Experimental Accuracy and Precision of Broadband Laser Ranging

PDV Conference 2018

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Position (BLR) and velocity (PDV) measurements can coexist on the same optical probe.

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Simultaneous broadband laser ranging and photonic Doppler velocimetry for dynamic compression experiments

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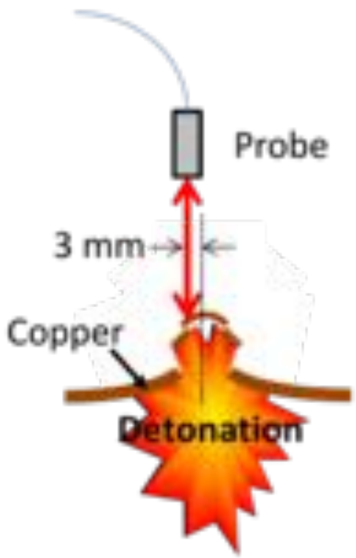
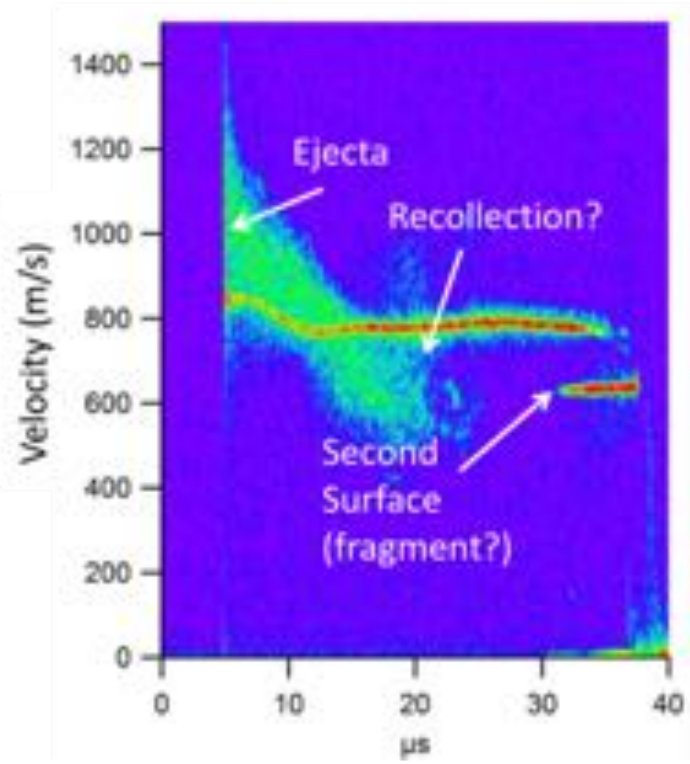
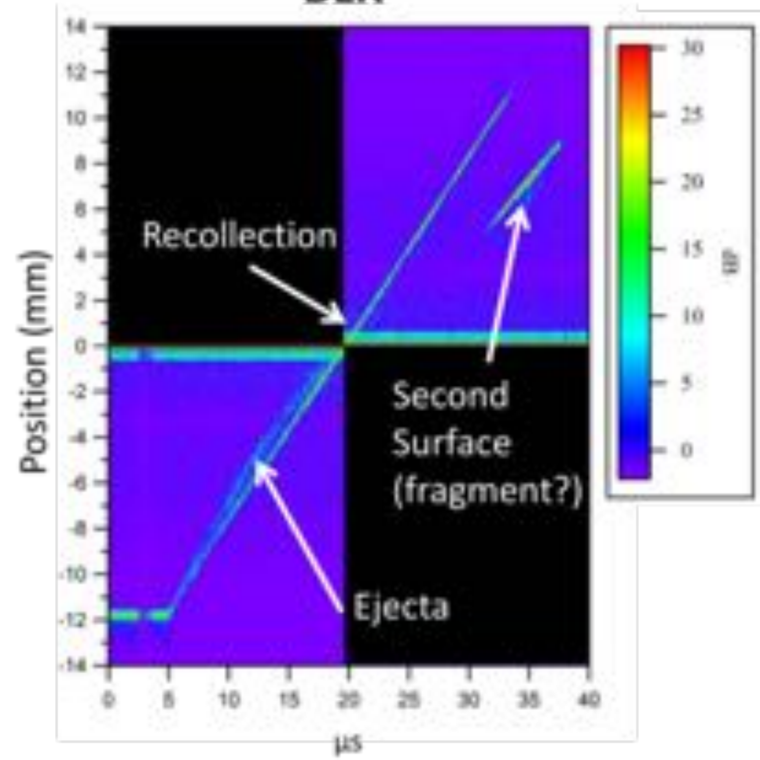


