A STUDY OF GEODETIC GRIDS FOR THE CONTINUOUS, QUASI REAL TIME ALIGNMENT OF THE ATLAS SEMICONDUCTOR TRACKER

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ABSTRACT

An alignment system based on Frequency Scanning Interferometry has been developed to monitor shape changes of the ATLAS semiconductor tracker. Movements of the detector modules will be monitored in quasi real time by combining precise distance measurements between nodes of a geodetic grid attached to the support structure.

The final geodetic grid will consist of eight hundred lines of sight in a complex geometry. As the first step in understanding such complex grids, several simple two and three dimensional prototype grids with adjustable geometry have been tested. Different opto-geometrical models of the grids have been used to reconstruct the node coordinates. Expected errors are compared with the spread on coordinates, reconstructed using different software models.

Sensitivity to likely deformations of the ATLAS semiconductor tracker, as modelled with FEA and studies of error propagation through the final ATLAS grid will be discussed.

1. INTRODUCTION

The ATLAS semiconductor tracker (SCT) will be the largest silicon detector ever built. The challenge of aligning this 6m long object to 12μm precision in rφ, has stimulated the development of novel optical techniques for in-situ monitoring of particle detectors.

An alignment system based on Frequency Scanning Interferometry (FSI) [1][2][3] has been developed to monitor micron level motion in the ATLAS SCT. This system offers an understanding of the detector on day one of physics and will be vital for unravelling short time scale motions and complex distortions that are very difficult to correct with tracks alone. Movements of detector modules will be reconstructed in quasi real time by combing precise length measurements between nodes of a geodetic grid attached to the support structure. This alignment system is described in section two.

The geodetic grid for the final system consists of over eight hundred lines of sight in a complex geometry. As a first step in understanding such complex grids, several two and three-dimensional prototype grids with adjustable geometries have been tested. These tests are summarised in section three.

Error propagation through the final ATLAS SCT grid has been simulated with the opto-geometrical software tool, SIMULGEO [4]. Finite Element Analysis (FEA) of the SCT structure will be used to check the predicted sensitivity of the grid to plausible distortions. These simulations are presented in section four.

2. THE ATLAS SEMICONDUCTOR TRACKER ALIGNMENT SYSTEM

2.1 Motivation and concept

The position of detector modules in the ATLAS semiconductor tracker (SCT) must be determined to 12μm in rϕ [5]. Several sources of instability could severely degrade track based alignment methods for the ATLAS SCT. For example, the power dissipation in the front-end electronics will vary with luminosity, leading to large and varying thermal gradients between the front-end chips and cooling pipes. These will induce distortions of the SCT on time scales potentially shorter than the twenty four hours needed to collect sufficient track data for averaging. The proposed alignment system will measure the SCT shape on a time scale of a few minutes. This system will complement track data in the final alignment strategy, allowing short time scale motions and complex sagitta distortions to be corrected. [6]

The alignment system is based on a geodetic grid of length measurements between nodes attached to the SCT. Combining these measurements allows the node positions to be reconstructed. These node positions are then interpolated to determine the detector module coordinates. In this system, each length must be measured with a precision of better than 1μm, to allow shape variations of the SCT to be followed to ~10μm.

A schematic of the geodetic grid design is given in Fig. 1, where each grid line represents a length measurement. The grid is divided into one barrel and two endcap sections and contains approximately 800 lines of sight in total. Lengths in the geodetic grid will be measured simultaneously using Frequency Scanning Interferometry (FSI) [1][2][3].

