Doppler shift pulsations on whistler mode signals from a VLF transmitter

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Abstract— Whistler mode signals from the NAA transmitter (24 kHz) received at Faraday, Antarctica are processed to obtain the Doppler shift at a much higher time resolution than has previously been possible. This has allowed the observation of pulsations of about 13 mHz frequency which are believed to be associated with hydromagnetic waves in the magnetosphere. The pulsations are observed separately on signals with a number of discrete group delay features that can be interpreted as individual whistler ducts. Using the measured pulsation phase over the array of ducts the phase velocity and wave normal direction of the hydromagnetic wave in the equatorial plane are estimated. The direction of propagation is consistent with a source on the day side magnetopause.

The association between whistler mode Doppler shifts and hydromagnetic waves has been reported before but not, as far as we are aware, using an experimental technique that allows measurements on individual ducts in order to determine the direction of propagation of the hydromagnetic wave.

1 INTRODUCTION

The VLF Doppler technique is a method of studying the evolution of whistler ducts using signals from high power VLF transmitters rather than natural whistlers. It was originally developed by workers in New Zealand (McNeill, 1967; McNeill and Andrews, 1975; Andrews *et al.*, 1978) using the NLK transmitter near Seattle. In 1986 a system was installed at Faraday, Antarctica using the NAA and NSS transmitters in the north-east USA (Strangeways and Thomson, 1986; Smith *et al.*, 1987).

The equipment comprises a set of VLF antennas (two orthogonal loops plus E field), a 'Doppler receiver' and a computer. The Doppler receiver is essentially a highly stable reference oscillator and a set of phase sensitive detectors. In the standard system nearly all the data processing is done on-line in real time to yield 15 minute averages of the whistler mode power as a function of group delay and Doppler shift.

While the Faraday system was being upgraded in 1988 the opportunity was taken to record a small amount of raw data (the unprocessed output from the phase sensitive detectors) to allow novel processing techniques to be investigated off-line.

The real time on-line processing of the standard system (Strangeways and Thomson, 1986) is structured to permit the required processing speed to be attained and as a consequence does not maintain the best possible signal to noise ratio. Specifically, only one of the two sidebands of the transmitters is processed and the cross-correlations (used to resolve the whistler mode group delay) are performed using one bit arithmetic. In addition the Doppler shift is obtained using a simple combination of phasors rather than a Fourier transform.

In the present work both sidebands are processed in parallel, the correlations are performed using 8 bit arithmetic and a Fourier transform is used to obtain the Doppler shift. This gives an improvement of about 6 dB in signal to noise ratio which permits useful results to be obtained using considerably shorter integration times than the 15 minutes employed in the standard system.

This paper presents data from 17 March 1988 which shows variations in the amplitude and Doppler shift with a period of the order of one minute. The amplitude variations were irregular, and different for each duct and different for one duct observed on each of the two sidebands. In contrast, the Doppler shift variations were more regular and approximately in-phase for all ducts and both sidebands.

2 EXPERIMENTAL TECHNIQUE

The NAA signal (200 baud MSK) was received on a single loop aerial aligned in the north-south direction. The signal was applied to in-phase and quadrature phase sensitive detectors operated with a reference frequency of 24 kHz, the centre frequency of the NAA transmission. The outputs from the phase sensitive detectors were digitised to 12 bits precision at a 400 Hz sampling rate. The digitised signals thus cover the range

24000 ± 200 Hz. The use of in-phase and quadrature detectors allows us to distinguish frequencies above and below the reference. A single run of 55 minutes was recorded which resulted in about 5.5 M bytes of data. Good whistler mode signals were received during the first 35 minutes of this data.

All subsequent processing was done off-line. The first stage was to re-create the signals that would be produced by standard Doppler receivers (THOMSON 1981, STRANGEWAYS and THOMSON 1986) phase tracking on the sideband frequencies. A pair of phase locked loops (PLL) were used to track the upper and lower sidebands. The raw data were multiplied by the PLL oscillator signal and low pass filters used to extract the difference frequencies sampled at the centre of each 5ms code segment.

