A 1000x Stabler Spectrograph using an Interferometer with Crossfaded Delays

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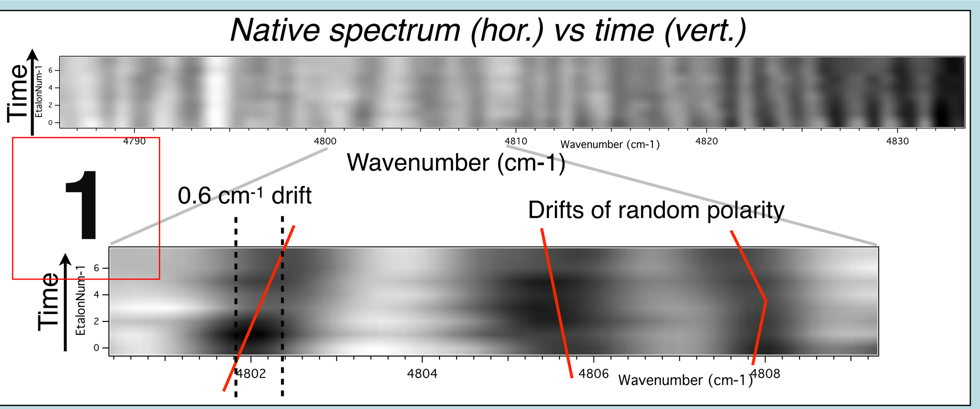
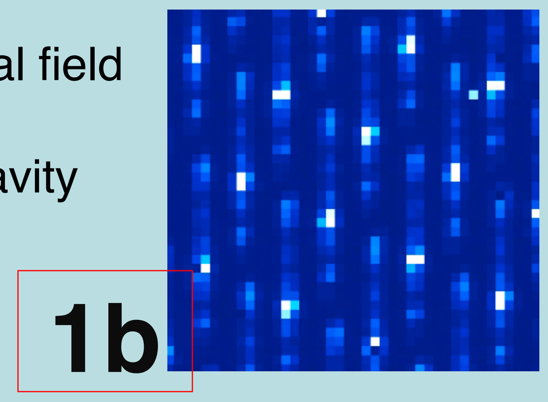
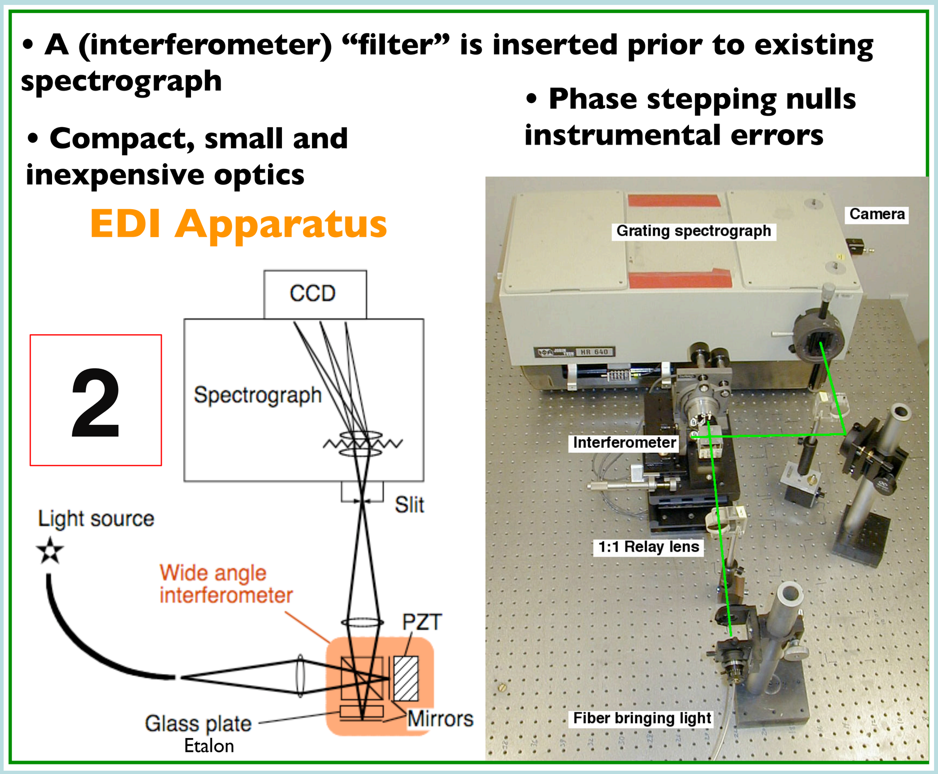


