Infrared Radial Velocimetry with TEDI - Performance Development

Jerry Edelstein*[a], Phillip Muirhead[b], Jason Wright[c], Kevin Covey[b], David Erskine[d], Matthew Muterspaugh[e], James Lloyd[b], Samuel Halverson[a], Mario Marckwordt[a], Daniel Mondo[a]
[a]Space Sciences Lab University of California Berkeley, CA, USA
[b]Cornell University, Space Sciences Building, Ithaca, NY, USA
[c]The Pennsylvania State University, State College, PA, USA
[d]Lawrence Livermore National Laboratory, Livermore, CA, USA
[e]Tennessee State University, Nashville, TN, USA

ABSTRACT

The TripleSpec - Exoplanet Discovery Instrument (TEDI) is a device to use interferometric spectroscopy for the radial-velocity detection of extrasolar planets at infrared wavelengths (0.9 - 2.4 µm). The instrument is a hybrid of an interferometer and a moderate resolution echelle spectrograph (TripleSpec, R=2,700,) at the Cassegrain focus of the Palomar 200" telescope. We describe our experimental diagnostic program using laboratory sources and standard stars in different optical configurations, along with performance analysis and results. We explain our instrumental upgrade development to achieve a long-term performance that can utilize our demonstrated, < 10 m/s, short-term velocity precision.

Keywords: interferometric spectroscopy, externally dispersed interferometry, near infrared, radial velocity

1. INTRODUCTION

The TripleSpec Exoplanet Discovery Instrument, TEDI, is an externally dispersed interferometer (EDI) that is coupled with the Triplespec spectrograph at the Palomar 200" telescope. The instrument's purpose it to identify exoplanets orbiting low mass stars by obtaining radial velocity measurements of low-mass stars in the near IR (0.9-2.4 um) band. Having established the basis of the method[1,2,3], and fielded a research development instrument[3], hereafter "TEDI 1.0", we conducted tests and developed analysis (see Muirhead et al., *this volume*) to characterize and comprehend the achievable radial velocity precision and stability. The consequence of our first round of testing was the discovery of performance limitations in efficiency and stability. We have modified and fielded an updated instrument, hereafter "TEDI 2.0", and commenced a second round of on-sky testing. Our goal is to understand this technique and its associated systematic errors at a fundamental level so that we can approach the instrument's ultimate performance and application.

Externally dispersed interferometry is used to increase the Doppler sensitivity of an existing spectrograph by substantial factors. The EDI uses a series combination of a small fixed delay interferometer with a conventional grating spectrograph. The interferometer creates a transmission comb that is periodic with wavelength. The comb, in multiplication with the input spectrum, heterodynes fine spectral features into a lower spatial-frequency moiré pattern that is recorded by the spectrograph detector. A Doppler velocity change induces a phase change in the moiré pattern relative to one from a simultaneously measured calibrant spectrum (a ThAr emission lamp). A vector data analysis procedure[2] measures the differential moiré phase between the input spectrum and a reference spectrum.

2. TEDI 1.0 TESTING

TEDI 1.0 instrument[6] was comissioned at the 200" telescope at Palomar in Jan '08 and thereafter operated on the sky for 10 good weather nights over six runs. In TEDI 1.0, the converging telescope beam was inserted directly into an unequal-arm Michelson interferometer cavity and focused onto the cavity mirrors. Insertion was via a pellicle that was used to mix

*jerrye@ssl.berkeley.edu; phone 1 510 643-0599

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean,
Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 773583 · © 2010
SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.858312

mix a separated ThAr calibration source into the beam. The cavity used a plate beam splitter off-axis to the f/16 insertion beam. The off-axis scheme allowed for simply reaching both cavity output arms and including a cavity alignment monitor system. The cavity arm outputs were collected by micro-lens tipped fibers and transferred to an optical relay system needed to return the focus and pupil into the Triplespec guider and spectrometer system.

