FREQUENCY SCANNING INTERFEROMETRY - A VERSATILE, HIGH PRECISION, MULTIPLE DISTANCE MEASUREMENT TECHNIQUE

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Abstract

Frequency Scanning Interferometry (FSI) has been developed for high precision, simultaneous, absolute distance measurements along multiple lines of sight. In the ATLAS semiconductor tracker, FSI will be used to measure lines of sight between nodes of a geodetic grid, attached to the support structure. Movements of the detector modules on the order of ten microns will be monitored by measuring changes in grid line lengths on the order of one micron.

In this paper, the FSI technique is explained and FSI measurement results, demonstrating achievement of the required precision, are presented. These measurements have been made using interferometer components of the final ATLAS design. This interferometer design complies with the following requirements: low mass, rugged, radiation hard, able to fit into the small spaces allocated and insensitive to all conceivable changes in interferometer alignment.

Future plans for using FSI within alignment systems for survey and operation of the next generation of linear colliders will also be discussed.

1 INTRODUCTION

Absolute distance interferometry (ADI) is a general, versatile technique for measuring an interferometer of unknown length by comparison with a reference interferometer [1, 2, 3, 4, 5]. A tunable laser is coupled to both interferometers and tuned through a known frequency interval. The ratio of phase change induced in the two interferometers is proportional to the ratio of interferometer lengths. This principle, described in more detail in Section 2, can be applied to measure many interferometers simultaneously. Another advantage of ADI is the ability to make length measurements without the need for moving parts in the measured interferometer. This allows for an interferometer design which is simpler, more compact and rugged, as required by many metrology applications in particle physics.

Frequency Scanning Interferometry (FSI) is a form of absolute distance interferometry developed specifically to exploit this ability to make multiple simultaneous measurements. A Frequency Scanning Interferometry system has been developed with 800 remote, fibre coupled interferometers being measured within the high-radiation hostile environment of the ATLAS semiconductor tracker [6, 7, 8, 9]. The ATLAS system for making this large number of simultaneous measurements is discussed in Section 3.

FSI will be a key technique in an optical metrology system proposed for use in the surveying of the accelerator of a future linear collider [10]. The refinements to FSI being investigated are discussed in Section 4.

TOC

2 MEASUREMENT PRINCIPLE

Absolute distance interferometry allows an interferometer of unknown length to be measured unambigously. This interferometer to be measured will be referred to below as the grid line interferometer (GLI).

The optical path difference of any GLI, $\mathcal{D}$, is compared with the optical path difference of a stabilised reference interferometer $\mathcal{L}$, by illuminating both interferometers with a laser and tuning over a frequency interval $\Delta\nu$.

The phase change induced in each interferometer by frequency scanning is therefore

$$\Delta\Phi = \frac{2\pi}{c}\mathcal{L}\Delta\nu \tag{1}$$

for the reference interferometer and similarly

$$\Delta\Theta = \frac{2\pi}{c}\mathcal{D}\Delta\nu \tag{2}$$

for the grid line interferometer.

The measured phase changes can be used to calculate the GLI optical path difference in the form

$$\mathcal{D} = \mathcal{L}\frac{\Delta\Theta}{\Delta\Phi} \tag{3}$$

This procedure is inaccurate if there are changes in the optical path of either interferometer during the frequency scan. If there are changes in the optical paths of the reference interferometer $\Delta\mathcal{L}$ and the grid line interferometer $\Delta\mathcal{D}$, the measured phase ratio

$$q = \frac{\Delta\Phi}{\Delta\Theta} = \frac{\mathcal{L}}{\mathcal{D}}\left(1 + \varepsilon\frac{\nu}{\Delta\nu}\right) \tag{4}$$

where ε is the relative proportional change in interferometer optical path difference given by

$$\varepsilon = \frac{\Delta\mathcal{L}}{\mathcal{L}} - \frac{\Delta\mathcal{D}}{\mathcal{D}} \tag{5}$$

and ν is the average frequency of the laser for the tuning interval. The $\frac{\nu}{\Delta\nu}$ factor in equation 4 means that a change in optical path of 1 nm in an interferometer during the frequency scan can produce an error in the measurement of the grid line interferometer length (using equation 3) of several microns. Thus optical path drift, during laser tuning, is an important source of error for absolute distance interferometry measurements made using a *single* laser.

