# Enabling 1000x More Sensitive Spectrographs for Exoplanet Search

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**Abstract**

Current diagnostic velocity resolution limits our ability to search for exoplanets within the habitable zone. We propose a new capability (Crossfading-EDI or X-EDI) that will boost optical spectrograph stability and spectral resolution, enabling 100x-1000x more sensitivity for the exoplanet search. This technique for increasing the stability of any dispersive (grating or prism) spectrograph to unwanted wavelength drifts has been simulated on real data and shown to produce a 1000x or more stability improvement, by use of an interferometer using *pairs* of overlapping delays placed in series with the disperser, rather than singly-used delays. This combines fringe shifts having opposite phase reaction, to cancel drift. This technique, "Crossfading Externally Dispersed Interferometry" (X-EDI) builds upon an earlier singly- delayed Doppler technique (EDI) demonstrated on a variety of telescopes including the 5-meter Hale telescope at Mt. Palomar. The single-delay EDI technique already affords a significant stability enhancement to a spectrograph, and has been used by others to discover exoplanets in 2006 and 2016. We expect that improving EDI technique further by the use of crossfading pairs of delays will dramatically improve the instrumental noise floor due to spectrograph focal point drifts or detector pixel misplacement, which can limit the detection of small exoplanets over long (months or years) time scales. The X-EDI has been simulated on EDI data on a ThAr lamp line measured at the Hale telescope*. A simulated drift insult was applied. The observed reaction to the line position drift was reduced 1000x. All spectrographs suffer drift insults of various kinds, and the X-EDI technique reduces the reaction to these by moving the fine wavelength determination from the dispersive spectrograph to the interferometer, which uses the symmetry of delay pairs to eliminate drift. This technique can greatly improve spectral precision and stability for (1) Doppler radial velocimetry, and (2) direct planet imaging using adaptive optics (such as the Gemini Planet Imager) that feeds a low resolution integral field multi-object spectrograph. *David J. Erskine, J. Astr. Tele. Instrum. Sys., 7(2):025006, June 2021. Prepared by LLNL under Contract DE- AC52-07NA27344.

