

Frequency Scanned Interferometer for ILC Tracker Alignment



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- Barrel – 5 layers, inner/outer radii – 20/125 cm,
Silicon drift detector or microstrips

$$\sigma_{r\phi} = 10 \mu\text{m}, \sigma_{rz} = 20 \mu\text{m}$$

- Forward – 5 disks, double-sided silicon microstrips

$$\sigma_{r\phi} = 7 \mu\text{m}, \sigma_{rz} = 7 \mu\text{m}$$

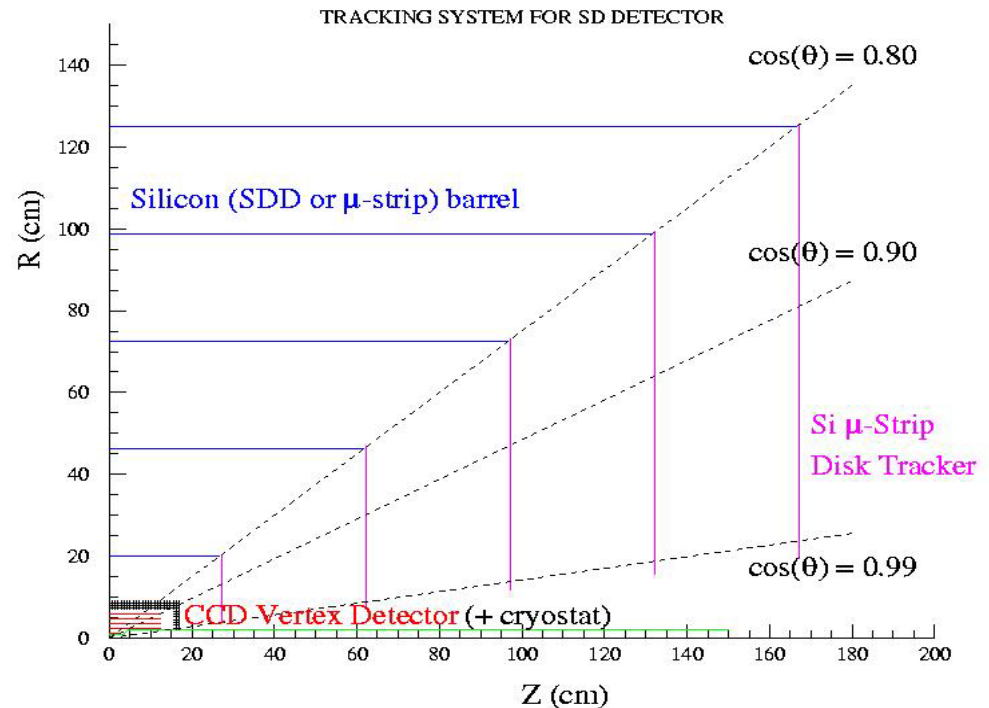
- Coverage - $|\cos(\theta)|=0.99$

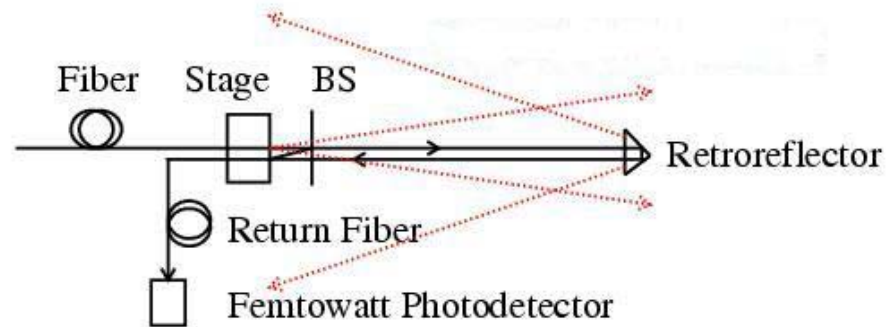
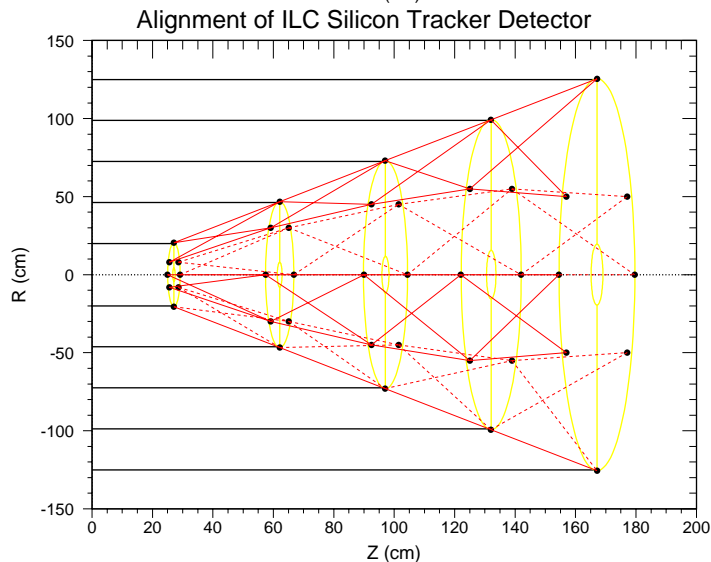
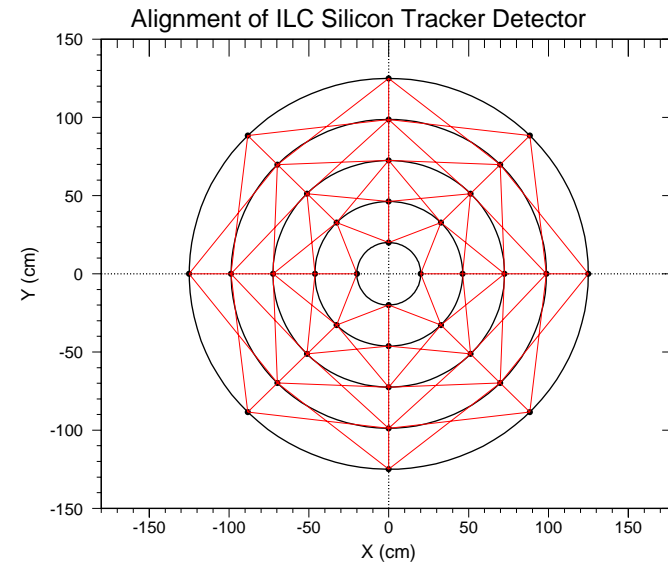
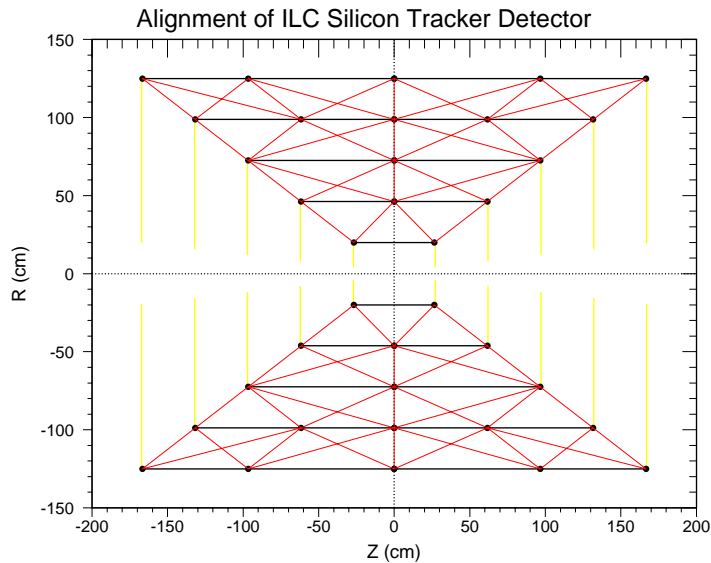
- Boundary between barrel and forward disks - $|\cos(\theta)|=0.80$

- Wafer size – 10cm x 10cm

- Wafer thickness – 150 μm

Ref: SLAC-R-570 (2001)
hep-ex/0106058





752 point-to-point distance measurements

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,
will be used in ATLAS and CMS
- Frequency Scanned Interferometer(FSI): will be used in ATLAS SCT
[A.F. Fox-Murphy et.al., NIM A383, 229(1996); P.A. Coe et.al., Meas. Sci & Tech. 15(11):2175(2004)]
- Focusing here on FSI system for ILC tracker detector

- The measured distance can be expressed by

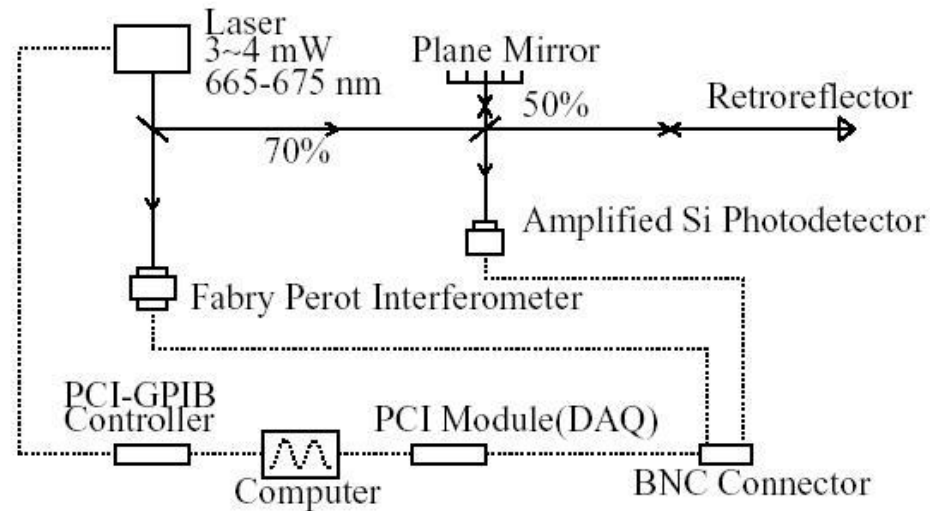
$$R = \frac{c\Delta N}{2\bar{n}_g\Delta\nu} + \text{constant end corrections}$$

