Frequency Scanned Interferometer for LC Tracker Alignment

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Physics Goals and Background

- To Carry out R&D toward a direct, quasi real time and remote way of measuring positions of critical tracker detector elements during operation.
- The 1-Dimension accuracy of absolute distance is on the order of 1 micron.
- Basic idea: To measure hundreds of absolute point-to-point distances of tracker elements in 3 dimensions by using an array of optical beams split from a central laser. Absolute distances are determined by scanning the laser frequency and counting interference fringes.
- Assumption: Thermal drifts in tracker detector on time scales too short to collect adequate data samples to make precise alignment.

Background – some optical alignment systems

- RASNIK system: used in L3, CHORUS and CDF
- Frequency Scanned Interferometer(FSI): used in ATLAS

  [*A.F. Fox-Murphy et al., NIM A383, 229(1996)*]
- Focusing here on FSI system for LC tracker detector

Principle of Distance Measurement

- The measured distance can be expressed by

$$R = \frac{c\Delta N}{2\bar{n}_g \Delta \nu} + \text{constant end corrections}$$

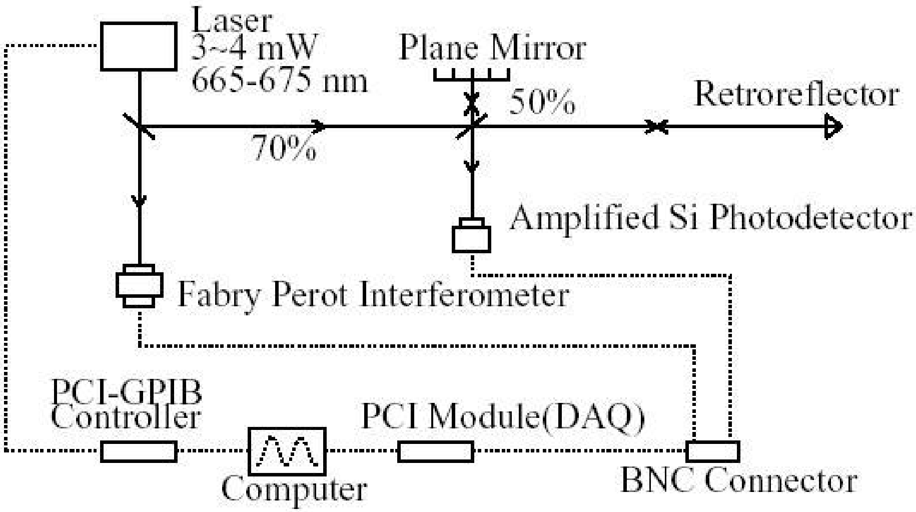
c - *speed of light*, ΔN – *No. of fringes*, $\Delta \nu$ - *scanned frequency*
n_g – *average refractive index of ambient atmosphere*

- Assuming the error of refractive index is small, the measured precision is given by:

$$(\sigma_R / R)^2 = (\sigma_{\Delta N} / \Delta N)^2 + (\sigma_{\Delta \nu} / \Delta \nu)^2$$

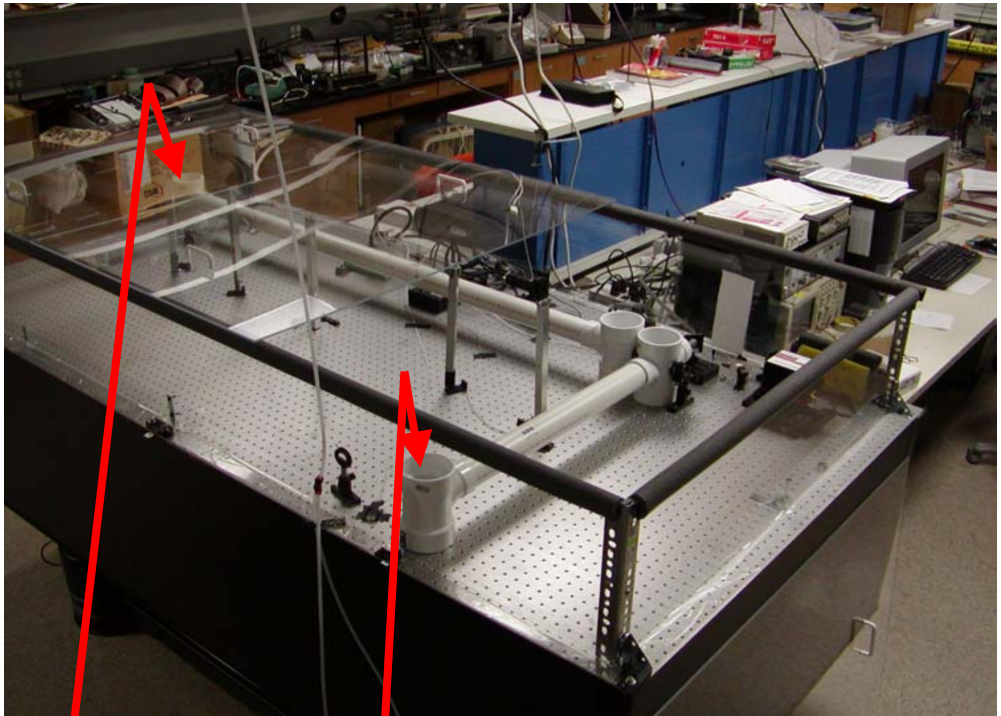
Example: R = 1.0 m, $\Delta \nu = 6.6$ *THz*, $\Delta N \sim 2R\Delta\nu/c = 44000$
To obtain $\sigma_R \simeq 1.0\ \mu m$, *Requirements:* $\sigma_{\Delta N} \sim 0.02$, $\sigma_{\Delta \nu} \sim 3$ *MHz*

