Results from upgrades to the radial velocity instrument, ET, at the KPNO 2.1m

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ABSTRACT

A radial velocity (RV) survey instrument, Exoplanet Tracker (ET), has been commissioned at the Kitt Peak 2.1m telescope. It is a fiber-fed, fixed-delay Michelson interferometer followed by a medium resolution volume phase holographic spectrograph (operating at $R \sim 5000$) for the visual band, and is planned to be opened to the public for RV related research in 2005. Since 2002 the measured total throughput of ET from above the atmosphere to the detector has been improved to about 18% (or 50% for the instrument itself from the fiber input to the detector), ~ 5 times higher than the current cross-dispersed echelle spectrometers for Doppler planet searches. We present new preliminary results from our improved version of ET, with 600Å wavelength coverage, showing RV measurements for HD 130322 (V=8.05), a known planet-bearing star, using 15 min exposures. A best short-term Doppler precision of 2.9ms^{-1} has been achieved with this new instrument. We will start a pilot planet search of around 500 V=8–9 mag. stars with the 2.1m telescope in the Spring of 2005, and a multiple object RV feasibility study will also be conducted at the Sloan 2.5m wide field telescope in Spring 2005.

Keywords: Extra-solar planets, radial velocity, Doppler, HD 130322, 36 UMa

1. INTRODUCTION

In order to obtain a clear understanding of the nature of extrasolar planets, it is necessary to have as large a sample as possible to work with. Currently a little over 100 planetary systems are known, but to be able to draw statistical conclusions it would be helpful to be able to increase this to thousands of planets. Achieving this on a reasonable timescale calls for multi-object observing capability, along with the ability to probe to magnitudes faint enough that there are sufficient numbers of stars to investigate within a single field of view.

During the annual SPIE meeting in 2003 we described and presented results from a new type of fibre-fed radial velocity (RV) instrument, an externally dispersed fixed-delay interferometer (DFDI) known as Exoplanet Tracker (ET).[1] ET is a combination of a michelson interferometer and medium resolution spectrograph, allowing high throughput and RV precision over a small waveband. The interferometer forms sinsoidal fringes along the slit direction of the spectra, and phase shifts in these fringes correspond directly to Doppler shifts in the underlying spectral lines.[2] Where previous RV instruments based on cross-dispersed echelles have been limited to single object observation (since a single spectrum fills the entire detector), ET's single-order mode of operation means that in principle multi-object operation should be achievable. The single-object version discussed here is being permanently installed at the KPNO 2.1m telescope, and is intended eventually to be opened for public use.

In Ref. 1 we presented a preliminary confirmation of the known planetary companion to 51 Peg,[3] to a precision of 17.6ms^{-1}, and reported a precision for η cas, a known RV stable star (Cochran, private communication) to 18ms^{-1}. Later improvements in the data reduction enabled us to bring these errors down to 11.5ms^{-1} and 7.9ms^{-1} respectively.[4] The ET instrument concept and details are described in more depth in Ref. 1 along with some of the data reduction techniques used, and underlying DFDI instrument theory is discussed in Ref. 2. Here we present early preliminary results from recent observations using an upgraded and significantly improved version of ET which shows substantially higher throughput.

