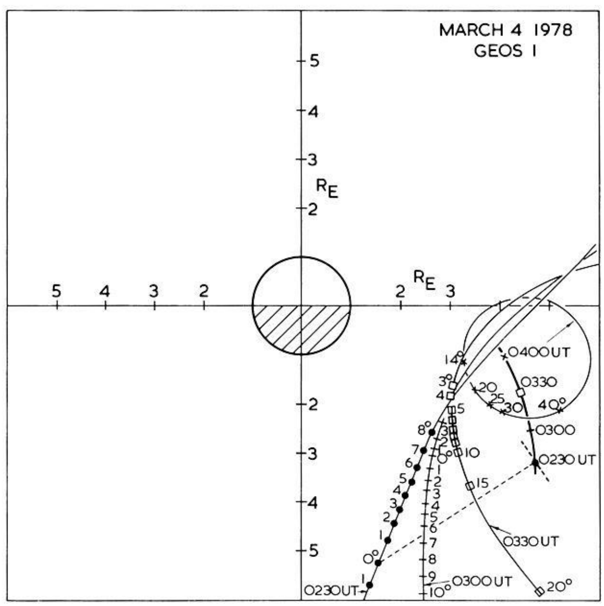

Fig. 5. The thick line represents the portion of the GEOS 1 orbit during which the spectrogram in Fig. 1 was recorded. Positions of the spacecraft at 0230, 0300, 0330 and 0400 UT are indicated by the different symbols. Source loci of 27 kHz TMR for each of these four positions are shown. Along these loci are marked the angle between the perpendicular to the magnetic field vector at the satellite and the satellite-source line. The short dashed line through the satellite position at 0230 UT represents the direction of the minimum wave electric field detected by the spinning spacecraft

Figure 5 shows the positions of GEOS 1 at half-hourly intervals during the observation of the TMR shown in Fig. 1. Also shown are the corresponding loci in the magnetic equatorial plane of possible sources of 27 kHz TMR, which is a frequency visible to the satellite from 0230 UT until just after 0350 UT. On the loci are marked the angle between the ray direction and the plane perpendicular to the magnetic field direction at the satellite, assuming a dipole magnetic field model. This angle is of the utmost importance when considering the spin modulation and the latter's use in direction-finding. For example, if at 0230 UT the source of TMR lies at the point marked 0° on the corresponding source locus, then at the satellite, the wave normal direction, assuming it to be parallel to the ray direction, is perpendicular to the magnetic field and thus the wave's electric field will be nearly linearly polarised along the magnetic field. Since the spacecraft spin axis is not parallel to the magnetic field, the dipole antenna will therefore observe a null when it makes the largest angle with B_0, and in general this bears no relation to the direction of the source. It is interesting to note that the direction of the null obtained at 0230 UT by Gough (1982) makes exactly an angle of $\pi/2$ with the direction of the "0° source" at 0230 UT. This would, therefore, be compatible with a source of 27 kHz TMR at 5.5 R_E, 0100 LT at 0230 UT, if the projection of the magnetic field direction on the spin plane of GEOS 1 makes an angle of ~20° with the radial direction at that time. Similar arguments may be made at the other times shown since the angles over most of the loci, except for those at 0400 UT when the radiation is not observed at 27 kHz, are of the order of 10° or less, implying that the electric vector at GEOS would be quite highly elliptically polarised nearly parallel to B_0 for any source position. It should also be noted that the magnitude of the maximum electric field of the TMR detected on GEOS will be an underestimate of the wave electric field.

It is of interest, therefore, to consider the other extreme where it is assumed that the true directions of the TMR sources, at least for the lower frequency band in Fig. 1, are perpendicular to those determined by Gough (1982). One may then plot their positions at the different times as shown in Fig. 6. Where possible, i.e. at 0300 and 0330 UT, the sources of a lower frequency, 25 kHz, and a higher frequency, 32 kHz, are shown. At 0230 UT only TMR having a frequency of ~25 kHz is observed, whereas at 0400 UT only frequencies in the vicinity of ~32 kHz are recorded. Figure 6 thus shows how sources rotating around from the night side at a speed greater than that of corotation with the Earth could, in theory, produce the TMR appearing in Fig. 1. The average supercorotation component is found to be approximately 3 km/s which is compatible with the plasma flow speeds computed from measurements made from the GEOS DC electric field experiment in the post-midnight sector (A. Pedersen, private communication), and also in agreement with the values derived by Lemaire and Kowolowski (1981). Clearly, however, before one can attach significance to the motions determined from Fig. 6 one must be able to determine the azimuth of the source.