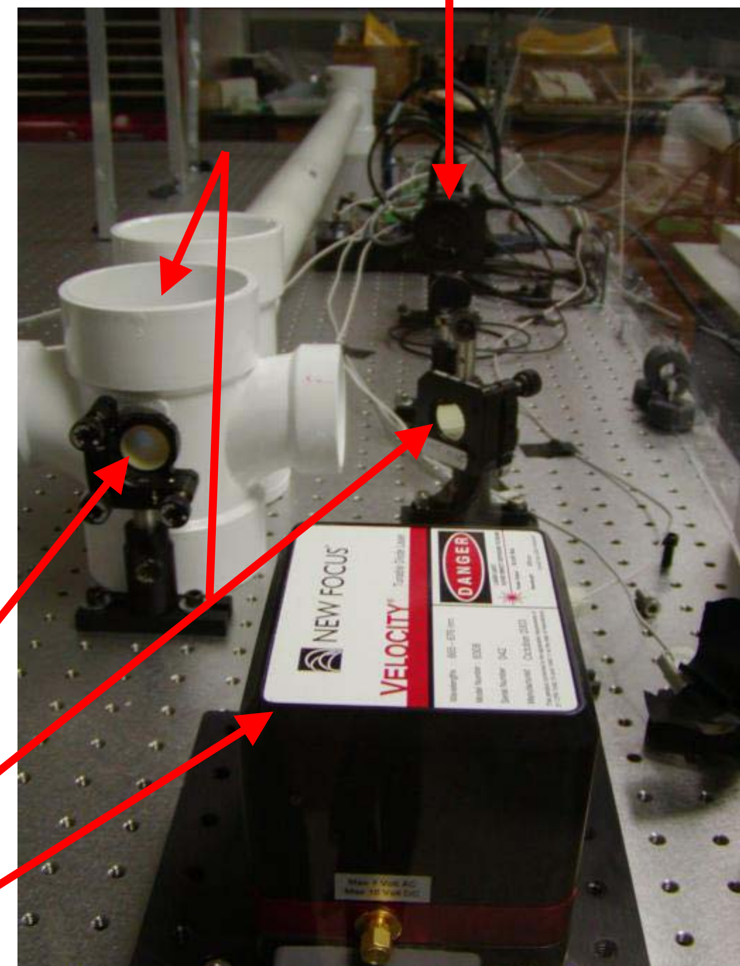
FSI Demonstration System



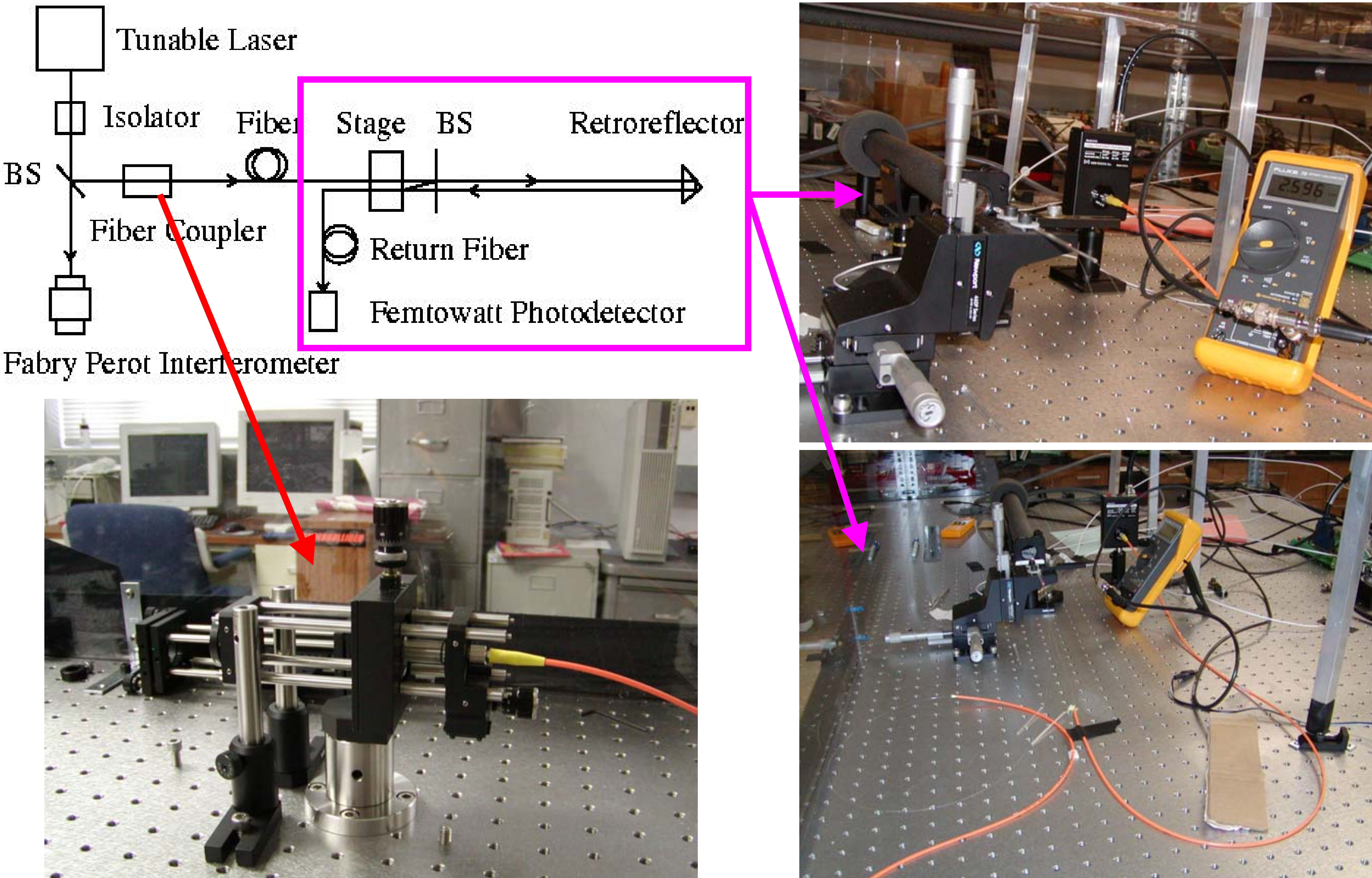
- ✶Tunable Laser: New Focus Velocity 6308, 3-4 mW, 665.1-675.2 nm.
- ✶Retroreflector: Edmund, D=2", angle tolerance: ±3 arc seconds.
- ✶Photodiode: Thorlabs PDA55, DC-10MHz, Amplified Si Detector, 5 Gain Settings.
- ✶Thorlabs Fabry-Perot Interferometer SA200, high finesse(>200) to determine the relative frequency precisely, Free Spectra Range (FSR) is 1.5 GHz, with peak FWHM of 7.5 MHz.
- ✶ Thermistors and hygrometer are used to monitor temperature and humidity respectively.
- ✶PCI Card: NI-PCI-6110, 5 MS/s/ch, 12-bit simultaneous sampling DAQ.
- ✶PCI-GPIB Card: NI-488.2, served as remote controller of laser.
- ✶Computers: 1 for DAQ and laser control, 3 for analysis.

