Dispersed interferometry for infrared exoplanet velocimetry

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ABSTRACT

The TEDI (TripleSpec - Exoplanet Discovery Instrument) is the first instrument dedicated to the near infrared radial velocity search for planetary companions to low-mass stars. The TEDI uses Externally Dispersed Interferometry (EDI), a combination of interferometry and multichannel dispersive spectroscopy. We have joined a white-light interferometer with the Cornell TripleSpec (0.9 - 2.4 μm) spectrograph at the Palomar Observatory 200” telescope and begun an experimental program to establish both the experimental and analytical techniques required for precision IR velocimetry and the Doppler-search for planets orbiting low mass stars and brown dwarfs.

Keywords: Doppler planet search, radial velocity, interferometry, high resolution spectroscopy, near infra-red

1. INTRODUCTION

The TEDI (TripleSpec - Exoplanet Discovery Instrument) is the first instrument dedicated to the near infrared radial velocity search for planetary companions to low-mass stars. The TEDI uses Externally Dispersed Interferometry (EDI), a combination of interferometry and multichannel dispersive spectroscopy. We have joined a white-light interferometer with the Cornell TripleSpec (0.9 - 2.4 μm) spectrograph at the Palomar Observatory 200” telescope and started an experimental program to establish both the experimental and analytical techniques required for precision IR velocimetry and the Doppler-search for planets orbiting low mass stars and brown dwarfs.

2. EXOPLANETS AROUND LOW MASS STARS

The development of the field of exoplanet studies has been truly explosive since the announcement of the first planet orbiting another star (51Peg). As of now, more than 270 exoplanets are known orbiting more than 200 stars. The vast majority of these planets have been discovered via the radial velocity technique. Known planets range in mass from super-Jupiters to sub-Neptunes down to 10-15 Earth masses. The quest now has turned toward finding and characterizing earth-like planets in the “habitable zone”. The interest in this quest has been emphasized by the Astronomy and Astrophysics Advisory Committee (AAAC) Exoplanet Task Force (ExoPTF) charged to “recommend a 15-year strategy to detect and characterize exo-planets and planetary systems, and their formation and evolution, including specifically the identification of nearby candidate Earth-like planets and study of their habitability.”

Finding terrestrial mass planets orbiting FGK and early M stars with current visible spectrographs is very difficult due to the small induced stellar reflex motion. The limits are instrumental (set by the resolution and stability of the spectrograph) and astrophysical (set by the stellar rotation speed and chromospheric activity). Because the radial velocity semi-amplitude is proportional to m_{planet}/m_{star}, there is great advantage to searching for low-mass planets around lower mass primary stars. For example, a 0.1 Msun late M dwarf with an Earth mass planet orbiting within its habitable zone at 0.02 AU would exhibit 2 m/s reflex motion. Although this is within the velocity precision of the best of the optical high dispersion spectrographs employed for planet searches, the challenge to detection then becomes the number of photons delivered to the spectrograph.

Analysis suggests that for later than M5 dwarfs, near infrared spectrometers will be more efficient for planet discovery because these late-type, cool photospheres have their peak flux in the near-infrared. Consequently, optical spectrometers, on the largest of telescopes, are practically limited to V ~ 12 mag. and have available only a few tens of desirable targets that meet the optical brightness requirements. Nonetheless, planets and indeed planetary systems have been discovered around several of these M stars[1,2,12].

Analysis suggests that observing mid-M dwarf stellar targets (~0.2-0.5 Msun) in the near-infrared is a 'sweet spot' for first detection of terrestrial-mass planets. Conducting Doppler surveys in the infrared alleviates some astrophysical limits in comparison to optical surveys. The number of nearby low-mass stellar targets is increased due to the distribution of solar neighborhood spectral types that is dominated by M stars, which outnumber AFGK stars within 10pc by roughly 3:1 (and more at closer distances). Variability due to chromospheric and other stellar activity is reduced in amplitude[5] due to the lower contrast between photospheric and spot temperatures, and is limited to younger stars. Rotation rates, associated with active chromosphers, are lower for later type stars (though the latest type stars and many brown dwarfs are rapidly rotating[11].