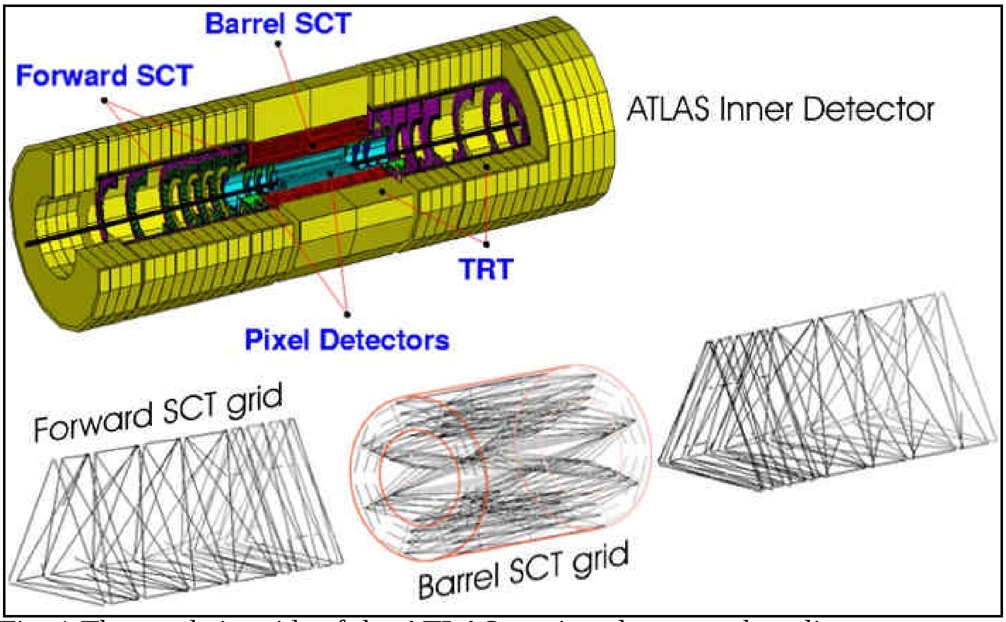

Fig. 1 The geodetic grids of the ATLAS semiconductor tracker alignment system

2.2 Frequency Scanning Interferometry

FSI is a technique for high precision, multiple, simultaneous length measurements. A common laser system powers the interferometers to be measured and also powers a thermally stabilised, evacuated, reference interferometer. The optical frequency is simultaneously scanned in all interferometers. Each length measurement is made by comparing the phase change in each measured interferometer with the phase change in the reference interferometer. The ratio of phase change gives the ratio of lengths.

In the ATLAS SCT, each grid line is a remotely measured fibre coupled interferometer. These 'Grid Line Interferometers' are of a compact, low mass, rad-hard design, requiring minimal pre-alignment and zero maintenance throughout the lifetime of ATLAS. Each 'grid line interferometer' consists of two components, as in Fig. 2. The first component is called a 'quill' consisting of a delivery and return fibre and a beam splitter. The second component is a retro reflector. The length between these two components is measured. [1]

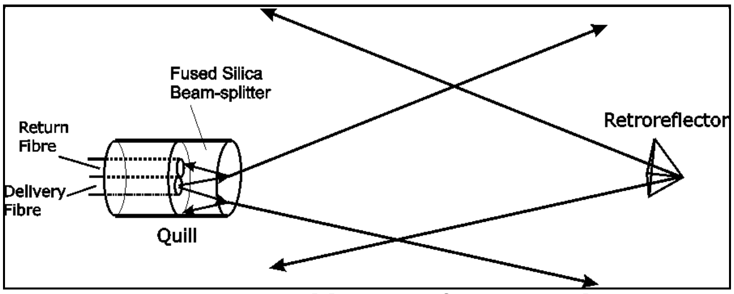

Fig. 2 ATLAS 'grid line interferometer' design.

A prototype FSI system [2] has been constructed at Oxford and was used for the tests described in section three.