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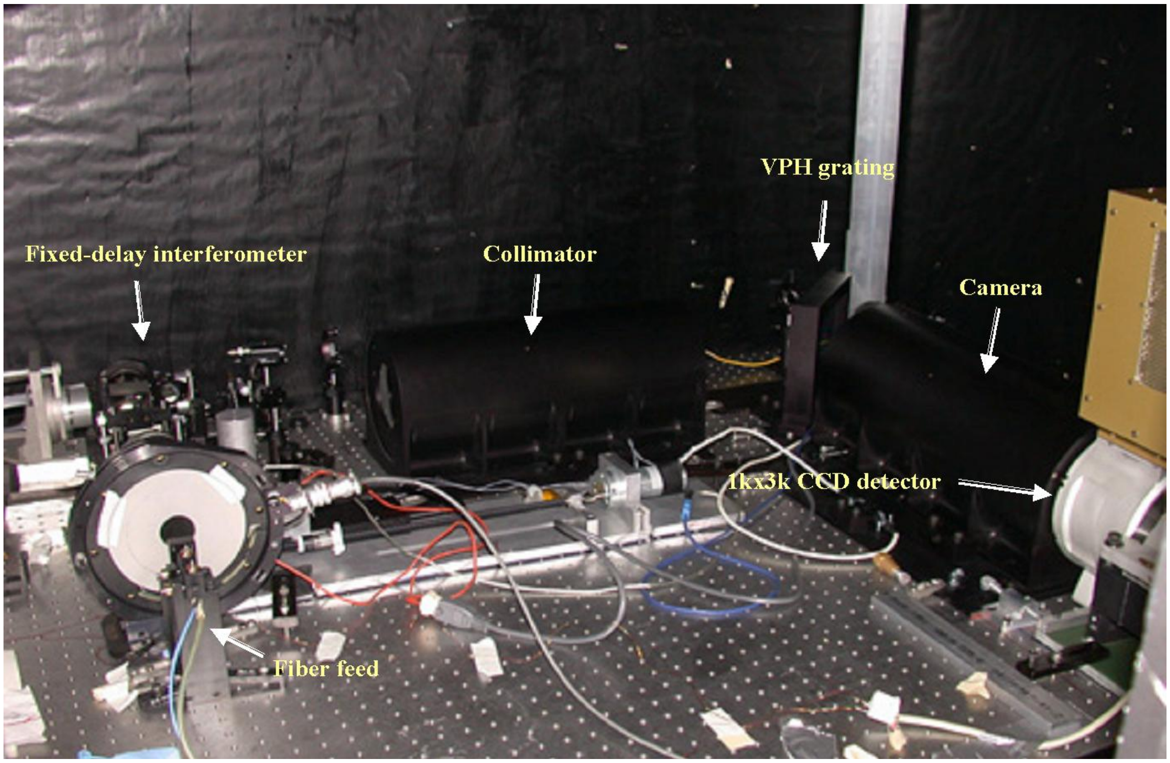

Figure 1. Newly commissioned upgrade of ET in KPNO 2.1m coudé room, March 2004, installed inside thermally insulated enclosure.

2. THE IMPROVED ET

Since the previous version of ET we have implemented a number of improvements, primarily affecting throughput, stability and wavelength coverage (see Fig. 1).

- The spectrograph has been completely replaced, with a custom designed and built collimator and camera, allowing for a faster focal ratio ($f/5$ collimator and $f/2$ camera, originally both $f/7.5$) with less aberration. The grating is now replaced with an optimized volume phase holographic (VPH) transmission grating with substantially higher throughput, operating at around R $\sim$ 5000 and designed to peak in transmission at 5300Å. The optical design is shown in Fig. 2.

- Both output beams from the interferometer are now utilised, where previously one beam was reflected back down the input and lost. The second beam is picked off and fed along a parallel path to the primary beam, imaging a second identical (though phase-inverted) spectrum onto the detector. A $1/\sqrt{2}$ improvement in precision is expected from averaging the results from the two spectra, equivalent to doubling the throughput. Note that in practice, although the design (Fig. 2 calls for roof-corner mirrors in the interferometer in order to pick off the second output beam, we are currently having more success using flat mirrors and picking off the second output beam where it is displaced relative to the input due to the required tilt in one of the mirrors.

- Anti-reflective coatings are now used on all surfaces.

- A new cryotiger-cooled 4kx4k back-illuminated Fairchild CCD detector has been installed, allowing $\sim$ 600Å wavelength coverage (compared with 270Å reported last year), centred around roughly 5510Å.

