MONITORING THE HEART OF ATLAS USING FREQUENCY SCANNING INTERFEROMETRY

S. M. Gibson, P. A. Coe, A. Mitra, D. F. Howell, R. B. Nickerson.
University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK.

Abstract

A novel Frequency Scanning Interferometry (FSI) alignment system has been developed to operate within the confined, inaccessible, high radiation environment of the ATLAS semiconductor tracker (SCT). The particle tracker shape will be precisely and remotely monitored using an in-situ network of interferometers. Fibre-coupled, radiation hard interferometers are being installed onto carbon fibre support structures of the ATLAS SCT. This "on detector" assembly of the ATLAS FSI system is discussed. The future completion of the system is outlined. The design, production and testing of interferometer components are discussed. FSI based three dimensional shape reconstruction within the required resolution is presented.

1 INTRODUCTION

The positions of the active detector elements within a particle tracker must be very well known to accurately reconstruct tracks left by long lived charged particles. The procedure of determining the relative detector positions is called *alignment*. In previous high energy experiments, sufficiently precise alignment has traditionally been achieved with track data alone, by examining the hit residuals from the fitted particle trajectories. The ATLAS experiment presents a new challenge, due primarily to the unprecedently large particle tracking detector at the heart of ATLAS. Short time scale, complex deformation of the 5.6 m long ATLAS SemiConductor Tracker must be determined to a precision of 12 μm in RΦ, for appropriate corrections to be applied to the particle physics analysis.

Conventional survey techniques are not practicable inside the operational particle tracker of ATLAS, due to the inaccessible, confined spaces and high radiation levels. To overcome these challenges a novel alignment system has been developed that will remotely measure the tracker shape on a time scale of a few minutes [1, 2]. The "on-detector" alignment system consists of a geodetic grid of length measurements between nodes attached to the ATLAS SCT. Combining these measurements will allow the node positions to be reconstructed. These node positions will be interpolated to determine the co-ordinates of the active detector elements. The 842 lengths in the geodetic grid will be measured simultaneously, to a precision of < 1 μm using Frequency Scanning Interferometry.

The FSI technique has been presented previously [3] so only a brief reminder is provided in Section 2. This paper focuses on recent developments that are turning the ATLAS FSI system concept into reality. In particular the assembly of the "on detector" FSI system is discussed in Section 3 and the mass production and testing of the fibre-coupled, radiation-hard interferometer components is summarized in Section 4. Additionally, several further tests have been performed with the prototype FSI system [4, 5, 6] and an interesting example is presented in Section 5, which demonstrates the precise three dimensional shape reconstruction possible using FSI.

2 FREQUENCY SCANNING INTERFEROMETRY (FSI)

FSI is a technique for remote, multiple, simultaneous and precise distance measurements in a hostile environment. A narrow line-width tunable laser simultaneously illuminates multiple interferometers to be measured and a reference interferometer. As the optical frequency is scanned, a phase shift is induced in all interferometers, at a rate that is proportional to the length of each interferometer. The phase shifts in the interferometers are compared to determine the ratio of interferometer lengths. [2, 3, 5, 6].

3 "ON DETECTOR" FSI SYSTEM ASSEMBLY

The ATLAS SemiConductor Tracker [7] is divided into the barrel and two end-cap sections. The shapes of these sections are monitored by an FSI geodetic grid, consisting of 842 interferometric length measurements between grid nodes, as shown in Figure 1.

In the Barrel SCT, the particle detector modules are mounted onto the outer surface of carbon-fibre support cylinders, as shown for the smallest SCT cylinder in Figure 2. The FSI components are attached to the inner surface of these cylinders, as in Figure 4. The interferometers must operate within a small annular region in the RΦ plane, between the module layers, services and support structures.

Around half of the components for the FSI geodetic grids have now been installed and the remainder will be completed in the next few months. The interferometer components are accurately positioned in small support structures called *jewels*, which are secured to the carbon-fibre of the SCT. *Grid Line Interferometers* are formed between the FSI jewels. The interferometers are pre-aligned in a jig as shown in Figure 3 and the interferometer signals are checked before the jewels are installed in ATLAS.