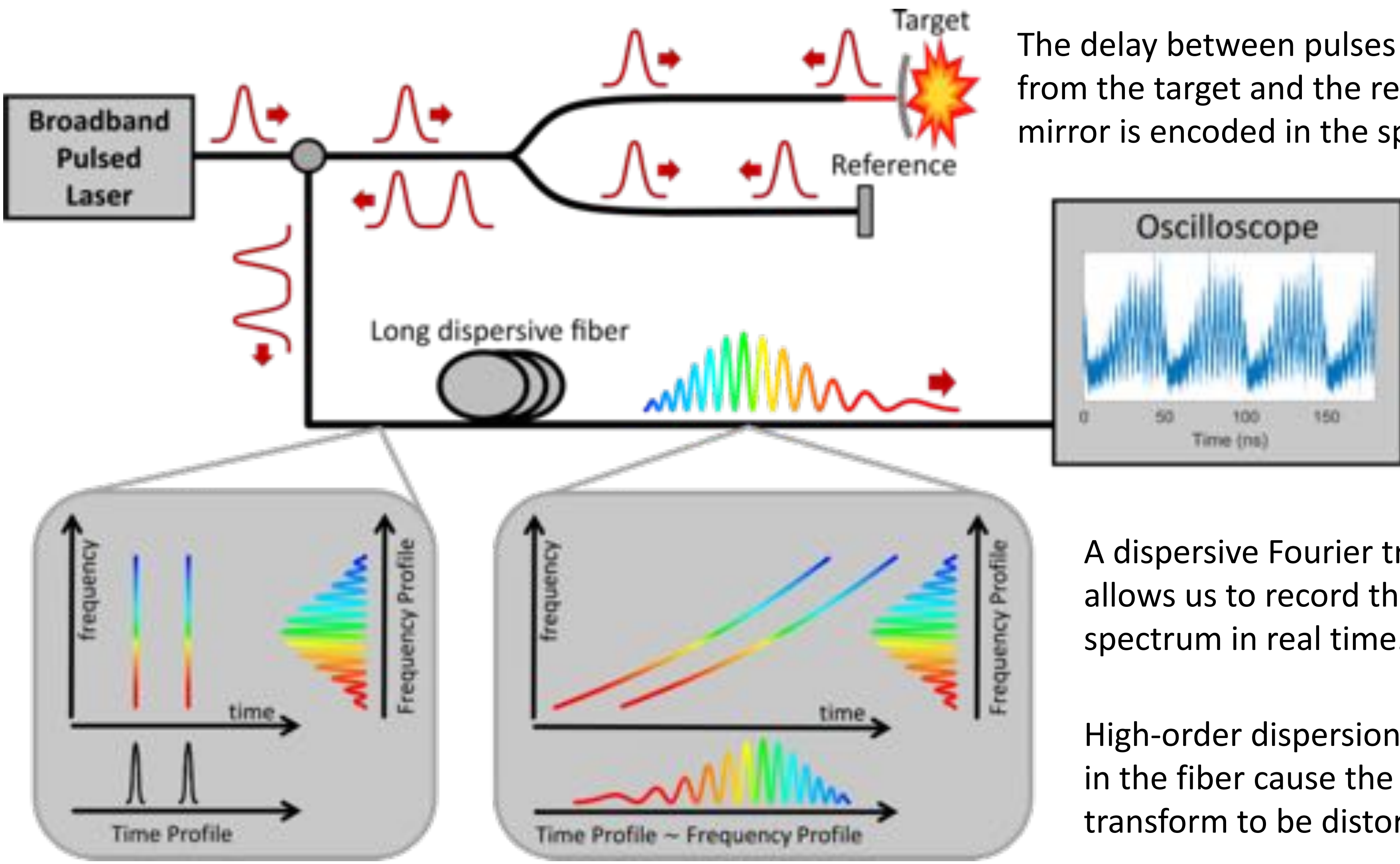
PDV



BLR



BLR is a broadband interferometer followed by a dispersive Fourier transform.



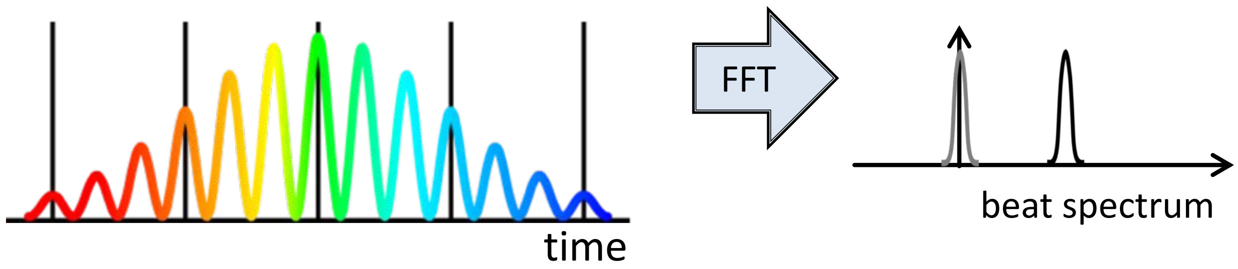
The delay between pulses returning from the target and the reference mirror is encoded in the spectrum.

A dispersive Fourier transform allows us to record the signal spectrum in real time.

High-order dispersion effects in the fiber cause the Fourier transform to be distorted.

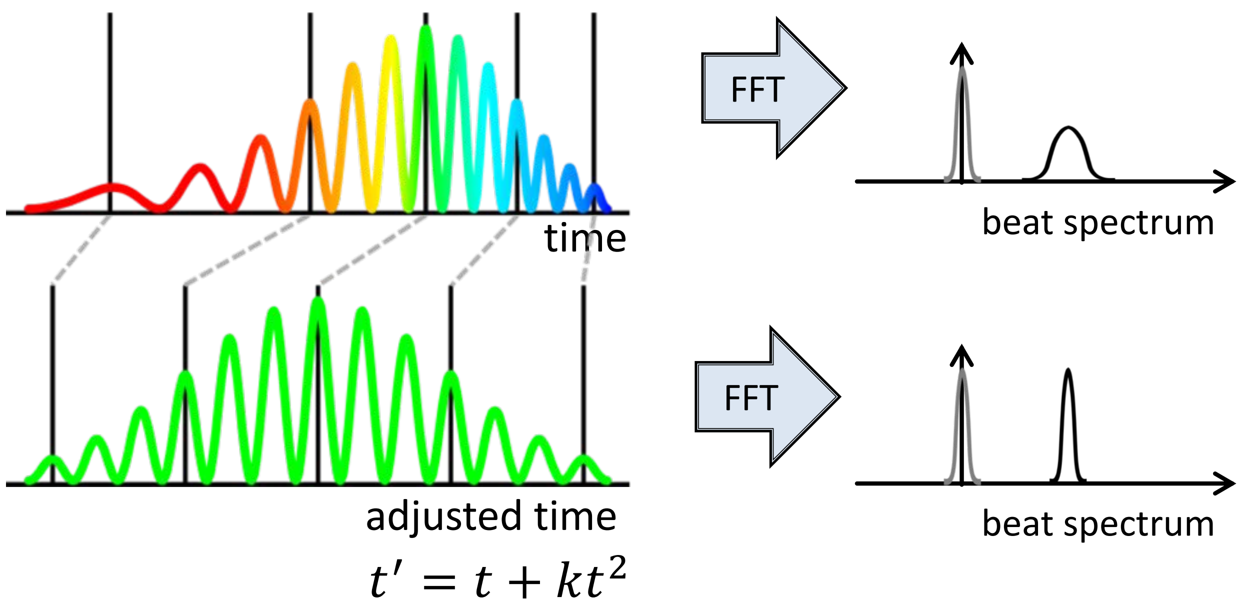
If the dispersive Fourier transform weren't distorted, the analysis would be simple.

Desired Data Analysis



The peak in the beat spectrum is proportional to the relative position.

