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The Rotation of Hydromagnetic Waves by the Ionosphere

M. K. Andrews,* L. J. Lanzerotti,** and C. G. Maclennan**

**Physics and Engineering Laboratory, DSIR, Lower Hutt, New Zealand*
***Bell Laboratories, Murray Hill, New Jersey, U.S.A.*

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We show that the Doppler shift on whistler mode signals from VLF transmitters may be used to infer the magnetic field of an hydromagnetic wave above the ionosphere in the magnetosphere. This inferred field can then be compared with that measured on the ground. We examine one event in detail and show the data imply that a $\pi/2$ rotation of the orientation of the wave ellipse has occurred between the magnetosphere and the ground.

1. Introduction

In this paper we summarize, from the work of Andrews (1977) and Andrews *et al.* (1979), how VLF whistler mode signals, propagating in the magnetosphere, can be used with ground-based recordings of hydromagnetic waves (magnetic pulsations) to demonstrate the existence of a rotation of the wave ellipse orientation between the magnetosphere and ground, as predicted earlier by several authors (e.g., Inoue, 1973; Hughes 1974).

Whistler mode (W/M) signals from high-power VLF transmitters in the northern hemisphere have been received in New Zealand and Antarctica for a number of years. The transmitted frequency is precisely known; the received signal is not very coherent and is usually Doppler shifted, implying the phase path in the whistler duct (in the magnetosphere) between receiver and transmitter is rarely constant. This means that either refractive index changes are occurring within the duct, or that the duct length is changing, usually as a result of cross-L drifts.

In addition to cross-L drift, it has been found that the Doppler shift gives a sensitive

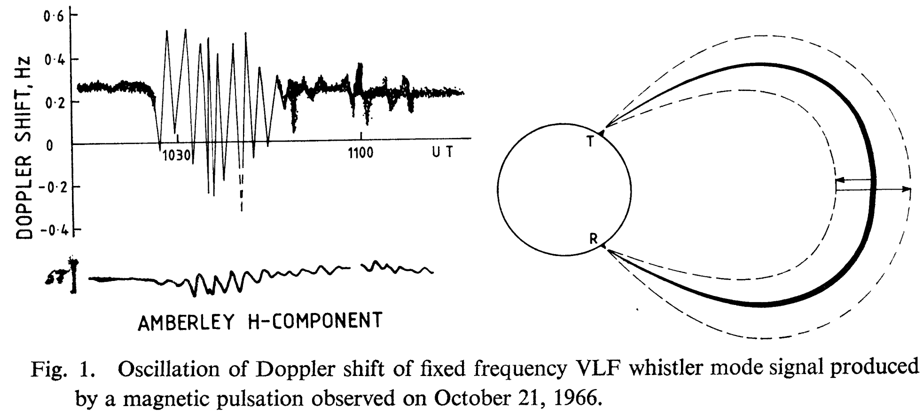

Fig. 1. Oscillation of Doppler shift of fixed frequency VLF whistler mode signal produced by a magnetic pulsation observed on October 21, 1966.

indication of the radial motion of a duct under the influence of an hydromagnetic wave (ANDREWS, 1977). Figure 1 shows an example of the phenomenon. Whistler-mode signals from NLK, Seattle (18.6 kHz) were being received at Wellington with a Doppler shift of 0.2 Hz on October 21, 1966. At 1027 UT, the W/M signal began executing a number of oscillations. Magnetograms from Amberley, near Christchurch, showed the simultaneous onset of a magnetic pulsation (Pc 4 type). The effect is explained in terms of standing poloidal oscillations of the W/M duct, oscillations which cause the VLF phase path to increase and decrease in time with the pulsation (ANDREWS, 1977). The existence of such effects on the VLF W/M signals is strong evidence in support of a standing wave interpretation of magnetic pulsations.

Toroidal (i.e., azimuthal) oscillations of a duct will scarcely affect the VLF phase path (ANDREWS, 1977; ANDREWS *et al.*, 1979). Therefore, such sets of observations constitute a ground-based method of identifying the phase of the standing hydromagnetic wave in the magnetosphere, which can then be compared with ground magnetic data.

Figure 2 outlines the method of analysis. If the mode of oscillation is half wave with nodes in the ionosphere, the field line (or duct) in its earthward position can be represented by the addition of a transverse standing wave field to the dipole line, as illustrated in Fig. 2.

