Applying the Michigan FSI Approach to SiD Final Focus Magnet Alignment

University of Michigan ILC Group

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MDI Teleconference

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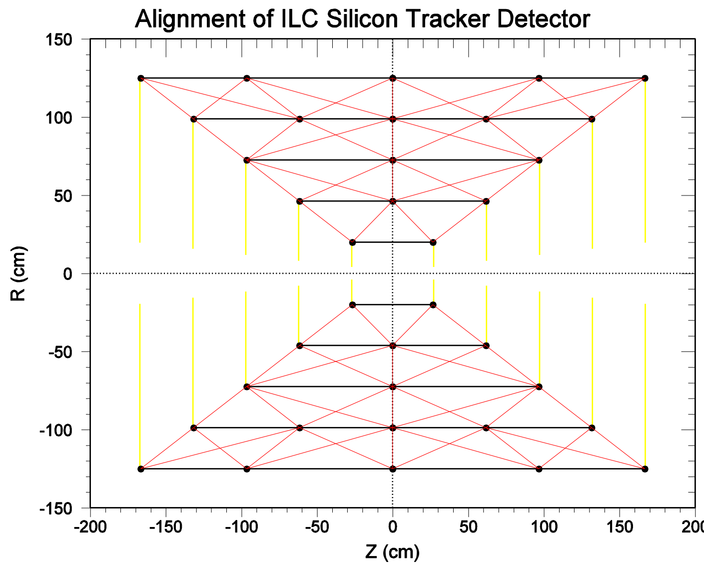
Background on Michigan FSI work

Began R&D work in 2003 on FSI system for an ILC tracker

Applied the principles pioneered by the Oxford ATLAS group



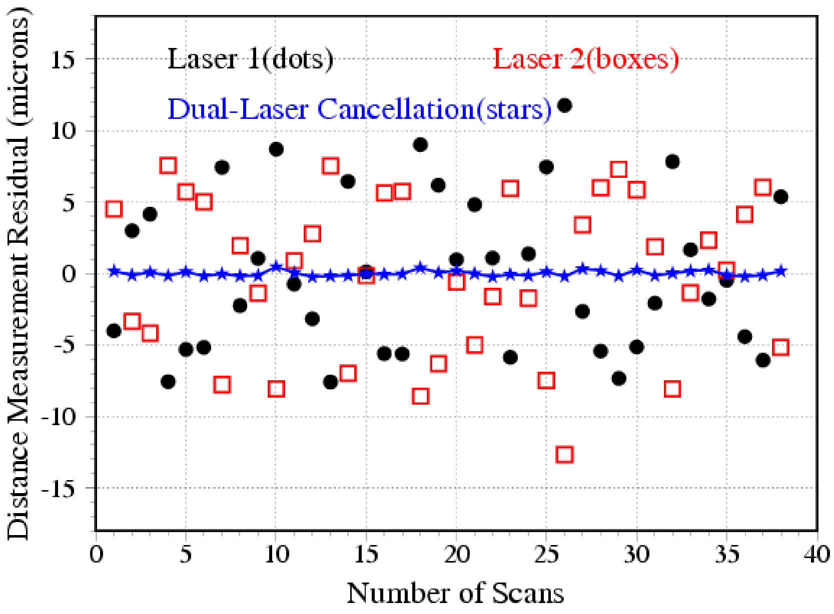
Built basic infrastructure on bench in Michigan lab and came up to speed over ~3 years

Many presentations at LC workshops and two articles:

***Appl. Opt* 19: 3937 (2005); *Nuc. Inst. Meth. A* 575:395 (2007)**

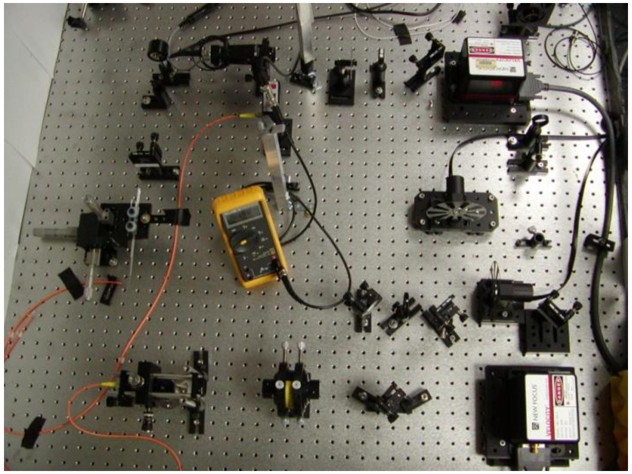
Background on Michigan FSI work

Achieved O(200 nm) precision in hostile environment (air currents, temperature gradients) using dual-laser approach pioneered by Oxford – good robustness



Checks:

- **Verified micrometer offset of 125 µm**
- **Verified thermal-driven 60 µm expansion**
- **Verified piezo-driven 2 µm displacement**
- **Verified piezo-driven 0.15 µm vibrations**



Caveats:

- **Single-channel system**
- **Used (large) commercial retroreflectors locked to table**
- **Manual alignment**

Background on Michigan FSI work

Funding dried up ~3 years ago

Modest work since then:

- **Looked at lightweight retroreflector arrays**
- **Talked with rapid prototyping companies, but didn't have funds to proceed**
- **Experimented with metallic coatings on PMMA using campus facility**
- **Some simulation work by undergraduate**
- **Recently "inherited" 3-D translation stage with tens of cm range and submicron precision in 2-D**
- **But project largely mothballed on optical table in Michigan lab**

Would like to resume R&D work for tracking system and very agreeable to helping out on magnet alignment if FSI approach is indeed useful there (which it seems to be)

Moving forward

We need to understand better the geometry & environment of QD0 and QF1 interface:

- **Clearances for retroreflectors**
- **Lines of sight for interferometer beams**
- **Launch points for fiber assemblies**
- **QD0 alignment w.r.t. bedrock or w.r.t. QF1 more important?**
- **Radiation levels**

Drawings & documents would be helpful!

Accuracies for QD0 support in functional requirements document (Mar 09):

