Improving crowded-field multiple target Doppler sensitivity with an interferometer addition to a slitless imaging spectrograph

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Ersatz proceedings for poster "sciencesconf.org:749664" to Habitable Worlds Observatory (HWO2026) conference, 30 Nov. - 4 Dec, 2026, Paris, France.
Technology & instrumentation - Instrument studies

Abstract. We explore potential benefits of inserting a small Michelson interferometer into the beam of a slitless imaging spectrograph, especially those having a severe constraint on size and mass such as in a space telescope. A 10x reduction of disperser resolution is enabled by use of EDI while meeting Doppler signal/noise or resolution goals. This can lead to 1000x reduction in a linear grating spectrograph volume, and commensurately high reduction in instrument mass. The EDI advantages stem from the heterodyning that produces moire patterns. We are also interested in expanding the usage of dispersed interferometry from single sources to multiple sources in an imaging mode.

Keywords: High resolution spectroscopy, Resolution Boosting, Exoplanets, Doppler radial velocimetry, Externally Dispersed Interferometry .

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1 References: Externally Dispersed Interferometry

We introduce externally dispersed interferometry (EDI)[1–13] as a solution to increasing the resolution of any spectrograph, by placing a fixed delay interferometer into the native spectrograph beam. This technology has been demonstrated on other linear and echelle spectrographs in the visible and near infrared. We conjecture that it would be advantageous to include an interferometer filter in a spaceborne spectrograph.

EDI can measure Doppler velocities[1,2,7,8] with a much smaller native resolution spectrograph than otherwise practical. The EDI technique has been used by other researchers to discover exoplanets[14,15] around HD102195 and HD87646, as well as confirmation of 51 Peg.[16]

EDI can boost the spectral resolution[3,4,9,10,12,13] of a spectrograph by a factor of several to an order of magnitude. The maximum resolution is limited only by the highest delay of a contiguous range of delays used. It uses staring style of data collection familiar to astronomers observing weak sources, not using a scanning delay such as in a Fourier Transform Spectrometer (FTS).

1.1 Monolithic interferometer references

Reference 17 from 1995 describes using monolithic interferometers (photo in Fig. 8) used to measure solar photospheric Doppler oscillations in a Michelson Doppler Imager.

References 18–21 from 2008-12 describe thermally stable monolithic interferometers constructed advantageously using two glasses (BK7 and LAK7) having different thermal responses

to cancel net drift.[22] These stable monolithic interferometers have been used as an EDI[23] to measure Doppler velocities, and in a white light illuminated calibration source in MARVELS (Multi-object Apache Point Observatory Radial Velocity Exoplanet Large-area Survey of Sloan Digital Sky Survey).[24]

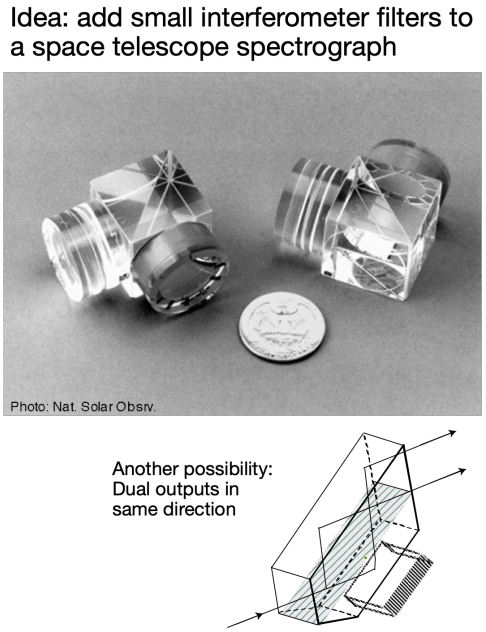


Fig 1 (FigD1) Idea: add small monolithic interferometer filters[17–21] to a space telescope spectrograph, and explore the benefits. For the design shown in the photograph, based on a beamsplitting cube, one output emerges 90 degrees to the input (which is easy to access), and a complementary output returns almost 180 degrees back toward the source (which is more difficult to access). A possible solution[5] to this awkwardness is the prism shown in drawing which directs both main and complementary outputs in the same direction, while displaced from each other.

2 Summary/Synopsis

We conjecture benefits of inserting a small Michelson interferometer into the beam of a slitless imaging spectrograph (Figs. 1-8), especially those having a severe constraint on size and mass such as in a space telescope. Figures 8 & 11 show that a 10x reduction of disperser resolution is enabled by use of EDI while meeting Doppler signal/noise or resolution goals. This can lead to 1000x reduction in a linear grating spectrograph volume, and commensurately high reduction in instrument mass. The EDI advantages stem from the heterodyning that produces moire patterns (Figs. 6, 7, 9, 10). We are also interested in expanding the usage of dispersed interferometry from single sources to multiple sources in an imaging mode (Figs. 2, 4, 12, 14).

