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Comparison of three techniques for locating a resonating magnetic field line

C.T. Russell[a,*], P.J. Chi[a], V. Angelopoulos[b], W. Goedecke[c], F.K. Chun[d], G. Le[a], M.B. Moldwin[e], G.D. Reeves[f]

[a]*Institute of Geophysics and Planetary Physics and Earth and Space Sciences Department, University of California, Los Angeles, USA*
[b]*Space Sciences Laboratory, University of California, Berkeley, USA*
[c]*Colorado School of Mines, Boulder, CO, USA*
[d]*US Air Force Academy, Colorado Springs, CO, USA*
[e]*Physics and Space Sciences Dept., Florida Institute of Technology, Melbourne, FL, USA*
[f]*Los Alamos National Laboratory, Los Alamos, NM, USA*

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Abstract

Three techniques for locating field lines in the magnetosphere that contain standing ULF pulsations are compared using dynamic spectra. The first technique compares ratios of the H- and D-components of the magnetic field at a single site; the second examines the ratios of the H-components at neighboring sites along a magnetic meridian; and the third displays the phase difference between H-components at neighboring sites. We find that the H:D ratio at a single station appears to detect magnetospheric standing waves but not their precise location. In contrast, the dual station H-ratio technique is sensitive to resonances local to the stations and has advantages over the widely used phase-gradient technique. In contrast to the latter technique calculating the H-power ratio does not require precise timing and provides two resonant locations, not one. We also find that the stations used need not be strictly confined to a single magnetic meridian. Resonance signatures can be detected with stations up to 1300 km in east–west separation. In our initial data near $L = 2$ multiple-harmonic structure is generally not observed. The resonant wave period, when assumed to be the fundamental of the standing Alfven wave, gives densities in the range 3000–8000 amu/cm^3. These mass densities agree with in situ observations at earlier epochs. The equatorial mass density varies most during the day (by over a factor of two for the case studied) at $L = 1.86$ and much less (20%) at $L = 2.2$. This is consistent with a constant upward flux of ions over this latitude range flowing into a flux tube whose volume increases rapidly with increasing L-value.

1. Introduction

While many spacecraft pass through the plasmasphere on their way to apogee, few spend much time within this region. Hence the study of the plasmaspheric plasma often depends on ground-based observations. Originally VLF whistlers were used. Their dispersed frequency signature can be used to determine the L-value of the whistler's path through the magnetosphere and the equatorial electron density along that path (see e.g., Helliwell, 1965). This method of determining the electron density does not provide a continuous measure of the equatorial density because whistlers

* Corresponding author. Tel.: +1-310-825-0900; fax: +1-310-206-3051.
E-mail address: ctrussel@igpp.ucla.edu (C.T. Russell).

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are not always present. They depend on the existence of lightning in the appropriate region and a duct to keep the whistler aligned along the field. Suitable ducts may not exist at all L-values for which measurements are desired. Furthermore, recording of VLF signals requires a substantial bandwidth, if done continuously at multiple stations.

An alternative approach is to identify the resonant frequency of Pc 3–4 ULF waves. Such waves are present almost always in the dayside magnetosphere and can be monitored continually for modest data bandwidth. Since the occurrence of Pc 3–4 waves is very closely controlled by the cone angle of the IMF the major source of these waves is thought to be in the Earth's foreshock (Greenstadt and Russell, 1994). In this model, waves are generated in the solar wind by ion beams traveling upstream from the bow shock. These waves are convected through the bow shock and against the magnetopause. Compressional waves of this nature are present in the magnetosheath (Song et al., 1998). They periodically compress the magnetopause and a compressional disturbance inside the magnetosphere travels across magnetic field lines as a fast mode wave. When the fast mode wave encounters a field line whose standing wave period equals that of the fast mode wave, the coupling to transverse oscillations (in the east–west or toroidal direction) can lead to significant wave amplitudes because the wave energy is not absorbed at the resonant frequency since the ionosphere is a node of the oscillation. Although the radial perturbation of the waves and the east–west perturbation might be expected at first glance to contribute on the ground to the H- and eastward D-components respectively, the high Hall conductivity of the dayside ionosphere rotates the perturbation so that beneath the ionosphere the east-west toroidal resonance in the magnetosphere is seen principally in the north-south H-component on the ground, and the radially propagating fast mode is largely in the D-component (Hughes and Southwood, 1976).