- **50 µm in x, y**
- **20 mrad in roll α**
- **20 µrad in pitch φ and yaw ψ**

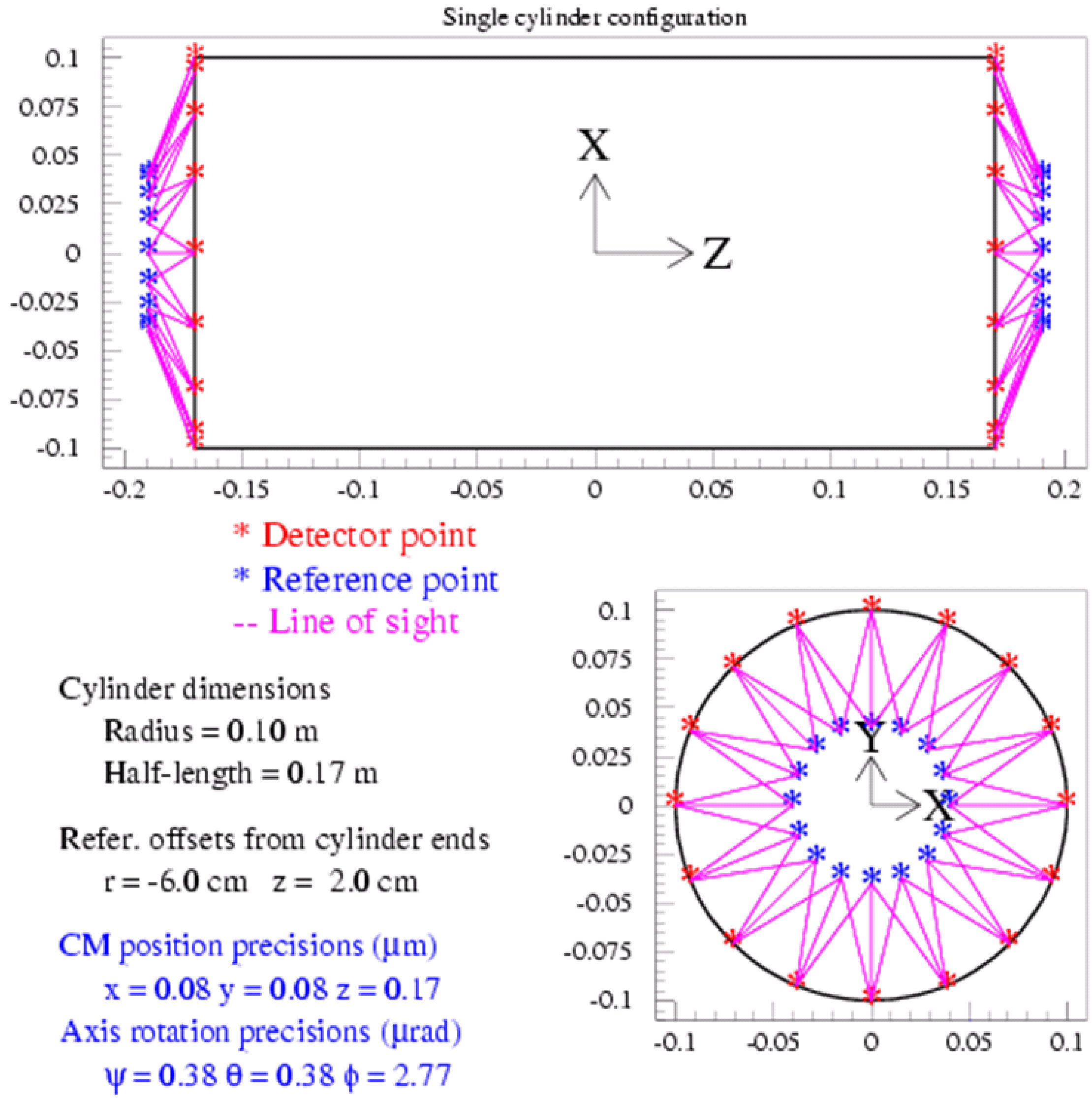
Moving forward

Have not yet attempted to simulate this system, but closest previous geometry examined was for a vertex detector cryostat:

This example suggests an FSI approach can "easily" meet MDI requirement, even with fewer readout channels

But much easier to do in software than in the real world!

(ψ=pitch, θ=yaw, φ=roll) →



Moving forward

Our understanding of SLAC priorities & Michigan constraints:

- **Current priority is verifying method works at all with actual magnet mover on bench at SLAC**
- **Michigan group being asked to develop and test multi-channel system and (if successful) duplicate the system on a bench at SLAC**
- **Equipment funds available very soon (?)**
- **Salary/wages funds available in late fall (LCRD)**
- **We will recruit a temporary exchange grad student from China to assist Haijun at Michigan (student available spring 2011)**

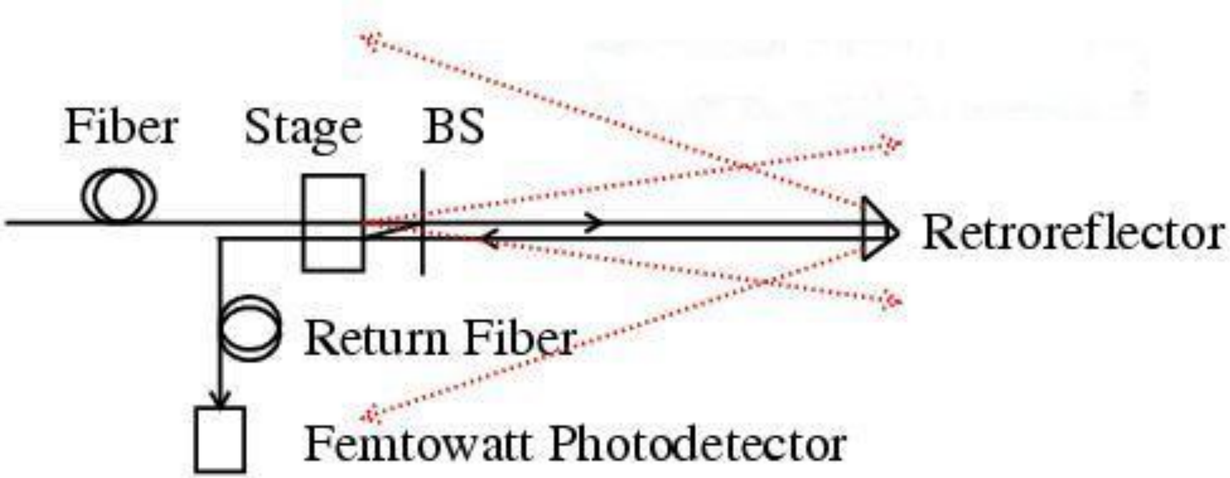
BACKUP SLIDES

Overview of FSI 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.**

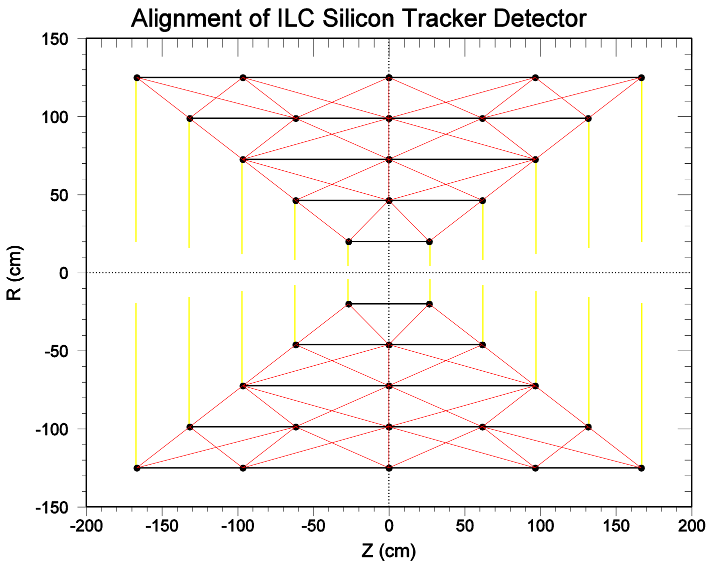
- **Absolute distances are determined by scanning the laser frequency and counting interference fringes.**

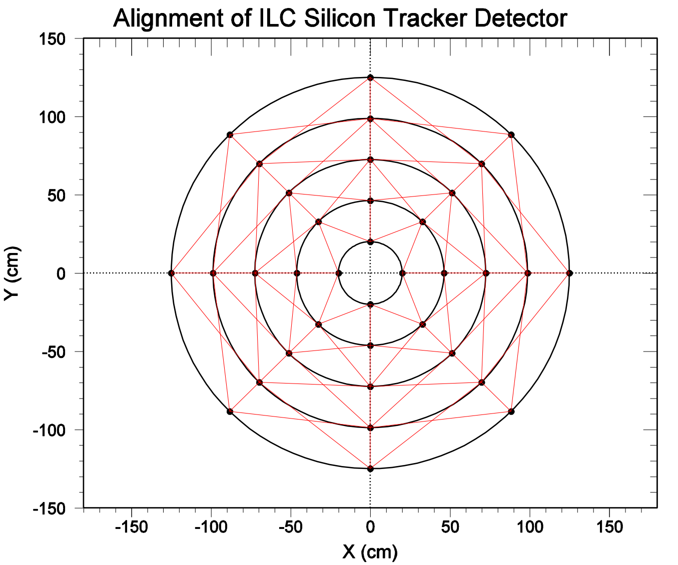
- **Grid of reference points overdetermined → Infer tracker distortions**

