Albedo Features and Jovian Seismology

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Schmider et al. (Schmider, F.-X., B. Mosser, and E. Fossat 1991. Astron. Astrophys. 248, 281–291) and Mosser et al. (Mosser, B., D. Mékarnia, J. P. Maillard, J. Gay, D. Gautier, and P. Delache 1993. Astron. Astrophys. 267, 604–622) report detection of Doppler shifts in reflected solar radiation from Jupiter purportedly induced by p-mode oscillations of the planet. We consider the possibility that these observations may be recording quasi-periodic albedo features in Jupiter's atmosphere rather than or in addition to jovian oscillations. We model the Fourier Transform Spectroscopy method of p-mode detection in detail and employ near-IR methane-band images of Jupiter to test the albedo feature hypothesis. The low frequency portion (<700 μHz) of the Fourier spectrum presented by Mosser et al. is indeed found to be contaminated by the photometric signal of albedo features rotating with Jupiter. Albedo features apparently are not responsible for the bulk of the higher frequency signal attributed to p-modes. © 1995 Academic Press, Inc.

I. INTRODUCTION

Current interior models of Jupiter (e.g., Chabrier et al. 1992) rely upon all available observational constraints, including the gravitational harmonics, mass, radius, shape, and atmospheric composition of the planet. There has thus been no independent method to evaluate the veracity of the interior models. Measurement of the frequencies of Jupiter's natural oscillation modes would provide such a new probe of the interior structure. Although there is a diversity of possible modes, astronomers have only searched for p-modes at Jupiter. These modes are the expression of the interference pattern created by acoustic waves trapped in the interior (Leibacher and Stein 1981).

Reviews of jovian seismology are given in Marley (1993), Lognonné and Mosser (1993), and Mosser (1994).

Prior to 1994, there have been three reported searches for jovian p-modes. Deming et al. (1989) (hereafter D89) searched for spatially coherent, temporally periodic tropospheric (~0.5 bars) brightness temperature fluctuations produced by p-modes of Jupiter. They did not detect any acoustic modes and placed an upper limit of 1 m sec⁻¹ on total mode velocities. Schmider et al. (1991) and Mosser et al. (1993) (hereafter S91 and M93 respectively) attempted to measure Doppler shifts produced by low degree jovian p-modes in sunlight reflected by Jupiter. Both groups reported positive results using different techniques. Mode velocities (up to 4 to 8 m sec⁻¹) reported by these teams exceed the upper limit placed by D89.

While surprising, the differing results of D89, S91, and M93 are not inherently contradictory. D89 maximized their sensitivity to sectoral p-modes with some sensitivity to other modes as well. Because of a limb-darkening correction, they had comparatively little sensitivity to very low degree modes, although they did detect a nonacoustic wave feature at wavenumber 5. M93 interpreted the spacing between individual peaks in their observed power spectrum as arising from rotational splitting of very low degree p-modes of order m < 3. If this interpretation is correct, the modes to which D89 and M93 were sensitive are somewhat different and their apparently contradictory results could be reconciled.

Another interpretation, however, is that some other signal is responsible for the apparent p-mode detection by S91 and M93. Doppler observations by both the sodium vapor cell (S91) and the Fourier Transform Spectrometer...
(FTS) (M93) techniques culminate in a measurement of flux in solar radiation reflected from Jupiter. Instrument design and data analysis connect the photometric observations to a Doppler shift measurement. A Fourier analysis of the temporal variation in flux results in a power spectrum of what is presumed to be atmospheric velocity fluctuations on Jupiter in the frequency range 200 to 2000 μHz (80 to 8 min). The solar 5-min p-modes, another potential source of Doppler shifts, are at a still higher frequency. Thus while both experiments attempt to correct for purely photometric variations, the possibility still exists that spatially periodic albedo features on Jupiter might be responsible for some or all of the signal recorded by both S91 and M93.

In this paper we briefly review the experimental techniques employed by the two groups, report on imaging observations obtained to test the albedo feature hypothesis, and present a model that calculates how photometric fluctuations in the source can induce a spurious velocity signal. We then present a detailed simulation of the M93 observations and conclude that jovian albedo features indeed contaminate a portion of the M93 and possibly the S91 power spectra as well.

