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Six-fold Spectral Resolution Boosting with an Interferometer upon the Mt. Palomar Near-infrared Spectrograph

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Abstract: An interferometric method for increasing a dispersive spectrograph's resolution by large factors beyond classical limits at full simultaneous bandwidth is demonstrated on Mt. Palomar's Triplespec near-infrared spectrograph.

OCIS codes: (300.6300) Spectroscopy, Fourier Transform; (300.6310) Spectroscopy, Heterodyne; (300.632) Spectroscopy, High Resolution

1. Introduction

Externally dispersed interferometry (EDI) is a relatively new technique [1-4] using a series combination of a fixed delay interferometer with a disperser, and has applications in both Doppler radial velocimetry [1,5,6], and high resolution spectroscopy [3,4]. It is a hybrid between purely interferometric (FTS) and purely dispersive techniques, and combines advantages of both. From the dispersive spectroscopist point of view, it effectively boosts the resolution and lineshape stability characteristics, allowing use of lower resolution spectrographs (lower cost & weight) in applications otherwise limited by focal blur & detector pixels. From the interferometrist's point of view, the inclusion of a disperser improves the photon limited signal to noise ratio by a factor of ~100 (square root of # of

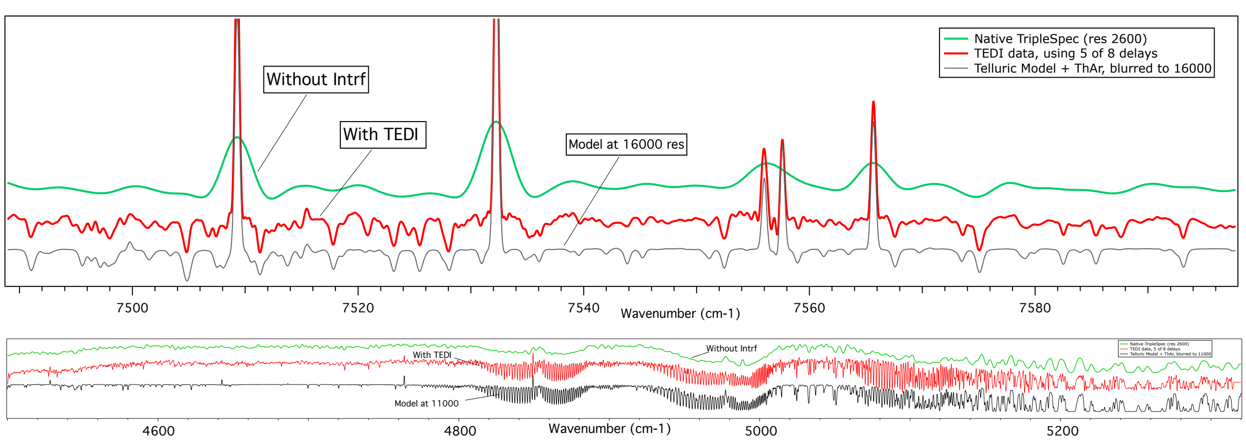

Fig. 1. Demonstartion of a six-fold boost in resolution observing telluric features in star HD219134 along with ThAr calibration lamp emission lines. In top graph, the green (top) curve is the spectrum measured without the interferometer, having resolution 2,600. The red (middle) curve is the reconstructed spectrum measured with 5 contiguous delays, up to 2 cm, and equalized to a Gaussian resolution of 16,000 (top graph) at 7500 cm^{-1} (1.33 μm). The gray (bottom) curve is a model of telluric and ThAr features blurred to 16,000, showing excellent agreement with data. Higher resolution can be obtained with larger delays. Only a small portion of the full Triplespec bandwidth (0.9-2.45 micron) is shown. Bottom graph shows 1.88-2.22 μm region having strong telluric features. This is only 1/5th of full recorded spectrum.