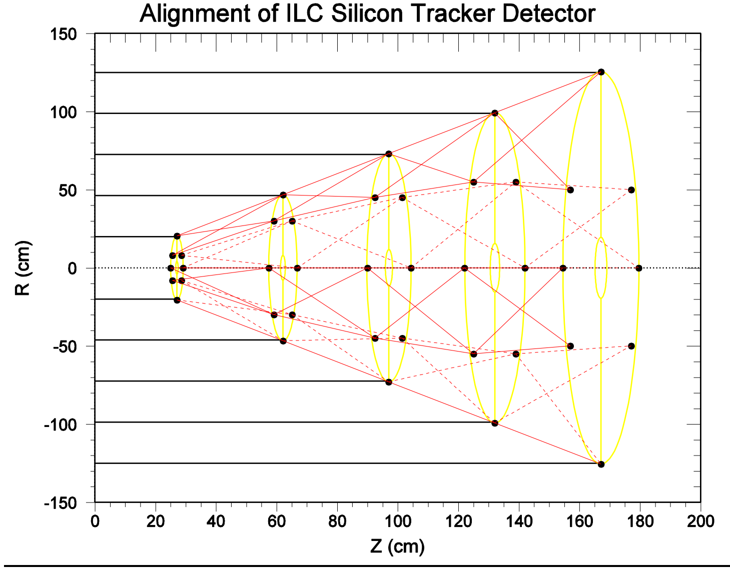


- **Technique pioneered by Oxford U. group for ATLAS detector**

A Possible SiD Tracker Alignment







752 point-to-point distance measurements

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

Principle of Distance Measurement

- The measured distance can be expressed by

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

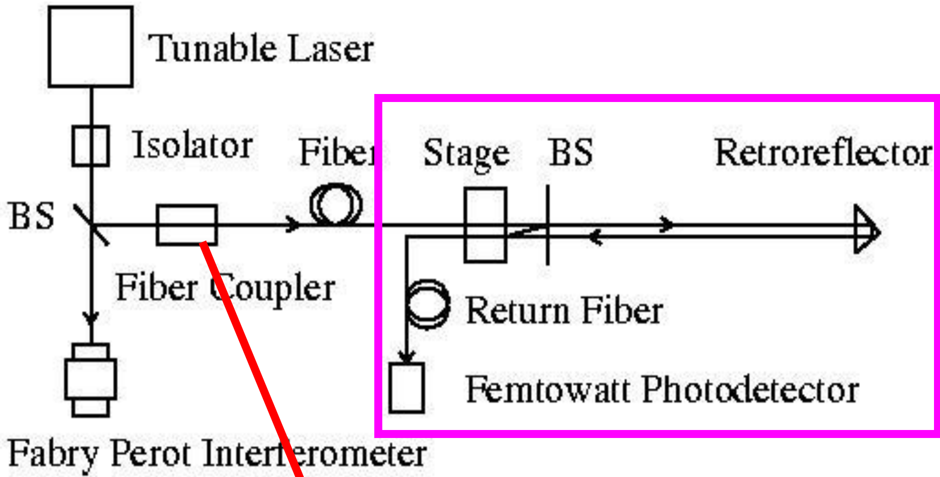
c - *speed of light,* ΔN *– No. of fringes,* $\Delta \nu$ *- scanned frequency*
n_g *– average refractive index of ambient atmosphere*

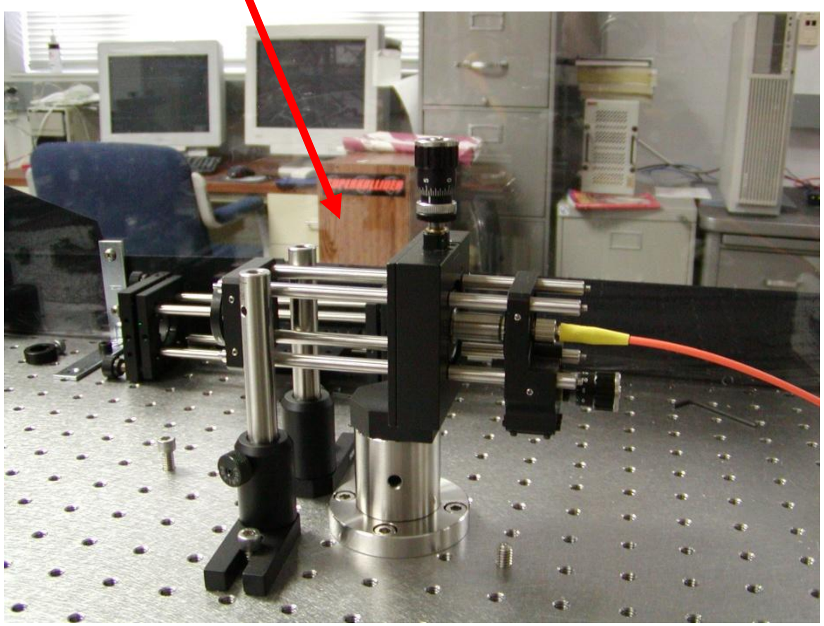
- Assuming the error of refractive index is small, the measured precision is given by:

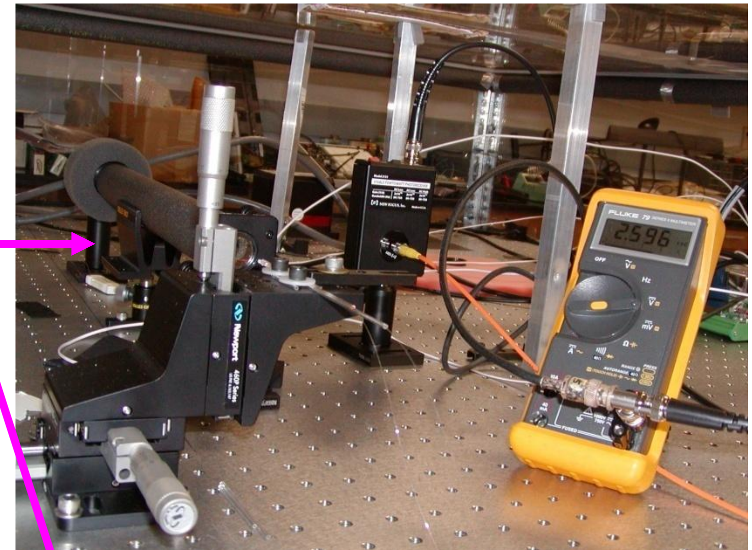
$$(\sigma_R / R)^2 = (\sigma_{\Delta N} / \Delta N)^2 + (\sigma_{\Delta \nu} / \Delta \nu)^2$$

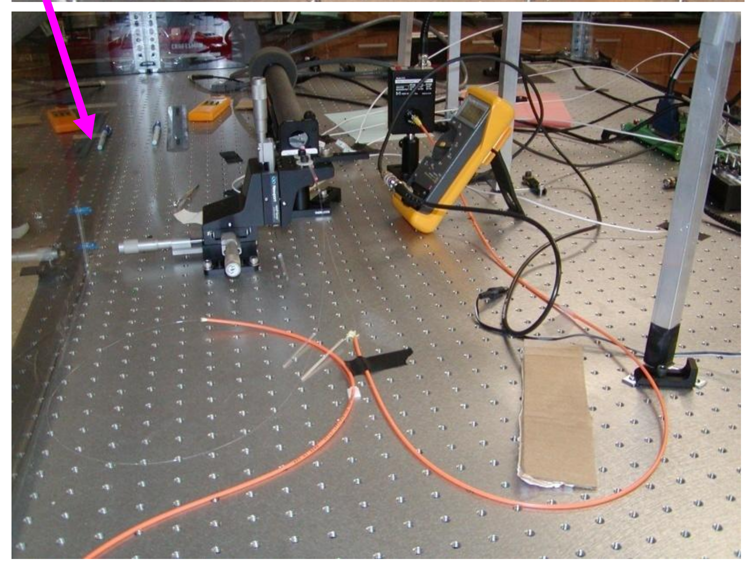
Example: $R = 1.0$ *m,* $\Delta \nu = 6.6$ *THz,* $\Delta N \sim 2R\Delta\nu/c = 44000$
To obtain $\sigma_R \simeq 1.0\ \mu m$*, Requirements:* $\sigma_{\Delta N} \sim 0.02$*,* $\sigma_{\Delta \nu} \sim 3$ *MHz*

