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Implication of the ionosphere in low latitude micropulsations

Manashi Roy
Indian Institute of Geomagnetism, Colaba, Bombay 400 005

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The low frequency hydromagnetic waves in the terrestrial magnetosphere, known as geomagnetic micropulsations, have to propagate through the ionosphere before they are detected on the ground. It is generally argued that the polarization suffers a 90° rotation while it crosses the ionosphere. All ground data are analysed on this premise. The arguments put forward to this theory have been briefly reviewed and it has been shown that this is not always true, certainly not in the low latitude ionosphere. A general expression is then derived for the low latitude ionospheric effects demonstrating that the rotation angle is substantially different from $\pi/2$. Moreover the amount of rotation is a function of the direction of the wave field. Since the transformation matrix is a complex quantity the ionosphere also introduces phase change among the two horizontal components. Thus the nature of polarization also changes as the wave penetrates the ionosphere.

1 Introduction

The geomagnetic micropulsations are hydromagnetic waves generated in the magnetosphere and beyond. Since they serve as useful diagnostic probes for the distant plasma, the correct identification of the polarization properties of these waves is important. This demands extensive spatial and temporal data coverage which is provided not only by satellite observations but also from ground observations. But the ground data suffer from serious effect of ionospheric modifications which must first be resolved before any comment can be made about the properties of the magnetospheric waves.

Since the early works of Nishida[1], it is generally assumed that apart from the screening effect the ionosphere introduces a rotation by $\pi/2$ to the horizontal component of the wave. Subsequent works of Hughes[2]. Hughes and Southwood[3], Lanzerotti and Southwood[4] offered theoretical arguments as well as computational verification of this premise. Observational support came from the works of Hasegawa and Lanzerotti[5]. Andrews[6] *et al.* and Walker[7] *et al.*, to mention a few.

Both the theoretical and observational studies were primarily concerned with the high latitude ionosphere where the incident wave can be mostly assumed to be a transverse Alfven wave normal to the vertical ambient magnetic field. In contrast the signals at low and mid latitudes are always of mixed mode character. In fact it is not even proper to characterize the waves as linear combination of transverse and compressional type. The situation is further complicated by the fact that the conductivity tensor depends very much on the latitude. Therefore it is not at all certain that the ionospheric effect can be described as a rotation of $\pi/2$, particularly at low latitude region.

Since most of the early ground observations were confined at high latitude regions where an incident Alfven wave may very well have an east-west polarization perpendicular to the vertical field line, the observed north-south ground polarization seemed to be consistent with the $\pi/2$ rotation hypothesis, particularly in the absence of detailed co-ordinated space and ground observations. Anyway, most of the time the polarization character of the waves just above the ionosphere need to be inferred only indirectly. Gradually more careful observations of Glassmeier and Junginger[8] started casting doubt on this firm belief in $\pi/2$ rotation theory. These authors studied a large number of micropulsation events from a chain of ground stations together with simultaneous data from Geos 2 satellite. For some events they found that the ionospheric rotations were considerably different from 90°. In fact theoretical arguments can be given[9] that the nonuniformity of the ionospheric conductivity can introduce any amount of rotation to the polarization vector.

The principal obstacle to resolve this question about the ionospheric rotation is the fact that it is very difficult to have wave data just above the ionosphere. Magnetospheric wave data collected either from geostationary or from high altitude satellites necessarily have to be mapped to the high latitude ionosphere. The mapping procedure itself depends on the assumptions about the nature of the magnetospheric waves. The magnetospheric region corresponding to the footprint of the low latitude field lines is rarely accessible by satellites. This is probably the reason that the theoretical works are mostly confined to the high latitude regions.

In spite of the fact that neither there is any observational indication nor any theoretical support, the same $\pi/2$ rotation hypothesis is routinely applied both to mid and low latitude micropulsation events. In this paper we shall briefly review the arguments put forward to the $\pi/2$ rotation theory. Then we shall derive a general relation between the horizontal wave vector $\mathbf{b}^m$ in the magnetosphere just above the ionosphere and the ground perturbation $\mathbf{b}^0$ on the assumption that the highly conductive metal like ionosphere can be represented as a thin surface discontinuity between the hydromagnetic region and the vacuum region terminated by the infinitely conducting earth. This relation is valid for all low and mid latitudes. The importance of it with respect to the interpretation of the ground micropulsation data will be discussed.