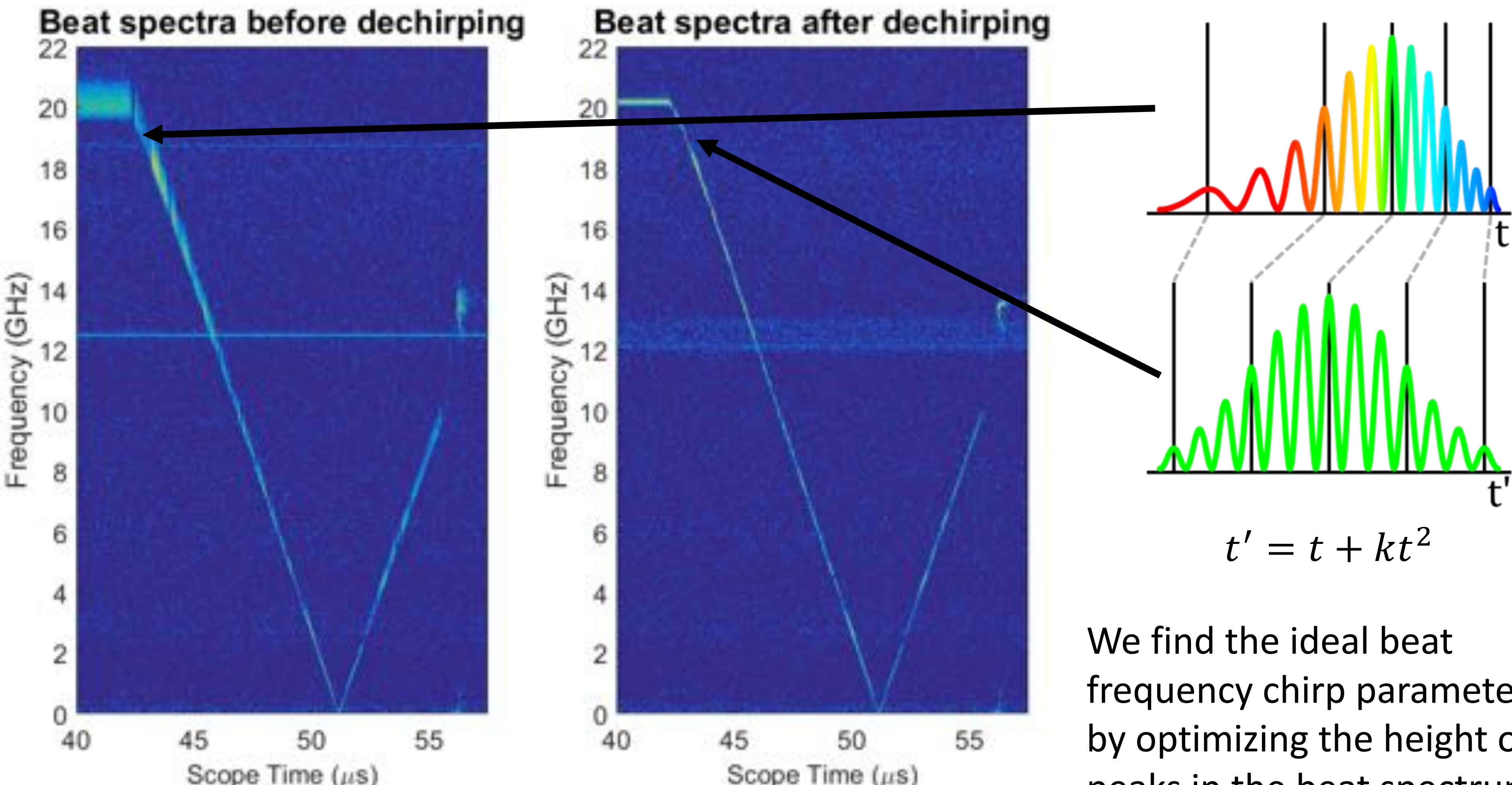
Actual Data Analysis



The peak is broadened, making the distance resolution very poor.

Remapping time and interpolating the signal (dechirping) compensates for the distortion.

Dechirping corrects for the distorted Fourier transform, so it works for all beat frequencies.

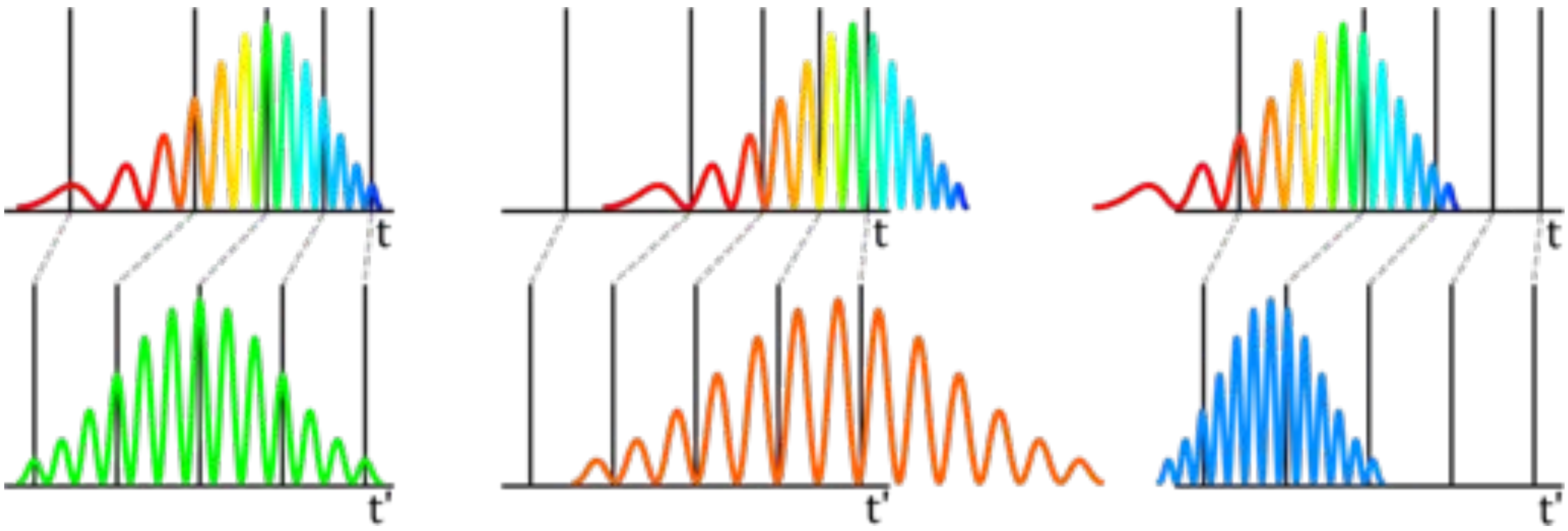


$$t' = t + kt^2$$

We find the ideal beat frequency chirp parameter k by optimizing the height of peaks in the beat spectrum.