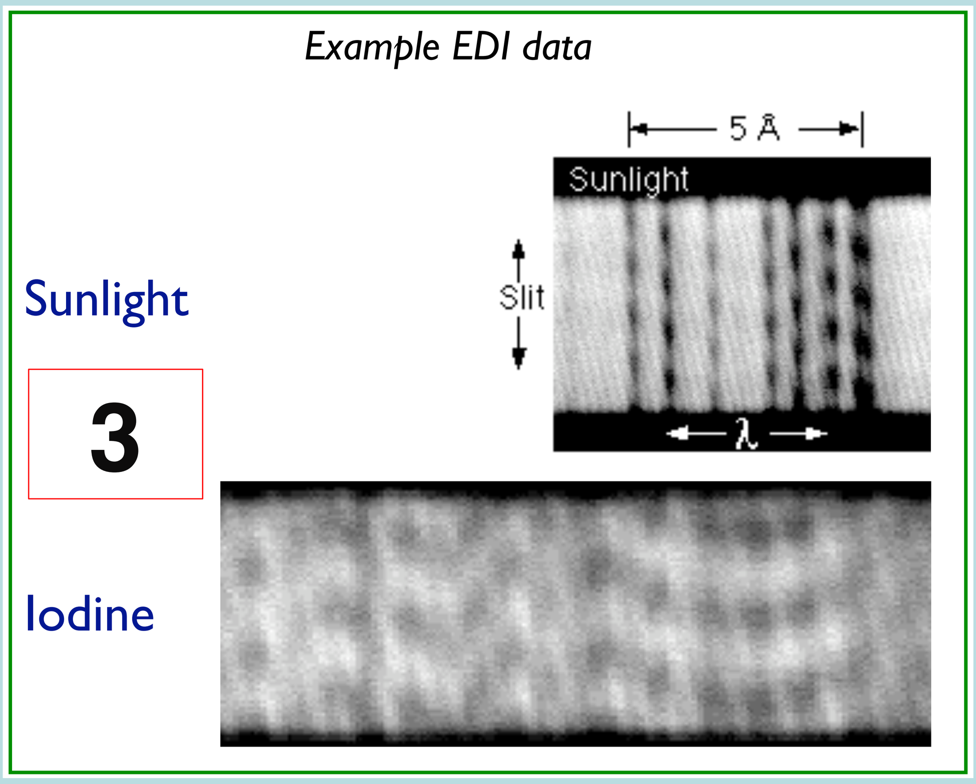
1. A PROBLEM: PSF DRIFT
A chief limitation to Doppler radial velocity precision is irregular drift of the spectrograph focal spot point spread function (PSF). Here is drift of Mt. Palomar Hale telescope echelle NIR Triplespec vs time (vertical). Note nasty random polarity and magnitude of drift vs position along dispersion axis.

1b. Another PROBLEM: **PSF Drift on IFS**
The Gemini Planet Imager uses a very low resolution (50-100) integral field spectrograph (IFS), spread over very sparse pixels, to characterize exoplanets. There are significant (~1 pixel) drifts due to changing gravity vector.



2. **A SOLUTION: Externally Dispersed Interferometry (EDI)**[1]
Use a passive spectral comb produced by passing starlight through a small Michelson interferometer. The instrument was assembled from off the shelf components. No environmental controls were used for this test version, and yet it was able to reach 0.76 m/s precision over 20 min and 2 m/s over 11 days comparing bromine to iodine spectra. An exoplanet around HD102195 was found[2] in 2005 by other researchers using this technique.