FSI with Optical Fibers





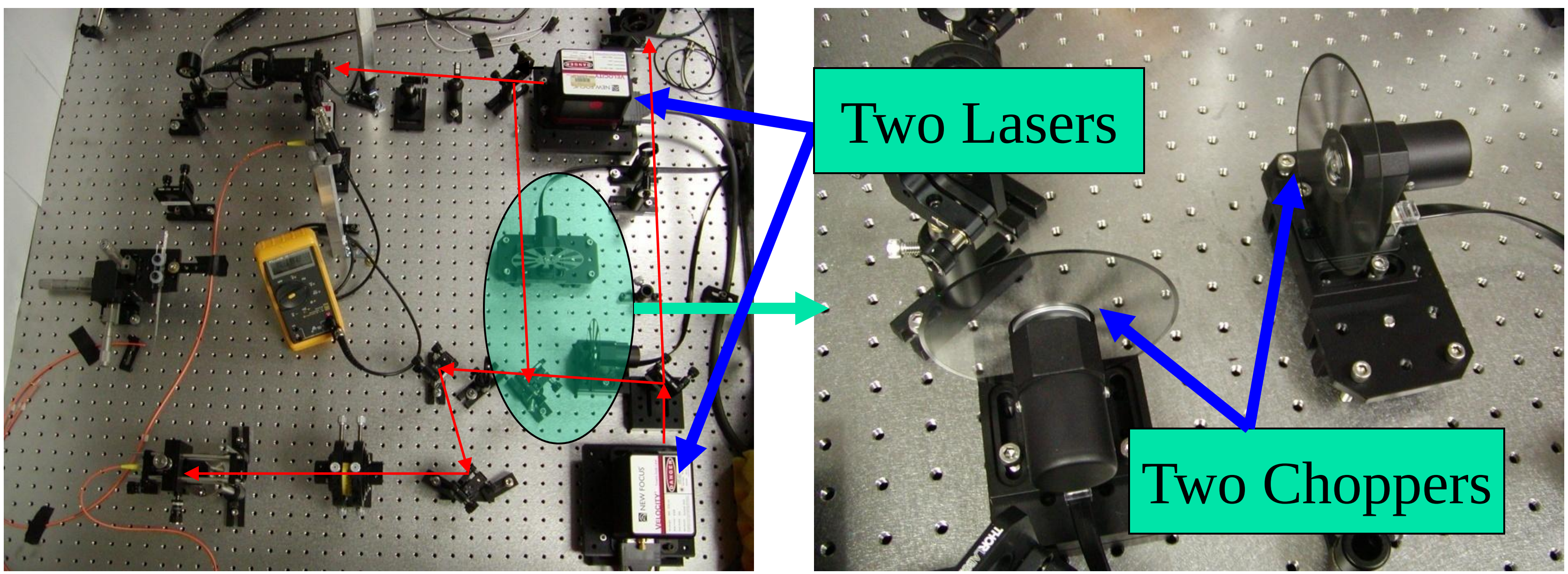




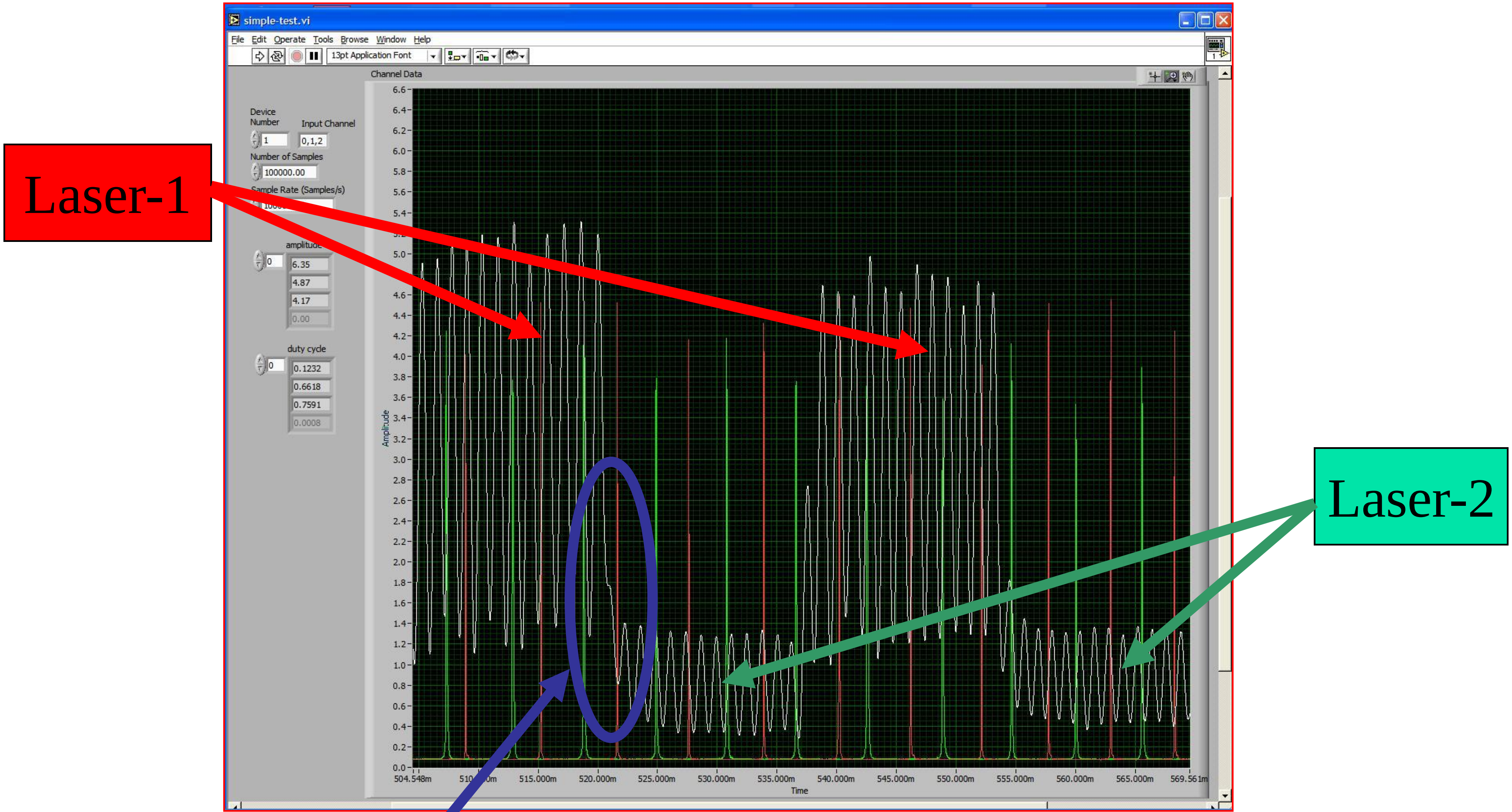
Dual-Laser FSI

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

Laser #1: $D_1 = D_{true} + \mathbf{\Omega}_1\varepsilon_1$
Laser #2: $D_2 = D_{true} + \mathbf{\Omega}_2\varepsilon_2$
Drift errors: $\varepsilon_1 \approx \varepsilon_2 = \varepsilon$
$D_{true} = (D_2 - \rho D_1) / (1 - \rho)$,
Where $\rho = \mathbf{\Omega}_2 / \mathbf{\Omega}_1$



Fringes & F-P Peaks (dual-laser)

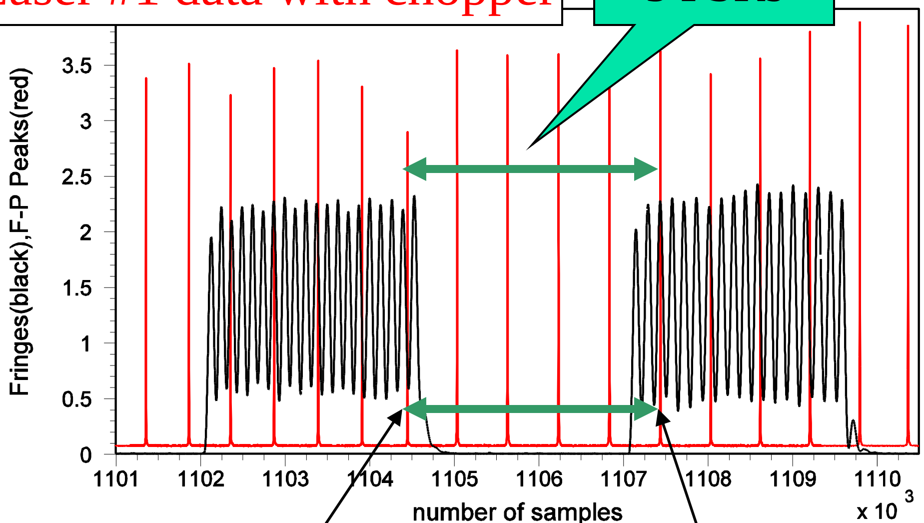


Chopper edge effects and low photodiode duty cycle per laser complicate measurement.