3. THE TEDI INSTRUMENTS

We are commissioning the Triplespec Exoplanet Discovery Instrument (TEDI), an instrument designed for the infrared RV search for exo-planets orbiting low mass stars. TEDI[4] adds a fixed delay Michelson interferometer before the Palomar 200", Cassegrain-mounted TripleSpec spectrograph[13] - an efficient $\lambda/\Delta\lambda$ ~2700 echelle spectrograph (0.9-2.5 µm) with a K-band slit view guider. The interferometer increases Doppler sensitivity and effective spectral resolution[6,7,9,10]. Light is modulated by the EDI cavity to a sinusoidal spectral fringe. This pattern multiplies the input spectrum to create a moiré pattern whose phase will be shifted across the full pass-band when a Doppler shift occurs. The moiré phase shift is measured compared to an absolute reference spectrum (ThAr emission lamp) to determine absolute radial velocity.

The interferometer cavity can be piezo-stabilized using a laser-fringe tracker and its optical path difference (OPD) is incrementally stepped during observations to isolate the RV-dependant signal from fixed pattern noise. Absolute OPD or fringe phase position control is not required. The OPD, together with field-widening etalons, can be selected to optimally sample the Doppler-relevant spectral frequencies. Multiple OPD data can be combined to yield factor of several increases in spectral resolution[8]. Both cavity outputs, along with a simultaneous background channel are imaged to the spectrograph slit via a micro lens-tipped optical fiber link (for seeing and injection tolerance) and after transiting absorption cells (CH_3, NH_3, SH_2) used for cross-calibration. The image can be nodded on the detector. A monitor camera allows for focus, telescope alignment, and cavity null tuning.

4. ANTICIPATED TEDI PERFORMANCE

The anticipated TEDI performance due to statistical and systematic effects has been estimated. TEDI can achieve σ_v ~2-5 m/s for mH=10 late-type stars in a 10 min integration. Verification of these estimates is part of the on-going TEDI commissioning program.

TEDI's theoretical photon-limited RV precision[3] has been calculated presuming anticipated spectrometer and interferometer throughputs. The calculations used high-resolution synthetic spectra of low mass stars with 1600 < Teff < 2400 K, surface gravity 300 < g < 3000 and rotational velocity $0 < v_{\mathrm{sini}} < 12$ km/s. We find that (1) For slowly rotating ($v_{\mathrm{sin}i} < 2$ km/s), relatively bright (H<10) late-type stars, TEDI could achieve a photon-limited precision of $\sigma_v \sim 3$ m/s in a 10 min. integration. (Precision σ_v scales as exposure^{-2}). (2) The precision depends relatively little upon the effective temperature. For K through L dwarfs of the same H magnitude, the precision varies by only a factor of 2. (3) Projected rotational velocity ($v_{\mathrm{sin}i}$) has the most significant effect. For a mH = 10 star observed for 10 min. with T = 2400 K, g = 1000, and $v_{\mathrm{sin}i}$ = (0, 3, 6, 9) km/s, the photon limited precision is, σ_{RV} = (3, 5, 8, 11) m/s, respectively. For T=2100 K, the σ_v increases by 3.3 m/s. The calculated uncertainty due to the ThAr calibration spectrum is σ_v ~0.4/(OPD /3 cm) m/s, where OPD = 2-5 cm.

Systematic uncertainties have historically been the ultimate performance limiting factors for RV surveys. We have estimated anticipated systematic errors for TEDI. Exposures durations are generally limited 60s by K band thermal background, resulting in a barycentric timing uncertainty of σ_t <30s that causes an RV error or σ_{RV}~1 m/s. Using non-destructive detector sub-reads available with NIR sensors could further reduce this error. The absolute OPD is determined during observations to obtain the fringe phase frequency change proportionality with velocity. We determined that the OPD value can be derived to <1 um precision by using a ThAr line atlas in comparison with actual data. This cam cause a σ_{RV} ~1 m/s error for the worst-case (v=30 km/s) barycentric effect on removal of a large included telluric signal. Known algorithmic uncertainties of telluric confusion and stellar variability have been simulated to be σ_{RV} ~<1 m/s when using bandpass selection and cross band comparisons, respectively. Instrumental systematic errors are difficult to estimate, although we anticipate that the cavity effective beam alignment stability and metrology precision could cause an apparent velocity shift of σ_{RV} = 5 - 20 m/s, depending on the observing configuration

