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Measuring Precision Wideband Stellar Spectra using a Dispersed Interferometer

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Abstract: We demonstrate an interferometric method for increasing a dispersive spectrograph's resolution by large factors beyond classical limits at full simultaneous bandwidth, on the Triplespec near-infrared spectrograph on Mt. Palomar's 200 inch telescope.
OCIS codes: (300.6300) Spectroscopy, Fourier Transform; (300.6310) Spectroscopy, Heterodyne; (300.632) Spectroscopy, High Resolution

1. Introduction

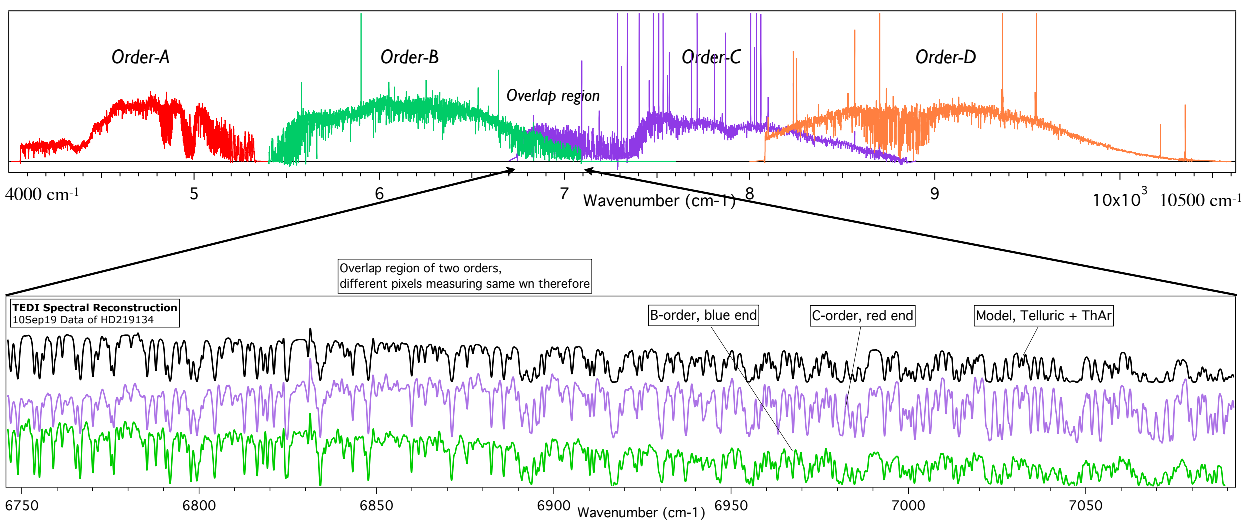

Fig. 1. Reconstructed spectra over 4 orders of spectrograph produce a very wide bandwidth in the near IR, using the TEDI interferometer combined with the Triplespec spectrograph at the Mt. Palomar Observatory 200 inch telescope, here observing HD219134 on Sep 19, 2010. The native spectrograph resolution 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].

Externally dispersed interferometry (EDI) is a technique [1-4] using a series combination of a interferometer with a disperser, and has applications in both Doppler radial velocimetry [1,2,6,11], and high resolution spectroscopy [1,3-5]. It is a hybrid between purely interferometric (FTS) and purely dispersive techniques, and combines advantages of both. For Doppler velocimetry a single fixed delay is used. For spectroscopy a sequence of delays, of order a few to 10, are used to sample Fourier space (delay space) contiguously up to a maximum delay, where each delay samples Fourier space in region of width ~R_{native}/wn, where R_{native} is the resolving power ($R=\lambda/\Delta\lambda$) of the native spectrograph and wn is wavenumber $1/\lambda$.

In a conventional dispersive spectrograph, the bandwidth (BW) is approximately inversely related to the resolving power, since the information must be spread across a finite number of resolution elements ($\#=\text{BW}/\Delta\lambda$) in the detector array, and this number is limited to about 1/2 to 1/3 the number of pixels to avoid Nyquist sampling artifacts. However in the EDI, the bandwidth-resolving power product can be arbitrarily higher. The bandwidth is set by the native spectrograph, and this can be very wide when the native resolution is low. The final spectral resolution is set by the highest contiguous delay used ($R \sim delay_{max} * wn$), and this can be arbitrarily high when the user takes a large sequence of exposures of different delays.

Hence the bandwidth-resolving power product and the number of effective resolution elements can be arbitrarily higher than with the native spectrograph alone. (The Palomar data in Figs. 1 & 2 produces 6x to 10x boosting of native resolving power, depending on local wavenumber and maximum contiguous delay of either 2 cm for early measurements or 3 cm for later.) Since the wavelengths are accurately measured by a fringe shift of an interferometer, which has fewer degrees of freedom and can be environmentally isolated more easily than a