Fringe Interpolating Technique

Laser #1 data with chopper

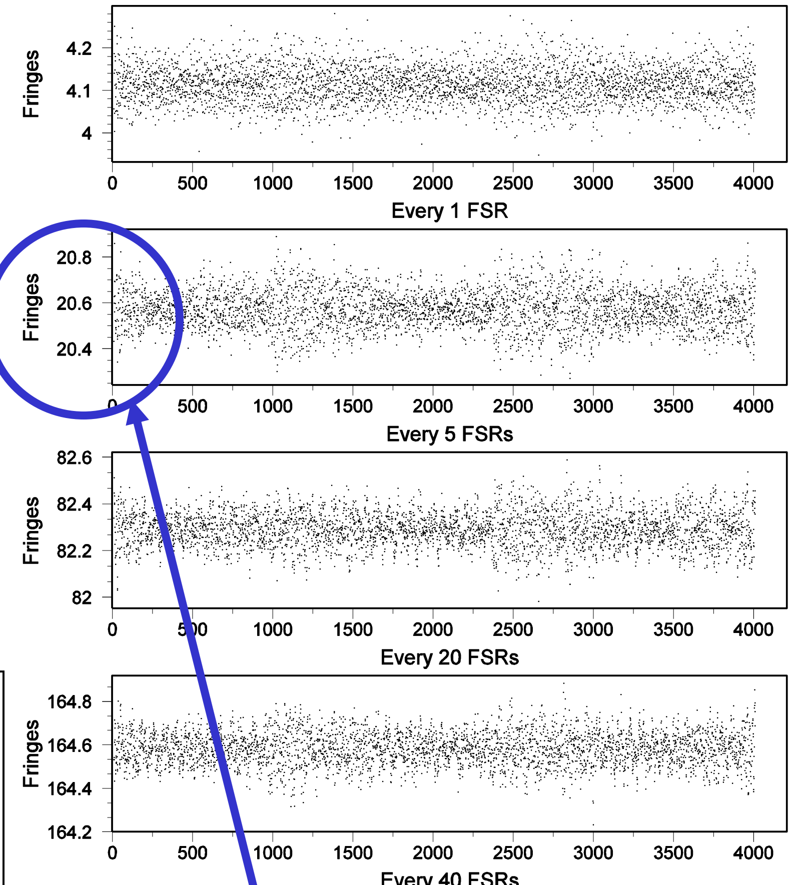
5 FSRs



Fringe phase = I+ΔI

Fringe phase = J+ΔJ

Laser #1 data without chopper



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.

Expected fringes for 5 FSRs

Distance Measurement Precision

Dual-Laser FSI Data Samples – Under Realistic Conditions

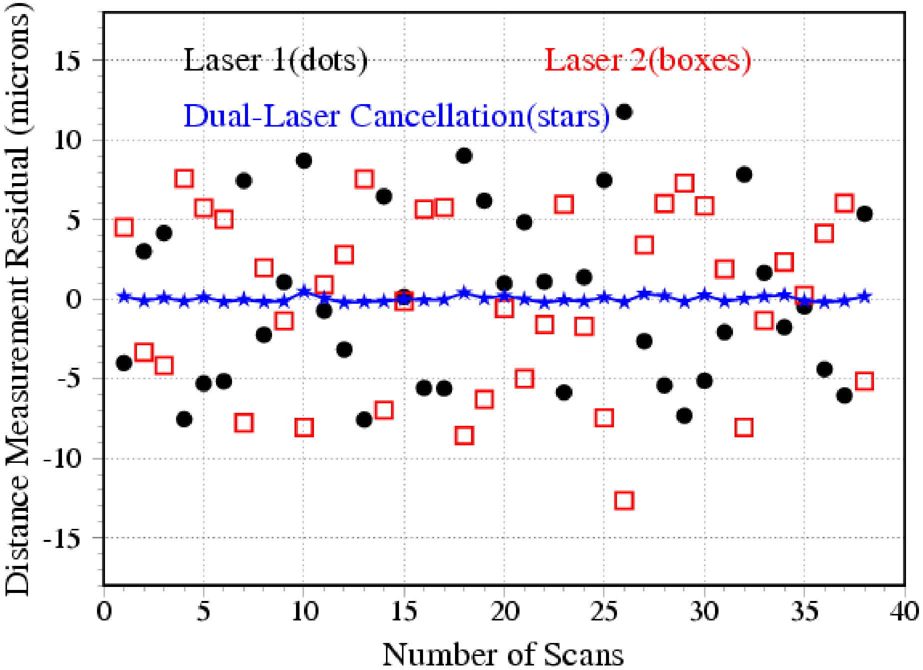
* with box open(20 scans), with fan on (10 scans), with vibration(8 scans).
* Scanning rates for Laser #1 and #2 are -0.4 and 0.4 nm/s, respectively.
* Scanning time is 25 seconds, sampling rate is 100 KS/s.
* Two lasers are operated simultaneously, 2-blade chopper frequency is 20 Hz.

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



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

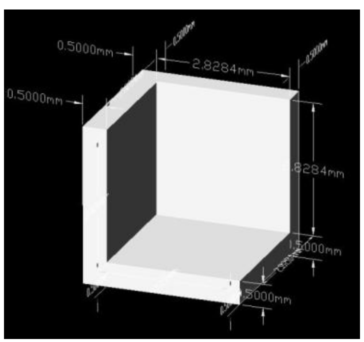
Miniaturization

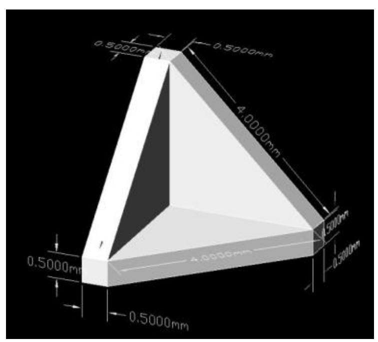
So far we have used large commercial optics:

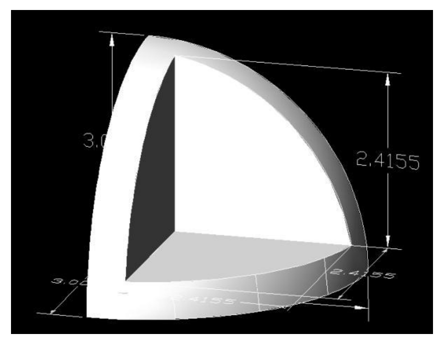
- **Retroreflector**
- **Beam splitter**

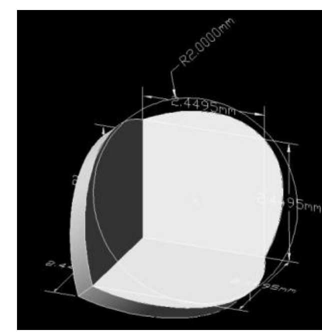
Need miniaturized, low-X_0 components for actual tracker

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

Similar performance seen with Edmunds reflector array

Promising indication, given simple design of the reflector pixels
(solid plastic corner cubes with no coating)

Multiple channels

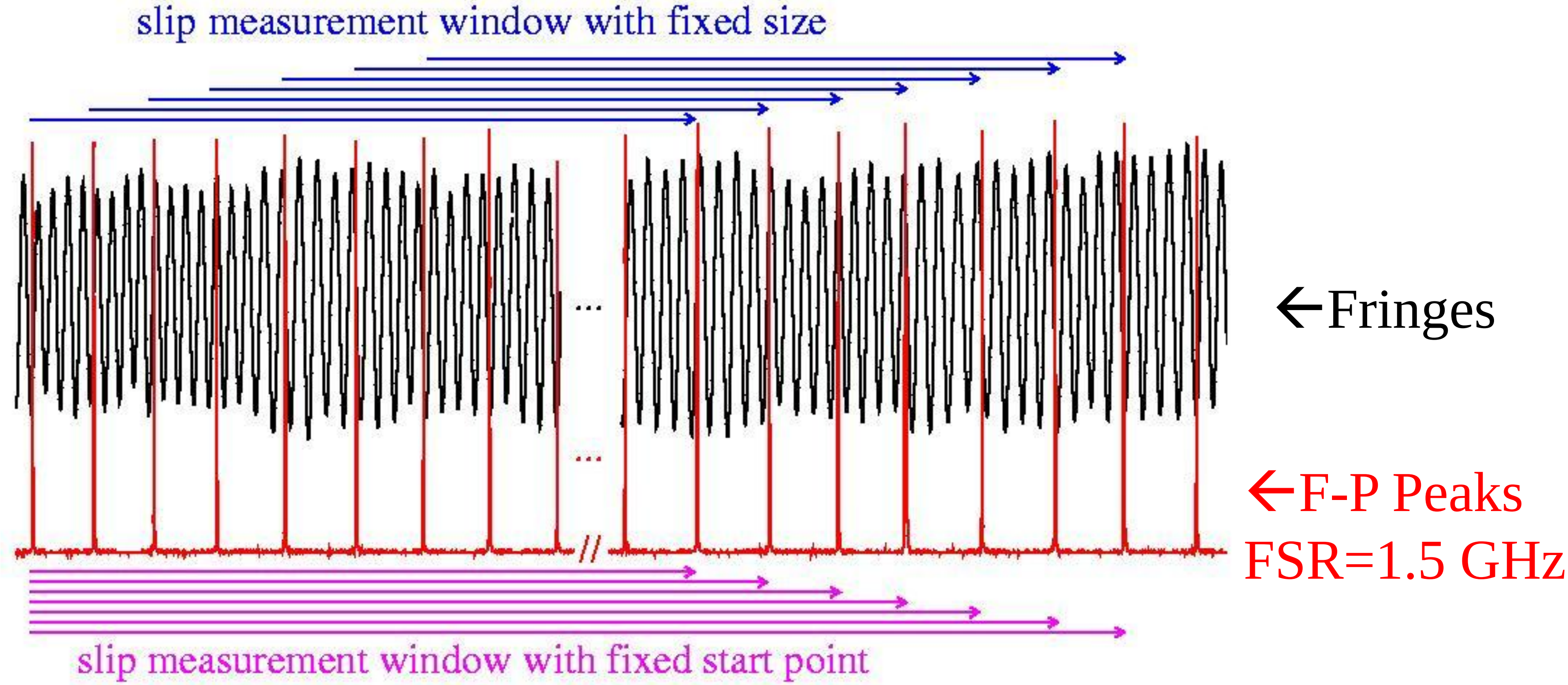
Plan to implement multiple channels fed by a tree of fiber splitter