This paradigm in turn suggests the following strategies for determining the resonant wave periods. On the ground under a resonating field line the H-component oscillation should be strongest relative to the D-component oscillations at the resonant frequencies. A dynamic spectrum of the ratio of the wave power in the H-component to that in the D-component vs frequency and time should then give a maximum or ridge at the resonance (Baransky et al., 1990; Vellante et al., 1993). However, the problem to be solved is not just to determine what signals are resonances but to determine which field line is resonating at the observed frequency and with this technique we cannot be sure a resonance is overhead. If one has a pair of stations in the north–south direction one can calculate the ratio of their H-component power. The resonances directly above the station, whose wave power is in the numerator, should result in ridges, and those above the station, whose wave power is in the denominator, should result in troughs (Baransky et al., 1985, 1989; Best et al., 1986). Finally, one can also compare the phases of the H-component oscillations at two stations separated in the north–south direction (Baransky et al., 1989). The necessary coherence between stations is enforced by the ionosphere over a finite width depending on the dissipation of the waves. The phase of oscillating field lines on either side of a resonance should differ significantly, being largest for the resonance centered between the stations and approaching 180° for infinite separation. This phase difference can be visualized as that occurring when a resonant system is forced to oscillate off its resonant frequency. The technique has been most extensively exploited by Waters et al. (1991, 1994) who pioneered the use of the dynamic spectrum to display the results of the phase-gradient technique. In this paper we employ dynamic spectral displays of each of these three techniques with measurements obtained by the newly installed IGPP-LANL array. We discuss their relative limitations and advantages, and illustrate that the resonant frequencies observed have physically reasonable interpretations. One technique, which is not in wide use, appears in our data to have advantages over the other techniques and thus merits wider consideration by the pulsation community.

2. Instrumentation

The Los Alamos National Laboratory through the mini grant program of the Institute of Geophysics and Planetary Physics has established a chain of high resolution, high sampling rate fluxgate magnetometers in the western US to study the inner region of the magnetosphere, presently from $1.7 \leq L \leq 2.2$ Re. In this report we examine data from the first three of these stations to be installed: the Air Force Academy in Colorado Springs, the Los Alamos National Laboratory, and the San Gabriel Dam, California. The locations of these stations are given in Table 1. The first two sites are roughly along the same magnetic meridian and separated by 350 km. The San Gabriel Dam site is located 1300 km to the west of the other two sites as well as being 3.5° south of Los Alamos.

The IGPP/LANL stations record at one sample per second continuously with an amplitude resolution of 0.01 nT, and precise GPS timing. The electronics unit is mounted on a single board in a PC that provides power and data storage. The sensors are buried in the ground at distances from 30 to 60 m from the electronics unit. The sensors, the analog to digital converter and the feedback resistors are kept at constant

Table 1
Station locations

Station	Geographic		Geomagnetic		*L*-value
	Longitude	Latitude	Longitude	Latitude	Earth radii
Air Force Academy (AFA)	104.9° W	39.0° N	39.2° W	47.5° N	2.19
Los Alamos (LAN)	106.7° W	35.9° N	40.9° W	44.4° N	1.96
San Gabriel Dam (SGD)	117.9° W	34.2° N	53.0° W	40.9° N	1.75