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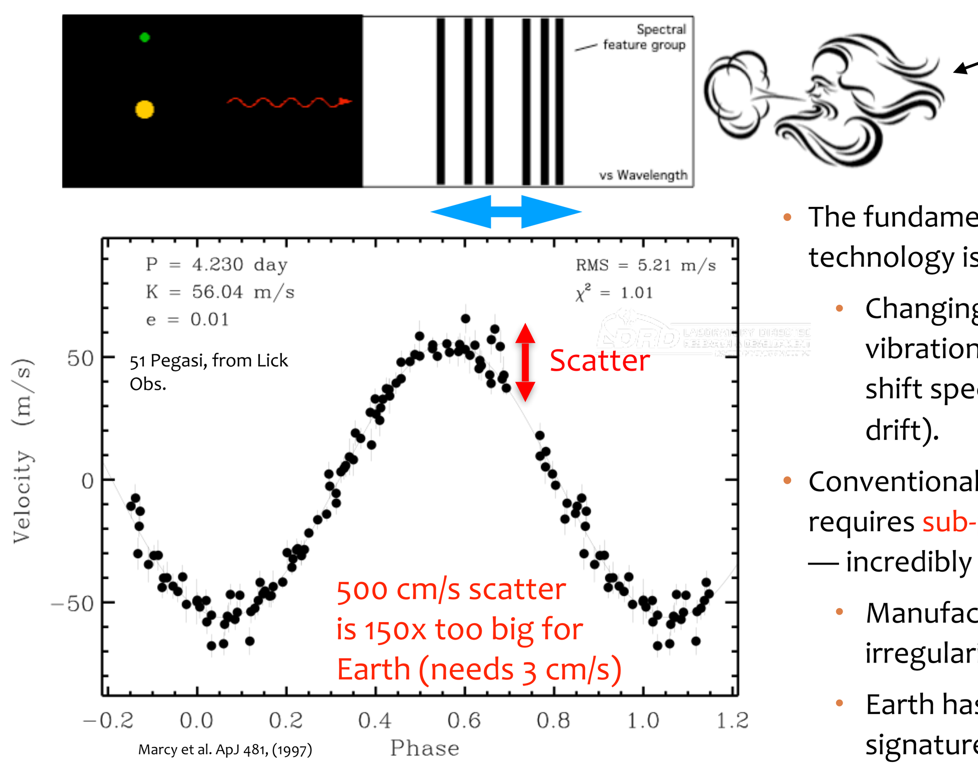
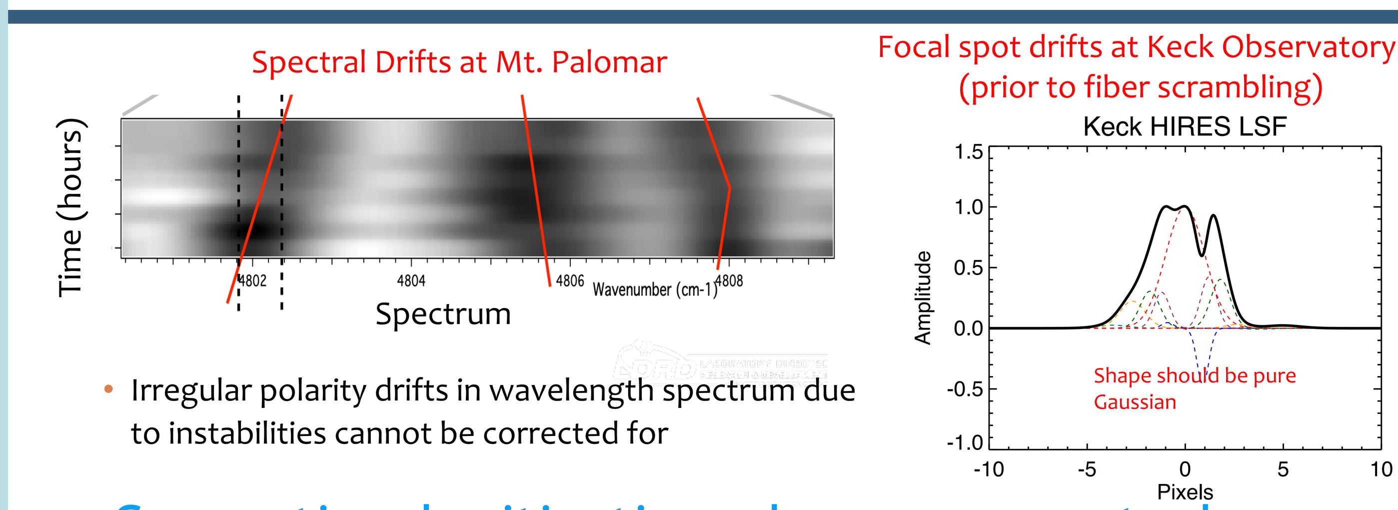
## Exo-Planets are discovered by Doppler velocity shifts of starlight




- The fundamental problem with current technology is the stability of the diagnostic.
  - Changing temperature, air pressure, vibration, gravity vector, accelerations shift spectrum with an offset (insult or drift).
- Conventional measurement of Earth requires sub-pixel ($10^{-5}$) stability over 1 year — incredibly difficult!
  - Manufactured detector pixel placement irregularities worsen the resolution
  - Earth has only 0.1 m/s amplitude signature



## Spectrograph Drift and focal irregularities define the system resolution




- Irregular polarity drifts in wavelength spectrum due to instabilities cannot be corrected for

### Conventional mitigations: large vacuum tanks, bulky thermal blankets, massive sturdy mounts

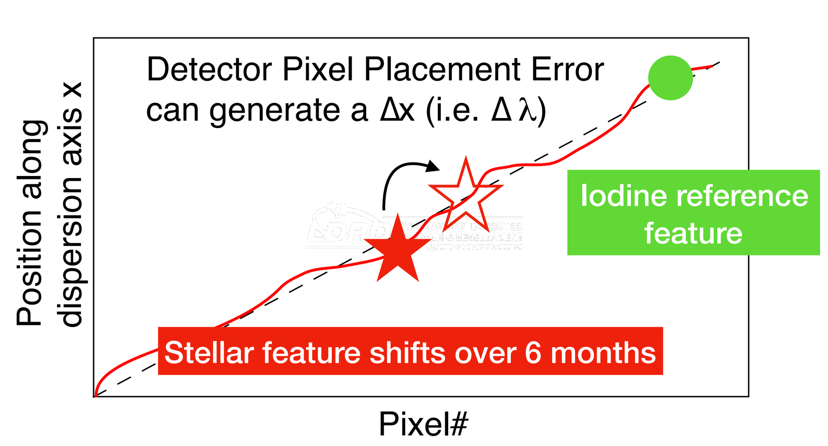
Still, the required $10^{-5}$ pixel stability needed is not achieved