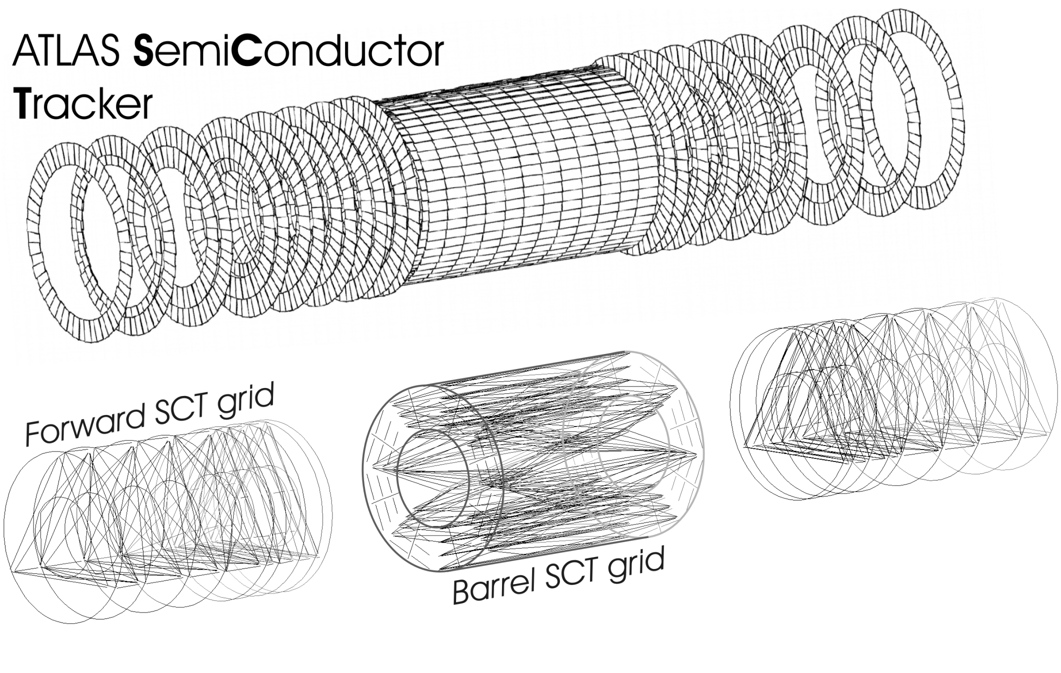

Figure 1: *The layout of the silicon detector modules in the ATLAS SemiConductor Tracker. The three SCT sections are monitored using FSI geodetic grids. Each of the 842 lines represents an interferometric distance measurement between grid nodes. The SCT is 5.6m long.*

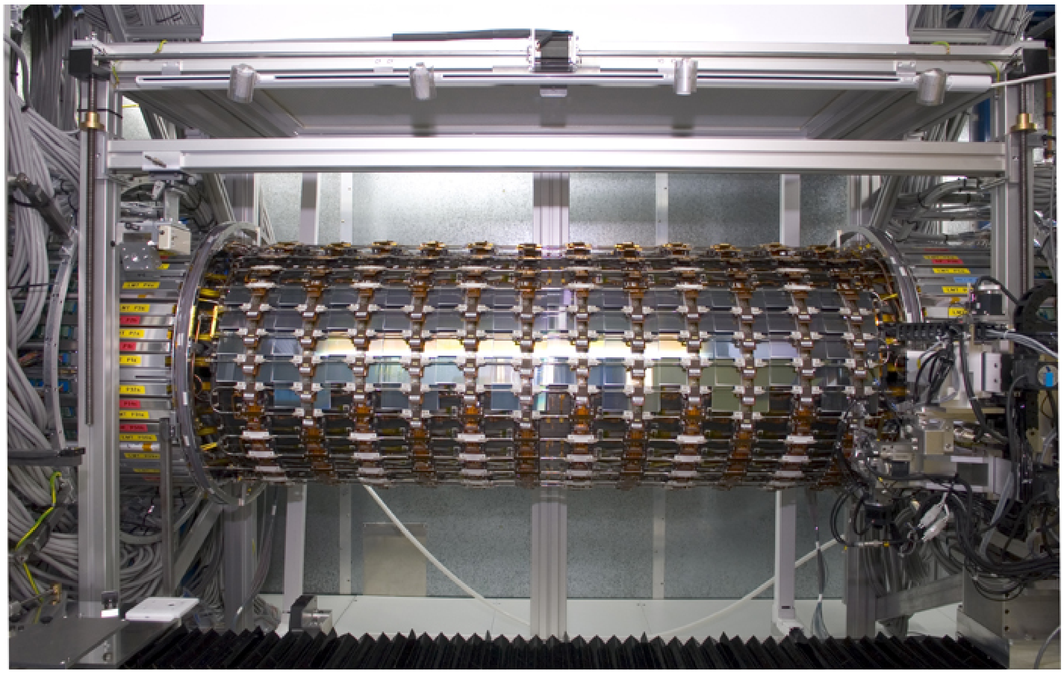

Figure 2: *The smallest barrel of the ATLAS SemiConductor Tracker. Silicon detector modules are robotically mounted onto the Ø 560 mm, 1.5m long carbon-fibre support cylinder.*