temperature. Fig. 1 shows dynamic spectra of the signals in the magnetic north (H), eastward (D) and vertical (Z) directions from 0700 UT on 3 October to 0700 UT on 4 October 1998 corresponding to a full day of data starting at approximately local midnight. This day was chosen because it was near the beginning of the period of three-station operation and had fairly constant signal amplitudes through the day. The behavior on this day is representative of the surrounding three week period. The data have been averaged to 6 s and overlapped by 3 s and the derivative taken before being Fourier transformed. The derivative is calculated to pre-whiten the spectra that are falling rapidly with increasing frequency. The dynamic spectra here consist of 512 point individual FFT spectra shifted 128 data points at a time and summed in the frequency direction in groups of five. As can be seen in Fig. 1 the spectrum is rather broad with no sharp spectral features. Rather the spectrum exhibits an enhancement from about 15 mHz to 60 mHz. The power is elevated during the day. The H-component power is generally the strongest followed by D and Z in that order. The spectra at the other two stations are similar but exhibit less power with increasingly lower latitude.

3. The three resonance finding techniques

As discussed in the introduction three different methods have been proposed to find the resonance frequencies of the field lines above a magnetometer site: ratioing H and D powers at a single site; ratioing H powers at two adjacent sites; and determining the phase difference between the H components at neighboring sites. We now apply these techniques in turn to this set of data at our three sites. We will examine only the daytime hours in the sections to follow i.e. 1300 UT on 3 October 1998 to 0100 UT on 4 October 1998.

3.1. Single station H/D ratio

The simplified picture of the rotation of the magnetospheric signal through 90° by the ionosphere implies that the D-component responds to the cross *L*-shell propagating fast mode and the H-component to the toroidal mode. Thus the ratio of H:D at a single station might be expected to show a ridge in the power ratio at the toroidal resonance frequency. The three panels of Fig. 2 show this ratio at each of our three stations. The AFA station shows a broad maximum at a wave period ranging from 30 to 55 s as the day progresses. AFA also shows a trough for part of the day at slightly shorter periods from 1700 to 2100 UT. The LAN station shows the same broad maximum as AFA but also exhibits a new ridge changing from 20 to 25 s in the course of the day. This ridge covers the region of the trough seen at AFA. The bottom panel shows the dynamic spectral ratio at San Gabriel (SGD) an hour earlier local time for the same universal time. The H/D ratio is weaker at SGD than LAN and AFA but shows some of the structure seen at AFA and LAN in the lower frequency band at about 35 s period. In short there appear to be waves with enhanced H/D ratios at all three stations at lower frequencies, and a ridge of enhancement seen only at LAN at higher frequencies. If this technique is sensing standing wave resonances, it is sensitive to a wide band of latitudes not simply those above the station. Thus this technique does not locate the field line that is associated with a particular resonant frequency.

3.2. Dual station H ratio

With our three stations we can create two ratios of adjacent pairs of H-component powers. These two ratios are shown in Fig. 3 for the daylight hours. As expected there is a clear trough and a clear ridge running across the top panel. We interpret the ridge as a resonance over the AFA station. It varies from 32 to 35 s. The trough varies from 20 to 28 s as the day progresses. The crossover line between the two is at 25 seconds at dawn and at 32 s at dusk. We interpret this crossover line as the resonant frequency halfway between the stations.

If we examine the ratio of the power spectral densities of H-component at LAN to that at SGD we obtain the bottom panel. Here we see only a ridge signalling that there is a resonance over LAN (where the trough was in the upper panel) but the absence of a