Data courtesy of Patrick Younk

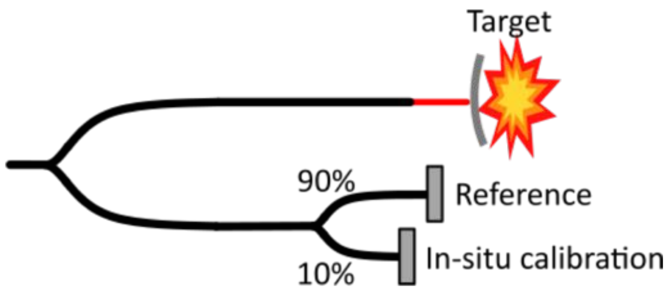
The dechirping process makes the beat frequency sensitive to temporal alignment.

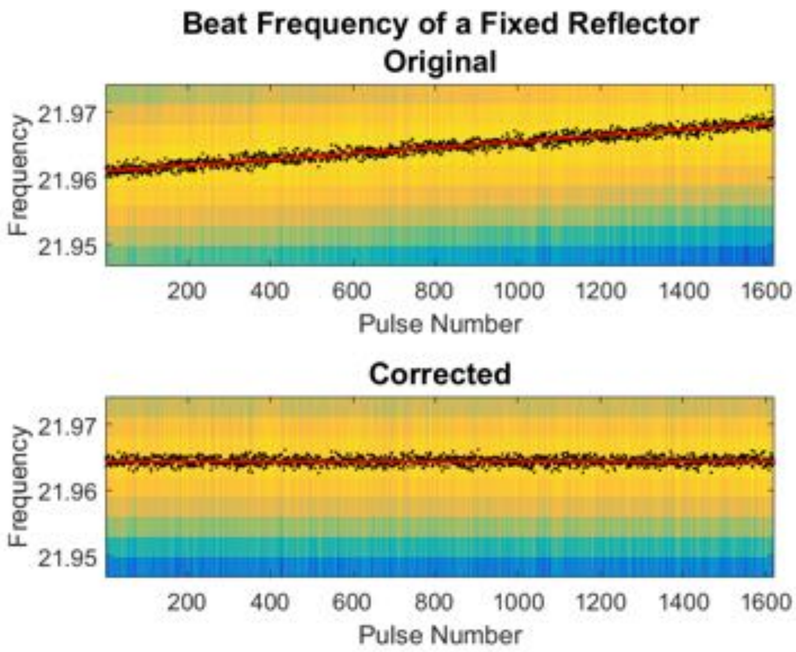


If a pulse is early or late with respect to the applied time map, we get a different beat frequency than if it were centered.

We must consistently align pulses in time to avoid introducing errors.

An in-situ calibration interferometer solves many problems.



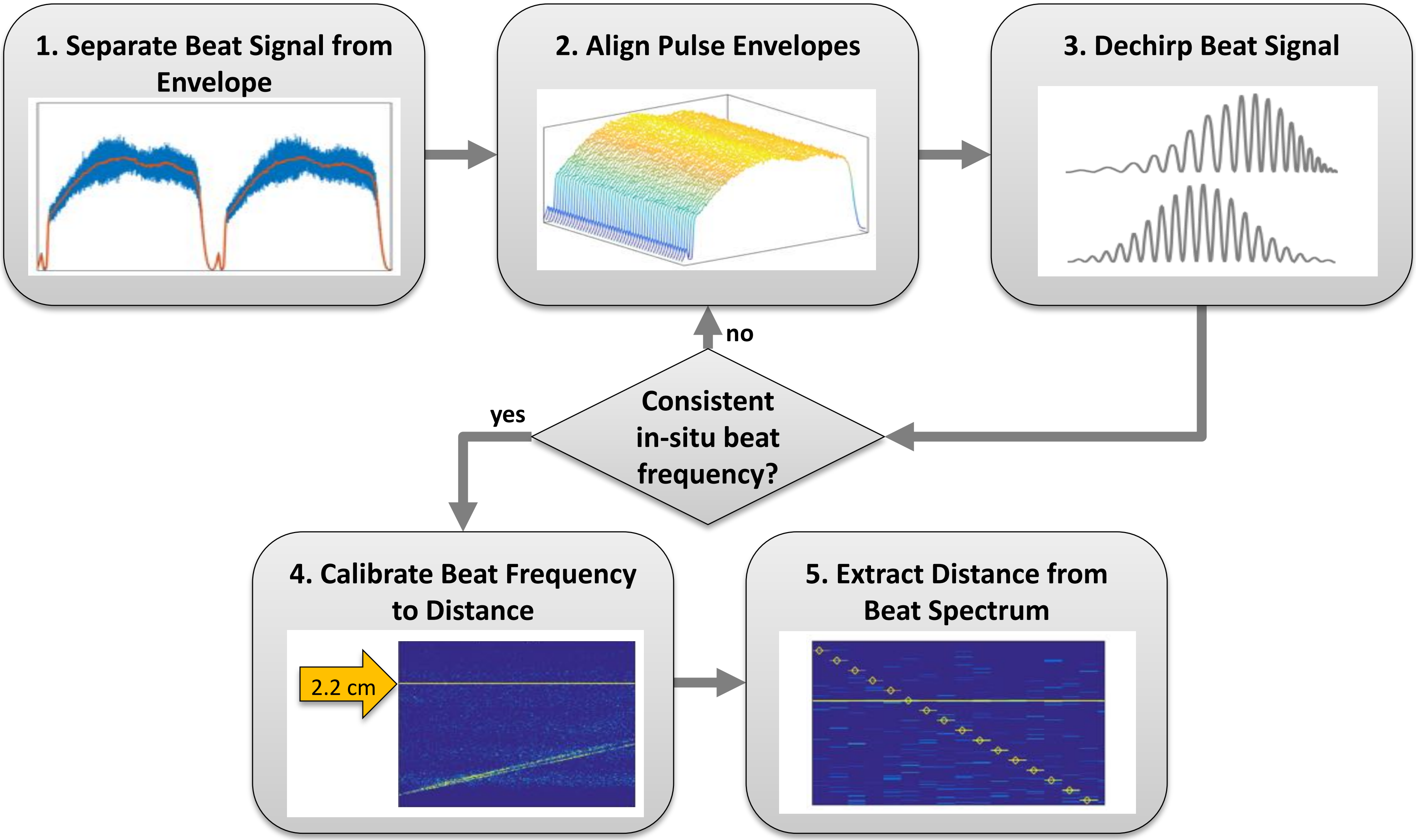


The relative delay and beat frequency generated should be constant.

