The TEDI Instrument for Near-IR Radial Velocity Surveys

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ABSTRACT

The TEDI (TripleSpec Externally Dispersed Interferometry) is an interferometric spectrometer that will be used to explore the population of planets around the lowest mass stars. The instrument, to be deployed on the Palomar 200 Cassegrain mount, includes a stabilized Michelson interferometer combined with a medium resolution, broad band (0.8 - 2.4 micron) spectrograph, TripleSpec. We describe the instrument design and its application to Doppler velocimetry and high-resolution spectroscopy.

Keywords: Doppler planet search, radial velocity, interferometry, high resolution spectroscopy

1. INTRODUCTION

The detection of extrasolar planets by the radial velocity (RV or Doppler) method is central to an unprecedented phase of discovery. RV has emerged as the primary and standard planet detection technique. Current Doppler velocimetry methods determine the radial velocity changes that an orbiting planet imposes upon a star by measuring the absorption line centroids of highly resolved spectra or using cross-correlation techniques. The RV measurement is extremely challenging. Typical planetary shifts are 1000 times smaller than the stellar line widths, requiring extremely stable and well-calibrated instrument characteristics in order to separate the shift from environmentally induced instrumental drift. The conventional RV measurement approach uses high-resolution dispersive spectrographs (R 50-100k) to obtain the velocity precision required for planet hunting. This approach, however, comes at several costs: These instruments are typically large and costly echelles with large optics and paths that must be held to high mechanical tolerances over many-meter distances. Classical seeing-limited echelle spectrometers must fundamentally be cumbersome due to the need to match the slit width and resolution. These instruments suffer from low throughput and maintaining long-term stability often requires substantial effort such as complex servo systems or huge vacuum tanks.[1–3] Furthermore, current planet search samples are limited to bright stars in the optical band, thus inhibiting knowledge about the populous low mass stars that is important to discriminating among planet formation theories.

We describe a program to study the radial velocity of low mass stars and brown dwarfs using Externally Dispersed Interferometry (EDI), a combination of interferometry and multichannel dispersive spectroscopy that dramatically improves the velocity resolution of moderate resolution, high throughput spectrographs. We are developing an EDI instrument using the Cornell TripleSpec infrared simultaneous JHK-band spectrograph[4] at the Palomar Observatory 200 telescope for a science-demonstration program that will allow a unique systematic Doppler-search for planets orbiting low mass faint M, L and T type stars and brown dwarfs. The throughput advantage of EDI with a moderate resolution spectrograph is critical to achieving the requisite sensitivity.

2. EXTERNALLY DISPERSED INTERFEROMETRY

The externally dispersed interferometer[5–12] increases the Doppler sensitivity and multiplies the spectral resolution of an existing spectrograph over its full and simultaneous bandwidth by a factor of several to an order of magnitude (Erskine et al., 2003). For example, our prototype observatory and laboratory instruments have demonstrated EDI visible-band velocimetry precision to 5 m/s using an R= 20,000 spectrograph, and a factor of six increase in conventional spectrograph resolving power (from R= 25k to R= 140k).[13]

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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 that multiplies the input spectrum to create moiré fringes. These fringes provide a periodic spectral fiducial comb covering the entire bandwidth of the spectrograph. This comb is analogous to the fiducial lines of an iodine absorption cell, but with lines of exceedingly uniform spacing, shape, and amplitude over the entire bandwidth. 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. The heterodyning can be numerically reversed to recover detailed spectral information otherwise unattainable by the spectrograph alone. The EDI fringing signal provides a precise internal fiducial that can be used to defeat systematic instrumental noise so that the tolerance to blur or pupil changes (Erskine & Edelstein 2003) is improved by orders of magnitude compared to classical high-resolution spectrographs that directly map telescope image quality and pupil stability to spectral performance.