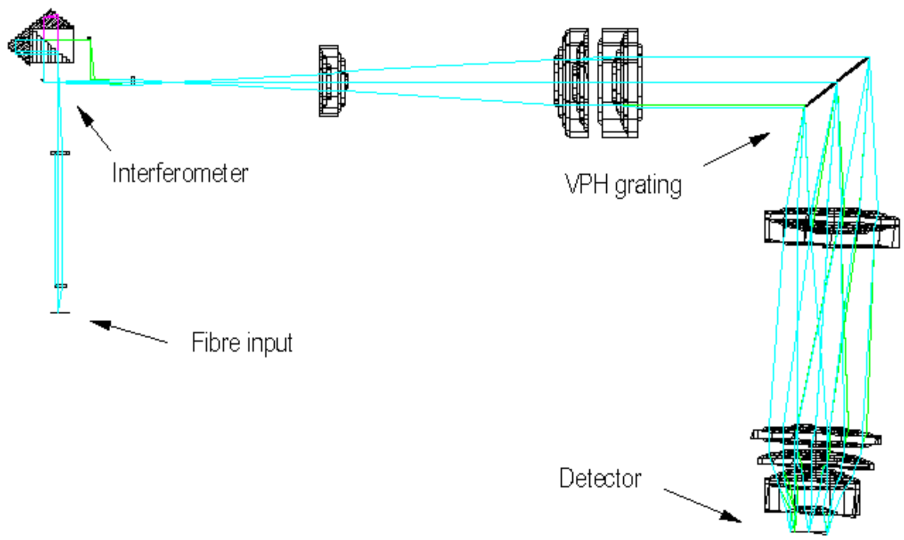

Figure 2. Optical design for the new upgraded ET.

- A calibration beam is now also passed through the instrument, allowing for simultaneous thorium argon fiducial measurements. The stability of this is under investigation and we hope to transition from using iodine as a reference in order to gain another factor of two in throughput. This will also allow subsequent adjustment of the central wavelength to operate over the range of 4000–6000Å, to investigate earlier and later types of stars.
- The interferometer cavity spacing is maintained by a computer-controlled active feedback system which monitors the phase of fringes formed by a laser beam passing though the cavity. Any drifts are compensated by adjustments to a PZT mounted interferometer mirror. The controller software has now been upgraded to lock mirror tilt in addition to controlling piston motion, improving stability across the three beams (two stellar beams and one calibration beam).
- The instrument is now positioned within its own thermal enclosure which is in turn situated in a room with improved temperature control. The RMS variation in temperature during observing over 8 days at several places in the instrument was measured to be around 0.03K.

3. RESULTS

Two engineering and observing runs were made with the modified instrument at Kitt Peak, during March and June/July 2004. The new CCD camera and temperature stabilisation were installed for the June run. The first run was largely lost due to bad weather. We were, however, able to obtain two nights of data for 36 UMa A (Vmag = 4.83), a known RV stable star (Cochran, private communication) which we report here. During the second run we were able to obtain regular observations over the period of just over one week of HD 130322, HD 143291, Rho Crb, HD 176377 and HD 179949. This data is still being reduced, but we present here preliminary results for HD 130322 (Vmag = 8.05), a known planet-bearing star[5] with a period of 10.7 days and a velocity semi-amplitude of $115 \mathrm{ms}^{-1}$.

3.1. 36 UMa A

Figure 3 shows the RV measurements obtained for 36 UMa A (Vmag = 4.83, corrected for Earth motion) in 10 minute exposures, showing the expected zero variation (within our measurement errors). The RMS scatter is

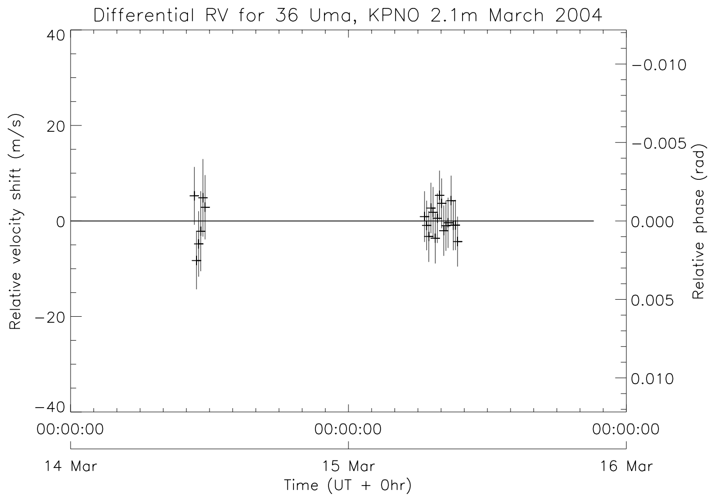

Figure 3. RV data obtained for 36 UMa, showing expected zero velocity shift. RMS scatter is 3.6ms^{-1}.

found to be 3.6ms^{-1} over the two nights. Treating the nights separately, we find an RMS scatter of 5.6ms^{-1} on the first night and 2.9ms^{-1} on the second, with mean S/N's per pixel of 100 and 140 respectively. The difference in S/N is probably due to difference in air mass (being somewhat higher on the first night), and cloud cover and guiding issues. The difference in RMS between the two nights broadly corresponds to the difference in S/N if we are operating at the photon limit (within the variation expected due to the small number of points for calculating RMS).