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:

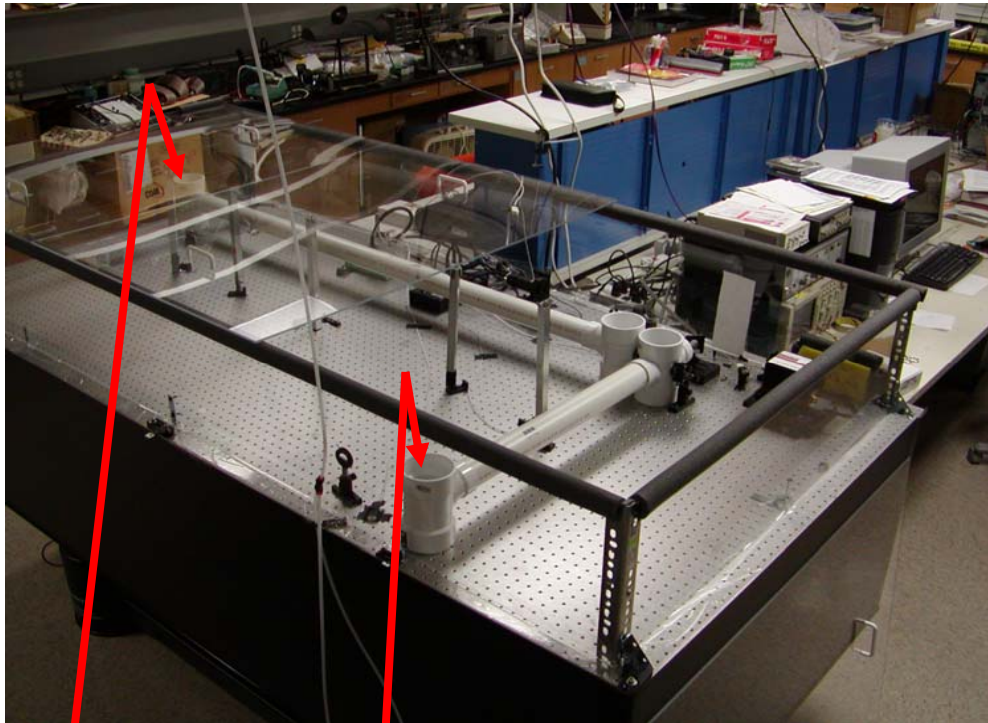
$$(\sigma_R / R)^2 = (\sigma_{\Delta N} / \Delta N)^2 + (\sigma_{\Delta\nu} / \Delta\nu)^2$$

Example: R = 1.0 m, Δν = 6.6 THz, ΔN ~ 2RΔν/c = 44000
To obtain σ_R ≅ 1.0 μm, Requirements: σ_{ΔN} ~ 0.02, σ_{Δν} ~ 3 MHz



- ★ **Tunable Laser: New Focus Velocity 6308, 3-4 mW, 665.1-675.2 nm.**
- ★ **Retroreflector: Edmund, D=1", 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 Spectral 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 (I)



Photodetector

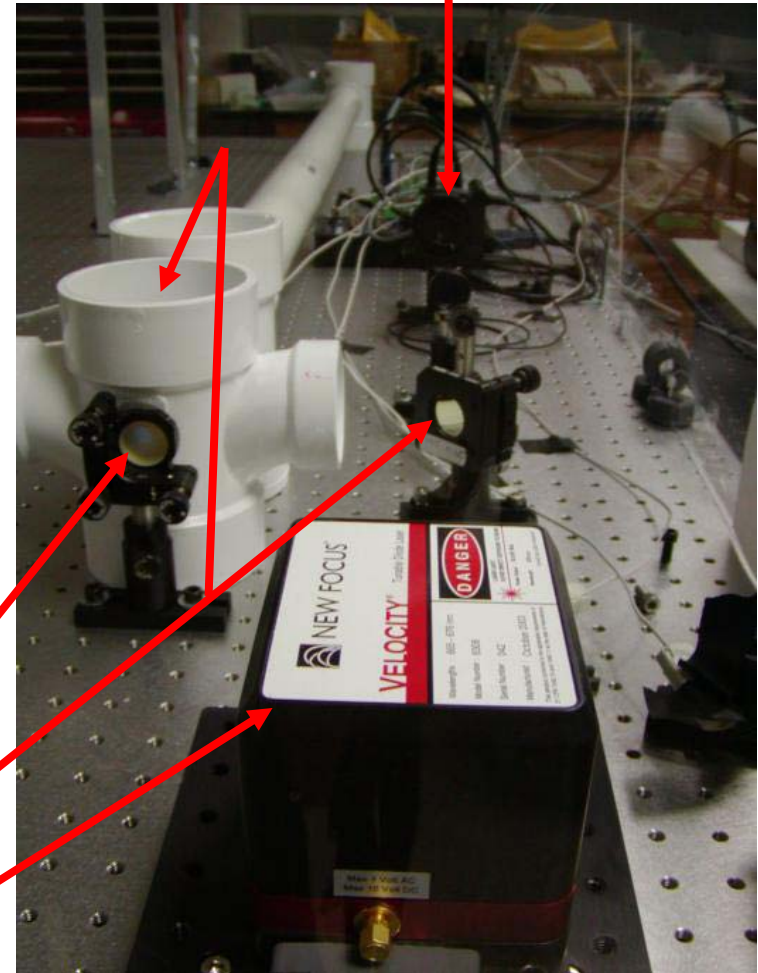
Retroreflector

Mirror

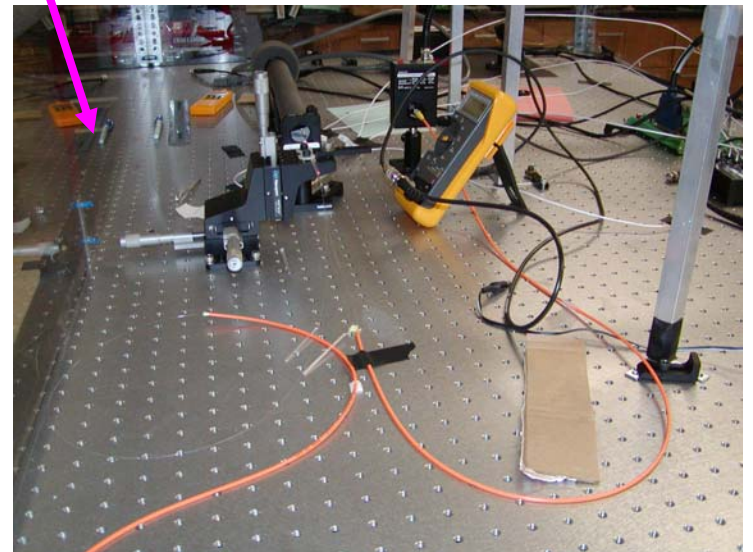
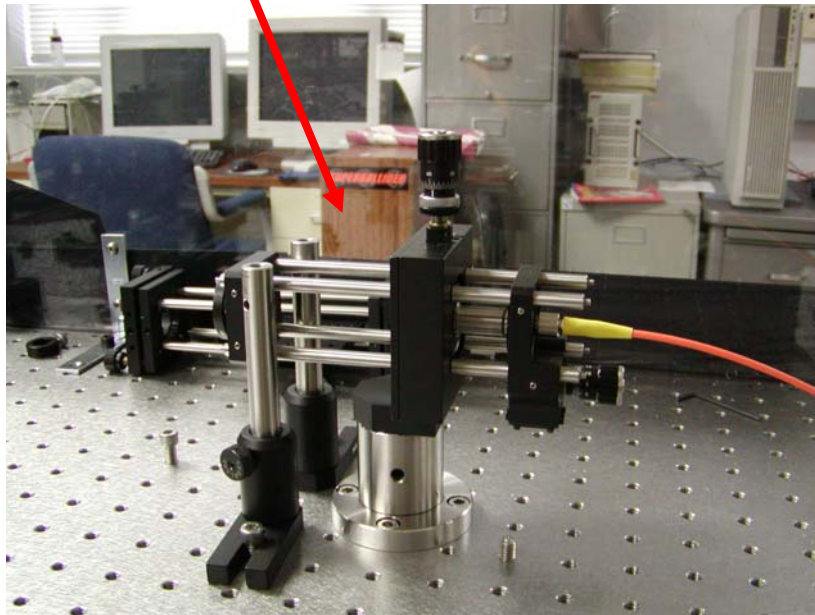
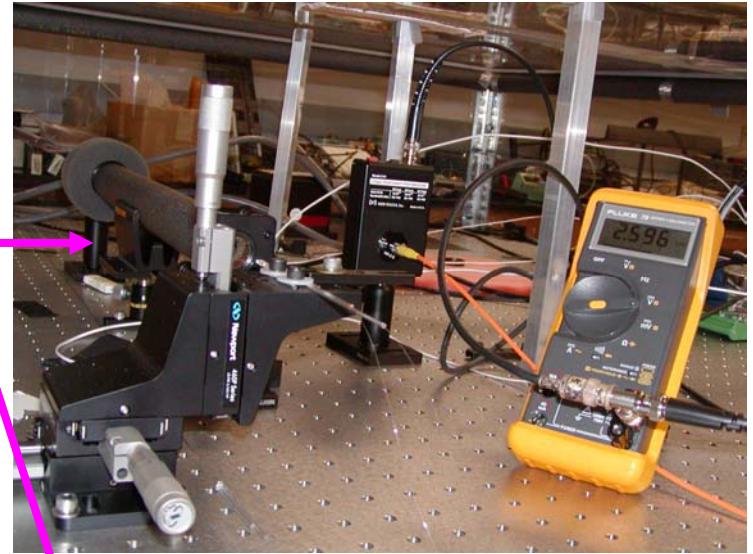
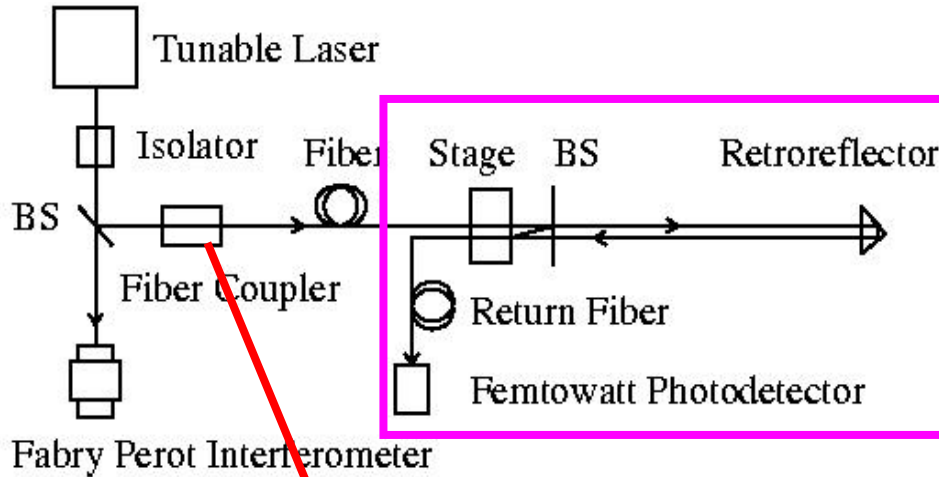
Beamsplitters