2 Classical derivation of $\pi/2$ rotation

Let the ionosphere be in the x-y plane with the ambient magnetic field $\mathbf{B_0}$ in the z direction as shown in Fig. 1. A hydromagnetic wave propagating downward along the z direction carrying the field-aligned current $j_\parallel$ is incident on the ionosphere. The wave magnetic field b_y^m and the electric field E_x are assumed to be in the y and x directions respectively. This is consistent with the transverse Alfven wave mode along the field line. Since for such low frequencies the ionosphere is almost metallic in character, the induced horizontal currents in the ionosphere can be represented as Pedersen current in the x direction, $J_x=\Sigma_P E_x$, and the Hall current in the y direction, $J_y=\Sigma_H E_x$, where Σ_P and Σ_H are the height-integrated Pedersen and Hall conductivities respectively. Since the horizontal electric field should be continuous, the magnetospheric and ionospheric electric fields are essentially the same E_x. Below the ionosphere the effect of $j_\parallel$ and J_x cancel with each other. The component J_y produces a magnetic field b_x^0 on the ground. Thus we see that the magnetic wave vector has undergone a rotation by $\pi/2$.

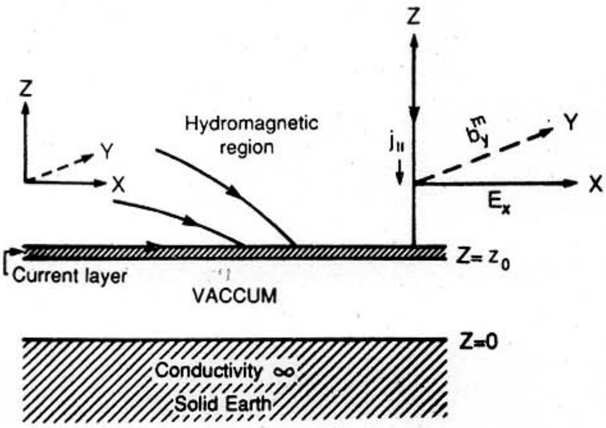

Fig. 1—The models of the ionosphere, vacuum and ground system. The vertical direction is not coincident with the field direction at the low latitudes. x, y and z are respectively south, east and vertical directions.

Another simple way to look at this effect is as follows: In the magnetosphere we have $\nabla\mathbf{b}^m = 0$. It is assumed that the wave variation along the z direction is much smaller than those along the horizontal directions, i.e.

$$b_x^m/b_y^m = -k_y/k_x \quad \ldots (1)$$

Here k_x and k_y are the spatial extents of the wave in the x and y directions respectively. On the other hand near the ground there is no vertical current so that for the ground magnetic vector $\mathbf{b}^0$ we can write, $(\nabla\times\mathbf{b}^0)_z=0$, which means

$$b_x^0/b_y^0=k_x/k_y \quad \ldots (2)$$

From Eqs (1) and (2) it is clear that the roles of k_x and k_y have actually reversed. A predominantly b_y^m in the magnetosphere will be converted into a predominantly b_x^0 on the ground implying a $\pi/2$ rotation.

3 Formal derivation of ionospheric rotation

To derive a more formal relation[9] between the magnetic perturbations in the magnetosphere and on the ground, let us still use the thin sheet model of the ionosphere. The ionospheric current $\mathbf{J}$ is composed of two components: the source free part $\mathbf{J}_1$ and $\mathbf{J}_2$ so that

$$\mathbf{J}=\mathbf{J}_1+\mathbf{J}_2 \quad \ldots (3)$$

$$\nabla\mathbf{J}_1=0 \quad \ldots (4)$$

$$(\nabla\times\mathbf{J}_2)_z=0 \quad \ldots (5)$$

The ionospheric current is again related to the horizontal electric field through the equation

$$\mathbf{J}=\Sigma_P\mathbf{E}+\Sigma_H(\hat{z}\times\mathbf{E}) \quad \ldots (6)$$