The drift errors can be removed by measuring the interferometer phase ratio using two lasers tuning in opposite directions.

The measured phase ratio using the first laser q_1 and the second laser q_2 can be combined using

$$q_0 = \frac{q_2 - \rho q_1}{1 - \rho} \tag{6}$$

where ρ is given by

$$\rho = \frac{\varepsilon_2}{\varepsilon_1}\left(\frac{\nu_2}{\Delta\nu_2}\right)\left(\frac{\Delta\nu_1}{\nu_1}\right) \tag{7}$$

where subscripts on all symbols represent the parameter for the corresponding laser.

If the measurement is arranged so that the two lasers are used simultaneously, (taking appropriate measures to separate the two signals in the data acquisition), then $\frac{\varepsilon_2}{\varepsilon_1} = 1$ in equation 7.

The two independent measurements of q_1 and q_2 can be used to obtain the two quantities q_0, which is calculated and ε, which is never evaluated explicitly. If instead, the two lasers were not used simultaneously there would be three unknown quantities q_0,ε_1 and ε_2 to be determined from two measurements and the drift error could not be removed.

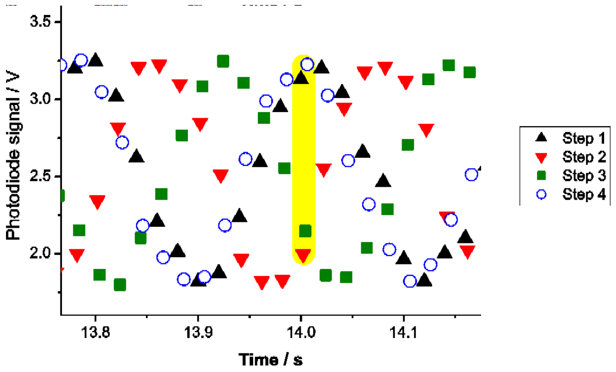

Figure 1: *Reference interferometer intensity measurements made at the four values of interferometer length. One cycle of four so-called phase step measurements is shown highlighted. The phase step between each measurement within the same cycle is approximately 110°.*

2.1 Measuring the phase changes induced by each laser.

The phase changes of the reference interferometer are measured by stepping the length of the interferometer through a cycle of four values. In each cycle, a group of four intensity measurements are recorded. An example of reference interferometer measurements is shown in

TOC

Fig. 1, with a single cycle of four measurements shown highlighted. Intensity measurements made at the same step position vary sinusoidally as the laser tuned.

The four interferometer intensity values (so-called phase steps) from each cycle are used to calculate the interferometer phase (to modulo 2π) using the Carré algorithm [11]. These extracted phases are unwrapped, by adding appropriate integer multiples of 2π, to generate a continuous function of interferometer phase versus time. This function is proportional to the laser tuning curve. An example is shown in Fig. 2.

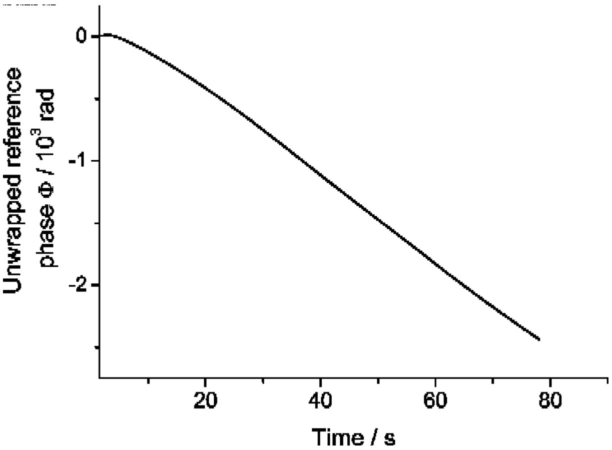

Figure 2: *The fine tuning curve from a single laser, based on the extracted and unwrapped phase from the reference interferometer.*