A Doppler velocity change induces a phase change in the moiré pattern relative to the moiré pattern of a simultaneously measured calibrant spectrum. In EDI, the moiré fringe phase becomes the primary diagnostic instead of classical spectral dispersion. A vector data analysis procedure (Erskine 2003) precisely measures the differential moiré pattern phase between the input spectrum and a reference spectrum (absorption cell or emission lamp) that has been simultaneously recorded in the same fringing signal. The moiré pattern has much broader features than the narrow stellar absorption lines that created it. Hence a much lower resolution spectrograph can be used to make precision Doppler velocities than otherwise practical without the interferometer. In fact the native spectrograph can have a low resolution (3k to 5k) such that the stellar lines are not fully resolved. Such an EDI has recently been used to discover an exoplanet in Virgo.[14]

3. THE EDI-TRIPLESPEC INSTRUMENT

The TripleSpec EDI system consists of an interferometer (see schematic Fig. 1, and illustration Fig.2) mounted to the TripleSpec front plate (in a 35cm radius volume available to the telescope Cassegrain feed) a remote control system. The interferometer consists of a fixed main optical unit and pick-up unit that can be moved to intercept the incoming f/16 telescope beam, divert it to the interferometer, and return the light to the beam path for TripleSpec. Commercially available optical elements, coatings, mountings and stages will be used with careful selection for optical performance and telescope environment compatibility (e.g. temperature & orientation). The instrument will also include a flux weighted exposure timer diode via a small pickoff to determine the effective exposure center for accurate RV periodigram analyses and barycentric correction.

The interferometer uses use an off-axis Michelson scheme that allows ready access to both the arms outputs and to a common-path secondary input for calibration, alignment and stabilization source input. This configuration has been demonstrated in the UCB lab. A selectable etalon in one arm creates a nearly angle-independent optical path to allow for a large field of view. Absorption cell selection can be actuated on the input path. Transfer optics reimage the interferometer output to the TripleSpec entrance slit. The relative alignment of the two output beams and absolute position on the slit is adjustable. The complementary outputs are simultaneously detected by displacing them vertically by 1/2 order. To allow simultaneous multiphase recording, a cylinder lens can be inserted to spread the starlight from each arm in one dimension along the slit length. We expect a net interferometer efficiency of $\sim$85% based on our plan to use both complementary interferometer outputs and components with high-quality AR and mirror coatings. The 2X read-noise penalty caused by having to record the two arm paths at different detector locations can be survived because we observe in the photon-limited regime.

Recording fringes over a long exposure requires a stable phase robust to thermal and mechanical drifts. If the phase wanders more than $\lambda/8$, then the net visibility will be significantly reduced and decrease S/N proportionally. Our data analysis can handle irregularly spaced phase steps, so only large phase wandering has impact on the net velocity resolution. We use a commercial PZT-transducer mounted mirror to actively compensate for optical path fluctuations. The system uses a 'piggy-back' diode-laser that propagates parallel to and above the science beam through the interferometer elements and forms a fringe on a small CCD camera. Software analyzes the location of the fringe pattern and the PZT is moved to compensate. The same piezo-system is conveniently used to phase step as desired for reduction of detector or instrument systematic noise.

4. RADIAL VELOCIMETRY REFERENCE STANDARDS

The introduction of the Iodine absorption-line reference cell was crucial to the current renaissance in precision radial velocity studies and to the detection of extrasolar planets. The reference cell provides a stable zero-velocity narrow-line

