Frequency Scanned Interferometry for ILC Tracker Alignment

University of Michigan ILC Group

(Hai-Jun Yang, Eui Min Jung, Sven Nyberg, Keith Riles)

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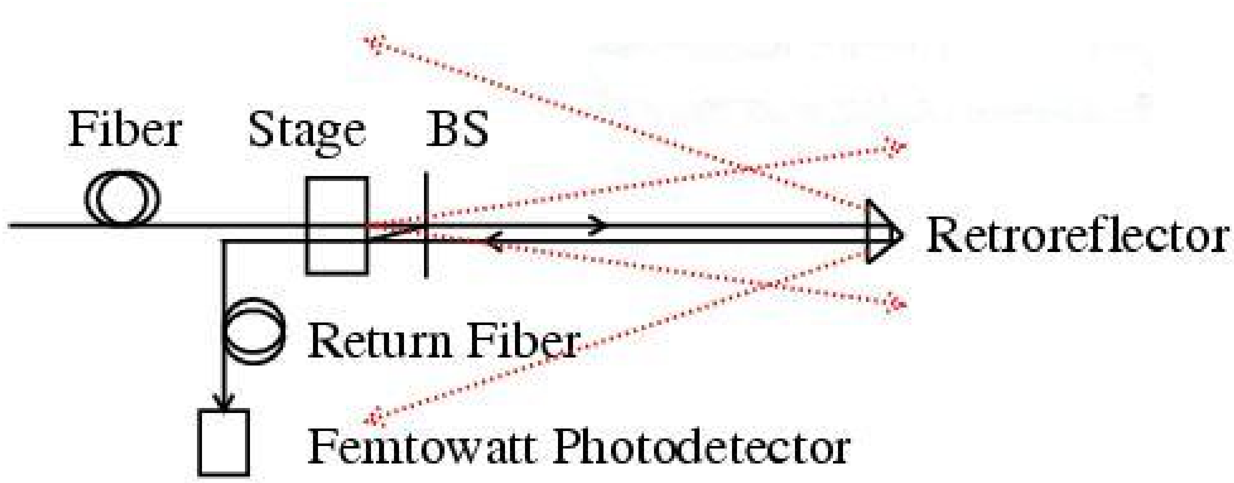
Outline

- Review of Frequency Scanned Interferometry (FSI) method
- Report on improvements & measurements since Snowmass 2005
  - Implementation of dual-laser technique
  - Results of measurements – estimated precision
  - Recent cross checks
- Plans
  - Miniaturization
  - Multiple channels

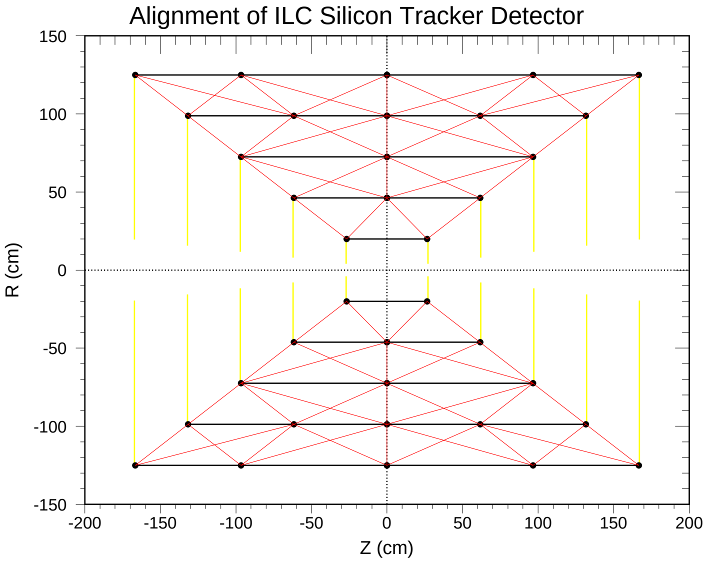
Overview of Method

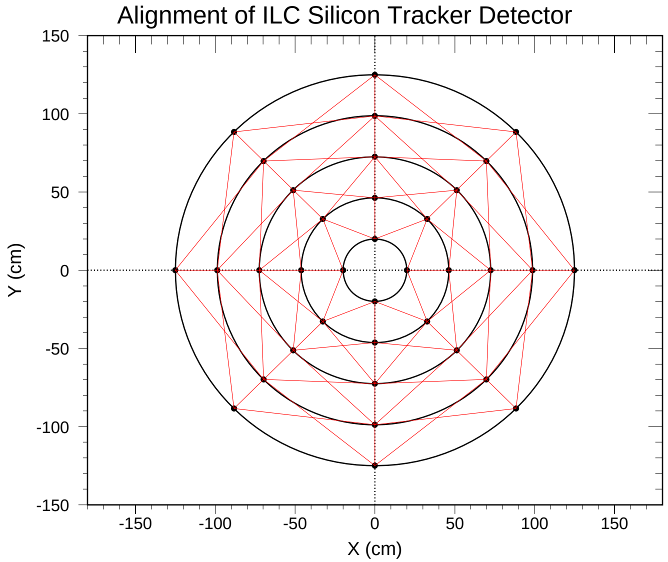
- Measure hundreds of absolute point-to-point distances of tracker elements in 3 dimensions by using an array of optical beams split from a central laser.
- Absolute distances are determined by scanning the laser frequency and counting interference fringes.
- Grid of reference points overdetermined → Infer tracker distortions

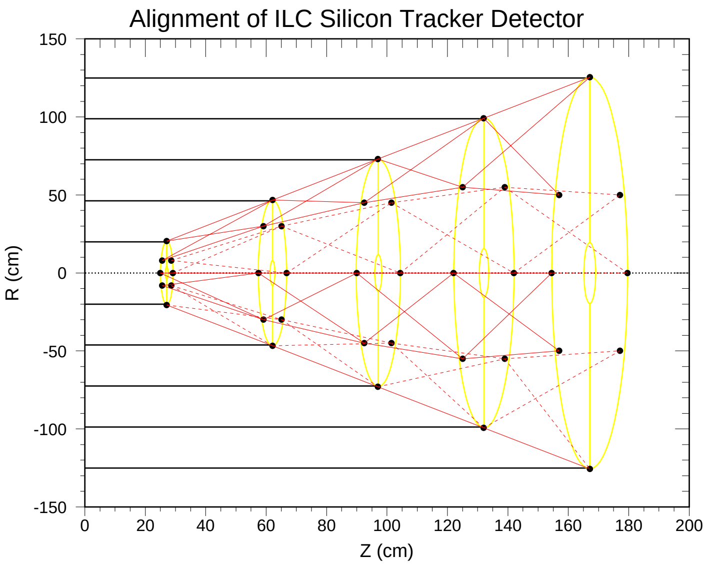


- Technique pioneered by Oxford U. group for ATLAS detector

A Possible SiD Tracker Alignment







752 point-to-point distance measurements

(Goal: $\sigma_{distance} < 1\ \mu m$)

Worldwide Study of the Physics and Detectors for Future Linear e+ e- Colliders

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

Background

Previous reports:

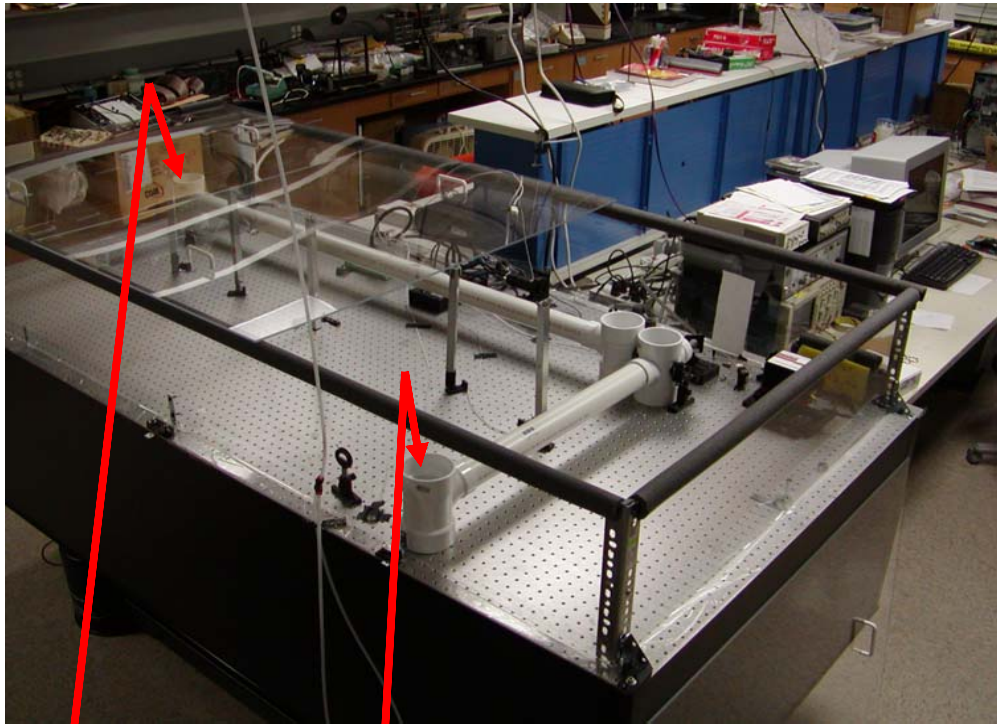
- FSI I – Single-laser demonstration with air transport of beam
- FSI II – Single-laser measurements with fiber transport
  → Results published in *Applied Optics,* ***44*** *3937 (2005)*