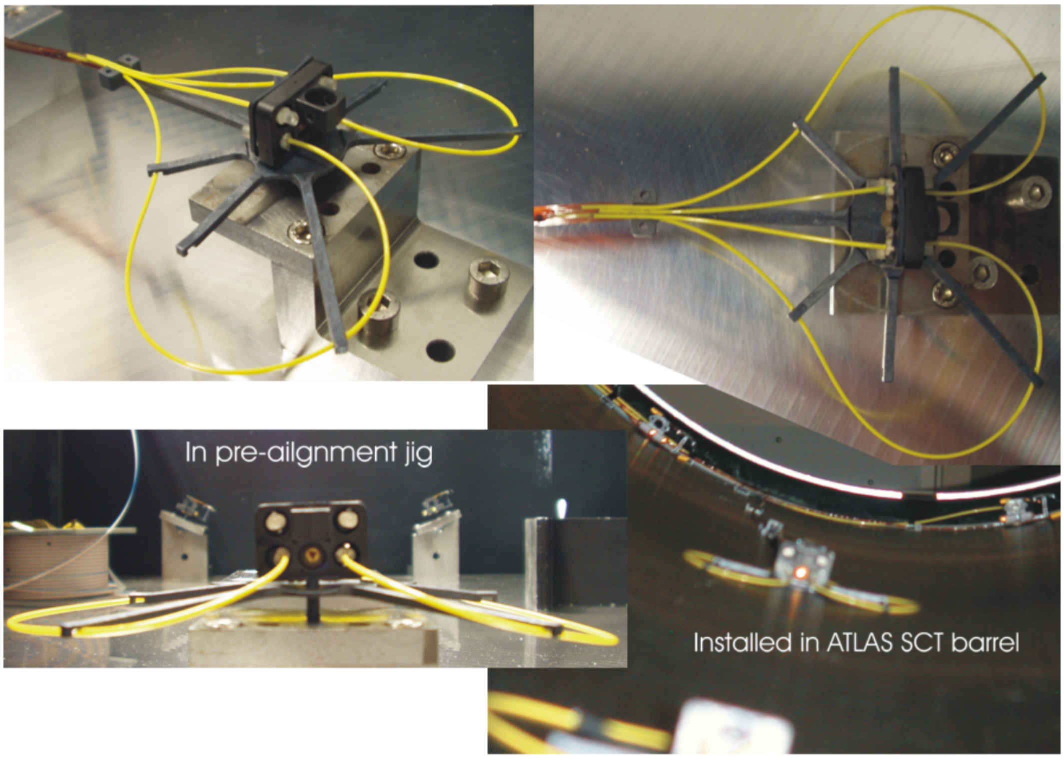

Figure 3: *An ATLAS FSI jewel, called a 'scorpion', is pre-aligned in a jig that replicates the layout of the ATLAS SCT barrel.*