It is reasonable to assume that the vertical component of the magnetic perturbation is small which is definitely the case for pure transverse Alfven waves at the high latitude region. This leads to

$$(\nabla\times\mathbf{E})_z=0 \qquad \ldots (7)$$

Again taking the divergence of the current **J** and using Eq. (3) through (7), we get

$$\nabla\mathbf{J}=\nabla\mathbf{J}_2=j_\parallel=\Sigma_P\nabla\mathbf{E}+\mathbf{E}.\nabla\Sigma_P+(\mathbf{E}\times\nabla\Sigma_H)_z \qquad \ldots (8)$$

If the Σ's are constant, then

$$\nabla\mathbf{J}_2=\nabla(\Sigma_P\,\mathbf{E})$$

This means that J_2 is actually Pedersen current and therefore J_1 should be Hall current. Consequently

$$J_1 \perp J_2$$

Just above the ionosphere the waves obey the standard hydromagnetic equations which means

$$(\nabla\times\mathbf{b}^m)_z=j_\parallel \qquad \ldots (9)$$

Therefore from Eqs (8) and (9), we get

$$\mathbf{J}_2=\mathbf{b}^m\times\hat{z} \qquad \ldots (10)$$

The magnetic vector $\mathbf{b}^0$ below the ionosphere is determined by the source free part of the ionospheric current. Therefore,

$$\mathbf{J}_1=-2\,\mathbf{b}^0\times\hat{z} \qquad \ldots (11)$$

From Eqs (9), (10) and (11) it is clear that the angle between $\mathbf{b}^m$ and $\mathbf{b}^0$ is that same as that between $\mathbf{J}_1$ and $\mathbf{j}_2$ which is $\pi/2$.

4 Ionospheric rotations for mid and low latitudes

So far we have assumed that the ionosphere is at a very high latitude so that the vertical direction coincides with the geomagnetic field direction. The geometry is quite different at mid and low latitudes where the field-aligned currents are no longer vertical. Actually the vertical current associated with the incoming hydromagnetic waves is very small compared with the source free conduction currents in the ionosphere. Therefore, let us take the following approach: The two dimentional currents J_x and J_y in the ionosphere represent the discontinuity between the magnetospheric field $\mathbf{b}^m$ just above the ionosphere and the vacuum field $\mathbf{b}^0$ just below so that

$$b_y^m-b_y^0=-(4\pi/c)J_x$$
$$b_x^m-b_x^0=(4\pi/c)J_y \qquad \ldots (12)$$

But the ionospheric currents are related to the ionospheric conductivities by the relation

$$J_x=\Sigma_{xx}E_x+\Sigma_{xy}E_y$$
$$J_y=\Sigma_{yx}E_x+\Sigma_{yy}E_y \qquad \ldots (13)$$

where the Σ's are the components[10] of the two dimentional conductivity tensor associated with the layer ionosphere. For very low frequencies we neglect the frequency dependence of the conductivities. One can find a relationship between the horizontal electric fields E_{xy} just below the ionospheric layer at a height of z_0 from the ground and the magnetic field $b^0_{x,y}$ on the ground by integrating the Maxwell's equation $\nabla\times\mathbf{E}=1/c\,(\partial\mathbf{b}/\partial t)$. For low frequency waves the solid earth can be assumed to be perfectly conducting so that the horizontal electric fields are zero on the ground, which leads to

$$E_x(z_0)\simeq -i\int_0^{z_0}(\omega/c)\,b_y(z)\,dz$$
$$\simeq -i(\omega/c)z_0 b_y^0 \qquad \ldots (14)$$

$$E_y(z_0)\simeq i(\omega/c)z_0 b_x^0 \qquad \ldots (15)$$

Rearranging Eqs (12) through (15) and remembering that the electric fields are continuous across the ionospheric layer we get a relation between the magnetospheric field $\mathbf{b}^m$ and the ground field $\mathbf{b}^0$ as

$$b_x^m=(1+\alpha\Sigma_{yy})b_x^0+\alpha\Sigma_{xy}b_y^0$$
$$b_y^m=-\alpha\Sigma_{xy}b_x^0+(1+\alpha\Sigma_{xx})b_y^0$$

$$\alpha=i(4\pi\omega z_0/c^2) \qquad \ldots (16)$$

This transformation is not a simple rotation as can be seen from Eqs (16). In general the ratio b_x^m/b_y^m, i.e. the angle the horizontal vector $\mathbf{b}^m$ makes with, say, y direction, will depend on the ratio b_x^0/b_y^0. Or in other words the rotation angle is a function of the orientation of $\mathbf{b}^0$. However at high latitude where $\Sigma_{xx}=\Sigma_{yy}$ the above transformation can be looked upon as a rotation matrix of some sort.

