Mem. Natl Inst. Polar Res., Spec. Issue, **48**, 183–195, 1987

WHISTLER MODE SIGNALS FROM VLF TRANSMITTERS, OBSERVED AT FARADAY, ANTARCTICA

A. J. SMITH[1], K. H. YEARBY[1], K. BULLOUGH[2], J. M. SAXTON[2], H. J. STRANGEWAYS[3] and N. R. THOMSON[4]

[1]*British Antarctic Survey (NERC), Madingley Road, Cambridge CB3 0ET, U. K.*
[2]*Department of Physics, University of Sheffield, Sheffield S3 7RH, U. K.*
[3]*Department of Electrical and Electronic Engineering, University of Leeds, Leeds LS2 9JT, U. K.*
[4]*Physics Department, University of Otago, Dunedin, New Zealand*

Abstract: The Doppler shift, one-hop group travel time and arrival direction of whistler mode signals from the NAA (24 kHz) and NSS (21.4 kHz) VLF transmitters in eastern U.S.A. have been measured in the conjugate region, at Faraday Station, Antarctica (65°S 64°W, $L=2.3$). Two identical narrow-band receivers of the type described by N. R. THOMSON (J. Geophys. Res., **86**, 4795, 1981) were used. The technique enables cross-L plasma drifts and flux tube filling and emptying rates in the inner magnetosphere to be inferred continuously with a time resolution of 15 min. Ducted whistler mode signals, of typical strength $\sim 1\ \mu\mathrm{Vm}^{-1}$ from both transmitters were observed every night during February–March 1986, usually with multi-duct structure evident. Such structure was generally similar for the two transmitters, indicating propagation along a common set of ducts. This permitted the determination of the L-values of the ducts without reference to natural whistler data. Typical one hop group travel times were in the range 300–900 ms and Doppler shifts in the range -500 mHz to $+500$ mHz. Most ducts could be tracked for several hours, and during the night their associated group travel times often exhibited a steady decrease followed by a steady increase, suggesting a change from inward to outward cross-L drifting under the action of east-west electric fields of magnitude $\sim 0.3\ \mathrm{mVm}^{-1}$. This drift reversal occurred at $\sim$02 LT and was accompanied by a rapid change from positive to negative Doppler shifts.

1. Introduction

Large scale quasi-DC electric fields in the magnetosphere, arising from the interaction of the geomagnetic field with the interplanetary medium or through ionospheric dynamo processes, play a crucial role in theories of plasma convection (AXFORD, 1969; MOZER, 1973). To test such theories, magnetospheric electric fields may be measured or inferred experimentally by a number of techniques, each having advantages and disadvantages. Double probe sensors on board high altitude satellites (PEDERSEN *et al.*, 1978) provide direct *in-situ* measurements but only along the satellite orbit. Ionospheric electric fields determined locally by balloon borne instruments (MOZER *et al.*, 1974) or over wide regions by incoherent scatter radars (EVANS, 1972; BLANC *et al.*, 1977) may be mapped upwards, but equipotential field lines must be assumed. The analysis of natural whistlers (originating from lightning strokes) observed on the ground at a single station can provide information about the $\boldsymbol{E}\times\boldsymbol{B}$ drift velocities of whistler ducts (field aligned plasma density irregularities which guide the whistlers), and hence perpendicular electric fields, over a considerable volume of the magnetosphere (CARPENTER *et al.*, 1972; RASH *et al.*, 1986). Unfortunately the analysis is time consuming and the technique relies on lightning discharges occurring at a suitable location and with sufficient intensity at VLF to illuminate any whistler ducts which may be present, and with an occurrence rate large compared to the reciprocal of the time for which the duct structure remains substantially unchanged (~5 min in active times). The probability of such conditions occurring depends on, amongst other factors, local time, season, and the latitude and longitude of the receiver.

The problem of source variability inherent in the natural whistler method can be overcome by observing instead whistler mode signals originating in high power VLF communications transmitters, using a receiver in the conjugate region of the transmitter. The source then has a known location, radiated power, frequency, and modulation format. Changes in the group travel time between conjugate points may be due either to cross-L plasma drifts (and hence electric fields), or changes in plasma density, or a combination of both; in the case of broad band natural whistlers, these effects may be distinguished by measuring the dispersion; in the case of narrow band whistler mode signals from VLF transmitters it may be done by measuring the Doppler shift of the received signals in addition to the group travel time between hemispheres.

The VLF Doppler technique has been developed by workers in New Zealand (MCNEILL and ANDREWS, 1975; ANDREWS *et al.*, 1978; ANDREWS, 1980) using the approximately conjugate NLK transmitter near Seattle. In this paper we describe a new experiment designed to measure large scale electric fields, plasma motions, and whistler duct properties in the inner magnetosphere (L~1.5–2.5) by means of two VLF Doppler receivers at Faraday, Antarctica tuned to the NSS and NAA transmitters in eastern USA (see Table 1 for station coordinates and transmitter characteristics, and Fig. 1 for a map). An important advantage of this arrangement is that, provided a given duct carries whistler mode signals from both transmitters, measurements at the two different frequencies allow the dispersion associated with the duct

Table 1. Coordinates of the VLF transmitters NAA and NSS, of the Faraday (FA) receiver, and of their conjugates (NAA′, NSS′, FA′). The latter have been calculated at an altitude of 100 km and epoch 1986.0, using the IGRF1985 geomagnetic field model. Also shown are great circle distance and bearing (east of north) from Faraday, transmission frequency, radiated power and modulation format, and maximum L-shell for ducted whistler mode propagation (in an enhanced density duct).