The following stage is similar to the standard Doppler receiver method (performed in parallel for both sidebands). The received signal contains contributions from both sub-ionospheric and whistler mode propagation. For each code segment the most probable state of the transmitted signal is determined. The contribution due to sub-ionospheric propagation for the current and previous code segments are subtracted out to leave the residual which contains the whistler mode signal plus noise. This is cross-correlated with the transmitted signal from 0 to 199 lags (each lag is 5 ms) and accumulated over one second intervals. This cross-correlation function (CCF) contains real and imaginary components which (in polar co-ordinate form) represents the amplitude and phase of the whistler mode signals as a function of group delay.

The most recent 32 CCF's (ie. those from the last 32 seconds) are stored in a circular buffer. For each lag in the CCF we thus have 32 pairs of values which represent a complex time series. By Fourier transforming these values a spectrum is obtained representing the amplitude as a function of Doppler shift. This process is performed for all lags in the CCF and for both sidebands of the signal. The magnitude of the spectra are then summed over both sidebands, and over the group delay range of a duct. A weighted mean is taken about the maximum amplitude bin in the spectrum to determine the Doppler shift. In the data presented here the Doppler shift determination was performed every 5 seconds using the most recent 32 CCF's in each case.

The result is a measure of the Doppler shift for each duct as a function of time as shown in figure 2. This is equivalent to the output from an FM (frequency modulation) detector. Like an FM detector it has the property of having a good signal to noise ratio provided the input signal to noise ratio is above a critical threshold. When the input signal to noise ratio approaches this threshold very large impulsive noise spikes start to appear at the output. It is necessary to suppress these if errors in subsequent measurements are to be avoided. Noise spikes were identified by the Doppler shift being outside the normal range, or the amplitude being below a set threshold. The rejected data was replaced by a linear interpolation of the valid data before and after.

The Doppler pulsation spectra like that shown in figure 3 were obtained by Fourier transforming the Doppler shift versus time data. The cross-spectrum of the Doppler shift data from a pair of ducts is used to obtain the pulsation phase.

Supporting data from the NSS transmitter were recorded and processed using the standard Faraday Doppler receiver technique described by Strangeways and Thomson (1986). These signals propagated mainly through the same ducts as the NAA signals and allowed the duct exit point positions to be determined (Smith *et al.*, 1987).

3 RESULTS

The raw data was first processed to obtain the whistler mode amplitude as a function of group delay averaged over the time interval 2256–2331 UT. This allowed the identification of the six ducts marked A to F on figure 1. A summary of the characteristics of each duct are given in table 1. For each duct the Doppler shift as a function of time was calculated. Figure 2 shows the results for each duct. The pulsations are very evident. The data was processed to remove impulsive noise spikes present for the reasons discussed in the previous section. The number of points rejected due to noise for each duct is listed in table 1.

Figure 3 shows the pulsation spectrum for duct C. The spectra for the other ducts are similar. The amplitude and phase of the prominent 13.2 mHz pulsation was measured for each duct. The results are included in table 1, where the amplitude figures are the peak amplitude of the 13.2 mHz Fourier component, and the phase is the phase lag in seconds relative to duct C. The pulsation amplitudes increase roughly in proportion with group delay (except for duct F) which is as expected for a constant amplitude of duct displacement. The variation of the pulsation phase is discussed in the next section.

The L value of each duct was estimated following the method described in Smith *et al.* (1987) which makes use of the difference in group delay, due to whistler dispersion, of the same duct observed on the NAA (24.0 kHz) and NSS (21.4 kHz) signals. Using direction of arrival information from the NSS receiver in conjunction with the L value it is possible to estimate the exit point positions of the ducts. This process relies on identifying the same duct features on the signals from both transmitters. The duct F could not be reliably identified on the NSS data so this duct has been excluded from further analysis.

4 DISCUSSION

The Doppler shift on a whistler mode signal is given by the rate of change of the phase path length. The phase path may change either due to plasma fluxes which change the refractive index or by duct drifts which change both the physical path length and the magnetic field strength (and hence the refractive index). The causes of Doppler shifts of whistler mode signals are discussed in detail by THOMSON (1976). ANDREWS *et al.* (1978) have shown that Doppler fluctuations of less than 30 minutes period are produced almost entirely by duct drifts.