TEDI 1.0 performance achievements included an interferometer fringing visibility of 95% and an output focal quality of 0.8 arc second under good seeing conditions. Substantial achievements were made in control and operations that allowed for high efficiency data taking. In particular, an on-sky injection alignment procedure and diagnostics and an automated phase-step sequence acquisition control were implemented. An extensive set of graphical observer interface control software was developed that provided for fast (~1.5 min.) absolute cavity delay tuning to 0.1 um precision. Semi-automated telescope sky-alignment schemes were developed and telescope alignment time was reduction from 3+ hours to 30 minutes. An observational efficiency of 85 % per night was achieved.

Advances were made in algorithm development, data reduction, and data diagnostics by using result comparisons between two independent reduction codes at Berkeley and Cornell, respectively, together with both on-sky data and that from a high-fidelity star simulator. The algorithms have proven essential for allowing us to isolate and distinguish between systematic errors arising from instrumental or reduction causes. The quality of the star simulator proved important to understanding the performance. We used an achromatic scheme to simulate the 400 um per arc second by f/16 telescope focus input to the instrument. The testing scheme used a 100 um fiber-fed 4:1 diamond turned elliptical reflector with continuum, laser, or line emission lamps.

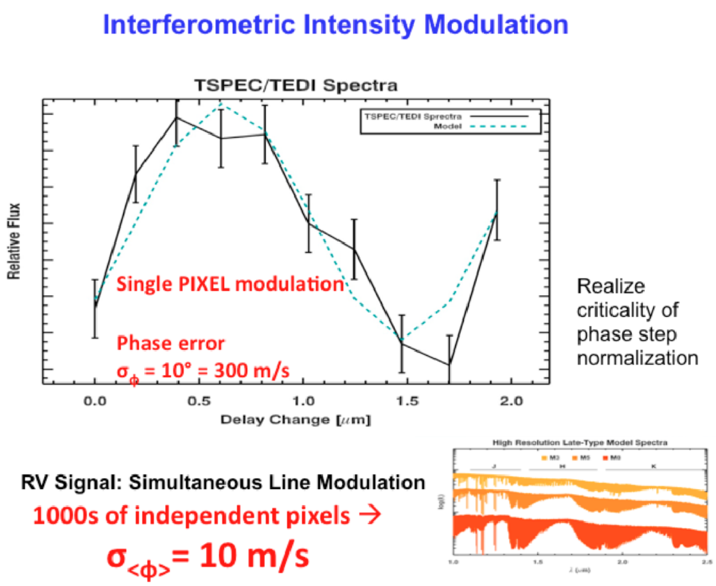

Fig 1. An observation phase set of the M-star, GJ411, shows the interferometer modulation of a single stellar spectral line within a spectrograph pixel (upper panel). The error in fitting the phase modulation corresponds to a velocity error of 300 m/s and is photon limited. Given the thousands of M- star spectral lines in the measured pass-band (inset lower right) whose phases are simultaneously and independently measured by TEDI, the net velocity measurement error is 10 m/s.

We measured a short-term emission lamp calibration velocity resolution of 6.0 m/s and a photon limited velocity resolution of 10 m/s per observation epoch using stellar standards (see Fig. 1). Mid to long term systematic RV errors were discovered at the 100's of m/s level. Subsequent analysis has revealed that a dominant instrumental systematic contributor to the RV errors was variable delay dispersion within the cavity, rather than the desired and expected fixed dispersion (see Fig. 2). While the variable dispersion appeared to follow a potentially characterizable and removable functional form (Fig. 3), its existence and removal would certainly contribute errors to the final result. Consequently we sought to understand and eliminate the problem. We first developed special rapid diagnostic codes to compare the phase observed simultaneously in each interferometer arm as a function of wavelength and to compare the dispersion of delay within each or both arms at different epochs. Using these codes, test showed that the delay dispersion variability was related to variations in the fiber pickups' sampling of the cavity image-plane and to the cavity's tuning. Further observations of the geometry of dispersion amplitude made apparent that the dispersion arises from the converging-beam interferometer's astigmatic optical aberrations being variably sampled by the input fiber acceptance region as pointing or guiding offsets moves the aberrated interference image (see Fig. 4).