A fundamentally different approach is needed to advance the sensitivity of Doppler spectroscopy



## Another problem: Manufactured Pixel Placement is Irregular on Detector

This error (~milli-pixel) is a "baked in" drift— not reduced by conventional mitigations (vacuum tank, thermal control, fiber scrambling).




6 month Earth orbital velocity change causes different pixels to be used, which can cause different Δx error

These could be much larger than the 10^-5 pixel tolerance needed to detect Earth-like planets



Prepared by LLNL under Contract DE-AC52-07NA27344.

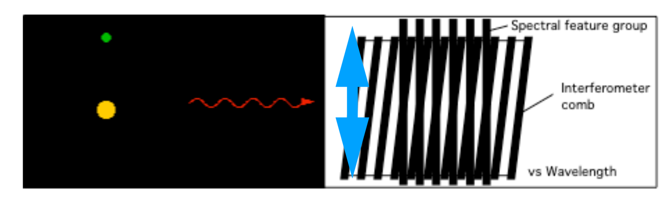
*See "Method for boosting dispersive spectrograph stability 1000x using interferometry with crossfaded pairs of delays", David J. Erskine, J. Astr. Tele. Instrum. Sys., 7(2):025006, June 2021
https://doi.org/10.1117/1.JATIS.7.2.025006

## Externally Dispersed Interferometery* (EDI), advantage for Doppler planet search:

**Horizontal Moire are perfectly robust to wavelength distortions**

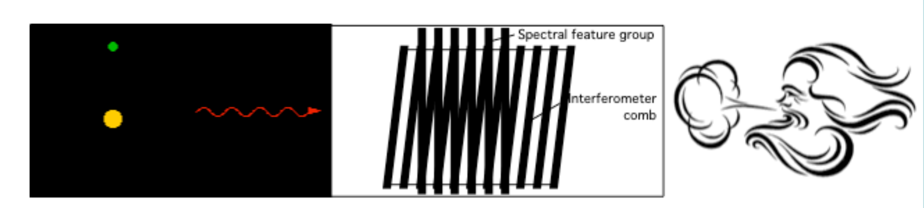
**Under a Doppler shift:**

(Feature moves relative to comb, producing phase change)




**Under a environmental wavelength shift:**

(Feature and comb move together since they are embedded in same beam, producing NO phase change)




**Horizontal Moire occurs when feature frequency matches interferometer comb**

**Problem: realist spectra have a variety of frequencies— will generate Moire with variety of tilts**

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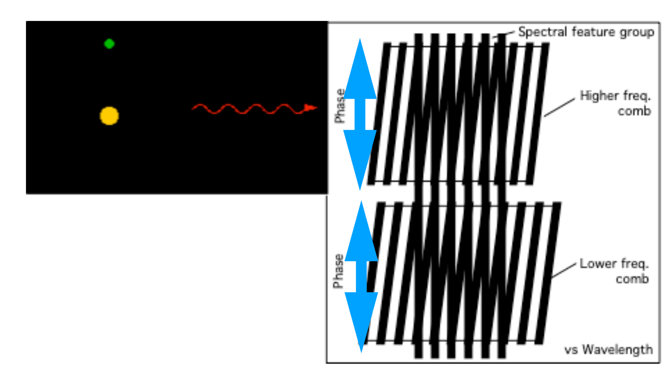
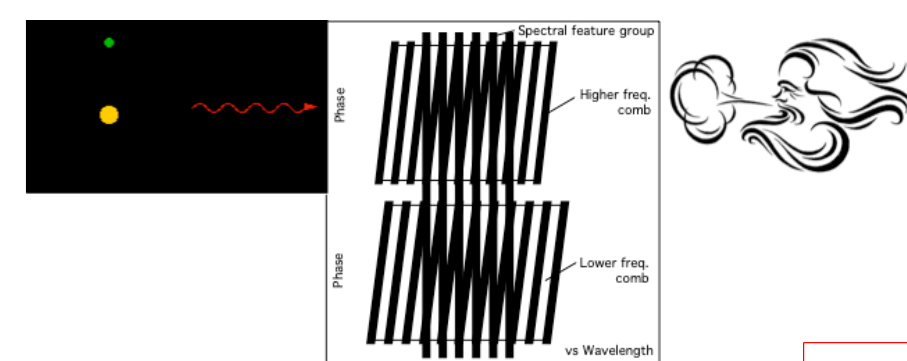
## New Idea: use two slightly different interferometers simultaneously