II. SEISMOLOGICAL OBSERVATIONS

Schmieder et al. (1991) relied upon photometry of full disk observations of reflected solar sodium D1 and D2 lines (0.5890 and 0.5896 μm) passed through a sodium cell. The Sun–Jupiter–Earth Doppler shift was chosen such that the wings of the solar line were just to the edge of the sodium cell bandpass. Any periodic atmospheric motions on Jupiter should result in a change in measured flux through the sodium cell as the filter bandpass shifts along the solar lines’ wings. At 0.59 μm reflected solar radiation is returning from Jupiter’s cloud tops. Subsequently, the instrument is sensitive to variations in cloud morphology and albedo as well as Doppler shifts on Jupiter.

Mosser et al. (1993) employed a Fourier transform spectrometer to search for Doppler shifts in reflected solar radiation in the 1.1-μm methane band through a 12" diameter circular aperture (equivalent to 45° in latitude on Jupiter; Jupiter’s diameter is about 48° at opposition) placed tangent to and alternately north and south of the equator. They also identified possible low degree p-modes between 500 and 2000 μHz with a similar power spectra to S91. Although a differencing technique (Section IV) employed by M93 eliminates any constant hemispheric albedo differences between the two apertures, a periodic albedo signal present in only one of the apertures, or present more significantly in one aperture than in the other, may not be fully removed.

Both instruments include a correction for global photometric fluctuations. For the sodium resonance cell, the Doppler signal is divided by the incoming flux. By the same manner, the FTS Doppler signal can be divided by the integrated flux seen in the aperture through the filter bandpass. Nevertheless, modulation of the central depth of the sodium lines or photometric differences between the two apertures induced by periodic albedo fluctuations can generate a pseudo-seismological signal.

The possibility that longitudinally periodic albedo features might create a seismological-like signal is raised in M93, but the authors conclude that Jupiter is too bland at the observed wavelength to produce such a signal. However, the plume structures at 6°N latitude (Fig. 1) rise sufficiently high into Jupiter’s atmosphere to be visible in near-IR methane-band images. About 10 similar plumes are spaced around the planet and could produce a quasi-periodic brightness variation with a period of about 1 hr (frequency ~280 μHz). In addition, other albedo features (including the Great Red Spot) and their overtones might produce higher frequency signals. To evaluate the spatially periodic appearance of Jupiter we obtained the images described in the next section.

III. JUPITER IMAGING AT 0.889 μm

III.a. Observations

CCD images of Jupiter were obtained on the NMSU 61-cm Cassegrain planetary telescope using the f/40 focus. The observatory is located at the Tortugas Mountain Station approximately 4 km east of Las Cruces, NM at an elevation of 1505 m. The images record spatial maps of albedo, or relative surface brightness, of the planet.

The M93 observations are in the 1.1-μm band of methane. Because of atmospheric and instrumental limitations, imaging of Jupiter is typically not performed at this wavelength. Instead we obtained CCD images of Jupiter through an 0.889-μm narrow band methane filter (FWHM = 0.018 μm). Although this wavelength differs from that used by M93, it is a band of comparable strength. Since the M93 observations utilized numerous individual methane lines of varying strengths at 1.1 μm, we conclude that albedo features detected in our images would also produce a signal at the longer wavelength.

A full simulation of the observational technique of M93 would require near continuous imaging of Jupiter over several nights. As this was not practical, our goal was to produce a 360° map of Jupiter at 0.889 μm that could be rotated to simulate Jupiter’s rotation under the M93 field of view.

The cylindrical map shown in Fig. 1 was constructed by concatenating six images of Jupiter together. Three of the images used were taken on the night of April 9, 1993, and the other three on April 10, 1993. After properly navigating the images to accurately determine the location of the planet center, a Minnaert filter (Minnaert 1941) was applied to help eliminate limb darkening. Each image was
then projected onto a cylinder and the resulting rectangular images seamed together so that longitude increases continuously. In order to match the seams, each of the six images was scaled by a multiplicative factor close to 1. The resulting image has a spatial resolution of about 2° corresponding to ~2590 km on Jupiter.