Laser

Fabry-Perot Interferometer



FSI with Optical Fibers (II)

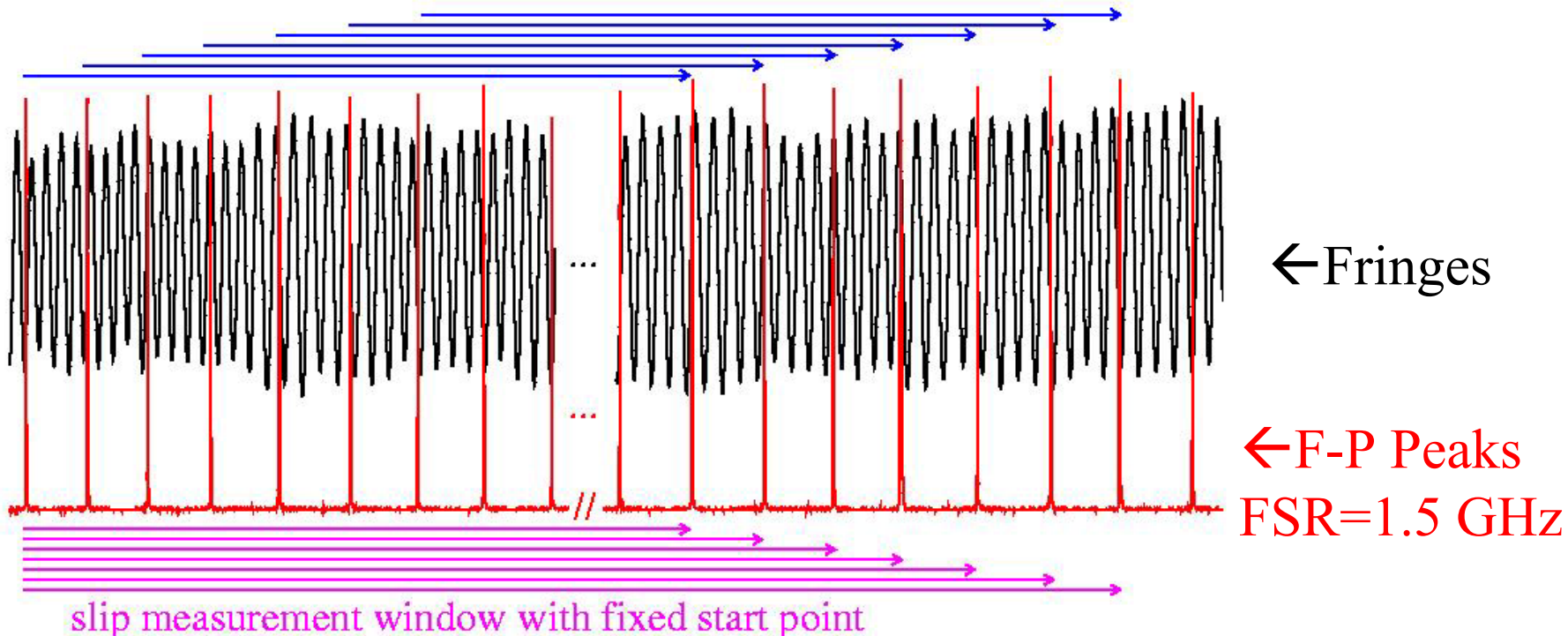




Two Multiple-Measurement Techniques

→ Fix the measurement window size ($t-t_0$) and shift the window one F-P peak forward each time to make a set of distance measurements. The average value of all measurements is taken to be the final measured distance of the scan.

slip measurement window with fixed size



→ If t_0 is fixed, the measurement window size is enlarged one F-P peak for each shift. An oscillation of a set of measured OPD reflects the amplitude and frequency of vibration.

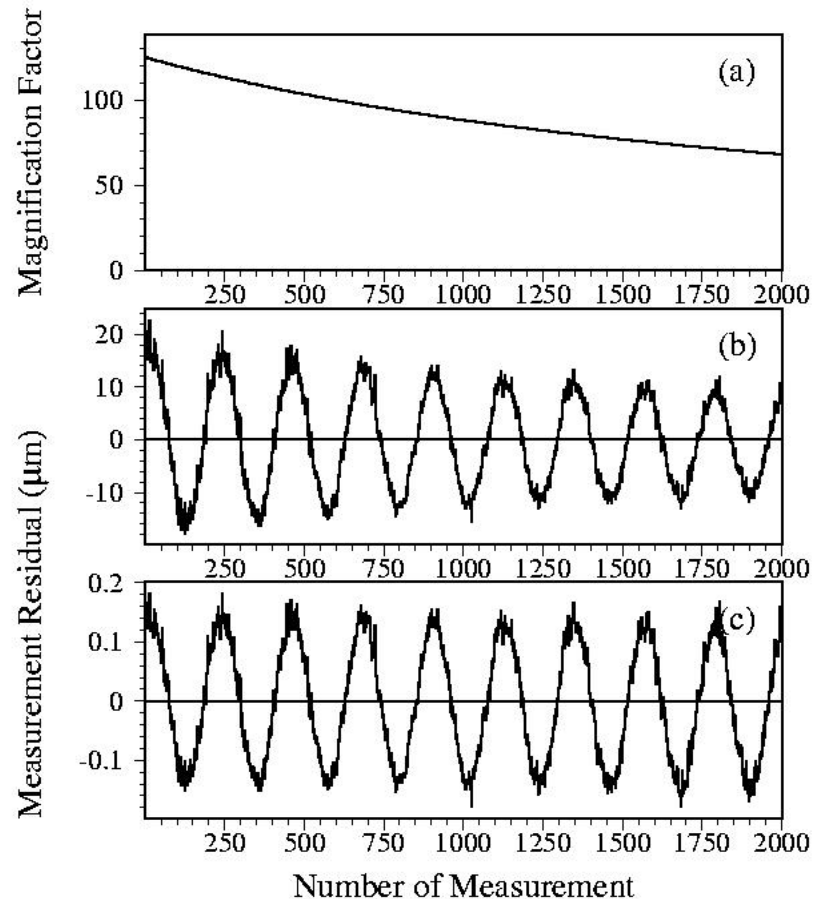
- A PZT transducer was employed to produce controlled vibration of the retroreflector, $f_{\text{vib}} = 1.01 \pm 0.01$ Hz, $\text{amp}_{\text{vib}} = 0.14 \pm 0.02$ μm

- Magnification factor Ω for each distance measurement depends on the scanned frequency of the laser beam in the measurement window with smaller Ω for larger window - plot(a). Since the vibration is magnified by Ω for FSI during the scan, the expected reconstructed vibration amplitude is ~ 10.0 μm assuming $\Omega \sim 70$ - plot(b).