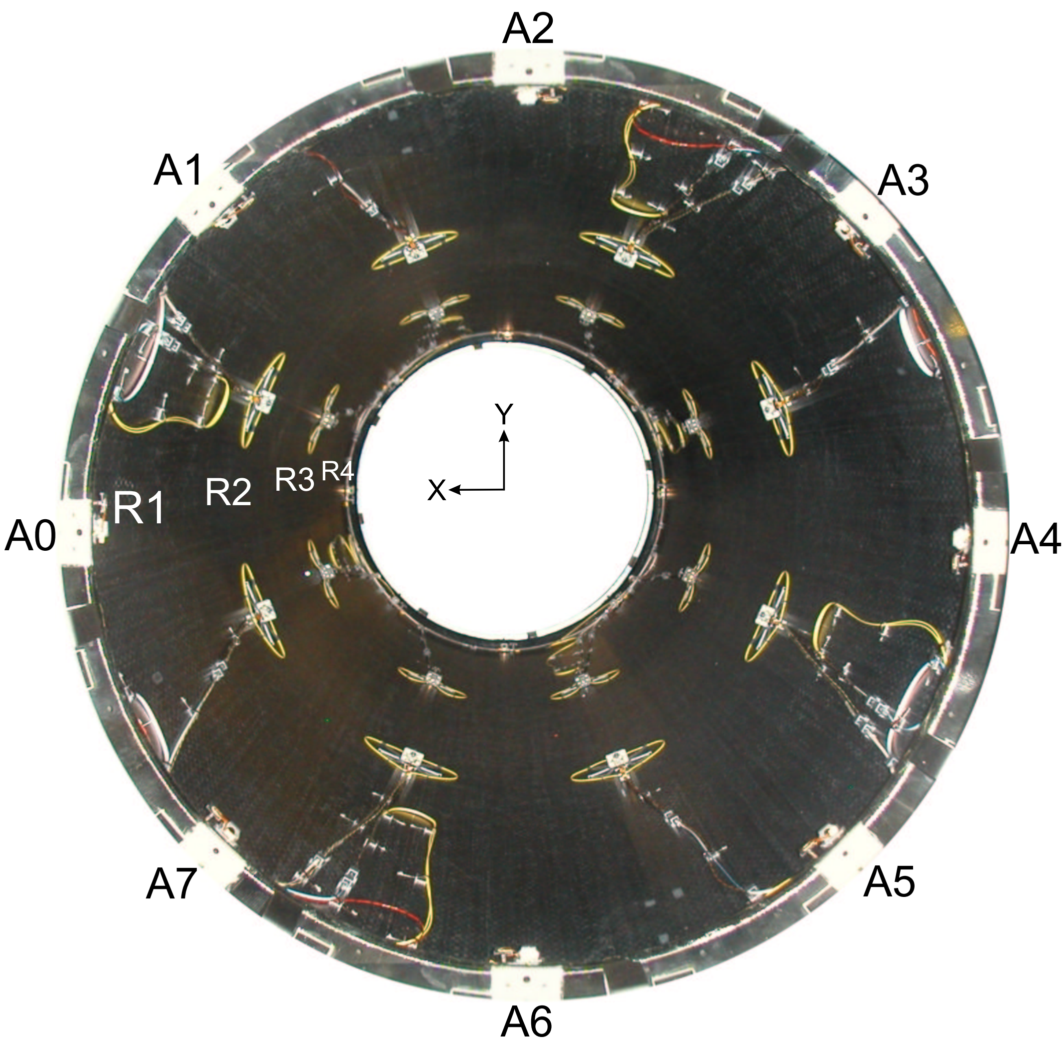

Figure 4: *One tenth of the "on detector" FSI geodetic grid. The view is along the axis of the smallest (Ø 560 mm) ATLAS SCT barrel, shown in Figure 2. 80 Grid Line Interferometers are formed between 32 FSI jewels. The jewels are rigidly attached to the carbon-fibre, forming 4 rings of grid nodes, which are approximately equidistant in Z along the 1.5 m barrel length. The jewels called 'scorpions', shown in Figure 3, can each be seen between a curving pair of yellow furcation tubes, which protect the optical fibre powering the inteferometers. The distances between the jewels are measured simultaneously to $< 1\mu m$ using FSI.*

4 TESTING OF GRID LINE INTERFEROMETER COMPONENTS

4.1 Grid line interferometer design

Over the ten year operating life of ATLAS, particle collisions at the centre of ATLAS will subject the SCT to a gamma dose of 10 MRad (in silicon) and a total flux of around 10^{14} (1 MeV equivalent) neutrons [7]. The hostile, inaccessible environment of the ATLAS SCT imposes strict requirements on the design of the interferometers that constitute the on-detector FSI system. The interferometers should be remotely measured and continue to function for $\gtrsim$10 years without access for adjustment or maintenance. The interferometer components should be very small, made from radiation tolerant materials and have low mass.

The solution is a fibre coupled interferometer for each line in the ATLAS grid. These *Grid Line Interferometers* (GLI) consist of two components with a compact, rugged, low mass, zero-maintenance design, as shown in Figure 5. The main component is called a *quill* consisting of two parallel single-mode fibres and a fused silica beam-splitter. The other component is an external retro-reflector. The GLI components are clustered into *jewels* that are secured to the SCT support structure to form the grid nodes. A quill in one jewel points to a retro-reflector in another jewel to form a GLI. The distance between the quill and retro-reflector is measured by FSI.

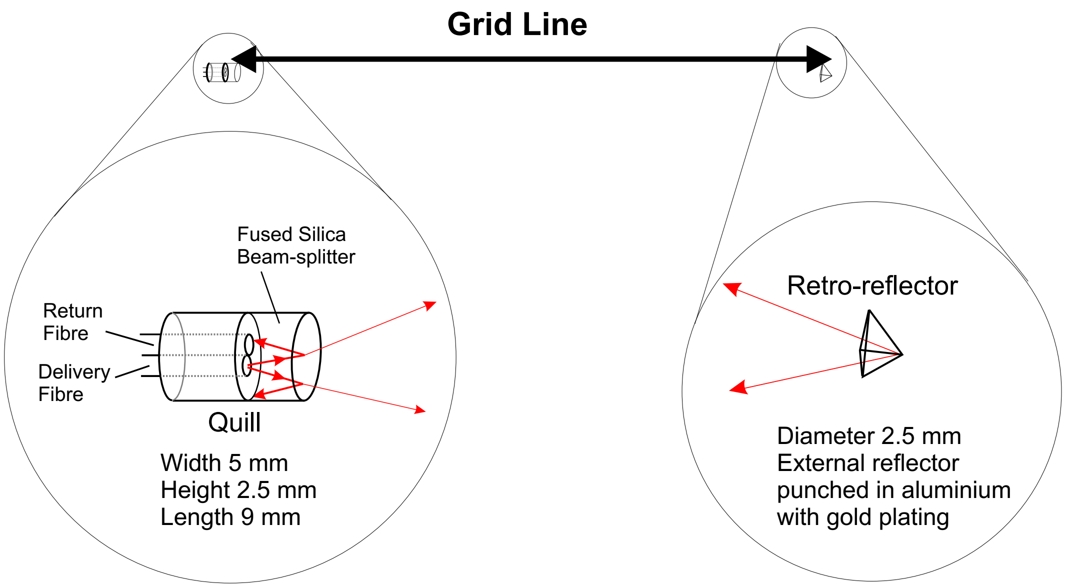

Figure 5: *The Grid Line Interferometer design for the ATLAS FSI system. The wide angle beam emerging from the quill provides tolerance to small misalignments which may occur during the 10 year operational lifetime. As a trade off, the interferometer provides a return signal of around only 1 pW per mW of input power, for a 1 m GLI length.*

4.2 Quill tests

The quills for the GLIs were manufactured by gluing two radiation-hard optical fibres into a 250 μm wide slot, formed in an injection moulded PEEK support. Several iterations of the mould were required to ensure the parallism of the two fibres to $<0.5°$. The front surface of each quill was polished, before a fused-silica beam-splitter was attached.