FSI Demonstration System In Lab



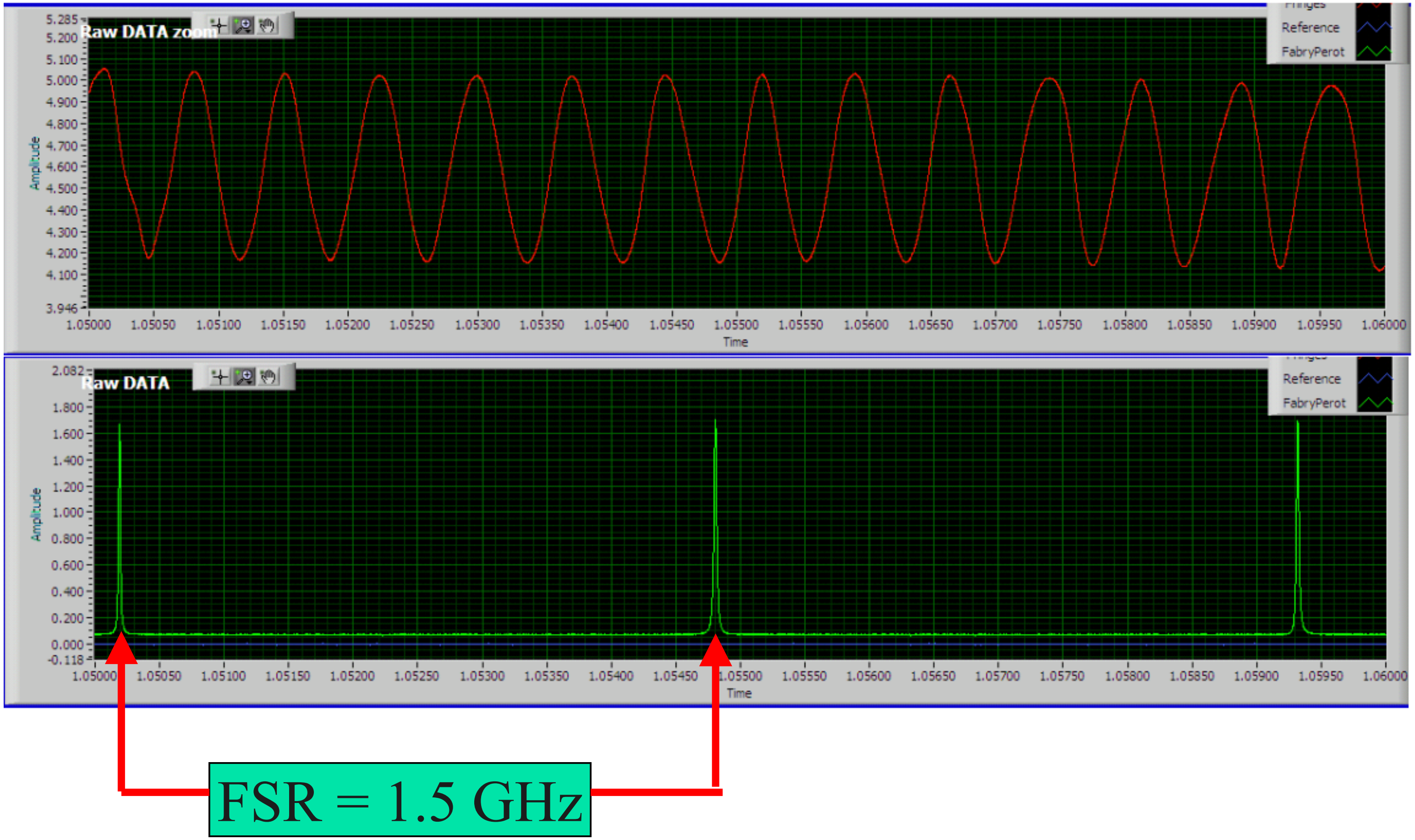


FSI with Optical Fibers In Lab



Fringe and Frequency

- Fringe is intensity oscillation of two interference laser beams while scanning.