→ The extracted vibration - plot(c)

$$f_{\text{vib}} = 1.007 \pm 0.0001 \text{ Hz,}$$

$$\text{amp}_{\text{vib}} = 0.138 \pm 0.0003 \mu\text{m}$$



* Controlled vibration source with very low amplitude

$$f_{\text{vib}} = 1.01 \pm 0.01 \text{ Hz}, \text{ amp}_{\text{vib}} = 9.5 \pm 1.5 \text{ nanometers}$$

* Measured vibration

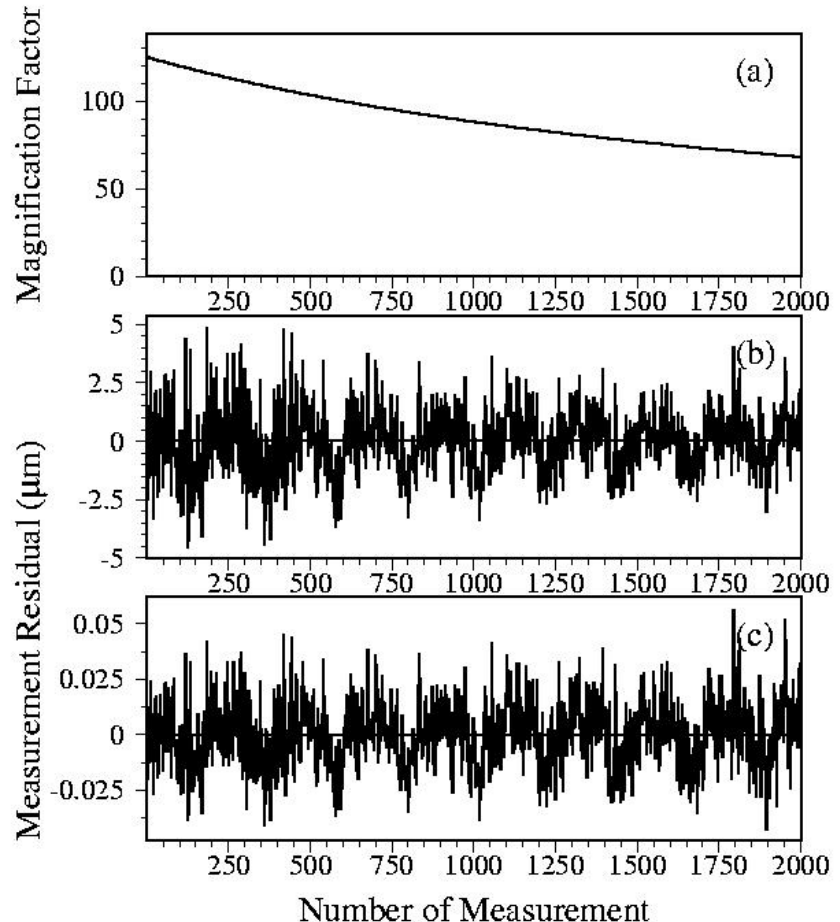
$$f_{\text{vib}} = 1.025 \pm 0.002 \text{ Hz},$$

$$\text{amp}_{\text{vib}} = 9.3 \pm 0.3 \text{ nanometers}$$

→ Measurable range

$$f_{\text{vib}} = 0.1 \sim 100 \text{ Hz},$$

$$\text{amp}_{\text{vib}} = \text{few nm} \sim 0.4 \mu\text{m}$$



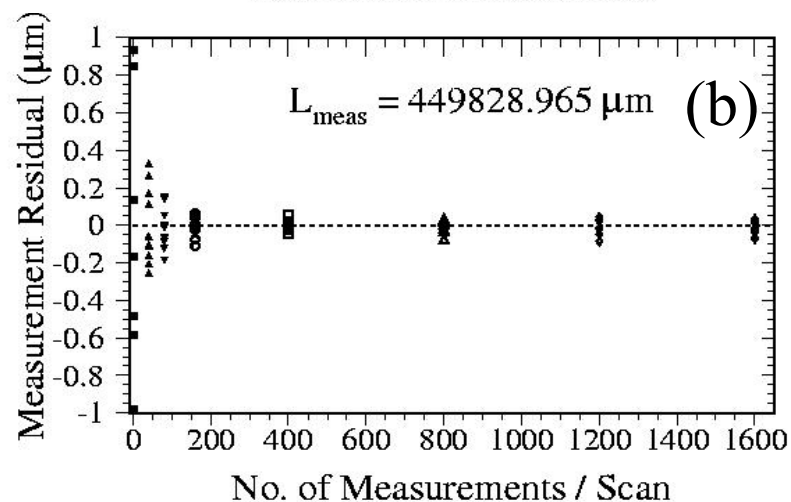
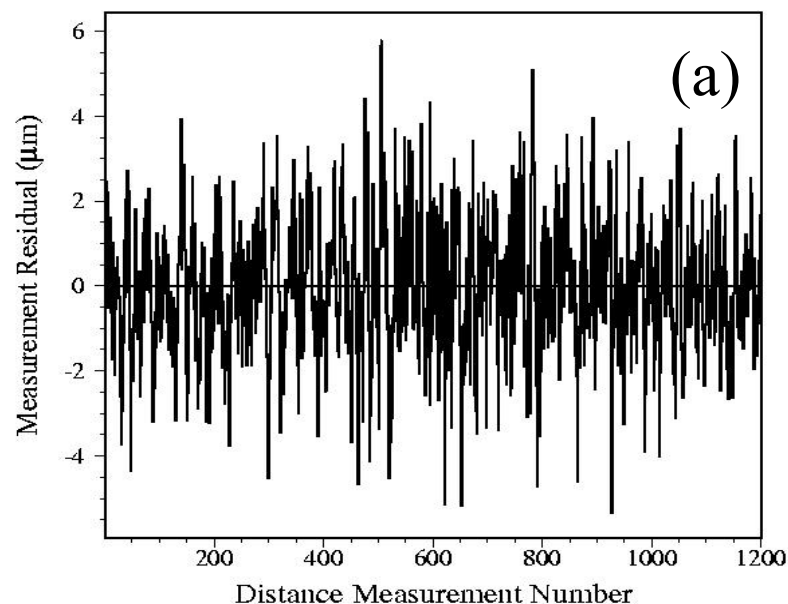
- The scanning rate was 0.5 nm/s and the sampling rate was 125 KS/s.
- The measurement residual versus the No. of measurements/scan shown in Fig.,
(a) for one typical scan,
(b) for 10 sequential scans.

→ It can be seen that the distance errors decrease with increasing N_{meas} .

$N_{\text{meas}}=1$, precision=1.1 μm (RMS)

$N_{\text{meas}}=1200$, precision=41 nm (RMS)

→ Multiple-distance measurement technique is well suited for reducing vibration effects and uncertainties from fringe & frequency determination, BUT not good for drift errors such as thermal drift.



Each precision listed is for standard deviation (RMS) of 10 scans.

Distance (cm)	Precision(μm)		Scanning Rate (nm/s)	FSI System (Optical Fiber or Air)
	open box	closed box		
10.385107	1.1	0.019	2.0	Optical Fiber FSI
10.385105	1.0	0.035	0.5	Optical Fiber FSI
20.555075	-	0.036, 0.032	0.8	Optical Fiber FSI
20.555071	-	0.045, 0.028	0.4	Optical Fiber FSI
41.025870	4.4	0.056, 0.053	0.4	Optical Fiber FSI
44.982897	-	0.041	0.5	Optical Fiber FSI
61.405952	-	0.051	0.25	Optical Fiber FSI
65.557072	3.9, 4.7	-	0.5	Air FSI
70.645160	-	0.030, 0.034, 0.047	0.5	Air FSI

* Distance measurement precisions for various setups using the multiple-distance-measurement technique.

Two FSI Demonstration Systems Constructed in the Lab:

Optical fiber FSI and air transport FSI

Measured Distance: 10 cm – 60 cm

Measured Precision:

~ 50 nm by using new multiple-distance measurement technique under well controlled laboratory conditions.

Vibration Measurement:

0.1-100 Hz, amplitude as low as few nanometers, can be extracted precisely using new vibration extraction technique.