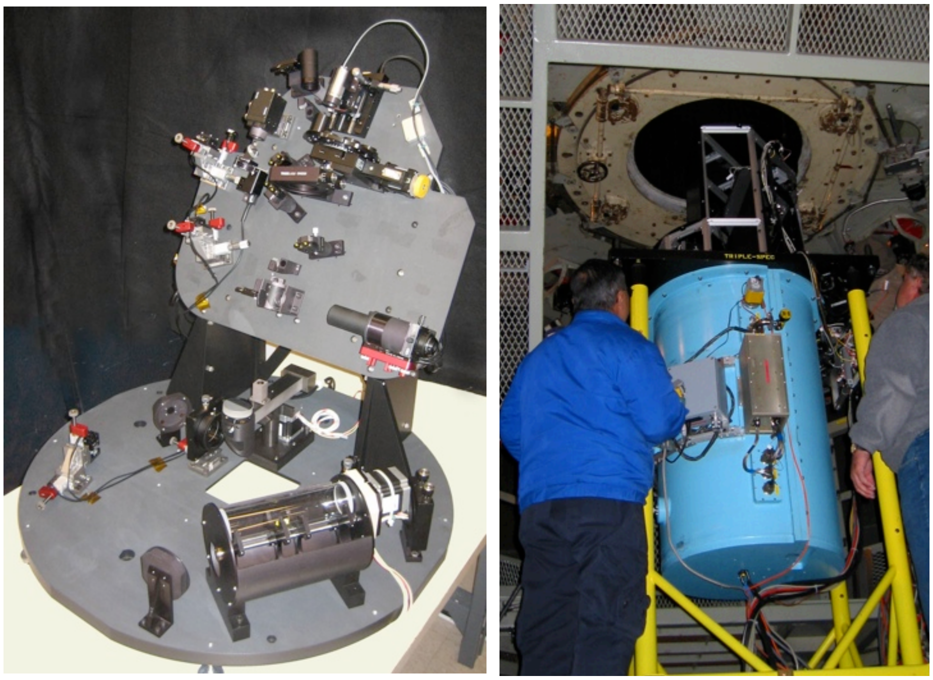

Fig. 2. Photograph of T-EDI interferometer, which sits atop Cornell's TripleSpec spectrograph (blue cylinder). The interferometer fits in the Cassegrain cavity of the Mt. Palomar 200 inch mirror, while the TripleSpec is bolted to the bottom of the mirror. The TEDI unit captures the starlight, passes it through an interferometer and optional gas cell, then re-injects both main and complentary outputs to form beams having same f/# and focus location as original beam, so that when a swing arm is removed the TripleSpec can operate without the interferometer.

independent spectral channels [7]), allowing practical use on faint astronomical targets. The EDI technique is mathematically related to dispersed FTS [8] but uses finer spectral channels, and uses a smaller number (1-10) of descrete fixed delays instead of scanning semi-continuously over a delay range, and thus uses a different algorithm to process the primitive fringing spectra into a reconstructed spectrum. All dispersed interferometer hybrids will enjoy improved photon limited signal to noise ratio over an undispersed interferometer.

We describe initial field tests of the "TEDI" interferometer at the 200 inch Mt. Palomar telescope, which is at the Cassegrain output (Fig. 2) in series with the near-infrared (0.9-2.4 µm) Triplespec [9] spectrograph (R~2,600). The primary motivation for TEDI was Doppler radial velocimetry for exoplanet search, but this presentation will focus on the enhanced high resolution spectroscopy capabilities, a technique which we call resolution boosting or

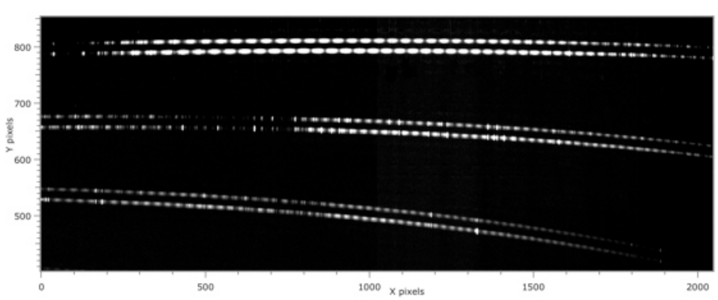

Fig. 3. Three out of five orders of the TripleSpec echelle spectrum for star GJ_338A are shown, using a small (0.3 cm) delay so that the interferometer comb period is easily resolvable, for demonstration and alignment. Much larger delays (up to 4.6 cm) are used during data-taking to create finer combs, having a period similar to the stellar features of interest. Those combs are unresolvable, but the moire patterns they create by being heterodyned against the stellar spectrum are resolvable. The moire pattern is the desired data product. The shift in moire phase yields the Doppler radial velocity (for detection of exoplanets). The shape of the moire pattern vs dispersion is Fourier processed and combined with others taken at a series of delays to yield a spectral reconstruction.

spectral reconstruction (SR). We have demonstrated a six-fold increase in the effective resolution (to R=16,000 at 7500 cm-1) observing star HD219134, looking at both stellar, telluric and ThAr calibration lamp features. This was done using only 5 of the 8 available delays values, up to 2 cm optical path difference (OPD). By expanding the contiguous delay series we anticipate R~30,000.

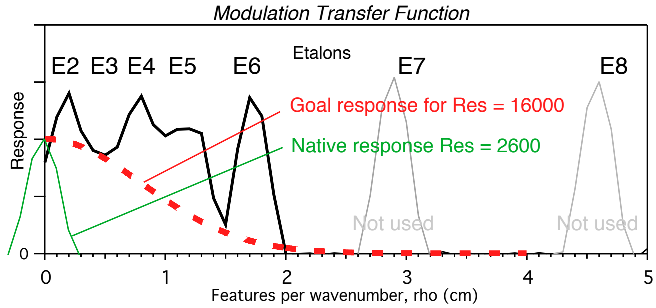

Fig. 4. Modulation transfer function (MTF) for the interferometer-spectrograph system. This is the Fourier transform of the overall instrument lineshape. The spectrograph alone has the MTF of the green peak centered at the origin, whose width is proportional to its spectral resolution, in this case 2600. Including the interferometer causes a new peak to appear (black or gray peaks) having same width but centered at the interferometer delay. By using a series of delays of values (E2-E6) which are contiguous, a conglomerated MTF is formed which is much wider. After equalizing to produce an ideal Gaussian shape (red dash), an effective resolution of 16,000 can be achieved (at the wavenumber 7450 cm-1). By expanding the delay series (different choices for delays E1, E7, E8) we anticipate achieving resolution of 30,000.

Figure 1 shows reconstructed spectra (red curves), assembled via Fourier processing from sets of phase-stepped data similar to that in Fig. 3 (but with much higher delay), using 5 delays (E2-E6) shown in Fig. 4. Note the much greater number of resolved features in Fig. 1 red curve compared to the native spectrum (green curves). The resolution boost occurs over the entire original bandwidth (0.9-2.4 µm) but is proportional to (max. delay/ wavelength).

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