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Moiré Effect Provides 10x Spectral Resolution Boost on Mt. Palomar NIR Triplespec Spectrograph

David J. Erskine
Lawrence Livermore National Lab., 7000 East Ave, Livermore, CA 94550
925-422-9545, erskine1@llnl.gov

Jerry Edelstein, E. Wishnow, M. Sirk, E. McDonald, Y. Ishikawa, and W. Shourt
Space Sciences Lab., 7 Gauss Way, Berkeley, CA 94720
510-642-0599, jerrye@ssl.berkeley.edu

Abstract: We demonstrate a 10x boost in spectral resolution on the NIR Triplespec spectrograph at Mt. Palomar using a moire effect created by an interferometer, reversing the heterodyning numerically, and assembling information from multiple exposures.

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

1. Introduction

Externally dispersed interferometry (EDI) is a technique [1-4], using a series combination of a interferometer with a disperser, and has applications in the Doppler planet search (Doppler radial velocimetry) [1,2,6,11], and high resolution spectroscopy [1,3-5], used in many sciences to identify atomic or molecular species and abundances. It has the ability to dramatically increase the effective resolution of an existing dispersive spectrograph by large factors beyond the classical limits imposed by lens blur, slit blur, and Nyquist pixel spacing, at full simultaneous bandwidth. We demonstrate a 10x boosting at the Triplespec NIR spectrograph at Mt. Palomar 5-meter telescope (Fig. 1). We measure over four orders of the native echelle spectrograph, 4000 to 10,500 cm^{-1}.

The EDI is based on a moire effect, also call heterodyning, which occurs between a sinusoidal transmission function created by the interferometer in the dispersion direction, with the input spectrum (Fig. 2). The sinusoidal period is set by the interferometer delay, which is changed in a sequence of exposures among several fixed values, typically 1 to 5 cm. Larger delays produce finer combs. Each moire pattern is most sensitive to spectral features having similar size as the comb periodicity. The moire patterns are Fourier processed and combined to reconstruct the intrinsic spectrum to a higher resolution than the native spectrograph by large factors (4 to 10 have already been demonstrated, and larger is anticipated). Figures 3 and 4 are example output spectra. The maximum resolution is proportional to how many average wavelengths fit into the maximum delay used. Delays up to 10 cm could therefore produce visible light resolutions of order 200,000, independent of the native spectrograph resolution (here it is 3000).

The instrument lineshape stability is also greatly increased, moving the responsibility of precision wavelength measurement to the interferometer, which has only three degrees of freedom, compared to the dispersive spectrograph which has orders of magnitude more and therefore suffers from complicate lineshape distortion from environmental drifts. Having an extremely well controlled instrument lineshape is a necessary and usually the dominating factor (rather than photon limited noise) in detecting small exoplanets in the Doppler planet search.

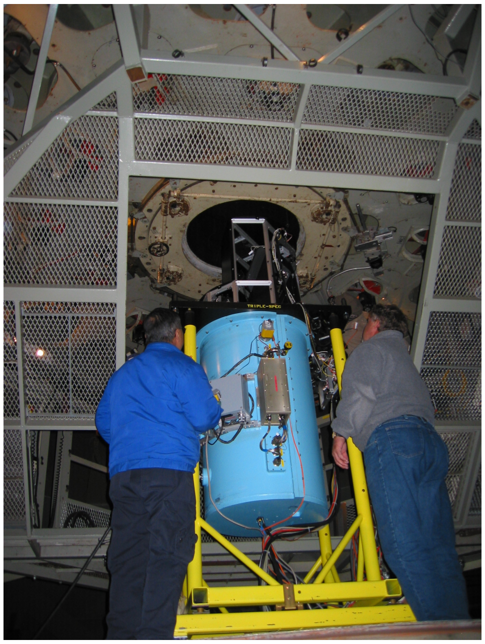

Fig. 1. The TEDI interferometer sits in the silver and black framework atop the blue cryogenic cylinder which houses the TripleSpec spectrograph, which is bolted to the 5-meter Mt. Palomar telescope at the Cassegrain output. The TEDI unit captures the starlight, passes it through the interferometer to imprint a sinusoidal spectrum, then re-injects it to the spectrograph with the original beam f/# and focus location.