5. TEDI ON-SKY COMMISSIONING

TEDI has been operated in 3 test runs - first light on 29 Dec-1 Jan '07, 2 nights on Mar 19, '08, and 3-nights on Mar 29 – Jun 1. An on-sky observing efficiency up to 65% per night was achieved, with ~1,000 phase exposures taken in one night. We report the performance from our preliminary analysis and algorithm tuning efforts. The end-to-end reduction pipeline coding is partially completed and under continued development. The NSF TEDI program will support further test runs through end Aug '08.

The Cavity optical alignment is excellent. Fringing with visibility exceeding 90% occurs through all orders. A raw spectrograph sensor image is shown in Fig.1 with the K-band order at the top (note thermal background). A stellar target's continuum (A-dwarf) from each cavity arm is recorded as the central two stripes per order, modulated as a 'beaded' pattern by the EDI fringe. A short cavity delay (4 mm) was used so the fringing did not exceed the sensor resolution. Here, the ThAr reference spectrum is recorded as the outside two stripes per order, and the sky background is found between the ThAr and star. Each orders's components are extracted into vectors for processing- a subset is portrayed in Fig.2.

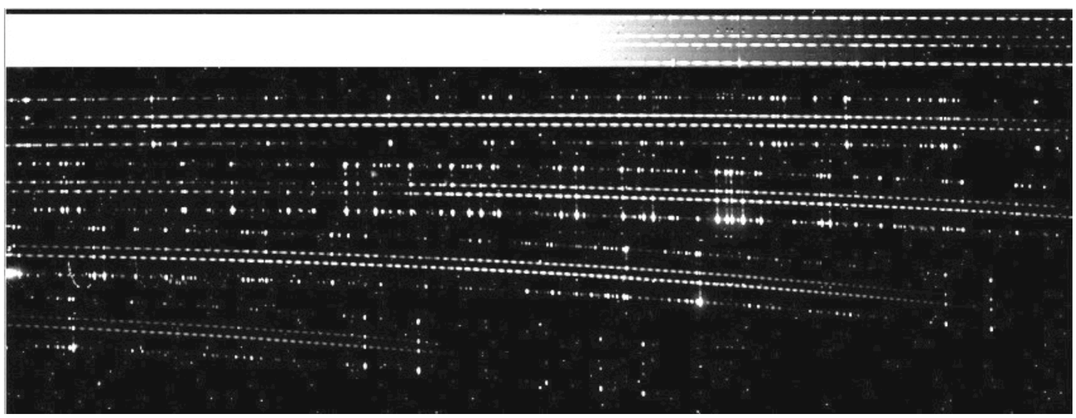

Fig. 1. A raw spectrograph sensor image. The K-band order is at the top. A stellar target's continuum (A-dwarf) from each cavity arm is recorded as the central two stripes per order, modulated as a 'beaded' pattern by the EDI fringe. The ThAr reference spectrum is recorded as the outside two stripes per order, and the sky background is found between the ThAr and star.

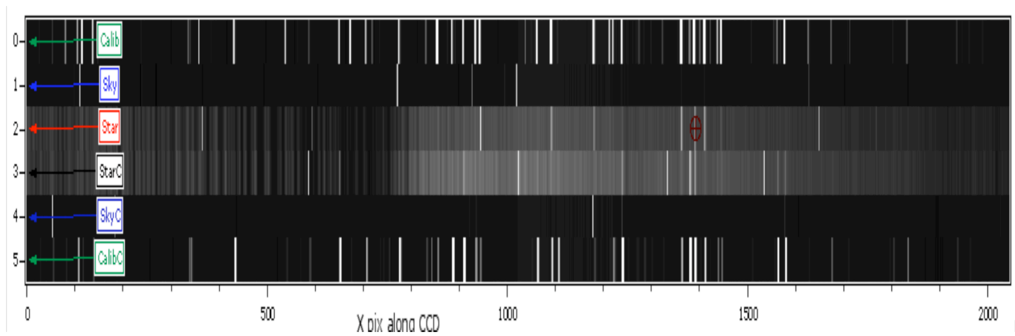

Fig. 2. A subset of one spectral order showing each order's components extracted into vectors for processing.