At the equator Σ_{xy} is zero[10] and Σ_{xx} is about three orders of magnitude larger[10] than Σ_{yy} for a typical daytime ionosphere. Consequently the east-west perturbation in the magnetosphere will be heavily damped in passing through the ionosphere. The predominant ground polarization is therefore expected to be along the north-south direction. Suppose a magnetospheric wave is very close to the y direction then the ground vector will be close to the x direction since the east-west component has been totally suppressed. This may appear to be a rotation by 90^0. But the fallacy remains in the fact that if the magnetospheric vector

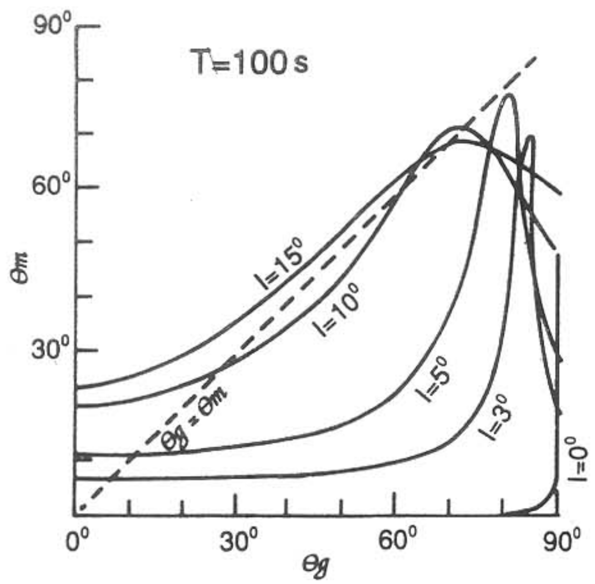

Fig. 2—θ_g versus θ_m for the wave period $T = 100$ s and for the inclinations of the ground stations as labelled (solid lines). The dashed line is for $\theta_g = \theta_m$.