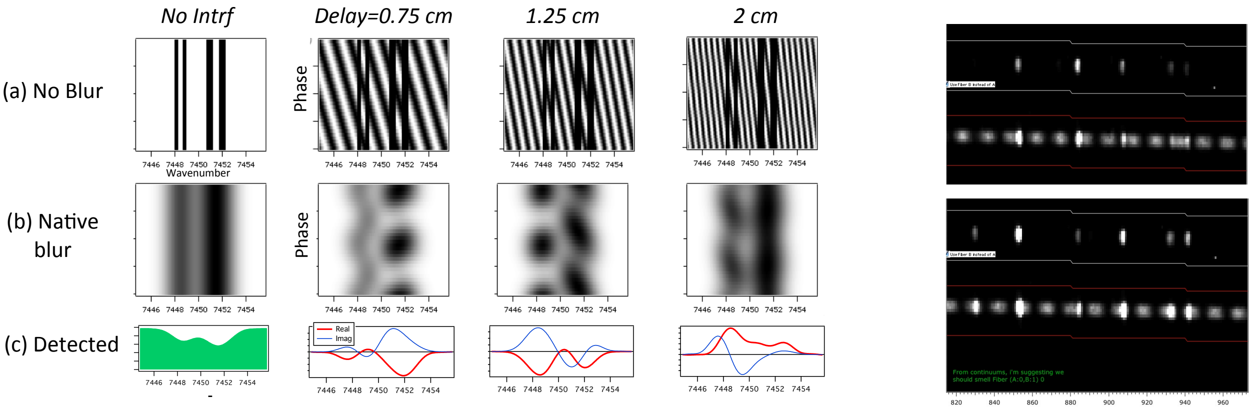

Fig. 2. (Left) Graphical illustration of a moire effect, using a hypothetical input spectrum consisting of two line pairs of different spacing. (a) Without blur, (b) with blur. Three different sinusoidal periods are shown-- larger interferometer delays create higher spatial frequency combs. The moire pattern is most sensitive to features having similar width to comb period. (This process also called heterodyning.) (c) Using several phase stepped exposures the fringing component of the moire is detected as real (red) and imaginary (blue) and the nonfringing component as green (nonfringing is same for all three delays). During Fourier postprocessing the heterodyning process is reversed to reconstruct the intrinsic spectrum by combining information from the several moire patterns. The effective resolution is set by the highest delay used, and can vastly exceed the resolution and Nyquist pixel spacing limit of the native spectrograph.
(Right) Stellar data in two exposures having different interferometer phase, showing one of four spectral orders, and for each order a ThAr calibration lamp is recorded slightly above the starlight (which also has ThAr). Note how the intensity of the ThAr lines changes because of phase shift of sinusoidal interferometer transmission. The stellar signal shows the sinusoidal comb because it has a continuum component.

