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Technique for Stabilizing a Spectrograph 1000x Using an Interferometer with Crossfaded Delays

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Abstract: By weighting signal components from at least two overlapping delays in an externally dispersed interferometer one can reduce by about 1000x the net shift in response to a wavelength drift in the disperser.

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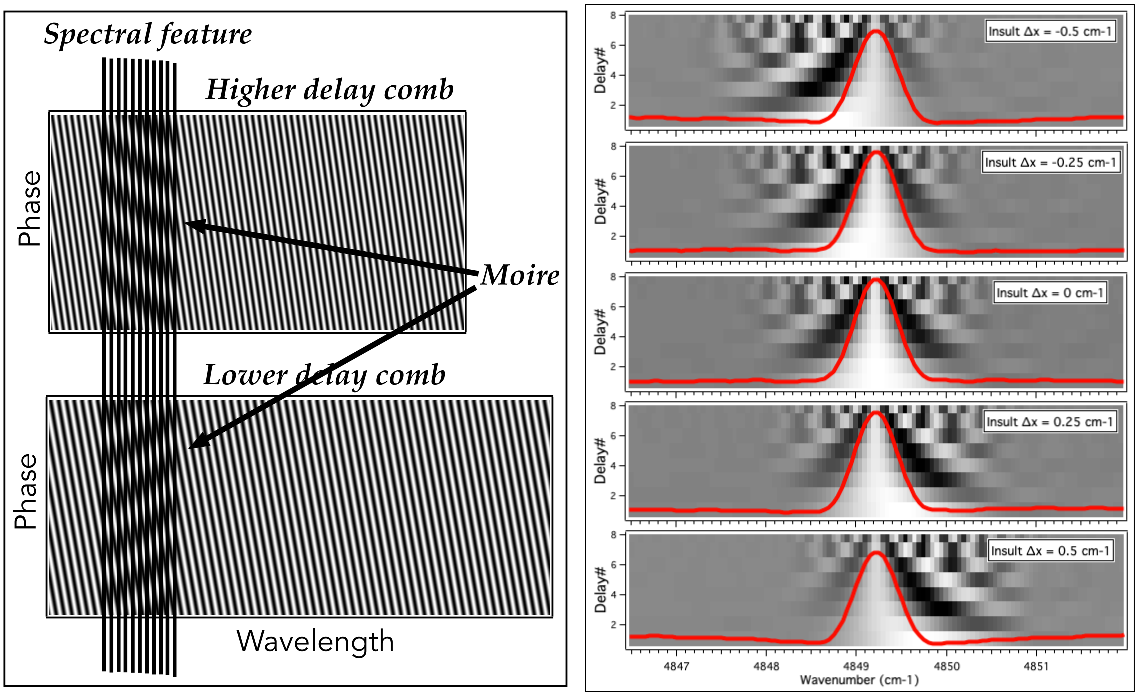

Fig. 1. (**Left panel**) The crossfading idea: instead of a single delay interferometer, have at least two slightly different delays so that the moiré patterns have opposite slopes, cancelling the susceptibility to wavelength or wavenumber drift. (**Right panel**) Demonstration on measured ThAr lamp EDI data having multiple overlapping delays, but with a simulated wavelength drift in the disperser. Each of several interferometer delays creates a wavelet instrument response when the measured moiré is processed and restored to its original higher frequency. The output spectrum is the sum of wavelets. The envelope of wavelets is dictated by the dispersive spectrograph, and shifts with the applied simulated drift. Remarkably, the ThAr peak location is dramatically insensitive (by a factor of 1000x) to the drift (from -0.5 to +0.5 cm^{-1}) in the dispersive spectrograph.