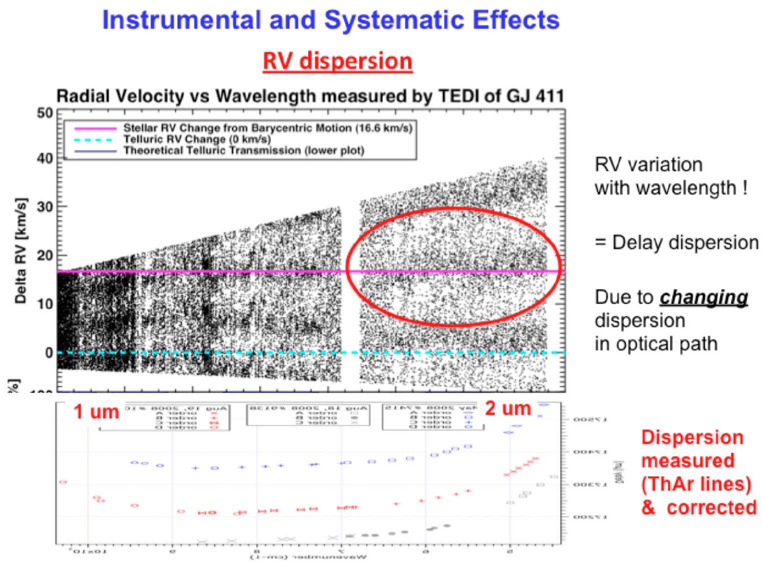

Fig. 2. The radial velocity (and equivalently delay) between epochs (top panel) observed across the NIR passband varies as a function of wavelength in a way that departs from the dispersion of the optical element materials (lower panel). The pink line shows the expected barycentric delay between the epochs. The calculated delays (black dots) at each spectrometer wavelength appear in bands due to 2*Pi phase wraps. Departures in heavy telluric regions are evident.

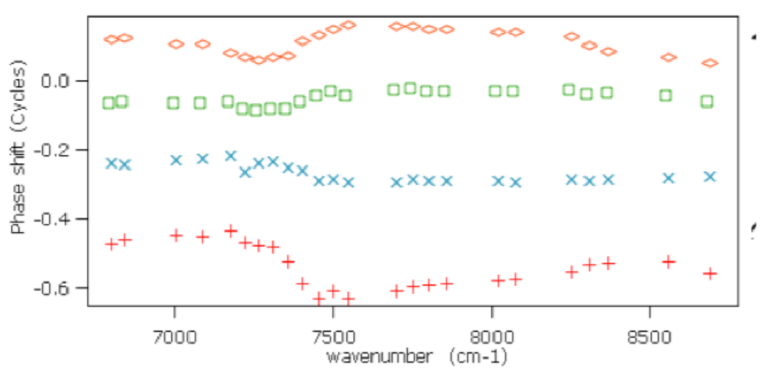

Fig. 3. The delay dispersion, shown here for a single spectrometer order, appears a symmetric function with respect to the cavity mirror delay. Each delay separated by 100 microns is shown by a different color and symbol.