It is unfortunate that the GEOS magnetometer was malfunctioning over a period including that shown in Fig. 1. It may be possible, however, that other experiments on the spacecraft could yield the information necessary to determine accurately the direction of the magnetic field at this time, and this possibility is being explored at present. Without such information it seems impossible to determine where, between the two extremes considered, the sources actually lie. The importance of obtaining an accurate field direction whenever direction finding measurements are made is emphasised by the example shown in Fig. 7, which shows the effects of wave polarisation on the depth of spin

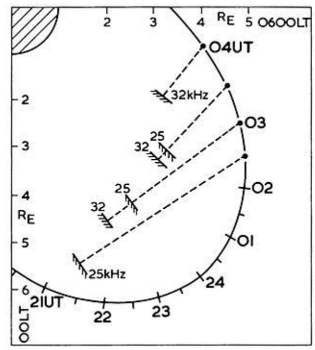

Fig. 6. Source positions of 25 kHz and 32 kHz TMR corresponding to the four times considered in Fig. 5, and assuming the sources are perpendicular to the directions of the null wave electric field detected on GEOS

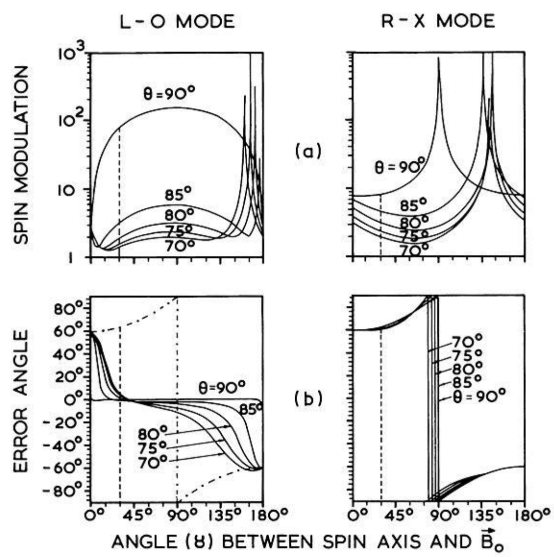

Fig. 7. a Depth of spin modulation of *L–O* and *R–X* waves as a function of γ (see text) for wave normal angles of 70°–90°. **b** Direction of wave electric field null compared with direction of k vector in spin plane (–·–·) as a function of γ for wave normal angles 70°–90°

modulation and on the direction of the minimum electric field detected. The wave normal k and spacecraft spin axis make angles θ and γ respectively with B_0 and the azimuth of the spin axis from the k–B_0 plane is assumed to be 30°.

The wave frequency is taken to be 30 kHz and the plasma and gyro-frequencies are set at 15 kHz and 6.5 kHz respectively, corresponding approximately to conditions at 0320 UT in Fig. 1. The five curves in each frame correspond to angles θ of 70° to 90° in 5° steps as labelled. The frames on the left of Fig. 7 relate to the *L–O* mode and those on the right to the *R–X* mode. The general case, in which a range of $\gamma, \theta, \phi, f, f_{pe}$ and f_{ce} are considered will be reported separately.

The parameters considered in Fig. 7 are the depth of spin modulation and the difference between the antenna direction when it observes minimum electric field (full lines) and the direction of the projection of k in the spin plane (dash-dot line). On the basis of a magnetic field model, for illustrative purposes, the angle γ corresponding to Fig. 1 can be assumed to be ~30°. Thus, the depth of spin modulation for the L–O waves is $\lesssim 2$ except for wave normal angles θ between 80° and 90°, when the spin modulation can become very large. The difference between the direction of the modulation null and that of the projection of k in the spin plane, which will be called the "error angle", is seen to be $\sim 60°$ for all wave normal angles $\theta \geqq 70°$. The parameters of the R–X mode are shown on the right merely for comparison. Until accurate values of γ and Φ corresponding to Fig. 1 are available, no concrete conclusions can be drawn, but the results serve to emphasise the very large errors in source directions which could arise unless wave polarisation is considered.