Station	Lat. (deg)	Long. (dcg)	L	Dist. (km)	Bear. (deg)	Freq. (kHz)	Power (kW)	Modn. (baud)	L_{max}
NAA	44.7N	67.3W	3.2	12220	358	24.0	1000	200 MSK	2.6
NSS	39.0N	76.5W	2.7	11640	350	21.4	265	200 MSK	2.7
FA	65.3S	64.3W	2.3	—	—	—	—	—	—
NAA′	71.0S	61.4W	3.2	650	171	—	—	—	—
NSS′	65.5S	84.8W	2.7	940	259	—	—	—	—
FA′	38.8N	68.6W	2.3	—	—	—	—	—	—

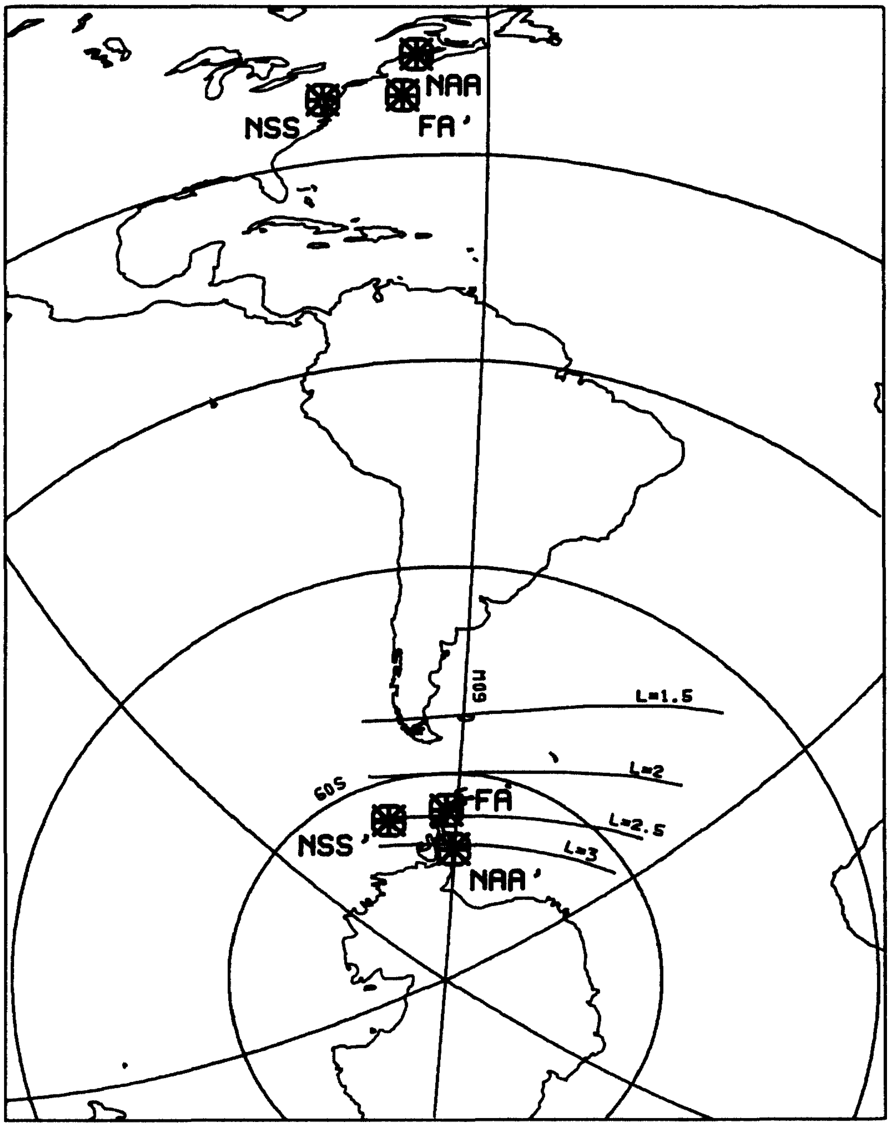

Fig. 1. *Great circle map centred on Faraday station (FA) showing the locations of NAA, NSS, and conjugates (FA′, NAA′, NSS′). The projections of the L=1.5, 2, 2.5, and 3 shells are shown in the region of Faraday.*

and hence its L-value to be determined. With the single transmitter configuration this is only possible by analysing natural whistlers travelling in the same duct. We now briefly review the principle of the VLF Doppler technique, describe the experimental arrangements at Faraday, and present some results from the first month of operation.

2. Principle of the VLF Doppler Technique

The method has been described by Thomson (1976a), and Andrews (1980), and will be reviewed only briefly here.

The phase and group travel times for a whistler mode wave propagating through the magnetosphere are given by:

$$t_p = \frac{1}{c}\int_S n_p \mathrm{d}s \simeq \frac{1}{c}\int_S \frac{f_p}{f^{1/2}(f_H - f)^{1/2}}\mathrm{d}s, \tag{1}$$

$$t_g = \frac{1}{c}\int_S n_g \mathrm{d}s \simeq \frac{1}{2c}\int_S \frac{f_p f_H}{f^{1/2}(f_H - f)^{3/2}}\mathrm{d}s. \tag{2}$$

Integration is over the whistler path S, which in the inner magnetosphere can usually be considered as a dipole field line; n_p and n_g are the phase and group refractive indices. The expressions for n_p and n_g as functions of the wave frequency f, the plasma frequency f_p and the electron gyrofrequency f_H, used in eqs, (1) and (2), are usually good approximations for the case of longitudinal propagation. It has been shown (SMITH, 1961) that travel times calculated using eq. (2) are generally within 1% of the true travel times of whistlers guided in field aligned density enhancements (whistler ducts) in the magnetosphere.