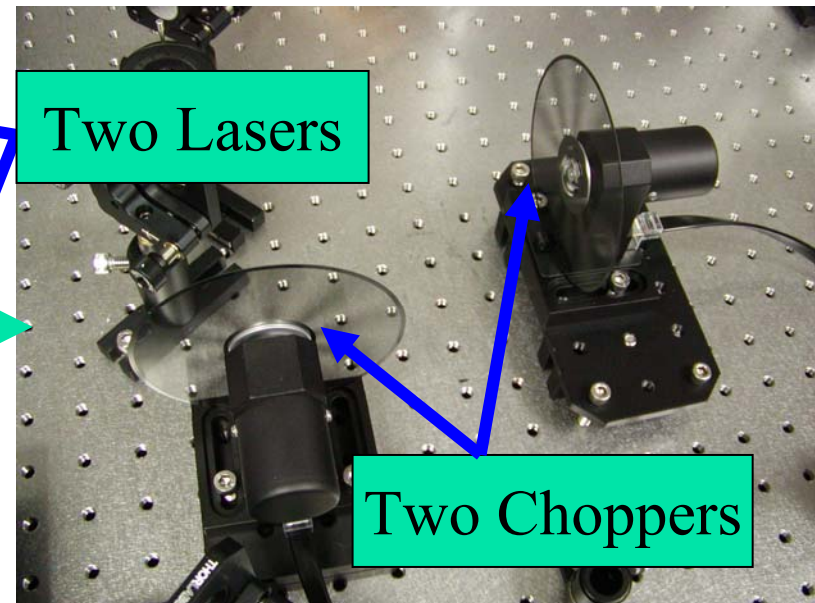
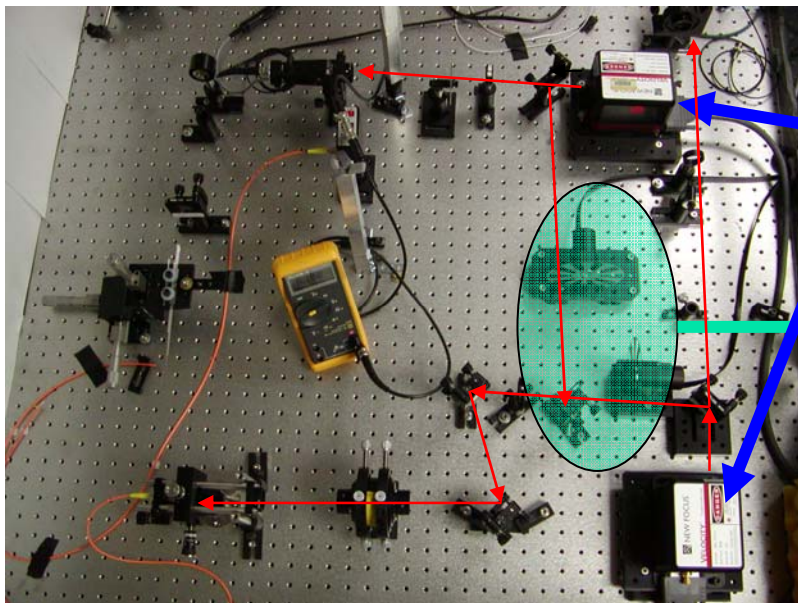
Reference:

“High-precision absolute distance and vibration measurement with frequency scanned interferometry”, physics/0409110
Applied Optics, Vol.44, 3937-3944, (2005)

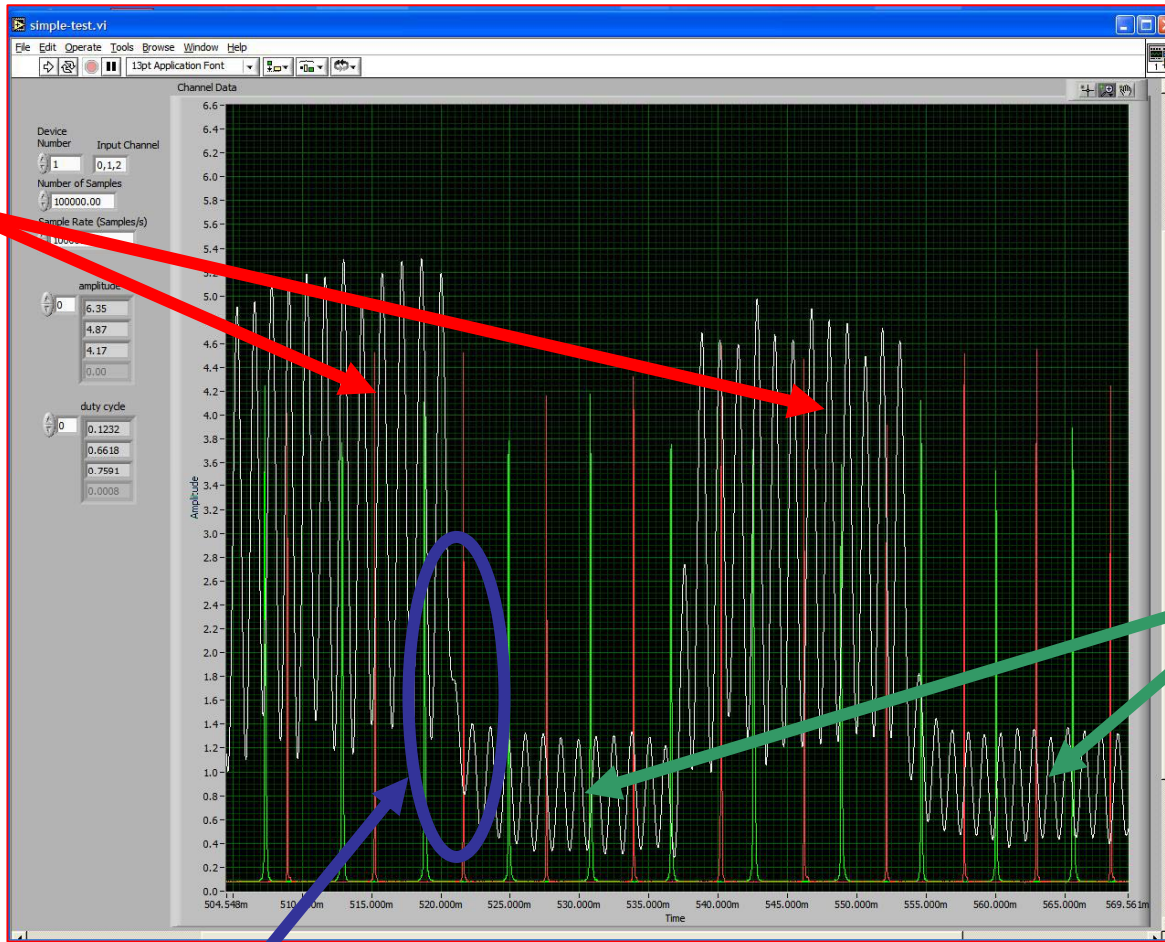
Dual-Laser FSI (III)

→ A dual-laser FSI intended to reduce the drift errors is under study currently. Two lasers are operating simultaneously, but the laser beams are isolated by using two choppers.

$$\begin{aligned} \text{Laser \#1: } D_1 &= D_{\text{true}} + \Omega_1 \varepsilon_1 \\ \text{Laser \#2: } D_2 &= D_{\text{true}} + \Omega_2 \varepsilon_2 \\ \text{Drift errors: } \varepsilon_1 &\approx \varepsilon_2 = \varepsilon \\ D_{\text{true}} &= (D_2 - \rho D_1) / (1 - \rho), \\ \text{Where } \rho &= \Omega_2 / \Omega_1 \end{aligned}$$



Fringes & F-P Peaks (dual-laser)



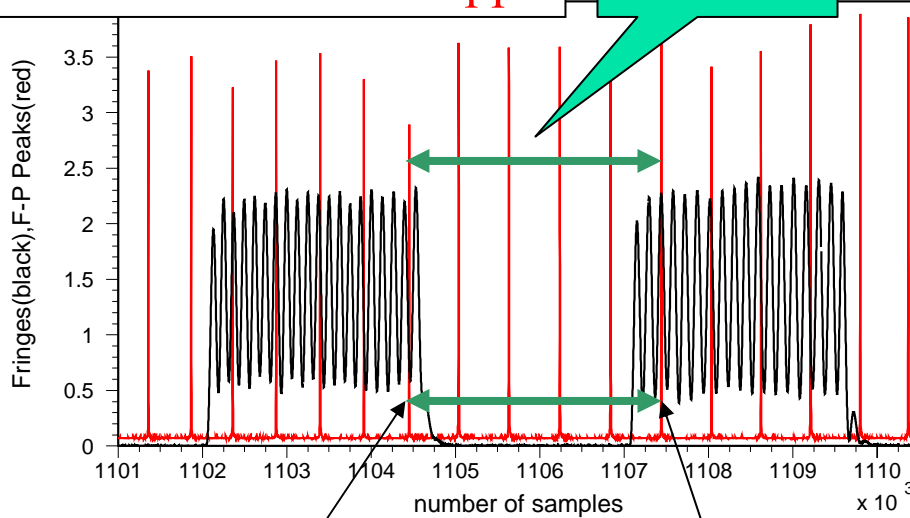
Chopper edge effects and low photodiode duty cycle per laser complicate measurement.

Fringe Interpolating Technique



Laser #1 data with chopper

5 FSRs

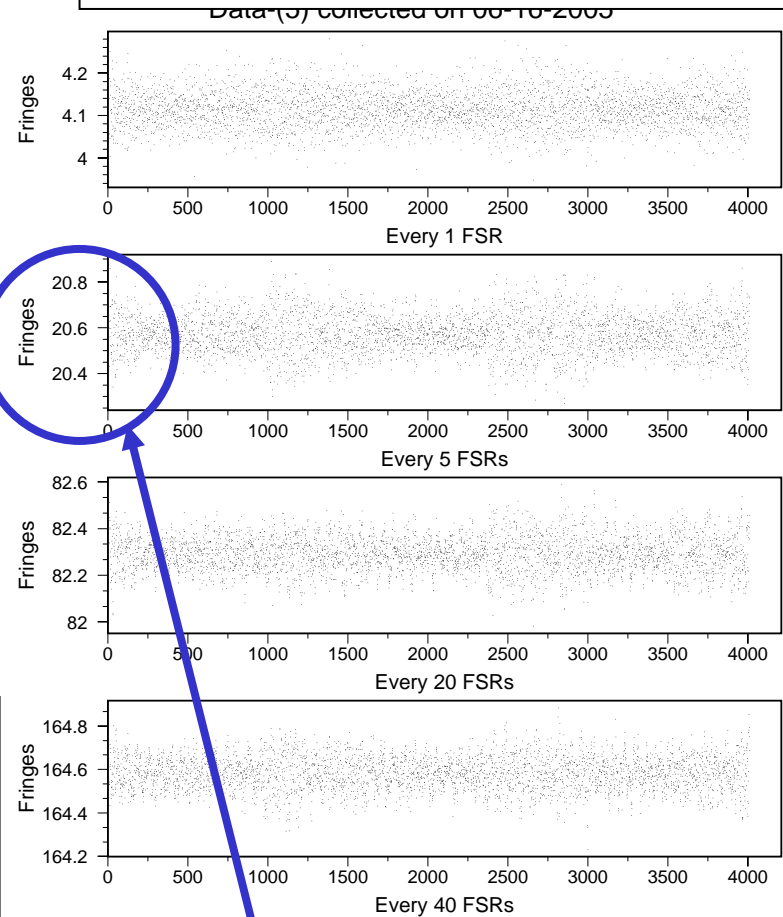


Fringe phase = $I + \Delta I$

Fringe phase = $J + \Delta J$

Fringe correction (N_{corr}) must satisfy:
 minimize $| N_{corr} + (J + \Delta J) - (I + \Delta I) - N_{average} |$
 Where, N_{corr} is integer number, $N_{average}$ is
 expected average fringe numbers (real) for the
 given number of FSRs.