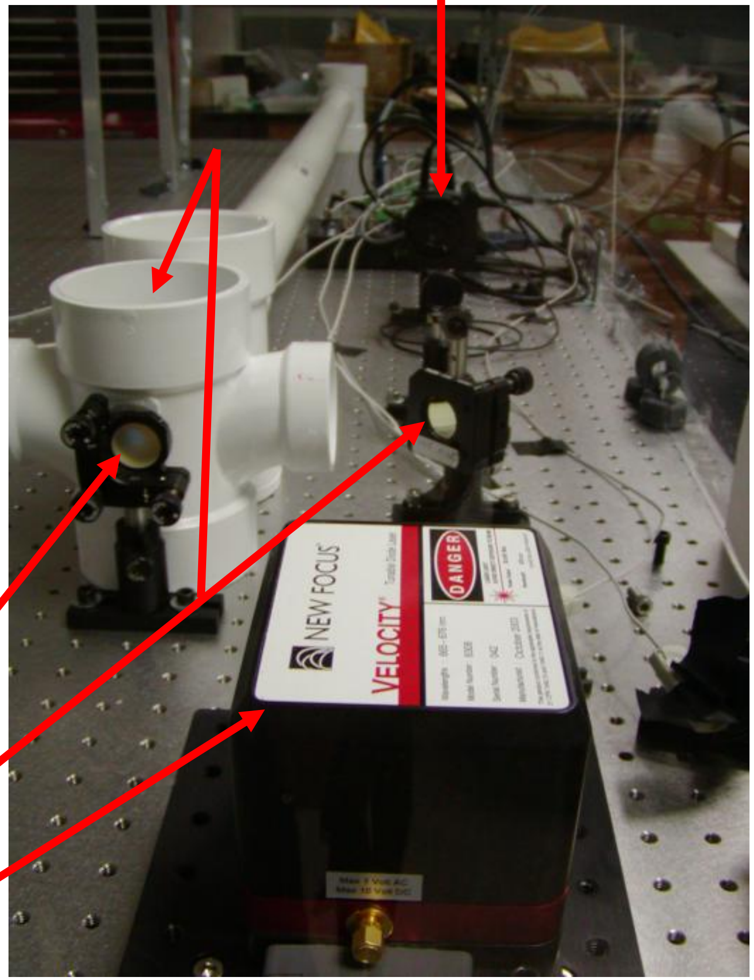
Results well within desired precision, but only for controlled laboratory conditions

(nested enclosures to minimize thermal fluctuations)

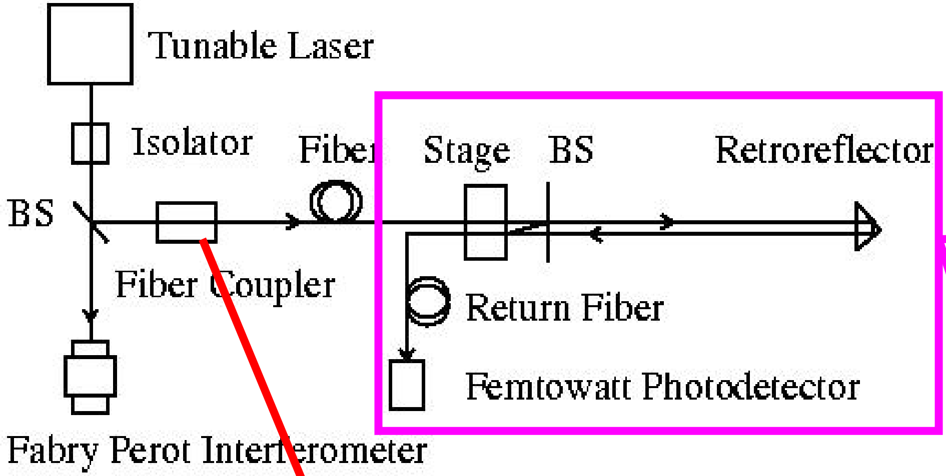
Worldwide Study of the Physics and Detectors for Future Linear e- e+ Colliders

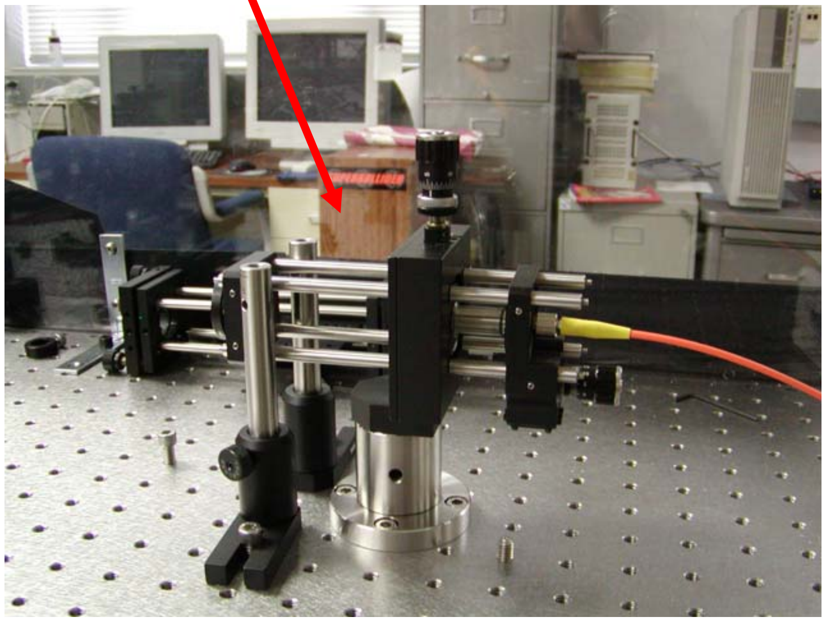
FSI Demonstration System (I)

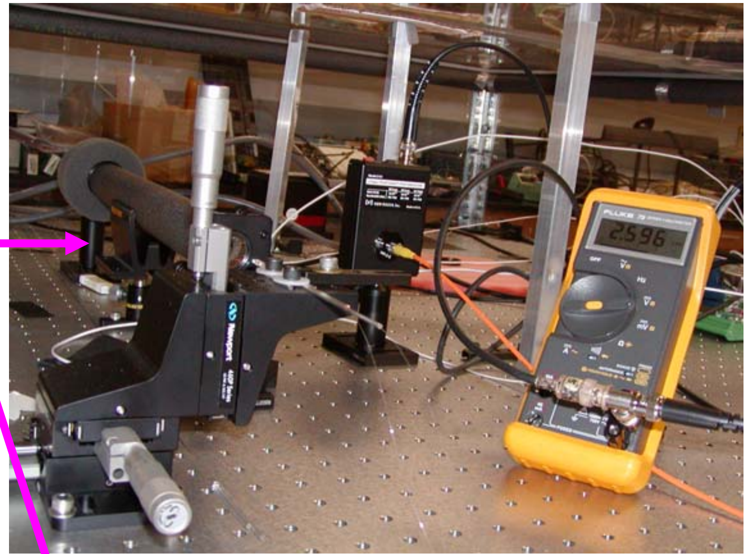


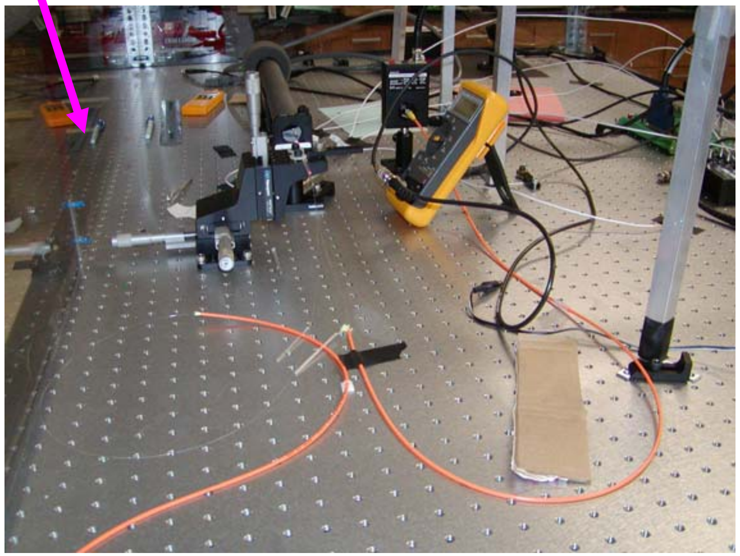


FSI with Optical Fibers (II)