Once the unwrapped reference interferometer phase has been determined, the corresponding grid line interferometer intensity signals I are fitted to a sinusoidal function of the reference interferometer phase values Φ given by

$$Y(\Phi) = I_{\mathrm{DC}} + I_{\mathrm{AC}} \cos\left(\frac{\Phi}{q} + \alpha\right) \tag{8}$$

where I_{DC},I_{AC},q and α are parameters tuned to achieve the best fit to the data. An example of a sinefit to grid line interferometer data is given in Fig. 3.

The best fit phase ratio q for each laser is used to extract the dual-laser corrected phase ratio estimate q_0 using equation 6.

An example of interferometer length measurements based on q_1, q_2 and q_0 are given in Fig. 4. The precision of the length measurement can be improved by combining values of q_0 made from different dual-laser fine tuning intervals known as subscans. The large errors in the single laser measurements at the start of these measurements was due to rapid temperature changes deliberately induced to test dual-laser reduction of the drift errors. Note that the length based on q_0 is stable to within 20 μm even with errors for single laser measurements as large as several mm.

If one of the lasers is coarse tuned over large frequency intervals between fine tuning subscans, the interferometer phase information in each subscan can be extrapolated to the

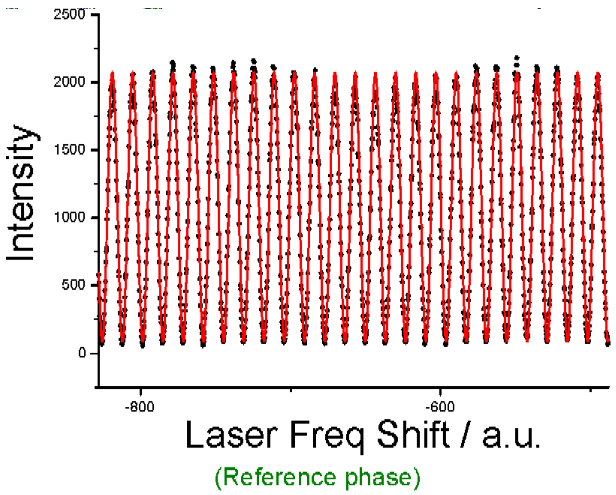

Figure 3: *An example of a sinusoidal fit to intensity data from a grid line interferometer, (in units of photons counted). In this example the interferometer signal was measured using a photomultiplier tube. In the ATLAS system, each grid line interferometer signal will be recorded using an avalanche photodiode.*

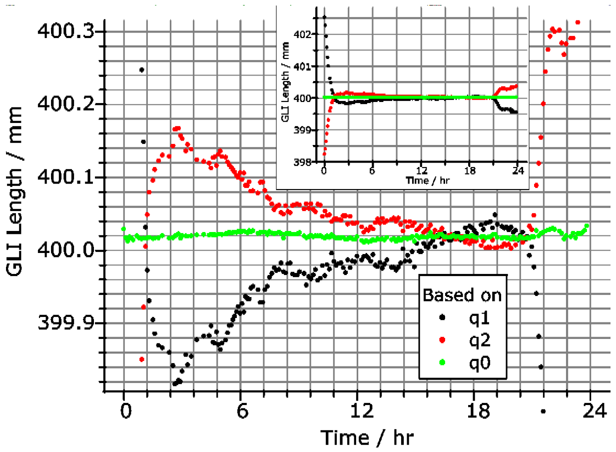

Figure 4: *An example of dual-laser reduction of drift errors. The length of a 400 mm grid line interferometer is estimated using the best fit phase ratios for each laser* q_1 *and* q_2 *and also using the drift reduced phase ratio estimate* q_0. *Note the anti-correlation in the errors for each single laser measurement as predicted for lasers tuning in opposite directions by equation 4. The inset shows the full range of the measured lengths, with the main plot showing the same data with a smaller range on the y-axis.*

