The Radial Velocity Precision of Fiber-fed Spectrographs

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ABSTRACT. We have measured the radial velocities of five 51 Peg-type stars and one star known to be constant in velocity. Our measurements, on 20 Å centered at 3947 Å, were conventional, using Th/Ar comparison spectra taken every 20 or 40 minutes between the stellar exposures. Existing IRAF routines were used for the reduction. We find $m_s$ provided that four measurements (out of 72) with residuals greater than $\sigma_{RV} \leq 20$ m s$^{-1}$ are neglected. The observations were made on five nights with the CFHT Gecko spectrograph $(R \sim 110,000)$, fiber-fed by the CAFE system; $\sigma_{RV} \leq 10$ m s$^{-1}$ seems possible with additional care. This study was incidental to the main observing program and is certainly not exhaustive, but the small value of $\sigma_{RV}$ implies that the fiber feed/image slicer system on Gecko+CAFE essentially eliminates the long-standing problem of guiding errors in radial velocity measurements. We are not promoting this conventional approach for serious Doppler planet searches (especially with Gecko, which has such a small multiplex gain), but the precision is valuable for observations made in spectral regions remote from telluric lines or captive-gas fiducials. Instrument builders might consider the advantages of the CAFE optics, which incorporate agitation and invert the object and pupil to illuminate the slit and grating, respectively, in future spectrograph designs.

1. INTRODUCTION

Radial velocity measurements are of fundamental importance in astronomy. For stars, absolute radial velocities can be uncertain by as much as 1 km s$^{-1}$ because of motions in the stellar photosphere. Differential velocities, on the other hand, can be much more precise, yielding important information about pulsation for single stars and masses for those in double or multiple systems. The most spectacular return from high-precision radial velocities in the last decade has been the detection of the minute reflex accelerations caused by unseen planetary companions for some 100 solar-type stars (see, for example, Marcy & Butler 2000).

The basic design of spectrographs most commonly used to determine stellar Doppler shifts has changed little in over a century. The telescope images a star on the spectrograph slit, which is collimated, dispersed, and then reimaged onto a detector. The principal improvements have been in detectors, from eye to photographic plate to photomultiplier or solid-state array.

In modern spectrographs, gratings largely replace prisms for dispersion. Precision in estimating wavelength displacements is compromised by motion and defocus of the star image at the slit. Both translate into a displacement of the stellar spectrum relative to the comparison spectrum. Flexure of the spectrograph decollimates Cassegrain instruments, while for bench-mounted spectrographs, flexure of the telescope causes its optical axis to wander in the spectrograph. Both effects lead to spectral shifts.

Petrie & Fletcher (1967) thoroughly studied these effects with the McKeillar spectrograph at the coude focus of the DAO 1.2 m telescope from photographic spectrograms. Working at a resolution of $\sim 55,000$, they found that even for bright stars with well-modulated spectra, there were external errors of nearly 300 m s$^{-1}$, while for the sky they were closer to 100 m s$^{-1}$, and internal errors were even lower at $\sim 70$ m s$^{-1}$. They pointed out that without some scrambling of starlight at the slit, such systematic errors would remain. The subsequent introduction of pupil or image slicers reduced this discrepancy by improving the uniformity of slit illumination. Campbell & Walker (1979) also used the McKeillar spectrograph to demonstrate that, with a captive gas to impose wavelength fiducials directly in the stellar spectrum, systematic errors could be dramatically

1 Visiting Astronomer, Canada-France-Hawaii Telescope, which is operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii.
reduced. Nowadays, with iodine vapor cells, errors have been reduced to a few meters per second, the level at which precision begins to be limited by the natural velocity noise of the star’s atmosphere (Marcy & Butler 2000).

For many programs, it is not always possible or appropriate to include either suitable telluric lines (generally water vapor) or captive-gas lines such as I$_2$. This is certainly true for the blue/ultraviolet at high spectral resolution. In this paper, we briefly demonstrate that, with minimal precautions, a precision of $\leq 20$ m s$^{-1}$ is possible for $R > 100,000$ with a fiber-fed spectrograph over runs lasting at least several nights and probably for much longer.

We became aware of this high precision following an observing run at CFHT in 2001 to observe Ca $\Pi$ H and K lines in the spectra of 51 Peg-type stars. These stars had been discovered to have Jupiter-mass secondaries with orbital periods of a few days from precise radial velocity measurements, mostly using captive-gas fiducials. Such high-quality radial velocity standards were not available to Petrie & Fletcher (1967) but offered us an excellent test of the Gecko+CAFE (Cassegrain Fiber Environment) radial velocity precision. In a run 1 year later, we deliberately took comparison arc spectra before and after every stellar spectrum, and it is these spectra that we discuss here.

Our data were certainly adequate to calculate improved periods for each of the stars. The revised periods and phases will be published in another paper.