If the propagation path changes, because either (a) the path moves through space by $\boldsymbol{E}\times\boldsymbol{B}$ drifting under the action of a perpendicular electric field (*i.e.* S changes), or (b) the plasma density or distribution (and hence f_p) change or (c) the magnetic field (and hence f_H) change, then eqs. (1) and (2) show that t_p and t_g will both be affected. Whilst t_p is not measurable directly, changes in t_p are, since

$$\frac{\mathrm{d}t_p}{\mathrm{d}t} = \frac{-\Delta f}{f}. \tag{3}$$

Previous work (*e.g.* ANDREWS, 1980) has shown that observed whistler mode Doppler shifts at $L \sim 2.3$ are largely due to path drifting under the action of electric fields. The relationship between cross-L drift and westward electric field in Vm^{-1} is (THOMSON, 1976b):

$$E_w = -\frac{B_0 R_E}{L^3}\frac{\mathrm{d}L}{\mathrm{d}t} \simeq \frac{-200}{L^3}\frac{\mathrm{d}L}{\mathrm{d}t}, \tag{4}$$

where B_0 is the magnitude of the geomagnetic field (assumed dipolar) at the surface equator, and R_E is the radius of the earth. Except near dawn and dusk, contributions due to flux tube coupling with the ionosphere have a relatively small effect. Plasma changes in the ionosphere below 1000 km altitude also contribute slightly ($\sim$10–20%) to Doppler shifts, and can be corrected for. Direct effects of a changing geomagnetic field on the integrals of eqs. (1) and (2) are negligible except in very disturbed conditions, although electric fields induced by the changing $\boldsymbol{B}$ may contribute to the path drift (ANDREWS *et al.*, 1978). Since experimentally t_g and Δf are determined with reference to the subionospheric signal received in the opposite hemisphere from the transmitter, a correction to t_g is needed to take account of subionospheric propagation; the subionospheric Doppler shifts are however negligible.

When non-zero Doppler shifts and changing t_g's are observed, the relative contributions of path drifting and electron tube content changes can be estimated from the relative changes in t_p and t_g, since their expressions, eqs. (1) and (2) above, involve different functions of f_p and f_H. THOMSON (1976a) has shown that $\mathrm{d}t_p/\mathrm{d}t_g \sim 1.7$ for a duct fixed in space, but $\mathrm{d}t_p/\mathrm{d}t_g \sim 0.8$–1.3 (depending on L) for a duct drifting in a magnetosphere in which the equatorial electron density n_{eq} is proportional to L^{-4}. Positive Doppler shifts and decreasing group delays are associated with the inward drifting of ducts (westward electric fields) and decreasing electron tube content (downward fluxes), and *vice versa*. When fluxes are neglected, an approximate relationship between the Doppler shift in Hz and the westward electric field in mVm^{-1} (for f=18.6 kHz and $L \sim 2.3$) has been given by ANDREWS (1980): $E_w = 2.5\ \Delta f$.

In previous work, using a single transmitter, it has not been possible to determine

