Externally Dispersed Interferometer Testbed Diagnosing Keck Planet Finder Spectrograph High Resolution Performance

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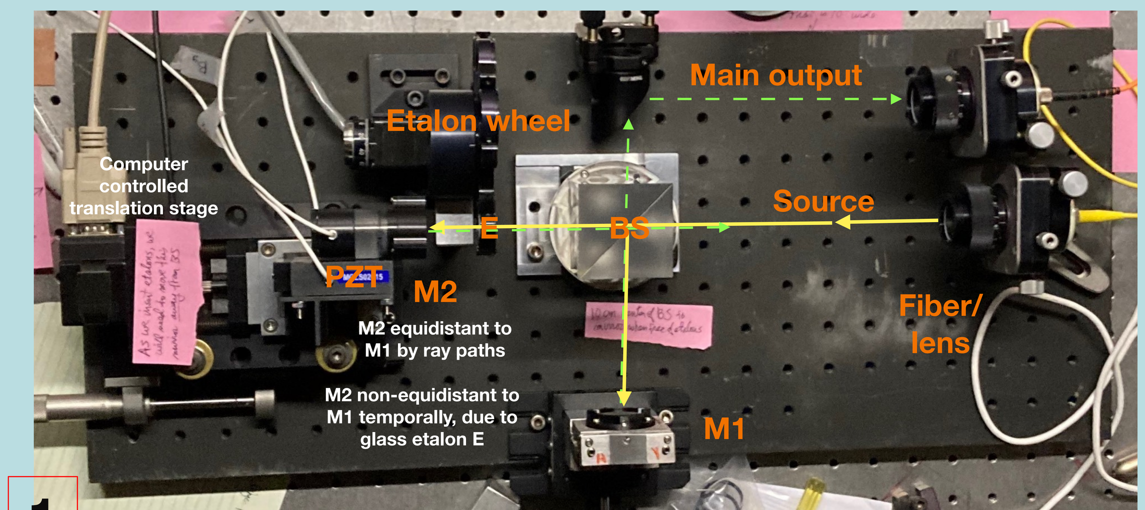
We built an externally dispersed interferometer (EDI) testbed for exploring methods of improving high resolution spectrograph performance. We tested the EDI on the Keck Planet Finder (KPF) spectrograph May 11, 2022 measuring a Fabry-Perot etalon back lit by white light. The data shows that the EDI is useful for diagnosing the point spread function (PSF) width and shape, in particular the asymmetry of the PSF.

Spectra measured two ways, simultaneously.
One method is limited by slit blur– the other is not.

The EDI simultaneously measures both the conventional nonfringing spectrum, and the fringing derived spectrum. Comparing the phases of the nonfringing and fringing components versus harmonic number in the Fourier transform (FT) measures the asymmetry in the PSF.

A heterodyning effect shifts the fringing sensitivity peak to arbitrarily higher frequency, set by the interferometer delay value, and thus its resolution can exceed the spectrograph used alone.

We report the first measurements of an EDI measuring a periodic source, which is a Fabry-Perot (FP) interferometer back illuminated by white light. This particular FP did not create very high frequencies due to its low finesse. The Laser Frequency Comb (LFC) was not operating when we took data, and it would have created much higher frequencies. The periodic character of the FP source created spikes in the Fourier transform, which was very convenient for analysis.