In summary, therefore, it has been shown that the TMR event reproduced in Fig. 1 may contain more information on the positions and movement of sources than was previously believed. Two interpretations of the data have been considered, one in which it is assumed that the source lies radially inward from the spacecraft and the other where the source is nearly perpendicular to that direction. In the latter case, the remarkable possibility of observing plasmasperic irregularities or cold plasma islands (Chappel, 1974) moving around from the night side has been demonstrated. When accurate magnetic field measurements become available it is believed that, in conjuction with DF measurements and information on the depth of spin-modulation, the technique of remote sensing considered here will allow a better understanding of the plasmapause and of the convection of associated irregularities.

TMR Sources not Restricted to Magnetic Equatorial Plane

The previous section dealt with the case of TMR sources restricted to the magnetic equatorial plane, as would be expected, for example, under quiet geomagnetic conditions. When magnetic activity increases, the intense electrostatic waves believed to be responsible for TMR are no longer rigidly confined to the magnetic equator (Gough et al., 1979) and the remote sensing technique must therefore be extended to accommodate such cases.

Figure 2 is an example of a short-lived continuum event recorded during 00–01 UT on 25 April 1980 by the GEOS-2 spacecraft which is in geostationary orbit at 6.6 R_E. The event is characterised by an intense emission appearing at $\sim$20 kHz at $\sim$00 UT which spreads in frequency upwards so as to cover the band 25–45 kHz by 0020 UT. The emission then splits into four or five discrete bands whose frequency and frequency separation increase as time progresses, the event coming to an abrupt end at $\sim$01 UT. The frequency spacing between bands is estimated to be $\sim$6.5 kHz at 0033 UT and $\sim$8 kHz at 0057 UT. The spacing in such events as this have been related to the electron cyclotron frequency f_{ce} at the source (Kurth et al., 1981; Gough, 1982; Kurth, 1982). At the plasmapause, the plasma frequency and hence the upper hybrid frequency f_{UHR} may increase rapidly compared to the electron cyclotron frequency, so that f_{UHR} may cross several gyro-harmonic bands in a short distance. The most intense electrostatic emissions occur where $f_{UHR} \approx (n+\frac{1}{2}) f_{ce}$ and hence it is natural to expect the resultant TMR to be similarly banded. Thus, from Fig. 2 it is possible to deduce the value of f_{ce} at the source from the spacing between the emission frequency bands and hence to obtain the f_{ce} harmonic lines as drawn. Since Fig. 2 was recorded during a period of moderate magnetic activity ($K=4$ at Kiruna, which is located near the foot of the GEOS 2 field line) it is probable that the TMR sources were not restricted in this case to the magnetic equatorial plane.

The remote sensing technique has now been generalised to include non-equatorial sources (Jones, Gapper and Herring, private communication). It is still assumed that the plasma density gradient is perpendicular to the magnetic field vector, but the restriction that the TMR source must lie at the equator has been removed. Thus, the source locus is no longer a line in the equatorial plane but a three-dimensional surface in space, certain longitudinal cuts of which, for example, are given in Fig. 8. The upper five frames in this Figure correspond to a wave frequency f of 30 kHz, whereas the lower frames are for $f=69$ kHz, these being chosen to represent approximately the lowest and highest frequency bands at $\sim$01 UT in Fig. 2. Concentrating on the first frame, two dipole field lines are shown for reference, one at $L=4$ and the other at $L=8.5$. At the time when Fig. 2 was recorded the electron gyrofrequency at the spacecraft was found to be $\sim$1.65 kHz (B. Higel, private communication). The position of GEOS 2 is represented by the radius vector to 6.6 R_E at $-3°$ latitude. The two quasi-elliptical lines are the contours of $f=1.4 f_{ce}$ and $f=2 f_{ce}$, and will not be considered further in the present paper. The lines of symbols in the first frame are the loci of possible sources of 30 kHz TMR which would be visible to GEOS 2 assuming the TMR emanates from field-aligned plasma density enhancements via the radio window. The symbols are coded so that the angle between the wave k-vector and B_0 at the spacecraft is known. On the original computer plots the symbols are colour-coded to allow one to distinguish between 5° and 50° for example, both of which appear as the symbol 5 in Fig. 8. The first frame is for loci in the same meridian plane as the spacecraft ($\delta=0°$) and the other frames show loci at 10° longitude steps away from this meridian plane, the maximum longitude difference considered in the present example being $\delta=40°$. It is seen that no low-latitude sources of 30 kHz TMR within 7 R_E are visible to GEOS-2 when $\delta=40°$; the low-latitude sources of 69 kHz TMR disappear from view before δ reaches 50°.