Acknowledgments

We are shocked by the untimely passing of Professor James Lloyd (Cornell University), who was a key instigator of the TEDI project at Mt. Palomar Observatory that produced data and shaped ideas in this paper. He will be greatly missed. Thanks to recent help from UC Berkeley colleague Micah Allard. This material is based upon previous work supported by the National Science

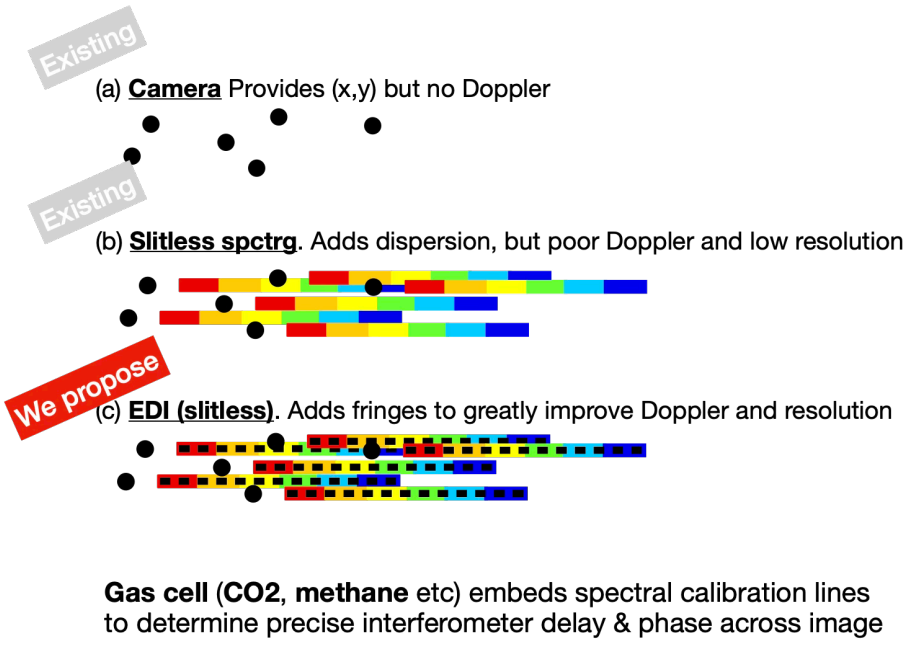


Fig 2 (FigD2) Cartoon. Rainbows represent dispersed order which is actually far displaced from undispersed order and thus probably does not fall on same detector chip. Horizontal dashes represent fringes in uniphase mode. (a) Camera: which provides (x,y) imaging of sources, but no Doppler information. (b) Slitless spectrograph: which we obtain from the camera by adding dispersion. This only has low resolution and thus poor Doppler signal. (c) Our proposal is a slitless EDI, which is obtained from (b) by adding an interferometer filter. A gas cell also inserted into the beam with CO_2, methane etc. could provide near infrared reference absorption lines that are independent of pathlength through instrument.

Foundation under Grant No. AST-0505366, AST-096064, PAARE AST-1059158, NASA Grant NNX09AB38G, and portions under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

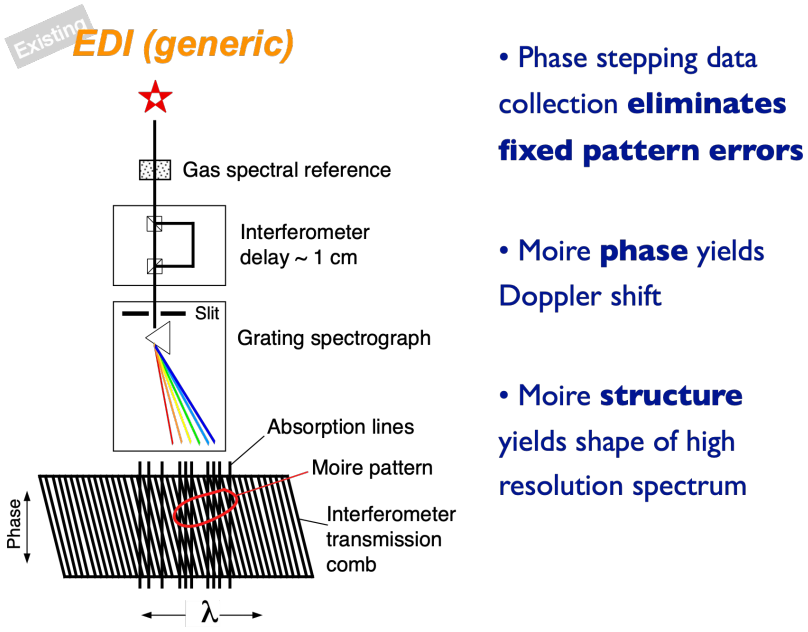


Fig 3 (FigD3) Generic EDI scheme using multiphase or phase-slanted[2] mode where interferometer phase varies linearly along a tall slit of a linear spectrograph, which is also convenient for displaying generation of moire patterns.