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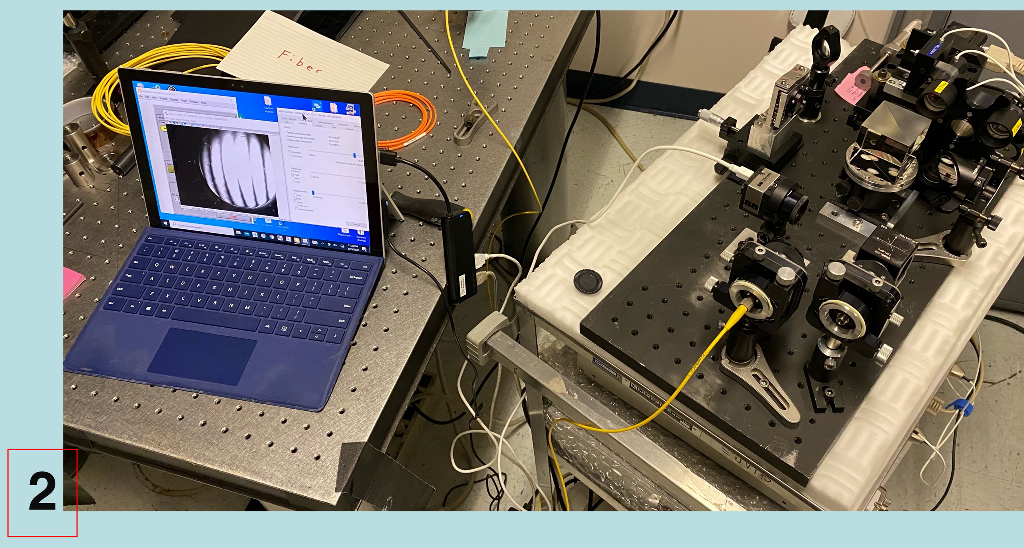

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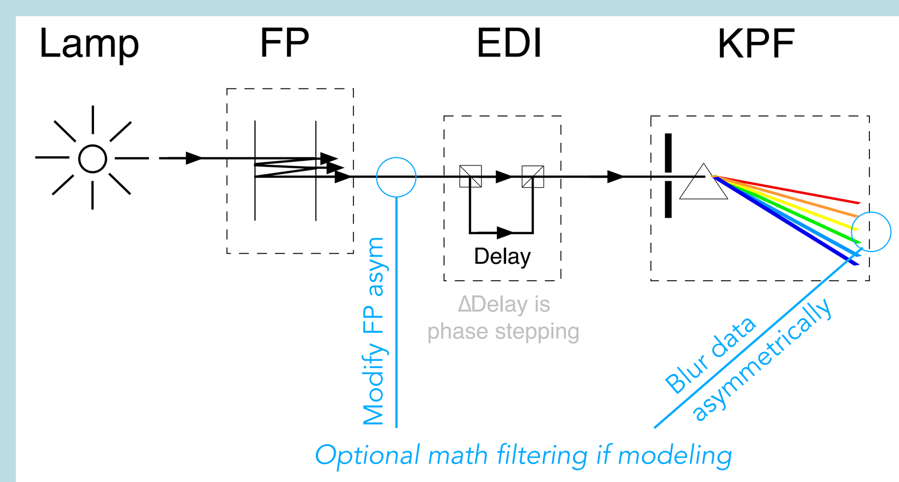
The Michelson interferometer was rapidly constructed from beamsplitter (BS) and two paths reflected by mirrors M1 and M2. The M2 path includes a glass etalon (E) in a rotary holder producing selectable time delays equivalent to path length differences 0.03 cm thru 6.7 cm. The virtual image of M2 behind E is superimposed on M1 by the BS. Hence by ray paths the interferometer acts like it has zero delay (field-widening), yet there is a time-of-flight difference due to slower propagation of light through glass. This condition allows uniform delay across a wide beam independent of incidence angle (no cosine effect vs angle, i.e. an infinitely wide bullseye pattern seen with a HeNe alignment laser). Both of two complementary outputs can be used in principle to produce mathematically uniform sinusoidal combs. The cavity is unstabilized for simplicity and uses a known calibrant wavelength to establish detailed delay and fringe phase.

3

Symmetrical PSF is desired for Doppler stability

An average symmetrical PSF is most rebust to pupil beamshape changes that redistribute energy, that otherwise could lead to Doppler errors for an asymmetrical PSF. Ray tracing can predict asymmetry of PSF-- but how well does it agree with reality? Our diagnostic can help answer that question. Graphic courtesy the KPF team.