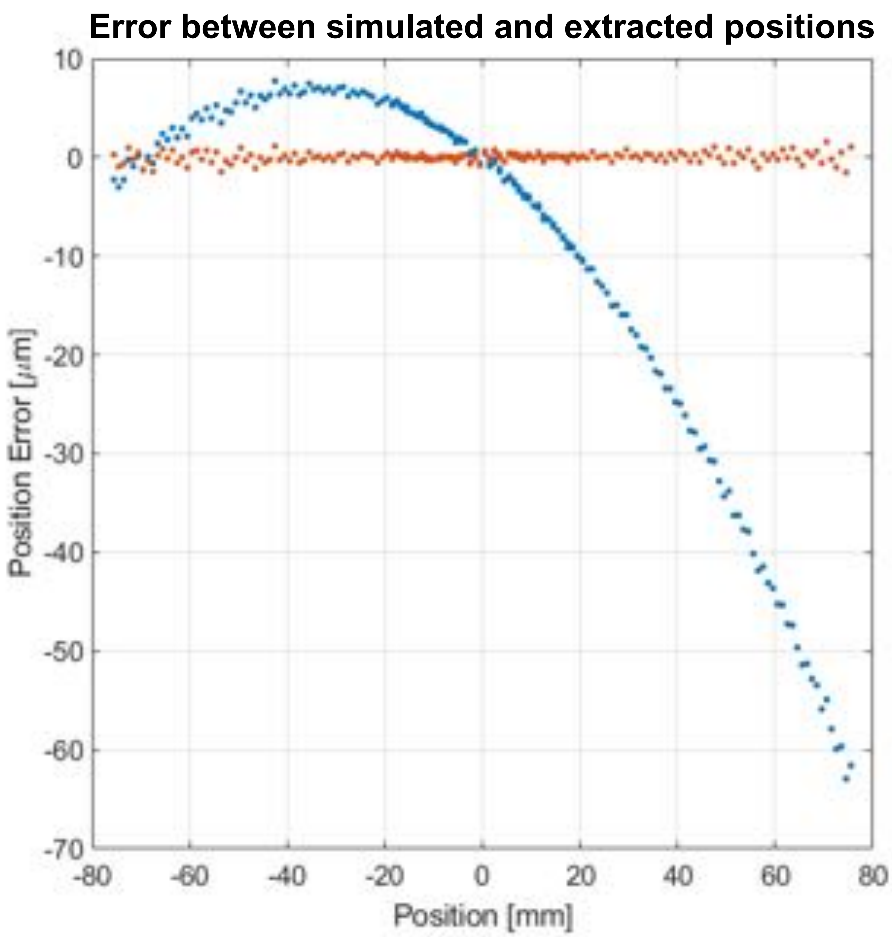
Temporal alignment in the analysis is correct when in-situ calibration beat frequency is constant.

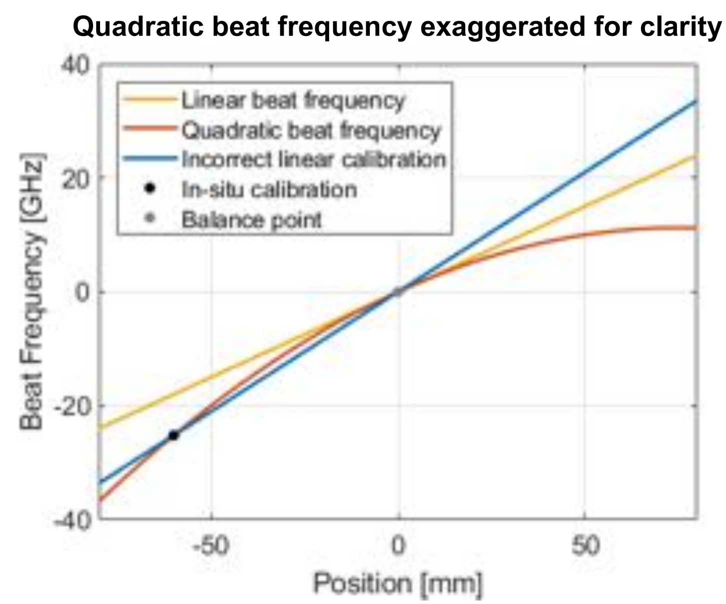
This delay can be precisely measured and used to calibrate the scaling of beat frequency to relative position.

Our analysis code prepares the raw signal for dechirping and extracts calibrated frequency peaks.



The distorted Fourier transform causes a quadratic distance error in addition to beat frequency chirp.