3. DEMONSTRATION SYSTEM

3.1 ATLAS SCT alignment system overview

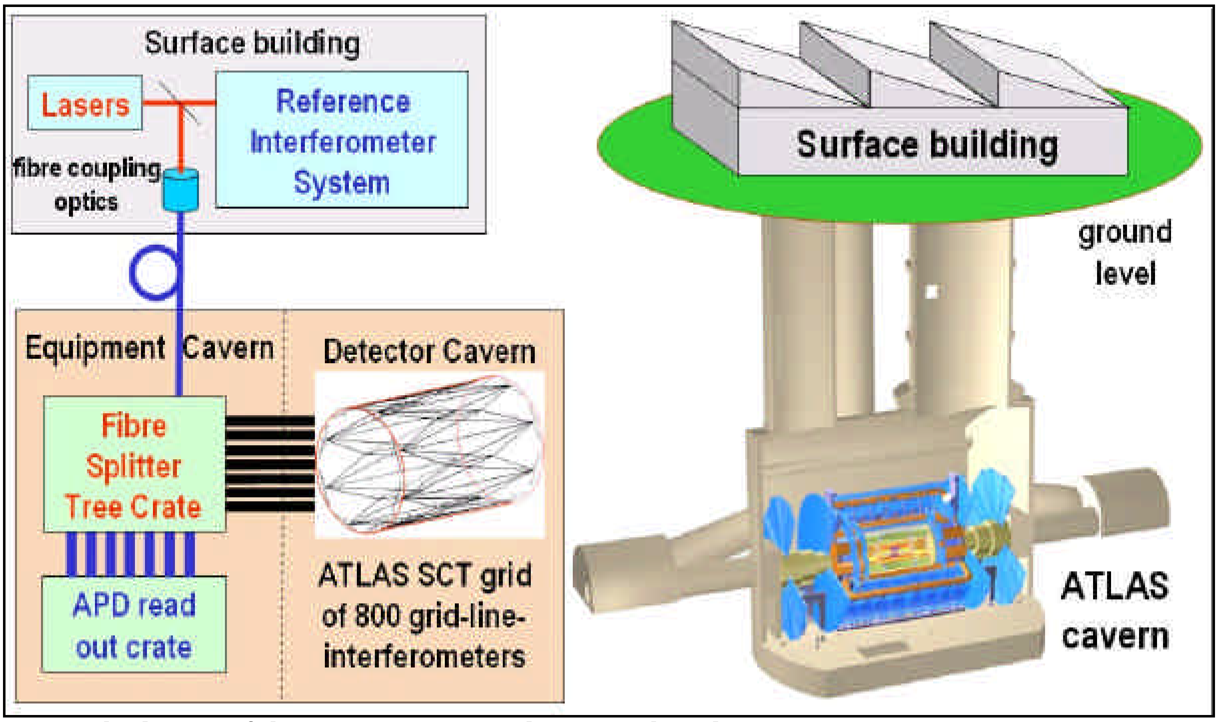

Fig. 3 The layout of the ATLAS semiconductor tracker alignment system

3.2 Demonstration system overview

As a first step in understanding the complex grids of the final system, several simple two and three dimensional prototype grids with adjustable geometry have been tested. These have demonstrated the high precision shape reconstruction possible using FSI. The layout of the ATLAS alignment system, Fig. 3, is mimicked by the demonstration system, part of which is shown in Fig. 4. Laser light enters the equivalent of the ATLAS equipment cavern (Fig. 4. left compartment) via the yellow fibre at the top left and is split six ways by the fibre splitter tree. The yellow fibres then convey light to the 'detector cavern' (right compartment), to power the prototype grid. Light returns from each grid line interferometer via the orange fibres and the signal is detected in the 'equipment cavern' by an array of Avalanche PhotoDiodes.

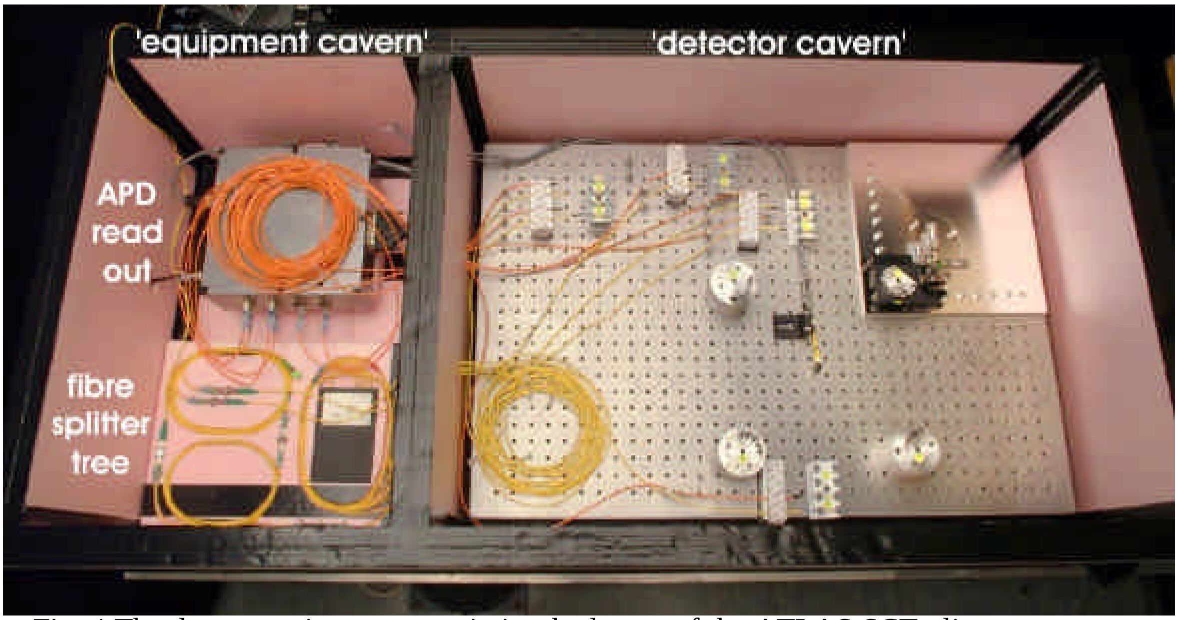

Fig. 4 The demonstration system mimics the layout of the ATLAS SCT alignment system