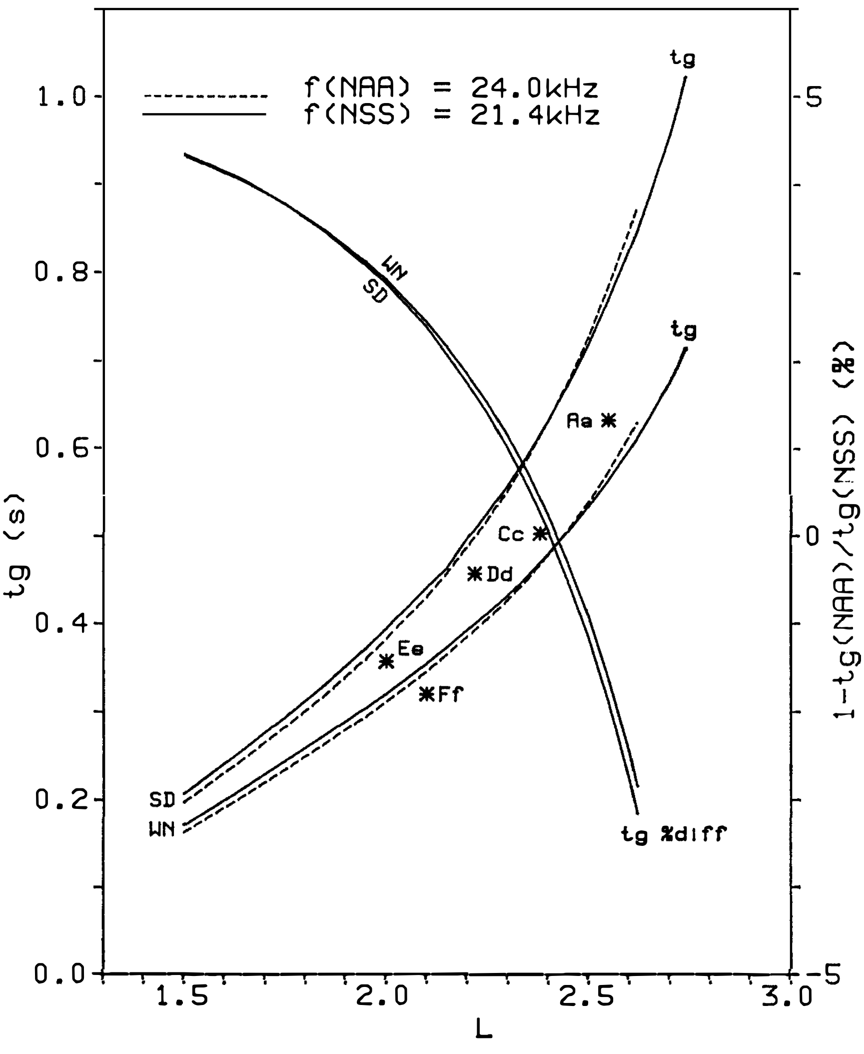

Fig. 2. The rising curves are group travel times t_g (left hand scale) calculated by ray tracing as functions of L, for whistler mode propagation in a 15% enhancement duct between 1000 km altitudes in opposite hemispheres. The calculations assume models of ionospheric density, ion composition and temperature appropriate to winter day and summer night conditions (SAGREDO and BULLOUGH, 1972) at the 1000 km reference altitude; diffusive equilibrium along field lines, and a dipole geomagnetic field geometry are also assumed. The solid curves are for NSS (21.4 kHz) and the dashed curves for NAA (24.0 kHz). The falling curves (right hand scale) show the percentage difference in group travel time, i.e. $100\% \times [1 - t_g(NAA)/t_g(NSS)]$, for the two models. The labelled points show the L-shells of whistler ducts observed on the night of 6–7 March 1986, see Fig. 4, at the midpoints of their simultaneous observation by the NAA and NSS receivers.

the L-shell of propagation of the observed whistler mode signals except by reference to natural whistlers, for which the nose frequency can either be measured directly from broadband spectrograms or by upward extrapolation of the observed lower frequency part of the whistler trace. This can be unsatisfactory since whistlers are not always present, and even when they are, the extrapolation procedure becomes inaccurate at low L values. In the present experiment we have the advantage that the receiver is situated where it can receive and measure the group delay of whistler mode signals from two different transmitters, NAA and NSS, operating at two different frequencies, which have travelled in the same duct. This is equivalent to measuring two points on the whistler profile from which the L-shell can be derived (DOWDEN and ALLCOCK, 1971; BERNARD, 1973) almost independently of the electron density model. Figure 2 shows calculations of t_g as a function of L for NAA (24 kHz) and NSS (21.4 kHz), and for two different models appropriate to a summer day and a winter night ionosphere (SAGREDO and BULLOUGH, 1972). The NAA and NSS curves cross over at an L value ($\sim$2.4) for which the whistler nose frequency lies between 21.4 and 24 kHz. It can be seen that the percentage difference in group delay, *i.e.* $100\% \times [t_g(\text{NSS}) - t_g(\text{NAA})]/t_g(\text{NSS})$ is almost independent of model and can be used to determine L for a particular ducted path illuminated by both transmitters. As in the natural whistler method, the accuracy decreases at lower L values since the error in the t_g difference remains constant and thus the error in the percentage difference increases.

3. Experiment Description

Two mutually perpendicular vertical loops (aligned north-south and east-west) and a vertical electric monopole, which are sensitive to the H_x, H_y, and E_z components respectively of the VLF wave field, are connected to broadband VLF preamplifiers which provide the inputs to two identical narrow band Doppler receivers and a conventional broadband VLF goniometer (BULLOUGH and SAGREDO, 1973).

Each Doppler receiver is essentially as described by THOMSON (1981). The two main differences, apart from the different operating frequencies, are firstly that the transmission modulation format is 200 baud MSK (minimum shift keying) rather than 100 baud, so that the basic sampling interval is 5 ms instead of 10 ms, and secondly that the system has a direction finding capability (see THOMSON, 1985).

The specific system at Faraday has been described by STRANGEWAYS and THOMSON (1986). In-phase/out-of-phase and quadrature phase sensitive detectors lock on to one of the shifted frequencies (*e.g.* 24.05 kHz in the case of NAA); the outputs of the phase sensitive detectors are sampled digitally. The subionospheric signal is much stronger (by $\sim$50 dB) than the whistler mode signal and unlike the latter is highly stable in amplitude and phase. This property enables it to be subtracted from the total signal to yield the whistler mode signal alone. The whistler mode and subionospheric signals are cross correlated digitally. The coefficients are accumulated linearly for 1 s, so that peaks in the resulting 200 point correlation function correspond to group delays in the range 0–1 s with a resolution of 5 ms in a 1 Hz bandwidth (in practice ± 1 ms resolution may be obtained by curve fitting; see ANDREWS *et al.* (1978)).

Doppler shifts are obtained by carrying out similar cross-correlations in 25 narrow band channels spaced 40 mHz apart throughout the range ± 0.48 Hz relative to the zero Doppler shifted signal. For each channel the in-phase and quadrature whistler mode signals are combined using a phasor of the appropriate frequency. The coefficients are linearly accumulated for 25 s.

The direction of arrival information is derived from two cross correlation functions computed using the H_x and H_y components, with sense information provided by the E_z component.

The linear accumulations of cross-correlation coefficients are squared and averaged over 15 min before being written on to a floppy disc. All the digital computations are performed by a micro PDP-11 computer (for each receiver).

Calibration is achieved both in hardware, by using a small coil to inject a known signal at the centre of the loop aerials, and in software by adding small whistler mode signals at a known group delay and amplitude.