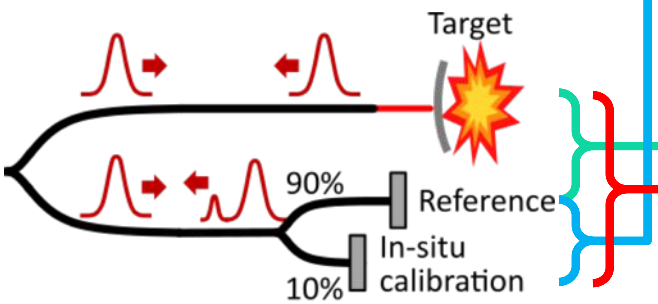
$$t' = t + kt^2, \qquad F \propto \tau - k\tau^2$$

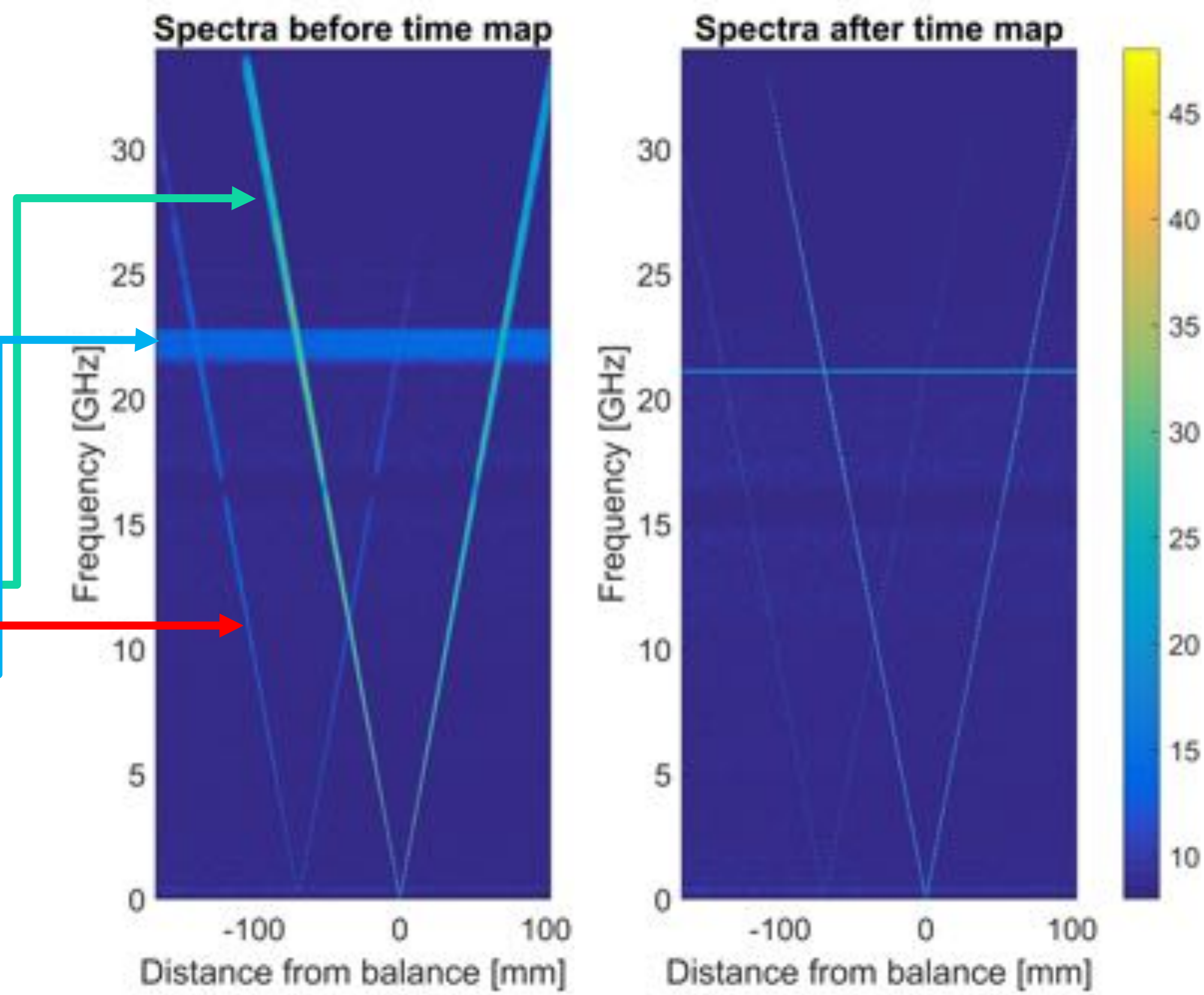
We can use the beat frequency chirp parameter from the dechirping step to correct extracted positions.

My colleagues have taken to referring to this as the "Rhodes correction".

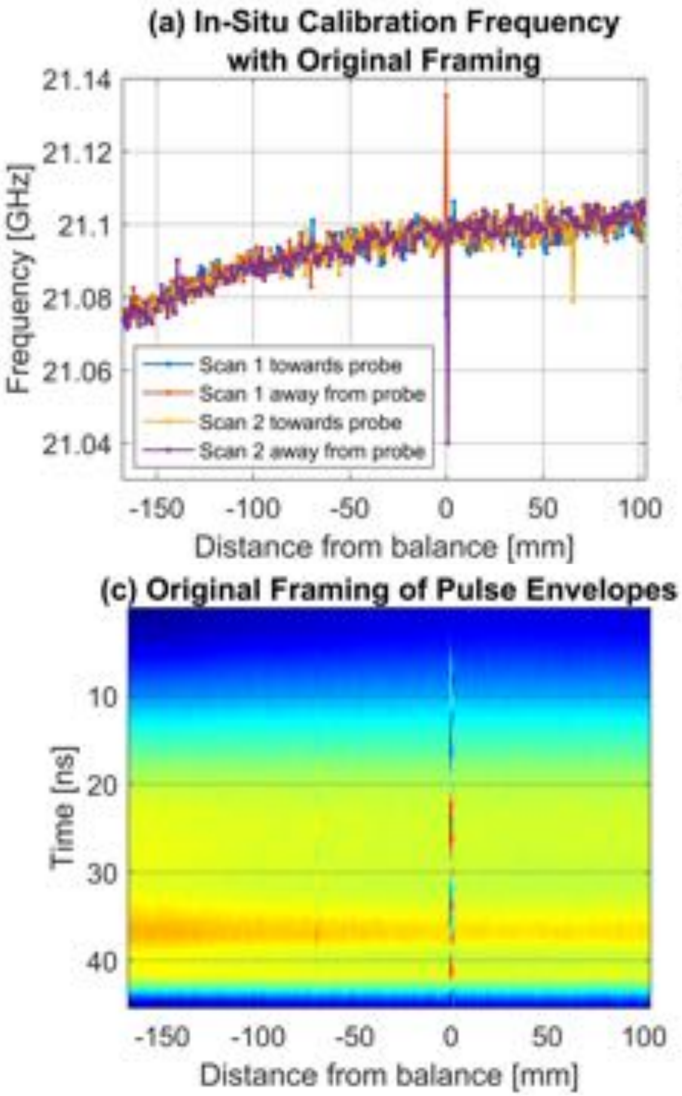
We compare BLR measurements with a slow, commercial interferometer to test accuracy.