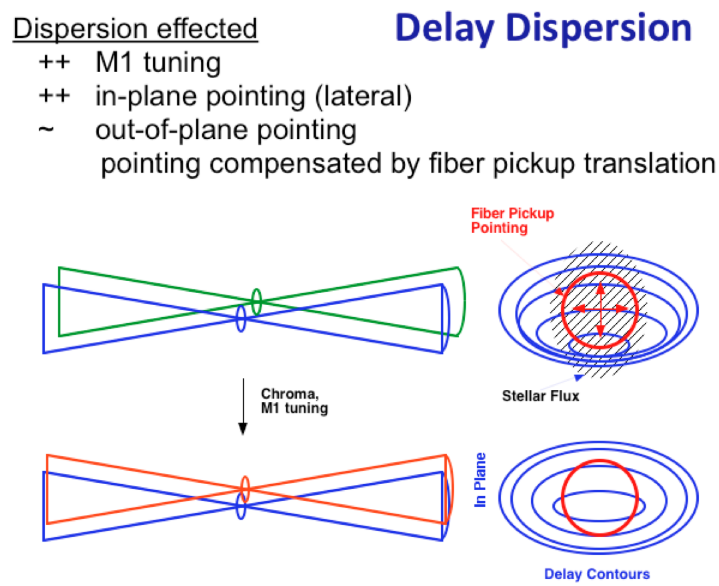

Fig. 4. The dispersion phenomenon is understood as being due to shearing effects between the interfering foci. In the top sketch, the plan shows the foci occurring offset in both an axial and lateral manner (green and blue lines). The corresponding image plane sketch, show to the plan view's right, shows the stellar flux (shaded area) and contours of relative delay (blue) that are more rapidly changing in-plane with the cavity opening angle due to astigmatism caused by primarily by the plate beam splitter. The perceived delay can change if the fiber pickup region (red circle) moves with respect to the delay contours due to pointing and guiding changes. Alternatively, the perceived delay can change if the delay contours vary over the pickup region if the relative location of the foci change due to chromatic or cavity tuning shifts (lower plan and image plane sketch).

Total throughput for TEDI 1.0 did not meet expectations. Individual components generally performed as anticipated, less a substandard NIR beam splitter received from ISP Optics that was replaced by an excellent component made by JDSU. Measured as sub-assemblies at 1.5 microns, the performance was reasonable for the open optical chains but less than desired for the fiber systems: from injection to interferometer cavity arm outputs were 52% and 66%, the fiber link throughput was 30%, and the final relay path was 66%. The product of the subassembly's throughput, 19%, should represent the total throughput but on-sky tests obtained values three to five times less than this. Contributing factors that caused this likely included fiber ratio degradation and poor injection alignment and guiding, both of which proved difficult as the Triplespec guider camera imaged only the interferometers *output* and not its stellar *input*.

3. TEDI 2.0

In order to overcome the limitations of TEDI 1.0, we have implemented instrumental modifications (see Fig. 5). The key aspects of our changes are to 1) convert the existing interferometer cavity from a converging to a collimated beam, 2) to feed the starlight, pre-mixed with the calibration source light, to the interferometer via a target-collection fiber, and 3) to use an active tracking system with sky-imaging and cavity-flux feedback to capture and guide the starlight into the collection fiber (see Fig. 6) In part because of the difficult geometry posed by having to fit TEDI into the Hale telescope primary mirror Cassegrain cutout hole, we elected to dedicate one of the cavity output arms for fringe monitoring and target flux peaking – we felt that the efficiency gained for target acquisition and guiding compared to TEDI 1.0 would mostly recover the lost flux.

The collimated beam cavity will mitigate deleterious effects of astigmatic and chromatic aberrations that arise from using a converging beam through a plate beam-splitter in a non- symmetrical interferometer cavity. In this way aberration-induced delay differences at the spectrograph input will be greatly diminished. Using a fixed position cavity injection fiber will eliminate path delay variations that occurred with the previous direct telescope injection scheme when pointing or guiding errors caused delay differences as the beam 'walked' about the cavity to different optical paths.

Pre-mixing the calibrant and the stellar flux in a fiber prior to cavity injection eliminates potential differences between the calibration and stellar flux paths. The fast, direct telescope-guiding scheme with feedback allows for rapid and efficient target acquisition and injection.