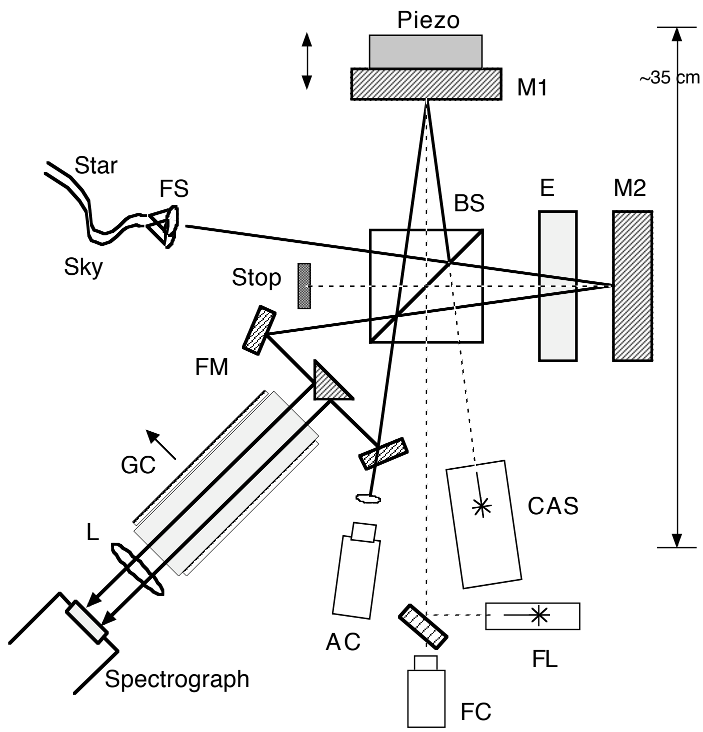

Figure 1. TEDI Interferometer Functional Schema: Representative sources(star & background) from the telescope feed launches the incoming beam through the unequal-arm off-axis Michelson interferometer cavity, via the beam-splitter (BS), to the cavity mirrors M_1, M_2). The etalon (E) compensates the unequal-arm path difference, providing large angular independence. Fold mirrors FM, and a mirrored prism direct the two complementary-arm output beams toward the TripleSpec spectrograph slit via transfer optics, summarized as the lens L. A reference absorption gas cell (GC) can be shifted into the beam output. A flux time-weighting pickoff/diode sensor (not shown) will be included in either the Interferometer or the Spectrograph. The fringe phase is set and stabilized by a piezo transducer (Piezo) controlled by monitoring a fringe-pattern, formed by a fringe laser (FL) to a fringe tracking camera (FC). Calibration and alignment emission source (CAS) light is injected to the cavity on an equivalent path to the star-light. An alignment camera (AC) is used to confirm internal and external interferometer alignment in advance of observational operations.

calibrant needed to precisely determine slight Doppler shifts over long time scales. Reference cells are still central to radial velocity studies today, although although some groups now use a Th-Ar emission lamp or a laster stabilized spectrographs instead. Conventional Doppler measurements are limited to bands where the standards have adequate transmission or dense and narrow spectral signatures.

The EDIs transmission comb will form beat patterns with absorption cell or emission lamp spectra to provide an absolute spectral reference frame. Injection of emission-lamp flux into an EDI is simplified in comparison to methods used for conventional spectroscopy (e.g, fiber-scrambling) because our angle-independent interferometer design imprints the same spectral fiducial comb upon both the stellar and lamp beams even if they are not exactly co-axial, and because of the insensitivity of EDI to pupil and point-spread function illumination. The interferometer also has an accessible secondary input path that mirrors the stellar flux path. Furthermore, because EDI produces a repeatable transmission comb throughout all wavelengths, the comb can be used to extend velocimetrys useful bandpass beyond the reference standards regular range.

The atmosphere itself provides a dense comb of NIR narrow absorption lines, similar to that of an absorption cell. Using the detailed atmospheric absorption models of Roe (2002) we find that the atmospheric spectrum has adequate spectral feature density and slope for use as a velocimetry absorption cell at precision of $\sim$ 10 m/s. Atmospheric variations, including line sight velocity perturbations, will constrain the usable velocity precision. While we expect substantial variability in the water vapor lines, many other atmospheric lines are not expected to change dramatically. The EDI determinations depends