The concatenated map extends over a range in longitude of 360°. Assuming solid body rotation in System III, this is equivalent to 595 min of Jupiter’s rotation through the central meridian. The zonal wind profile was not taken into account to correct for any relative movement of clouds over the time elapsed between the first and last images.

For the second dataset we applied a high pass filter to the concatenated map to accentuate the variations in pixel value (representing relative surface brightness) followed by a low pass filter to smooth the graininess created by the high pass filter. The resulting image is not representative of the natural reflectivity of Jupiter, but does allow examination of the higher frequency content of the images.

III.b. Periodogram Analysis

Clearly, albedo features exist in the 0.889-μm images. To investigate them, we obtained scans from each dataset for latitudes (within the ±45° latitude range included in the M93 observations) that appeared to have longitudinal brightness variations in 0.889-μm images (Table 1). Since the M93 technique eliminates constant albedo differences between the north and south apertures, we did not take scans from the latitudes with little or no azimuthal brightness variations. Each scan consists of a one-dimensional sampling of pixel value as a function of longitude along a particular latitude. A given datapoint is comprised of the average pixel value in a box spanning 2° of latitude and 0.75° of longitude. For Dataset 1, we obtained 480 datapoints per scan. Scans in Dataset 2 have 477 datapoints.

To investigate the spatially periodic content, periodograms were calculated for each scan (Figs. 2, 3). For better comparison with the M93 data, datapoint longitude was converted to time assuming the System III rotation rate. The resulting power spectra are not a direct simulation of either S91 or M93, but do give some information about potential sources of contamination in the Doppler experiments. The filtering applied to Dataset 2 (Fig. 3) results in significantly more structure at higher frequencies.

These periodograms suggest that the spatially varying jovian albedo features visible in the 0.889-μm methane band indeed exhibit power at temporal frequencies comparable to those seen in M93. In both datasets (Figs. 2a, 3a), periodograms of scans from the plume latitudes, 4°, 6°, 8°, and 10°N, show significant peaks near 250 μHz. Many other peaks coincide at three or all of these latitudes ranging from 180 to 1070 μHz. All of the major peaks apparent in Dataset 1 also appear in the filtered Dataset 2.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Scans of Set 1 (April 9–10, 1993)</th>
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<tbody>
<tr>
<td></td>
<td>Northern latitudes</td>
</tr>
<tr>
<td>4°</td>
<td>0°</td>
</tr>
<tr>
<td>6°</td>
<td>8°</td>
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<tr>
<td>8°</td>
<td>17°</td>
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<td>10°</td>
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<td>16°</td>
<td>33°</td>
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<tr>
<td>27°</td>
<td>41°</td>
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</table>
FIG. 2. (a) Periodogram of the northern latitude scans taken from Dataset 1. Latitudes are listed in Table 1. The most prominent power is seen at 250 and 370 μHz in the 4°, 6°, 8°, and 10°N scans. These are associated with the plumes which are evident at these latitudes. (b) Same as (a), only for the southern latitudes. The strong peaks seen in both the 17° and 23°S data are signatures of the Great Red Spot. The peaks from the 33°S scan may be associated with several white ovals present in the Dataset 1 image. These ovals are also apparent in images taken at the Tortugas Mountain observatory during the same time frame as the 1990 run of M93.

The peaks between 100 and 200 μHz and around 280 and 400 μHz (Fig. 2b) correspond to features visible at the latitudes that include the Great Red Spot (GRS) (17° and 23°S). In Dataset 2, peaks around 400 and 800 μHz from the 23°S scan are possible overtones. Features including the white ovals at 33°S are the likely source of the signal at approximately 530 μHz (Fig. 2b). A significant amount of structure between 400 and 1600 μHz is apparent at this latitude as seen in the filtered dataset (Fig. 3b).