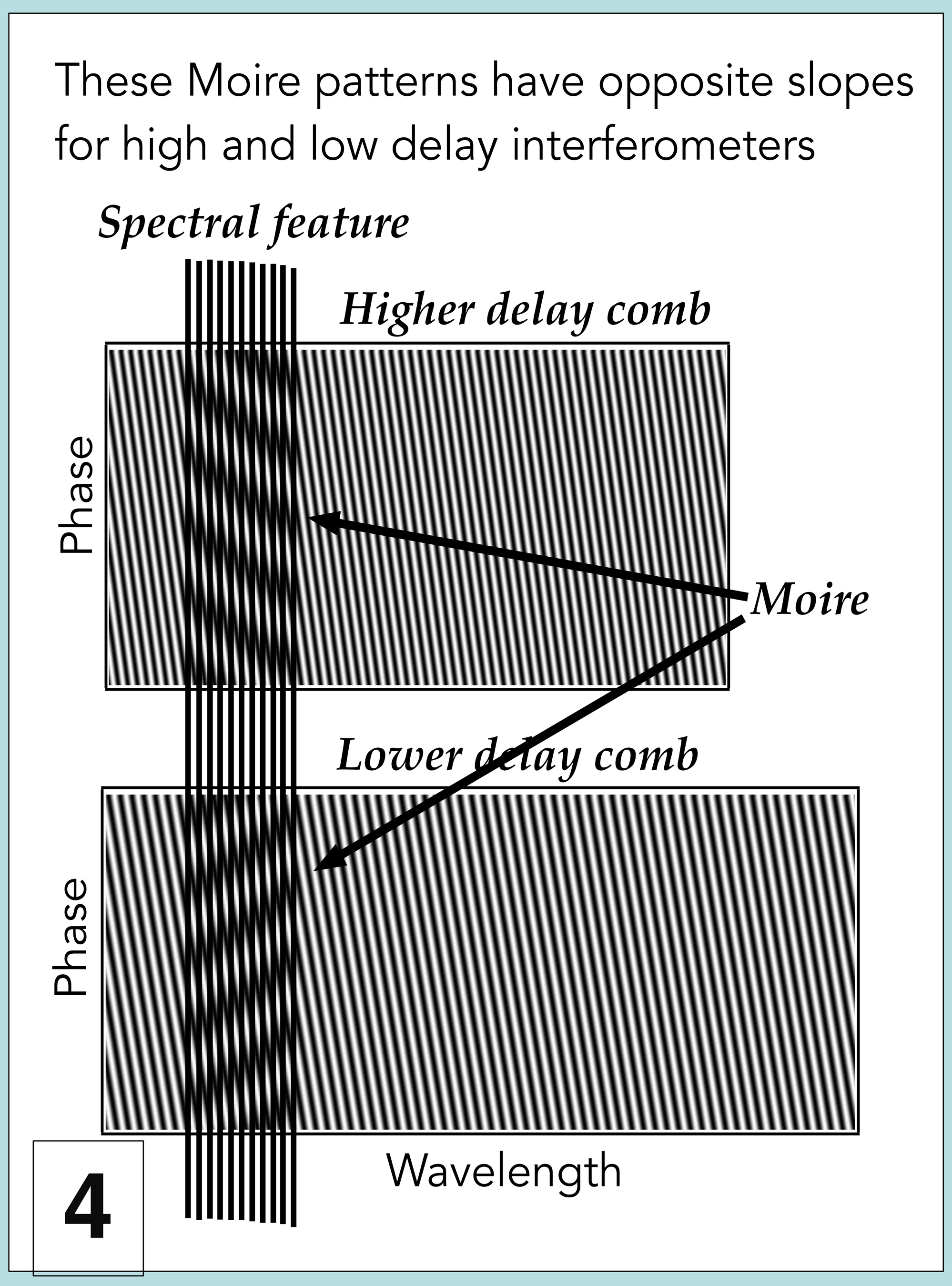


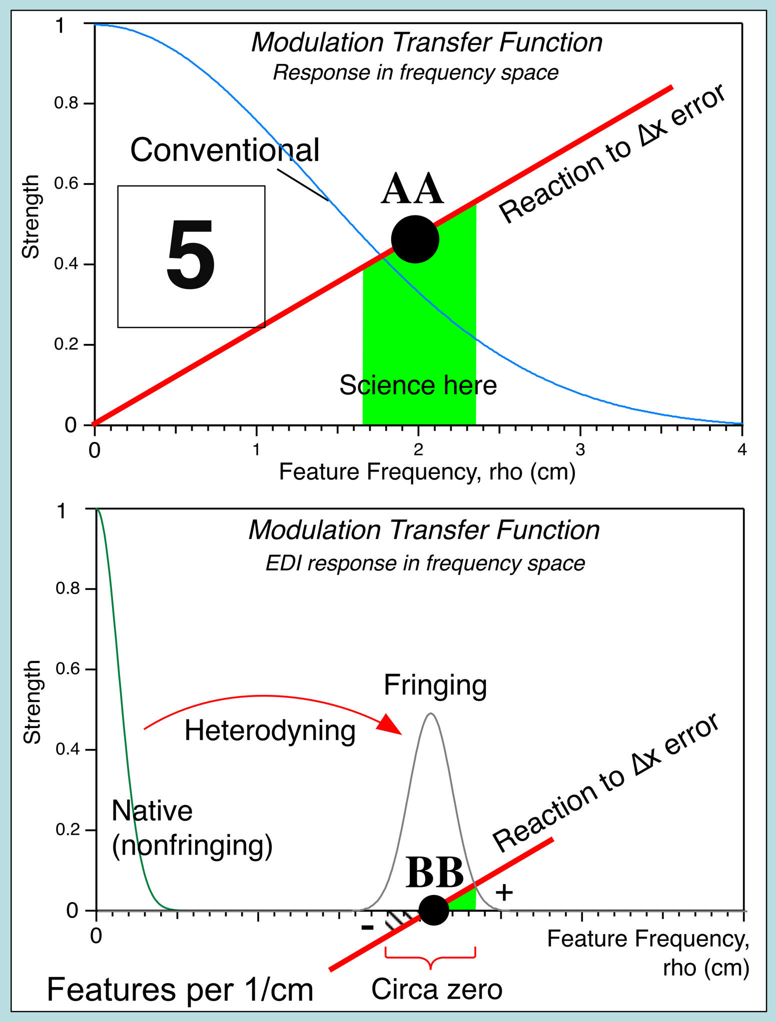


3. **Example DATA**
Solar and iodine spectra data show MOIRE patterns created by sinusoidal grid overlaying spectral features. Doppler velocity is relative phase shift of solar moire to iodine moire (changes in temperature/pressure of interferometer effect solar and iodine phases equally, so cancel). EDI has also been used on Lick Obs. and Mt. Palomar Obs. echelle spectrographs[1] using only 1 pixel high beams and phase stepping vs time.