4. Preliminary Results

The experiment began producing data in mid February 1986. Since then both the NAA and NSS receivers have been run almost every night. At the time of writing, however, the only data to hand are those obtained during the month of operation before the departure from Faraday in March 1986 of the last ship before the Antarctic winter. Thus the results below are from a relatively small sample and are presented with the caveat that they may not be representative.

Whistler mode signals from both NAA and NSS were received every observing night—35 nights for NAA and 21 nights for NSS. This occurrence is greater than the 70% reported by McNeill and Andrews (1975) in eight years of observations at Wellington of whistler mode signals from the NLK transmitter, Seattle. Group time delays were almost all in the range 0.3–0.9 s. In the majority of cases most of the whistler mode power was received in one or more narrow ($\lesssim$20 ms) ranges of group time, each being associated with a whistler duct. In a few cases the power distribution was spread more widely in group time ($\sim$100 ms), as in "swishy" natural whistlers.

On average, whistler mode signals appeared at $\sim$02 UT (22 LT at Faraday) and disappeared at $\sim$10 UT (05 LT at Faraday). This is consistent with the finding of McNeill and Andrews (1975) that whistler mode signals are cut off when both ends of the path are sunlit, assuming that the paths lie between the (magnetic) meridians of Faraday (FA) and NAA or NSS. During the February–March time frame under consideration, *i.e.* before the March equinox, the northern hemisphere ends of likely paths (*i.e.* NAA, NSS, FA′, where ′ denotes conjugate) are in darkness longer than their conjugates (FA, NAA′, and NSS′). 02 UT is after sunset at NAA, NSS, and FA′, and 10 UT is before sunrise. On a few occasions whistler mode signals were present until after 13 UT, *i.e.* up to 2 h after sunrise; however the paths in these cases could have been well to the west of the Faraday meridian. Further analysis using the direction finding data should allow this to be checked.

Whistler mode amplitudes measured were typically in the range 0.3–3 μVm^{-1}, but sometimes exceeded 5 μVm^{-1}. The effective receiver sensitivity, limited by spheric noise, was variable, typically around 0.2 μVm^{-1}. The amplitudes of the subionospheric signals were ~100–200 μVm^{-1}.

Whistler ducts were associated with narrow peaks in the cross-correlation functions which varied slowly in t_g and amplitude from one 15 min averaging interval to the next. The duct structure observed was highly variable from night to night. Usually several (~5–10) ducts were distinguishable during a night, each lasting for several hours. This was expected since it is known from studies of natural whistlers that ducts, particularly those well inside the plasmasphere, can be identified for many hours from a single ground station (*e.g.* RABE and SCOURFIELD, 1977). In most cases the duct structures seen on the two receivers were very similar, except for small systematic differences in t_g due to the different frequencies, implying that essentially the same set of ducts were accessible to signals from both transmitters. This is not surprising since the distance between NAA and NSS, ~1000 km, is small compared to the 3000 km over which MCNEILL and ANDREWS (1975) found that signals could propagate under the ionosphere before entering a duct.

Doppler shifts have been observed throughout the entire receiver bandwidth, *i.e.* ± 0.48 Hz with respect to the unshifted signal. In general the whistler mode energy corresponding to a single duct was spread over several of the Doppler channels. The average Doppler shift for the duct could be found by curve fitting using the channel which had the highest amplitude at the t_g of the duct together with its adjacent channels.

In general the observed ducted paths had non-zero Doppler shifts (Δf) and slowly changing t_g's, primarily associated with their cross-L drift; this was confirmed by values of dt_p/dt_g near to 1.0. Often several ducts closely spaced in t_g also had very similar dt_p/dt and Δf. This suggests that the ducts were spatially closely clustered and drifting together. The inferred drifts were consistent with east-west electric fields of magnitude ~0–0.3 mVm^{-1} (*cf.* THOMSON, 1976b).

The most repeatable feature of the data was a change from decreasing t_g and positive Δf to increasing t_g and negative Δf occurring before dawn, at 6.6 h $\pm$ 1.1 h UT (~02 LT at Faraday). For NAA, this reversal was observed on 19 nights out of 35. A similar effect has been observed in New Zealand by ANDREWS (1980) on NLK whistler mode signals, for which the Doppler shifts in February and March turned negative at about 1530 UT (~03 LT), and by ANDREWS and THOMSON (1977) on whistler mode signals from NAA observed at Siple station, Antarctica; it can be interpreted as due to a morning change from inward to outward drifts, also seen in natural whistler data (CARPENTER and SEELY, 1976), with some contribution from flux tube filling from the ionosphere.

5. Whistler Mode Signals on 6–7 March 1986

We will now illustrate some of the general results described above with data from a single night, namely 6–7 March 1986. Magnetic conditions were fairly disturbed (Kp ~4–6).