Several of these frequencies are also apparent in the power spectra of M93. It is difficult to compare relative power amplitudes, however, because in both S91 and M93 different low frequency filters were applied to limit noise below about 500 μHz. Nevertheless, the strongest peak in the 1990 M93 dataset is at 250 μHz and is also apparent in the S91 dataset. This frequency seems to be the signature of the plumes (Fig. 2a). The GRS signature (Fig. 2b) may also be apparent in the M93 data near 100 μHz, although these frequencies are severely filtered.

IV. SIMULATIONS

The comparison of periodograms of individual scans with the S91 and M93 power spectra provides circumstantial evidence that periodic albedo features on Jupiter may be contaminating the low frequency portion and to a lesser degree the higher frequency portion of the Doppler power spectra. To fully investigate this possibility, we conducted a more detailed simulation of the entire observational procedure of M93. The S91 dataset is less conducive to simulation, but should also be less sensitive to albedo variations since the Doppler shift is measured from the integrated disk.

To fully simulate the observations of M93 requires a complete treatment of the seismological capability of the FTS. As explained in M93, this instrument has been used in a very uncommon way: it works at a fixed path difference instead of recording a full interferogram. Consequently, we consider exactly how each stage of the M93 acquisition procedure affects the resulting Fourier spectrum. Specifically, we have developed a model which calculates how the photometric fluctuations of the source can also induce a spurious velocity signal. It introduces a few parameters which can be determined or estimated with the help of the planetary images taken in the thermal 0.889-μm methane band.

In this section, we first briefly recall how an FTS can be used as a Doppler velocimeter. For a complete description, see M93. The main result, given by their Eq. (5), expresses how the velocity of the scattering region of the atmosphere is translated into the intensity change measured in the interferogram.

We have then simulated a sequence of five nights of observation. The input signal is constructed from the scans taken from the cylindrical map from Dataset 1. It reproduces as precisely as possible the conditions of seismological observations with the FTS at the CFH telescope in 1990 and 1991: it respects the geometry of the detection, as explained by Fig. 6 of M93. The output Fourier spectrum then represents the signature of the albedo fluctuations.
**IV. a. Seismometry with an FTS:**

**Sensitivity to Photometry**

Equation (1) of M93 defines the terms in the interferogram obtained from the FTS based at the CFH telescope. We first suppose the influence of one single absorption line. With \( v \) the radial velocity of the source, \( \Gamma(\delta) \) the visibility function of the line \( \sigma_0 \), \( A \) the central depth of the line (%), \( W_0 \) the energy in the line profile, \( W_c \) the total energy within the filter bandpass, and \( \tau \) the overall transmission of the system including the atmosphere, the output signal beyond the zero path difference as a function of the path difference \( \delta \) can be approximated by

\[
S(\delta) \propto \tau \left[ W_c + W_0 A \Gamma(\delta) \cos 2\pi \sigma_0 \left(1 - \frac{v}{c}\right) \delta \right]
\]  

**IV. a.1. Rejection of the continuum and internal modulation.** Fluctuations in transmission \( \tau \) are rejected using the signals \( S_1 \) and \( S_2 \) of the dual-output interferometer. These signals, recorded with the two detectors of the FTS equipped with cat's eyes, have the same DC component but opposite modulated terms. The difference and the sum of the two signals is recorded and stored by the data acquisition chain:

\[
\begin{align*}
\Delta S &= S_1 - S_2 = 2\pi W_0 A \Gamma(\delta) \cos 2\pi \sigma_0 \left(1 - \frac{v}{c}\right) \delta \\
\Sigma S &= S_1 + S_2 = 2\pi W_c
\end{align*}
\]  

The results obtained in 1990 were based on the signal \( \Delta S \). The ratioing technique, which filters out the fluctuations of the transmission \( \tau \), was first introduced in the observations conducted in 1991:

\[
\begin{align*}
S_{1990} \approx \frac{\Delta S}{\Sigma S} \approx \frac{2\pi W_0 A \Gamma(\delta) \cos 2\pi \sigma_0 \left(1 - \frac{v}{c}\right) \delta}{2\pi W_c}
\end{align*}
\]  