The assembled quills were tested in the prototype FSI system, to assess the quality of the interferometer signals. Each quill was tested by forming an interferometer with a retro-reflector, placed at one of three different distances from the quill. In longer interferometers, the divergence of the output beam from a quill, reduces the power of the signal returned from the retro-reflector. The quills were classified according to the length of grid line, for which they were suitable. Only the highest quality quills were selected for the longest, 1.5 m grid lines inside ATLAS.

The quill tests were performed by recording the interferometer signal, as the optical frequency was scanned. The frequency was monitored by the phase shift in a reference interferometer. A sinusoidal fit to these data is shown for a poor and a good quill in Figure 6. For perfectly sinusoidal interference the variation of a χ^2 related fit quality parameter, takes the form of an inverted sinc function [5], exhibiting a distinct, deep minimum into which the fit should settle. Deviations from this form enabled poorer quality quills to be rejected, or classified as only suitable for shorter lines in the grid. Poor quill signals typically exhibited other fake minima, due to unwanted spurious reflections within the quill beam-splitter that interfered with the signal from the retro-reflector. 75% of the quills tested to date were found to be suitable for use in the ATLAS FSI system.

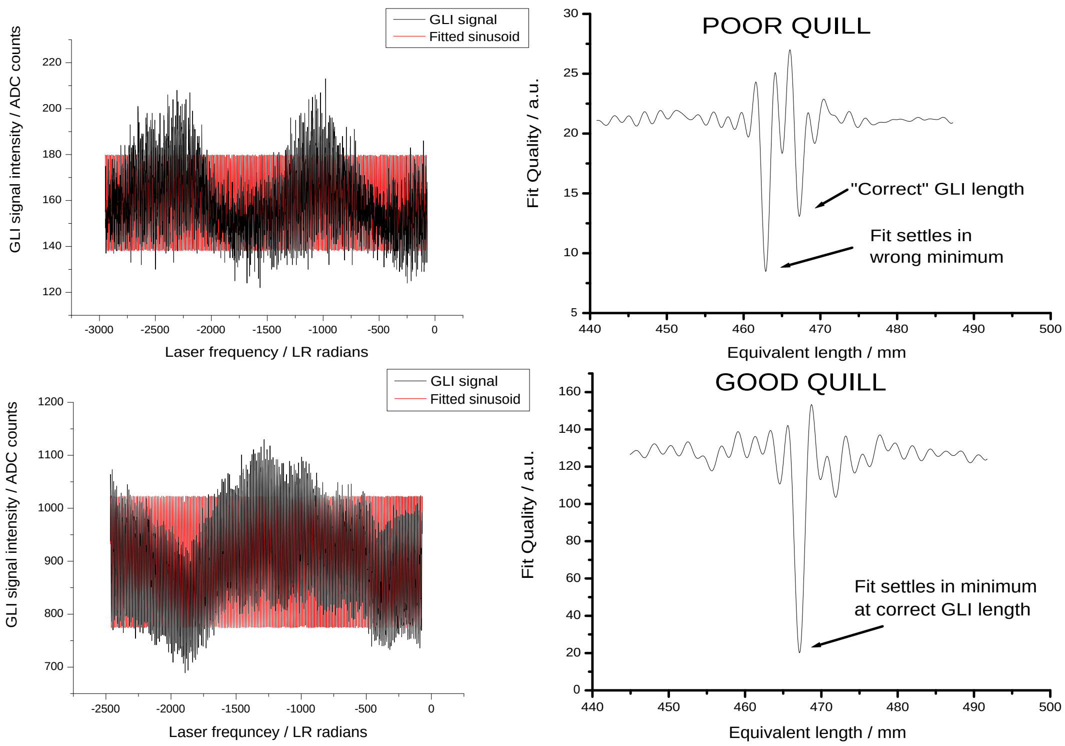

Figure 6: *The quills were assessed by examining the quality of fit to the interference signal, generated as the optical frequency was scanned. A distinct, deep minimum at the correct GLI length was required.*

4.3 Retro-reflector tests

The prohibitive cost of suitably small, commercial retro-reflectors stimulated the in-house manufacture of the 696 retro-reflectors required for the FSI system. The retro-reflectors were punched from aluminium pellets with a carbon steel corner cube, cleaned and then coated with nickel followed by gold to enhance reflectivity [8].