Laser #1 data without chopper



Expected fringes for 5 FSRs

Dual-Laser FSI Data Sample

- * 10 sequential scans with box open (large thermal fluctuation).
- * Scanning rates for Laser 1/2 are 0.6 and 0.3 nm/s, respectively.
- * Scanning time is 16.5 seconds, sampling rate is 150 KS/s.
- * Two lasers are operated simultaneously.

➔ Distance Measurement Precision ($D = 41.11346$ cm)

Laser #1 only : Precision (RMS) = 1.89 microns

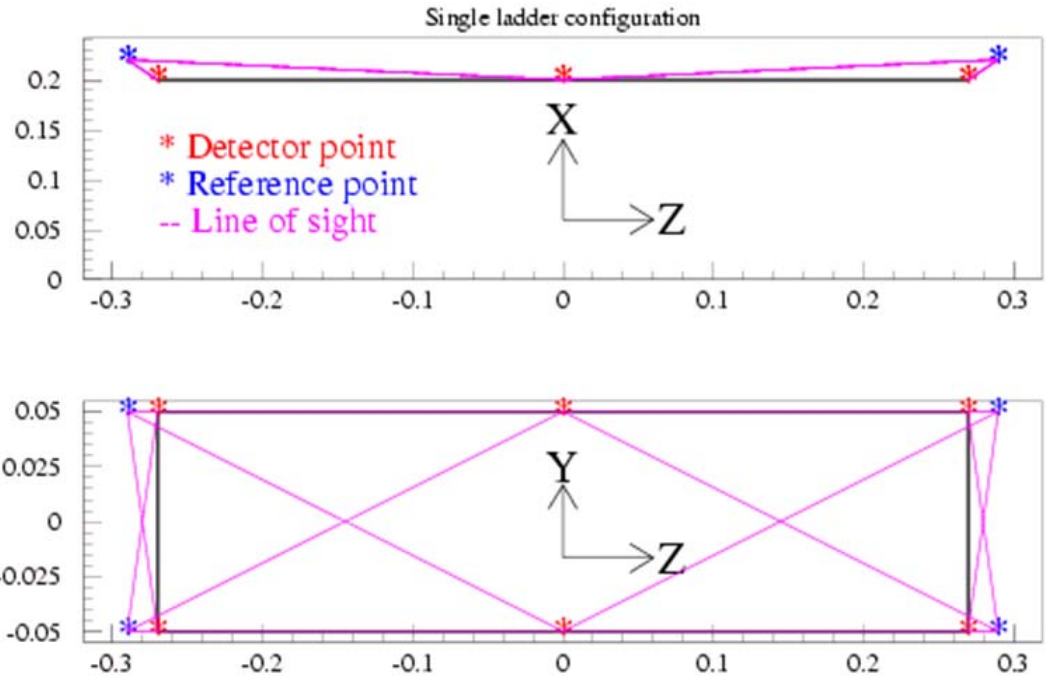
Laser #2 only : Precision (RMS) = 4.17 microns

➔ Combining measured distances from two lasers

Dual-laser precision (RMS) = 0.58 microns

- Will eventually use hundreds of distance measurements along lines of sight to determine tracking component positions, rotations (**pitch/roll/yaw**), and internal distortions.
- System simulations starting – first steps with **rigid bodies**:
 - **Align single silicon ladder**
 - **Align single cylinder (e.g., Si disk, TPC, or CCD cryostat)**
- Assumes (for now) distance resolution of 0.5 microns for all lines of sight [**optimistic for $d > 1$ meter, conservative otherwise**]
- Assumes rigid supports for off-tracker reference points and known positions of reference points [**from combination of surveying and triangulation between reference points**]

Alignment of Single Silicon Ladder



Ladder dimensions

Radius = 20.0 cm
Half-length = 27.0 cm
Width = 10.0 cm

Refer. offsets from ladder ends

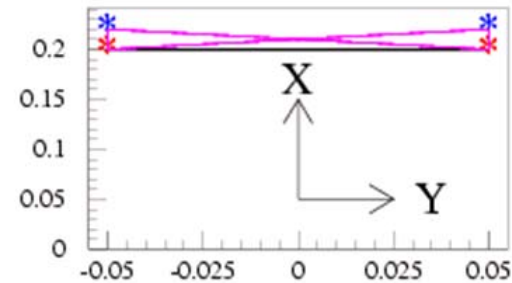
$r = 2.0$ cm $z = 2.0$ cm

CM position precisions (μm)

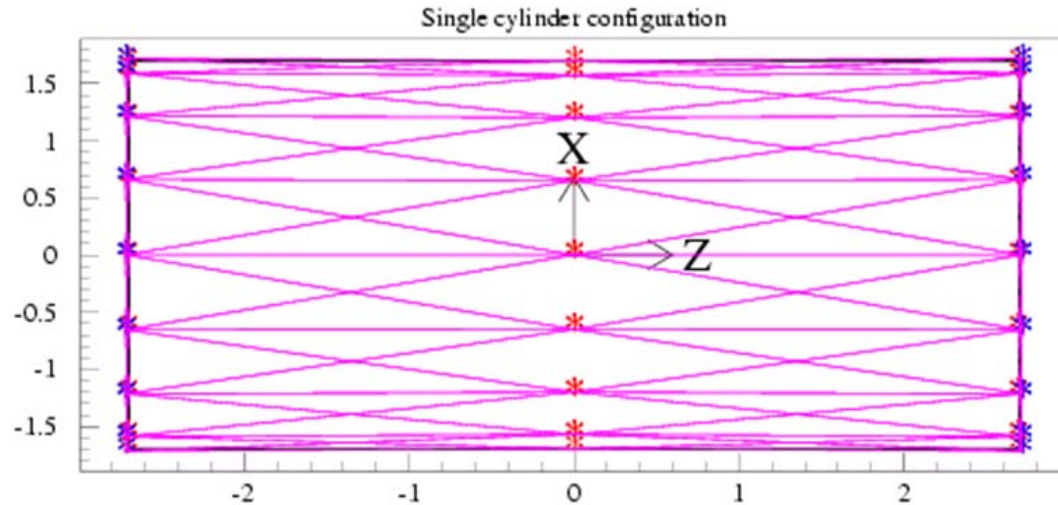
$x = 0.3$ $y = 0.3$ $z = 0.2$

Axis rotation precisions (μrad)

$\psi = 0.9$ $\theta = 1.4$ $\phi = 7.0$



Alignment of Single TPC Cylinder



* Detector point
* Reference point
-- Line of sight

Cylinder dimensions

Radius = 1.70 m

Half-length = 2.70 m

Refer. offsets from cylinder ends

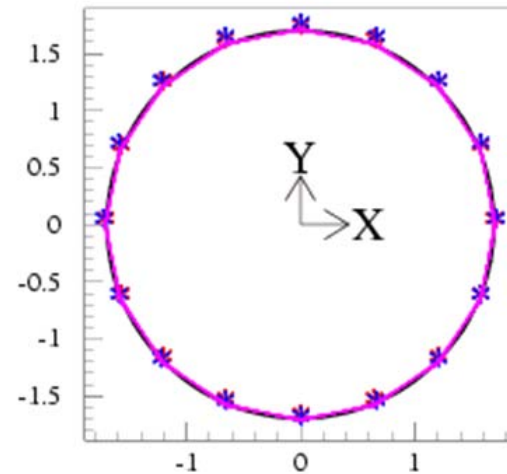
$r = 2.0$ cm $z = 2.0$ cm

CM position precisions (μm)

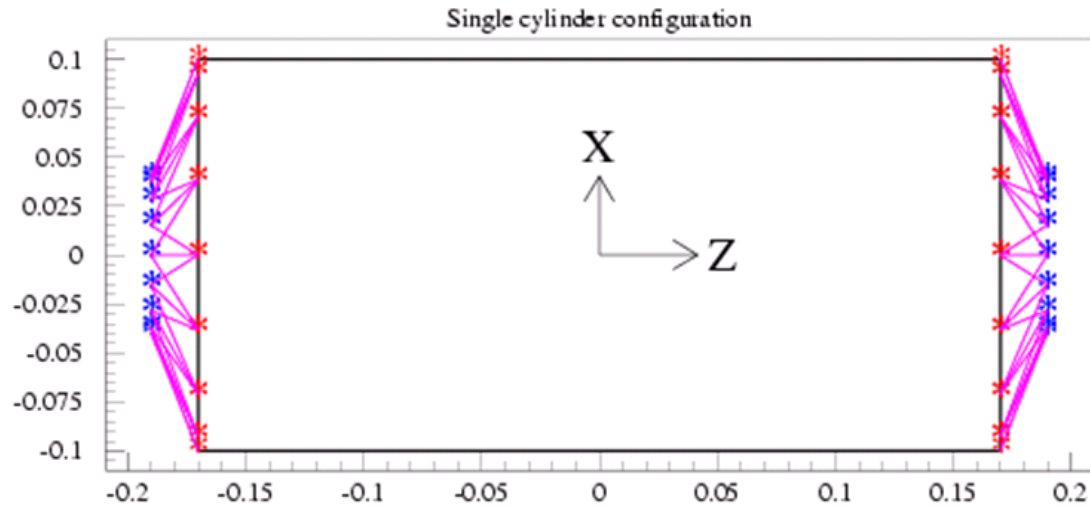
$x = 0.08$ $y = 0.06$ $z = 0.05$

Axis rotation precisions (μrad)