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

MORE BACKUP SLIDES

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

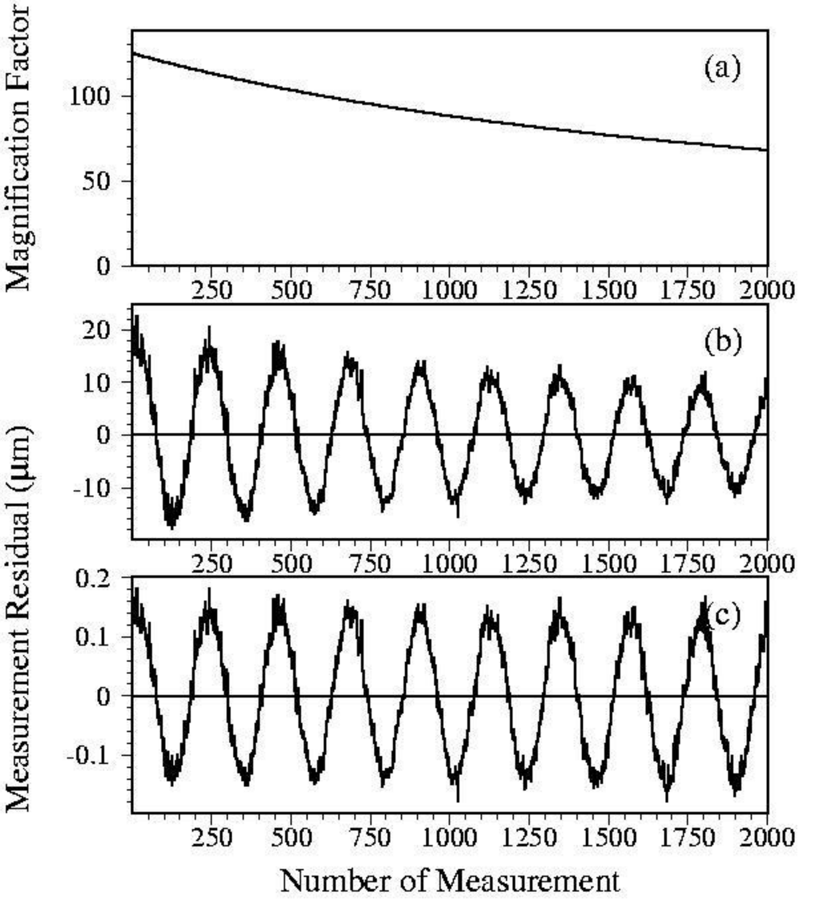
- A PZT transducer was employed to produce controlled vibration of the retroreflector, $\mathbf{f_{vib} = 1.01 \pm 0.01}$ **Hz,** $\mathbf{amp_{vib} = 0.14 \pm 0.02}$ **μm**

- 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)

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

$\mathbf{amp_{vib} = 0.138 \pm 0.0003}$ **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,

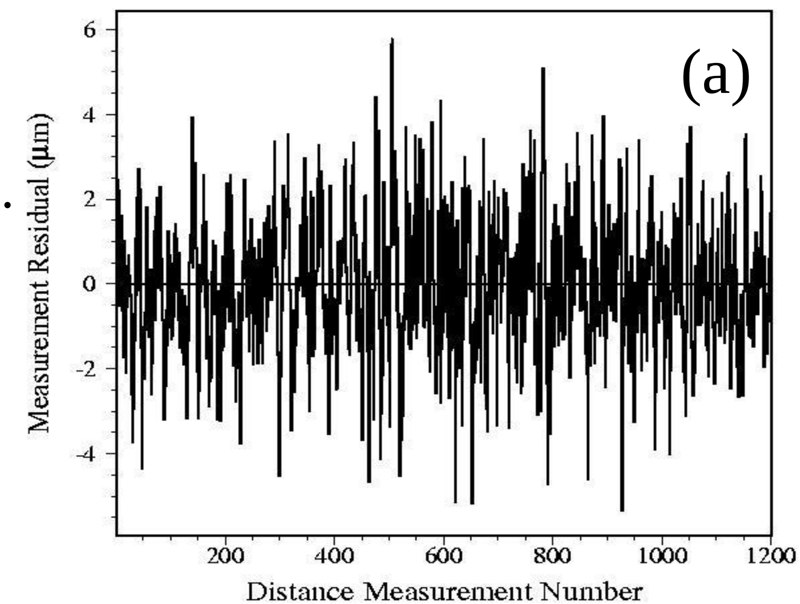
  (b) for 10 sequential scans.

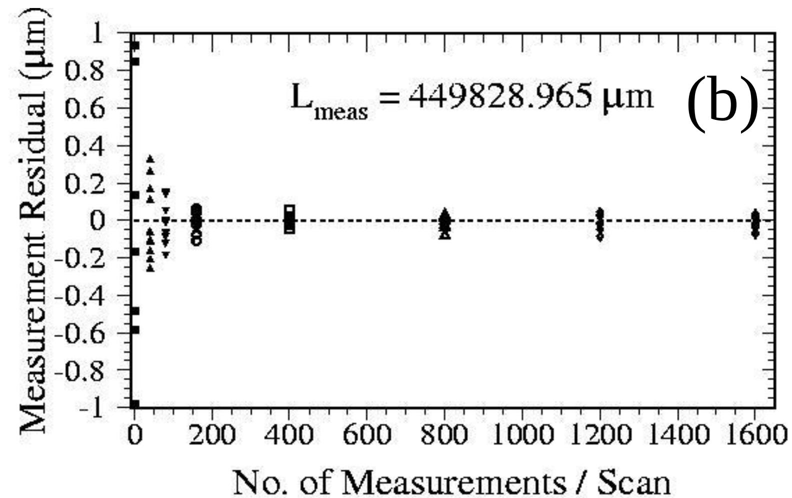
➔It can be seen that the distance errors decrease with increasing N_{meas}.

N_{meas}=1, precision=1.1 μm (RMS)

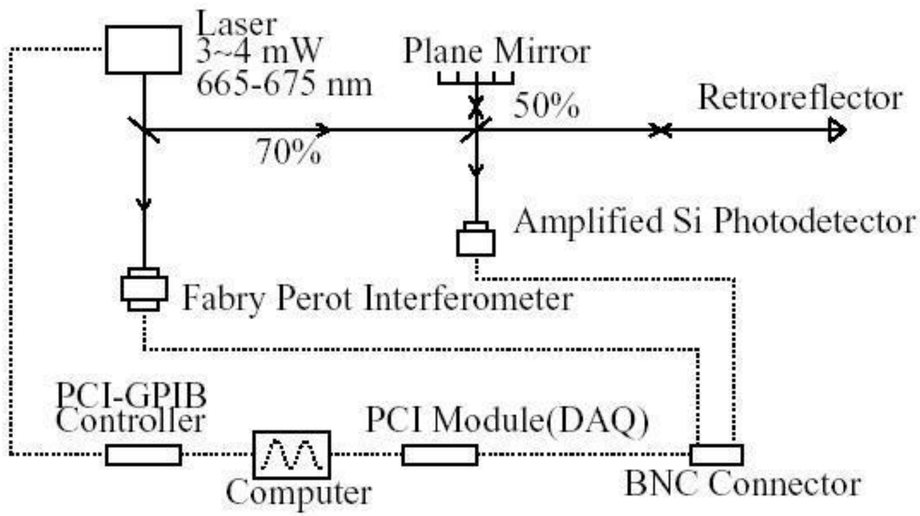
N_{meas}=1200, precision=41 *nm* (RMS)

➔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 Demonstration System



✶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.