3.3 Square Grid

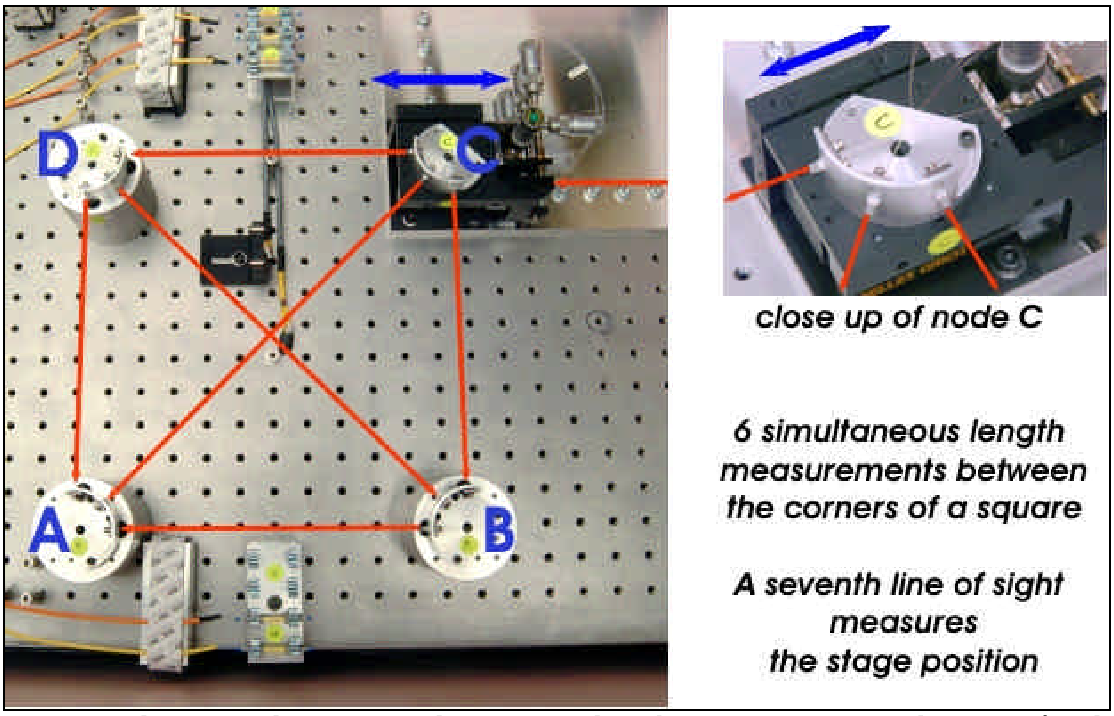

Fig. 5 A two dimensional, prototype alignment grid, with square geometry. The inset of node C shows the glass beam splitters of three 'quills' protruding from the circular support frame. The fibres for these quills trail from the back of this frame. The grid is 254mm by 254mm square.

A prototype alignment grid was constructed by arranging six 'grid line interferometers' in a square geometry, as in Fig. 5. The six lines of sight of each grid line interferometer can be seen overlaid by the thick lines. At each corner node of the square, a circular structure called a 'jewel' supports either the quill (section 2.2) or retro reflector component of the three grid line interferometers converging on that node.

An FSI scan simultaneously measured the six lengths, on the timescale of a few minutes. Node C was displaced along a straight line using the translation stage. Five FSI scans were made at each of the seven stage positions, to allow measurement errors to be assessed.

The FSI length measurements of the six grid line interferometers were used to reconstruct the grid shape with the SIMULGEO software package [4]. The results in Fig. 6-8 are from a shape reconstruction model in which node A is the origin, the line from node A to node B forms the X-axis and all four nodes are assumed to be coplanar. The rotational degrees of freedom of the jewels were assumed to be fixed. The length between nodes A and B defines one degree of freedom and nodes C and D are both free to translate in the X-Y plane but constrained in Z[1], giving five degrees of freedom in total. The six length measurements thus make the grid over constrained. The scatter on reconstructed coordinates is shown for node B in Fig. 6 and for node D in Fig. 7. In both cases the reconstruction resolution is well within the precision required for ATLAS.

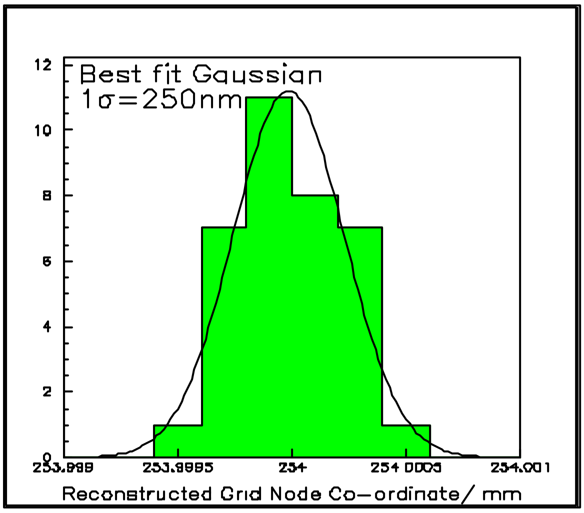

Fig. 6 The scatter in reconstructed X-coordinate of node B, which by definition of the X-axis, is fixed so that y=0. The 1σ scatter about the mean position is 250nm.

