Use of pitch angle dependence of flux oscillations as a diagnostic tool for determining the spatial structure of oscillations

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Abstract. Waves and instabilities in the ULF range make crucial contributions to processes that transfer energy from the solar wind into to the magnetosphere and produce geo-space events like geomagnetic storms and sub-storms. While ULF waves are known to efficiently energize and transport relativistic electrons through resonant interactions leading to radial diffusion, their global structure, occurrence and characteristics are not well understood. At the same time use of realistic spectral characteristics and structure of the ULF waves are required for determination of rate of diffusion of relativistic electrons via drift resonance. We show here that pitch angle structure of energetic particle fluctuations can be used to determine the structure of the ULF oscillations along the field lines through the use of multivariate analysis techniques. Using AMPTE CCE particle data, we use variations of the principle component analysis to examine the technique.

Index Terms. Natural orthogonal components, non-local modes, pitch angle dependence, ULF waves.

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1. Introduction

Waves and instabilities in the ULF range make crucial contributions to processes that transfer energy from the solar wind into to the magnetosphere and produce geo-space events like geomagnetic storms and sub-storms. Dynamic impulses from the coupled solar wind/magnetosphere system can lead to substantial reconfiguration of the radiation belts on time scales of a few minutes while ULF waves in the magnetosphere provide a reservoir of energy capable of accelerating particles on time scales of a few hours to several days (Elkington et al., 2004). However, methods used for identifying these ULF modes uniquely from satellite and ground based data are still inadequate. Pitch angle fluctuations can be used as powerful diagnostic tool for the study of wave characteristics. The particle fluctuations observed by the satellite detector have signatures of the local structure of the wave field but they also carry the information of the acceleration that the particles are subjected to along their bounce trajectory.

In order to estimate the pitch angle dependence of the diffusion and other dynamical processes associated with ULF waves, it is essential to know the spectral characteristics of the fluctuations along with their spatial structure along the field and across the line. To recover useful data on the large-scale structure of the wave characteristics from the particle flux measurements, it is necessary to have the full pitch angle description of the particle flux changes with a sampling rate much smaller than the wave period under scrutiny. We use the Medium Energy Particle Analyzer (MEPA) (McEntire et al., 1985) on board AMPTE CCE which provides the pitch angle sampling rate required for such an effort. The problem due to the drifting of the boundary of the energy channels has been circumvented by re-evaluating the fluxes and presenting them in terms of canonical channels corresponding to the originally intended channel energy bins (cf. home page: http://sd-www.jhuapl.edu/MIDL/ for details).

The method of natural orthogonal components (Rajaram et al., 1992) is used to derive the natural modes of oscillations from the data. In section 2 we describe the method used and in section 3 we present the analysis of the actual data.

2. Method of natural orthogonal components (MNOC)

The particle flux $\Phi(\alpha_i, t_j)$, at times t_j (j=1,N) are available for the pitch angle α_i $(i = 1, \mathrm{M})$. We write

$$\Phi(\alpha_i, t_j) = \sum_{k=1}^{M} \Psi_{i,k}(\alpha_i).T_{k,j}(t_j) \tag{1}$$

where $\Psi_{i,k}$ and $\mathrm{T}_{\mathrm{k,\,j}}$ satisfy the constraints

$$\sum_{i=1}^{M} \Psi_{i,l}\Psi_{i,k} = \partial_{l,k} \quad \text{and} \quad \sum_{j=1}^{N} T_{l,j}.T_{k,j} = \lambda_k \partial_{l,k}$$

$\partial_{l,k}$ is unity when k=l and zero otherwise. We can, thus, expand $\Phi(\alpha_i, t_j)$ as sum of M modes, $\Psi_{i,k}(\alpha_i)$, each having a temporal variation given by the components $T_{k,j}(t_j)$. $\Psi_{i,k}$ are eigen vectors of Matrix **R,** defined by

$$\mathbf{R}_{i,l} = \sum_{j=1}^{N} \Phi(\alpha_i, t_j).\Phi(\alpha_l, t_j)$$

The temporal variation of the components is given by

$$T_{k,j} = \sum_{i=1}^{M} \Phi(\alpha_i, t_j).\Psi_{i,k}(\alpha_i)$$

Eigen values are arranged in descending order and the percentage of variation explained by each component k is given by $p_k = \frac{\lambda_k}{\sum \lambda_j} \times 100.$

3. Analysis of MEPA data

AMPTE CCE is a spinning spacecraft with a spin period of about 6 seconds. The spin rate is not strictly constant, so the exact value for each spin has been used in calculating flux values. MEPA divides the spin into 32 sectors. The data used in the present analysis consist of the first four ion (proton) channels E_ION_P_0(25-34 keV), E_ION_P_1(34-50 keV), E_ION_P_2 (50-83 keV), and E_ION_P_3(83-151 keV).