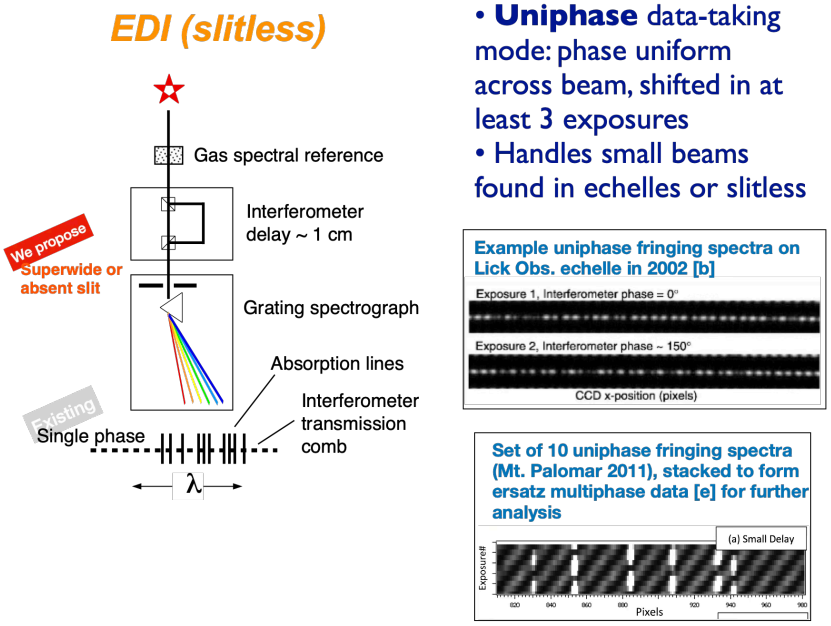


Fig 4 (FigD4) Uniphase mode of taking EDI data was demonstrated in 2002 at Lick Observatory Hamilton echelle spectrograph[3] and the TripleSpec NIR echelle spectrograph[25] on the Mt. Palomar Hale telescope in 2011.[8–10] In this mode, interferometer phase is uniform across the beam and incremented in at least three separate exposures (phase-stepping).