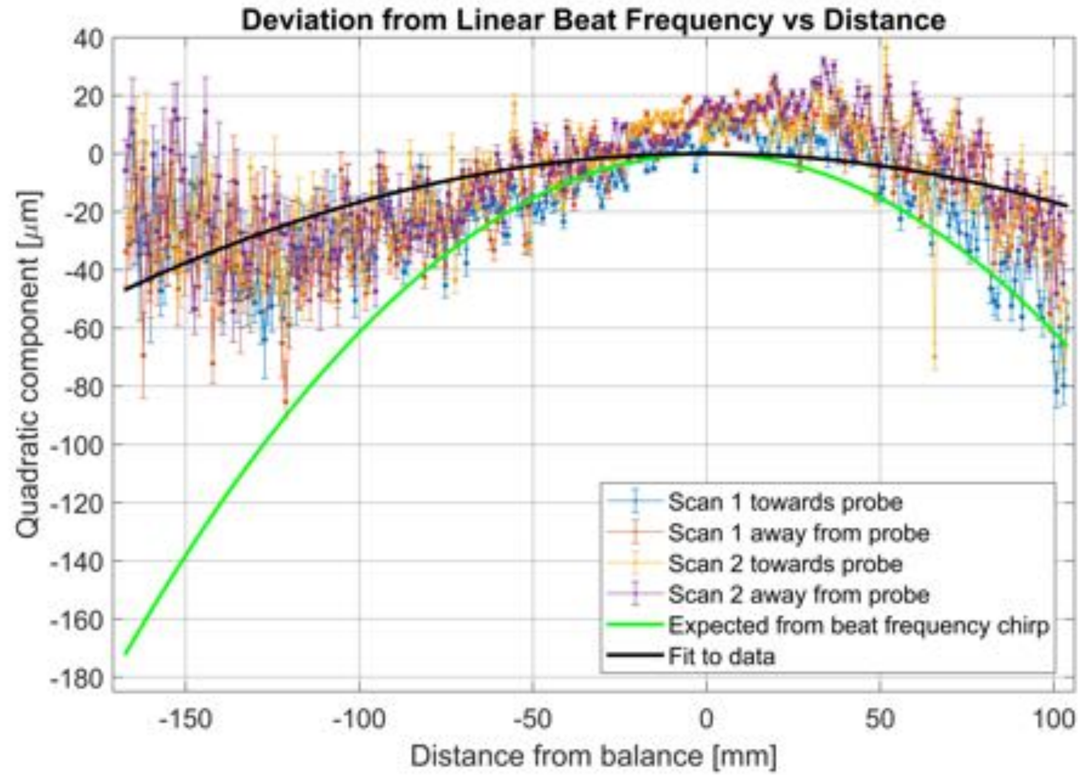
Interference between the target and the in-situ mirror extends the potential measurement range to a total scan range of 270 mm.





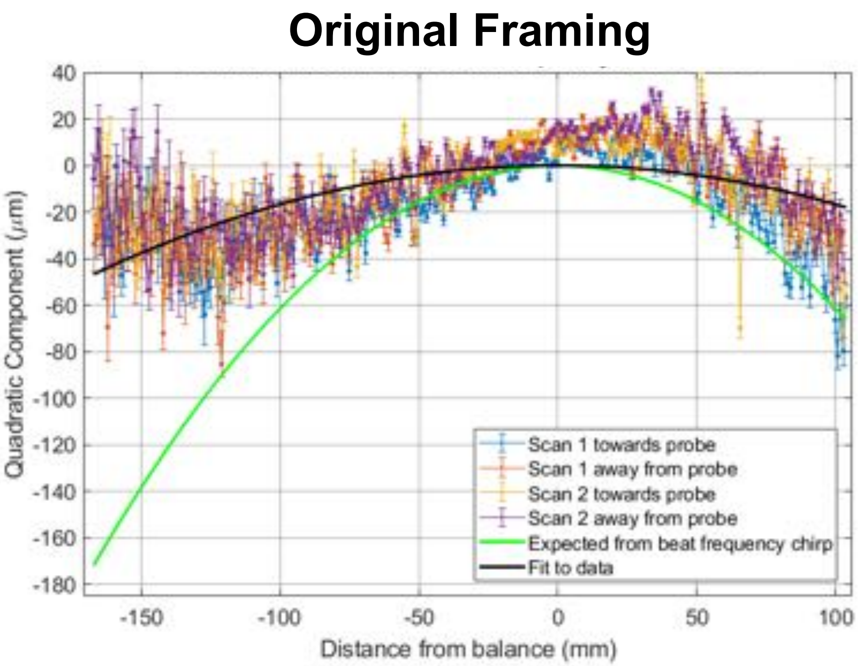
Scanned measurements proved difficult to analyze because the temporal alignment is harder.

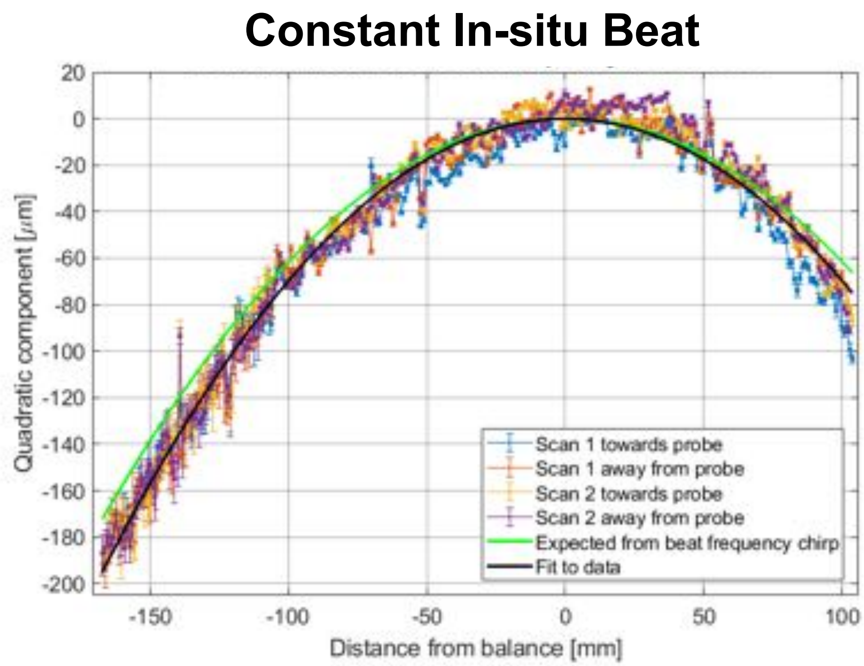




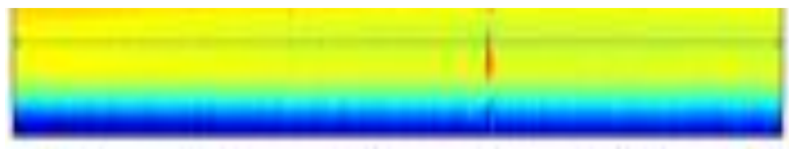
Each pulse is individually aligned in time, so each measurement has substantial independent error in its beat frequency.