The ion flux channels are "canonical" channels referred to in section 1. These are provided in the units of counts/ (sq. cm. sec. keV. ster.). The direction of the incoming flux was given in the GSE co-ordinate system in terms of the latitude and longitude angle with respect to the earth-sun line (measured positive eastward).

In addition to these energetic ion channels, there also engineering channels MCP1, MCP2 and MCP3, which provide an integrated ion count which may be interpreted as total flux of ions with energies greater than 3kev (Takahashi et al., 1990a).

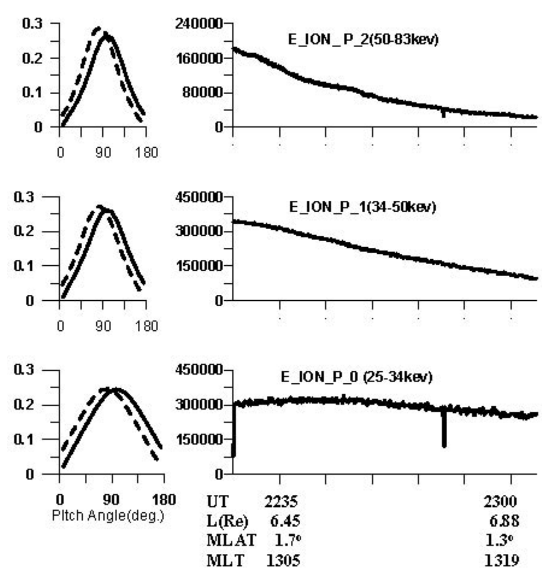

Fig. 1. Pitch angle and radial dependence of the first component of energetic particle flux on day 324, 1985. Full lines are flux from east and dashed lines represent flux from the west.

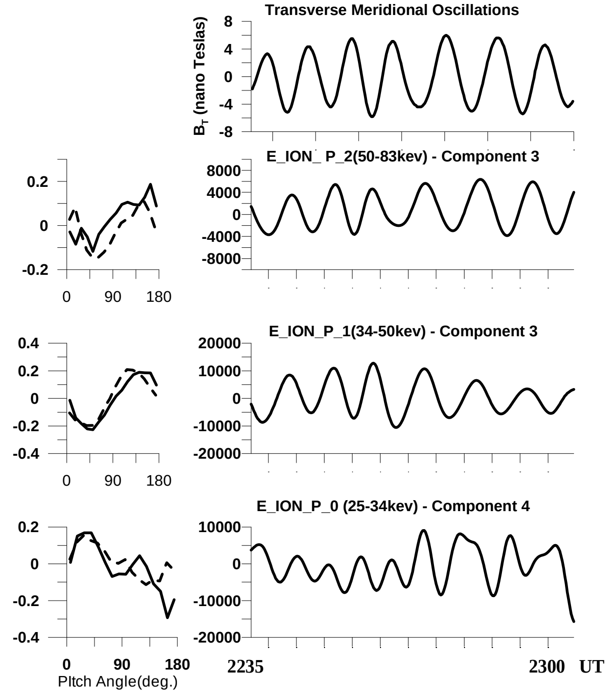

Fig. 2. Pitch angle dependence of energetic particle flux response to transverse meridional oscillations in the magnetic field on Day 324, 1985.

The data sampling of a complete pitch angle scan could range from around 6 - 24 seconds depending on the read out interval for the particular channel but are interpolated here to give a uniform 6 second sampling interval. Interpretation of the directional properties of the fluxes in terms of the pitch angle and azimuth require the use of either the model geomagnetic field or the observed vector magnetic field on board the satellite. We use the long term trends in the measured field as a measure of the background field required to define the pitch angle and azimuth of the particle fluxes.

In the present communication, we concentrate on two data intervals, which have special events that have been examined by earlier investigators (Takahashi et al., 1990a, b). The first data segment was from 2200 UT to 2315 UT on day 324, 1985. The satellite was in the local noon meridian close to the equatorial plane moving outward from its position at around 6 earth radii. This period was marked by very regular Pc5 pulsation oscillating at a period of around 6 minutes with classic radial polarization (Takahashi et al, 1990b). The low pass filter designed to eliminate short period noise was required to cut off periods less than 2 minutes or so.