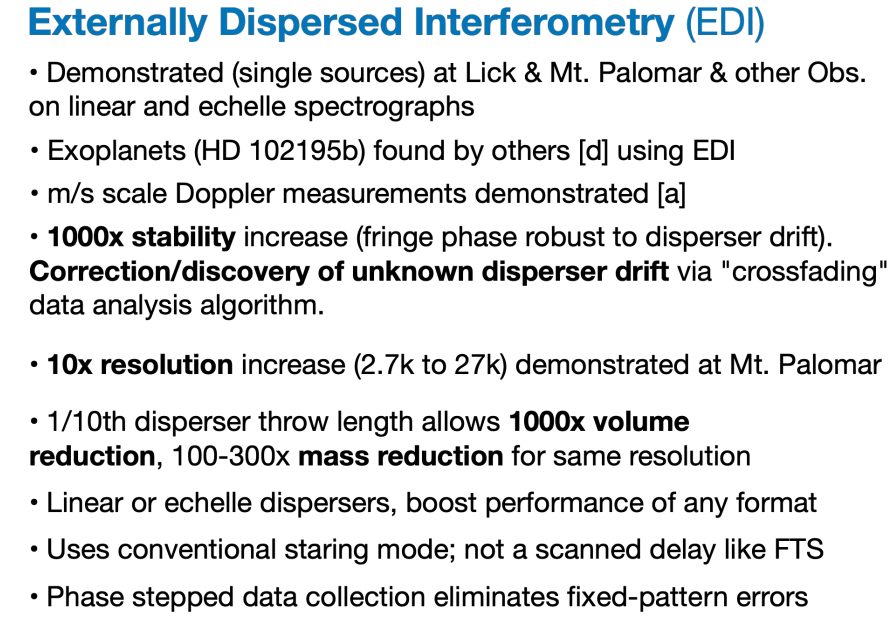


Fig 5 (FigD5) Externally dispersed interferometry (EDI)[23] has been demonstrated at Lick Obs. Hamilton echelle,[3] and Mt. Palomar Obs. Hale telescope[8–10] on TripleSpec NIR echelle[25] on starlight, as well as on linear grating spectrographs.[1,2,4,26] Exoplanets measured[16] and discovered[14,15] by others using EDI. Meter per sec scale Doppler reproducibility described in Ref. 1, 2. We have studied how fringing and nonfringing components respond differently to a disperser wavelength offset. By strategic weighting of fringing and nonfringing components during data analysis, using a "crossfading" algorithm, we can cancel the effect of an unknown wavelength offset, as well as discover its value. We have shown this for both multiple[12] and single delays.[13,27] A 10x resolution (2.7k to 27k) has been demonstrated on the Hale Telescope and TripleSpec NIR echelle spectrograph.[9] Such a resolution boost could allow for a 10x reduction in throw length (for a linear grating) while achieving the same net resolution (with a mild worsening of photon signal to noise). That could allow for a 1000x volume reduction and commensurately large mass reduction, useful for a spaceborne instrument. EDI uses familiar conventional staring mode to collect data with long time exposures for weak sources, unlike a Fourier Transform Spectrometer which scans the delay and requires high frequency readouts. Phase-stepped data collection eliminates detector bias and fixed pattern errors for the fringing signals (since only the portion changing synchronous to the phase stepping survives).

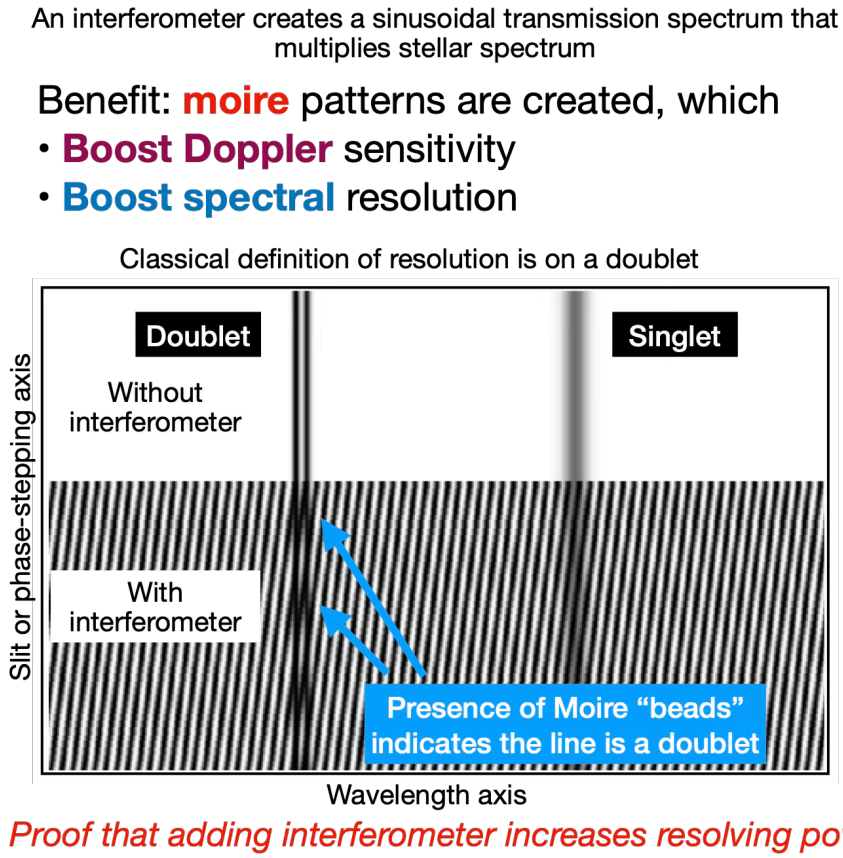


Fig 6 (FigD6) Graphical illustration of a moiré for the doublet (bottom of left feature), but not for the singlet (right feature), proves that including a periodic interferometer transmission comb in series with a disperser increases resolving power, since the classic definition of resolution is the ability to distinguish a doublet from a singlet. Without the interferometer comb (top portion) the two features would look similar when view from across the room. The two features were created to have equal net grayscale weight. Graphic is similar to Fig. 3 of Ref. 4.