other subscans using the best current estimate of the phase ratio. Initially this is the average of the values of q_0 obtained from each subscan. Once the first subscan pair are linked an improved phase ratio estimate is obtained. This is used to guide the next extrapolation, between two subscans which are further apart. In this iterative process, each link improves the estimate of phase ratio.

The phase extrapolation from one subscan to a second subscan, allows phase in the second subscan to be predicted to within one fringe cycle as shown schematically in Fig. 5. This extrapolation can be locally corrected (within $\pm\pi$) using the phase information in the second subscan. The application of this correction is known as subscan linking and is discussed in greater detail elsewhere [6].

The largest link cannot be made without the improvements to the phase ratio, from earlier links, because the extrapolation could be in error by more than $\pm\pi$ and the linking correction is then invalid.

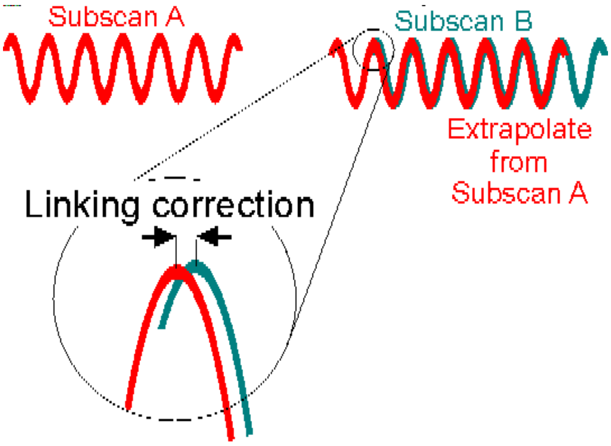

Figure 5: *A schematic representation of the process known as subscan linking, by which an extrapolation of interferometer phase from one subscan to another is corrected to within* $\pm\pi$ *using the local phase information from the second subscan. This linking correction improves the interferometer phase ratio estimate, by greatly reducing important systematic errors.*

Frequency Scanning Interferometry measurements of grid line interferometer lengths based on dual-laser drift correction and subscans linking have been regularly demonstrated on interferometers with lengths from less than 200 mm to 1.5 mm to a precision of less than 1 μm. An example set of measurements of a 1 m grid line interferometer built on a steel bench is shown in Fig. 6. The thermal expansion of the steel can be seen by plotting the measured interferometer length against the steel temperature.

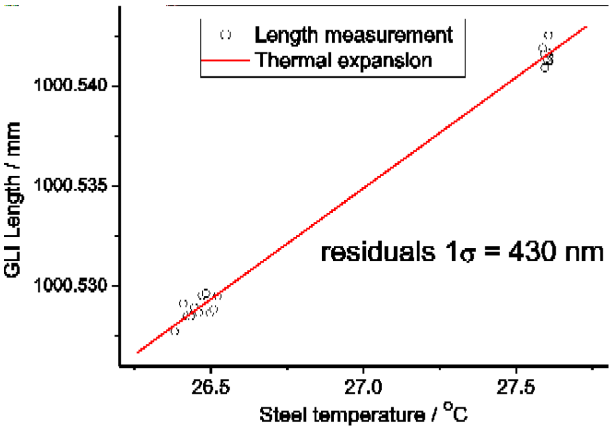

Figure 6: *Length measurements for a grid line interferometer built on steel are shown as a function of steel temperature. The best fit linear thermal expansion trend (with a gradient of 11 ppm.K^{-1}) is shown in red. The residual differences between the thermal expansion trend and the length measurements have a spread of 430 nm at one standard deviation.*

3 ATLAS FSI SYSTEM

The real time alignment of the ATLAS semiconductor tracker will be monitored to a resolution of 10 μm using a set of geodetic grids, measured using Frequency Scanning Interferometry. The aim is to detect changes in shape of the tracker, by recording changes in the measured lengths along grid lines.