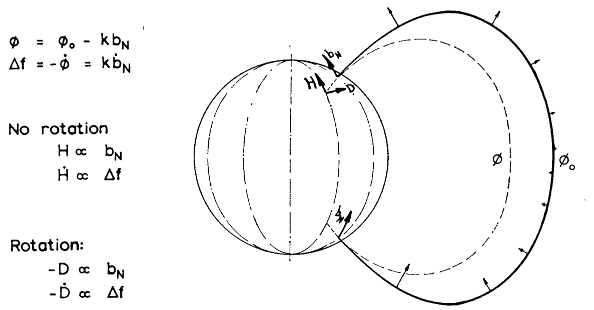

Fig. 2. Relation of VLF phase path to pulsation signals on the ground.

The radial wave field just above the ionosphere is northward and is denoted by b_N. The result is a shorter VLF duct, with a phase path length ϕ (which is loosely related to the physical path length) less than the phase path ϕ_0 of the unperturbed, dipolar magnetic field line. Thus, if k is a positive constant (whose value will depend on the duct latitude)

$$\phi = \phi_0 - kb_N$$

$$\Delta f = -\dot{\phi} = k\dot{b}_N \,.$$

If the ionosphere does not rotate the orientation of the wave ellipse, the pulsation signal b_N will be seen on the ground as a northerly component; i.e.,

$$H \propto b_N$$

so that

$$\dot{H} \propto \Delta f \,. \tag{1}$$

On the other hand, if the ionosphere does produce the rotation predicted by theory, b_N will be observed on the ground as a westerly component in the northern hemisphere, i.e.,

$$-D \propto b_N$$

$$-\dot{D} \propto \Delta f. \tag{2}$$

From (1) and (2), the existence, or otherwise, of a signal rotation may be tested by comparing the Doppler shift Δf with the time differentials of the measured ground magnetic components.

A preliminary attempt to do this was made by ANDREWS (1977), but accuracies were limited by the magnetic data available. Subsequently, W/M recordings made at Siple, Antarctica, have shown the existence of many pulsation signals on the dayside during southern winter, and accurate vector magnetometer data is available from the Bell Labs chain in Antarctica and North America. Here we show one long-lived VLF W/M event and determine that the ground magnetic signal is rotated compared to that in the magnetosphere. The work is reported in detail elsewhere (ANDREWS *et al.*, 1979).

2. Data

The pulsation event illustrated here occurred near local noon on 6 July 1975. The mean period was 140 s, and magnetic activity was low. Figure 3 shows polarization data for the event from the magnetometer chain. At the time of interest (16–17 UT) there is a polarization reversal in the hydromagnetic waves at about $L=3.5$. This suggests a spatial resonance occurred near $L=3.5$, and is supported by a pulsation amplitude peak at this latitude. Plasmaspheric electron densities would be consistent with the oscillation mode being the fundamental. The VLF W/M duct was near $L=3$; i.e., on the low latitude

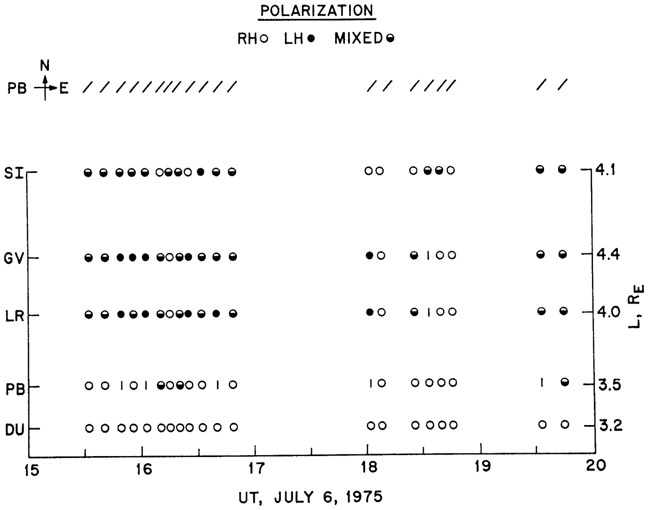

Fig. 3. Polarization data from the magnetometer chain. DU=Durham, PB=Pittsburg, LR=Lac Rebours, GV=Girardville, SI=Siple. The data at the top, for PB, indicate the orientation, in the horizontal plane, of the wave ellipse.