3.2. HD 130322

Figure 4 shows RV measurements for HD 130322, corrected for Earth motion. More work is needed to fully link these observations together from night to night at this preliminary stage, although we do find clear evidence for significant RV variation between the nights when compared against other stable reference stars. Overplotted are the predicted RV curves due to the known planetary companion, using orbital parameters previously published by Udry et al.,[5] RMS residuals about the predicted curve on UT June 4, 5, 6 and 8 are 8.2ms^{-1}, 18.5ms^{-1}, 23.2ms^{-1} and 15.8ms^{-1} respectively (cf. overall RMS scatter of 15.4ms^{-1} found in Ref. 5. Exposures were 15 minutes long, giving a typical mean S/N per pixel of around 40. It is likely that the pparticularly low scatter on UT Jun 4 is due to statistical coincidence, since the scatter is significantly lower than the error bars. However, it is worth noting that the scatter for the two separate star beams were both individually about 10ms^{-1} before averaging together, suggesting that the error bars may be overestimated and that such a precision may in fact be achievable at some point.

Figure 5 is a raw data frame showing a fringing spectrum for HD130322. The two stellar beams output from the interferometer can be seen alongside a ThAr calibration spectrum.

3.3. Throughput

Throughput is now substantially higher than reported last year, and close to our goal. We have measured a total throughput of 18% from above the atmosphere to the detector* (or 50% for the instrument itself from the fiber input to the detector), an improvement by a factor of several times over the previous year, and around 5 times better than current traditional crossed-dispersed echelle spectrographs used for planet searches (see eg., Ref. 6.)