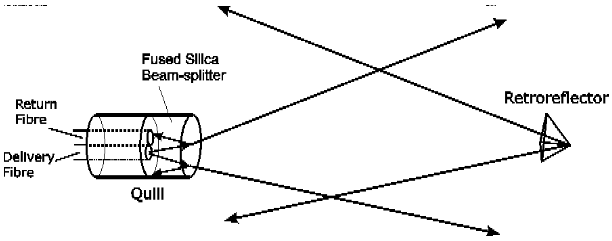

Figure 7: *The fibre-coupled, common path, low mass compact design of the grid line interferometers which will be installed in ATLAS.*

Each grid node is formed by placing interferometer components on the tracker support structure. Each grid line between a pair of nodes is measured using a single grid line interferometer, the design of which is shown in Fig. 7. There are two components, one at each end of the interferometer; the quill placed on one node of the grid, which acts as source and receiver of light and the retroreflector which is place on another node of the grid. The interferometer measures the distance along the grid line, between the two nodes.

Light enters the interferometer along a single mode delivery fibre and is collected by the single mode return fibre. The short arm of the interferometer is formed by reflection from

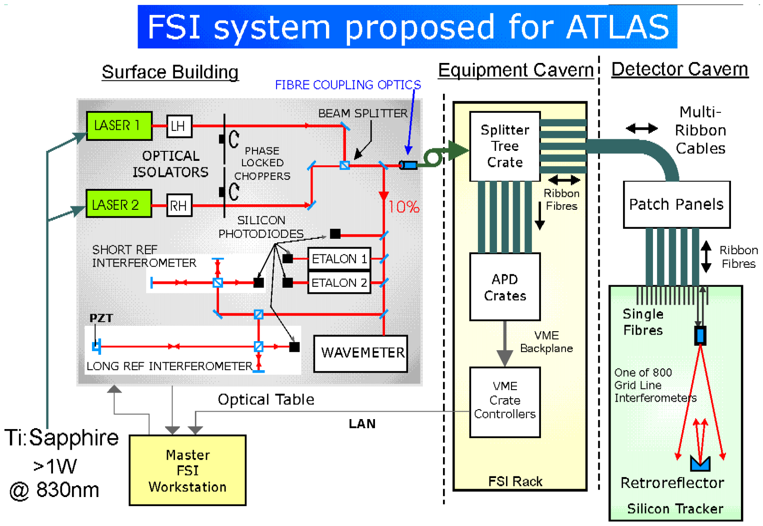

Figure 8: *The FSI system being constructed for ATLAS. This system is designed to make 800 simultaneous length measurements on the ATLAS detector, each to a precision of around 1 μm.*

the beam-splitter surface at the end of the quill. The long arm of the interferometer is via reflection from the retroreflector.

The system need to measure the 800 grid line interferometers installed in ATLAS, is shown schematically in Fig. 8. There are three main locations for the equipment in this system; a surface building, a shielded underground equipment cavern protected from the radiation produced by ATLAS and the ATLAS detector cavern.

In the surface building the two Ti:Sapphire lasers and the reference interferometers are housed in a controlled environment. The lasers each deliver around 1 W of light, tunable over a range of wavelengths in the region 800 nm to 850 nm. The reference interferometers are designed to be thermally stable and are kept in a vacuum. A small fraction of the laser power is used by the reference interferometer system.

Most of the light from the lasers is coupled into a main delivery fibre, which runs from the surface building to a splitter tree in the equipment cavern. This tree divides the power amongst the delivery fibres of the 800 grid line interferometers. The interferometer lengths range from less than 60 mm to 1.5 m.

