HELIOSEISMIC OBSERVATIONS AT STANFORD, 1977-1986

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ABSTRACT. Observations of low degree modes of solar oscillation have been made at The Wilcox Solar Observatory at Stanford University for more than a decade. We are presently re-examining the set of observations from 1977 through 1986. We have first tested the stability of the p-mode frequencies for modes of degree l=2-5 in each year. We find a marginally significant trend of a decrease in p-mode frequencies of 0.06 μHz per year. We have also examined the continuity of the observed signal at 160.01 minutes. We find that the previously reported phase stability is no longer present. However, due to uncertainties in calibration we can not exclude the reality of the reported signal.

Data Preparation

The observations are measurements of differential velocity made by comparing the position of the 512.4 nm Fe I line integrated over the central portion of the disk with that from a surrounding annulus. The method, originally suggested by Kotov (Severny et al., 1976), has been described in Scherrer et al. (1983) and references therein. Most of the useful data used in this analysis have been obtained in the months of June through August from 1977 to 1986.

The advantage of a differential technique is that, to first order, it is not affected by spectrograph seeing or the earth's rotation. A disadvantage of any low resolution method is that it is sensitive to fluctuations in sky transparency. The method also is sensitive to guiding errors and to certain other instrumental sources of drift. Previous analyses of this data have dealt with the drifts, guiding errors, and daily zenith angle part of the transparency variations by an *ad hoc* procedure of removing a fit parabolic trend (Delache and Scherrer, 1983; Scherrer and Wilcox, 1983). We have identified three sources of drift and the cause of the variation in sensitivity. These drifts can be removed in a less arbitrary way or filtered out depending on the portion of the spectrum of interest.

The largest drift is due to variations in photomultiplier tube gain with changes in brightness. The light from the red and blue wing of the line is measured by two separate phototubes. The difference signal is used by a servo system to keep the slits positioned on the average line center. If the phototubes are not balanced, the average position will be wrong. The phototube gain depends on the recent history of brightness with a time constant of about 30 minutes. The effect of brightness changes due to atmospheric extinction results in a line position error of about 200 m/s during a day. That corresponds to only about 1/20 of the slit width, so for differential observations the response should still be linear with no offset. However, the line profiles for the center and limb are different by the broadening due to solar rotation. The net effect is a drift in the differential signal that has the same shape as the line position error, but with about a tenth the amplitude. Since we have the line position error recorded, we can use that data to correct the differential velocity signal. Another drift is due to a small guiding error of up to 10 arc-sec, corresponding to drifts of 1 to 10 m/sec. It is correlated with brightness and can thus be removed. The final source of drift considered is differential atmospheric extinction across the disk. This amounts to a few m/s near sunrise and sunset, and can be computed from observed intensity. Sky transparency variations can produce spurious signals at higher frequencies which can not be simply removed.

The combination of these sources of drift accounts for most of the daily trends in the data. They all change slowly through the day and affect the observed spectrum at frequencies below about 60 μHz. In the present analysis these drifts are removed in three ways. The first is to compute them from simultaneous line position and brightness data. This is intellectually satisfying, but since the computed drifts do not account for an undetermined drift in the first hour of each observation it is not completely satisfactory. As a second method we remove a simple quadratic fit to each day's data. This is the same

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procedure that was used in earlier analyses and is appropriate for the first years when the individual observations were typically less than 6 hours in duration. However, for longer observations we know that the sources of drift are not well fit by a parabola. Therefore, as a third method, we have used low order Chebychev polynomials which will not remove much of the power of interest or introduce spurious power in the 1 to 4 hour period range. The resulting set of data was used in the analysis of the 160 minute oscillation reported here.

We have previously noted (Delache and Scherrer, 1983; Henning and Scherrer, 1986) that the apparent sensitivity of our instrument varies from day to day. We have now identified the source of this variation as a mechanical problem. Since the proper daily calibration is still uncertain we have decided to continue to normalize each day's variance before combining the data for high resolution power spectra. Thus, we cannot report absolute power levels. Also, since there is some inherent error in the resulting relative calibrations, the window function will be degraded somewhat, adding noise to the spectrum. These problems primarily affect the analyses of long period oscillations.

After removing questionable data we are left with 2505 hours of data spanning 10 years. The resulting set of data was used in the analysis of the 160 minute oscillation reported here.