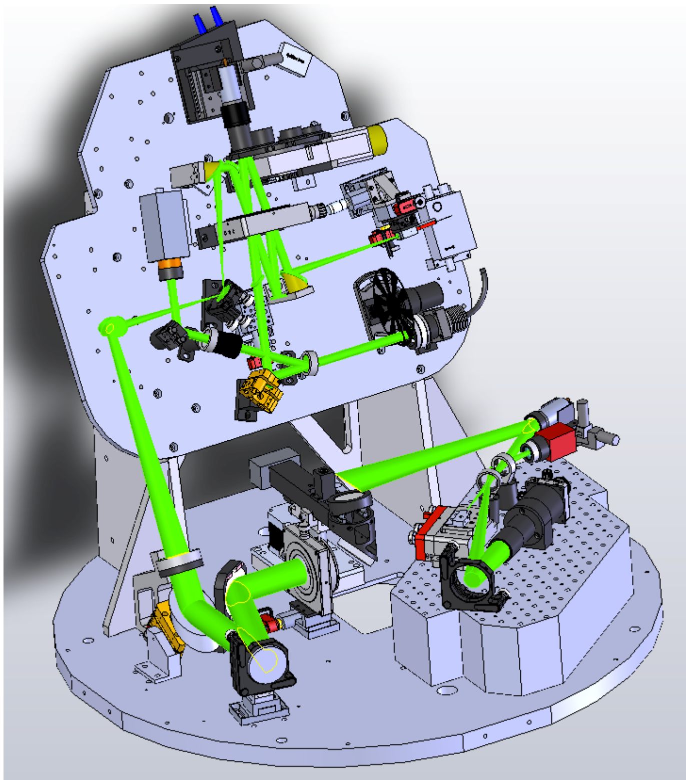

Fig. 5. TEDI 2.0 uses a dichroic split input tracking system (lower right) to feed a symmetric, collimated interferometery cavity (top center). One interferometer arm is dichroic split to a sensitive chopped IR diode for flux maximization and a fringe tracking camera for cavity nulling. The other interferometer arm is open-path relayed to the Triplespec slit.

Potential difficulties with the new scheme include that using a collimated beam in the cavity enlarges the area on the cavity mirror over which flux is incident. In this case the cavity optics must be very flat and stable during data acquisition or fringe contrast will be lost. We added strain-gauge closed loop feedback to the cavity mirror to improve its stability and, after careful low-stress mounting efforts of the cavity optics, have measured 90 to 95% visibilities at 1.5 microns in the TEDI 2.0 cavity. Another possible problem with the new scheme is that the ThAr light and the starlight could illuminate different parts of the cavity mirror at different intensities due to guiding or speckling variations between the two source paths. If the delay is not uniform across the cavity mirrors, this difference could appear as a velocity shift. We find that our fiber link scrambles the input from both sources and so should mitigate this problem, but only on-sky tests can confirm the ultimate performance.

TEDI 2.0 was commissioned at Palomar mid-June 2010, with target acquisition and science grade data being taken within 30 minutes of going on-sky. The target acquisition and flux peak-up system performed very well. Preliminary on-star indications show that 90% visibilities' are common, that the TEDI 2.0 throughput is at least factors of several improved from TEDI 1.0, and that delay dispersion has been reduced or eliminated. Standard stars have been observed and data reduction is under way to assess the velocity performance.

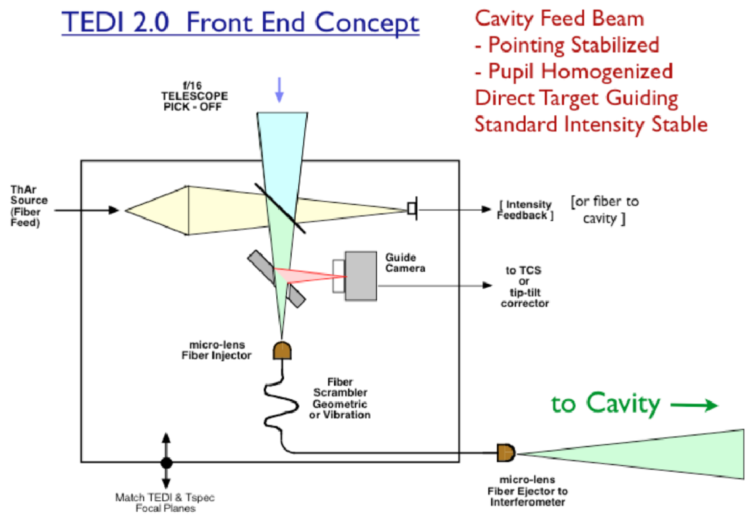

Fig. 6. The TEDI instrument modification concept mitigates the dispersion variability by injecting the telescope light (light blue cone) and calibrant light (tan cone) into a fiber pickup that feeds the cavity with a fixed position (green cone) which is collimated by an achromatic reflective optic (not shown). In TEDI 1.0 the telescope and calibrant beams were injected directly into the cavity.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. AST-0505366 and by by NASA under Grant No. NNX09AB38G. TEDI 2.0 was produced with the essential contributions of Philip Andelson, David Kimber, and Andrew Vanderberg.

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