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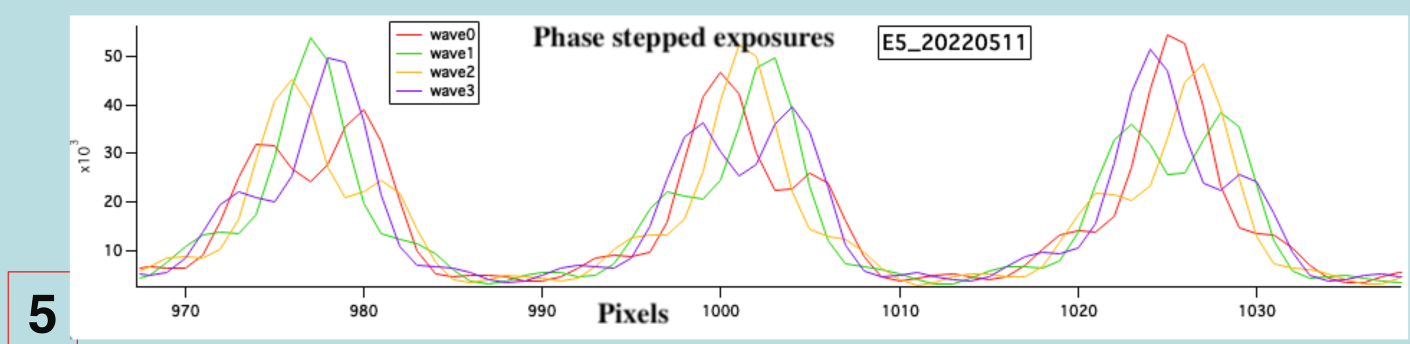
Three devices in series: FP * EDI * KPF, Fabry-Perot etalon, Externally Dispersed Interferometer (Michelson), and the Keck Planet Finder echelle grating spectrograph. During modeling, asymmetry of data was artificially changed at two places (blue circles) to explore response.

Phased-stepped data separates nonfringing from fringing



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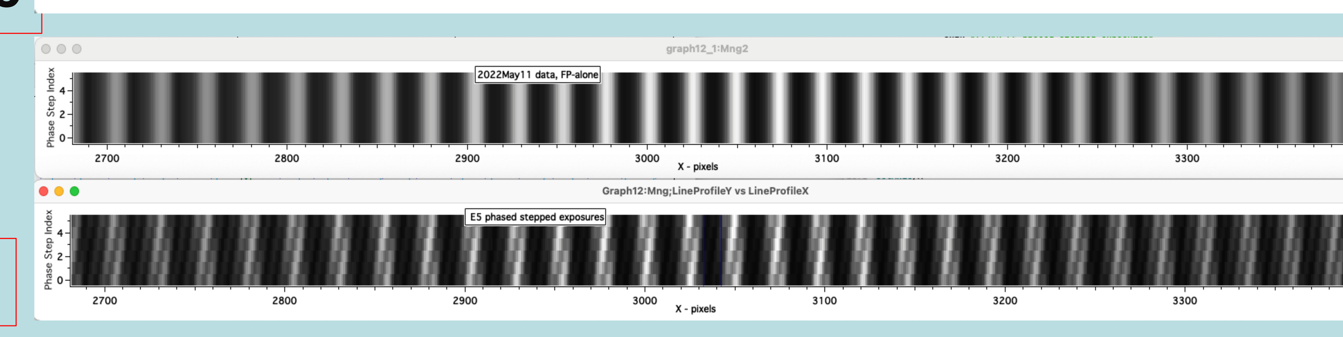

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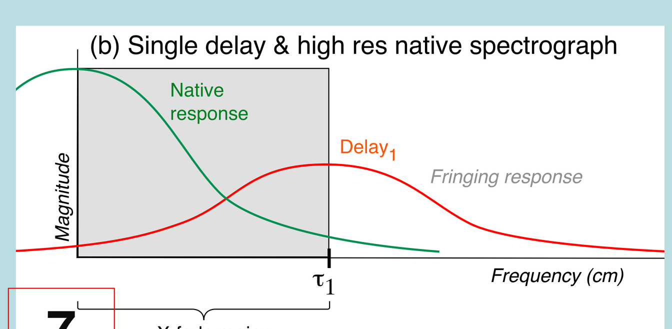
Phase stepping data taking makes EDI robust to background offsets and fixed pattern noises. A 3.3 cm delay (E5) used here.