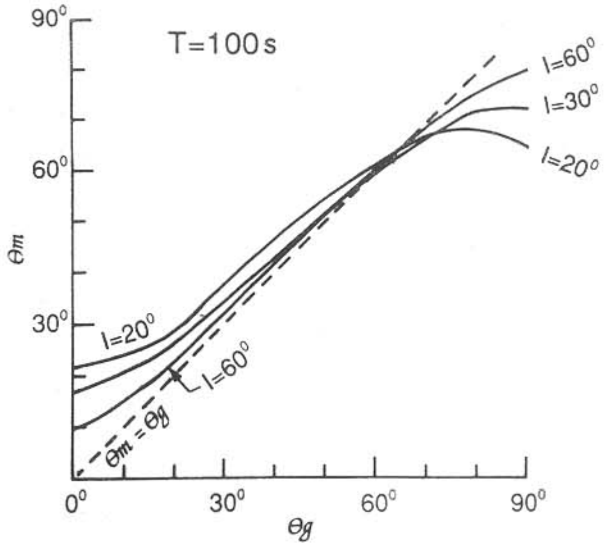

Fig. 3—Same as Fig. 2, but for higher inclinations

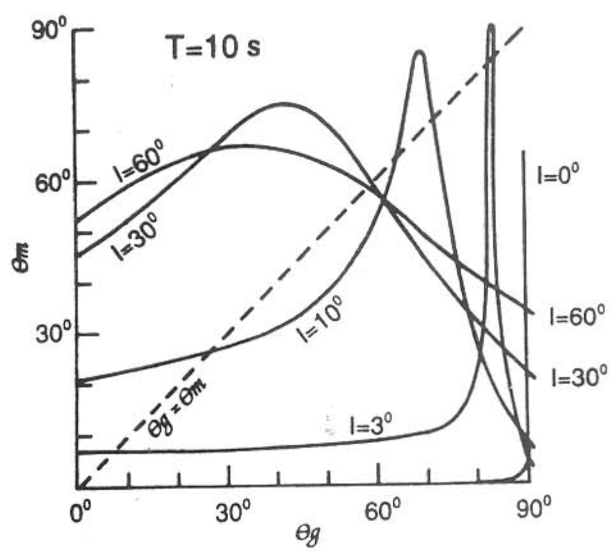

Fig. 4—Same as Fig. 2, but for wave period $T = 10$ s.

is close to the north-south direction then also the predominant ground vector will be along the north-south direction. In the next section we discuss the various orientations of the ground vector vis-a-vis the orientation of the magnetospheric vector.

5 Results and discussion

The thin sheet model of the ionosphere assumed here is valid for low frequency waves. Therefore, as examples, we shall carry on the calculations for time period of 100s and 10s respectively. The ratio b_x^0/b_y^0 is a measure of the orientation of the vector $\mathbf{b}^0$ in the horizontal plane. From Eqs (16), the ratio b_x^m/b_y^m is a known function of the ratio b_x^0/b_y^0 and the conductivities. Denoting the absolute value of b_x^0/b_y^0 as tan θ_g and the absolute value of b_x^m/b_y^m as tan θ_m we have plotted θ_g verses θ_m in Figs 2-4 for various values of inclination I of the ground station. The conductivities are assumed to be appropriate for a typical daytime ionosphere[10].

For all the periods the equatorial graph ($I = 0$) is a sharply vertical line near 90^0 value of θ_g. As explained previously large b_x^0 will be translated as large b_x^m in the magnetosphere. But even a small b_y^0 on the ground means a very large b_y^m in the magnetosphere. Thus for θ_g slightly less than 90^0, θ_m sharply falls to zero. Physically this means that irrespective of the magnetospheric field orientation the ground variation is essentially aligned along the north-south direction. Therefore it would be very difficult to conjecture about $\mathbf{b}^m$ from the observation of $\mathbf{b}^0$ but not vice versa.

As the latitude increases the θ_m-θ_g curve shows a narrow peak. The width of the peak broadens with latitude. A broad peak implies that a small change in the orientation of $\mathbf{b}^m$ reflects a large change in $\mathbf{b}^0$ direction. Thus observations on the ground with even some scatter in θ_g will be able to predict fairly accurately the orientation angle θ_m for the magnetospheric signal.

The peaks in the graphs are sharper for higher frequencies than for lower frequencies as can be seen by comparing Figs 2 and 3 for $T = 100$ s with Fig. 4 for $T = 10$ s signals. For a given frequency again the peaks are sharper at lower latitudes. Thus ground observations to predict the magnetospheric wave will be more efficient for lower frequencies and for off equatorial latitudes.

It is clearly seen that the rotation of the field vector, i.e. $\theta_m - \theta_g$, is definitely not $\pi/2$; it is not even constant. A constant rotation angle, however, will be represented by a straight line parallel to the dashed lines in Figs 2, 3 and 4 labelled as '$\theta_m = \theta_g$'. Although the amount of rotation is dependent on the orientation of the signal there are some regions where the curves are approximately parallel to the '$\theta_m = \theta_g$' line. For example, in Fig. 2 the graph for $I = 10^0$ the ground orientation θ_g between 40^0 and 60^0 almost represents a constant rotation. Similarly at the inclination of $I = 15°$ the rotation is almost constant for the region of θ_g between 40^0 and 60^0. In mid latitude region also (Fig. 3) the rotations seems to be constant for low values of θ_g. This implies that those signals which have high b_y^0 perturbations on the ground at mid latitudes can be relied upon to introduce a constant rotation to the magnetospheric signals.

Here we have calculated only the absolute values of b_x^m/b_y^m. Since the transformation matrix in Eqs (16) is a complex quantity there will be a phase difference between b_x^m and b_y^m even if the ground polarization is assumed to be linear. Therefore, the polarization of $\mathbf{b}^m$ will be actually elliptic although we are not discussing the ellipticity at the moment.

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