Concentrating on source loci in the same meridian plane as the satellite and initially on sources in the Northern hemisphere, i.e. in the hemisphere opposite to that of the satellite, Fig. 9a shows the variation in f_{ce} as a function of latitude for sources corresponding to the frequency bands in Fig. 2. At 0033 UT, the bands are observed to be at frequencies of 30, 36.5, 43 and 49.5 kHz, yielding a frequency spacing of 6.5 kHz. Assuming the latter to be the source gyrofrequency, the emissions are seen from Fig. 9a to emanate from magnetic latitudes covering 2.54–3.63°, i.e. at a latitude of $\sim 6°$ with respect to the latitude of the satellite. The corresponding radial distance of the sources, which is shown in Fig. 9b, lies at 4.18 R_E. At 0057 UT, the bands have frequencies of 30, 36.5, 45, 53, 61 and 69 kHz indicating a source $f_{ce} \approx 8$ kHz. Thus from Fig. 9a, the latitude range of the sources at this time is 2.63°–4.56° and, from Fig. 9b, the sources lie at 3.9 R_E. Hence, the effect of the magnetic substorm which occurred just after 00 UT on April 25 1980 is to cause the plasmapause to move to a smaller radial distance, and the average speed of motion is found from Fig. 9b to be 1.24 km/s. This is more clearly illustrated in Fig. 10 which shows the positions of the plas-