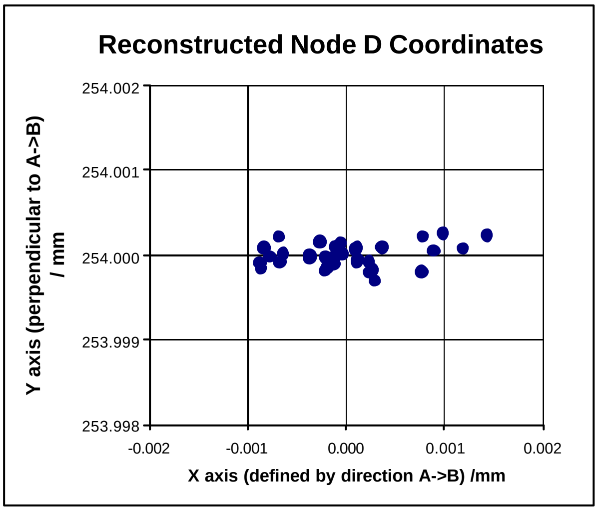

Fig. 7 The two-dimensional scatter in reconstructed positions for grid node D. The scatter is greater in the X-direction due to choice of coordinate frame.

[1] Due to the near-planar grid geometry any small movements of the nodes in Z are tangential to the length measurement line, so do not affect the reconstruction process to first order.

The redundancy of the grid was used to check the reconstruction process. Each of the six lines of sight was removed in turn, so that only five lines were used to solve for the five degrees of freedom in the model; making the model just constrained. It was found that the nodes were still successfully reconstructed to within the requirements for ATLAS, despite the removal of any one of the six lines of sight. [7]

Node C was set to seven different positions in X using one axis of the motion stage shown in Fig. 5. The stage position was measured independently using a seventh line of sight (shown to the right of the stage in Fig 5). This independent measurement was used to verify the reconstructed X-coordinate of node C. The residual differences between the reconstructed versus independently measured X-coordinate of node C and the best fit linear trend are shown in Fig. 8. These residuals have a standard deviation of 400nm, well within the precision requirements for the ATLAS SCT alignment system.

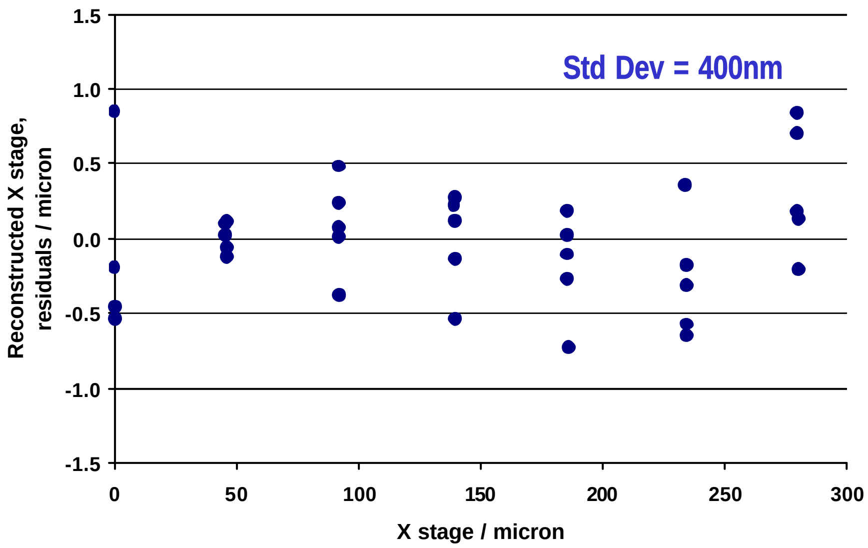

Fig. 8 Residuals of the X-coordinate of node C as reconstructed from the square prototype grid, versus an independent measurement of the stage position.

3.4 Tetrahedral Grid

The stage was raised vertically by 100mm to form the tetrahedral grid in Fig. 9. This allowed the three dimensional reconstruction of the node coordinates, due to sensitivity in the vertical direction.

The shape reconstruction model was rewritten for the tetrahedral grid. As with the square grid, node A is defined as the origin and the line from node A to node B forms the X axis. However, the plane of nodes A, B and D defines the X-Y plane, leaving node C free to translate in Z with respect to this plane. Nodes A, B and D have the same degrees of freedom as in the square grid model, but node C is now free to translate in all three degrees of freedom. Again all rotational degrees of freedom of the jewels were fixed. The model thus has six degrees of freedom that were measured by six lines of sight, so the grid is just constrained.