Figure 3 summarises the group delay and Doppler shift data for this night. The

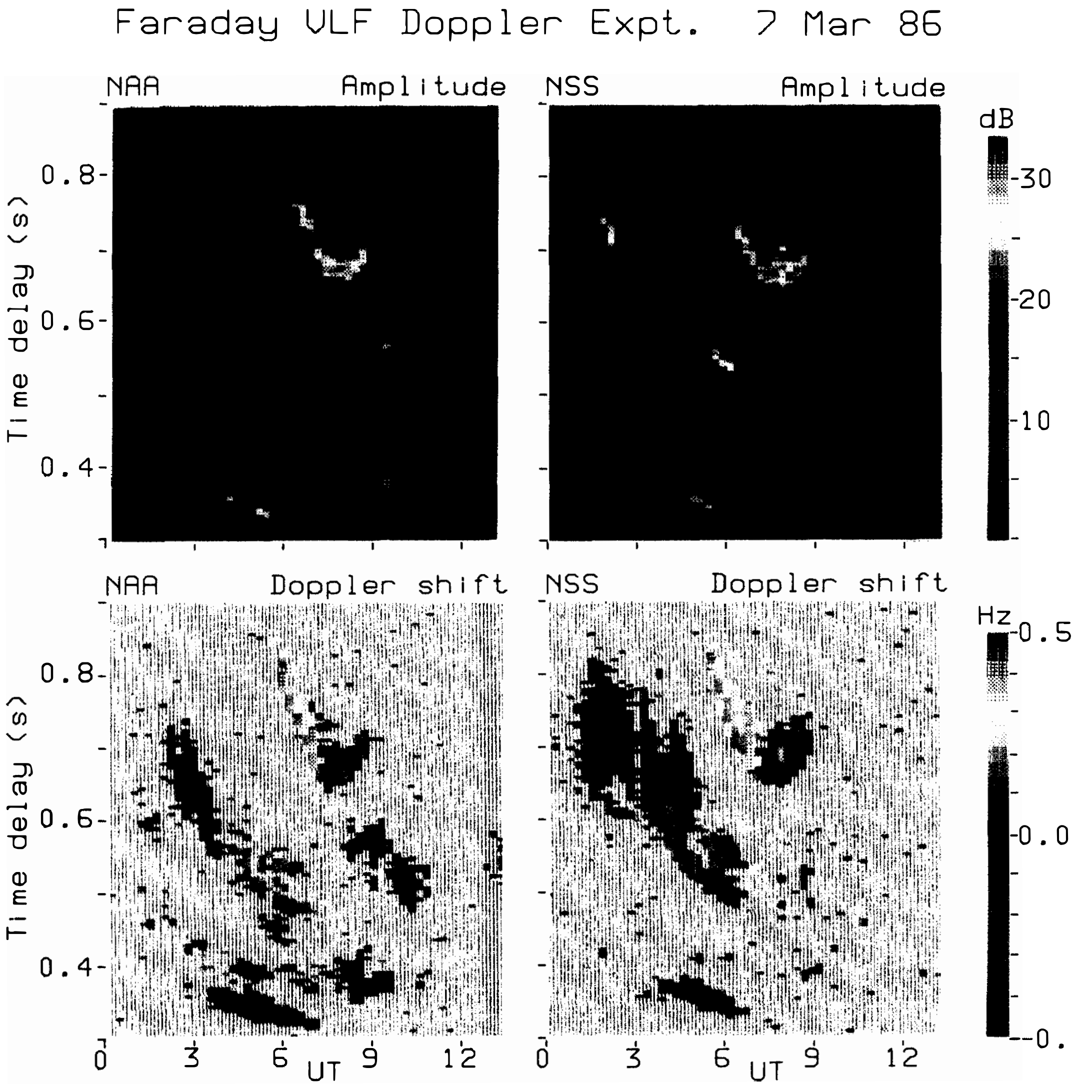

Fig. 3. Upper left panel: plot of NAA whistler mode intensity, shown qualitatively by the colour scale, vs. t_g and UT. One pixel corresponds to 5 ms in t_g and 15 min in UT. Upper right panel: similar plot for NSS. Lower left panel: NAA Doppler shifts shown in colour for all signals exceeding a threshold; the t_g and UT scales are the same as for the upper panels. Lower right panel: similar plot for NSS.

top two panels show time delay *vs.* UT plots for NAA and NSS. One pixel corresponds to 15 min in UT and 5 ms in t_g. Colour represents whistler mode amplitude qualitatively; the strongest signals correspond to about 1 μVm^{-1}. A vertical column of pixels represents the central part of one 15 min average cross correlation function between whistler mode and subionospheric signals. This form of presentation is helpful in showing cross correlation peaks which change slowly and systematically in their time delay, thus enabling ducts structures to be identified. Prominent ducts are evident at t_g ~350 ms between 04 and 07 UT, t_g ~700–500 ms between 02 and 07 UT, and t_g ~800–650 ms between 06 and 09 UT.

The two lower frames of Fig. 3 show Doppler shifts. For all pixels with an amplitude above a certain threshold, chosen to isolate the duct structures, the Doppler shift corresponding to the channel with the largest amplitude at that group delay is indicated by colour. Most Doppler shifts are near zero (± 100 mHz). However the prominent duct at 06–09 UT shows a marked and rapid change from positive Doppler shift ($\sim$350 mHz) to negative (~ -250 mHz) at about 0730 UT, at the same time that the rate of change of group time delay changes from negative to positive. This U-shaped feature in the t_g *vs.* UT plot, with corresponding change in sign of the Doppler shift, was seen on most nights, as discussed in Section 4.