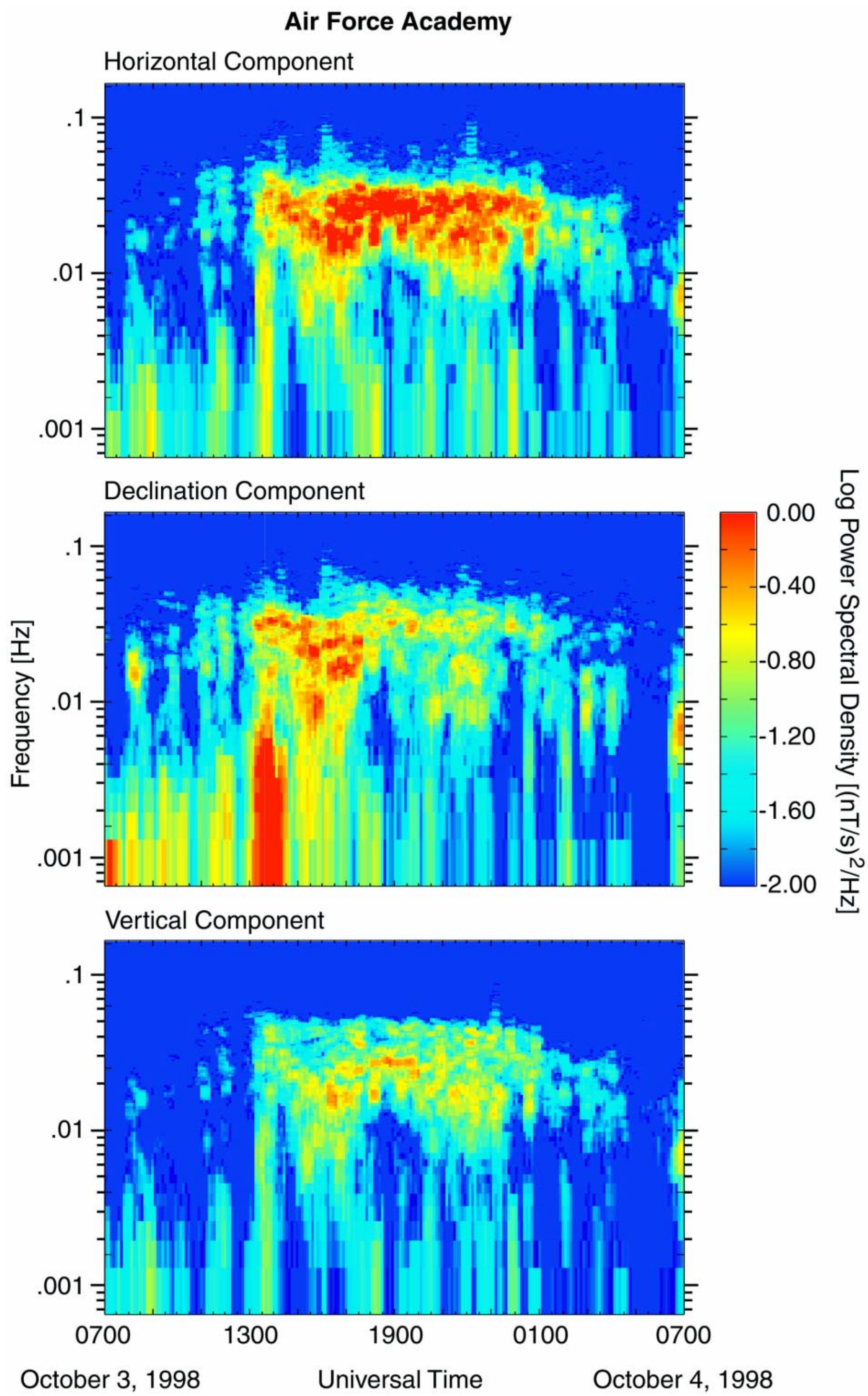

Fig. 1. Dynamic spectra of the power spectral density of the three components observed by the IGPP/LANL magnetometer at the Air Force Academy in Colorado Springs, Colorado for 24 h beginning at midnight local time on 4 October 1998. The vertical scale is logarithmically spaced. The original 1-s data were averaged to 6-s averages with a 3-s overlap. The derivative of the field components were calculated for prewhitening before the dynamic power spectra were constructed. In constructing the dynamic spectra, the fast Fourier spectrum was calculated for 512 data points and shifted by 128 for the next calculation. Spectral estimates have 10 degrees of freedom.