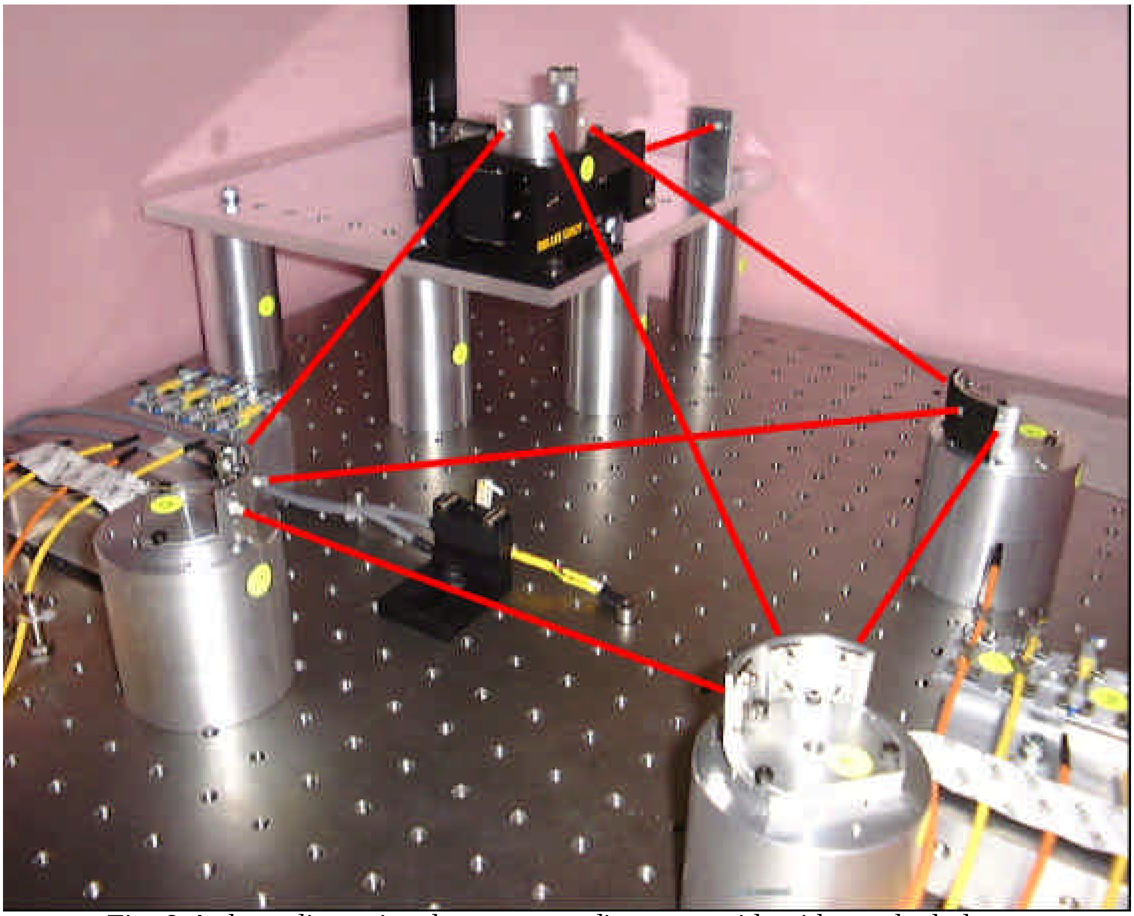

Fig. 9 A three dimensional, prototype alignment grid, with tetrahedral geometry.

A preliminary test with the stage stationary determined the precision of the three dimensional node reconstruction in the new geometry. Fig. 10 shows the three dimensional reconstructed coordinates of node C, for a set of 26 FSI scans. The scatter in the Z-coordinate is more than double the scatter along the X- or Y- coordinates due to the small component of sensitivity of the lines of sight in the vertical direction. This is a result of the small angle made between the lines of sight to node C and the X-Y plane. The RMS scatter about the average position is 640nm, well within requirements for ATLAS.