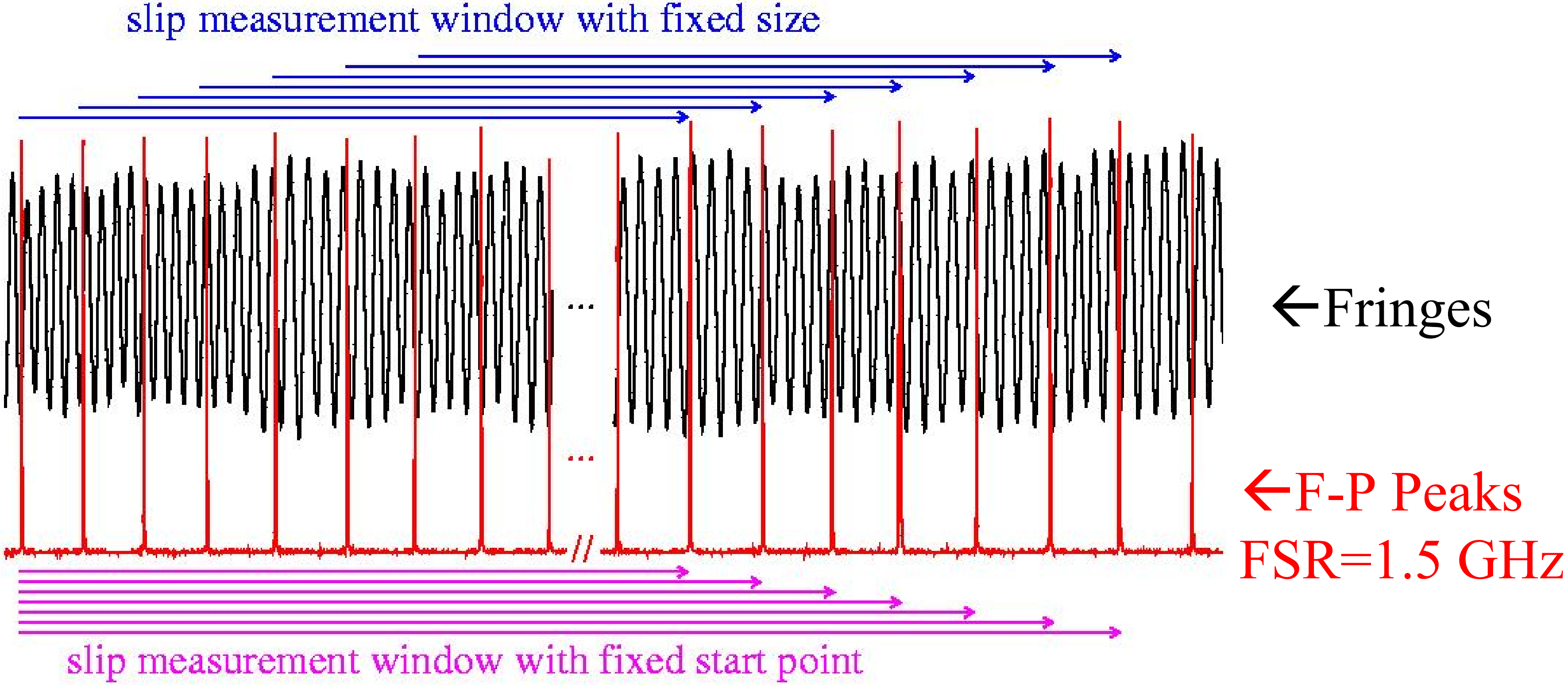






Two Multiple-Measurement Techniques

➔Fix the measurement window size (t-t0) 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.



➔If t0 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.

Vibration Measurement

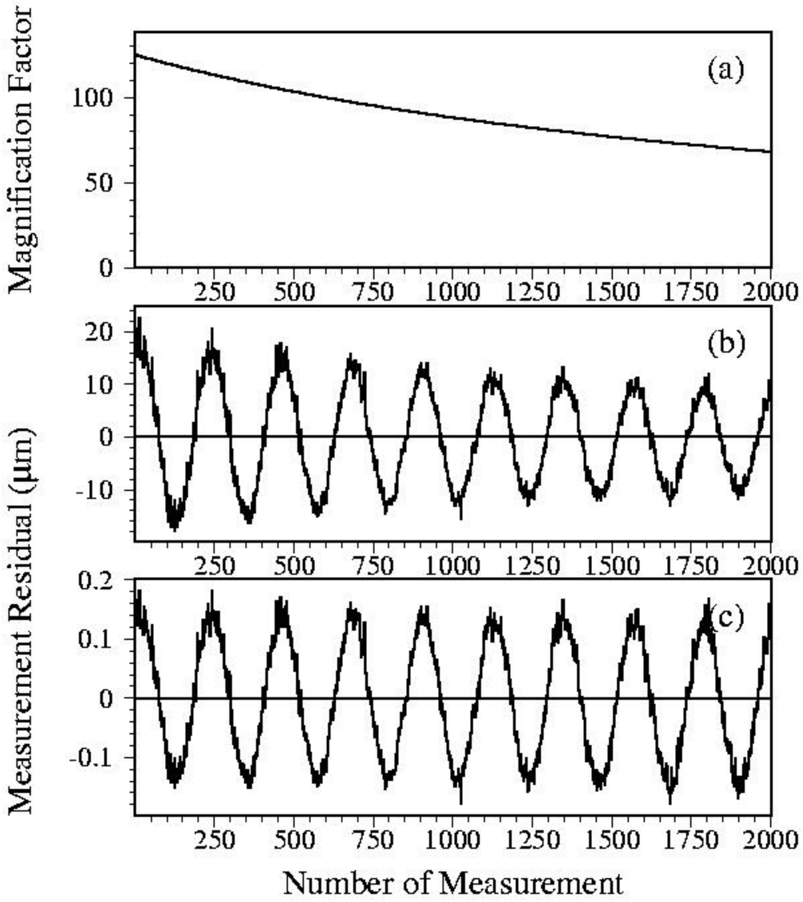
- A PZT transducer was employed to produce controlled vibration of the retroreflector, **f_{vib} = 1.01 ± 0.01 Hz, amp_{vib} = 0.14 ± 0.02 μm**

- Magnification factor Ω=ν/Δν 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 Ω ~70 – plot(b).

➔The extracted true vibration–plot(c)

f_{vib} = 1.007 ± 0.0001 Hz,

amp_{vib} = 0.138 ± 0.0003 μm



Absolute Distance Measurements

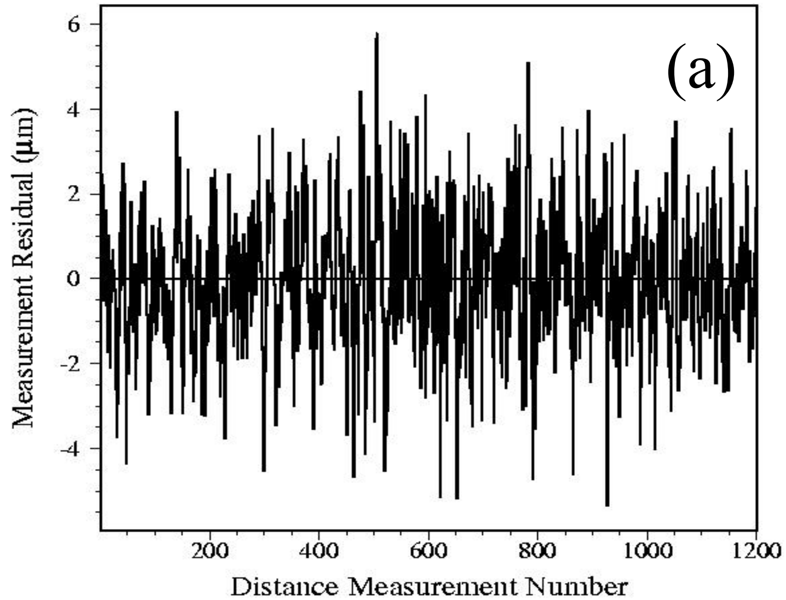
- The scanning rate was 0.5 nm/s and the sampling rate was 125 KS/s.
- The measurement residual versus the No. of measurements/scan shown in Fig.,
  - (a) for one typical scan,
  - (b) for 10 sequential scans.