$\psi = 0.02$ $\theta = 0.02$ $\phi = 0.03$



Alignment of Single CCD Cylinder



* Detector point
* Reference point
-- Line of sight

Cylinder dimensions

Radius = 0.10 m

Half-length = 0.17 m

Refer. offsets from cylinder ends

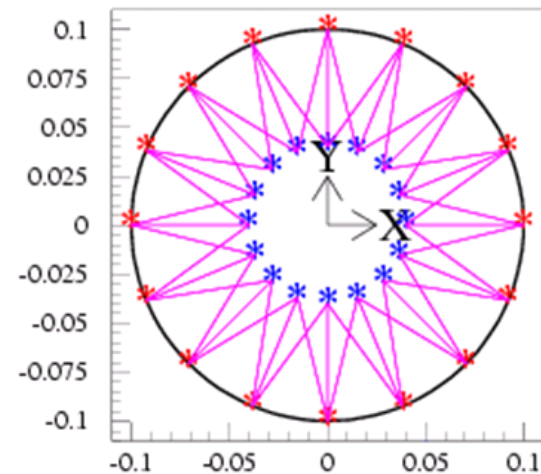
$r = -6.0$ cm $z = 2.0$ cm

CM position precisions (μm)

$x = 0.08$ $y = 0.08$ $z = 0.17$

Axis rotation precisions (μrad)

$\psi = 0.38$ $\theta = 0.38$ $\phi = 2.77$



- ➔ Simulate internal distortions:
 - Thermal expansion
 - Mechanical deformations (e.g., twist, sag)
- ➔ Simultaneous fit to multiple tracker components
- ➔ Address systematic errors from reference point uncertainties (and possible drifts)
- ➔ Propagate uncertainties from ladder/cylinder position, orientation, distortion to errors on track hits and evaluate gain in momentum / impact parameter resolution from alignment corrections

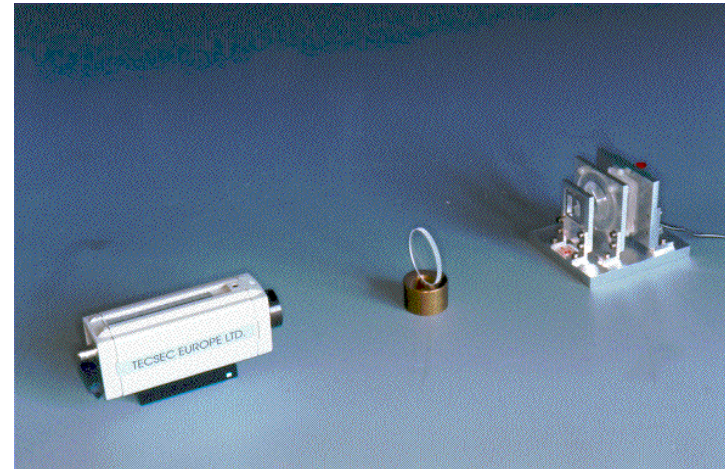
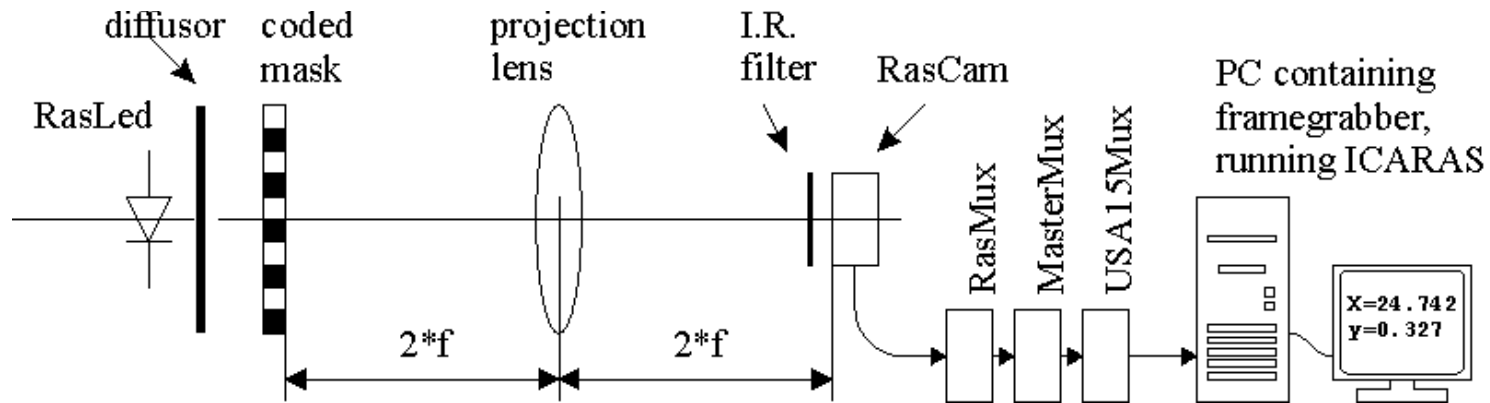
Summary and Outlook

- ➔ Two FSI demonstration systems, with and without optical fibers, were constructed to make high-precision absolute distance measurements.
- ➔ Two new multi-distance-measurement analysis techniques were presented to improve absolute distance measurement and to extract the amplitude and frequency of vibration.
- ➔ A high precision of ~ 50 nm for distances up to 60 cm under well controlled conditions was achieved.
- ➔ We are investigating dual-laser scanning technique under realistic conditions. A precision of ~ 0.6 micron was achieved so far for measured distance of ~ 41 cm.

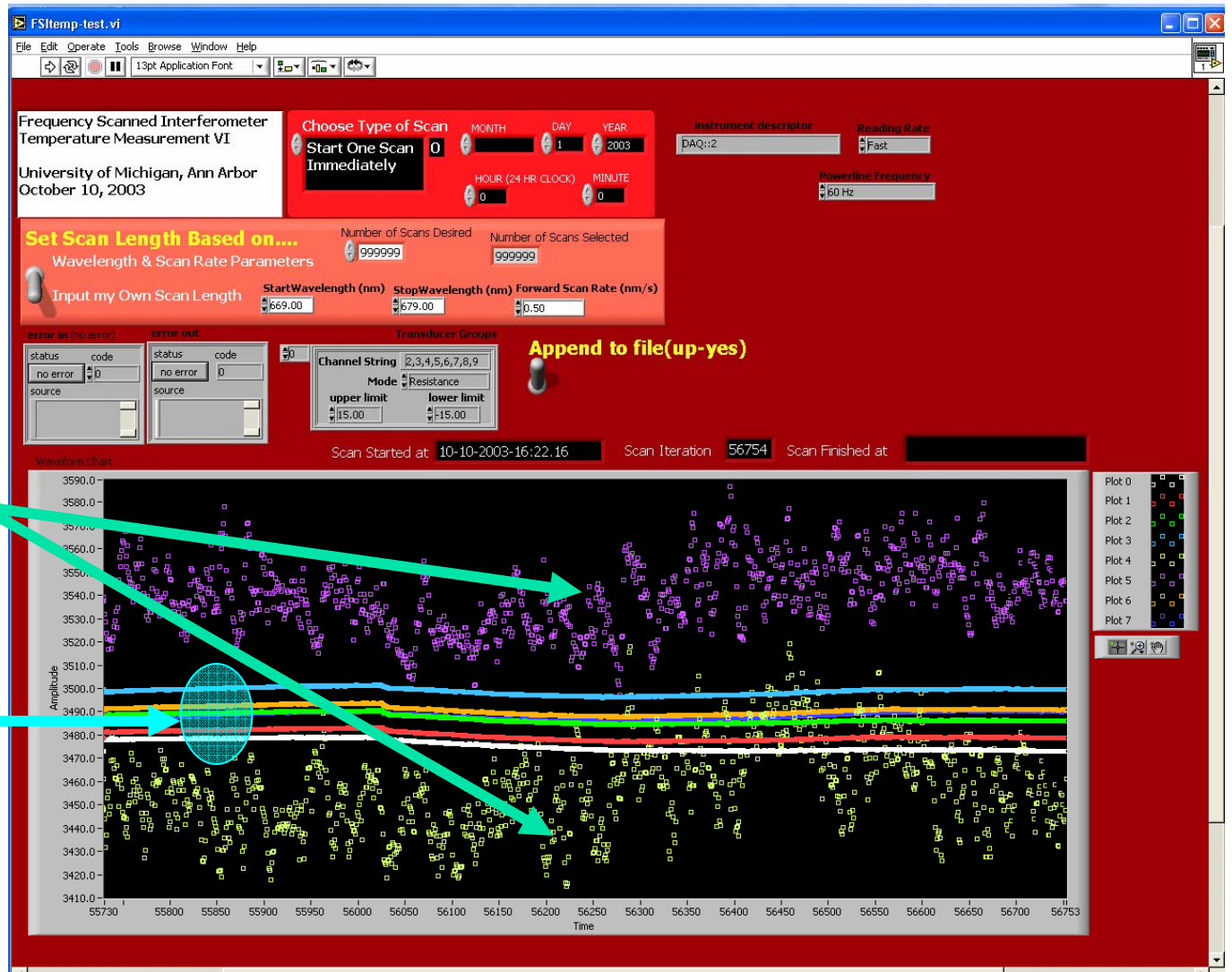
- Improved precision expected with further R&D
- Miniaturization of interferometer optics (a la ATLAS) is next challenge
- Detailed simulation work for complete system starting ...