*Not including iodine cell losses

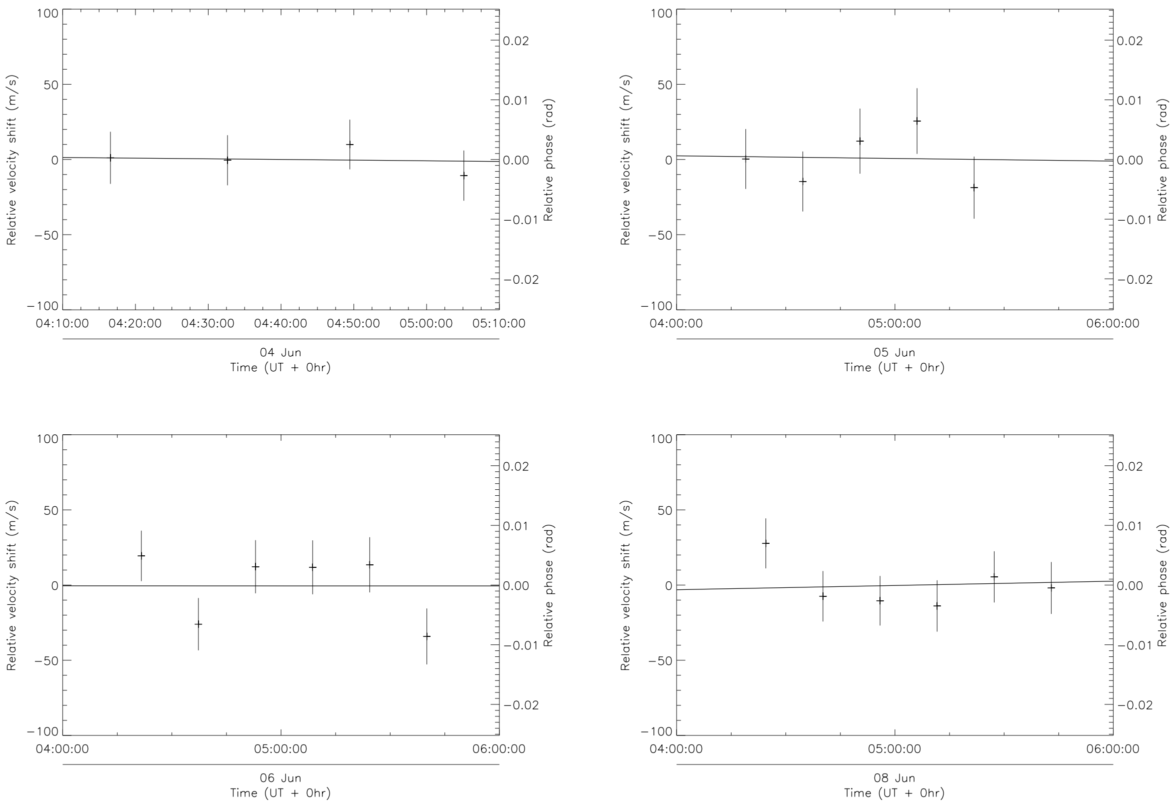

Figure 4. RV data obtained for HD 130322 on four separate nights, with predicted RV curve overplotted. RMS scatters for UT June 4, 5, 6, and 8 are $8.2\mathrm{ms}^{-1}, 18.5\mathrm{ms}^{-1}, 23.2\mathrm{ms}^{-1}$ and $15.8\mathrm{ms}^{-1}$ respectively.

4. DISCUSSION

In addition to the results shown here, preliminary examinations of some of the other data do appear to give results consistent with the radial velocities expected for the stable star HD176377 and the known planet bearing star, HD179949. The data here show that we are now approaching sufficient precision to detect extrasolar planets down to 8th magnitude in 15 minute exposures, at least over the short term. Throughput and precision are approaching the goals set last year for the instrument, and temperature stability is considerably improved.

A number of issue still remain to be addressed in order to make further improvements.

- Flux monitoring during the exposure has yet to be implemented. This will allow flux weighting in order to find the effective central time of each exposure, so that variations in flux during the length of the exposure (eg. due to cloud cover or guiding problems) can be compensated for.
- There is still room for improvement of focus and aberration in the instrument, which would lead to more reliable results and possibly higher visibility fringes and hence better precision.
- We are working toward switching over from using an iodine absorption cell as a fiducial reference to using a separate thorium argon emission beam, as illustrated in Fig. 5. This would effectively almost double the throughput of the instrument, since the iodine cell would no longer be absorbing light from the stellar spectra. The fact that the thorium argon beam travels on a separate path through the instrument, however, means that instrument stability is more critical in this approach. Tests were performed during the May 2004 run to assess how well this can now work in the new instrument, but the data has yet to be reduced.