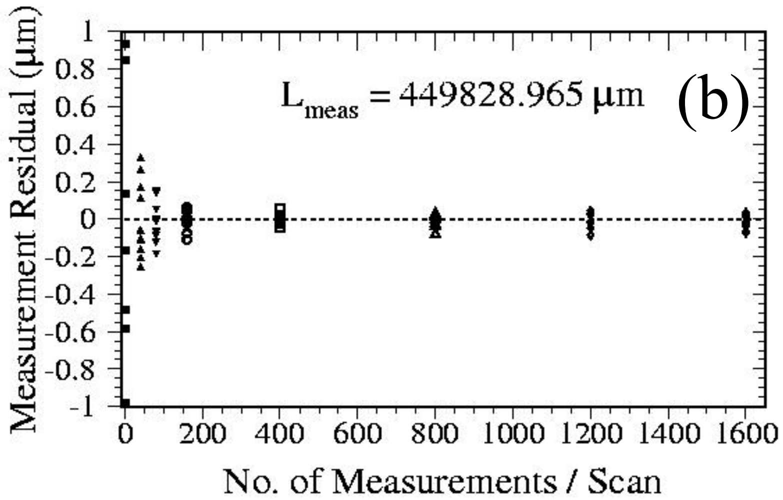
➔It can be seen that the distance errors decrease with increasing N_{meas}.

N_{meas}=1, precision=1.1 μm (RMS)

N_{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(needs dual-laser scanning technique).





FSI Performance - Published Results

Controlled Conditions

Measured Distances: 10 cm – 60 cm

Distance Precision:

~ 50 nm by using 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.

Publication:

"High-precision absolute distance and vibration measurement with frequency scanned interferometry",
H.J. Yang, J. Deibel, S. Nyberg, K. Riles, Applied Optics, 44, 3937-3944, (2005)

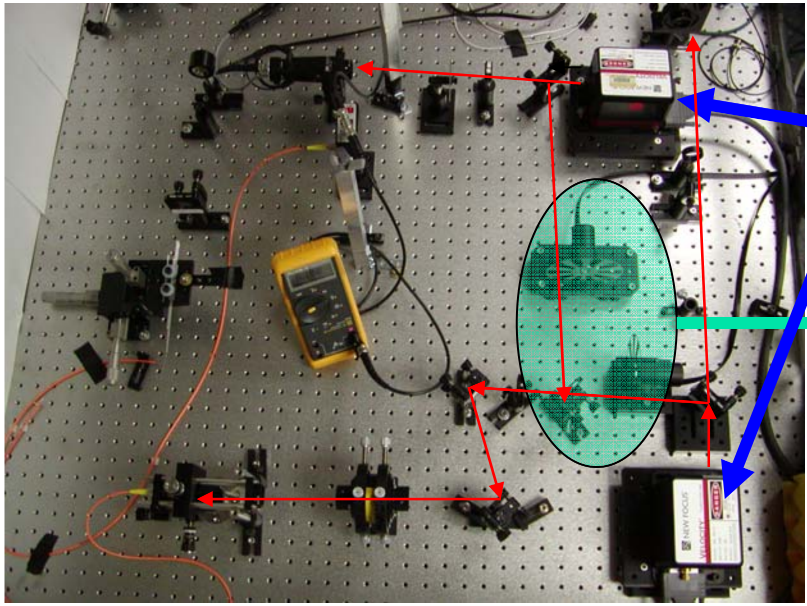
“Real World”

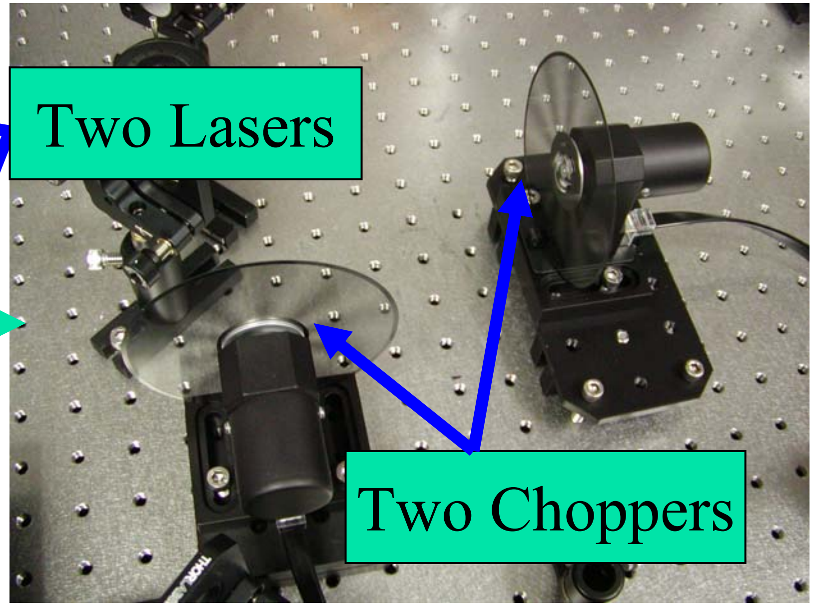
- Cannot count on precisely controlled conditions in ILC detector tracker.
- Thermal fluctuations and drifts likely
  → Refraction index and inferred distance affected
- Can measure temperature, pressure, humidity, etc. and apply empirical formulae, but preferable to measure effects directly
- Use dual-laser technique (Oxford):
  - **Two independent lasers alternately chopped**
  - **Frequency scanning over same range but with opposite slope**

Dual-Laser FSI (III)

➔A dual-laser FSI (Oxford Atlas method) has been implemented with optical choppers.

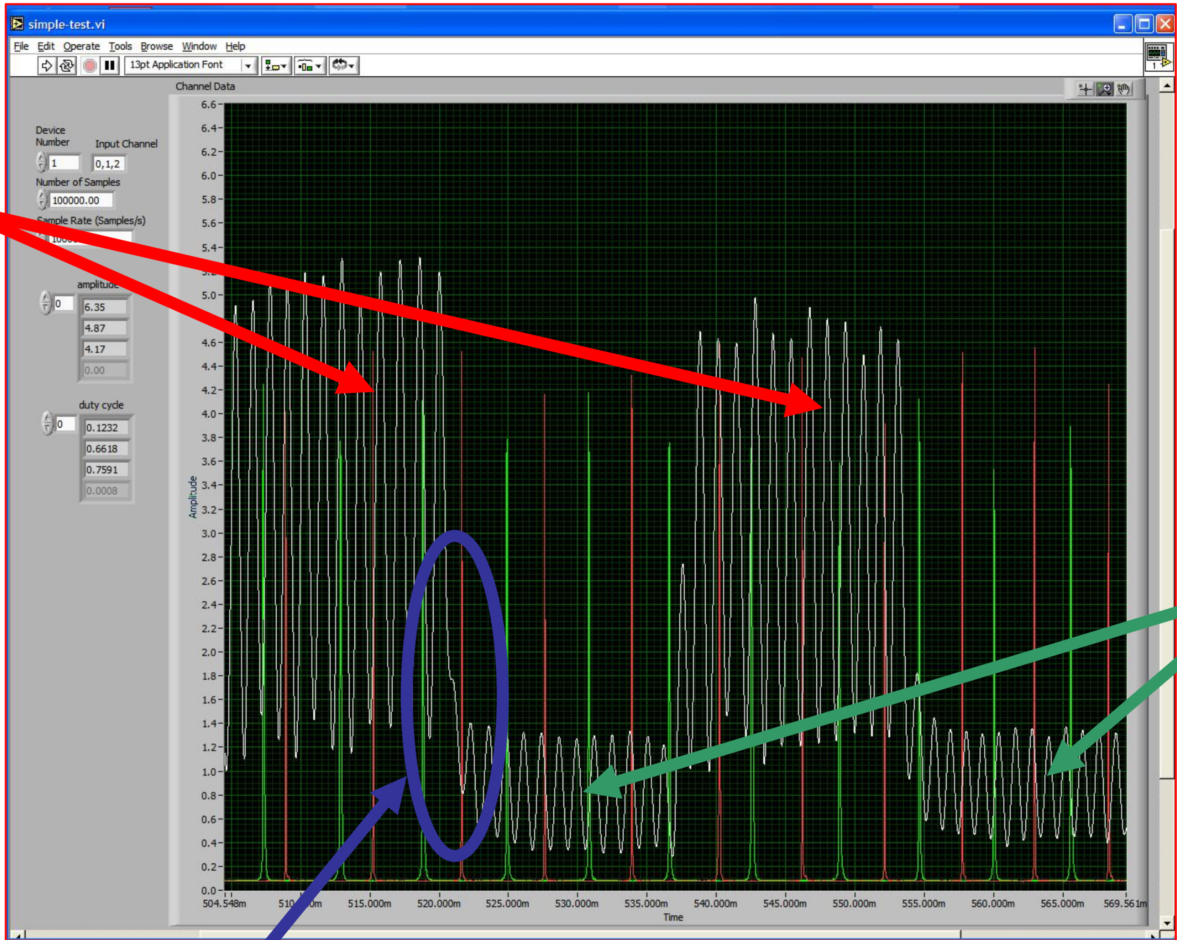
Laser #1: $D_1 = D_{true} + \Omega_1 \varepsilon_1$
Laser #2: $D_2 = D_{true} + \Omega_2 \varepsilon_2$
Drift errors: $\varepsilon_1 \approx \varepsilon_2 = \varepsilon$
$D_{true} = (D_2 - \rho D_1) / (1 - \rho)$,
Where $\rho = \Omega_2 / \Omega_1$