-- NEW IDEA --

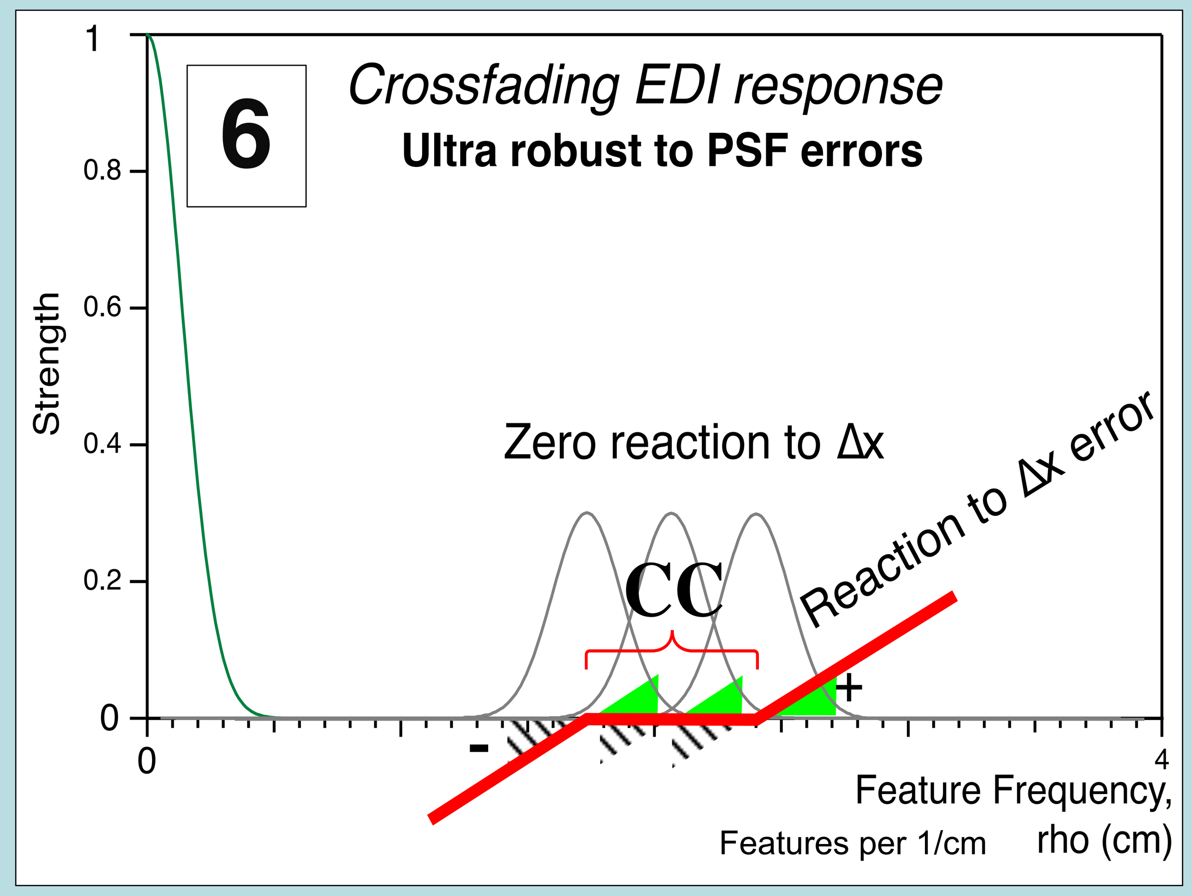
4. **NEW IDEA: CROSSFADING**
Use *PAIRS* of delays, that are only slightly different (called "Crossfading"). A spectral feature can produce opposite sloping moire patterns. These react oppositely to an uncontrolled wavelength drift and cancel in analysis, producing perfect stability, provided the same wavelength drift applies to both.