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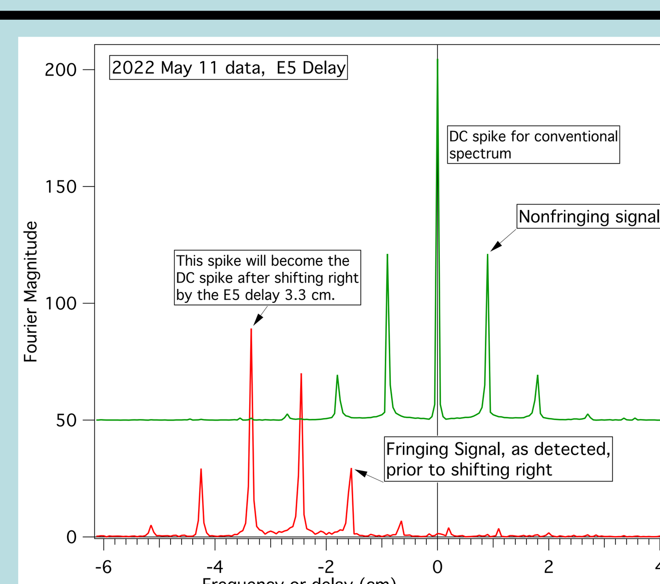
The sensitivity peaks of the EDI instrument, which consists of two peaks: the native (nonfringing), and the fringing. Both peaks have the same shape, but the native peak is centered at 0 frequency, and the fringing peak is centered at the interferometer delay (in our case 2.26 cm for the E4 etalon we used for most of this analysis).



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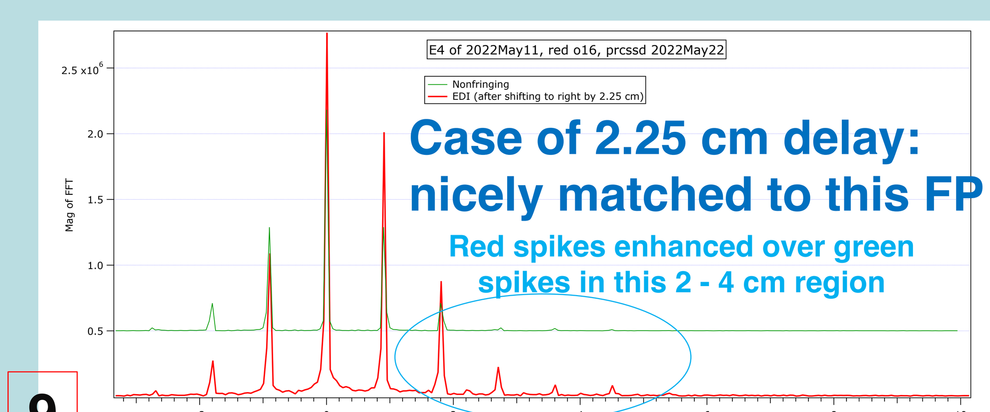
Fourier transform of the two outputs of the phase stepping algorithm, are the nonfringing spectrum (green), and fringing moire (red). It appears in negative frequencies because it was down shifted by a heterodyning effect when multiplied by the interferometer sinusoidal transmission. During processing it is shifted to right to restore the signals to their original frequencies.