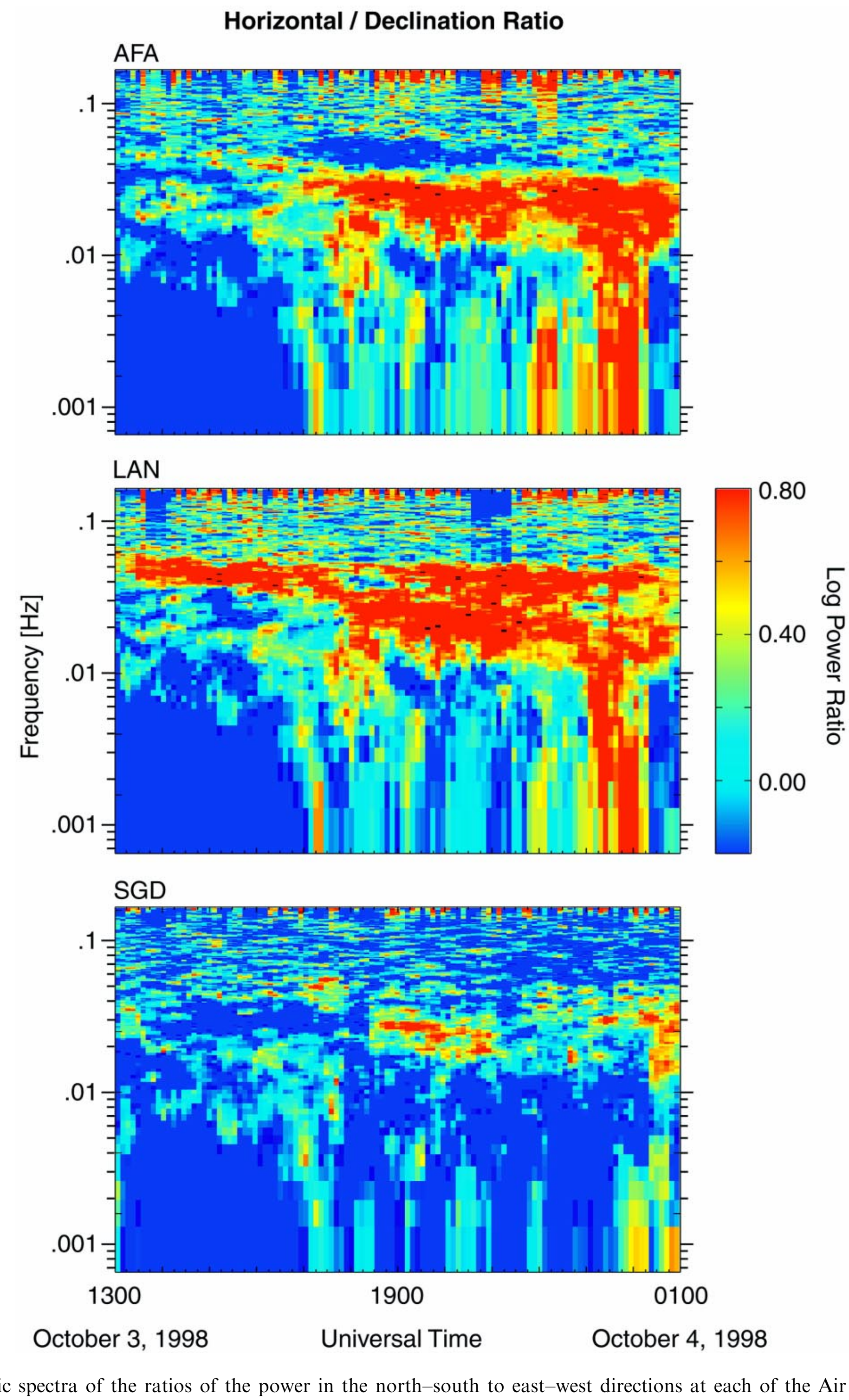

Fig. 2. Dynamic spectra of the ratios of the power in the north–south to east–west directions at each of the Air Force Academy, Los Alamos and San Gabriel Dam. See Fig. 1 for details about the construction of this figure. Only the daylight hours are shown on this and subsequent figures.