Images are recorded for each target at 10 phase steps of 0.25um. After bad-pixel correction and dark & sky subtraction, and normalization, the fringing signal is extracted. Comparison of the GJ411 observed (Fig.3 top) and theoretical (bottom) whirl magnitude relative to the stellar continuum shows that the EDI fringing content is excellent, an indication of high quality cavity visibility, stability, phase stepping, and algorithmic reduction.

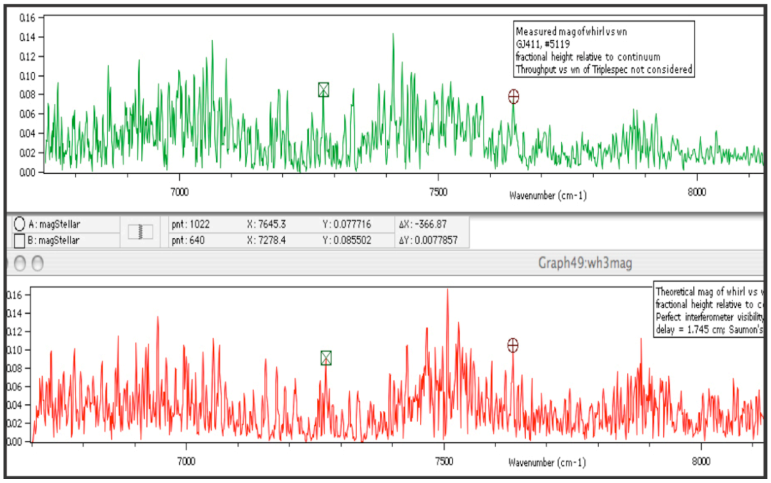

Fig. 3. The observed (top) and theoretical (bottom) magnitude of the derived fringing signal relative to the stellar continuum.

We made a preliminary estimate of the short-term stability by deriving the absolute delay and using the ThAr whirl phase from both complementary cavity arms. Fig.4 shows the ThAr velocity relative to a zero-epoch recording. The time between each measurement is ~5 min and the sample spans over 1 hr. The rms deviation from the best fit zero line for the combined cavity arms is ~12.5 m/s, and for each single cavity arm is 13.1 and 14.3 m/s rms, respectively.

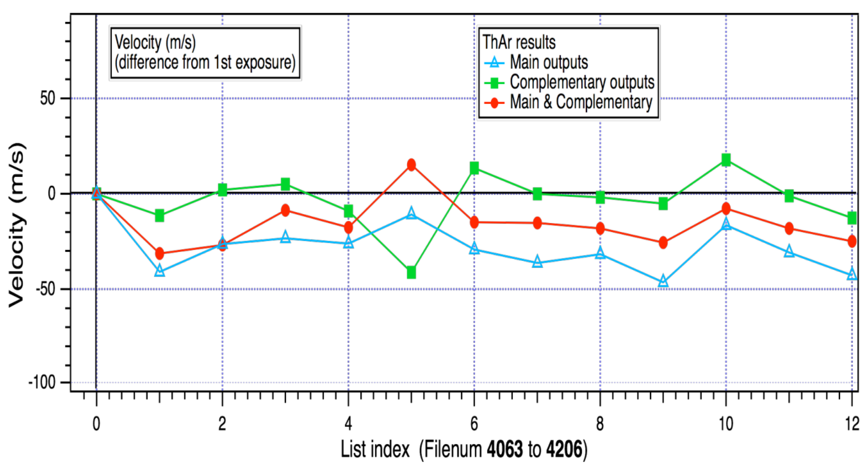

Fig. 4. The ThAr velocity relative to a zero-epoch recording. The time between each measurement is ~5 min and the sample spans ~1 hr. The RMS deviation to velocity from the best fit zero line for the combined cavity arms is ~12.5 m/s, and for each single cavity arm is 13.1 and 14.3 m/s rms, respectively.