At $\sim$0645 UT, before the drift reversal, dt_g/dt for NSS$\simeq -20\times 10^{-6}$. Writing eq. (4) as:

$$E_w = \frac{-200}{L^3} \frac{dt_g}{dt} \bigg/ \frac{dt_g}{dL}, \tag{5}$$

and using a value of 0.76 for dt_g/dL derived for $L=2.55$ from the slope of a line intermediate between the SD and WN curves through the point Aa of Fig. 2, we find that $E_w=0.30$ mVm^{-1}. At this time $-dt_p/dt = \Delta f/f \simeq 17\times 10^{-6}$, so that $dt_p/dt_g \simeq 0.85$, con-

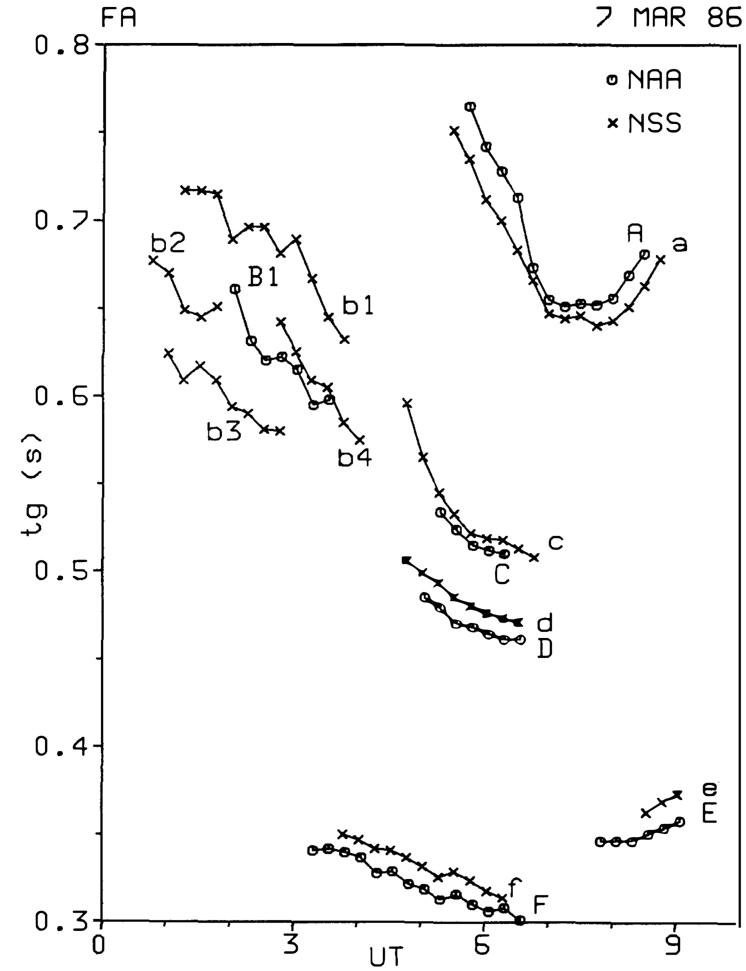

Fig. 4. *A t_g vs. UT plot for the centres of the discrete traces of Fig. 3, corresponding to identifiable whistler ducts. NAA data are indicated by circles and upper case duct labels, NSS by crosses and lower case duct labels.*

sistent with $n_{eq} \propto L^{-4}$ (THOMSON, 1976a). At ~0815 UT, after the drift reversal, $dt_g/dt \simeq 11 \times 10^{-6}$, implying $E_w \simeq -0.16$ mVm^{-1}.

In Fig. 3 the NAA and NSS plots are very similar to each other. In Fig. 4 we plot for each transmitter the central t_g (found by curve fitting around the peaks in the cross correlation functions) for each of the duct traces present in Fig. 3. In five cases, labelled Aa, Cc, Dd, Ee and Ff, the corresponding NAA and NSS traces run closely parallel; the Bb traces have a more complex structure. For the Aa pair, NAA group delays are slightly larger than NSS, indicating an L-shell of propagation with a whistler nose frequency less than the transmitter frequencies; the reverse is true for the other pairs. As described earlier, the fractional t_g differences can be used to infer the L-shell of propagation, almost independently of the assumed plasma distribution model. The resulting values, for the midpoints of simultaneous observation by the two receivers, are shown as points in Fig. 2. We note that all except point *Ff* lie between the SD and WN curves, suggesting that the actual plasma distribution on this night was intermediate between the SD and WN models. It is not clear why *Ff* does not fit into the same pattern, but it could be that the NAA and NSS signals are in different ducts with similar t_g and dt_g/dt—possibly closely spaced elements of a complex multiduct structure (LESTER and SMITH, 1980; STRANGEWAYS, 1982).

6. Conclusions

Whistler mode signals from the NAA and NSS VLF transmitters have been received at Faraday, Antarctica, since February 1986. This paper has described some preliminary results from the first month of data.

Each receiver separated the whistler mode signal from the much larger subionospheric signal by a digital cross correlation method, and the group time delays t_g, Doppler shifts Δf, and arrival bearings were recorded, averaged over each 15 min interval. Whistler mode signals were received from both transmitters on every observing night.

The technique allowed individual whistler ducts to be identified and tracked. Usually several well defined ducts were present and each lasted several hours on average.

Whistler mode signal strengths were typically in the range 0.3–3 μVm^{-1}, compared to subionospheric field strengths of ~150 μVm^{-1}. Group delay times were usually in the range 300–900 ms and Doppler shifts in the range ± 500 mHz.

Very similar signals were usually seen by the two receivers, implying that whistler mode signals from NAA and NSS were travelling in the same set of ducts. Using this assumption it was possible to deduce the L-shell of propagation, almost independently of assumed electron density model, without reference to natural whistlers. Only ducts with $L < 2.6$ could be observed; at higher L values, the half equatorial gyrofrequency cutoff for ducted propagation forbids interhemispheric travel at the transmitter frequency.

In general, whistler mode signals exhibited slowly changing t_g's and non zero Δf's, consistent with duct drifting under the action of an east-west electric field of up to 0.5 mVm^{-1}, in agreement with previous work on natural and manmade whistler mode signals.