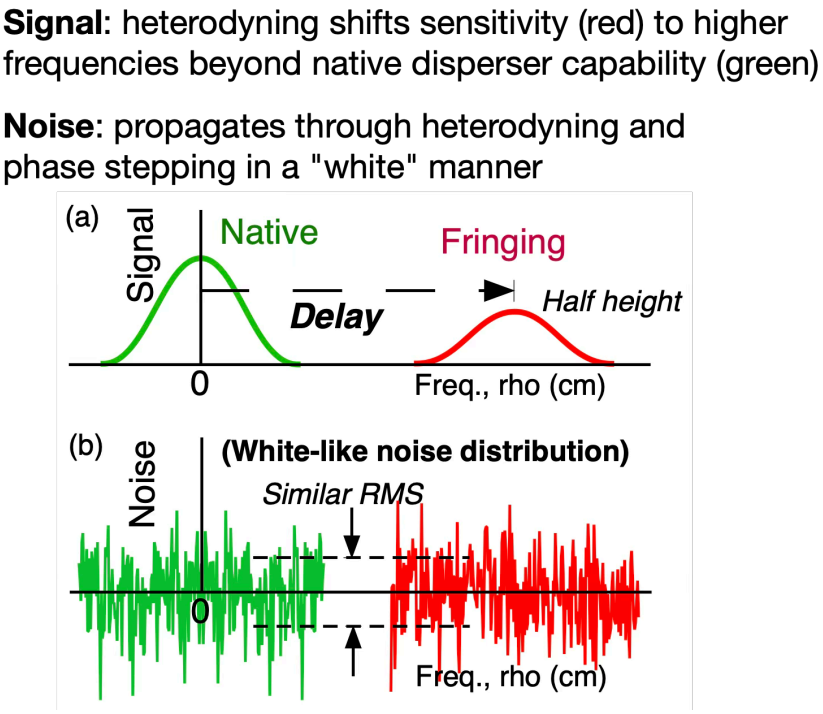


Fig 7 (FigD7) How photon and detector noises propagate through the EDI analysis is explored in Reference 10. It shows that the noise propagates in a white manner through the heterodyning and phase stepping, ie. the root mean square (RMS) noise is about the same for the fringing signal as for the native (conventional) spectrograph. The fringing signal is reduced by a factor of 2x compared to the native sensitivity peak, due to the heterodyning effect producing both a positive and negative frequency shift of the input spectrum when multiplied by the sinusoid interferometer transmission, but only one of these produces the low frequency detectable moire patterns. (Consider the 0.5 prefactor and the positive and negative arguments in the identity $\cos x = (0.5) * (e^{ix} + e^{-ix})$).

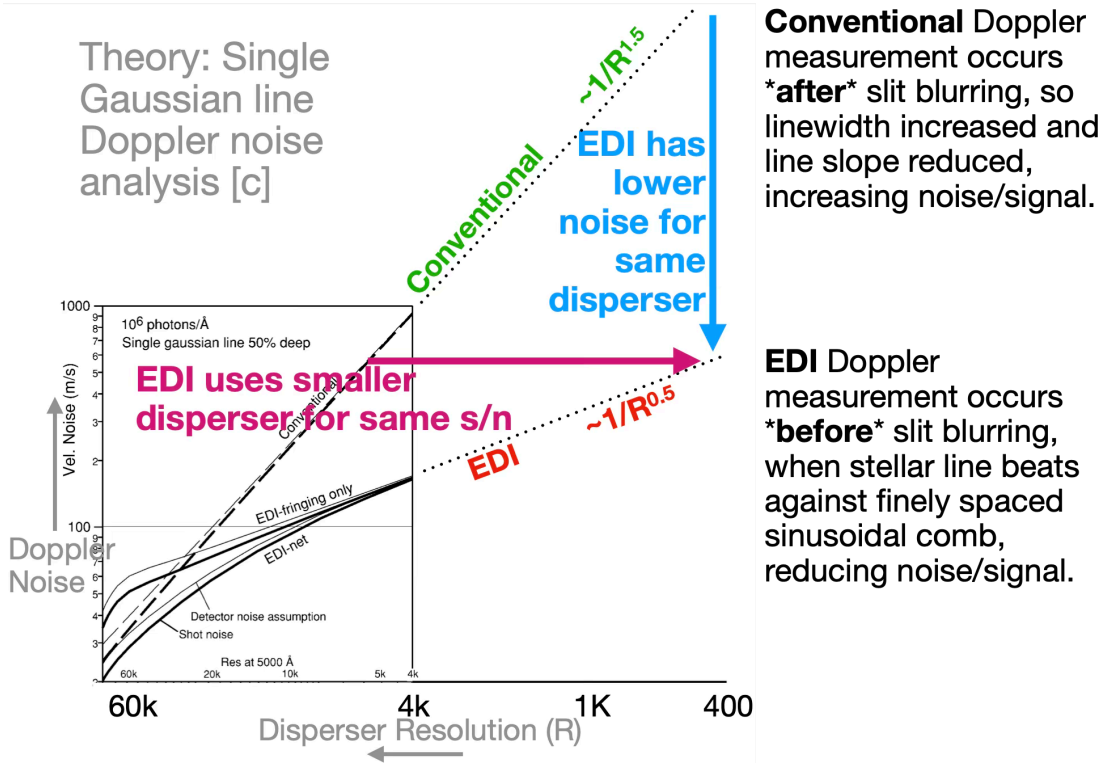


Fig 8 (FigD8) Calculation of Doppler noise measuring a single Gaussian line with EDI, and with conventional spectroscopy, is described in Reference 2. For the conventional, the Doppler measurement occurs after slit blurring where the linewidth is increased. Thus the slope of the sides of the line is smaller, and the signal to noise ratio is reduced (increasing the Doppler noise). For the EDI, the Doppler measurement occurs before slit blurring, when stellar line beats against the finely spaced sinusoidal comb produced by the interferometer. This reduces the Doppler noise.