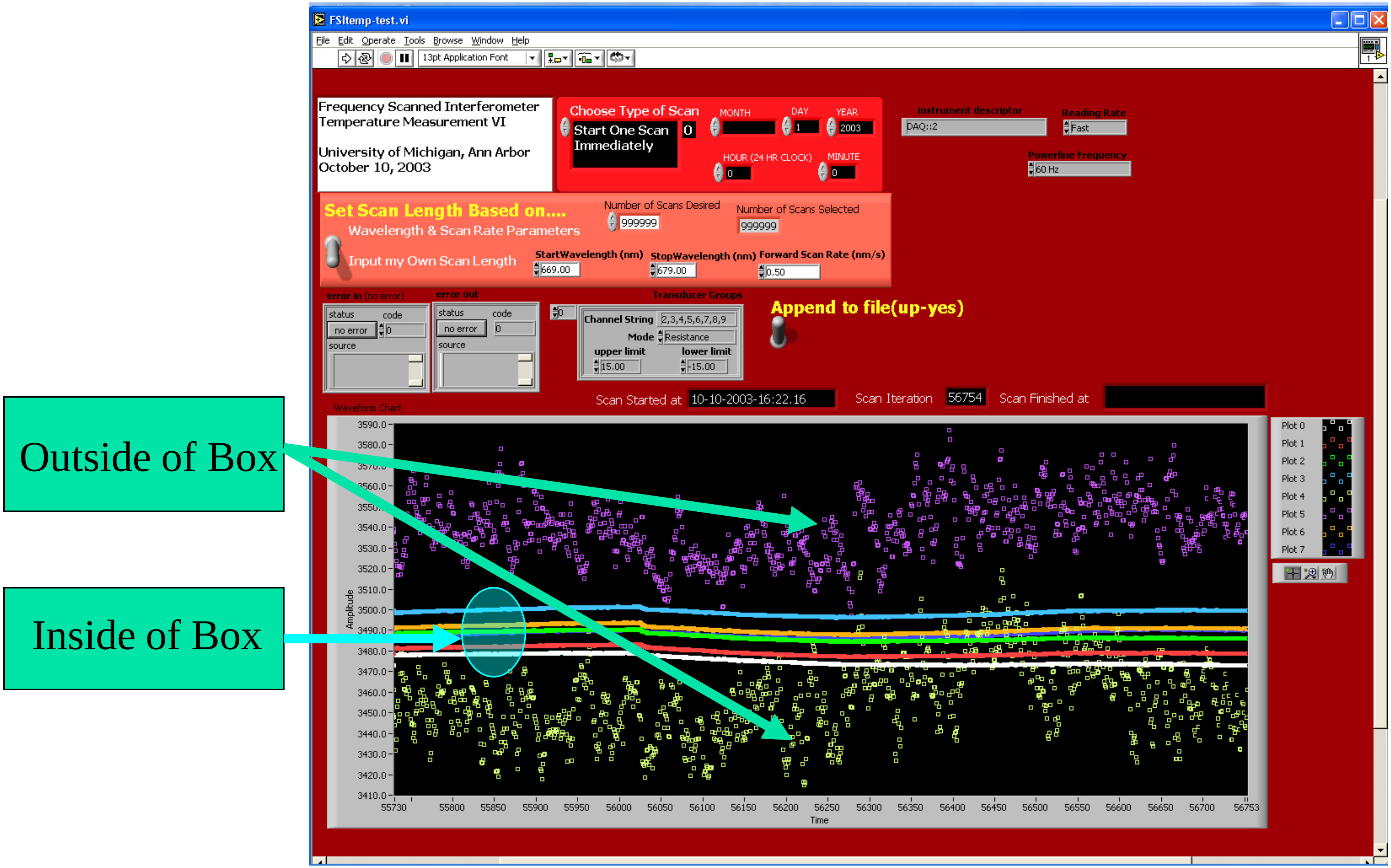
✶ Thermistors and hygrometer are used to monitor temperature and humidity respectively.

✶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



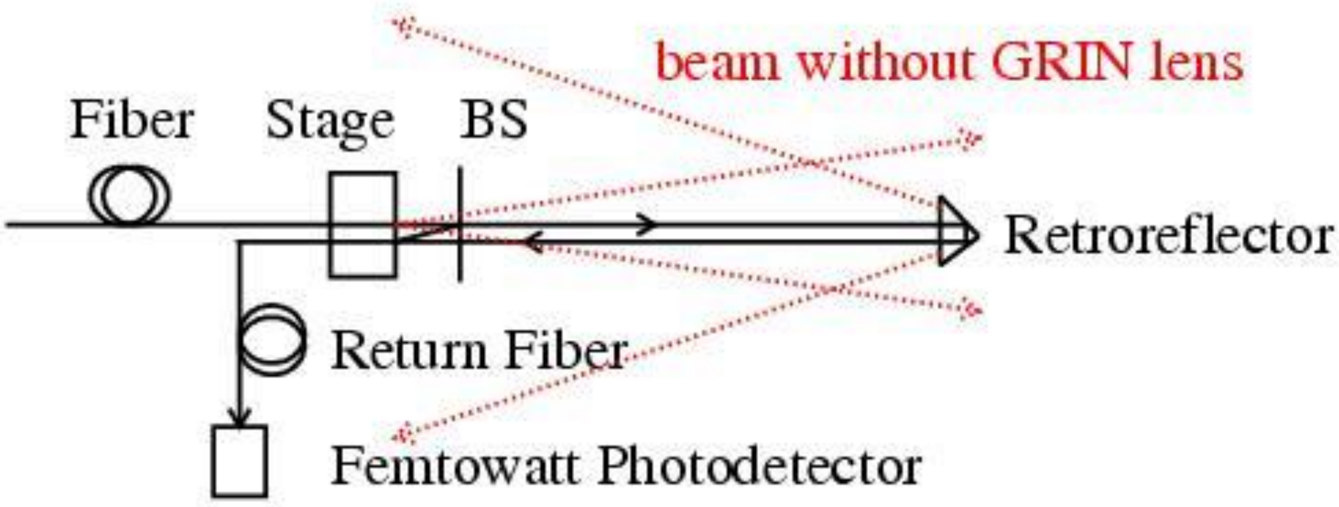
FSI with Optical Fibers

♦ 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

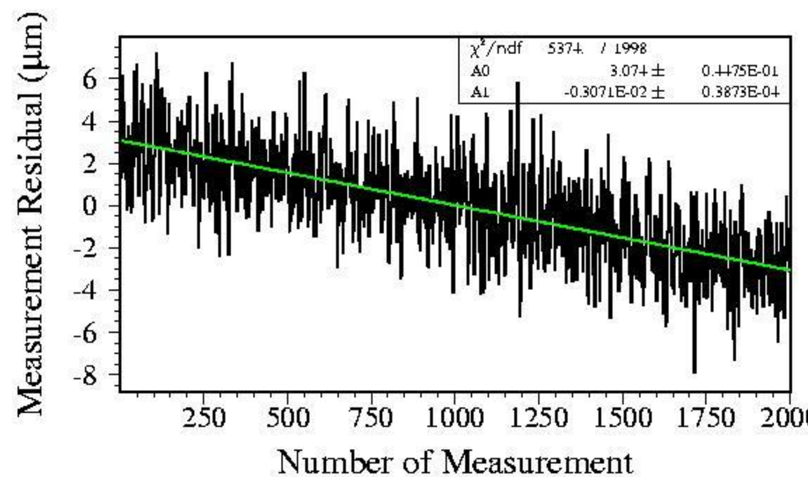
  C1=0.00600069867, C2=0.0200179144, C3=103.560653
- Numerical simulation results **(thickness of the corner cube prism = 1.86 cm)**

  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.