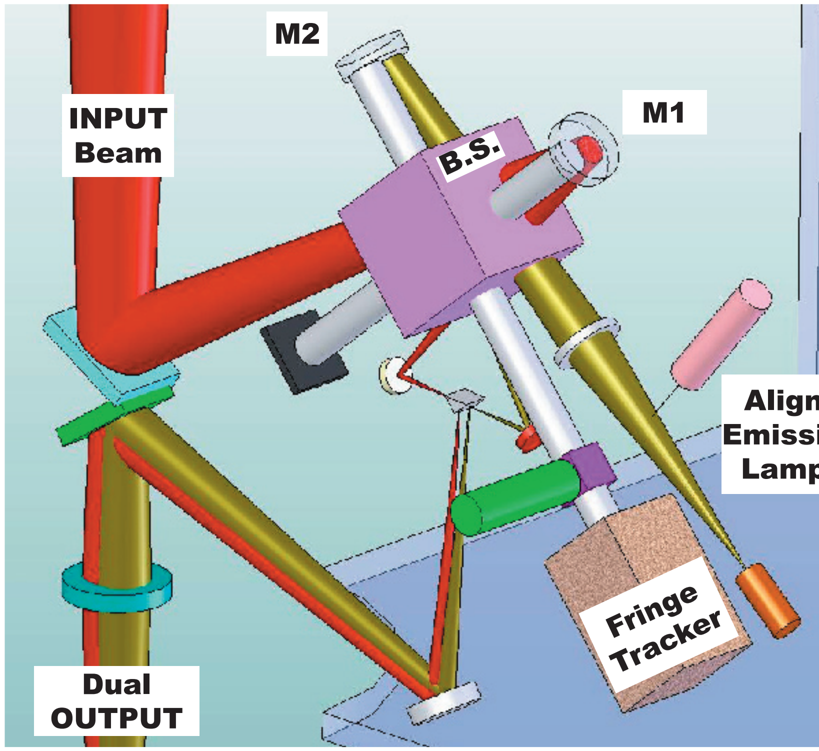

Figure 2. T-EDI Palomar Interferometer Mechanical Layout: The TEDI Palomar mechanical layout. The interferometer cavity consists of a beam splitter (BS) and two mirrors (M1, M2). An etalon is inserted before one of the mirrors (not shown). The complementary outputs are folded to parallel dual outputs. Alignment and Emission lamp sources are injected into the BS complementary input and mix with the science-source output beams. A Fringe Tracker camera stabilizes fringes formed by from a monitor laser traversing a parallel but separate path through the BS. In this scaled perspective illustration, the BS is 5 cm on one edge.

on velocity centroids of reference lines, not the reference line profile. Consequently we anticipate that the non-aqueous telluric lines can be used for RV reference as their centroids are unlikely to be altered by optical depth effects.

Absorption cells may be used for more precise and non-variable reference in the near IR. We only require that these materials have a dense stable field of narrow lines in our bands of interest. We do not require absolute knowledge of their spectral line locations. We have identified several potential vapors for NIR absorption cells, primarily simple organic molecules. These and similar organics have high vapor pressures at low temperatures and have been measured by precise FTIR spectra. CH3, CO, HCCH, and HCN are used as primary wavelength reference standards in the 1.5 micron telecom band. Other molecules such as NH3, H2S, HF, HCl have useful NiR absorption signatures that have been extensively cataloged for atmospheric science work.

5. SENSITIVITY

Because the EDI process recovers both a conventional and a fringing spectrum, both can be combined to form a net EDI response. The two spectral components are determined from different spatial frequencies on the detector and are statistically independent with uncorrelated errors. The net EDI response is then formed from the component's quadrature sum. Forming the net EDI signal can provide a useful gain when Doppler information is limited by large stellar rotational velocities, which limits high spatial frequency content. The systematic errors suffered by the conventional and the fringing spectrum are different however. The EDI derived velocity is orders of magnitude lower than the common limiting systematic errors for the conventional spectra, such as variation in pupil illumination or point spread function.