Our first taste of determining a stellar velocity uses observations of the stable standard GJ411, taken March 20, ’08. In Fig.5, the measured stellar velocity (O) is shown with the simultaneous measured ThAr reference velocity (X) for a series of 5-minute observations taken over ~1 hour. These particular data were taken open-loop, i.e. without an active cavity stabilization. The rms scatter for ThAr is ~12 m/s and for the star GJ411 is 56 m/s about the best-fit line. For the stellar data, we anticipate the scatter about the trend represents the random velocity error and that the slope in the stellar result likely results from an uncorrected change in the delay with wavelength and/or from yet unaccounted instrumental cavity drift. Our ThAr processing experience shows that normalization prior to whirl formation is important, and we expect that optimizing the immature analysis for stellar normalization to certainly differ from the emission line method. The stellar-velocity scatter derivations used only one (6740 to 8850 cm^{-1}) of five available orders. Using all orders is expected to decrease photon and algorithm uncertainty as uncorrelated errors average and improve delay and step accuracy, although systematics will likely establish a noise floor.

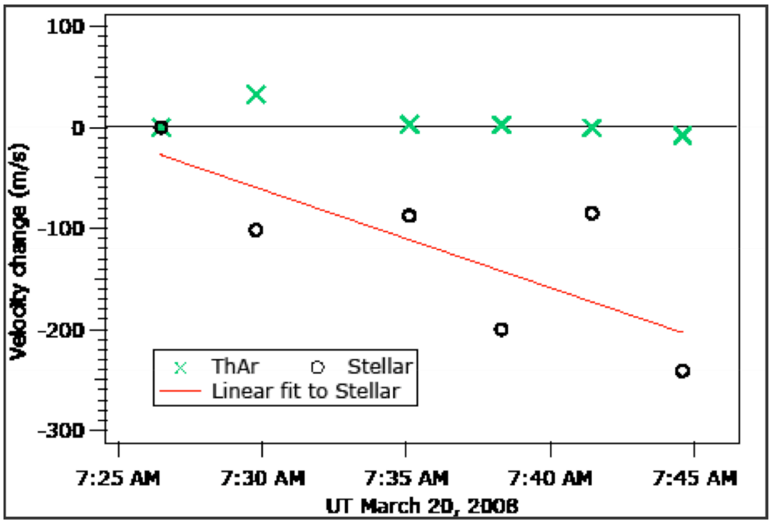

Fig. 5. The measured stellar velocity (O) for a stable standard star is shown with the simultaneous measured ThAr reference velocity (X) for a series of 5-minute observations. The RMS deviation to velocity about the instrumental drift line is 56 m/s.

We have made rough determinations of TEDI throughput as we iteratively improve the system internal and external alignment, pointing, and guiding, and as the 200” telescope facility tuning progresses. We compared the exposure time to record a fixed S/N per spectral bin to that calculated for model stellar spectra and an ideal TEDI efficiency (50%) and the TripleSpec design curve. In the first the throughput was ~40 X reduced from ideal. In the second run, it was reduced to ~4 X of ideal. TripleSpec is performing close to specification, but there is some loss in the Y and J bands. We hope for a significant factor of improvement from spectrograph element coating work and more careful TEDI pupil alignment. More comprehensive throughput testing will be undertaken following the immediate TEDI effort toward obtaining optimized velocity precision and stability measurements.

Our preliminary TEDI analysis shows total open-loop on-sky Th-Ar data velocity errors over a single observation (~1 hour) of σ_v <12.5 m/s that sets an upper-limit to the co-planarity stability. Test data from our 30 May 30 - 1 Jun’08 run is being analyzed to evaluate the stability over days. Following these results, further development to substantially mitigate beam walk error will be undertaken, such as improving the cavity-alignment, metrology precision and the cavity mirror flatness, and by using calibration or sky spectra to bracket the starlight and measure mirror slope.

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