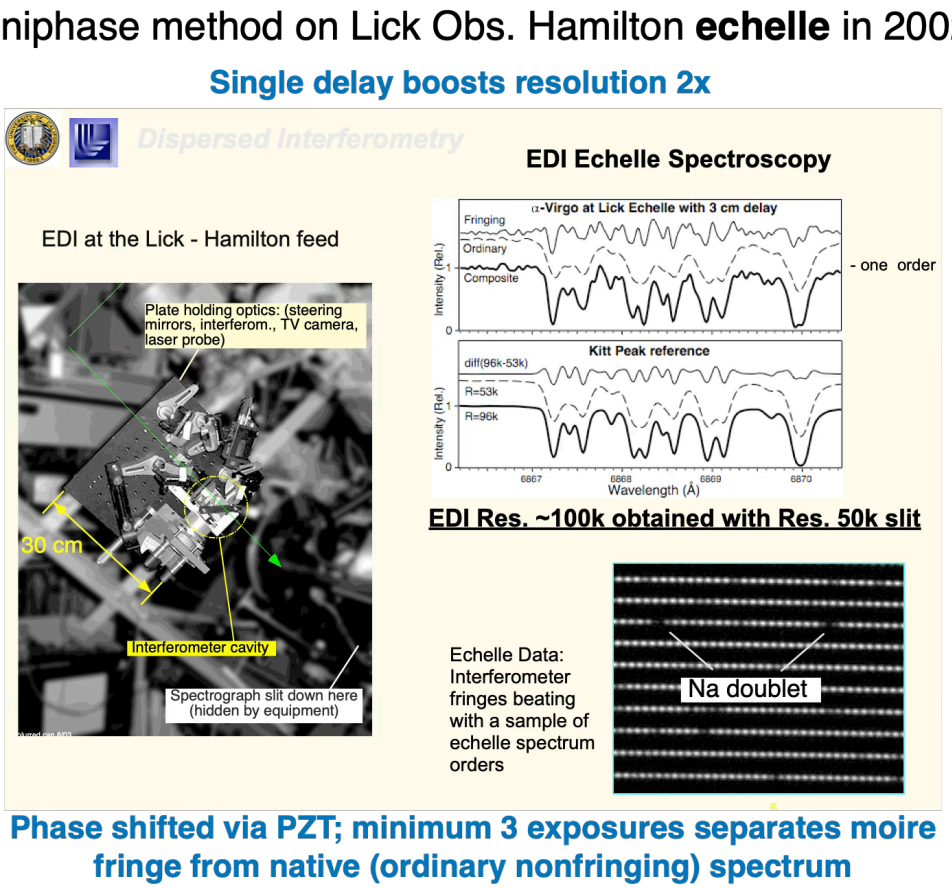


Fig 9 (FigD9) Demonstrations[3] of EDI 2x resolution boosting with a single 3 cm delay on the Lick. Obs. Hamilton echelle spectrograph.