Fringes & F-P Peaks (dual-laser)

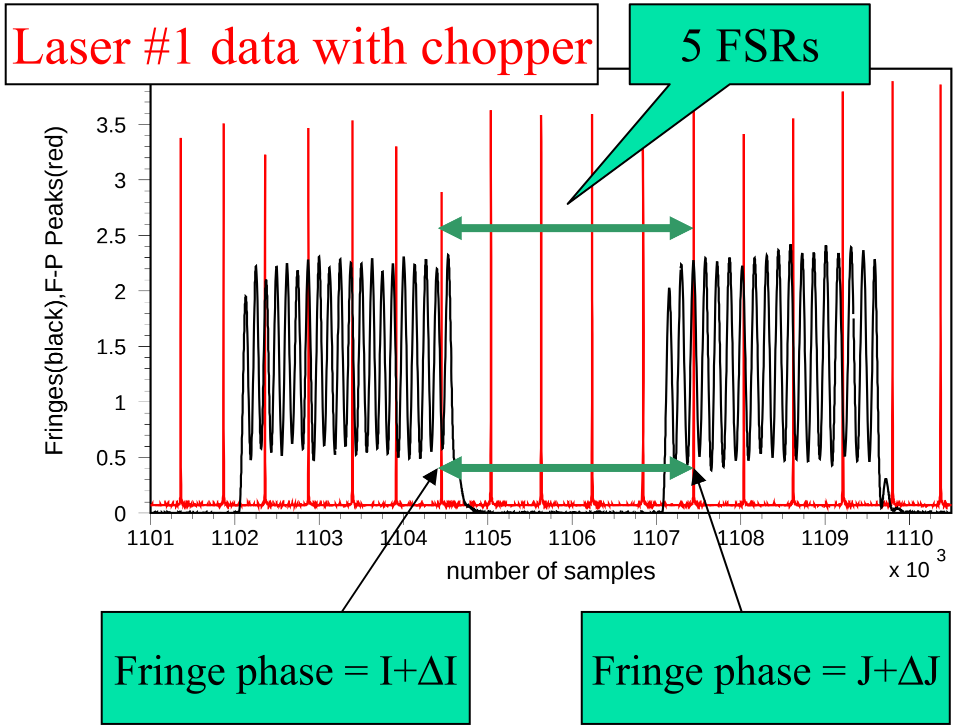
Laser-1

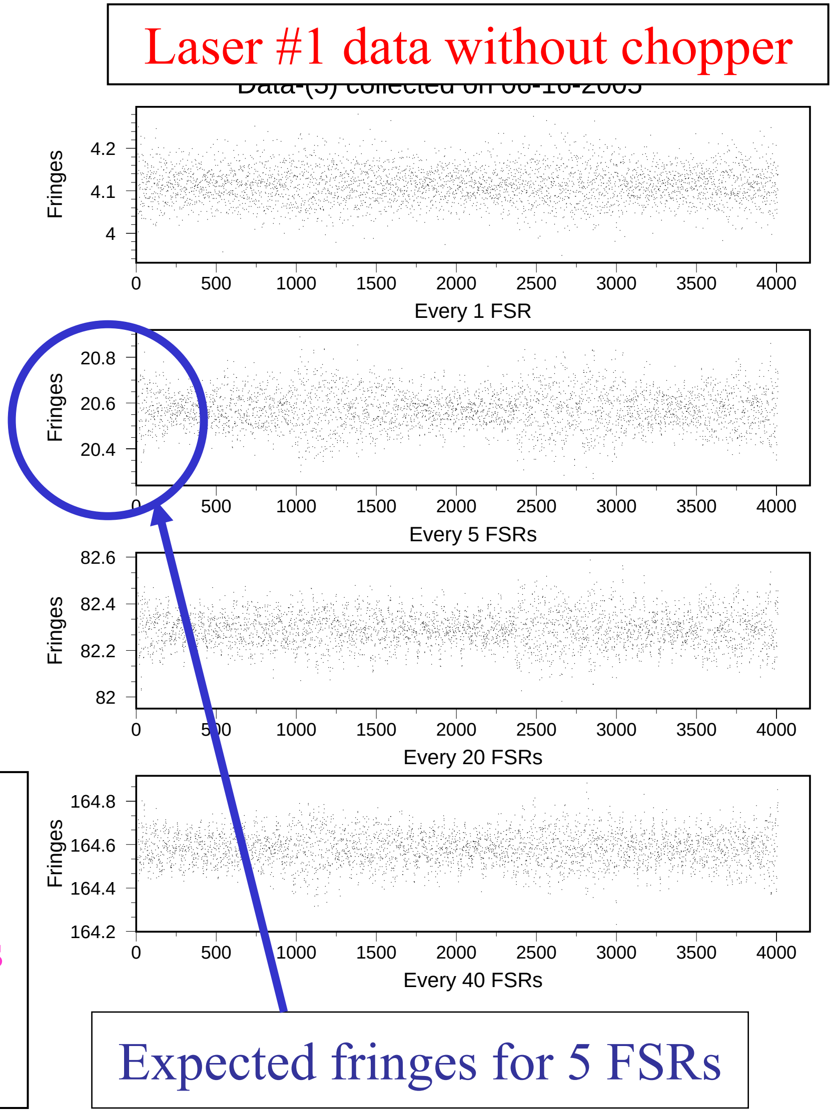


Laser-2

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

Fringe Interpolating Technique





Fringe correction (N_corr) must satisfy:

minimize | N_corr+(J+ΔJ)-(I+ΔI)-N_average |

Where, N_corr is integer number, N_average is expected average fringe numbers (real) for the given number of FSRs.

Distance Measurement Precision

Dual-Laser FSI Data Samples – Under Realistic Conditions

* with box open(20 scans), with fan on (10 scans), with vibration(8 scans).
* Scanning rates for Laser #1 and #2 are -0.4 and 0.4 nm/s, respectively.
* Scanning time is 25 seconds, sampling rate is 100 KS/s.
* Two lasers are operated simultaneously, 2-blade chopper frequency is 20 Hz.

Data	Scans	Conditions	Distance(cm) from dual-laser	Precision(μm) for multi-dist.-meas./scan					
				2000	1500	1000	500	100	1
L1	10	open box	–	5.70	5.73	6.16	6.46	5.35	6.64
L2	10	open box	–	5.73	5.81	6.29	6.61	5.66	6.92
L1+L2	10	open box	41.13835	0.20	0.19	0.18	0.21	0.39	1.61
L1	10	open box+fan on	–	5.70	4.91	3.94	3.49	3.29	3.04
L2	10	open box+fan on	–	5.70	5.19	4.23	3.78	3.21	6.07
L1+L2	10	open box+fan on	41.13841	0.19	0.17	0.20	0.22	0.31	3.18
L1	10	open box	–	6.42	5.53	4.51	3.96	4.41	3.36
L2	10	open box	–	6.81	5.93	4.86	4.22	4.63	5.76
L1+L2	10	open box	41.13842	0.20	0.20	0.26	0.19	0.27	2.02
L1	8	open box+vibration	–	4.73	4.82	3.60	3.42	4.62	8.30
L2	8	open box+vibration	–	4.72	4.66	3.66	3.65	4.63	5.56
L1+L2	8	open box+vibration	41.09524	0.17	0.21	0.17	0.15	0.39	1.75