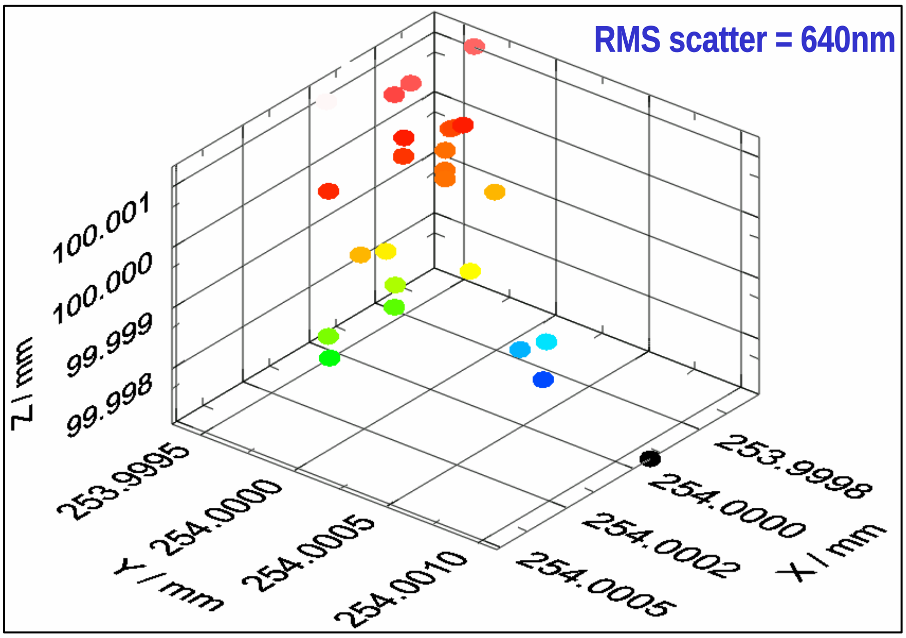

Fig. 10 Three dimensional reconstruction of node C for the tetrahedral prototype grid.

The stage was also translated in X, and FSI measurements made as previously described. A seventh line of sight was also used to independently measure the stage position. A similar comparison with the reconstructed X-coordinate of node C is given in Fig 11. The error of 460nm is more than the square grid results, Fig. 8, due to the reduced sensitivity in the X-coordinate caused by the change of geometry. The reconstructed coordinates are well within ATLAS requirements.

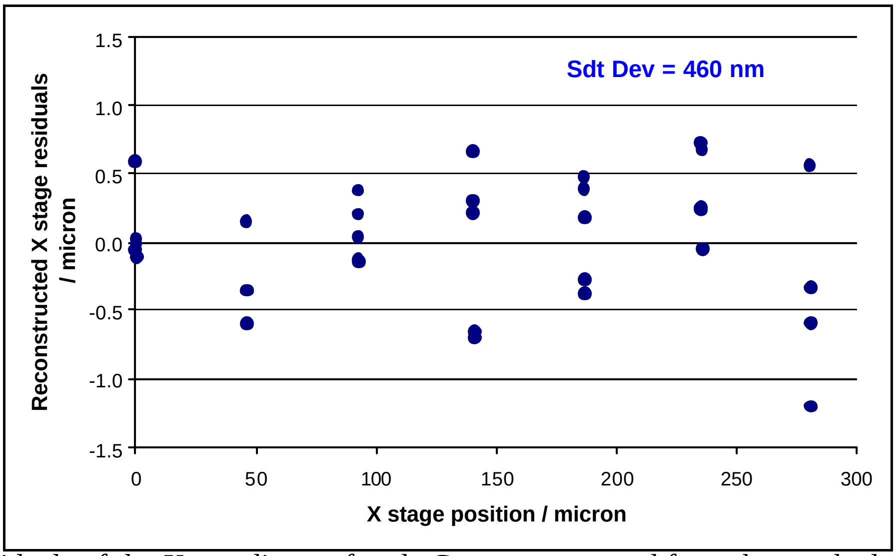

Fig. 11 Residuals of the X-coordinate of node C as reconstructed from the tetrahedral prototype grid, versus an independent measurement of the stage position.

4. GEODETIC GRID SIMULATIONS

4.1 Introduction

The geodetic grid for the final system consists of over eight hundred lines of sight in a complex geometry. For the grid to be over constrained, the number of measurements and imposed physical constraints must be greater than the number of degrees of freedom of the grid nodes. A well designed grid will then solve to allow reconstruction of the node positions, including orientations for extended objects. The error propagation through sections of this grid has been evaluated using the opto-geometrical simulation and reconstruction software, SIMULGEO [4].

4.2 Grid Simulations

The Barrel SCT consists of four concentric carbon-fibre cylinders supporting the silicon strip detector modules. Objects called jewels, containing a combination of quills (section 2.2) and retro reflectors, are rigidly attached to the carbon-fibre. An FSI length measurement is made between a quill on one jewel and a retro reflector on another jewel. The Barrel SCT grid is not over constrained solely by length measurements, but also relies on additional physical constraints imposed by the allowed deformations of the carbon-fibre support structures. For example, these constrain the rotation of each jewel in the central section of the barrel to some maximum angular tolerances, which have been estimated with FEA.