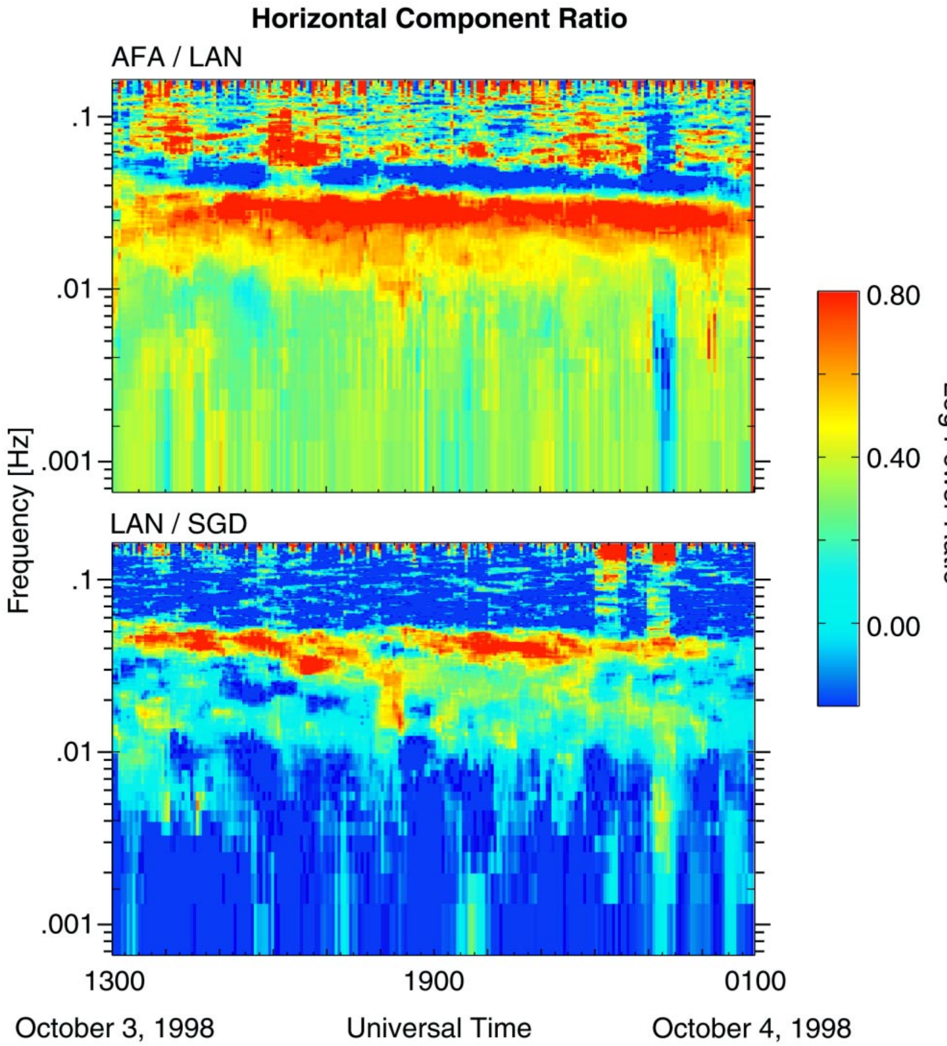

Fig. 3. Dynamic spectra of the ratios of the north–south component of the magnetic field at adjacent pairs of stations. Comments of Fig. 1 apply.

narrow trough suggests that there is no resonance over SGD. We presume that there is no resonance at SGD because the local resonance frequency is above the frequency band of the exciting signals. The expected resonance period at SGD varies from about 12 to 20 s in the course of the day and reference to Fig. 1 shows that there is no wave power at these periods.

3.3. Phase gradient in the H-component

Recently the favored technique to find resonant frequencies has been through the difference in the phase of the H-component at two adjacent stations. Again we can do this for two pairs of stations as shown in Fig. 4. The AFA-LAN phase difference maximizes at a wave period that changes from 22 to 32 s in the course of the day. The LAN–SGD phase difference maximizes at a wave period that changes from 16 to 25 s in the course of the day.