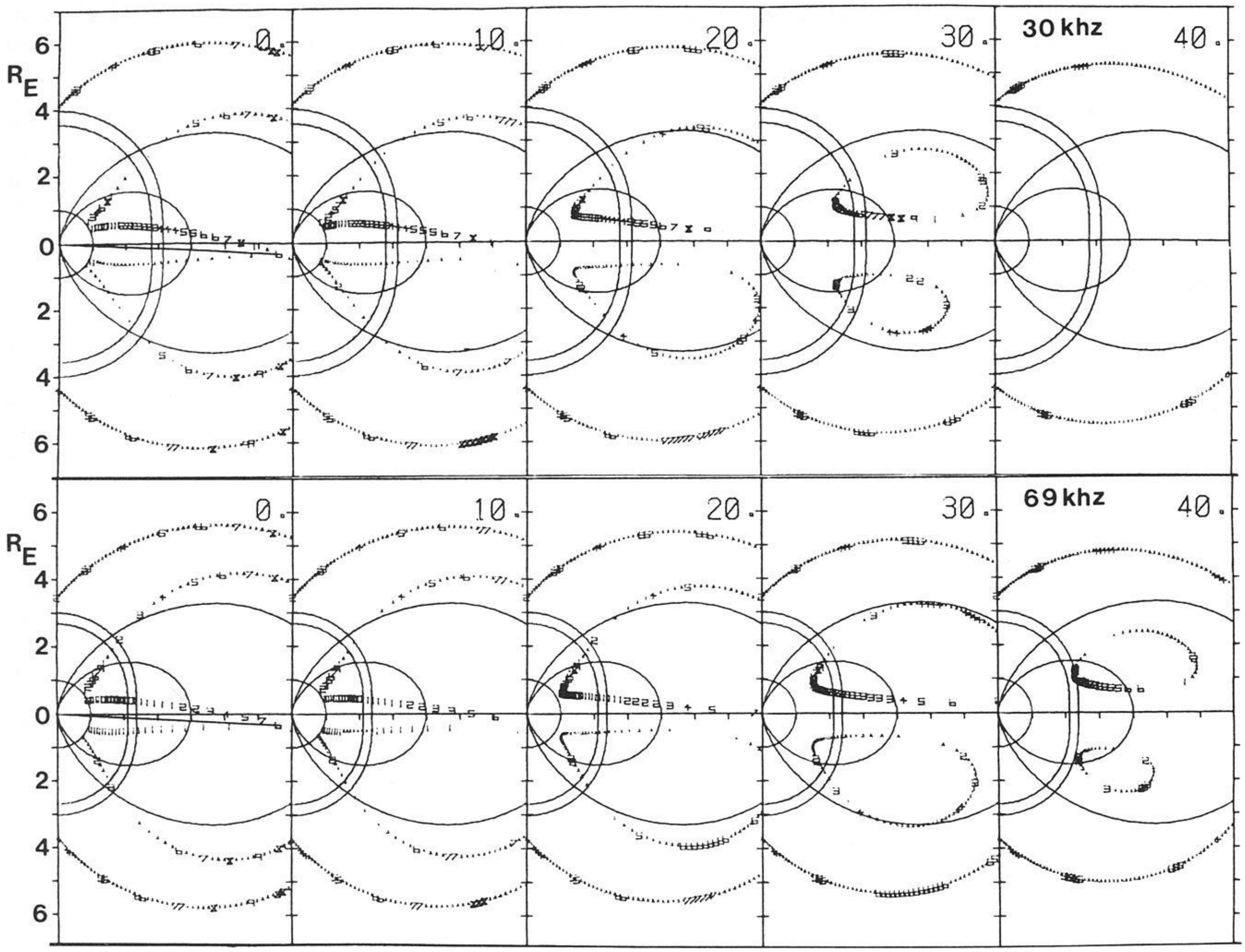

Fig. 8a and b. Loci of TMR sources visible to a geostationary spacecraft at $-3°$ magnetic latitude. The upper **a** and lower **b** sets of frames are for frequencies of 30 and 69 kHz respectively. The first frame in each set is for the meridian plane through the satellite; the satellite position is shown by the line of length $6.6 R_E$ at $-3°$. The other frames are for loci in meridian planes at 10°–40° longitudes relative to that of the spacecraft. The symbols on the loci are coded to yield the direction of the wave normal with respect to the magnetic field at the spacecraft (see text)

mapause at the two times considered, with a sketch of the most intense TMR at $f \approx (n+\frac{1}{2})f_{ce}$ being beamed away into the magnetospheric cavity, the beaming angles with respect to the magnetic field being given by arctan $(f/f_{ce})^{\frac{1}{2}}$ (see Jones, 1982).

A number of other important conclusions can be drawn from Figs. 9 and 10. It can be deduced from Fig. 9 that the TMR wave-normal at the spacecraft makes an angle of $\sim 85°$ with B_0 for $f=30$ kHz and $\sim 88°$ for $f=69$ kHz. Thus the wave electric field will be quite highly elliptically polarised along B_0 and it is again of the utmost importance to know the spacecraft orientation with respect to B_0 if one is to arrive at meaningful source directions from spinning dipole DF measurements. An added complication in the present example, where the spacecraft is near to local midnight, may be the relatively rapid temporal and spatial variation of the local magnetic field direction due to magnetic activity. This could result in a change in the position of the electric field nulls detected by the dipole antenna, even if the source remains fixed relative to the spacecraft. This will to some extent also affect the remote sensing which, at present, is based on the assumption of a dipole magnetic field. In the present example, the magnetic latitude of GEOS-2 is assumed to be $-3°$ as is shown in Fig. 8, but clearly the exact latitude of the spacecraft when the magnetic field is changing is unknown. Had the latitude been assumed to be 0°, the difference between the latitude of the sources and the satellite latitude is found to be reduced by $\sim 1.3°$ from the 6° deduced from Fig. 9. However, the radial positions at 0033 and 0057 UT of the sources are both decreased by $\sim 0.68 R_E$, thereby resulting in the same value for the speed of inward motion of the plasmapause.

The constancy of the frequency separation with frequency in Fig. 2 implies that the plasmapause is very steep, the gradient being far larger than the value obtained from Fig. 4 corresponding to the event in Fig. 1. Such a large density gradient has the effect of greatly increasing the window dimensions compared to those computed by Jones (1982). This will, in turn, render the TMR beam wider and hence the remote sensing technique less accurate; this is an effect which will be the subject of further study.