Arbitrarily higher resolution obtained by using higher interferometer delay

Resolution exceeds this particular FP source



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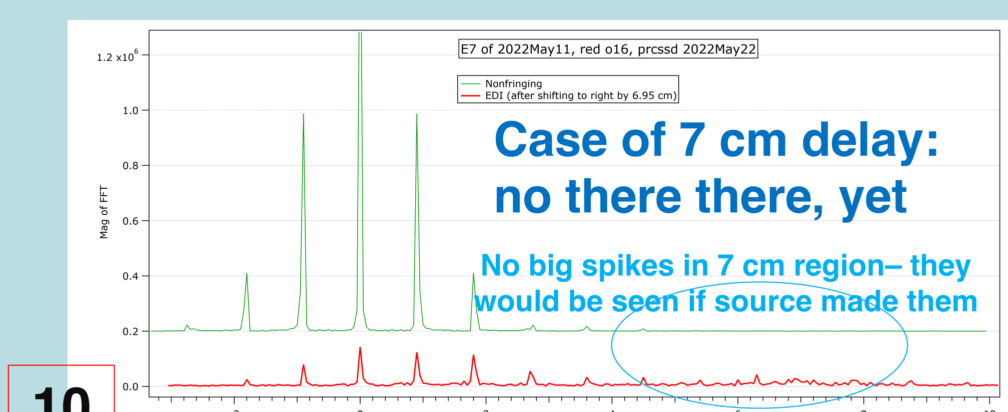
Fourier transforms. EDI (red spikes) and Nonfringing (green spikes) are the harmonics of FP source. Comparing their phases yields the asymmetry of the spectrograph blur. The interferometer delay here of (E4) 2.26 cm is more matched to the frequency width of this FP, compared to the 7 cm delay (E7) below.



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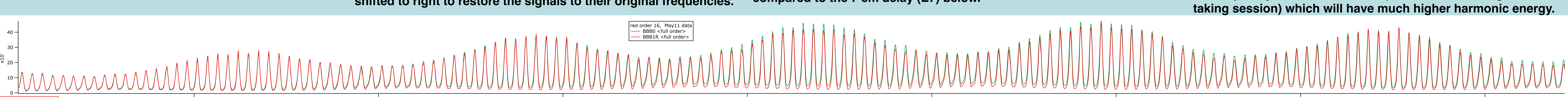
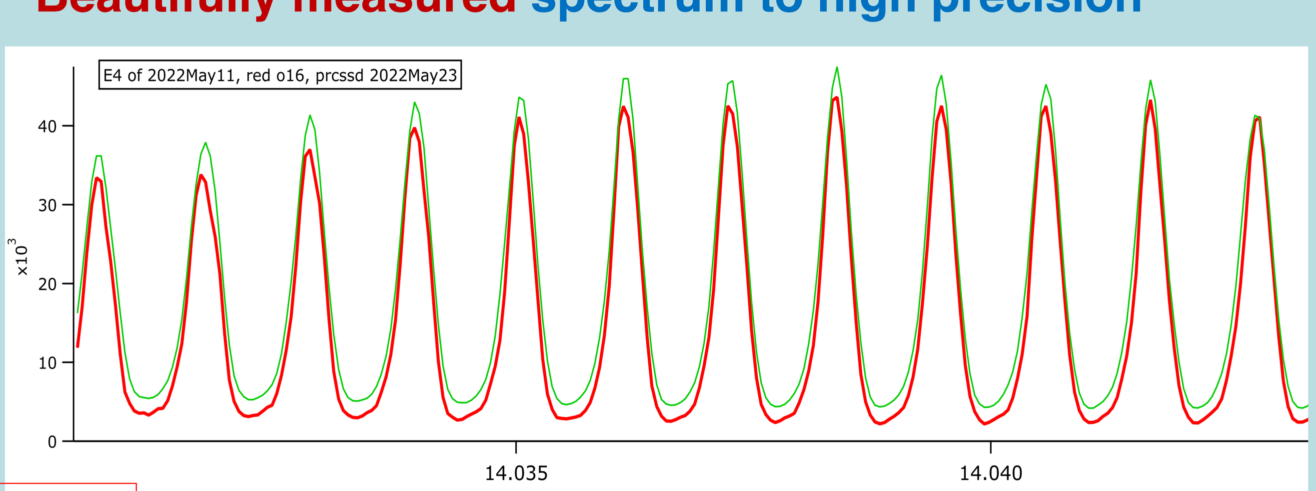
Fourier transforms. EDI (red curve, 7 cm delay) would detect super high harmonics, but this particular FP is not emitting much energy there due to low finesse. We anticipate this E7 delay will be very effective in future measurements using the Laser Frequency Comb as a source (not available during our data taking session) which will have much higher harmonic energy.