These periods are consistent with those periods deduced above from the dual-station H-ratio technique when account is taken of the fact that the H-ratio technique has ridges and troughs at the resonances over the stations used and the phase difference is a maximum for the resonance between two stations.

4. Discussion and conclusions

Of the three techniques for locating the standing waves in the magnetosphere, the power-ratio method using the H-component appears to be the most infor-

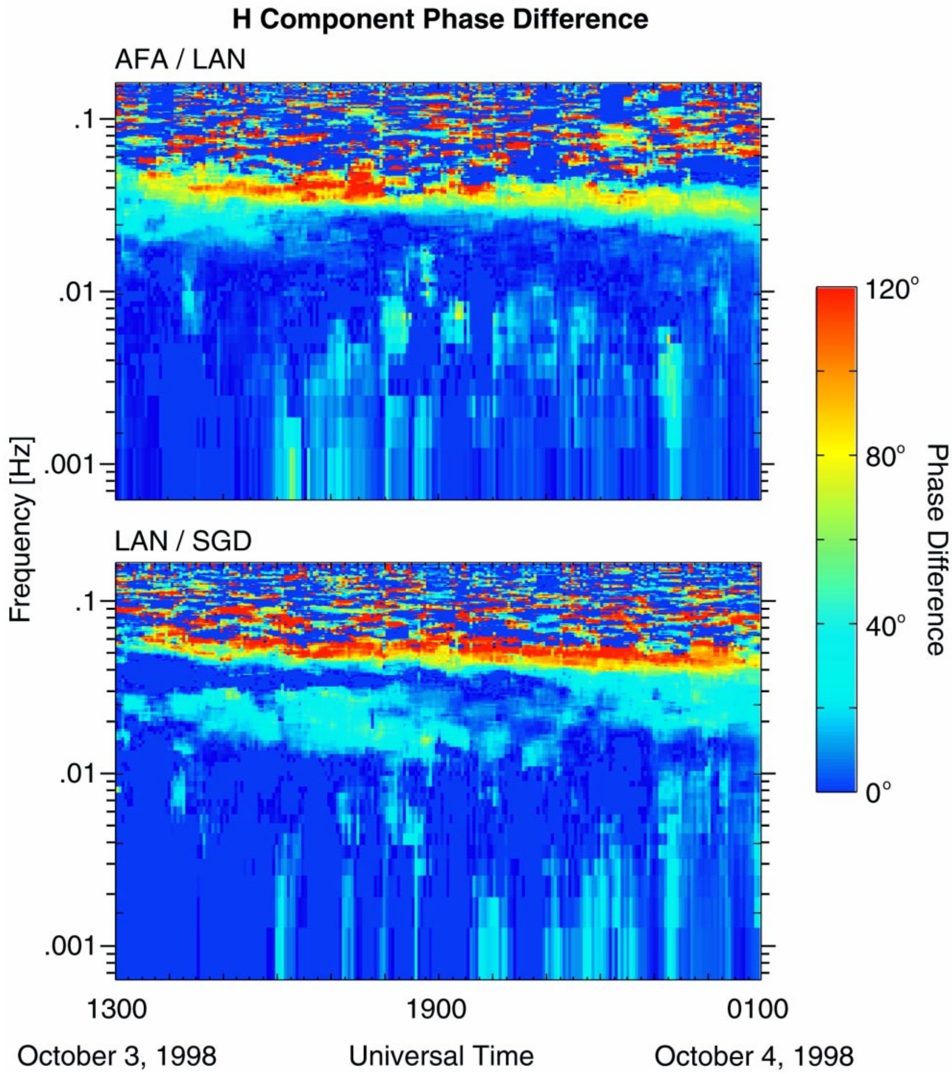

Fig. 4. Dynamic spectra of the phase differences between the components of the north–south component of the magnetic field at adjacent stations. Comments of Fig. 1 apply.

mative by providing the resonant period over both stations. Moreover, this technique does not require the precise timing needed to perform the phase-gradient technique. The IGPP/LANL array does have such accurate timing, much more than needed in fact, and can confirm that the same resonant frequency is returned by both the dual-station H-ratio and the phase-gradient methods. In contrast the single station H/D ratio technique is not successful. The broad frequency range of H-power enhancement relative to the D-power indicates that it is sensitive to a broad latitude band. This technique shows that resonant oscillations are present but does not identify resonances that are unique to a particular location.