BACKUP SLIDES

RASNIK provides alignment monitoring with submicron precision, developed at NIKHEF.



Temperature Measurements



Outside of Box

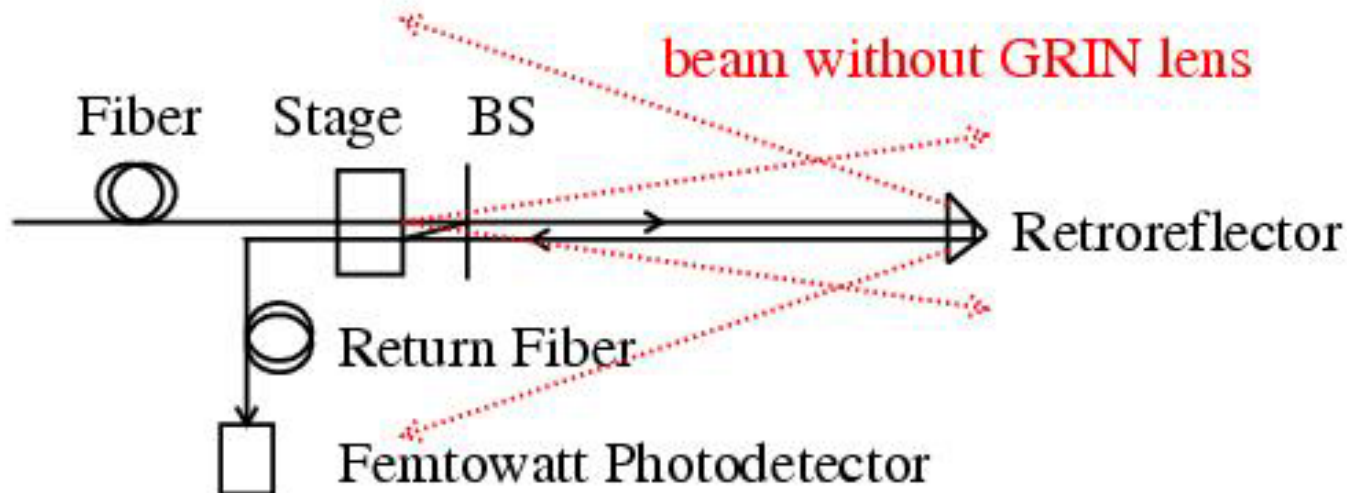
Inside of Box

- ◆ A key issue for the optical fiber FSI is that the intensity of the return beams received by the optical fiber is very weak.

e.g. the core of the single mode optical fiber has diameter of $\sim 5 \mu\text{m}$.

Geometrical Efficiency: $\sim 6.25 \times 10^{-10}$ for a distance of 0.5 m

- ➔ A novelty in our design is the use of a gradient index lens (GRIN lens – 0.25 pitch lens with $D=1\text{mm}$, $L=2.58\text{mm}$) to collimate the output beam from the optical fiber.
- The density of the outgoing beam is increased by a factor of ~ 1000 by using the GRIN lens. This makes it possible to split the laser beam into many beams to serve a set of interferometers simultaneously.



- If drift error(ε) occurs during the laser scanning, it will be magnified by a factor of Ω ($\Omega \equiv v/\Delta v \sim 67$ for full scan of our tunable laser),

$$\text{OPD}^{\text{measured}} = \text{OPD}^{\text{true}} + \Omega\varepsilon$$

➔ *Plastic box and PVC pipes are constructed to reduce thermal drift.*

- Assuming a vibration with one frequency:

$$x_{\text{vib}}(t) = a_{\text{vib}} \times \cos(2\pi f_{\text{vib}} t + \phi_{\text{vib}})$$

- Fringe phase at time t:

$$\Phi(t) = 2\pi \times [\text{OPD}^{\text{true}} + 2x_{\text{vib}}(t)]/\lambda(t)$$

$$\Delta N = [\Phi(t) - \Phi(t_0)]/2\pi = \text{OPD}^{\text{true}} \times \Delta v/c + [2x_{\text{vib}}(t)/\lambda(t) - 2x_{\text{vib}}(t_0)/\lambda(t_0)]$$

- If we assume $\lambda(t) \sim \lambda(t_0) = \lambda$, measured OPD can be written as,

$$\text{OPD}^{\text{meas}} = \text{OPD}^{\text{true}} + \Omega \times [2x_{\text{vib}}(t) - 2x_{\text{vib}}(t_0)] \quad (1)$$

$$\text{OPD}^{\text{meas}} = \text{OPD}^{\text{true}} - \Omega \times 4a_{\text{vib}} \sin[\pi f_{\text{vib}}(t-t_0)] \times \sin[\pi f_{\text{vib}}(t+t_0) + \phi_{\text{vib}}] \quad (2)$$

- ➔ Two new multiple-distance measurement techniques are presented to extract vibration and to improve the distance measurement precision based on Eq.1 and Eq.2, respectively.

Dispersion Effect



- Dispersive elements, beamsplitter, corner cube prism etc. can create significant offset in measured distance for FSI system since the small OPD change caused by dispersion is magnified by a factor of Ω .

- Sellmeier formula for dispersion in crown glass (BK7)

$$n^2(\lambda^2) = 1 + B1 * \lambda^2 / (\lambda^2 - C1) + B2 * \lambda^2 / (\lambda^2 - C2) + B3 * \lambda^2 / (\lambda^2 - C3)$$

$B1 = 1.03961212, B2 = 0.231792344, B3 = 1.01046945$

$C1 = 0.00600069867, C2 = 0.0200179144, C3 = 103.560653$

- Numerical simulation results (thickness of the corner cube prism = 1.86 cm)

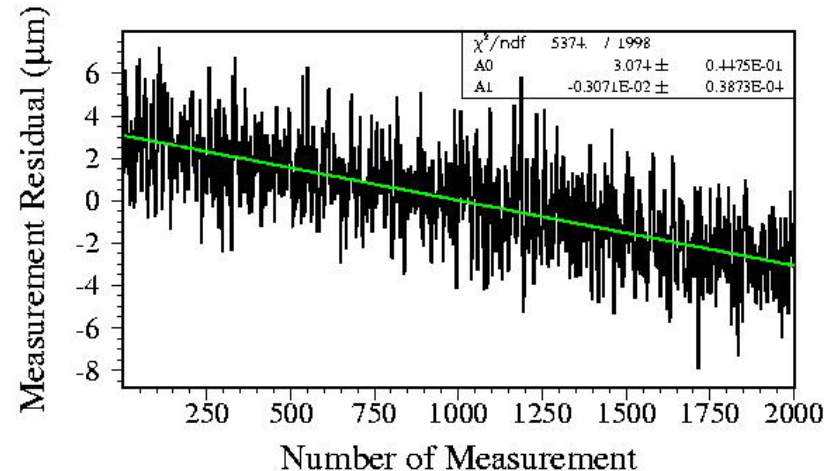
$R_1 - R_{true} = 373.876 \mu\text{m}, R_{2000} - R_{true} = 367.707 \mu\text{m}$

$R_1 - R_{2000} = 6.2 \pm 0.2 \mu\text{m}$

- Real data - fitted result

$R_1 - R_{2000} = 6.14 \pm 0.1 \mu\text{m}$

→ Dispersion effects can be avoided by using hollow retroreflector and put the beamsplitter's anti-reflecting surface facing the optical fiber.



Error Estimations

- Error from uncertainties of fringe and frequency determination, $dR/R \sim 1.9$ ppm; if $N_{\text{meas}} = 1200$, $dR/R \sim 77$ ppb
- Error from vibration. $dR/R \sim 0.4$ ppm; if $N_{\text{meas}} = 1200$, $dR/R \sim 10$ 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 °C will result in a 0.9 ppm change of refractive index at room temperature. The drift will be magnified during scanning. if $N_{\text{meas}} = 1200$, $dR/R \sim 0.9$ ppm/K \times 0.5mK \times $\Omega(94) \sim 42$ ppb.
- Error from air humidity and pressure, $dR/R \sim 10$ ppb.

The total error from the above sources is ~ 89 ppb which agrees well with the measured residual spread of ~ 90 ppb over different days and times of measurement.

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 $dR/R \sim 50$ 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.
- * The systematic bias from the multiple-distance-measurement technique was also estimated by changing the starting point of the measurement window, the window size and the number of measurements, the uncertainties typically range from 10-30 nanometers (< 50 ppb).
- * The systematic bias from uncertainties of temperature, air humidity and barometric pressure scales should have negligible effect.

The total systematic error is ~ 70 ppb.