Multi-Distance-Measurement Techniques

- Assuming a vibration with one frequency: $x_{vib}(t) = a_{vib} \cos(2\pi f_{vib} t + \phi_{vib})$
- Fringe phase at time t: $\Phi(t) = 2\pi[OPD^{true} + 2x_{vib}(t)]/\lambda(t)$

$$\Delta N = [\Phi(t) - \Phi(t0)]/2\pi = OPD^{true} \bullet \Delta\nu/c + [2x_{vib}(t)/\lambda(t) - 2x_{vib}(t0)/\lambda(t0)] \quad (1)$$

- If we assume $\lambda(t) \sim \lambda(t0) = \lambda$, measured OPD can be written as,

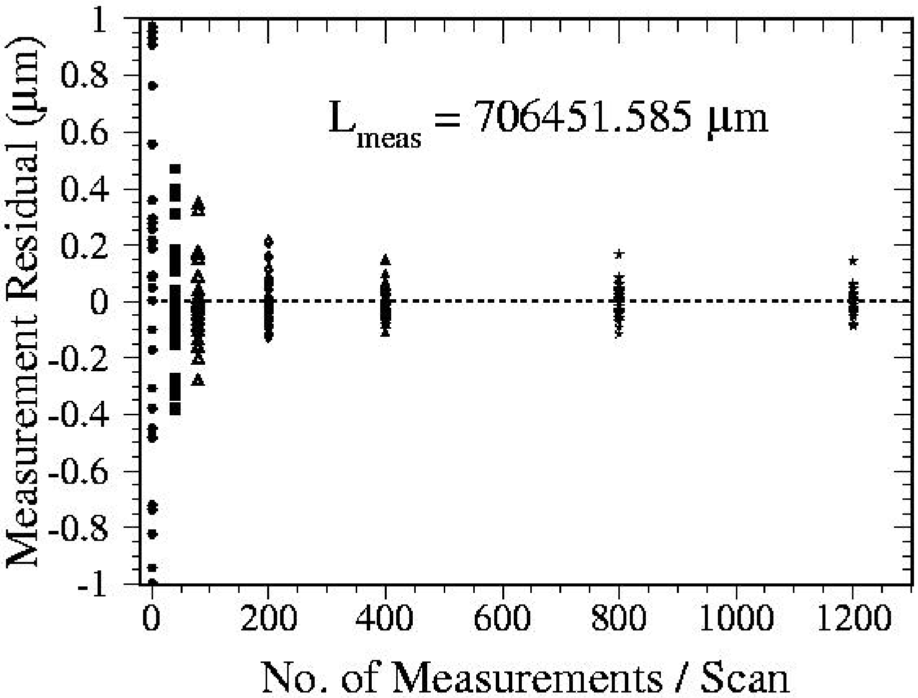
$$OPD^{measured} = OPD^{true} - 4a_{vib} \times (\nu/\Delta\nu) \times \sin(\pi f_{vib}(t-t0)) \times \sin(\pi f_{vib}(t+t0) + \phi_{vib}) \quad (2)$$

Two new analysis techniques presented:

1. If the measurement window size (t – t0) is fixed and the window to measure a set of OPD is sequentially shifted, the effects of vibration will be evident. The average of all measured OPD is regarded as the final value of the measured distance. This new analysis technique is called **'slip measurement window with fixed size'**. If the number of measurements is large enough, the vibration effect and uncertainties from fringe/frequency determination can be suppressed significantly.
2. In order to extract the amplitude and frequency of the vibration, another technique called **'slip measurement window with fixed start point'** was presented. If t0 is fixed, the measurement window size is enlarged for each shift. A periodical oscillation of a set of measured OPD reflects the amplitude and frequency of vibration.

Absolute Distance Measurements

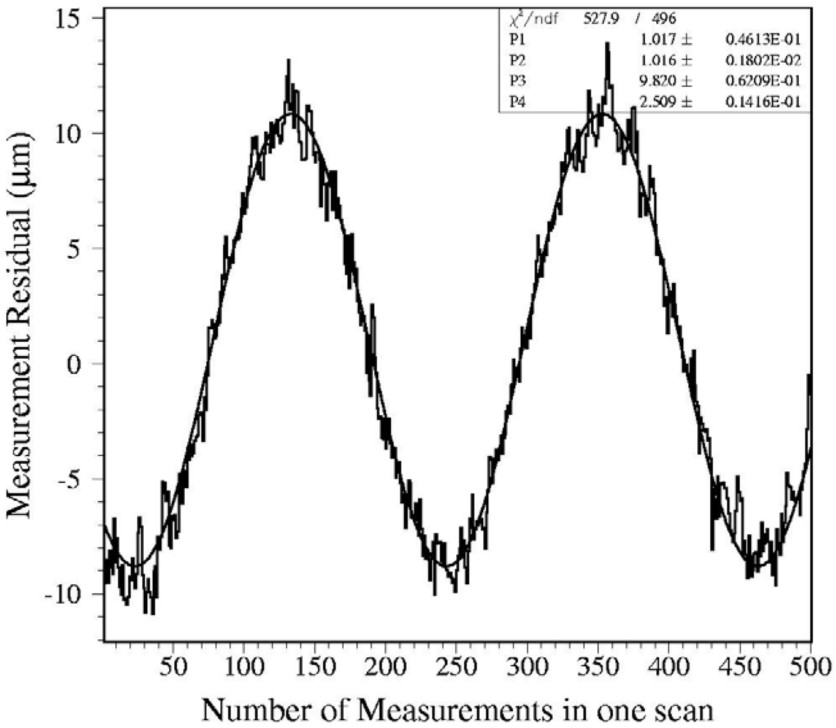
- The measurement spread of 30 sequential scans performed vs. number of measurements/scan(N_{meas}) shown below. The scanning rate was 0.5 nm/s and the sampling rate was 125 KS/s. It can be seen that the distance errors decrease with increasing N_{meas}. If N_{meas} = 1200, the standard deviation (RMS) of distance measurements is ***50 nm***, the average value of measured distances is ***706451.585 µm***. **The relative accuracy is 70 ppb**.