The variable production quality required suitable tests to be developed for quality assurance. These developments culminated in a test to examine the far field pattern from the retro-reflector. A retro-reflector was placed in a special holder that allowed it to be rotated to any orientation about its axis of symmetry and also rotated about the apex of the retro-reflector by 0° to 12.5° with respect to an incident laser beam, as shown in Figure 7. A CCD recorded the far field image. Importantly, the intensity at the centre of this image is a measure of the intensity at the quill return fibre.

An ideal retro reflector should have a bright central spot at all rotation angles permitted by the holder. The majority of tested retro-reflectors did not meet this requirement. The quality was assessed primarily from the central spot intensity at the extreme orientations of the holder. The far field images from *poor* and *very good* quality retro-reflectors are shown in Figure 8.

The signal in a functioning GLI was significantly diminished by reorienting a poor quality retro-reflector about its axis, when angled by ∼10° to the beam from the quill. The far field test accurately predicted the orientation in which a poor quality retro-reflector resulted in

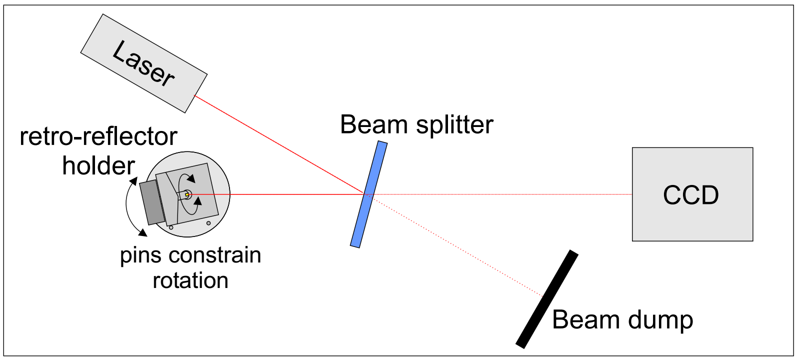

Figure 7: *The configuration for the far field retro-reflector test.*

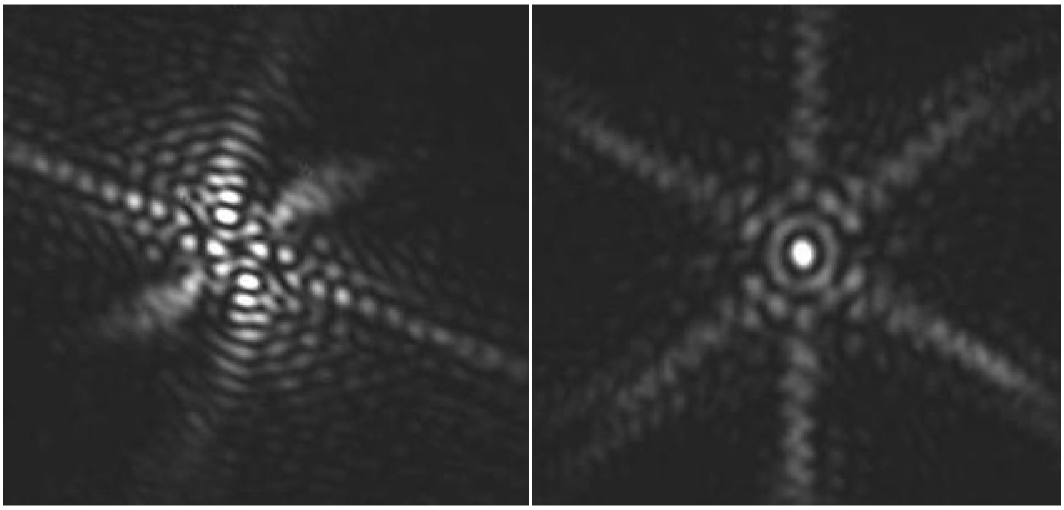

Figure 8: *The far field images from a poor and very good quality retro-reflector, distinguished by the absence or presence of a central bright spot, which indicates the intensity at the return fibre of a quill.*

the success or failure of FSI measurements. This test underlies the quality assurance for the retro-reflectors installed in ATLAS. Of the ten thousand retro-reflectors manufactured to date, around 7 % were of suitable quality for the ATLAS FSI system, so that the quantity requirements have now been met.

5 DEMONSTRATION SYSTEM

5.1 Overview and experimental method

A prototype FSI system has been built to demonstrate the precise grid shape reconstruction possible using FSI. Initial results from this prototype system have been presented previously [4, 9]. Further tests with the prototype grids have since been completed [6]. This section summarizes an interesting example from these series of tests. The presented test aimed to demonstrate the typical role of FSI in ATLAS, in which a single FSI scan is required to precisely determine the SCT shape.