A repeatable feature, observed on 54% of nights, was a change from decreasing to increasing t_g and from positive to negative Δf occurring before dawn at $\sim$02 LT. This may be explained in terms of a reversal from inward to outward plasma drifts.

In principle the data contain a wealth of information on plasma motions and structures and on whistler mode propagation in the inner magnetosphere. Much further detailed analysis needs to be done and the results will be reported in future papers.

Acknowledgements

We wish to thank Mr. C. HOWE and Mr. P. HUGHES for construction of the equipment and other technical assistance, and Mr. M. CLILVERD for operating the system at Faraday. The work was funded by NERC under the Antarctic Special Topic Programme. J.M. SAXTON acknowledges support in the form of a SERC CASE studentship.

References

ANDREWS, M. K. (1980): Night-time radial plasma drifts and coupling fluxes at $L=2.3$ from whistler mode measurements. Planet. Space Sci., **28**, 407–417.

ANDREWS, M. K. and THOMSON, N. R. (1977): Doppler shifts on whistler mode signals received at Siple station, Antarctica. Geophys. Res. Lett., **10**, 399–401.

ANDREWS, M. K., KNOX, F. B. and THOMSON, N. R. (1978): Magnetospheric electric fields and protonospheric coupling fluxes inferred from simultaneous phase and group path measurements on whistler-mode signals. Planet. Space Sci., **26**, 171–183.

AXFORD, W. I. (1969): Magnetospheric convection. Rev. Geophys., **7**, 421–459.

BERNARD, L. C. (1973): A new nose extension method for whistlers. J. Atmos. Terr. Phys., **35**, 871–880.

BLANC, M., AMAYENC, P., BAUER, P. and TAIEB, C. (1977): Electric fields from the French incoherent scatter facility. J. Geophys. Res., **82**, 87–97.

BULLOUGH, K. and SAGREDO, J. L. (1973): VLF goniometer observations at Halley Bay, Antarctica—I. The equipment and measurement of signal bearing. Planet. Space Sci., **21**, 899–912.

CARPENTER, D. L. and SEELY, N. T. (1976): Cross-L plasma drifts in the outer plasmasphere; Quiet time patterns and some substorm effects. J. Geophys. Res., **81**, 2728–2736.

CARPENTER, D. L., STONE, K., SIREN, J. C. and CRYSTAL, T. L. (1972): Magnetospheric electric fields deduced from drifting whistler paths. J. Geophys. Res., **77**, 2819–2834.

DOWDEN, R. L. and ALLCOCK, G. MCK. (1971): Determination of nose frequency of non-nose whistlers. J. Atmos. Terr. Phys., **33**, 1125–1129.

EVANS, J. V. (1972): Measurements of horizontal drifts in the E and F regions at Millstone Hill. J. Geophys. Res., **77**, 2341–2352.

LESTER, M. and SMITH, A. J. (1980): Whistler duct structure and formation. Planet. Space Sci., **28**, 645–654.

MCNEILL, F. A. and ANDREWS, M. K. (1975): Quiet-time characteristics of middle-latitude whistler-mode signals during an 8-yr period. J. Atmos. Terr. Phys., **37**, 531–543.

MOZER, F. S. (1973): Electric fields and plasma convection in the plasmasphere. Rev. Geophys. Space Phys., **11**, 755–765.

MOZER, F. S., SERLIN, R., CARPENTER, D. L. and SIREN, J. (1974): Simultaneous electric field measurements near $L=4$ from conjugate balloons and whistlers. J. Geophys. Res., **79**, 3215–3217.

PEDERSEN, A., GRARD, R., KNOTT, K., JONES, D. and GONFALONE, A. (1978): Measurements of quasi-static electric fields between 3 and 7 earth radii on GEOS-1. Space Sci. Rev., **22**, 333–346.

RABE, E. and SCOURFIELD, M. W. J. (1977): Plasmasphere response to the onset of quiet magnetic conditions; Plasma convection patterns. Planet. Space Sci., **35**, 303–308.

RASH, J. P. S., HANSEN, H. J. and SCOURFIELD, M. W. J. (1986): Electric field sources in the quiet plasmasphere from whistler observations. J. Atmos. Terr. Phys., **48**, 399–414.

SAGREDO, J. L. and BULLOUGH, K. (1972): The effect of the ring current on whistler propagation in the magnetosphere. Planet. Space Sci., **20**, 731–746.

SMITH, R. L. (1961): Propagation of whistlers trapped in field-aligned columns of enhanced ionization. J. Geophys. Res., **66**, 3699–3707.

STRANGEWAYS, H. J. (1982): The effect of multi-duct structure on whistler-mode wave propagation. J. Atmos. Terr. Phys., **44**, 901–912.

STRANGEWAYS, H. J. and THOMSON, N. R. (1986): 24 kHz MSK Doppler receiver at Faraday, Antarctica. IERE Publ., **68**, 41–47.

THOMSON, N. R. (1976a): Causes of the frequency shift of whistler-mode signals. Planet. Space Sci., **24**, 447–454.

THOMSON, N. R. (1976b): Electric fields from whistler-mode Doppler shifts. Planet. Space Sci., **24**, 455–458.

THOMSON, N. R. (1981): Whistler mode signals; Spectrographic group delays. J. Geophys. Res., **86**, 4795–4802.

THOMSON, N. R. (1985): Reflection of VLF radio waves from distant mountain ranges. J. Atmos. Terr. Phys., **47**, 353–362.

(Received November 25, 1986; Revised manuscript received April 8, 1987)