The second event was between 0645 UT to 0820 UT on day 58 of 1985. The satellite was in the early morning sector (MLT around 4) and off the equatorial plane of the magnetosphere by around 5^o in magnetic latitude. It was just outside 8 earth radii and moving outwards during the period of our interest. The period was characterized by Pc 5 waves with harmonically related transverse and compressional components (Takahashi et al., 1990a). The primary harmonic oscillation is associated with radially polarized transverse oscillations around 20 minute periods. Related to this pulsation is a non-linearly generated compressional oscillation in the strength of the magnetic field oscillating with a period of around 10-12 minutes. The filter design to be used for removing high frequency noise has to have a high frequency cut off at frequency corresponding to a periodicity of 5 minutes.

For each of the events, a 101 points sine terminated low pass filter was used to remove rapid fluctuations and glitches from the fluxes recorded in each of the 32 channels.

Next the longer series of vector magnetic field data recorded on board the satellite was taken up for digital low pass filtering using a 201 point sine terminated filter to remove all fluctuations having periods less than around 30 minutes. This provides a long period trend in each of the vector components of the magnetic field that could be used to define the background magnetic field. This background field was used to define the direction of the ambient magnetic field at each instant in the GSE co-ordinate frame. The satellite ephemeris was used to define the direction of the radial vector and the plane defined by the radial vector and the direction of the ambient magnetic field vector was defined as the meridional plan. The unit vector in this plane perpendicular to the unit magnetic field vector defined from the ambient magnetic field data defines the direction of transverse meridional oscillations. The azimuthal direction is fixed by the cross product of these unit vectors.

The fluctuating component of the magnetic field vector is obtained by subtracting out the background vector magnetic generated above form magnetic field vector obtained from each instant of time. The dot product of the fluctuating magnetic filed with the unit magnetic field vector defined by the ambient field gives the wave component of the magnetic field variations. The wave field perpendicular to this ambient field but in the meridional plane gives the transverse meridional oscillations of the pulsations.

The ambient background magnetic field data is also required to define the pitch angle associated with each of the 32 channels. The latitude and longitude (with respect to the earth-sun line) of the direction from which the flux is coming is available for each read out of the satellite data. It is possible to define straightaway the unit vector in the flux “look” direction. The dot product of this vector with the unit vector defining the direction of the ambient magnetic field gives straightway the cosine of the pitch angle corresponding to the instantaneous channel record.

The spread in the pitch angle corresponding to given channel is small in comparison with the difference in the assigned pitch angle of two neighboring channels. Thus it is possible, in a meaningful way, to assign a pitch angle to each of the 32 channels. During one satellite spin the pitch angle span is repeated but the longitude of the flux direction helps us to distinguish particles coming from the east and west of the satellite locations.

For each of the events, we now have the time series of the particle fluxes for each of the pitch angle channels for each of the energy channels. Each of the time series is then subjected to MNOC described in section 2. This involves the computation of the covariance matrix and evaluation of its eigen values and eigen vectors. The eigen vectors provide the characteristic pitch angle functions for each of the components while the eigen value specifies the percentage of variability that the component can account for. The time series corresponding to each of the components is then readily evaluated and compared to the fluctuations in the magnetic field components.

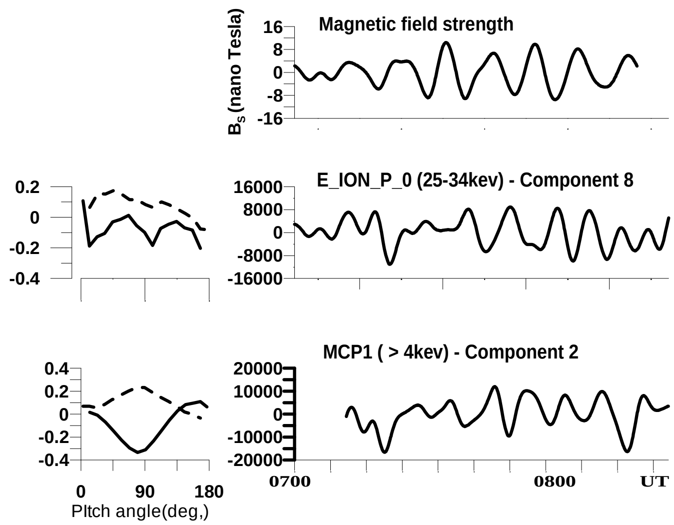

Fig. 3. Pitch angle dependence of energetic particle flux response to pressure fluctuations in magnetic field strength on day 58, 1985