We can use the periods found with the dual-station H-ratio and phase-gradient techniques to deduce the mass density above AFA, LAN and a latitude midway between SGD and LAN. Table 2 lists the resonant periods at each location at both dawn and dusk. We estimate that we can measure these periods to within 10% from our spectrograms. We calculate the inferred mass density at the equator under the assumption that the observed pulsations are oscillating at the fundamental, second and third harmonic frequencies (n = 1, 2, 3 respectively) (Schulz, 1996). We have assumed an r^{-3} (m = 3) dependence for the density where r is the geocentric distance of the point along the field line but the rate of falloff of the density does not much affect our derived equatorial densities because most of the wave travel time is spent in the equatorial regions. The

Table 2
Resonant periods and corresponding equatorial densities

Station	L-value	LT	Period	Mass density (proton masses)		
				$n = 1$	$n = 2$	$n = 3$
SGD[a]	1.855	06	16	3200	15,300	36,500
		18	25	7800	37,400	89,000
LAN	1.96	06	20	3000	14,500	34,700
		18	28	5900	28,400	68,000
AFA	2.19	06	32	2900	14,400	34,500
		18	35	3500	17,200	41,300

[a] Resonance point halfway between SGD and LAN.

densities for $n = 1$ are quite similar to the densities observed in this region by the OGO-5 thermal ion spectrometer (Chappell et al., 1971) and the ISEE-1 sweep frequency receiver measurements (Carpenter and Anderson, 1992). Thus it appears that we are observing the fundamental frequency. This is also consistent with observations on four consecutive passes of CCE that recorded only the fundamental mode in the inner magnetosphere (Takahashi et al., 1990) and the pulsation studies of Waters et al. (1994) near $L = 2$.

The density increases from dawn to dusk as expected due to the upward flux of ions from the sunlit ionosphere and their subsequent corotation. This diurnal variation is consistent with the earlier work of Waters et al. (1994) who examined the diurnal variation of the resonance frequency over a 21-day period in October and November 1990 and presented plots for six of these days at two L-values. This paper did not attempt to calculate equatorial mass densities. They found a variable diurnal variation of the resonant frequency at both $L = 1.8$ and 2.8 but did not attempt to explain this variation nor compare the variation at the two locations. We find that the diurnal change in density on the day studied is close to a factor of 2 at $L = 1.9$ and about 20% at $L = 2.2$. This change in density is consistent with similar upward fluxes of ions at the two locations flowing into different volumes of the flux tubes. It can be shown that the flux tube volume in a dipole field is proportional to the L-value raised to the power 3.5. Thus, we expect the change in density at the two locations to differ by a factor of 1.7, the value observed.

In summary the IGPP/LANL array can detect field line resonances routinely by two techniques: dual station H-component ratios and dual station H-component phase gradients. We strongly recommend the former technique as it provides more information about the location of the resonant frequencies and is simpler to implement. The latter provides only the resonant frequency between the two stations and requires precise and accurate timing. Near $L = 2$ the pulsations appear to be occurring at the fundamental of the field line resonance for the limited sample of data that we have examined. The deduced mass densities are similar to those observed on the very infrequent observational passes through this region with spacecraft. It is clear that the mass density of the inner plasmasphere is being accurately measured by the IGPP/LANL observatory chain. We intend to maintain these stations as permanent observatories of the plasmaspheric density in order to determine how the inner plasmasphere responds to diurnal, seasonal and solar cycle variations in ionizing flux as well as to variations in geomagnetic conditions.

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