Distance Measurement Precision

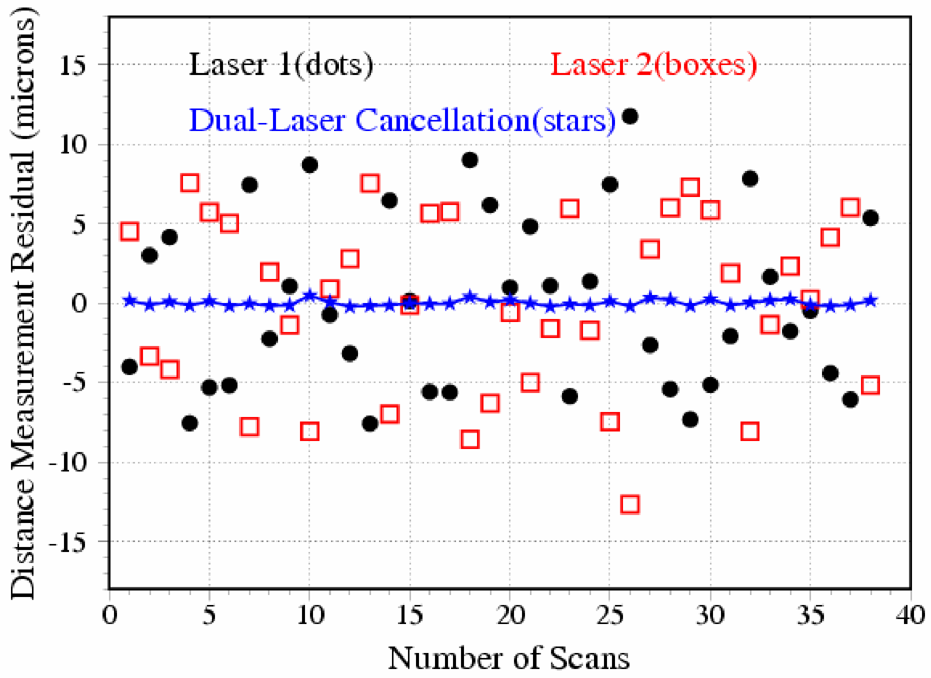
➔ Distance Measurement Precision (~ 41.1384 cm)
Laser #1 or #2 only : Precision (RMS) = 3 ~ 7 microns

➔ Combining multi-distance-measurement and dual-laser scanning techniques to reduce and cancel interference fringe uncertainties, vibration and drift errors
Dual-laser precision (RMS) ~ 0.20 microns under realistic conditions

➔ A 2nd report:

"High-precision absolute distance measurement using dual-laser frequency scanned interferometry under realistic conditions"

will be submitted to *Applied Optics*.



FSI Cross Checks

➔Used a Micrometer to change the position of retroreflector by large amount (127+/- 3 microns), and check FSI performance. Laser #1, 5 full scan data for each independent test.

dR1 = 128.68 +/- 0.46 microns

dR2 = 129.55 +/- 0.63 microns

dR3 = 127.44 +/- 0.63 microns

dR4 = 124.90 +/- 0.48 microns

Single-laser scans – unstable temps

➔Used a Piezoelectric transducer (PZT, 20% tolerance) to change the position of the retroreflector by 2.0 +/- 0.4 microns. Laser #1, 5 full scans for each test.

dR5 = 2.33 +/- 0.12 microns

dR6 = 2.23 +/- 0.07 microns

Single-laser scans – stable temps

FSI Thermal Test

To verify correct tracking of large thermal drifts, we placed a heating pad on a 1' X 2' X 0.5'' Aluminum breadboard

➔Test 1: increased temperature by 6.7 +/- 0.1 ^{o}C

dR_expected = 62.0 +/- 0.9 microns

dR_measured = 61.72 +/- 0.18 microns

➔Test 2: increased temperature by 6.9 +/- 0.1 ^{o}C

dR_expected = 64.4 +/- 0.9 microns

dR_measured = 64.01 +/- 0.23 microns

➔Test 3: increased temperature by 4.3 +/- 0.1 ^{o}C

dR_expected = 39.7 +/- 0.9 microns

dR_measured = 39.78 +/- 0.22 microns

➔Test 4: increased temperature by 4.4 +/- 0.1 ^{o}C

dR_expected = 40.5 +/- 0.9 microns

dR_measured = 41.02 +/- 0.21 microns

Dual-laser scans – closed box

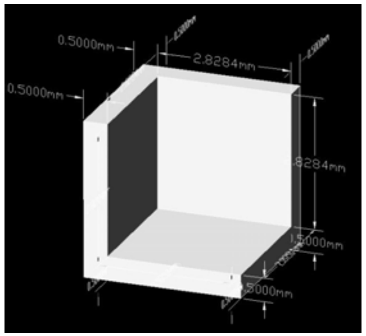
Miniaturization

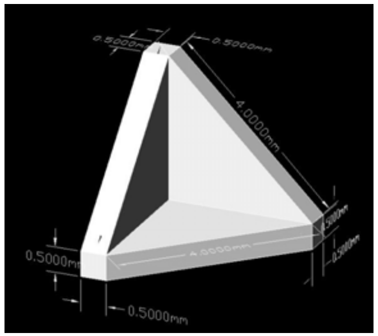
So far we have used large commercial optics:

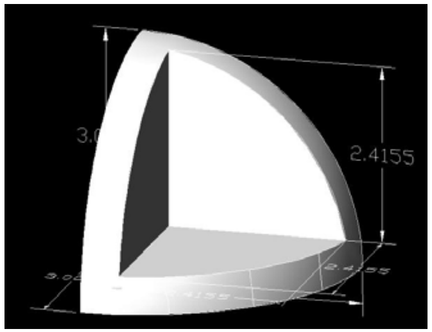
- **Retroreflector**
- **Beam splitter**

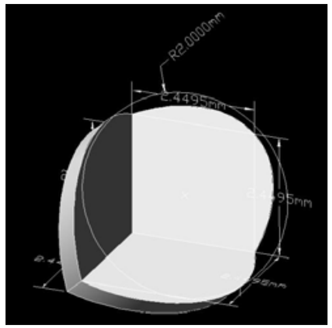
Need miniaturized, low-X_0 components for actual tracker

Now starting to investigate options for the retroreflector (contacting rapid prototyping companies)









Miniaturization

Quick test with a bicycle reflector:

(all but one pixel masked off)

Measurement precision for a distance of 18 cm: ~ 0.4 μm

Promising indication, given simple design of the reflector pixels

(solid plastic corner cubes with no coating)

Multiple channels

Plan to implement multi-channels fed by an optical fiber splitter

- → **Double-check systematics**
- → **Implement multiple distance measurements and test over-constrained algorithm for a prototype set of reference points**
- → **Preparation for test of silicon ladder prototype alignment**

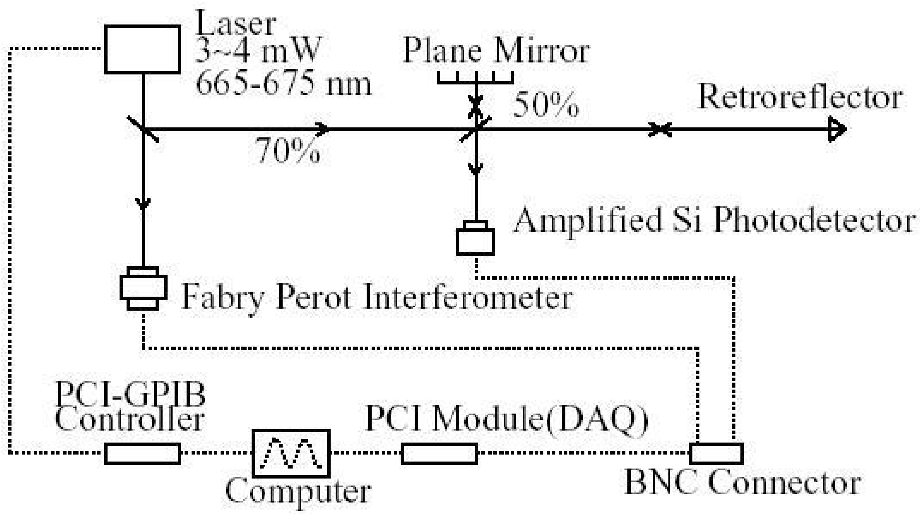
Summary and Outlook

- Several FSI demonstration systems with increasing realism have been implemented
- Results on achievable measurement precision are quite promising (~0.2 μm with dual-laser scanning)
- Plans:
  - Miniaturization
  - Multiple channels
  - Simulation (not discussed today)

