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DATA ANALYSIS TECHNIQUES FOR DETERMINING HIGH PRECISION DOPPLER SHIFTS USING IODINE ABSORPTION CELLS

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ABSTRACT Some details of the data analysis used to determine high precision Doppler shifts from data obtained using an absorption cell are briefly discussed.

INTRODUCTION

High precision Doppler measurements require stable wavelength reference due to instabilities inherent in spectrographs. One solution is to use an absorption cell placed in the optical path of the starlight (cf. Campbell and Walker 1979, and Marcy and Butler 1992). The reference spectrum is then subject to the same temporal changes in the spectrograph that cause shifts of the stellar spectrum on the detector. If an iodine absorption cell is used as the wavelength reference source for observations, a precision of $\sim$ 10 $m\ s^{-1}$ can be obtained (Marcy 1991).

DATA ANALYSIS PROCEDURE

If a stable wavelength reference can be established, the principal difficulty with measuring Doppler shifts at the meter–per–second level is that the spectral lines are slightly undersampled, and the shifts must be measured to the 0.01 or 0.001 pixel level. The conventional wisdom is that the optimized spectrograph PSF should result in spectral lines with a FWHM of 2 pixels. Line profiles of this width contain small but significant components at spatial frequencies higher than the detector's sampling frequency. These components lead to problems in interpolating the line, which in turn result in shift errors that are roughly sinusoidal with shift. This problem is more serious for the

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iodine than for stellar spectrum, because of the iodine's smaller intrinsic line width.

Initially, we attempted to analyze the data by cross–correlating the observations of the program stars with the I_2 spectrum superimposed, against the I_2 spectrum *alone*, then against the stellar spectrum *alone*. The blending of the two superimposed spectra resulted in large errors in determining the shift, as Figure 1 shows using artificial data.

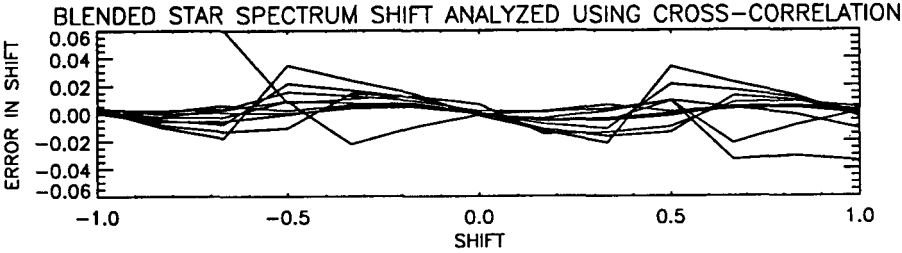

Fig. 1. The error in determining the Doppler shift (in pixels), versus the shift for artificial data consisting of stellar and I_2 spectra using the cross–correlation method. The errors seen result mostly from shift–dependent blending of stellar lines with iodine lines.

Another technique for analyzing spectra taken with an iodine absorption cell is the "least squares" technique. We can represent the star times the iodine spectrum as

$$D = S(\lambda + \delta_1)\, I(\lambda + \delta_2). \tag{1}$$

Where D is the data with I_2 spectrum superimposed over the star spectrum, S is the star spectrum, I is the I_2 spectrum, and δ_1 and δ_2 are the shifts of the stellar and I_2 spectra respectively. By performing a Taylor series expansion on Equation (1), and dropping all terms above first order, we have, for small shifts δ_1 and δ_2,

$$D = [S(\lambda) + \delta_1 \frac{\partial S}{\partial \lambda}]\,[I(\lambda) + \delta_2 \frac{\partial I}{\partial \lambda}]. \tag{2}$$

Then we determine δ_1 and δ_2 using a least squares procedure, minimizing the difference between the observed spectrum of star with I_2 and the result of Equation (2) calculated using reference spectra of star alone (S) and I_2 alone (I). We then shift shift S and I by δ_1 and δ_2 respectively using an interpolation scheme (we are currently using Fourier interpolation), and iterate.

These techniques are complicated by the existence of cosmetic defects on the detector, which demand the application of a window function to remove the bad pixels. The bad columns of some CCDs can be aligned parallel to and between orders, so they are entirely on unused portions of the detector. For other detectors, especially CCDs with large numbers of bad columns, it is more practical to arrange the detector so the orders run perpendicular to the bad columns. The bad columns then compromise a few pixels in each order rather than rendering an entire order unusable. These problems will be reduced when the current generation CCDs are more widely available on spectrographs. For those of us using early CCDs, the window function must be dealt with carefully. With the cross-correlation method, it is unclear how to properly

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account for the window function. This, however, adds additional error to the Doppler shifts. An advantage of the least squares technique is that the bad pixels can simply be left out of the summation, so only the data from the pixel is lost, and no additional error source is introduced. Figure 2 shows the result of analyzing the artificial data using a realistic window function and the least squares method.

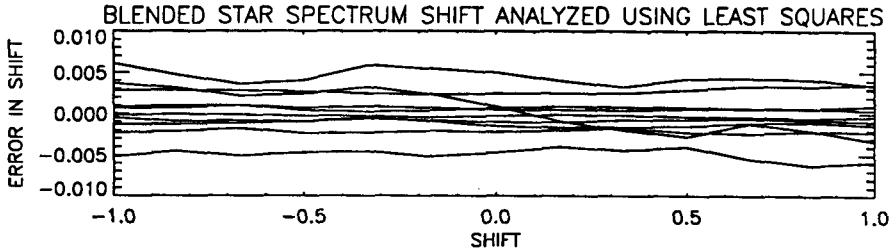

Fig. 2. The error in determining the Doppler shift (in pixels), using the least–squares method versus the shift with a realistic window function applied to the artificial data consisting of stellar and I_2 spectra.

A disadvantage of using I_2 in the absorption cell is the density and narrowness of the spectral lines. The I_2 spectrum is essentially saturated with lines and molecular band structures from 5000Å to 6000Å. The location of the continuum is thus lost. The spectra must be flattened to remove the spectrograph blaze function and flat fielding errors due to the different temperatures of the star and flat fielding source. Incorrectly flattening the spectra leads to unacceptably large errors (see Figure 2). By iterating the least squares procedure, and using the low–order trends in the residuals to correct the continuum level, the errors can be reduced to an acceptable level, as Figure 3 shows.

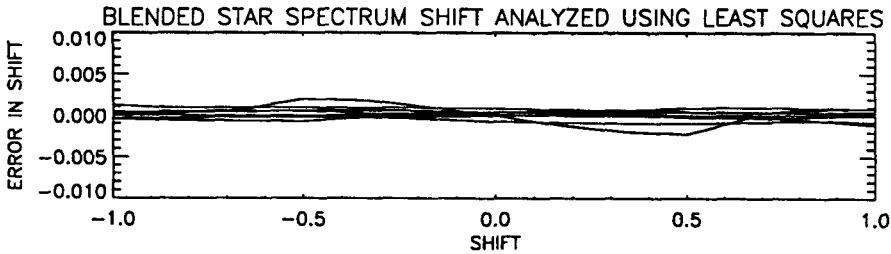

Fig. 3. The error in determining the Doppler shift (in pixels), using the least–squares method versus the shift with a realistic window function applied to the artificial data and using the residuals to correct the normalization of the continuum.

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