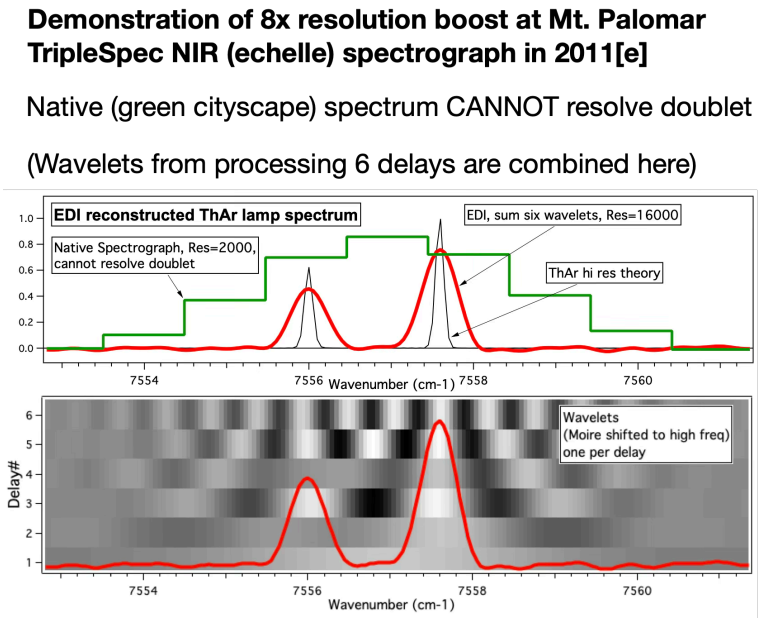


Fig 10 (FigD10) Demonstration[9] of 8x resolution boost at Mt. Palomar Observatory Hale telescope TripleSpec NIR (echelle) spectrograph[25] in 2011. Here the doublet of a ThAr spectral lamp is unresolved by the native disperser (green cityscape) having R ∼2000. Each of 6 delays used produce wavelets when the detected moiré are frequency upshifted through data analysis to their original frequencies (shifted by the interferometer delay values). The wavelets are summed and then equalized to minimize ringing, with a final resolution of 16,000. The maximum resolution is set by the highest available delay value. Purchase of more and longer delays, and filter wheels on which to mount them, would have enabled higher resolutions. By using fixed delays, rather than a scanning delay (as in a Fourier Transform Spectrograph), the data is taken in long exposures as conventionally done for weak starlight, minimizing detector readout noise.

Dramatically reduce spectrograph size & mass while maintaining resolution

10x EDI resolution boost allows 10x smaller disperser res (throw length of linear grating) to achieve same final resolution
—> 1000x volume reduction
—> mass reduction by 100 ~ 300x?

10x resolution boost (2.7k --> 27k) achieved at Mt. Palomar using multiple delays in 2011 [e]

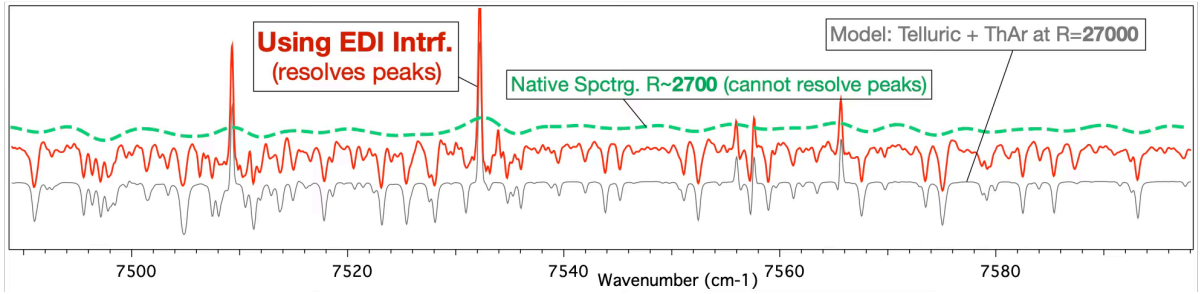


Fig 11 (FigD11) The native resolution of disperser (TripleSpec NIR spectrograph[25]) was R ~2700. The 10x resolution boost (2700 to 27000) is described in Reference 9.

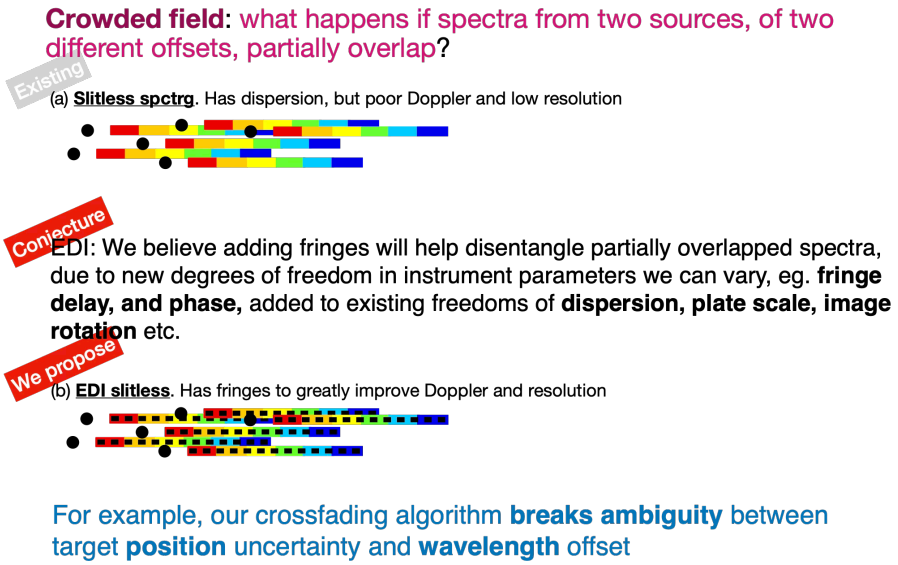


Fig 12 (FigD12) (a) Slitless spectrograph is formed from an imaging camera by adding dispersion. (b) A slitless EDI is formed from a slitless spectrograph by adding an interferometer in series with the spectrograph. The ambuiguity between target position and wavelength offset is broken by the crossfading algorithm, described in the next Figure.

