A novel method for ATLAS FSI alignment based on rapid, direct phase monitoring

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Outline

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Overview of Frequency Scanning Interferometry

• Frequency Scanning Interferometry (FSI) is a technique to remotely measure multiple distances between a set of fiducial points, so that the relative position of components can be monitored.
• Based on absolute distance interferometry, the FSI technique was originally developed for ATLAS
  ✓ to monitor the shape of the particle tracking detector during the operation of the LHC.
• The FSI technique has also been applied to alignment research for a future Linear Collider:
  ✓ robotic survey of the accelerator chain (LiCAS )
  ✓ the alignment of the final focus quadrupoles (MONALISA)
  ✓ monitoring the tracking detector.

• The Benefits of FSI :
  ✓ Capability to autonomously track micrometer motion per meter.
  ✓ Access to short timescale motions
The alignment challenge:
- The silicon strip detector (SCT) is large (6.2m long, 1m diameter) and may move slightly, e.g. due to heat dissipated in the front end electronics.
- We need to monitor the SCT stability to better than $10 \, \mu\text{m}$ to not degrade track parameters by more than 20%.

**Pixels** = particle tracking and vertex detector with 80M silicon pixels.
**SCT** = SemiConductor Tracker; intermediate particle tracker with 6M silicon strips.
**TRT** = Transition Radiation Tracker, drift tube system, with particle identification.
Semiconductor Tracker alignment monitor

Solution: Interferometry!

- A geodetic grid of length measurements between nodes attached to the SCT support structures.
- All 842 grid lengths are measured simultaneously using Frequency Scanning Interferometry (FSI) to a precision of $< 1\mu m$.

- Each line shown is a length measurement. FSI monitors shape and relative positions of SCT barrels and end-cap wheels.
Basic principle of Frequency Scanning Interferometry

Ratio of phase change = Ratio of lengths

\[ \frac{\Delta \theta_{GLI}}{\Delta \phi_{REF}} \approx \frac{D}{L} \quad \text{if} \quad \Delta D = 0 \]

\[ \Delta \theta_{GLI} = \frac{2\pi}{c} (D\Delta \nu + \nu \Delta D) \]

D is unknown length of grid line to be measured
Each length measurement line of the alignment grid inside the SCT consists of a quill (two parallel fibres and a beam splitter) and a retro-reflector. The optical path difference is measured. GLI lengths range from 40mm to 1500mm.
Frequency Scanning Interferometry

FSI alignment system: 842 simultaneous micron precise distance measurements between grid nodes attached to SCT.

Repeated grid measurements monitor shape changes of the SCT.
FSI System Overview

- An automated FSI system operates within the inaccessible, confined spaces and high radiation levels of ATLAS, where a conventional survey is not possible.
- Lasers illuminate reference interferometer and on-detector geodetic grid via optical fibres.
Conventional FSI for absolute distance measurement

Scan a LARGE frequency range ($\Delta \nu \sim 10$THz):

$$\Delta \theta_{GLI} = \frac{2\pi}{c} (D\Delta \nu + \nu \Delta D)$$

- Measure absolute length $D$ every 8 minutes. (wrt reference)
- $\nu \Delta D$ term is cancelled using two lasers and a wavemeter.

Pros:
- Precise absolute measurement, $D$.
- Can power cycle laser without loss of precision.
- Excellent for long term monitoring.

Cons:
- Need large $\Delta \nu$ & two lasers to reduce systematic errors arising from $\Delta D$.
- Slow, about 8 minutes per measurement.
- Remaining errors are largest when the components are moving: limits resolution during interesting rapid events.
Novel method for precise displacement measurement

Like a vibrato note!

- Rapidly oscillate laser frequency over small range (<10 GHz).
- Use 4 phase steps to directly measure interferometer phase every 8 seconds.
- Measure relative displacement \( \Delta D \) every 8 seconds.
- \( D \Delta \nu \) term is corrected using reference interferometer system.

Pros:
- Rapid, relative measurement, \( \Delta D \).
- Sensitive to length changes at a fraction of wavelength (typ. < 50 nanometers)
- Excellent for ultra-precise short term monitoring.
- Simplified setup (single laser, small \( \Delta \nu \))

Cons:
- Lasers must run continuously, otherwise reference point is lost.
- May miscount fringes in rare case movements are extremely rapid (\( > \lambda/2 \) over 8s sampling time).

\[
\Delta \theta_{GLI} = \frac{2\pi}{c} (D\Delta \nu + \nu \Delta D)
\]
FSI monitors the relative movement between any two barrels of the SCT, using many assemblies of the type shown below. If there is a relative shift between barrels, we expect to see anti-correlations in the lengths of grid line D1 and grid line D2.

Grid line D1 monitors the positive RΦ direction
Grid line D2 monitors the negative RΦ direction
Grid line D3 monitors the positive R direction

An FSI assembly with three grid lines, between adjacent barrels.
Vibrato mode principle

One 8s ramp of the laser frequency generates fringes in all grid line interferometers. The instantaneous phase is measured.