Amplitude and Frequency of Vibration

In order to test the second analysis technique which was developed to extract the amplitude and frequency of vibration, a PZT transducer was employed to produce vibration of the retroreflector. The amplitude and frequency of controlled vibration was set to ***1 ± 0.02 Hz*** with amplitude of ***0.14 ± 0.02 μm*** .Since the vibration is magnified for FSI during the scan, the expected reconstructed vibration amplitude is ***10.0 ± 1.4 μm.***

The extracted vibration frequency and amplitude using this technique is ***1.016 ± 0.002 Hz*** and ***9.82 ± 0.06 μm***, respectively.



Error Estimations

- Error from uncertainties of fringe and frequency determination, dR/R ~ 1.27 ppm; if N_{meas} = 1200, dR/R ~ 51 ppb
- Error from vibration. dR/R ~ 0.4 ppm; if N_{meas} = 1200, dR/R ~ 13 ppb
- Error from thermal drift. Temperature fluctuations are well controlled down to 0.5 mK(RMS) in Lab by plastic box on optical table and PVC pipes shielding the volume of air near the laser beam. An air temperature change of 1 ^{0}C will result in a 0.9 ppm change of refractive index at room temperature. The drift will be magnified during scanning. if N_{meas} = 1200, dR/R ~ 0.9 ppm/K × 0.5mK × Ω(94) ~ 42 ppb.
- Error from air humidity and pressure, dR/R ~ 10 ppb.

The total error from the above sources is ~ 68 ppb which agrees well with the measured residual spread of 70 ppb.

Systematic Error Estimations

The major systematic bias comes from uncertainty of the Free Spectral Range (FSR) of the Fabry Perot interferometer used to determine scanned frequency range precisely, the relative error would be dR/R ~ 50 ppb if the FSR was calibrated by an wavemeter with a precision of 50 ppb. A wavemeter of this precision was not available for the measurement described here.

Systematic bias from uncertainties of temperature, air humidity and barometric pressure scales should have negligible effect.

The total systematic error of above sources is ~ 50 ppb.

Summary and Outlook

- Two simple FSI demonstration systems, with or without optical fibers, were constructed to make high-precision absolute differential distance measurements.
- A high accuracy of 50 nm for a distance of about 0.7 meter under laboratory conditions was achieved.
- Two new multi-distance-measurement analysis techniques were presented to improve absolute distance measurement and to extract the amplitude and frequency of vibration.
- Major error sources were estimated, and the expected error was in good agreement with measured residual spread from real data.
- One paper, 'High-precision Absolute Distance Measurement using Frequency Scanned Interferometry', was submitted to Optics Letters.

Summary and Outlook

- Optical fibers are necessary for remote inner tracker interferometer. The key issue for optical fiber FSI is that the geometrical efficiency are extremely low, e.g. 6.25e-10 for a distance of 0.5 m, a novelty of our design is the use of a GRIN lens to collimate the output beam from the optical fiber which improves the density of the output beam by a factor of approximately 1000. It makes possible to split the laser beam into many beams to serve a set of interferometers simultaneously.
- The technique shown here does NOT give comparable accuracy under realistic detector conditions (poorly controlled temperature).
- We are investigating dual-laser scanning technique used by Oxford ATLAS group currently.
- Michigan group rapidly coming up to speed on technology, but much work lies ahead.