2. THE OBSERVATIONS

2.1. The Spectra

The observations were made on 2002 July 26–30 UT with the Gecko echellette spectrograph fiber-fed by CAFE (Baudrand & Vitry 2000) from the Cassegrain focus of the Canada-France-Hawaii 3.6 m telescope (CFHT). Spectra were centered at 3947 Å in the 14th order, which was isolated by a UV grism with some 60 Å intercepted by the CCD. The dispersion was 0.0136 Å pixel$^{-1}$, and the 2.64 pixel FWHM of the thorium-argon (Th/Ar) lines corresponded to $R = 110,000$. The spectra were part of a long-term program to monitor variations in the Ca $\Pi$ H and K reversals of stars with short-period (3–4.5 days) planets. For this reason, they were of high signal-to-noise ratios (S/Ns) in the continuum. The detector was a back-illuminated EEV CCD (13.5 $\mu$m$^2$ pixels) with spectral dispersion along the rows of the device. Single Th/Ar arcs were taken immediately before and after each stellar spectrum and, like the flat fields, were fed through the same fiber as the starlight. Probably more comparison spectra should have been taken but, as time was of the essence for this program, only single comparison spectra were taken.

Fiber modal noise was suppressed by continuously agitating the fiber close to its output (see Baudrand & Walker 2001). A Fabry lens at the fiber output projects the pupil as input to the spectrograph while simultaneously illuminating the grating with the object field. Baudrand, Jocou, & Guinouard (1998) have pointed out that inversion of object and pupil improves both spectral resolution and spectral stability. In this arrangement, the image projected on the grating is the fiber core output aperture enlarged 1000 times, while the fiber far-field image is transformed into a pseudoslit by a four-slice Bowen-Walraven slicer made of silica that projects to some 50 pixels length in the spectrum. For this program, there was no on-chip binning of pixels.

Because the CCD has a number of pixels that suffer from nonlinear dark signal, we took a large number of dark exposures with integration times matching those of the various stellar, Th/Ar, and flat-field exposures and created an average dark for each exposure time. Then, rather than using conventional biases to remove the baseline from each observation in the data reduction, the appropriate mean darks were subtracted from the stellar, Th/Ar, and flat-field exposures. Flat fields were then normalized to a mean value of unity along each row, and the exposures for all stars observed on a night were combined into a mean object to define a single aperture for the extraction of all stellar and comparison exposures, including subtraction of residual background between spectral orders (prior to flat-fielding). This aperture was ultimately used to extract one-dimensional spectra of the individual stellar and comparison exposures and a one-dimensional extraction of the mean, normalized flat field (without an interorder background subtraction). The extracted stellar and comparison exposures were then divided by the one-dimensional flat field to obtain flat-fielded spectra.

A specimen flat-fielded spectrum of $\tau$ Ceti is shown in Figure 1 with the $\sim$20 Å of the spectrum used to measure the radial velocities indicated.
2.2. The Radial Velocities

Table 1 lists the five program stars and the standard, \( \tau \) Ceti, plus spectral types and \( U \) magnitudes, the planetary orbital periods, and velocity amplitudes, with details of the observations such as average S/N and exposure time.

Radial velocities were estimated with the \texttt{fxcor} routine in \texttt{IRAF}.\(^3\) The Th/Ar comparison lines were used to provide dispersion-corrected stellar spectra. A Fourier cross-correlation was carried out on the dispersion-corrected spectra taking the first spectrum in the series for each star as the template. Hence, all differential radial velocities (\( \Delta RV \)) are relative to the first spectrum on the first night. Both the template and the spectrum being measured were normalized with a low-order polynomial, and the correlation was taken over that part of the spectrum bounded by (and including) two strong aluminum lines (\( \sim 3942–3963 \) \( \text{Å} \)).

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In Figure 2, the \( \Delta RV \)s for the five 51 Peg stars are plotted as a function of relative phase, and for \( \tau \) Ceti as a function of time. The sine curves have the published planetary orbital period and \( K_{\text{max}} \) from Table 1 and were shifted in phase and \( \Delta RV \) to give the best fit. For \( \tau \) Ceti, the best fit is to a line of constant velocity. Below each velocity curve are shown the \( \Delta RV \) residuals from the curves. Note that, because the amplitude of the stellar reflex velocity is very different in each case, the individual \( \Delta RV \) scales vary widely. Values of \( \sigma_{\text{RV}} \) corresponding to the residuals are listed in Table 1. If four out of the 72 data points with \( \sigma_{\text{RV}} > 100 \) m s\(^{-1} \) are omitted, all of the \( \sigma_{\text{RV}} \)s are less than 20 m s\(^{-1} \), and the two stars observed at the highest S/N have \( \sigma_{\text{RV}} \sim 10 \) m s\(^{-1} \).

2.3. The Four Extra-large Residuals

The motions of the comparison spectra expressed as \( \Delta RV \) on each of the five nights are shown in Figure 3. The results are surprising. The \( \Delta RV \) scales on nights 3 and 5 are an order of magnitude greater than on the other three nights. NIGHTS 1 and 4 show a trend and modest scatter, with rms about the trend being 9 and 18 m s\(^{-1} \), respectively. Night 2 (only partially clear) shows no trend and an rms scatter of 9 m s\(^{-1} \). Nights 3 and 5 have rms scatters of 96 and 83 m s\(^{-1} \), respectively.