11a

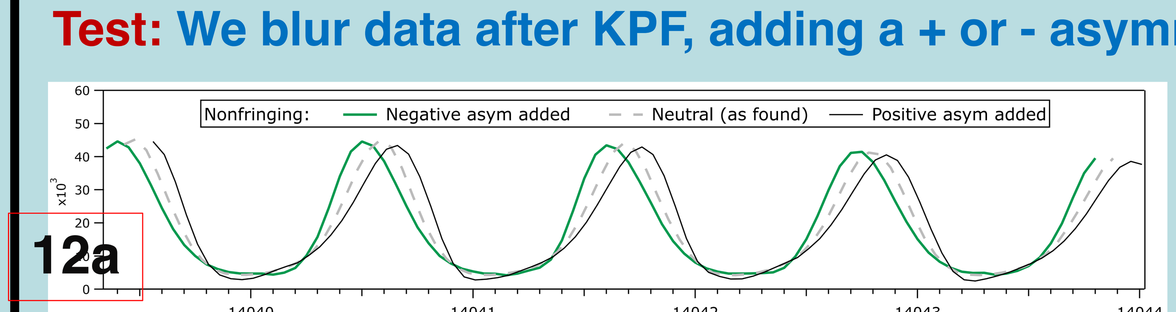
Beautifully measured spectrum to high precision



11b

EDI output spectrum (red) agrees with conventional nonfringing spectrum (green) but red has higher resolution. (There is little high frequency content of source to distinguish). Note that the EDI curve (red) does not have the small background intensity offset remaining in the conventional KPF spectrum (green). This is because the EDI continuum is actually measured as a dithered AC signal (immune to intensity offset), then frequency shifted to 0 freq DC.

Test: We blur data after KPF, adding a + or - asymmetry



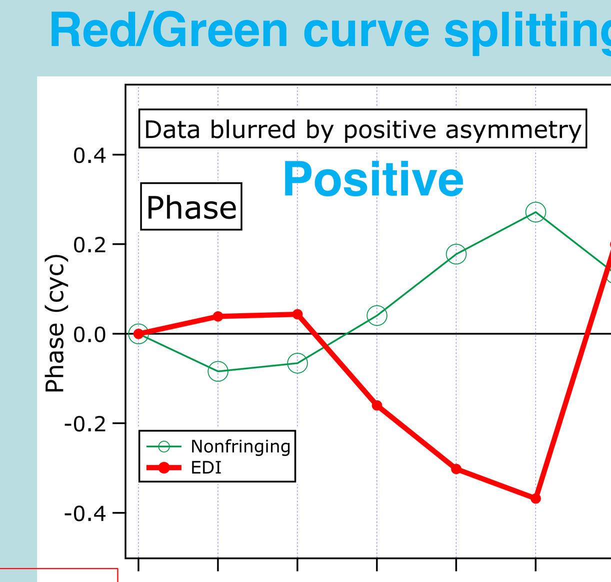
12a

We apply a custom asymmetrical blur to the original data, then process as usual. A quadratic phase vs frequency curve is used in argument of a phasor, which multiplies FFT of data.