Externally Dispersed Interferometry [1–5] (EDI) is a sensitive and robust method for Doppler velocimetry and high resolution spectroscopy, An interferometer of fixed (but selectable) delay is in series with a dispersive spectrograph. The interferometer creates a periodic transmission function which beats against the stellar spectrum to produce lower frequency moiré patterns. These are more stable to detect than the original spectrum alone, since an instrumental wavelength drift will shift the interferometer comb and the stellar spectrum on the detector the same amount, preserving the moiré phase, which depends on the relative position of stellar to comb spectra. Doppler velocities are proportional to the stellar moiré phase shift minus a reference spectrum moiré phase shift. Figure 1 (left) plots phase vertically and wavelength or wavenumber horizontally.

In previous EDI's a *single* delay has been used for precision velocimetry and has detected exoplanets [6]. The single delay EDI has large robustness for features having frequencies (features per cm^{-1}) near the interferometer comb frequency (set by the delay in cm), but is less robust for other frequencies. (Yet a single delay EDI is still many times more robust than a spectrograph used alone). Since stellar spectra contain wide distribution of frequencies, this could limit velocity precision at the most challenging level, in the centimeter per second regime, of interest to Earth-like Doppler exoplanet measurements (needing $\sim$3 cm/s precision) and direct measurement of the cosmic redshift drift [7] over multi-year time scales. A wavelength drift can be caused by vibrations, thermal, barometric, gravity vector, or pupil changes. These are conventionally mitigated by heavy vacuum tanks, insulation and fiber scrambling [8]. Static drifts can be caused by mis-placement of detector pixels. These are not mitigated by vacuum tanks or fiber scrambling. Stellar observations 6 months apart can cause features to fall on different pixels having different placement errors. Note, 3 cm/s precision is 1x10^{-5} pixel precision, assuming typical spectrograph scaling of 3 pixels per stellar linewidth of 10 km/s. This is an extremely challenging tolerance to achieve.

The recent idea of "crossfading" [9, 10] is to use at least two slightly different delays. These create moiré patterns having opposite slopes (phase vs wavelength) for the same spectral feature Fig. 1 (left). Under a spectrograph wavelength drift these create opposite phase errors which can be made to cancel by choice of weightings. This creates a combined velocimetry measurement that is dramatically more robust to drifts and changes in instrument lineshape than a single delay EDI, which is already more robust than a conventional spectrograph used alone.

The crossfading method dramatically increase stability for high resolution spectroscopy by using multiple overlapping delays and analyzing the data in pairs with strategically chosen weights that cancel the net reaction to a wavelength drift. The simulation of Fig. 1 (right) uses actual EDI data of a ThAr lamp but with artificially created drifts from -0.5 to +0.5 cm^{-1}, as seen in the shift of wavelets (whose envelope is set by conventional spectrograph). Remarkably, the crossfading reduces the shift of the output peak (red), which is the sum of wavelets, to 1000 times less than the applied insult drift (Δx in cm^{-1} or $\delta\lambda_{insult}$ in wavelength).

The drift $\delta\lambda_{output}$ in the processed output spectrum (which for EDI is distinct from the insulting drift on the detector chip) is given by $\delta\lambda_{output} = \delta\lambda_{insult} * TRC$, where TRC is the translation reaction coefficient of the spectroscopic method. For dispersive spectroscopy TRC = 1; but for EDI using multiple delays we have shown theoretically (Sect. 10 of Ref. 4) that TRC = 0, and Fig. 1 (right) shows TRC $\sim$0.001.

The crossfading technique can be used together with conventional mitigations to reduce the output drift by one to three orders of magnitude beyond the conventional used alone. This is because crossfading EDI reduces TRC, whereas conventional mitigations reduce $\delta\lambda_{insult}$. The EDI stabilization benefit can greatly exceed its disadvantage of increased complexity of data analysis and minor loss of light by insertion of an interferometer, since conventional measurements are often not limited by photon noise but by instrumental drifts (e.g. note floor in noise at high flux in Fig. 5 and others of Ref. 8). Prepared by LLNL under Contract DE-AC52-07NA27344.

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