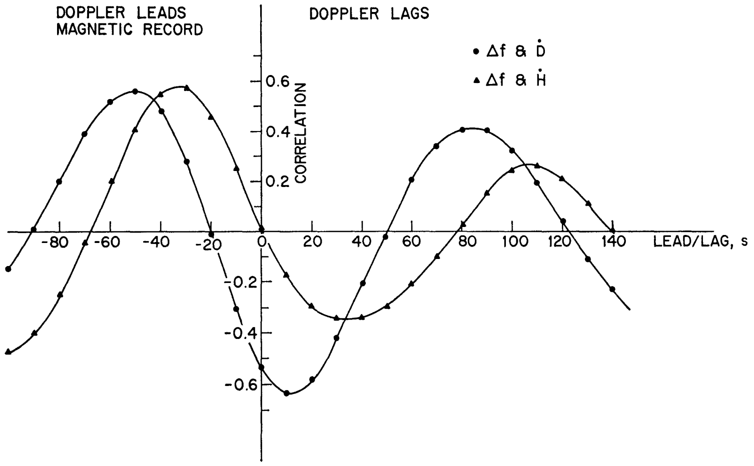

Fig. 4. Cross correlation of Siple whistler mode signals and magnetic data from Durham, hour 16, July 6, 1975.

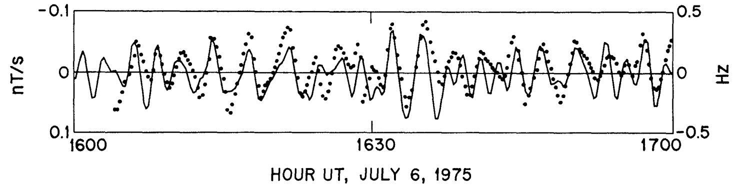

Fig. 5. Superposition of $-\dot{D}$ and VLF Doppler shift to show agreement over a one hour interval.

side of the resonance region.

For the hour 16–17 UT, when the VLF data were unbroken, a cross correlation was done between Δf and $\dot{H}$ and $\dot{D}$ from Durham ($L=3.2$), the station nearest the foot of the VLF duct. Figure 4 shows the result. The periodic nature of the correlation reflects the quasi-sinusoidal character of the pulsation. Near zero time lag, Δf and $\dot{H}$ show zero correlation, but Δf is highly anticorrelated with D; i.e.,

$$\Delta f \propto -\dot{D}$$

which is the relation indicating that the signal in the magnetosphere is observed on the ground with a 90° rotation. (Maximum anticorrelation is actually reached at +11 s, but this is within the ±15 s timing accuracy of the VLF records.)

In Fig. 5, $-\dot{D}$ and Δf are superimposed to show the degree of agreement, which is considered to be good.

Figure 6 shows a frame of data occurring one hour later, when W/M data were particularly well defined, and illustrates, on a non-statistical basis, the better agreement between $-\dot{D}$ and Δf than between $-\dot{H}$ and Δf. Note in particular that the VLF trace near the eighth minute is matched better by the $-\dot{D}$ trace than by the $\dot{H}$ trace. The latter

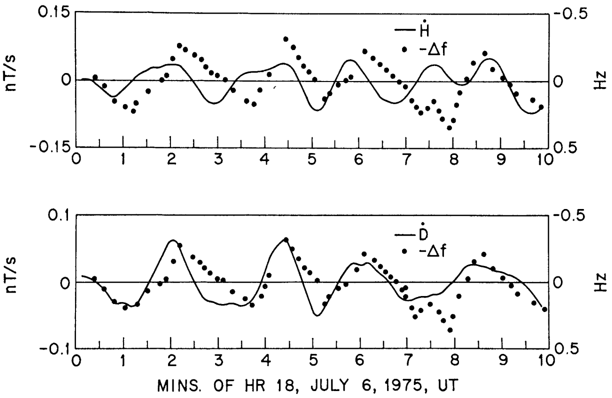

Fig. 6. Comparison of a well-defined W/M record with Durham magnetometer data. The agreement of Δf and $-\dot{D}$ implies an ionospheric rotation. (See note added in proof).

shows an extra oscillation at this time not present on $\dot{D}$.

We draw two conclusions from this study. First, the existence of pulsation effects in the Doppler shift of fixed-frequency VLF W/M records is strong evidence in support of a standing wave interpretation of magnetic pulsation signals. Second, the VLF signal can be used to give information on the phase of the hydromagnetic wave signal in the magnetosphere. Our data show that the northward signal in the magnetosphere matches the westward signal on the ground; i.e., a rotation in wave orientation has occurred, as predicted by theory. We note that a similar result on wave orientation was achieved using the STARE radar in Scandinavia to measure pulsation electric fields in the ionosphere (Walker *et al.*, 1979).

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Note added in proof

The upper diagram in Fig. 6 should have $-\dot{H}$ superimposed on $-\Delta f$ for comparison with Eq. (1). If this is done the disagreement between $\dot{H}$ and Δf is very obvious.