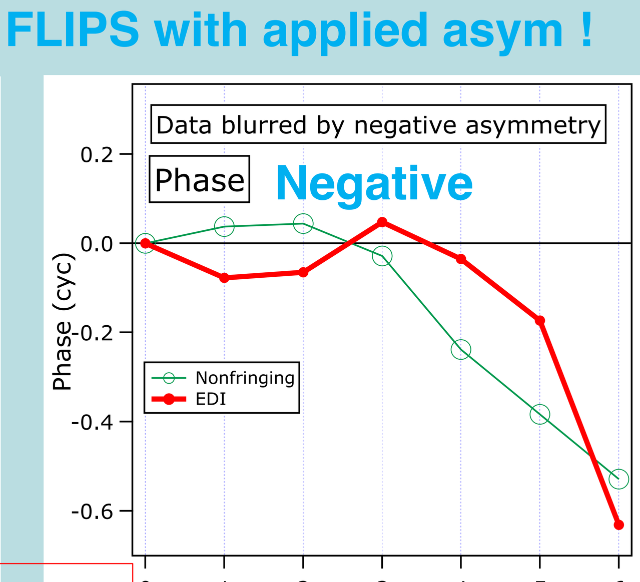
The spectrograph asymmetry can be measured from the splitting between the fringing (red) and nonfringing (green) curves. Simulation: Effect of math asymmetrical distorting data (as if at KPF slit blur). The fringing (red) to nonfringing (green) curve splitting flips polarity when asymmetry of slit blur flips. This Is due to frequency shifting of the heterodyning effect. 4[th] harmonic is at frequency of 3.6 cm.

Result: Slit blur asymmetry creates a splitting in harmonic phase

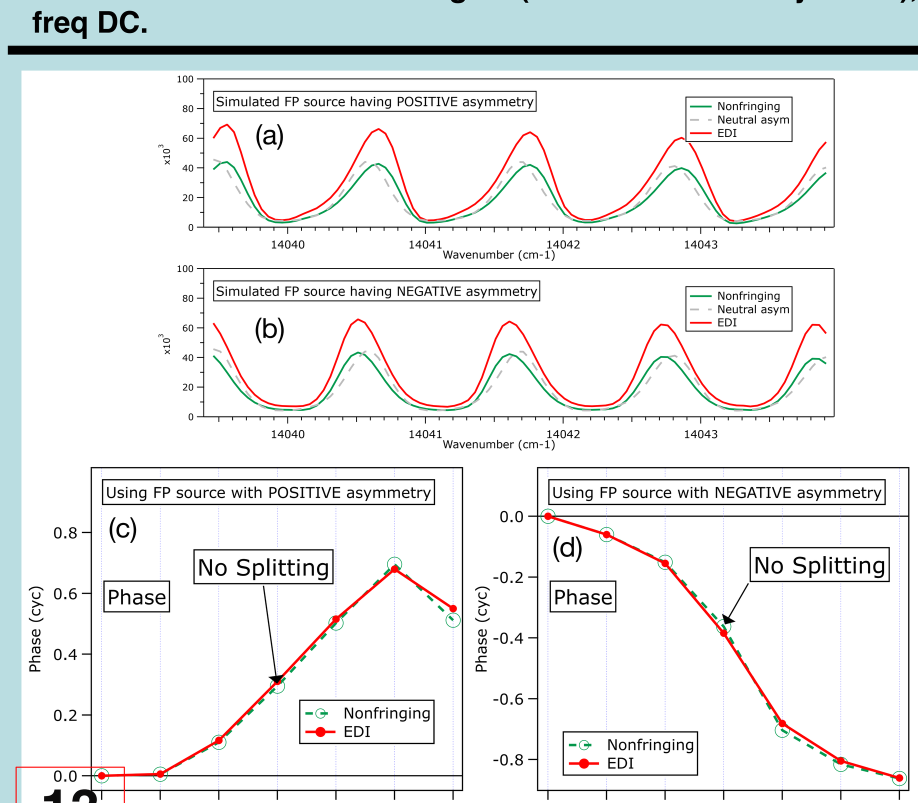
Red/Green curve splitting FLIPS with applied asym !