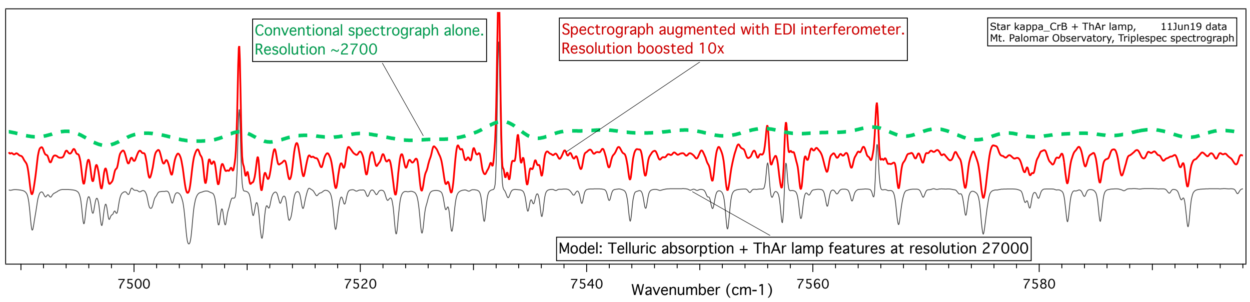

Fig. 2. Demonstration of a 10-fold boost in resolution observing telluric features mixed into spectrum of star kappa CrB on June 19, 2011, along with ThAr calibration lamp emission lines. The green dashed (top) curve is the "ordinary" spectrum measured without interference, having native resolution 2,700. It cannot resolve any of the telluric features. The red (middle) curve is the TEDI 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. (A recently purchased 2.4 cm delay "E6.5" filled the gap between E6 and E7 allowing inclusion of E7 bringing max delay to 3 cm, compared to data of Fig. 1 having 2 cm max delay.)

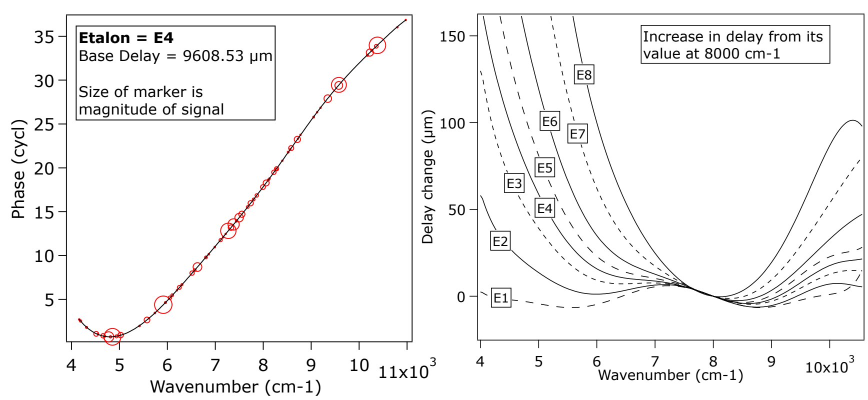

Fig. 3. The dispersion characteristics of set of glass etalons are calibrated over a 4000-11000 cm^{-1} bandwidth by phase shift comparison with ThAr emission line model [10]. The resulting phase vs wavenumber curve, taken with a specific base delay value, is then used to "untwist" stellar fringing spectra so that a constant delay (the base value) can be used during reversal of heterodyning effect, in the processing prior to summing the individual channels to assemble the reconstructed spectra. The derivative of a 10th order polynomial fit to the phase data provides a delay vs wavenumber curve (right graph). The delay curves are not needed for the spectral reconstruction, only the phase curves. But plotting the family of delay curves is useful for detecting an integer fringe skip error in the phase shift measurement, which manifests an unusual deviation in the delay compared to its family members. The dispersion characteristic of beamsplitter substrate (most obvious in the smallest delay E1) is a component of each measurement. Nominal delay values are 0.1, 0.3, 0.7, 1, 1.3, 1.7, 3 and 4.6 cm.

spectrograph due to its smaller size, this precision is decoupled from the number of detector pixels, the spectrograph irregularities in focal blur or pupil variation.

Some proposed configurations of EDI can measure many different delays simultaneously (assigning different portions of the slit to different steps of a staircase-like delay), allowing snapshot recordings of instantaneous events. This addresses a weakness of a scanning delay FTS, in observing transient or time-dependent phenomenon.

From the dispersive spectroscopist point of view, 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. 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 number of 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 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.)

We describe field tests of the TEDI interferometer at the 200 inch Mt. Palomar telescope, which is at the Cassegrain output in series with the near-infrared (0.9-2.4 μm) Triplespec [9] spectrograph (R~2,700). Raw fringing spectra were taken by Phil Muirhead et al. during observations whose primary purpose was to demonstrate stellar Doppler velocimetry[6], and hence emphasized using a single 4.5 cm delay "E8" rather than a set of delays. For some stars which were recorded with multiple delays, we have demonstrated a 6-fold to 10-fold increase in the effective resolution (Figs. 1 & 2), depending on the maximum delay that produces a contiguous set, which was limited to either 2 cm for early data and 3 cm for later data. (We have a gap in available delays between 3 and 4.5 cm which prevents us from including the 4.5 cm data without producing non-Gaussian final lineshape.) We used ThAr emission lines and Kerber's wavelength measurements[10] to calibrate the phase shift vs wavenumber for each glass etalon (Fig. 3), to remove the dispersive effects of the glass.

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