A three dimensional prototype geodetic grid, shown in Figure 9, was measured sequentially by a procedure that replicated the expected use of the FSI system in ATLAS. A single FSI scan was recorded for a particular grid shape, so that six simultaneous length measurements were made between the four grid nodes. The grid geometry was then adjusted and a further, single FSI measurement of the new grid shape was performed. This process was repeated, until a total of 39 grid shape measurements had been performed at 39 different grid geometries. The changes in grid geometry were carefully chosen so that one of the grid nodes traced out an interesting pattern. This node was sequentially repositioned using a motion stage, so that the step size between adjacent node positions was 12 μm ± 1 μm. This step size is equivalent to the RΦ precision required for the ATLAS FSI system.

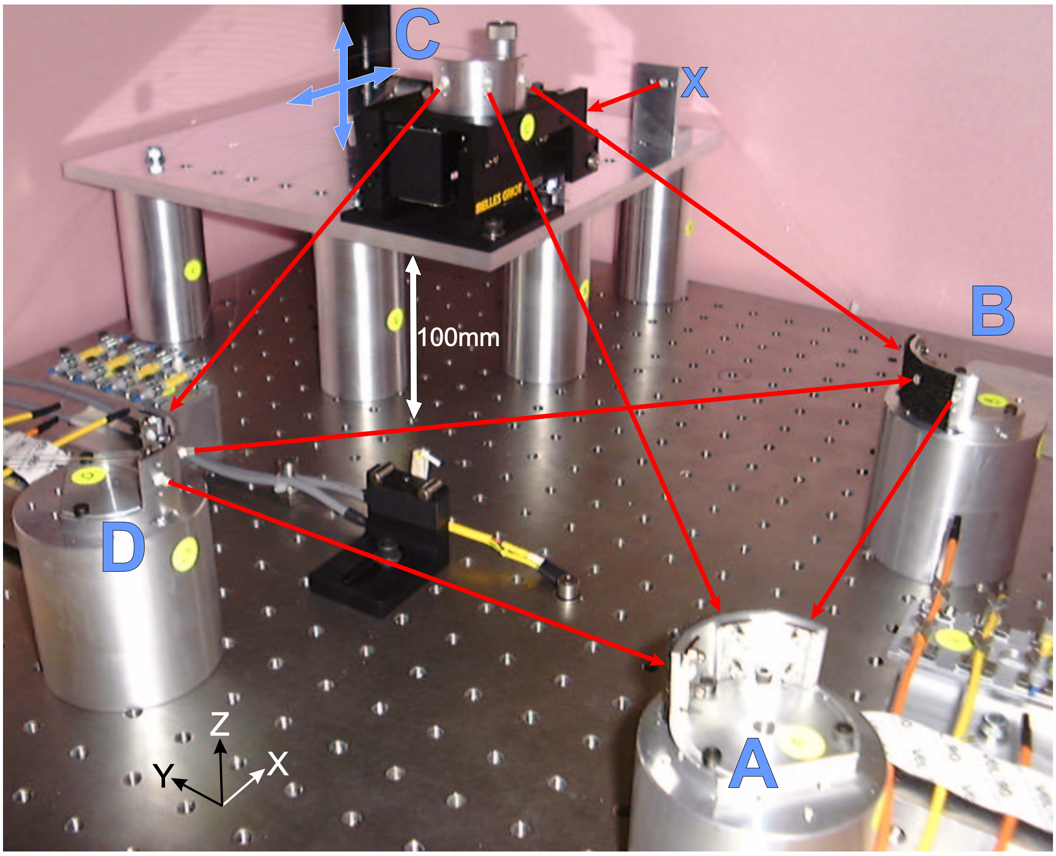

Figure 9: *A three dimensional prototype FSI grid with tetrahedral geometry. Grid node C was sequentially repositioned using the motion stage, between each FSI scan.*

5.2 Precise Prototype Grid Shape Reconstruction

The grid shape was reconstructed for each FSI scan using a model written in SIMULGEO [10]. The reconstructed co-ordinates of node C followed closely the 39 positions of the stage, as plotted in Figure 10.

Importantly, the FSI grid shape measurements precisely determined the complex pattern of node movements to well within the ATLAS requirements. The precision was demonstrated by taking the residual differences between the reconstructed co-ordinates and a set of expected co-ordinates based on a quantized constant separation of the node positions, as in Figure 11. The scatter in these residuals is dominated by errors on setting the motion stage, rather than the FSI measurement precision. The equivalent plot from a test in which the grid geometry was not adjusted is shown in Figure 12 for comparison. On average, the precision on the six length measurements were a factor of ∼4 better than the 1 μm precision required for ATLAS.