BACKUP SLIDES

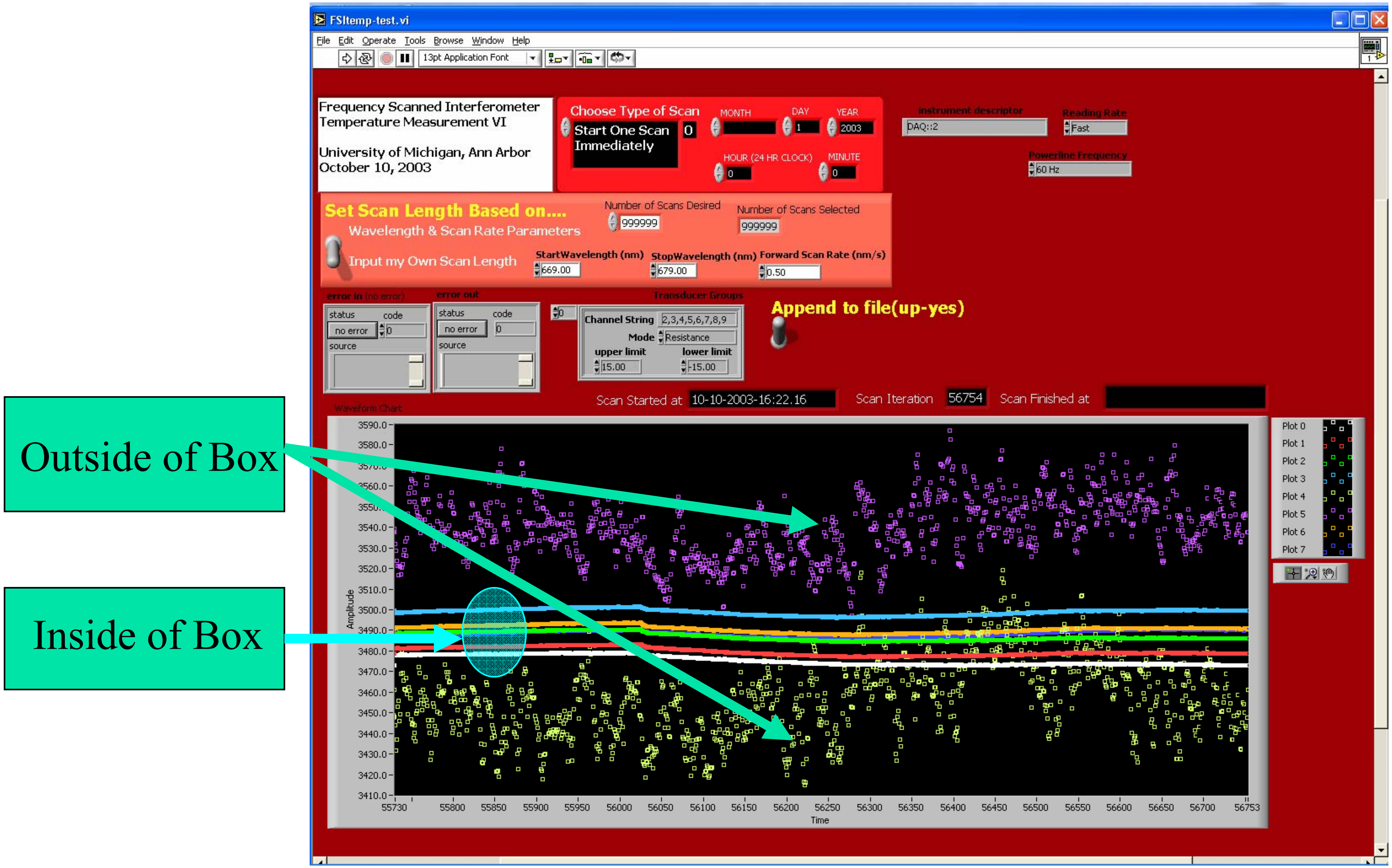
BACKUP SLIDES

FSI Demonstration System (I)



- ✶**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.**

Temperature Measurements



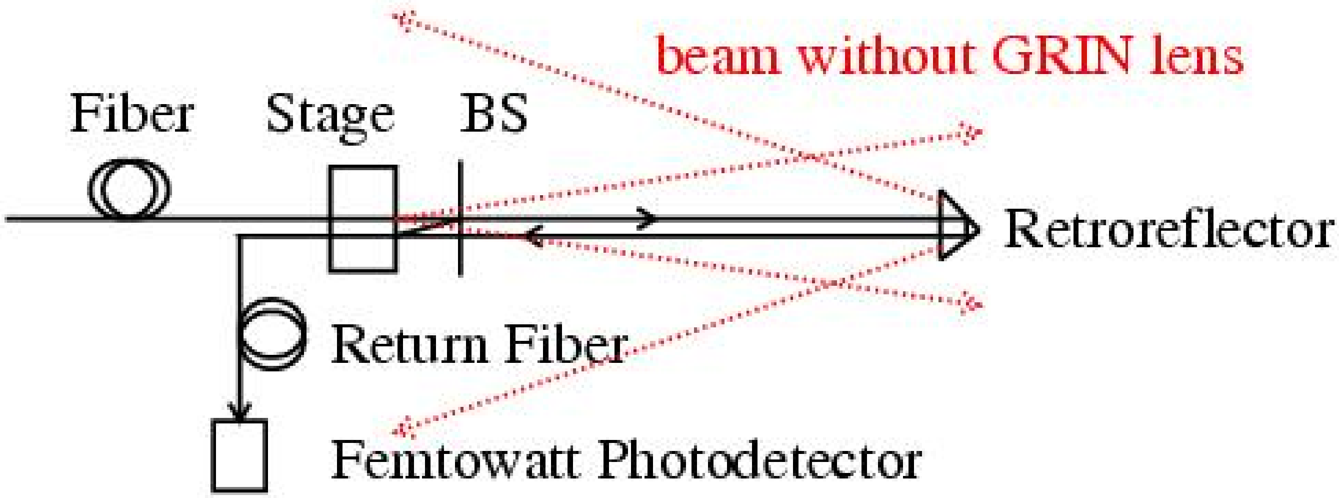
FSI with Optical Fibers (II)

♦ 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 ~5 μm.

Geometrical Efficiency: ~ 6.25×10^{-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=1mm, L=2.58mm) 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.



Multiple-Measurement Techniques

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

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

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

- Assuming a vibration with one frequency:

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

- Fringe phase at time t:

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

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

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

$$OPD^{meas} = OPD^{true} + \Omega \times [2x_{vib}(t) - 2x_{vib}(t0)] \quad (1)$$

$$OPD^{meas} = OPD^{true} - \Omega \times 4a_{vib}\sin[\pi f_{vib}(t-t0)] \times \sin[\pi f_{vib}(t+t0)+\phi_{vib}] \quad (2)$$

➔ 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

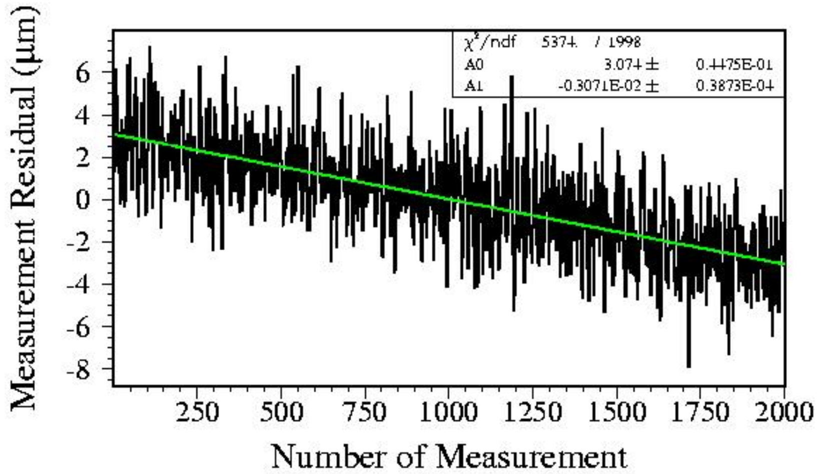
  C1=0.00600069867, C2=0.0200179144, C3=103.560653
- Numerical simulation results **(thickness of the corner cube prism = 1.86 cm)**

  R_1 – R_true = 373.876 um, R_2000 – R_true = 367.707 um

  R_1 – R_2000 = 6.2 +/- 0.2 um
- Real data - fitted result

  R_1 – R_2000 = 6.14 +/- 0.1 um

➔ 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 ~ 1.9 ppm; if N_{meas} = 1200, dR/R ~ 77 ppb
- Error from vibration. dR/R ~ 0.4 ppm; if N_{meas} = 1200, dR/R ~ 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 ^{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 ~ 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 ~ 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.

Simulation of Alignment System

➔Will eventually use hundreds of distance measurements along lines of sight to determine tracking component positions, rotations (pitch/roll/yaw), and internal distortions.