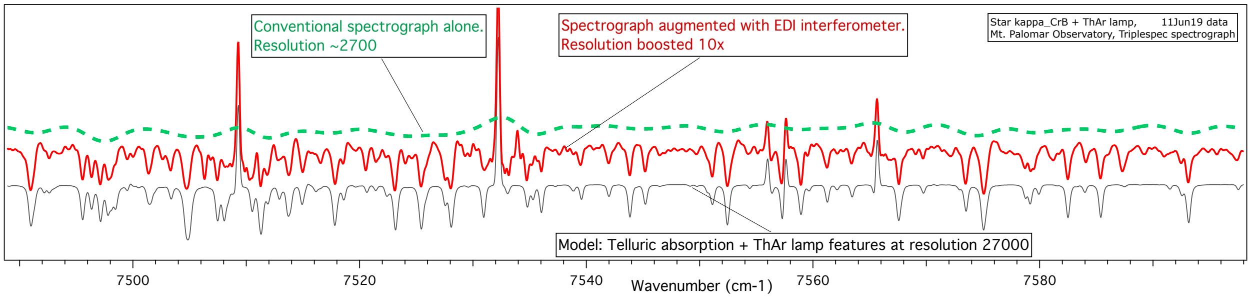

Fig. 3. Demonstration of a 10-fold boost in resolution observing telluric features mixed into spectrum of star kappa CrB on June 19, 2011, along with ThAr calibration lamp emission lines. The green dashed (top) curve is the native ordinary spectrum measured without interference, having resolution 2,700. It cannot resolve any of the telluric features. The red (middle) curve is the EDI reconstructed spectrum measured with 7 contiguous delays, up to 3 cm, and equalized to a Gaussian resolution of 27,000. The gray (bottom) curve is a model of telluric [12], and ThAr [10], features blurred to res of 27,000, showing excellent agreement with EDI data.

The EDI is a hybrid technique that combines the best features of dispersive and interferometric methods of spectroscopy. Compared to purely dispersive spectroscopy, the EDI 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. Compared to purely interferometric spectroscopy (i.e. Fourier Transform Spectroscopy, FTS), the inclusion of a disperser improves the photon limited signal to noise ratio by a factor of ~100 (square root of number of independent spectral channels [7]), allowing practical use on faint astronomical targets. Otherwise FTS is usually too insensitive for stellar astronomy. The EDI technique is mathematically related to dispersed-FTS [8], but uses finer spectral channels, and uses a smaller number (1-10) of discrete fixed delays instead of scanning semi-continuously over a delay range. However, all dispersed interferometer hybrids will enjoy improved photon limited signal to noise ratio over an undispersed interferometer.

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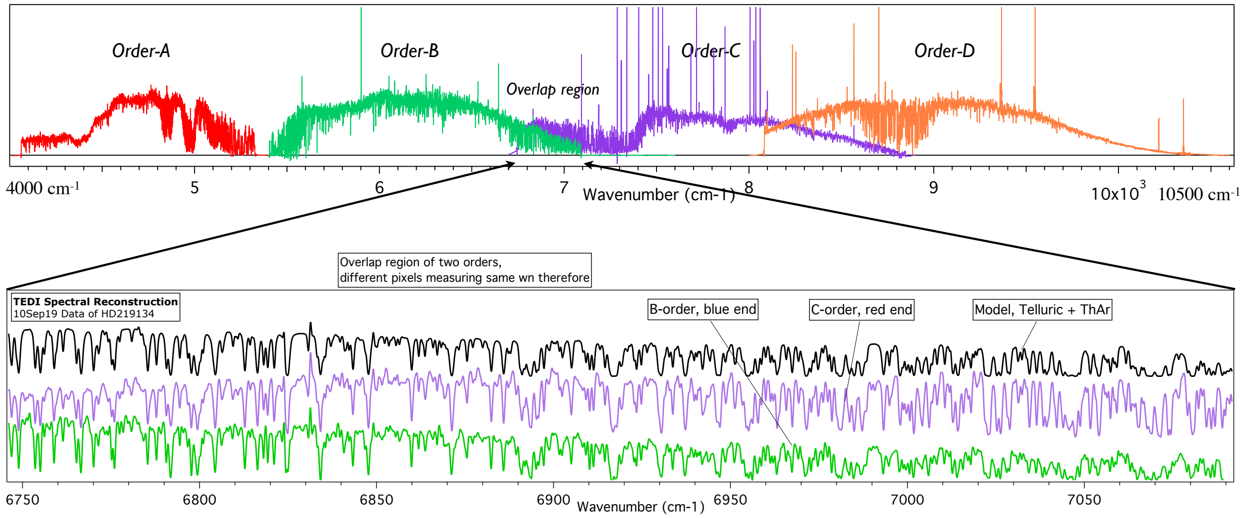

Fig. 4. Reconstructed spectra over 4 orders of spectrograph produce a very wide bandwidth in the near IR, using the TEDI interferometer combined with the Triplespec spectrograph at the Mt. Palomar Observatory 200 inch telescope, here observing HD219134 on Sep 19, 2010. The native spectrograph resolution of ~2700 is boosted by a factor of 6x to 10x or more by the use of multiple delays and combining exposures after Fourier processing. The lower graph is zoomed in region of overlapping orders B & C, showing agreement between each other and with telluric model (black) [12].

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