160.01 Minute Phase Stability

When analyzing the ten year span of data we addressed the continuity of the 160.01 minute oscillation signal. We have previously been concerned that the subtraction of a parabola might shift some of the power from the daily trends into higher harmonics of a day. We now understand the sources of the trends and have prepared the data in the ways described above. All three ways produce similar spectra. In all cases there are peaks near 160 minutes for the entire data and for each year separately. Since power is expected and found at all day harmonics, only the phase stability and phase agreement with other observatories can indicate non-instrumental origin. We have computed the phase of the signal at 160.00 minutes in the way previously described (Scherrer et al., 1980) for each year.

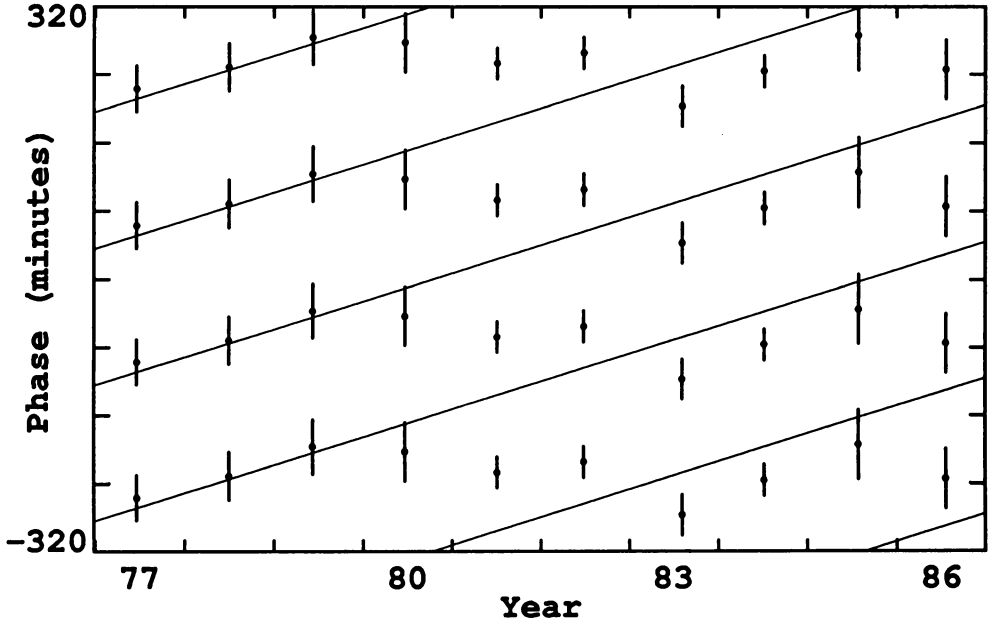

Figure 1. Phase of 160.000 minute harmonic analysis of Stanford observations. Data for 1977-1980 was prepared by removing a quadratic fit. Data for 1981-1986 had a Chebychev polynomial fit removed. The vertical bars are ± the uncertainty in the phase.

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Figure 1 shows each year's results four times, at phases ± n × 160 minutes. Phase stability for a signal in the range 159.976 to 160.024 minutes would result in sloping lines across the plot with phase shifts less than 80 minutes per year. The lines correspond to the previously reported 160.010 minute signal determined for both Stanford (1976-1980) and Crimean observations (1974-1984) (Kotov, 1985). The agreement in later years is not as strong as for the years through 1979. The data for 1980 and 1981 had very low amplitudes during the best weather, and 1982 and 1983 had increased noise due to spectrograph seeing. Although the 1985 season was short, the years 1984 through 1986 had good weather, good observing windows, and correctable drifts.

We conclude that the analysis of the full set of data does not make a definitive statement concerning the reality of a 160.01 min signal. While the cleaner part of our data agrees with the predicted phase better than our noisier data, other interpretations are possible. The data is better described as showing a 160.005 min period through 1980, and a 160.018 min period through 1986. The full power spectrum shows equal peaks at both 160.000 and 160.017 min with 1/year sidebands.

P-Mode Frequency Variation

The preparation of the data for investigations in the p-mode regime of the spectrum is much simpler. A 20-minute high-pass filter was applied to each day's data. The daily variance was normalized and the data for each year combined into a time series. The uncertainties of detrending and calibrating have much less effect in this part of the spectrum. The window function however makes peak identification complex. Since the accurate identification of a large number of peaks from data with a complex window function is difficult, we have used statistical methods to search for possible yearly variations in p-mode frequencies. Such variations have recently been found in the p-mode spectra from ACRIM (Woodard and Noyes, 1985 and these proceedings).