**IV. a.2. Internal modulation.** The subtraction described by Eq. (2) supposes that the appropriate gain has been applied to each channel to balance the continuous component. Therefore although it cannot completely reject this component, it reduces it efficiently. The complete rejection is ensured by the next step of the data recording, namely the internal modulation. This operation perfectly excludes the most important possible contamination due to photometric fluctuations. The modulated part of the signal is given as

\[
s \propto 2\pi \sigma_0 \delta - \frac{U}{c} \sin 2\pi \sigma_0 \delta + \cos 2\pi \sigma_0 \delta. 
\]  

The maximum sensitivity is obtained at a zero-crossing of the fringe signal for a path difference \( \delta_{\text{max}} \) chosen such that

\[
\cos 2\pi \sigma_0 \delta_{\text{max}} = 0. 
\]
Because of the difficulty of guiding exactly on a fixed point on the planet, it is practically impossible to ensure that the mirror of the FTS will remain exactly on a zero position of the interferogram during an entire night. Thus we introduce the velocity factor \( V \) which accounts for the drift of the cosine factor of Eq. (5). The part of the signal depending on the path difference \( \delta \) is then

\[
s \propto v + V, \quad \text{with } V = c \frac{\cot 2\pi \sigma_0 \delta}{2\pi \sigma_0 \delta}.
\]

(6)

The observed lines were in the methane \( 3\nu_3 \) band around 1.1 \( \mu \text{m} \) (\( \sigma_0 \approx 9045 \text{ cm}^{-1} \)). Using a band instead of a single line does not change the analysis (but presents the multiplex advantage). The path difference was fixed in 1990 around 0.9628 cm. The velocity factor \( V \) is then

\[
V = 5.5 \text{ km sec}^{-1} \times cot 2\pi \sigma_0 \delta.
\]

(7)

The efficiency of the method, e.g., the position of the path difference \( \delta \) in the vicinity of the optimal position \( \delta_{\text{max}} \), was checked regularly during the observations with the FTS. The cosine factor was always less than 0.4 which corresponds to a velocity factor \( V \) less than about 2.5 km sec\(^{-1}\).

**IV.a.3. Meridian modulation.** The detection is in fact a differential detection resulting from the difference of two interferometric signals. These signals are obtained by chopping, with the secondary mirror of the telescope, between two planetary fields (Fig. 6 of M93). The direction of the chopping is parallel to the planetary rotation axis so that this technique eliminates spurious velocities introduced by a combination of guiding errors and planetary rotation. As a result, the signal is the difference between the two output signals \( s_N \) and \( s_S \) corresponding to the two positions of the diaphragms:

\[
\begin{aligned}
\Delta s_{\text{1990}} &\propto \tau_N W_{\sigma N} (u_N + V) - \tau_S W_{\sigma S} (u_S + V) \\
\Delta s_{\text{1991}} &\propto \frac{W_{\sigma N}}{W_{\sigma N}} (u_N + V) - \frac{W_{\sigma S}}{W_{\sigma S}} (u_S + V).
\end{aligned}
\]

(8)

The subscripts \( N \) and \( S \) refer to the two fields North and South respectively, the subscript \( \sigma \) to the spectral information, and the subscript \( c \) to the continuum. The velocity factor \( V \) is the same for both fields. The differences between the two fields appear through the oscillation's velocity difference \( \Delta v = u_N - u_S \). The other terms indexed with \( N \) or \( S \) may have absolute variations (common to both positions of the diaphragms) and relative fluctuations, expressed by the factors \( \eta \) and \( \xi \) as depicted in the system of definition

\[
\begin{aligned}
\Delta v &= u_N - u_S \\
\tau_{N,S} &= \tau_0 [1 + \eta_\tau] \left[ 1 \pm \frac{\xi_\tau}{2} \right] \\
W_{\sigma N,S} &= W_{\sigma 0} [1 + \eta_\sigma] \left[ 1 \pm \frac{\xi_\sigma}{2} \right] \\
W_{c N,S} &= W_{c 0} [1 + \eta_c] \left[ 1 \pm \frac{\xi_c}{2} \right].
\end{aligned}
\]

(9)