We have calculated the sensitivity and velocity noise for EDI and conventional spectroscopy using a surrogate cool star spectrum, a sunspot, in the J and H bands. The high-resolution umbral input spectrum was first blurred to simulate the stellar rotational rate and then filtered according to either the conventional or EDI frequency response. We used a Gaussian R=3,000 spectrograph response with a delay best matched to the Doppler information content. Our results (see Tab. 1) show that the EDI sensitivity far exceeds the conventional sensitivity and that the H band contains more Doppler information that the J band. The EDI Doppler sensitivity (number of photons, N, required to obtain a velocity error, δV, is improved by up to an order of magnitude compared that of the conventional spectrograph. The absolute sensitivity and spectral noise is shown for the J and H band in Tab. 2 for our proposed EDI instrument attached to the TripleSpec spectrograph on the Palomar 200 telescope, with an estimated total throughput of 20% The velocity noise for the J and H band is similar since the higher J band flux offsets the better H band Doppler information content. By combining the J and H band data for a m_H = 10 star, a velocity noise of 100 m/s can be obtained in 1 minute, and for a m_H = 14 star, in 1 hour. We expect that the K band can also be used for further sensitivity gain. Note that a reference cell and the atmosphere also imprints spectral information in the signal and so can effect the velocity noise. If these components have high information content, they will not significantly degrade the result since the noise adds in quadrature. High-resolution model atmosphere spectrum show that the telluric lines will not add significant velocity noise in the H and J bands.

Our EDI instruments have already demonstrated a $<$ 5 m/s RV measurement noise performance in the observatory and in benchtop tests (Ge, Erskine & Rushford 2002) over durations from 11 days to a month, and achieved near photon limited velocity noise, a remarkable result given the prototype instrument quality and absence of environmental controls. The proven duration of stability for EDI is more than sufficient for the 3 to 5 day periods that our observing plan is seeking to test. Nonetheless, we plan to conduct long term (multi-year) stability testing using a zero-velocity reference cell in order to understand the systematic limitations of our method.

Spectrum	Band	Rotation km/s	Delay cm	Q edi	Q conv	Q c+e	Senstivity c+e/conv
Stellar	H	7.5	2.2	600	180	625	12.1
Stellar	H	15	1.3	300	180	350	3.8
Stellar	H	30	0.5	200	180	270	2.3
Stellar	J	7.5	2.2	160	100	190	3.6
Telluric	H or J	0	2.2	1200	200	1216	37.0

Tab. 1 - The Relative Sensitivity of EDI vs conventional spectroscopy (R=3,000) for a surrogate cool star spectra (sun spot) at different stellar rotational rates v sin(i). The RMS spectral slope (Q_{edi}) for an EDI measurement using an optimized delay far exceeds the conventionally measured value (Q_{conv}). The net EDI slope (Q_{c+e}) is obtained by the combination of conventional and EDI signals. The net EDI Sensitivity exceeds that of the conventional spectrograph by up to an order of magnitude. Telluric lines will not degrade the spectral Doppler signal because the telluric Q far exceeds the stellar Q.

Band	f_0	$N_{10}(1hr)$	Q_{net}	$\delta V_{m=10}$	$\delta V_{m=14}$
J	$2.4\text{x}10^{10}$	$8.6\text{x}10^{9}$	190	17 m/s	107 m/s
H	$1.5\text{x}10^{9}$	$5.4\text{x}10^{8}$	625	21	132
J+H				13	82
K	$1.5\text{x}10^{9}$	$5.4\text{x}10^{8}$	--	--	--

Table 2 - EDI Doppler Velocity Noise calculated ($\delta V = \frac{c}{Q}\frac{1}{\sqrt{N}}$) for a 1 hour observation of H=10 and H=14 stars with v sin(i) = 7.5 km/s, for the proposed EDI-TripleSpec on the Palomar 200" telescope with a 20% end to end efficiency. f_0 is the H=0 photon flux in the given band. N_{10} is the number of photons acquired for an H=10 star in 1 hour. The K band response has not yet been calculated and should contribute to further reduce the velocity noise. The H=10 star can be measured at the desired δV = 100 m/s in 1 minute.

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