The statistical method used is a cross-correlation between the power spectra of the real data and artificial data. To build artificial time series, the list of p-mode frequencies determined from our 1984 observations (Henning and Scherrer, 1986) were used. Each tabulated mode gives the frequency for a sinusoidal function which was put into the window of the real data. The amplitude of each sinusoid was set to the average power in a 136 μHz section of the spectrum of the real data centered at that frequency. This results in a time series of coherent noise-less data from a non-rotating sun. The power spectrum of this constructed data will be complicated solely by the window function. A correlation between the observed power spectrum and this idealized power spectrum is insensitive to systematic

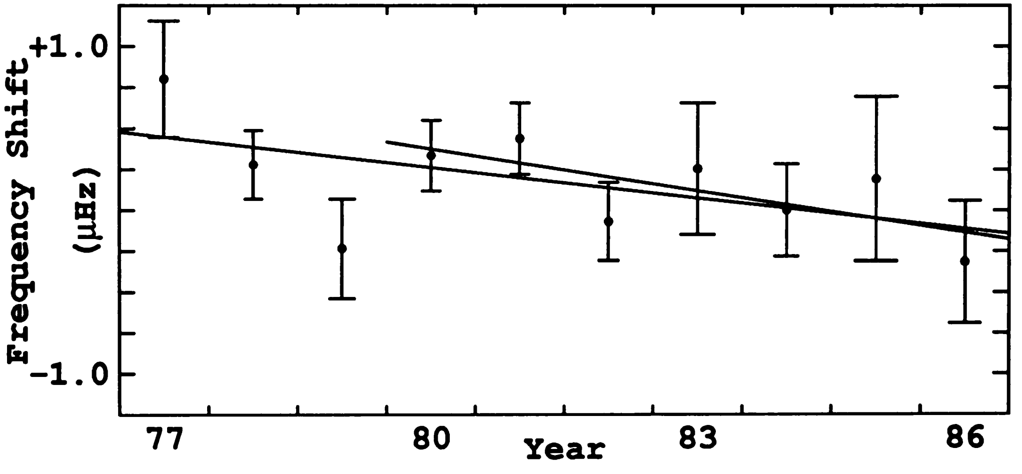

Figure 2. Relative average p-mode frequencies for 1977 through 1986.

pulling that might be introduced by the window function. This important advantage makes the correlation a powerful tool for comparing a large number of spectral peaks to find a secular shift.

The real data is quite noisy, and the real peaks are not pure sinusoids, but are split into a broad band of spikes by rotation, phase changes and amplitude changes. These effects broaden the correlation maximum to a few μHz, and can also cause a systematic shift of the maximum. The cross-correlation function was filtered with a 4 μHz low-pass filter to eliminate high-frequency variations resulting from these sources and from the window. The centroid of this peak gives the secular shift.

To get some idea of the error of a secular shift determined in this way several different time intervals were used for each year. We found that the scatter due to different (but still constant) phases was minimal. However, when each summer was divided into several sub-intervals the variations in average frequency shifts were found to be quite large. The resulting samples, numbering from 4 to 7 per summer, depending on the quality and quantity of the data, were averaged and the standard deviation calculated. Figure 2 shows the results. The value for the summer of 1984 is forced to 0.0 by shifting the ordinate. Actually, the peak for 1984 was at about -0.4 μHz. It is likely that this offset is due to the systematically larger amplitude of the spikes on the lower frequency side of each peak, i.e the negative m values, rather than a systematic error in our peak frequencies.

A linear least squares fit to the data gives a decrease in frequency in time with a slope of -0.06 μHz per year. If only the data from 1980 onwards are used, leaving out the time before solar maximum which includes some of the years with the worst data window, the slope becomes -0.08 μHz.

Discussion

Woodard and Noyes (1985) reported a frequency decrease of $0.36 \pm .15$ μHz between the years of 1980 and 1984. Our analysis supports this conclusion. Using the slope of the line fit to all 10 years, the decrease for four years is 0.24 μHz. If only the data from 1980 onwards is used, the increased slope of the least squares fit results in a decrease of 0.32 μHz over four years, or about 1 part in ten thousand. If the decrease is interpreted as the result of a secular diameter variation, then the direction would disagree with the measurements made by Delache et al. (1985 and these proceedings). Delache's results show a decrease in solar radius, which, on the simplest level, would imply a frequency increase, in contradiction with our conclusion.

The results do not support a cyclical change in frequency with an 11 year period, making it difficult to understand the shift as the result of altering magnetic flux conditions in the convective zone. A possible 22 year variation cannot be ruled out.

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