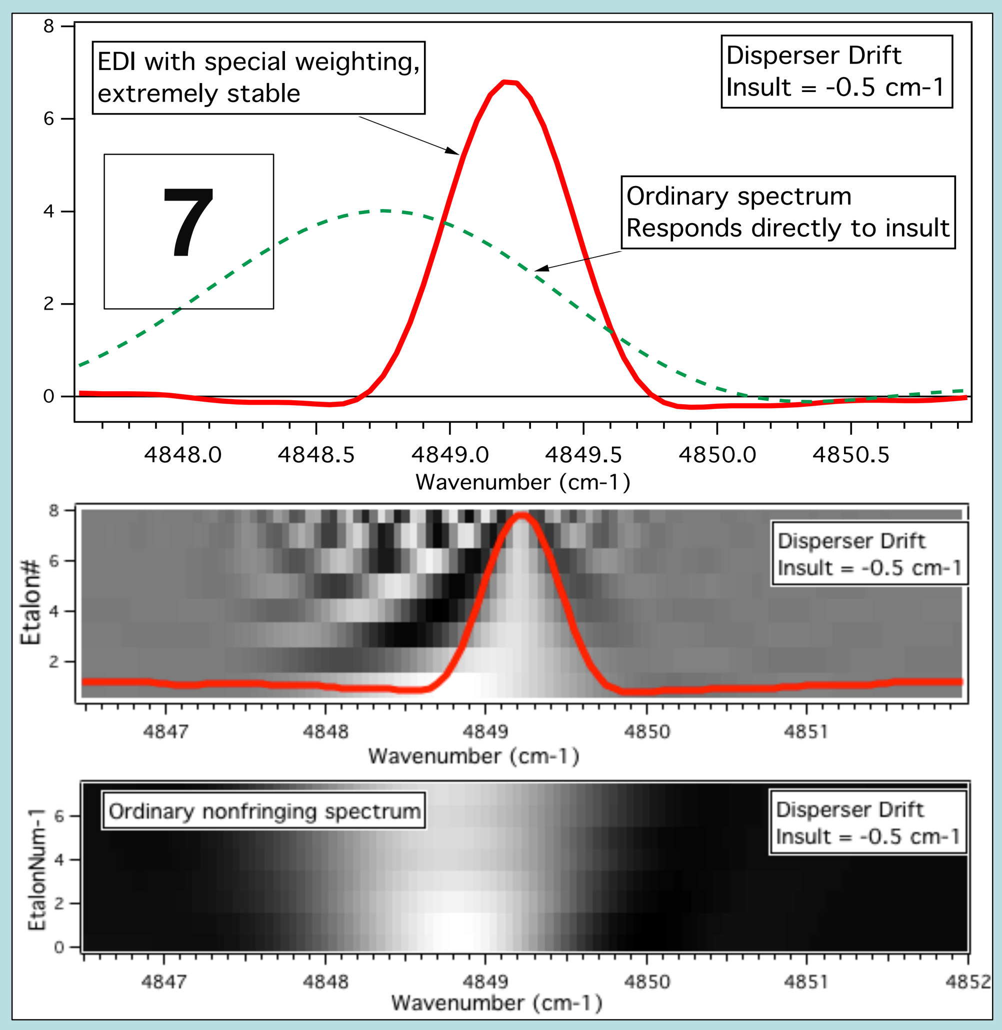


6. **CROSSFADING zeroes it!**
We overlap the positive phase reaction of one peak with the negative reaction of another, use appropriate weightings to sum, and thereby cancel the net phase reaction in a region. This creates perfect PSF stability (CC) under insult of Δx, although for a limited frequency range. Having more delays increases this range of perfect stability

5. **Fourier space explanation of REACTION to PSF drift**
Horizontal axis has frequency units (features per cm-1) same as interferometer delay (cm). A wavelength drift Δx of the PSF creates a phase shift that increases linearly with frequency (the reactive error to minimize). (a) For a conventional disperser this is the red line starting at the origin, and so is high where the science frequencies lie, say 2 cm (AA). (b) For EDI the sensitivity peak is shifted up to high frequency (2 cm) by a heterodyning effect, and the phase reaction line (red line) thus passes through zero (BB) there. This greatly reduces the reaction for a single frequency, but is slightly nonzero in the wings of the peak.