We note that the first eight components can account for more than 99.99% of variability in all the energy channels for both the events. The first component gives the ambient pitch angle dependence of the background plasma in the magnetosphere and its temporal variations reflect the radial distribution of the energetic particle fluxes. This is demonstrated in Fig. 1 for day number 324. The pitch angle distribution is a typical loss cone type expected around near noon conditions at the satellite locations. The figure also shows the existence of radial gradients in particle fluxes, with gradients sharpening with increasing energies.

Fig. 2 brings out components that bring out the pitch angle fluctuations on day 324, 1985 driven by meridional component of transverse magnetic field fluctuations. The asymmetric nature of the mode is clearly brought out. There appears to be no resonance effect in the particle response, as the flux oscillations appear to be in phase across the large range energies.

Figs. 3 and 4 are drawn for event of day 58 in 1985. The equilibrium distribution (not shown here) was typically anti-loss cone. Fig. 3 shows how the analysis brings out the response of particle fluctuations to the compressional mode. Note that the MCP1 dominated by low energy particles seems to react to local electric field while the energetic particles have, in addition to local response, a structured pitch angle dependence associated with the spatial dependence of oscillations along the field line.

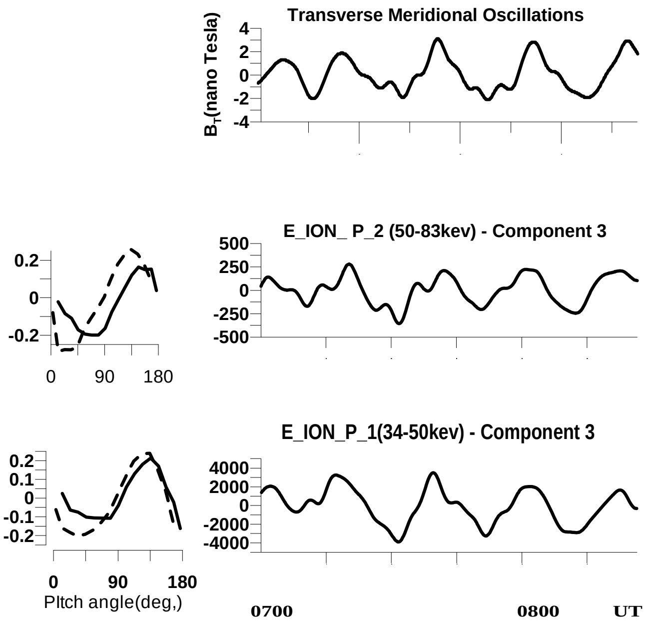

Fig. 4. Pitch angle dependence of particle flux response to transverse radial oscillations in the magnetic field on day 58, 1985.

Finally Fig. 4 again confirms the response of particle flux oscillations to transverse oscillations of the magnetic field in the meridion plane. The pitch angle response is anti-symmetric and stable in structure and phase over a range of energies. There is no evidence of resonance with bounce or gradient motion. The clean and systematic pitch angle structure suggests that it should be possible to perform a robust inversion to obtain the spatial structure of the wave field along the ambient magnetic field.

4. Discussion

Earlier workers (cf. Hasegawa, 1979) appeared to suggest that presence of parallel electric field was essential for the phase particle flux oscillations to respond to the hydro-magnetic waves. However, Southwood and Kivelson (1981) and Kivelson and Southwood (1985) have shown that particle flux oscillations as seen by satellite detectors can respond to both transverse and compression waves with and without the presence of parallel electric fields.

Particle response to transverse oscillations can be generated by local acceleration due to a wave electric field and due to adiabatic acceleration and due to convection of a gradient.

The first of these dominates the low energy response and this is consistent with the MCP1 response in Fig. 3. The response of the energetic particles to meridional oscillations is consistent with convection of gradient, given the radial gradients are manifest in the first component.

In case of response to a compressional mode, the "mirror effect" is also present and there is an evidence of this in the energetic particle response in Fig. 3. The peaks in response at low pitch angles may be associated with peak in the magnetic compression at around 5^{o} latitude (Takahashi et al., 1990a).

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