12b



12c



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We confirm that asymmetry in FP source does not create the splitting

Here asym is applied before EDI, not after it.

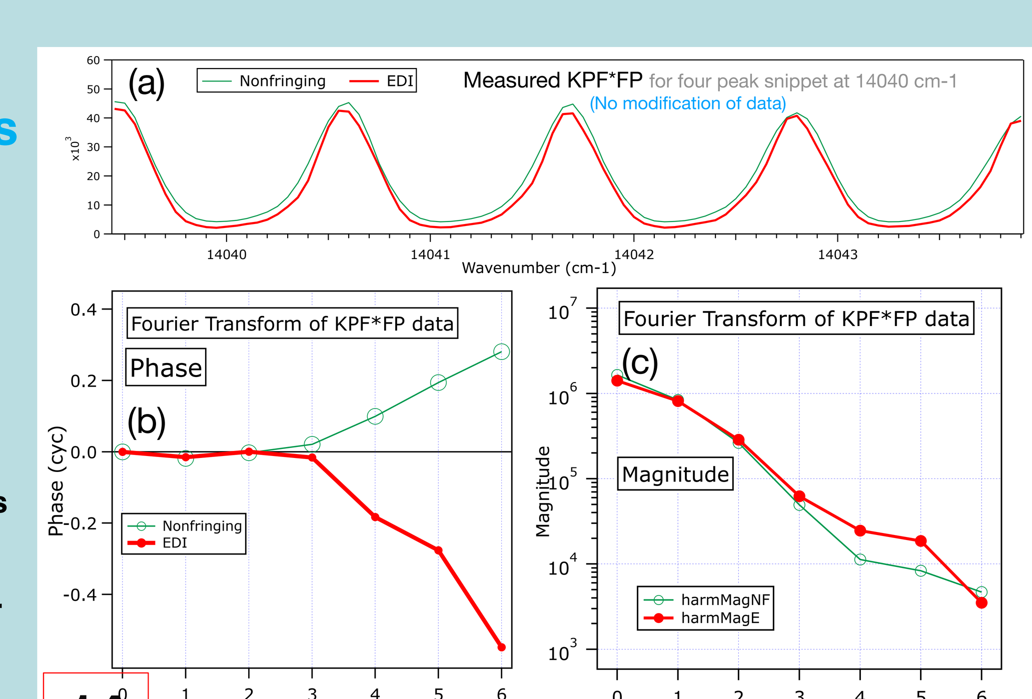
Asym is applied before the (1+cosine) multiplication in the model

Effect of changing asymmetry polarity of FP source, while slit blur is symmetrical. We create model phase stepped data, starting with a spectrum that is already asymmetric. Result: the red to green curves maintain overlap. Hence our diagnostic can distinguish FP source asymmetry from slit blur asymmetry, and measure both. 4[th] harmonic is at frequency of 3.6 cm.

Now we apply diagnostic to KPF

Little asym found in lower harmonics, but some in higher ones

Measurement of the phase and magnitude of the Fourier transform of the FP source, for conventional nonfringing (green) and for EDI (red), for a four-peak section of the spectrum starting at 14039.5 cm−1. For the lower harmonics 1 to 3 there is insignificant asymmetry of the spectrograph blur. For the 4th and 5th harmonic some asymmetry begins. The signals become too weak for harmonics higher than 5, for this particular source. (The EDI is capable of resolving much higher harmonics if the source emitted them, and if we use higher delays such as E7 shown in Fig. 11). We are still investigating how high (how weak) of a harmonic do we trust for this diagnosis. We look forward to measuring a source which has higher frequency harmonics, which could be the Laser Frequency Comb (LFC), or another Fabry-Perot but having a higher finesse. 4[th] harmonic is at frequency of 3.6 cm.



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Proceedings associated with this poster ⟶