Sources in the same hemisphere as the satellite and those out of the satellite's meridian plane (see Fig. 8) show very

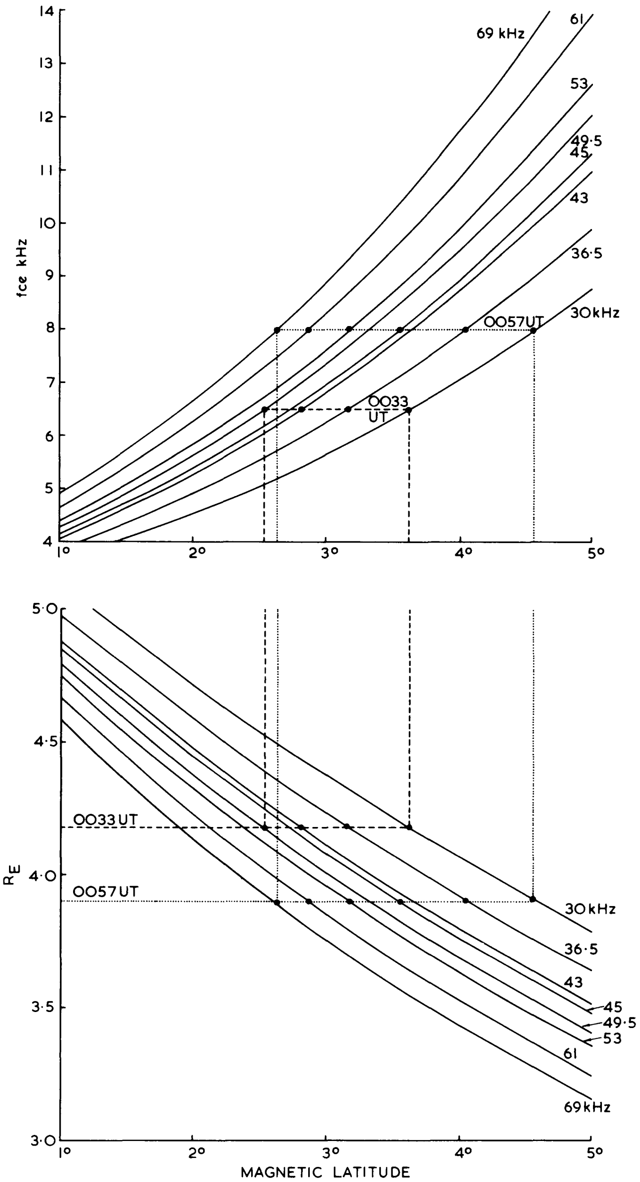

Fig. 9. The upper frame shows the variation of the source gyrofrequency f_{ce} as a function of latitude for the Northern equatorial sources derived from computations similar to those shown in Fig. 8. The TMR frequencies (30–69 kHz) are taken at two times, 0033 UT and 0057 UT, from Fig. 2. The spacings between the TMR bands are taken as indicative of the source $f_{ce}=6.5$ kHz and 8.0 kHz respectively. The lower frame shows the variation of the source radial distance as a function of latitude corresponding to the upper frame

similar characteristics to those discussed above. Clearly the gyrofrequency spacing restricts the source radial distance to quite strict limits if latitudes $\lesssim 10^\circ$ only are considered and hence the speed of inward motion of the plasmapause is close to 1.24 km/s in all cases. However, the angle between the magnetic field and the k-vector at the spacecraft does change, but is within 10° of being perpendicular except when the longitude difference between source and spacecraft is $\gtrsim 30^\circ$, i.e. close to the limit of observation.

In conclusion, it has been demonstrated that it may be possible to obtain both the radial distance and latitude of the sources of TMR which exhibit harmonic structure

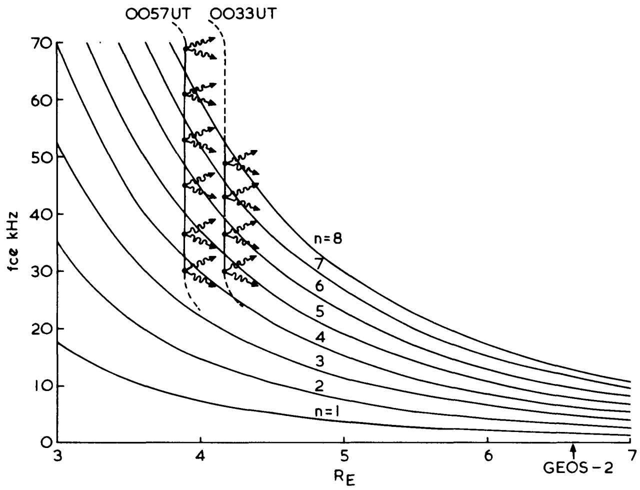

Fig. 10. Variation of the gyrofrequency f_{ce} fundamental ($n=1$) and its harmonics ($n=2$ to 8) as a function of radial distance. The lines labelled 0033 UT and 0057 UT indicate the positions of the plasmapause at the two times. The sources of the banded TMR are as shown.