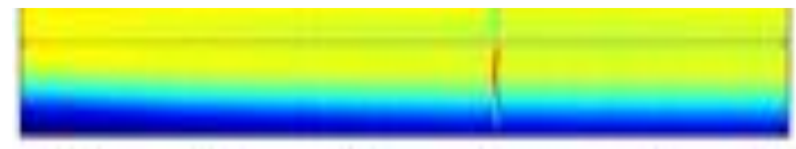
Changing the temporal alignment to keep the in-situ calibration frequency constant is a large improvement.



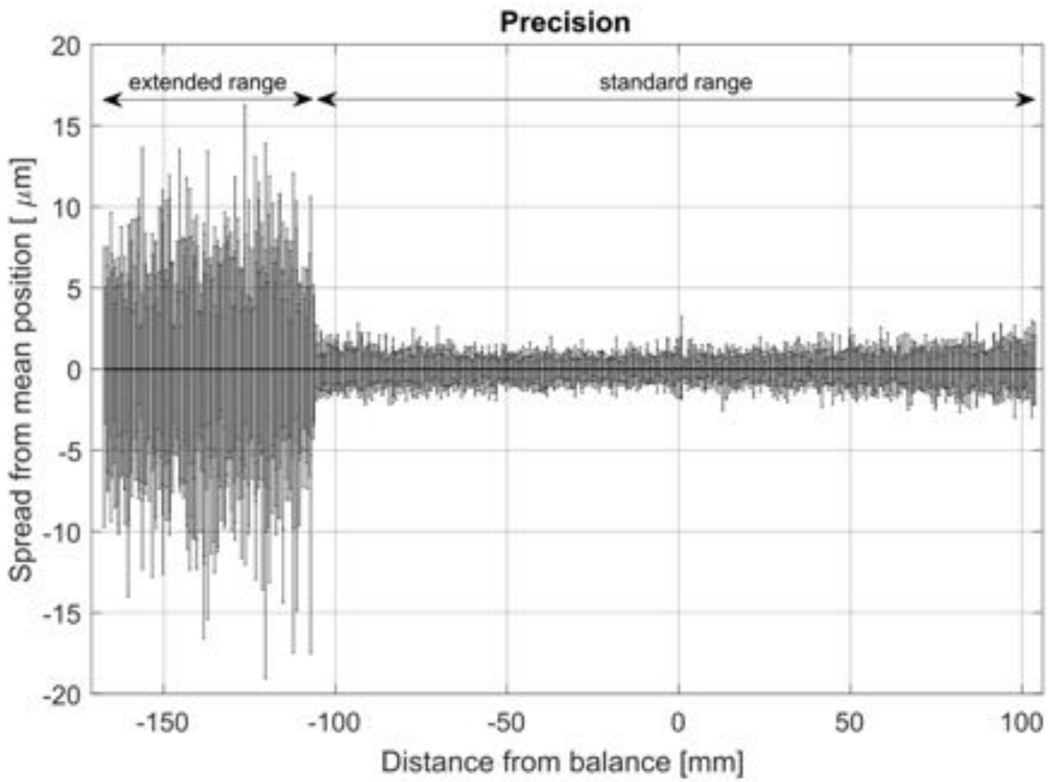


Data closely follows the expected quadratic curvature and no higher order effects are visible. Alignment of temporal envelopes is also improved.





Sequential pulses give very consistent positions.



- These bars show the full spread from the mean value measured at each position.
- Overall standard deviations are 0.7 microns for standard range and 5 microns for extended range.

Summary

- High-order fiber dispersion has a detrimental impact on dispersive Fourier transforms in BLR.
- Distortions in the dispersive Fourier transform can be corrected in analysis, but this must be done carefully.
- A consistent in-situ calibration signal is very helpful for analyzing data.
- **When these effects are taken into account, measured positions are very accurate (~10^{-4} of the range).**

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Quantifying Beat Frequency vs Distance

The transit time of light through fiber is written using a Taylor expansion.

$$t(\omega - \omega_0) = \beta_1 L(\omega_0) + \beta_2 L(\omega - \omega_0) + \frac{1}{2}\beta_3 L(\omega - \omega_0)^2$$

These coefficients are related to the index of refraction.

To write the optical frequency as a function of time, we invert this equation by solving for ω.

$$\omega(t) = \omega_0 + \frac{1}{\beta_2 L} t - \frac{\beta_3 L}{2(\beta_2 L)^3} t^2 + \cdots$$

Quantifying Beat Frequency vs Distance

- Taking the delay of the reference pulse to be zero, we can write the optical frequency of a pulse arriving at delay τ relative to the reference as:

$$\omega(t+\tau) = \omega_0 + \frac{1}{\beta_2 L}(t+\tau) - \frac{\beta_3 L}{2(\beta_2 L)^3}(t+\tau)^2$$

- The beat frequency is the difference between the optical frequencies of the target and reference.

$$\Omega(t) = \omega(t+\tau) - \omega(t)$$

$$\Omega(t) = \frac{\tau}{\beta_2 L} - \frac{\beta_3 L \tau^2}{2(\beta_2 L)^3} - \frac{\beta_3 L \tau t}{(\beta_2 L)^3}$$

$$= \frac{1}{\beta_2 L}(\tau - k\tau^2 + \boxed{2kt\tau)}$$

This is the beat frequency chirp caused by the imperfect Fourier transform. We estimate this term to correct for the distortion.