Grid line D1 monitors the positive $R\Phi$ direction
Grid line D2 monitors the negative $R\Phi$ direction
Grid line D3 monitors the positive $R$ direction

![Diagram showing fringes and phase steps over time for different grid lines.](image-url)
Vibrato mode analysis

\[ \Delta D = \frac{c}{2\pi} \cdot \frac{\Delta \theta_{GLI}}{\nu} + D \frac{\Delta \nu}{\nu} \]

D1 length expands, positive phase shift
D2 length contracts, negative phase shift
D3 length expands, positive phase shift
Event: solenoid magnet ramped up (8kA provides 2 Tesla)

Gas temperature is stable (<0.2 °C).

Interferometers with different locations in the SCT barrel are very stable before and after ramp: \textbf{stdev} \textasciitilde 25 nanometres over 2 hours.

Up to +/- 2.6µm shifts observed during the solenoid ramp.

Movements are anti-correlated in opposite measured directions in +/- RΦ. Interferometers on the same assembly are plotted in the same colour.

The interferometers between all barrels show similar movements, which are correlated locally within an octant.
Event: solenoid magnet ramped down and then back up.

The interferometer lengths were found to be very stable: \textbf{stdev }\sigma \approx 11 \text{ nanometres} in the hour before the ramp.

Correlated movements of up to $\pm 3 \mu m$ are seen when the solenoid field changes between on/off.

After the solenoid cycle the interferometers show very small hysteresis and return to the start values to within \textbf{stdev }\sigma \approx 49 nm.
Plot 3: 24hr stability

Event: smooth SCT operation, followed by a fast magnet ramp down, which also triggered a stoppage of the Inner Detector cooling system.

Result 1: The barrel flange interferometers are stable with individual stdev $< 50\text{nm}$ over a 24 hour period.

Result 2: Correlated movements of up to $\pm 5\mu m$ are seen following the magnet ramp down and cooling stoppage.
Event: Inner Detector cooling shutdown and then restarted.

Individual interferometer movements of typically up to $\pm 5\mu m$ are observed during the cooling stoppage.

The interferometer movements show the expected effect of the SCT initially cooling and then warming when the evaporative cooling plant is stopped.

After the cooling is restarted, the interferometers return to their original lengths to within $\pm 3\mu m$, indicating some residual hysteresis compared with the solenoid cycle of Plot 2.
Plot 5: Pixel Scans and SCT shutdown

Event: Two calibration scans in the silicon pixel detector (Pixels), followed by the shutdown of the silicon strip detector (SCT).
Up to +/- 3µm between the two smallest SCT barrels, closest to the Pixels. The effect is reduced between the middle and outer pairs of SCT barrels.

Heat dissipated in the Pixels by these scans appear to cause small deformations which propagate via the support structure to the SCT.

With the cooling off, the SCT warms gradually and after 24hrs the temperatures and movements tend to flatten.

The largest movement, of +25µm, may be due to thermal expansion of cooling pipe close to interferometer components.
FSI operation status since last IWAA (Feb 2008)

Phase 1: (2008 / 2009)
- Initially ran in conventional FSI (coarse tuning) mode for absolute length measurement, with the precision improving with time as frequency scan range was increased.
- Optical power reduced in end-caps to limit photocurrent induced in silicon.
- First results during SCT temperature scan show $10\mu$m shifts in opposite measured directions.

Phase 2: (Sept 2009)
- After gaining experience with rate of SCT movements, experimented with Michelson mode interferometry to investigate events.
- See interference changes correlated with solenoid B-field, ON/OFF and cooling cycles
- More precise, but sign ambiguities are inherent with this method.

Phase 3: (12 Oct 2009 – now)
- Developed a new technique (vibrato FSI), which enables far more precise and rapid measurements, without sign ambiguity.
  - Relative length measurements, every 8 seconds, sensitive to <50 nanometres over 24hrs.
  - Have run in this mode since 12 October throughout LHC beams / collisions.
  - Operation is now routine, with FSI runs typically lasting around a month between LHC maintenance days.
- Run conventional FSI either side of maintenance days to provide long term monitoring.
- Initial track-based alignment also sees stable mean residuals over 7 weeks. Rapid global deformations seen by FSI, yet to be checked with tracks.
Conclusions

• The ATLAS FSI system is in full time operation mode to monitor length variation inside the silicon strip detector (SCT).

• A novel method for ATLAS FSI alignment based on rapid, direct phase monitoring is introduced.
  ✓ Relative length measurements every 8 seconds, sensitive to <50 nm over 24hrs.

• The preliminary results presented here reveal that the SCT Barrel is very stable during operation, but does move at the level of typically +/- 3 to +/- 5 \( \mu \)m between barrels and that these movements are correlated with changes in the detector environment, namely:
  • Solenoid ramp and cycles
  • Inner Detector cooling stoppage or restart
  • Calibration scans of the silicon pixel detector
  • Shutdown of the silicon strip detector (SCT).
Backup
The 144 interferometers of the barrel flange FSI system are shown below overlaid in red lines. The 24 interferometers shown in the following plots are from 8 assemblies of 3 interferometers each. 4 evenly spaced assemblies are chosen at either end of the barrel, between the smallest two barrel layers, to be representative of the distortions (and closest to the Pixels to highlight the effect of Pixel scans).
Reference Interferometry System

- Fibre collimators provide low $M^2$ beam.
- Super-invar / steel thermally compensating design to balance CTEs. $\Delta T(C_1L_1 - C_2L_2) = 0$.
- Both interferometers have four-fibre read-out for instantaneous phase measurement.
- Long reference has piezo for phase stepping.