Hydromagnetic waves in the magnetosphere can cause changes in the phase path length through changes in duct position and to a lesser extent changes in the magnetic field strength. The theoretical basis for this is described in detail by ANDREWS (1977) who observed Doppler shift pulsations on the signal from NLK, which corresponded to micro-pulsations in the Pc5 range recorded on the ground. It is shown that the VLF path length is affected primarily by meridional oscillations of the field line with an anti-node in the magnetosphere. PASCHAL *et al.* (1990) have reported correlations between Pc3 micro-pulsations and VLF phase delay on signals from the Siple VLF transmitter received at Roberval. RIETVELD *et al.* (1978) have observed similar effects on signals from an experimental 6.6 kHz transmitter.

All the above authors were able to directly relate variations in the VLF phase path with variations in the magnetic field observed on the ground. This has not been possible in this case. Magnetometer data recorded with a 20 second sampling rate was available for Faraday, but an analysis of this data has failed to find any obvious correlation with the Doppler shift pulsations. However this may be because the pulsations associated with the Doppler data were too weak to be observed with the magnetometer used.

ANDREWS (1977) derives the equation reproduced as (1) below relating the observed Doppler shift to the radial displacement (d) of the field line

$$d = \Delta f_{max} T / 2\pi C T_g \qquad (1)$$

where Δf_{max} and T are the amplitude and period of the Doppler pulsation and T_g is the group time. For the constant C Andrews gives a value of approximately 1.56×10^{-3} m^{-1}s^{-1} for a signal frequency of 18.6 kHz. For 24.0 kHz we use the value 2.01×10^{-3} m^{-1}s^{-1}. Inserting values of Δf_{max}, T and T_g appropriate to our data we obtain a radial displacement of 0.85 km. Using a figure quoted by Andrews of 4.5 km/nT this corresponds to a magnetic field perturbation at the base of the ionosphere of 0.19 nT. The field at the ground will be somewhat smaller than this (Hughes and Southwood, 1976a). In contrast the Faraday magnetometer data at this time showed an instrumental noise level of several nT. We were unable to find any suitable magnetic pulsation data from a nearby or conjugate station.

An advantage of the technique discussed in this paper is that it allows pulsation behaviour to be measured simultaneously at several locations within the magnetosphere. This contrasts with earlier work with Doppler pulsations which does not resolve individual ducts and with ground based magnetometer measurements which are considerably affected by the presence of the ionosphere (Hughes and Southwood, 1976a, b). On the minus side it does require whistler mode ducts to be present and is only sensitive to radial motions of the ducts.

There are two types of hydromagnetic wave expected to propagate in the magnetosphere, Alfvén waves, and fast magneto-acoustic waves (Orr, 1973). The former propagates along the magnetic field lines and involves transverse vibrations whereas the latter is a longitudinal vibration. Radial motions of whistler ducts could be due to either Alfvén waves with a radial component to the polarisation, or to fast magneto-acoustic waves with a radial component in the propagation direction. In fact the non-uniform nature of the background magnetic field leads to coupling of the two modes so both may be present simultaneously.

A simple model has a source region at the magnetopause, waves propagating inwards in the fast mode, coupling to Alfvén waves which may undergo field line resonance. The variation of pulsation phase with duct location would be due to the sum of three components; the propagation delay of the fast mode, the effect of field line resonance, and the whistler mode propagation time.

The effect of whistler mode propagation on the pulsation phase will be about half the one hop propagation time (ie. 188–270 ms). Therefore the phase difference due to this effect will be at most 82 ms which is small compared to the measured phase differences.

Orr (1973) provides some estimates of the fundamental resonant periods for the poloidal mode of oscillation (radial duct motion). Using equation 8 from that work, with n_o=1.6 × 10^9 m^{-3} (the equatorial proton number density) and kC=3.3 we estimate the periods vary from about 28 s (36 mHz) at L=2.16 to 47 s (21 mHz) at L=2.45. The 13.2 mHz pulsations are thus well below the resonant frequency at the latitude of observation so field line resonance probably does not contribute greatly to the observed phase differences.

Therefore we suggest that the observed phase differences are primarily due to the propagation delay of the fast mode. If this is so it should be possible to use the phase measurements to estimate the phase velocity and wave normal direction of the wave. We assume that the wave is propagating close to the equatorial plane and that the phase velocity is approximately constant in the neighbourhood of the ducts.