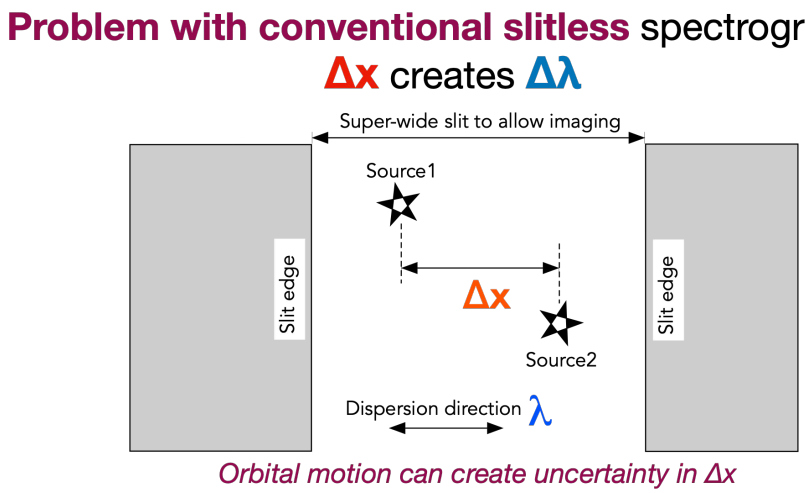


Fig 13 (FigD13) Crossfading data analysis algorithm[12,13] is a way of correcting for an unknown wavelength offset by summing fringing and nonfringing signals with strategically chosen weights, and the fringing signals have been filtered to eliminate signals having frequencies above the interferometer delay. (Fringing signal frequencies below the delay react to a disperser wavelength offset in opposite phase shift to the nonfringing signals, producing a cancellation if the weights are chosen wisely.) Once the corrected spectrum has been obtained, comparison to the conventional uncorrected spectrum discovers the value of the wavelength offset.

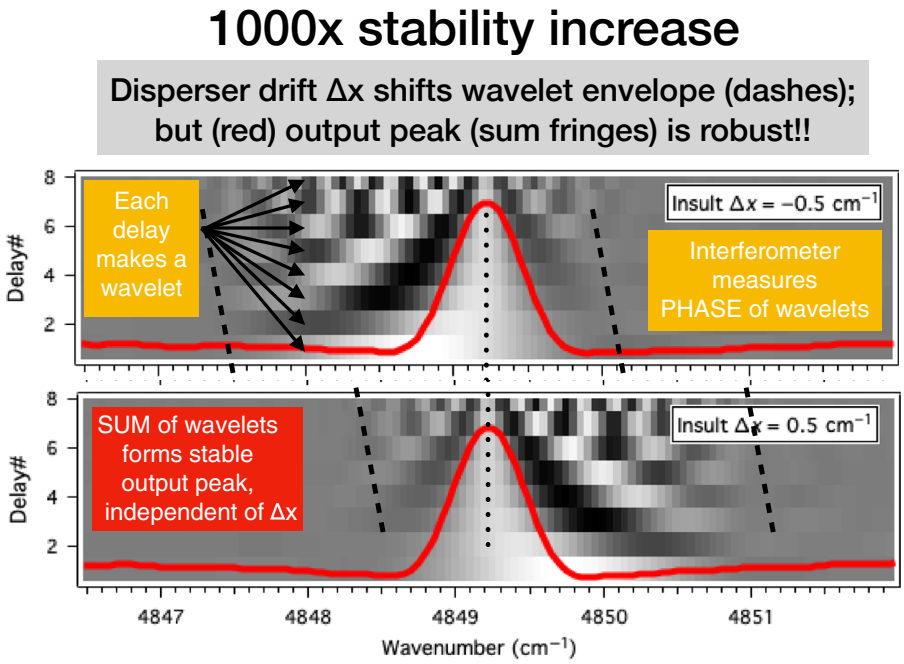


Fig 14 (FigD14) Crossfading simulation.[12,13] Note that sum of wavelets (red peak) has same position in output wavenumber space, even though native disperser shifted by Δx of 1 cm^{-1}. Takeaway: fringes can be very robust to wavelength offsets. Disperser used alone is not– it is directly linked 1 on 1 to Δx.

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David J Erskine, orcid.org/0000-0002-7094-458X , received his PhD from Cornell in 1984. He retired in October 2024 from a career as an experimental physicist at Lawrence Livermore National Laboratory with experience in femtosecond lasers, semiconductor physics, superconductivity, diamond anvil cell high pressure physics, shock physics, high speed recording techniques, Doppler interferometry, white light interferometry, digital holography, Fourier signal processing, image reconstruction, and phase stepping algorithms for interferogram analysis. He continues to collaborate with astronomers on interferometric techniques for the Doppler planet search and high-resolution spectroscopy. He is a member of SPIE.

Biographies for the other authors are not available.

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