of the form shown in Fig. 2. The broadband nature of the event shown prior to 0020 UT may indicate that another mechanism, such as the Cerenkov production of Z-mode waves, may be operating in parallel with the $(n+\frac{1}{2})f_{ce}$ e.s. instability during this period. The abrupt termination of the event at 0.1 UT could be due to a number of effects, such as a switching off of the source instability, the movement of the TMR source from the vicinity of the spacecraft meridian plane, or the swinging of the TMR beams away from the spacecraft by a change in the direction of the density gradient at the source.

Discussion

The technique of remote sensing of the plasmapause and its associated irregularities by TMR is still very much in its infancy and it is clear that a number of problems remain to be solved.

The first problem concerns the TMR emission mechanism itself. Although the linear theory outlined here appears to be the favoured candidate at present, it requires an independent confirmation by some means or other. This could come from measurements of the wave-distribution function of the UHR source waves as is being done by Kurth (private communication). If the k-vectors are found to be clustered in the plane containing the density gradient and magnetic field vectors, this would, as Barbosa (1982) puts it, "elevate the linear theory to a paramount position". Indeed, the non-gyrotropy of the waves may provide a means of determining the direction of the density gradient vector which is a very difficult parameter to measure. Alternatively, or in parallel, the convective behaviour of the e.s. instability in the sort of density gradients encountered at the plasmapause needs to be investigated theoretically. It should be added that it is becoming evident that the density gradient does indeed play a crucial role in the conversion mechanism and/or in the basic instability relevant to the type of planetary emissions considered here (Kurth et al., 1981; Gurnett et al., 1981). The gradients observed by Kurth (1982) and inferred from Fig. 10 in the present paper are far greater than those used in the window calculations of Jones (1982) with the result that the window dimensions are expected to be considerably larger; full-wave calculations are underway to investigate this. It may also be possible to test the window theory by using two spacecraft such as ISEE-1 and 2 which are not too far apart. If the TMR is beamed as predicted by the window theory, dual spacecraft measurements could obtain valuable information on the beamwidth. Etcheto et al. (1982) have endeavoured to investigate this effect using GEOS-1 located at $6.9 R_E$, 23° magnetic latitude, 6.26 magnetic local time (MLT) and ISEE-1 at $8.7 R_E$, −4.2° magnetic latitude, 8.03 MLT. TMR with similar spectra were observed on both spacecraft and this was taken as evidence of no beaming. Surprisingly, however, the wave intensities were greater on ISEE which was at the larger radial distance, and this seems to be more compatible with a magnetosheath source, in which case the beam characteristics cannot be as easily defined since the source magnetic field and density gradient orientations are not well-known. It should also be added that the direction-finding measurements of Etcheto et al. (1982) which indicated a plasmaspheric source were made without considering wave-polarisation effects.

The remote sensing technique at present assumes a dipole magnetic field for the Earth. It is believed that this is sufficiently accurate for plasmaspheric sources under quiet geomagnetic conditions, in which case it may also be sufficient to assume that the source e.s. waves are confined to the magnetic equatorial plane. Under geomagnetically active conditions, however, especially on the nightside, it may be necessary to introduce a more complicated magnetic field model if one requires more exact source locations.

The importance of taking wave polarisation effects into account when performing DF measurements cannot be over-stressed. When accurate magnetic field measurements for GEOS-1 and 2 do become available it should be possible to pinpoint the sources in radial distance, local time and possibly in latitude and hence to track their motion, thereby obtained valuable information on plasma convection in the magnetosphere.

Acknowledgements. Valuable discussions with K.G. Budden, J. Etcheto, P. Christiansen, G. Gapper, E. Gershuny, P. Gough, B. Higel, W. Kurth, B. Lembege, A. Pedersen, M. Rycroft and R. Stoneham are gratefully acknowledged, and R.M. Laws is thanked for his encouragement and support.

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Received November 15, 1982; Revised version January 24, 1983
Accepted March 8, 1983