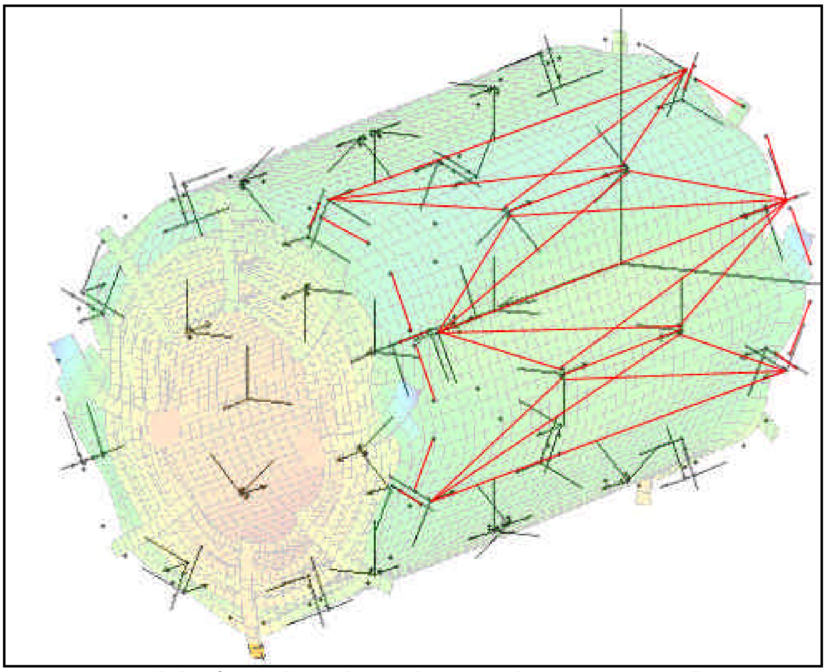

Fig. 12 A SIMULGEO model of one barrel geodetic grid superimposed on an FEA model of the Barrel SCT. A quarter of the grid lines in one barrel grid are shown.

One barrel grid was modelled in SIMULGEO, with each of the central jewels free to translate, but constrained in rotation by the angular tolerances calculated with FEA. The SIMULGEO rendering of the opto-geometrical system is given in Fig. 12. The lines of sight of one quadrant of one barrel grid have been overlaid in red for clarity.

The carbon-fibre end flanges of the barrel were assumed to be rigid rings. One end flange was fixed with an infinite weight in the Z direction, with the opposite end flange free in all six degrees of freedom. A precision of one micron was assumed for each length measurement. The errors on determining the shape of one barrel and its position and orientation with respect to an inner barrel were calculated. The grid simulation yielded identical errors for each of the central jewels, as expected by symmetry. The calculated errors are given in Table 1. The last three results shown in blue are an artefact of the imposed constraints on the central jewel rotations.

Table 1 Simulated alignment performance for one barrel of the geodetic grid

Measured Object	Degree of Freedom	Free or Constrained	Calculated Error
End Flange	Translation in X	Free	0.29 µm
	Translation in Y	Free	0.29 µm
	Translation in Z	Free	0.34 µm
	Rotation about X	Free	1.31 µrad
	Rotation about Y	Free	1.31 µrad
	Rotation about Z	Free	0.61 µrad
Each Central Jewel	Translation in rφ	Free	2.19 µm
	Translation in r	Free	13.54 µm
	Translation in Z	Free	0.90 µm
	Rotation about rφ	Constrained 100 µrad	97.07 µrad
	Rotation about R	Constrained 10 µrad	9.91 µrad
	Rotation about Z	Constrained 100 µrad	99.47 µrad

These results show the ATLAS requirements of are met for one barrel with respect to a fixed inner barrel, with above assumptions. Further reconstruction software is being developed to eliminate the need for some of these assumptions.

The Forward SCT consists of a series of nine separated discs, with the axes parallel to the beam pipe. A rigid geodetic grid, based on equilateral triangles, has been designed and the alignment performance of the full grid evaluated. [8]

4.3 Future work

Simulations of the full barrel grid will predict the sensitivity of the alignment system to likely deformations of the barrel. These simulations will be cross checked by using FEA models of the ATLAS SCT. The lengths of the geodetic grid lines will be extracted from an FEA model with nominal geometry. Random errors will be added to these lengths to simulate length measurement error. The lengths will be passed to shape reconstruction software for calibration of the model. The FEA model will then be subjected to typical mechanical loads, to produce a distorted model. The new lengths will be extracted, random errors added to these lengths, which will then be used by the reconstruction software to determine the shape of the SCT. This reconstructed shape should compare well to the distorted shape of the FEA model within the predicted errors.

5. CONCLUSIONS

A novel alignment system, based on Frequency Scanning Interferometry, is under construction for the ATLAS semiconductor tracker (SCT). It has been demonstrated that prototype geodetic grid nodes can be reconstructed to well within the ATLAS requirements (<1ppm). Error propagation through the final SCT grid has been simulated. These predict that the alignment system will be sensitive at the required level to distortions of the SCT. Future work with FEA models will aid understanding of these simulations.

6. ACKNOWLEDGEMENT

We acknowledge kind permission from Laurent Brunel to use SIMULGEO.

7. REFERENCES

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