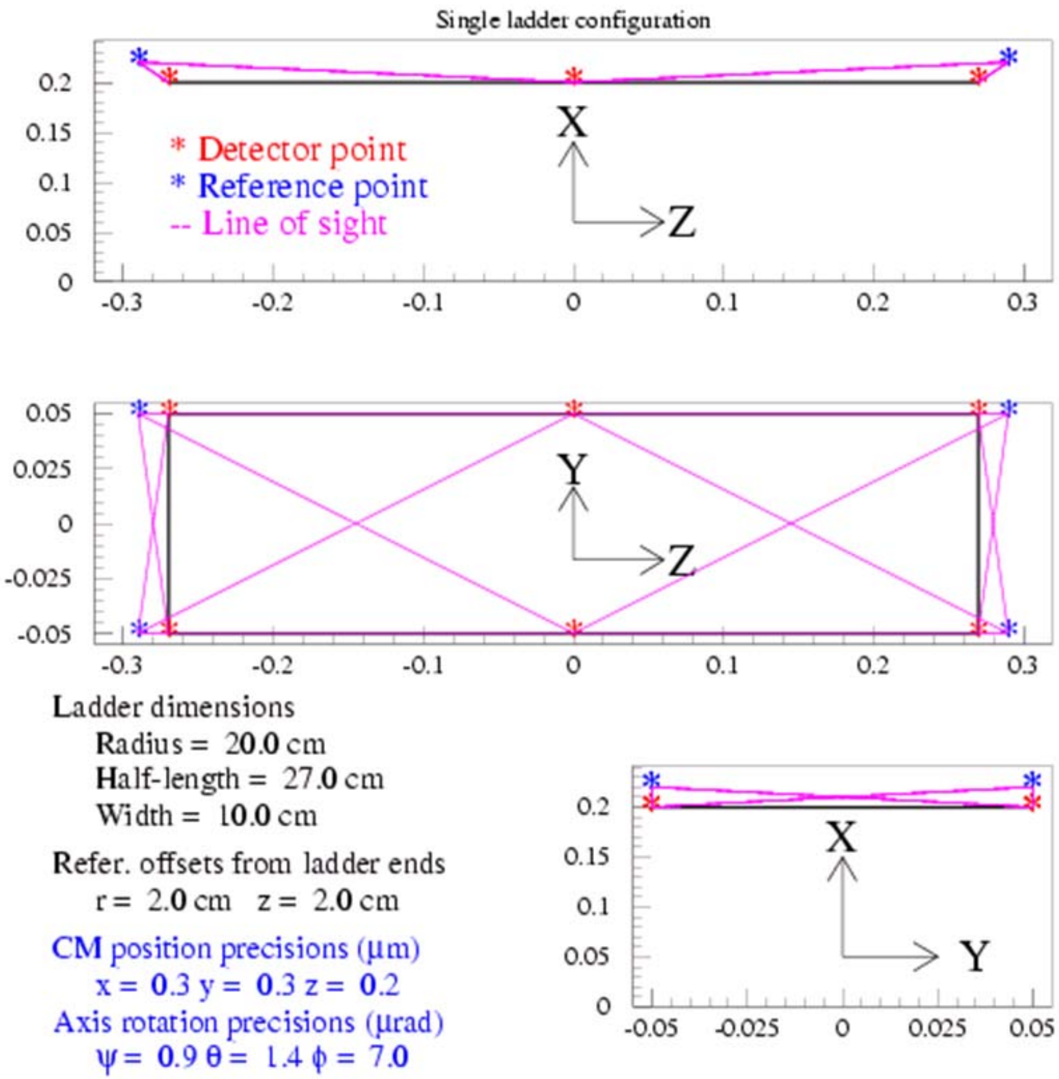
➔ System simulations starting – first steps with rigid bodies:

- Align single silicon ladder
- Align single cylinder (e.g., Si disk, TPC, or CCD cryostat)

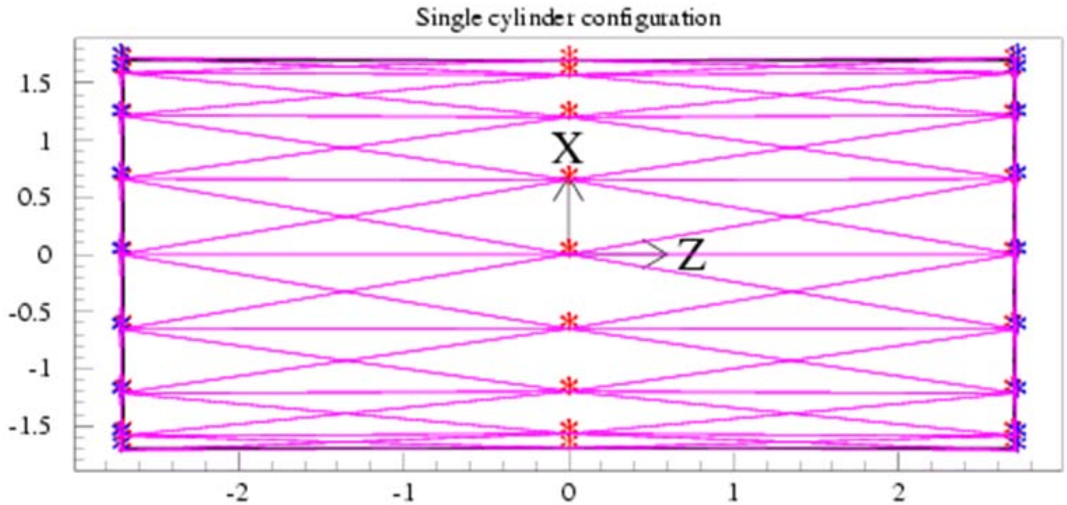
➔ Assumes (for now) distance resolution of 0.5 microns for all lines of sight [optimistic for d > 1 meter, conservative otherwise]

➔ 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



Alignment of Single TPC Cylinder



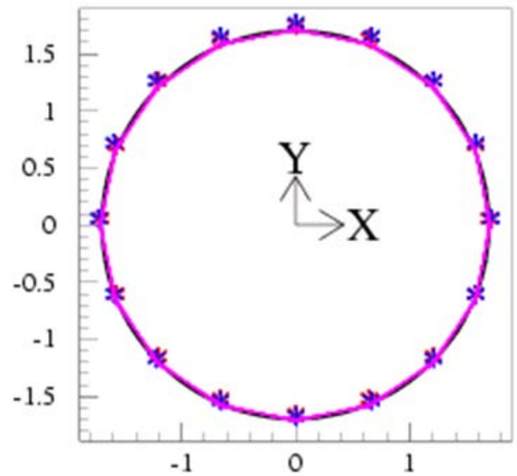
* Detector point
* Reference point
-- Line of sight

Cylinder dimensions
Radius = 1.70 m
Half-length = 2.70 m

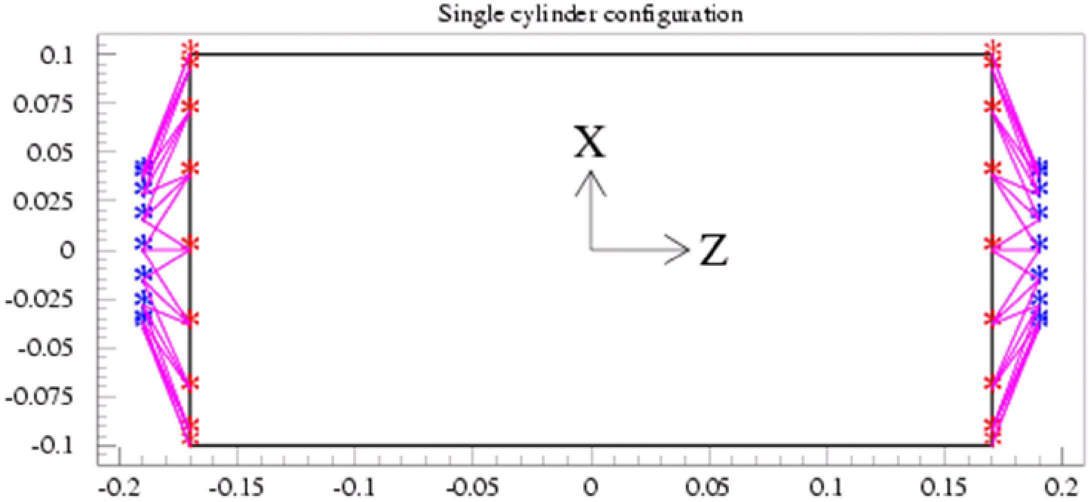
Refer. offsets from cylinder ends
r = 2.0 cm z = 2.0 cm

CM position precisions (μm)
x = 0.08 y = 0.06 z = 0.05

Axis rotation precisions (μrad)
ψ = 0.02 θ = 0.02 ϕ = 0.03



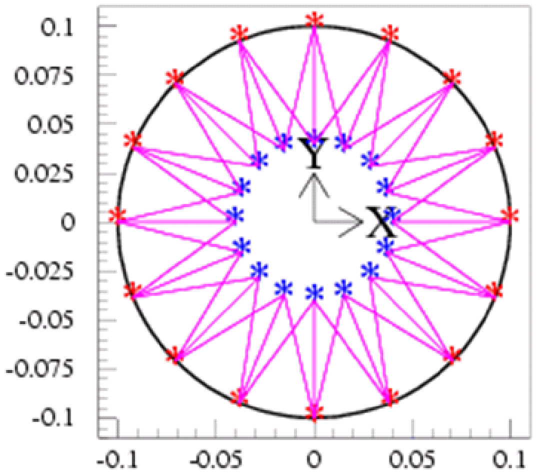
Alignment of Single CCD Cylinder



* 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)

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

Much More Simulation to Do …

➔ 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