For each frequency, select weights and combine data to effectively cancel slope of moire

**Under Doppler the pair produces phase shift as usual**




**Under wavelength offset, the two moire behave like a horizontal moire and have zero net phase reaction to offset**

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## Demo of software using multiple pairs of intrfr. delays

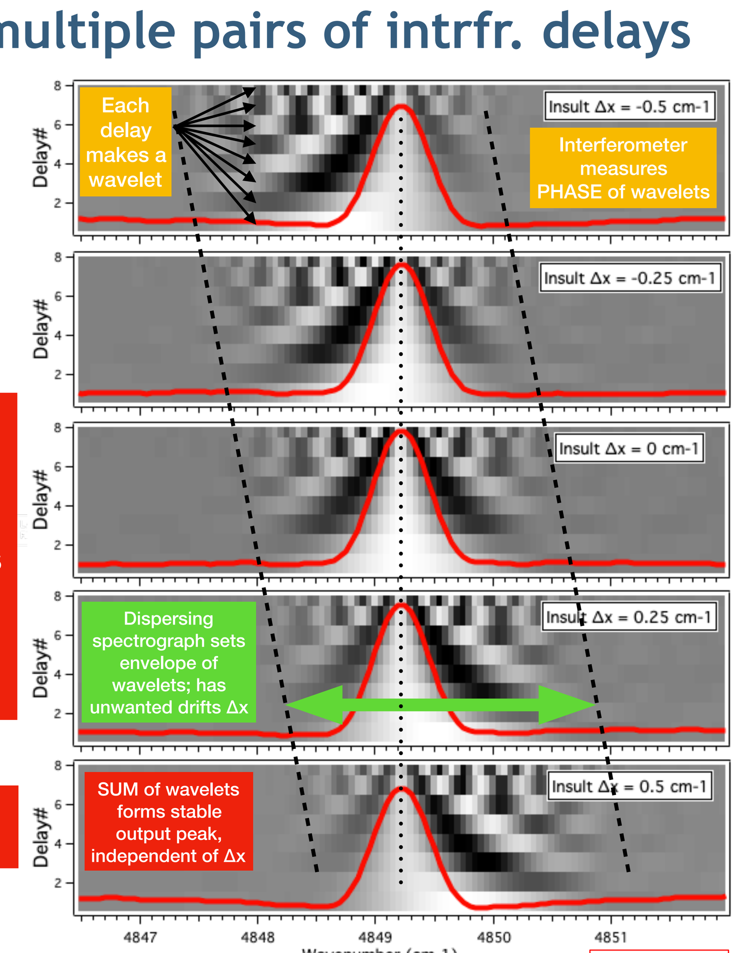
**Using EDI measured data of ThAr lamp at Mt. Palomar project**

**but simulated insult Δx**

The wavelet location is deliberately shifted sideways to simulate Δx.

The EDI output is the sum of wavelets which is the red peak, which is nearly stationary.

**1000x reduction in drift!**






**We recommend using BOTH conventional mitigations and EDI**

**Conventional mitigations: reduces environmental insult Δx**

**EDI: reduces TRC to ~0.001 - 0.1**

**Output spectrum shift** $$\Delta\lambda_{out} = \Delta x * TRC$$

**TRC is Translational Reaction Coefficient**

**(Conventional: TRC = 1)**

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