The duct exit point positions were projected up to the magnetospheric equatorial plane and their positions determined in a cartesian coordinate system. In this system the Y axis passes through the centre of the earth and through the longitude of Faraday (64.3 W), while the X axis is perpendicular with +X in an eastward direction. The projection used was:

$$x = \quad 6.4L\sin(\phi + 64.3^\circ) \tag{2}$$

$$y = -6.4L\cos(\phi + 64.3^\circ) \tag{3}$$

where x an y are the coordinates in Mm, L is the L value, and ϕ is the longitude (in degrees east).

The observed phase (θ) was fitted to the duct position using a least squares method to estimate the coefficients in the relation:

$$\theta = ax + by + c \tag{4}$$

The estimated coefficients were:

$a = 0.67 \pm 0.16 \times 10^{-6}$ sm^{-1},
$b = 0.85 \pm 0.29 \times 10^{-6}$ sm^{-1}
with a residual standard deviation of 0.37 s. This gives a phase velocity of 0.92×10^6 ms^{-1} and a wave normal direction of 52° anti-clockwise from the X axis. Figure 4a shows the location of the ducts and lines of constant phase in this coordinate system, whilst figure 4b shows this region within a larger scale diagram of the magnetospheric equatorial plane.

The estimated wave normal direction is consistent with a source at the dayside magnetopause. The possibility of a source in this region due to the Kelvin-Helmholtz instability has been discussed by several authors (eg. DUNGEY 1955; DUNGEY and SOUTHWOOD 1970). The wave normal direction will vary due to diffraction as the wave crosses the different regions of the magnetosphere, but the source should be somewhere in the afternoon sector.

The estimated phase velocity may be compared with the expected propagation velocity for hydromagnetic waves at the location of the ducts. The Alfvén velocity is given by

$$V_A = B(\mu_0 \rho)^{-1/2} \tag{5}$$

where B is the magnetic field, $\mu_0 = 4\pi \times 10^{-7}$, and ρ is the plasma density. From whistler dispersion analysis we estimate n_o=1.6 × 10^9 m^{-3} at L=2.32, and hence ρ=2.7 × 10^{-18} and V_A=1.3×10^6 ms^{-1}. The speed of sound is low enough so that V_A is also approximately the velocity of fast magneto-acoustic waves. The estimated phase velocity is rather less than the Alfvén velocity, but the difference is within the bounds of experimental error.

5 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

We have presented an example of whistler mode Doppler shift pulsations with a period of 75 seconds probably caused by a hydromagnetic wave in the magnetosphere. Measurements of the pulsation phase over an array of ducts has provided an estimate of the wave normal direction and phase velocity. The former is consistent with a source on the dayside magnetopause, while the latter is consistent with the expected propagation velocity for Alfvén or fast magneto-acoustic waves.

The main advantage of this technique is that it allows pulsation behaviour to be measured simultaneously at several locations within the magnetosphere without the screening effect of the ionosphere experienced by ground based magnetometers. It does however require whistler mode ducts to be present and is only sensitive to radial motions of the ducts.

The present work was based mainly on measurements of a single field component of the signal from one transmitter (NAA), with duct location information derived (in part) from direction of arrival measurements on another transmitter (NSS). It would be quite straight forward to extend the technique to measure both Doppler pulsations and direction of arrival independently on each of the two transmitters, thus leading to better estimates of the wave normal direction and phase velocity. Supporting measurements from magnetometers with a good sensitivity in the Pc3–5 range would also be important.

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Table 1. Characteristics of whistler ducts. T_g and L are the average group delay and estimated L value of the duct. The amplitude and phase refer to the 13.2 mHz component of the Doppler pulsation.

Duct	T_g (ms)	L	Exit point Lat.	Exit point Long.	Amp. (mHz)	Phase (s)	Rejects
A	375	2.16	-58.75	-77.60	34	-1.85	10/420
B	405	2.25	-59.85	-64.25	55	-0.40	14/420
C	440	2.32	-60.98	-61.08	62	0.0	1/420
D	480	2.40	-62.00	-62.00	69	-1.26	9/420
E	505	2.45	-62.88	-67.21	73	-1.87	9/420
F	540				62	$+3.12$	26/420

Figure 1: 30 min average of WM power versus group delay showing the 6 ducts.

Figure 2: Doppler shift verses time for each duct.

Figure 3: Spectrum of Doppler pulsations for duct C.

Figure 4: (a) Location of ducts on magnetospheric equator. Estimated lines of constant phase for the 13.2 mHz pulsation are shown dashed. (b) location of above region in larger scale diagram of magnetospheric equatorial plane.