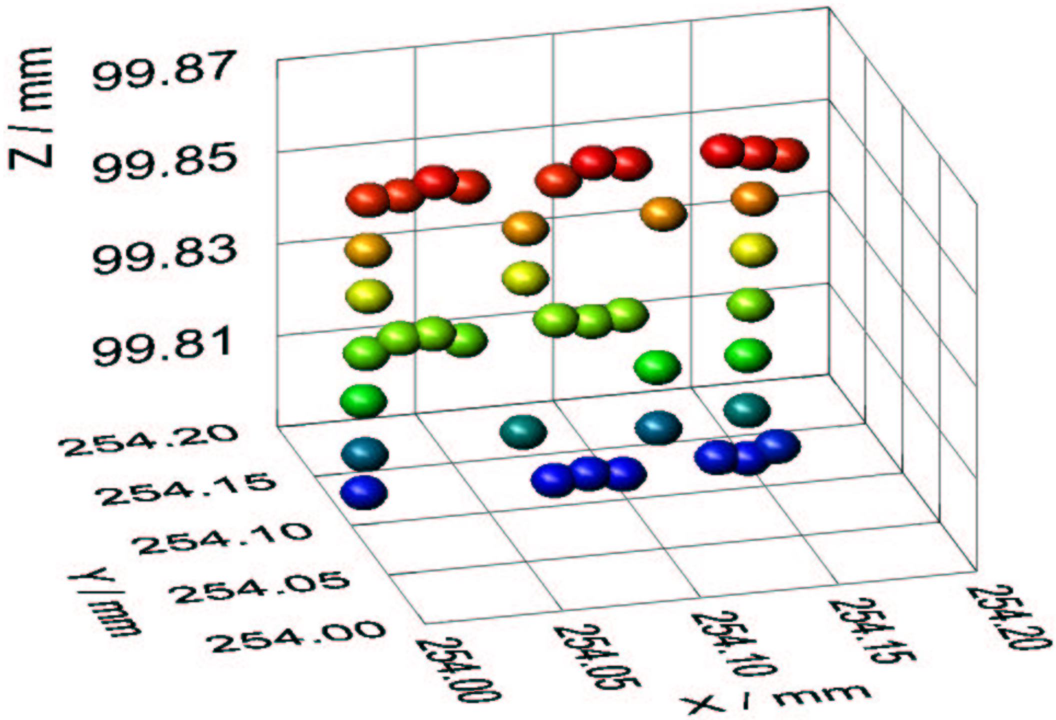

Figure 10: *The reconstructed co-ordinates of node C of the tetrahedral grid precisely followed the complex pattern of 39 node positions to which node C was sequentially set. The positions are clearly distinguishable, despite the small separation between adjacent points of 12 μm, corresponding to the required $R\Phi$ precision for the ATLAS FSI system.*

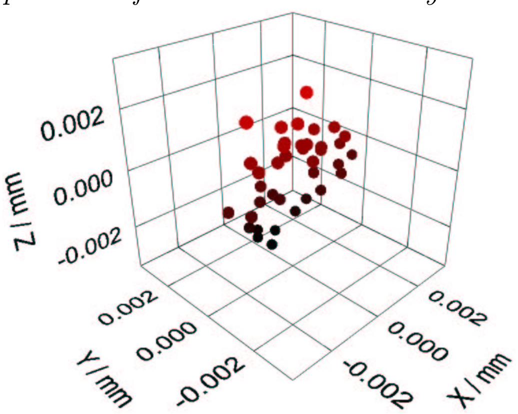

Figure 11: *The residuals of the positions in Figure 10, and the expectations from perfect stage movements. The scatter was dominated by the stage setting sensitivity, rather than the FSI precision, in Fig. 12.*

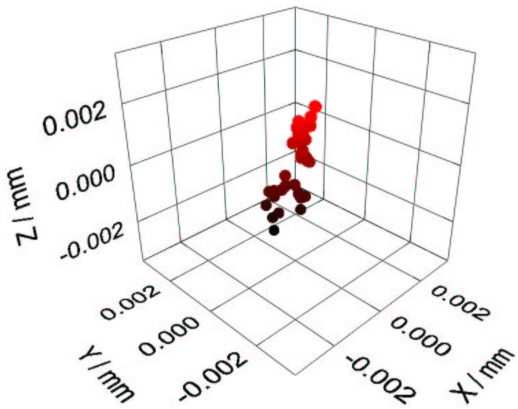

Figure 12: *The scatter in reconstructed positions of node C for the stability test, in which the stage supporting node C was not adjusted. The scatter is due to the FSI precision (and the thermal expansion of the set-up).*

6 CONCLUSION

A novel shape monitoring system has been developed for the alignment of the ATLAS SemiConductor Tracker. This system will use the specially developed technique of Frequency Scanning Interferometry to make 1 μm precise length measurements between the nodes of a geodetic grid attached to the SCT support structure. A prototype system has demonstrated three dimensional FSI grid measurements to well within the required precision.

Developments are in full progress to turn the FSI system concept into reality. Several hundred fibre-coupled, radiation-hard interferometers have been produced. Rigourous testing procedures have been developed to assure high quality interferometer components are installed into ATLAS. Around half of the "on detector" components have now been installed and the remainder will be completed in the next few months. The next phase for the ATLAS FSI project will be the assembly of the "off detector" components and the commissioning of the FSI system.

ACKNOWLEDGMENTS

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