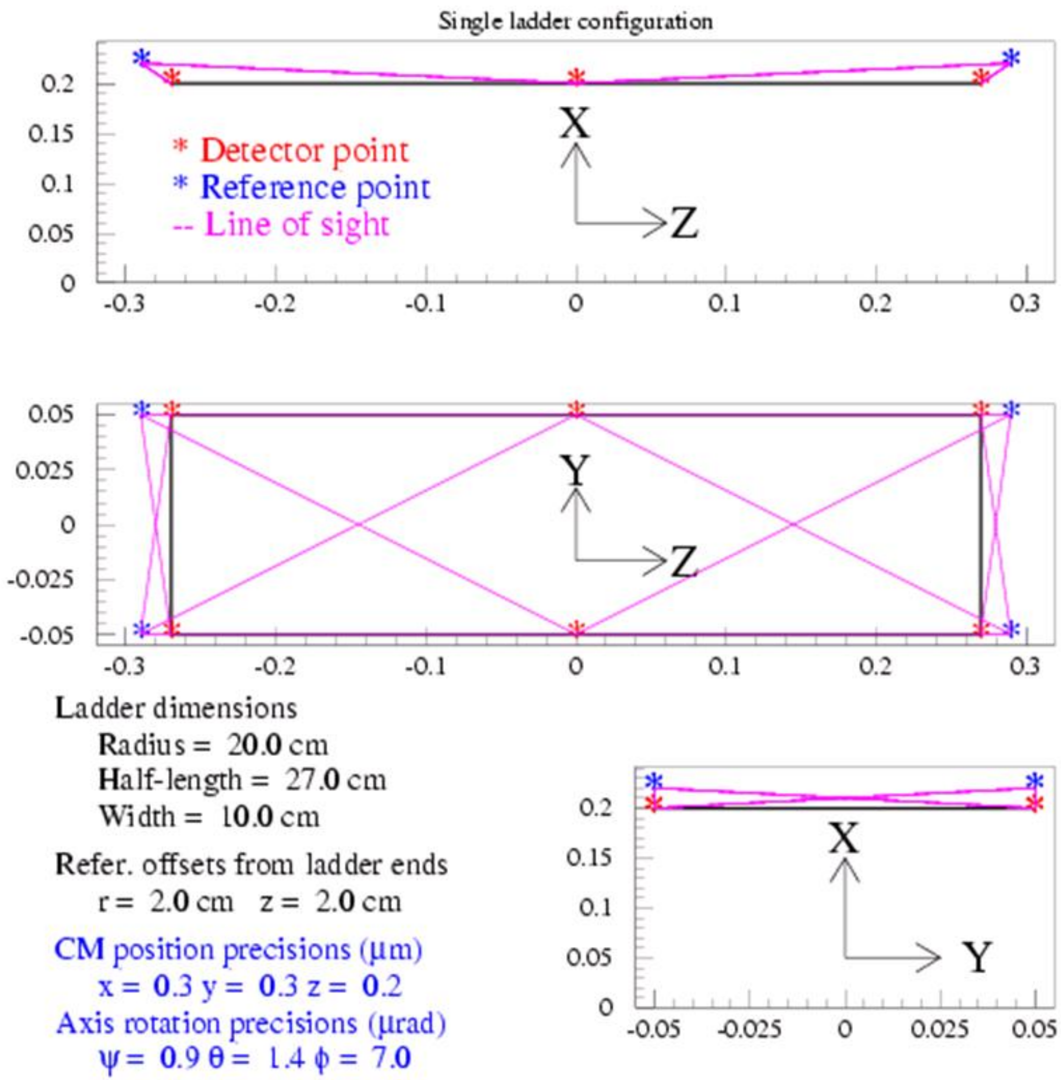
➔ System simulations starting – first steps with rigid bodies:

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

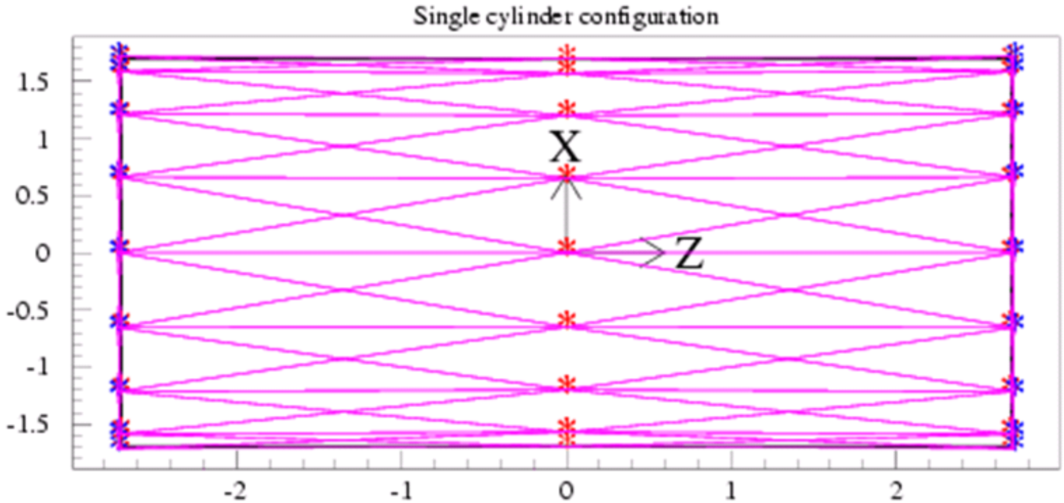
➔ Assumes (for now) distance resolution of 0.5 microns for all lines of sight [optimistic for d > 1 meter, conservative otherwise]

➔ 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



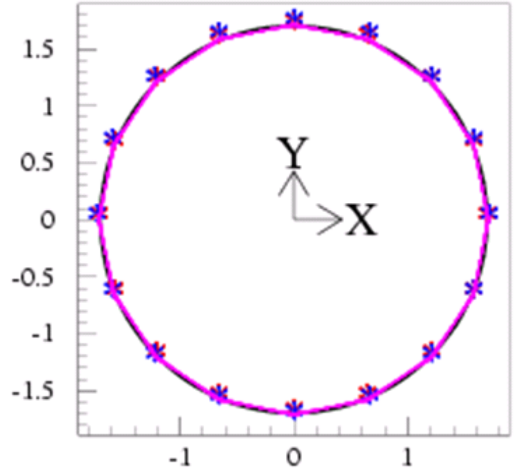
Alignment of Single TPC Cylinder



* 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

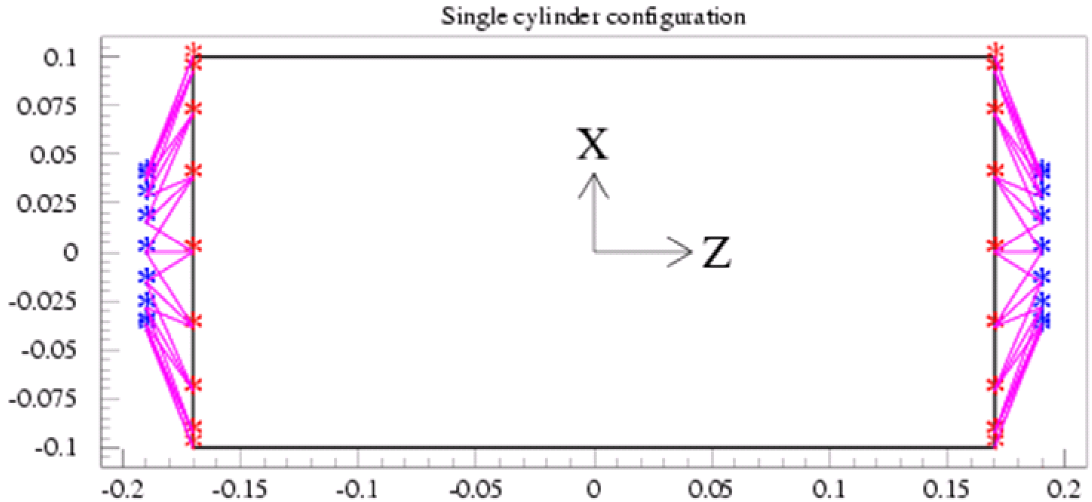
CM position precisions (μm)

x = 0.08 y = 0.06 z = 0.05

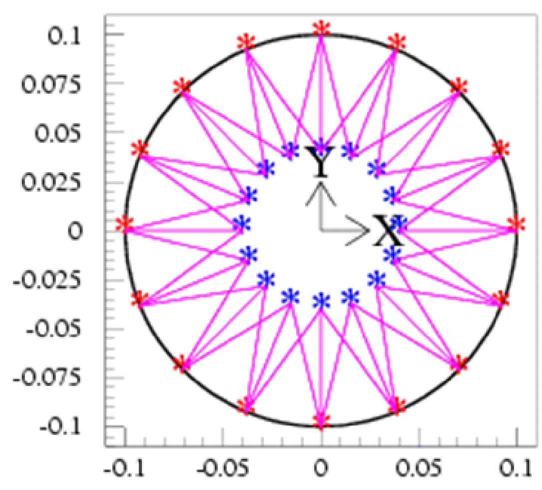
Axis rotation precisions (μrad)

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

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)

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

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