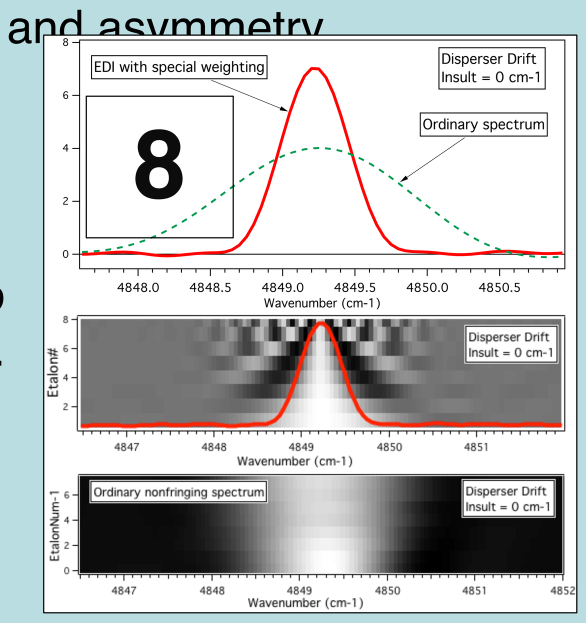


-- DEMONSTRATION --

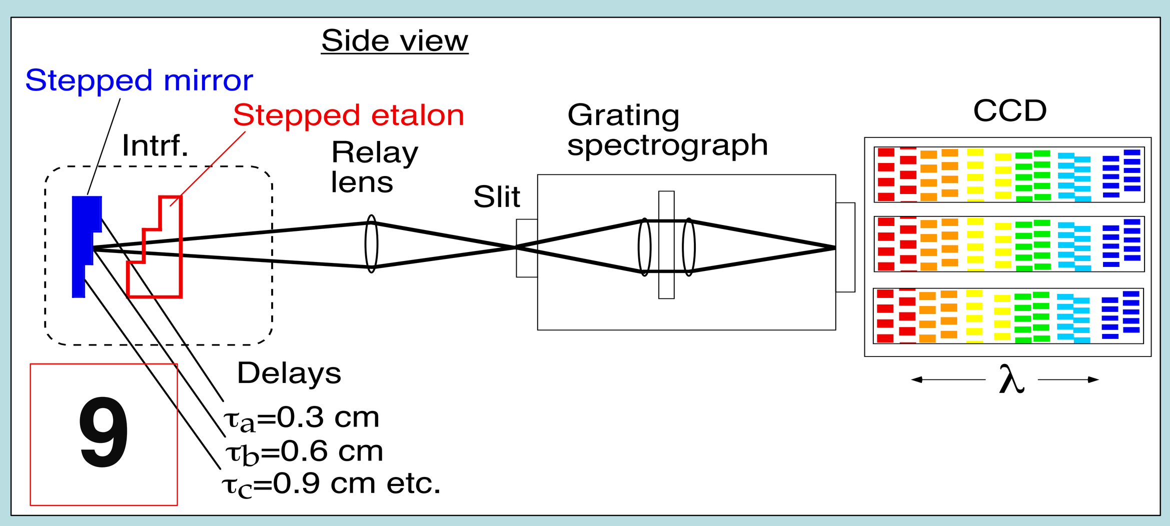


7. **DEMONSTRATION of 1000x STABILITY**
improvement under a simulated shift of data at detector (green dashes & bottom panels). Multiple delay EDI data from Mt. Palomar NIR echelle TripleSpec. Ordinary spectrum (green dashes) responds directly to the Δx insult, while the net EDI result (red peak) only shifts 1/1000th of Δx. Middle panels show how net EDI peak is a sum multiple wavelets, each from a different interferometer delay (etalon#). Precision wavelength is obtained from the interferometer phase, not from the disperser (which mainly affects the wavelet envelope). Another spectral line calibrates the interferometer absolutely. This EDI peak is also stable to deliberate changes in native PSF width and asymmetry.

8. Same as 7, but no insult Δx applied.



-- PROPOSED --



9. **Proposed scheme** for implementing simultaneous **MULTIPLE DELAYS**, to mitigate high speed (e.g. atmospheric) fluctuations. Sequentially changing a single physical delay (easier) mitigates slower changing drifts.

[1] "**High-resolution broadband spectroscopy using externally dispersed interferometry at the Hale telescope: Part 1, data analysis and results**", D.J. Erskine, J. Edelstein, E. Wishnow, M. Sirk, P.S. Muirhead, M.W. Muterspaugh, J.P. Lloyd, Y. Ishikawa, E. McDonald, W. V. Shourt, and A. M. Vanderburg, J. Astr. Tele. Instrm. Sys. 2(2), 025004 (2016), doi: 10.1117/1.JATIS.2.2.025004.

[2] "**The first extrasolar planet discovered with a new-generation high-throughput Doppler instrument**," J.Ge, J. van Eyken, S. Mahadevan, C. DeWitt, S.R. Kane, R. Cohen, A. Vanden Heuvel, S.W. Fleming, P. Guo, G. W. Henry, D. P. Schneider, L. W. Ramsey, R. A. Wittenmyer, M. Endl, W. D. Cochran, E. B. Ford, E. L. Martín, G. Israelian, J. Valenti, and D. Montes, ApJ 648, 683–695 (2006).

http://spectralfringe.org/EDI/MyPubs4/TediTenxPart1gen.pdf
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http://spectralfringe.org/EDI/MyPubs5/Poster2019AAS-StLouis-Gen.pdf
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