Finally, when retaining only the first-order terms and taking into account the dependence with time, the interferometric signal of the FTS is

\[
\begin{aligned}
\Delta s_{\text{1990}}(t) &\propto (1 + \eta_\tau + \eta_\sigma)(\Delta v + V(\xi_\tau + \xi_\sigma)) \\
\Delta s_{\text{1991}}(t) &\propto (1 + \eta_\sigma - \eta_c)(\Delta v + V(\xi_\sigma - \xi_c)).
\end{aligned}
\]

(10)

**IV.b. Simulated Signature of Albedo Fluctuations**

**IV.b.1. Estimation of the parameters.** The simulated photometric signal \( \Delta s(t) \) has been obtained in the following manner. The 12 individual scans from Dataset 1 are considered as a map of pixels. At each time step, the longitudinal phase is increased with the rotation phase. The visibility of each pixel is tested through the diaphragm. The visible pixels are then used to simulate the flux through one diaphragm as integrated by the FTS detector. This makes it possible to reproduce the functions \( \eta_c(t) \) and \( \xi_c(t) \). In fact, these values were derived from the observations concerning the fluctuations of the continuum around 0.889 \( \mu \text{m} \), not at 1.1 \( \mu \text{m} \). However, as noted in Section III, we consider them to be representative of the continuum fluctuations at 1.1 \( \mu \text{m} \).

The direct estimation of the same functions for the line profile \( (\eta_\tau \text{ and } \xi_\tau) \) or for the transparency fluctuations \( (\eta_\sigma \text{ and } \xi_\sigma) \) is not possible. We assume that they have the same variations as the measured values \( \eta_c(t) \) and \( \xi_c(t) \) in order to construct the Doppler signal due to the photometric fluctuations

\[
\delta_{\text{phot}}(t) = V(1 + \eta(t))\xi(t),
\]

(11)

with \( \eta(t) \) and \( \xi(t) \) being twice \( \eta_c(t) \) and \( \xi_c(t) \). The absolute albedo fluctuations of the line profile \( \eta(t) \) are in fact on the same order as the relative fluctuations between the two fields \( \xi(t) \). According to the images at 0.889 \( \mu \text{m} \), the maximum variations of both parameters are about 4%.

The absolute fluctuations \( \eta \) are in fact negligible whereas the relative fluctuations \( \xi \) which directly balance the velocity factor \( V \) are not. According to Eq. (10), the ratioing technique as made since 1991 surely has a very positive influence. First, it allows one to avoid the trans-
Figures 5a and 5b are the Fourier and power spectra of the signal of Fig. 4 displayed above the spectrum recorded with the FTS in 1990. It shows that the photometric fluctuations can be responsible for a major part of the low frequency noise under 700 µHz. This limit can be understood by keeping in mind that a given feature on Jupiter crosses the diameter of the 12" wide detector in about 1.25 hr which corresponds to about 200 µHz. The plume signature, occurring around 250 µHz, is visible as are several of the other features apparent in Figs. 2 and 3.

V. DISCUSSION

The above results reveal the sensitivity of the M93 seismological observations to the real periodic albedo features on Jupiter. It is interesting to note that models of artificial albedo features, such as a single bright spot, do not reproduce the low frequency behavior of the spectrum. We tested the photometric influence of such a spot in the model. The results differed greatly from the observed data and therefore are not presented here in great detail. The spot rotates with the planet and consequently produces a fundamental signature at 28 µHz (period of Jupiter’s rotation)⁻¹. Even when the amplitude of the fundamental frequency is fairly large, the amplitudes of the overtones decrease as frequency⁻¹. Combining this with the effects of the diaphragm size, signatures above 700 µHz (18th overtone) do not produce any recognizable signal above noise.

The simulation using the 0.889-µm data investigates the effect of actual higher spatial frequency jovican features passing through the aperture. It demonstrates that albedo features indeed do introduce signals in the M93 power spectra that may be responsible for most of the signal below 700 µHz. Note that the low frequency contribution has reached a peak comparable to the largest peaks seen in the M93 data. Therefore we conclude that our simulation does not underestimate the signature of the photometric inhomogeneities at these frequencies.