The most likely reason for spectral shifts on the detector are liquid nitrogen boil-off from the CCD Dewar, distortion of the coude room floor (Earth tides, dome stress etc.), and spectrograph “seeing” effects. If these changes are slow and linear as they appear to be on nights 1, 2, and 4, then interpolation of the comparison line positions should properly calibrate the shifts for the stellar spectra. Most of the shifts are remarkably small considering that \( \Delta RV = 10 \) m s\(^{-1} \) corresponds to \( 1.3 \times 10^{-4} \) \( \text{Å} \) at 3947 \( \text{Å} \), which is \( 10^{-2} \) of a pixel or 0.13 \( \mu \text{m} \). Monitoring the exposure meter to estimate the centroid of the stellar exposures would have allowed more accurate barycentric velocity corrections, but we did not have such a system at hand.

One might expect that the large, erratic residuals on nights 3 and 5 would be reflected in large reflex residuals for the stellar radial velocities on those nights, but this is not always so. The delinquent velocity for 51 Peg on night 3 (see Fig. 2) corresponds to the very large comparison residual (\( >300 \) m s\(^{-1} \)). By contrast, the velocity for \( \upsilon \) And observed immediately afterward, which uses the same comparison spectrum, agrees within a few meters per second with the second value for \( \upsilon \) And on that same night.

On the face of it, there is no consistent reason to reject the four large residuals. They may represent “creaking” in the system that introduces occasional uncalibratable jumps. Unfortunately, because of the nature of the program, we were not able to take comparison spectra more often than every 20 or

\(^3\) \texttt{IRAF} is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.
Fig. 2.—Differential radial velocities for the five 51 Peg stars are plotted as a function of phase, and the unvarying star τ Ceti is plotted as a function of time. The sine curves have the published planetary orbital period and \( K_{\text{max}} \) for each star (see Table 1) and have been shifted in phase and \( \Delta \text{RV} \) to give the best fit to the \( \Delta \text{RVs} \). For τ Ceti, there is a best-fitting line of constant velocity. Below each velocity curve are shown the residuals of the \( \Delta \text{RV} \) from the curves.

40 minutes. In two cases, the comparison lines show a residual of more than 100 m s\(^{-1}\), which is reflected as an almost equally large residual in the stellar velocity. In these cases (51 Peg and HD 209458), using a mean Th/Ar that ignores the bad points restores the stellar velocities to the curve. In the other two cases (τ Boo and HD 209458), there is no problem with the Th/Ar comparison.

Some of the large residuals may be inherent to the reductions and not the spectrograph. We used the same version of IRAF on two different platforms, PC-IRAF version 2.11.3 and SUN/IRAF version 2.11.3. The former generated several very large residuals in the Th/Ar comparison positions, which disappeared on reduction on a SUN. The data presented in this paper were all reduced on a SUN, but it is still possible that some of the
large residuals are artifacts of the reduction. In short, we cannot be sure that occasional large residuals are not a risk with such conventionally determined velocities without a more extensive study.

Differential variations between the strengths of comparison arc lines can also limit precision. The temperature of the arc, its age, “on” time, voltage stability, etc., cause relative line-strength variations and introduce line shifts, especially when lines are unresolved blends. To judge from the low scatter in the comparison spectral shifts and values of $\sigma_{\text{RV}} \sim 10 \text{ m s}^{-1}$ for the two stars observed at high S/N, variations in the arc lines have not been important above this level, and this $\sigma_{\text{RV}}$ may be
the best achievable for single spectra with this spectrograph, but a more careful study is necessary.

3. CONCLUSIONS

The effectiveness of fiber agitation in overcoming modal noise has already been demonstrated (Baudrand & Walker 2001). In this paper, we believe that we have demonstrated that the optics of the CAFE fiber system, which invert the conventional object and pupil (Baudrand et al. 1998) illumination of slit and grating, together with agitation effectively eliminate the large guiding and tracking errors that once plagued conventional radial velocity measurements. Our experience suggests that comparison arcs taken with sufficient frequency are adequate to track slow spectrograph drifts for a bench-mounted fiber-fed instrument in a stable environment. The precision depends on the resolution, which, at 110,000 for Gecko, is better than 10 m s$^{-1}$. Being an echellette format, the spectral curvature is small, but an echelle format would provide a multiplex gain of 1 or 2 orders of magnitude over the single spectra captured by Gecko (in this paper, we used only 20 Å). From the point of view of radial velocities, an echelle would be much more sensitive.

Instrument builders might want to consider the advantages of CAFE in future spectrograph designs. From our observations alone, we cannot say much about the stability of such conventional radial velocities over periods of years, but it will be interesting to follow it up.

Conventional radial velocities even of the precision reported here are not a substitute for those made with captive-gas fiducials in serious Doppler planet searches, but the precision is important for observations made in spectral regions remote from telluric lines or captive-gas fiducials such as we have described here.

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