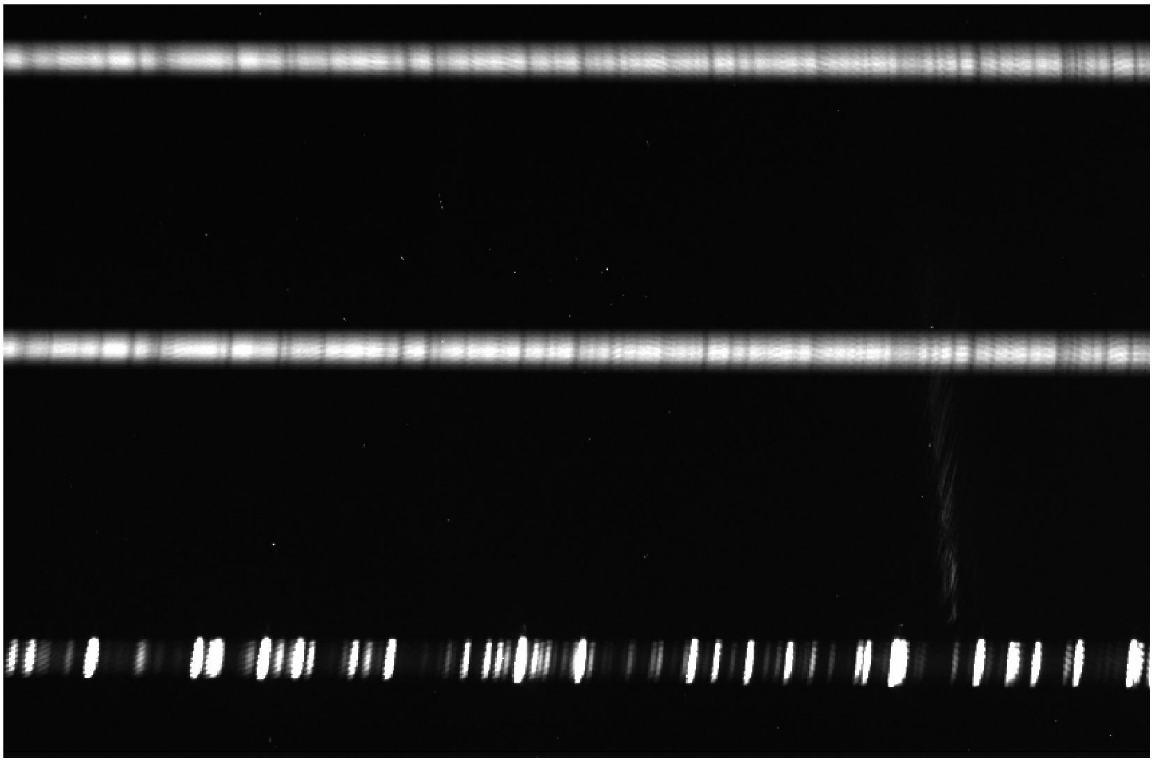

Figure 5. Fringing raw data frame for HD 130322. Top/middle: double output stellar beams from interferometer; lower: ThAr reference spectrum.

It is anticipated that the ET installation at the KPNO 2.1m will eventually be frozen and made available for public use. This will be an important prototype in developing a full multi-object version of the instrument for installation at either the Sloan or WIYN telescopes in the near future. A passively stabilised temperature-compensated interferometer is also being designed and tested at this time. These developments are discussed in more detail elsewhere in these conference proceedings (see Ge et al. and Mahadevan et al.) Once the multi-object instruments are operational, the single-object ET will provide an important follow-up instrument for measuring in more detail the radial velocities of any objects that are marked as interesting by the multi-object surveys.

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REFERENCES

1. J. C. van Eyken, J. Ge, S. Mahadevan, C. DeWitt, and D. Ren, "First planet confirmation with the Exoplanet Tracker," in *Techniques and Instrumentation for Detection of Exoplanets.*, D. R. Coulter, ed., *Proc. SPIE* **5170**, pp. 250–261, Nov. 2003.
2. J. Ge, "Fixed Delay Interferometry for Doppler Extrasolar Planet Detection," *ApJ* **571**, pp. L165–L168, June 2002.
3. M. Mayor and D. Queloz, "A Jupiter-Mass Companion to a Solar-Type Star," *Nature* **378**, p. 355, Nov. 1995.

4. J. C. van Eyken, J. Ge, S. Mahadevan, and C. DeWitt, “First Planet Confirmation with a Dispersed Fixed-Delay Interferometer,” *ApJL* **600**, pp. L79–L82, Jan. 2004.
5. S. Udry, M. Mayor, D. Naef, F. Pepe, D. Queloz, N. C. Santos, M. Burnet, B. Confino, and C. Melo, “The CORALIE survey for southern extra-solar planets. II. The short-period planetary companions to HD 75289 and HD 130322,” *A&A* **356**, pp. 590–598, Apr. 2000.
6. S. S. Vogt, S. L. Allen, B. C. Bigelow, L. Bresee, B. Brown, T. Cantrall, A. Conrad, M. Couture, C. Delaney, H. W. Epps, D. Hilyard, D. F. Hilyard, E. Horn, N. Jern, D. Kanto, M. J. Keane, R. I. Kibrick, J. W. Lewis, J. Osborne, G. H. Pardeilhan, T. Pfister, T. Ricketts, L. B. Robinson, R. J. Stover, D. Tucker, J. Ward, and M. Z. Wei, “HIRES: the high-resolution echelle spectrometer on the Keck 10-m Telescope,” in *Instrumentation in Astronomy VIII*, D. L. Crawford and E. R. Craine, eds., *Proc. SPIE* **2198**, pp. 362–375, June 1994.