Analyzing these inhomogeneities from a velocity viewpoint, Fig. 4 indicates that although the low frequency filtering decreases the relative albedo fluctuations (dotted lines) to less than half of that seen in the raw data (solid lines), a difference of ~1% still yields a significant photometric equivalent velocity. In fact, these velocities exceed the Doppler velocities created by the p-modes. Comparison of the simulations to the results of M93 supports this (Fig. 5), especially in the low frequency range. In particular, the amplitude of the signal between 350 and 400 µHz in our simulations is comparable to the data of M93. Significant signal at 150 µHz also is not eliminated by the technique. However, the signal at 250 µHz is greatly reduced compared to the original transforms. We believe that in the case of the 250-µHz frequency, the photometric

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**Fig. 4.** Five-night simulation of the relative albedo fluctuations $\xi(t)$ (Eq. (1)) between the two positions of the diaphragm, obtained from the 12 scans from Dataset 1. The correspondence between the two vertical axis (relative fluctuation [%] and equivalent velocity) is given by the velocity factor $V = 2.5 \text{ km/sec}^{-1}$. The full line corresponds to the raw data. The dotted line shows the fluctuations after the low frequency filtering (cutoff at 1 hr⁻¹).
correction made by the FTS accounts for the missing signal.

At higher frequencies, albedo features do not appear to introduce significant peaks into the power spectrum as measured by the model. However, as Fig. 3 illustrates, quasi-periodic albedo features on Jupiter can produce a temporal signal at frequencies as high as 1550 μHz. While the M93 technique eliminates most of this signal (Fig. 5), care must be taken in any Doppler measure of jovian oscillations that photometric fluctuations do not conspire to mimic p-modes of Jupiter. Ideally, future observations will incorporate simultaneous imaging of Jupiter, thus eliminating any such ambiguity.

Although simultaneous imaging would allow removal of contamination from noise created by resolved features, it would not eliminate any high frequency signal that may originate in unresolved albedo features. In particular, images of star spots can be reconstructed from stellar spectra containing unresolved intensity variations by the technique of Doppler imaging (e.g., Vogt et al. 1987). Similarly, unresolved features on Jupiter may affect the Doppler signal obtained by M93 and could possibly account for an appreciable amount of high frequency signal currently linked to p-modes. Therefore, the calculations shown here may only provide a lower limit to the effects of albedo inhomogeneities.

Furthermore, several sources of noise indirectly related to the albedo features would directly affect the Doppler signal and therefore may contribute to the M93 detections. Namely, either the line of sight component of the zonal wind velocities near the edge of the 45° diameter diaphragm or the vertical upwelling of the plumes may contaminate the observations by M93. Given the maximum zonal velocity of 108 m sec⁻¹ at the plume latitude 7°N (Gierasch et al. 1986), trigonometric arguments indicate that the corresponding line of sight velocity is 30 m sec⁻¹. However, assuming the zonal winds are in steady state, the technique used by M93 should eliminate this component.

In contrast, upwelling events such as those that create the plumes likely have significant vertical velocities that are not in steady state. The moist-convection model (Stoker 1986) estimates that moderately sized clouds in the plumes (2 to 10 km) can attain at least 100 m sec⁻¹ vertical velocities in the central upwelling region. It is possible that such contributions from individual plumes present in the aperture used by M93 could also contaminate the signal.

VI. CONCLUSIONS

The rapid rotation and rich detail of Jupiter’s atmosphere conspire to make Doppler measurements of atmospheric velocity challenging. The existing Doppler techniques fundamentally rely upon a photometric measurement and are subsequently susceptible to variations in albedo. Furthermore, quasi-periodic features are present in Jupiter’s atmosphere, even in moderately strong methane bands. As these features rotate around the planet they indeed produce temporal variations in the photometric signal from Jupiter at frequencies < 700 μHz. Given the absence of significant power in our simulation (Fig. 5) above 700 μHz, we conclude that the high frequency p-mode signals of M93 are not due to resolved
albedo features on Jupiter. However, the M93 detections are strongly contaminated by these features at low frequencies.

REFERENCES