The radiation hard, single-mode delivery fibre for each grid line interferometer goes from the splitter tree in the equipment cavern to the quill of the interferometer inside the semiconductor tracker, along a route of approximately 100 m. The radiation hard, single-mode, return fibre of the same interferometer takes the same route back to the equipment cavern. The interferometer signal from each return fibre is read out using a silicon avalanche photodiode [7].

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4 FUTURE USES OF FSI

The use of a pair of powerful lasers as in the ATLAS FSI system does not offer much flexibility in the available power and hence the number of interferometers which can be measured simultaneously using the same laser. If technology developed for telecommunications can be be harnessed in an FSI system, there is the possibility of constructing a modular system in which extra power is provided as needed by the addition of fibre amplifiers.

The scope for use of erbium doped fibre amplifiers in a modular FSI system is currently being investigated at the University of Oxford. In such a system, many lasers could be operated and amplified simultaneously. Each laser tunes over a subscan at a different wavelength, oofering a much faster linked measurement without the need for coarse tuning from one subscan to the next.

Other advantages of using communications technology is the wider availability of cheap optical components for the wavelength range 1500 nm to 1650 nm, including single mode fibre, splitters, optical filters, optical fibre amplifiers, widely tunable lasers and photodetectors.

The Linear Collider alignment and survey group propose an optical metrology tool for use in the accelerator tunnel of a future linear collider. FSI will form a key part of this optical metrology tool [10].

The FSI system for the survey train will need to measure much longer grid line interferometers than those found in ATLAS, up to 5 m. This is only possible if the interferometer quill is redesigned to collimate the transmitted beam, rather than allowing it to expand as is done in the ATLAS system.

5 SUMMARY

Frequency Scanning interferometry is a versatile form of absolute distance interferometry which has been developed for use in metrology and alignment systems in particle physics. The potential limitations of the absolute interferometry technique on which it is based have been overcome, allowing measurements with a precision of 1 μm in 1 m to be demonstrated.

A purpose built 800 interferometer system is being installed in the ATLAS semiconductor tracker to follow alignment changes of the support structure and hence the detector module positions.

The FSI technique will play a key role in the proposed metrology and survey tool for a future linear collider. The use of readily available modern telecommunications equipment is being investigated for flexible, cost effective future FSI systems. The linear collider metrology and survey tool will be the first of these telecommunications wavelength FSI systems.

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References

[1] Pfeifer T and Thiel J 1993 Absolutinterferometrie mit durchstimmbaren Halbleiterlasern *Technisches Messen* **60** (5) 185-91

[2] Stone J A, Stejskal A and Howard L 1999 Absolute interferometry with a 670-nm external cavity diode laser *Appl. Opt.* **38** (28) 5981-94

[3] Salewski K D, Bechstein K H, Wolfram A and Fuchs W 1996 Absolute Distanzinterferometrie mit variabler synthetischer Wellenlänge *Technisches Messen* **63** (1) 5-13

[4] Bechstein K H and Fuchs W 1998 Absolute interferometric distance measurements applying a variable synthetic wavelength *J. Opt.* **29** 179-82

[5] Thiel J, Pfeifer T and Hartmann M 1995 Interferometric measurement of absolute distances of up to 40 m *Measurement* **16** 1-6

[6] Coe P A 2001 *An investigation of Frequency Scanning Interferometry for the alignment of the ATLAS semiconductor tracker* Doctoral Thesis (Oxford : University of Oxford).

[7] Mitra A 2002 *Development of an APD amplifier for the runtime alignment of the ATLAS inner detector and SUSY studies* Doctoral Thesis (Oxford : University of Oxford).

[8] Coe P A, Howell D F and Nickerson R B 2003 Frequency Scanning Interferometry in ATLAS : Remote, multiple, simultaneous and precise distance measurements in a hostile environment *Meas. Sci. Technol.* (To be published).

[9] Gibson S M, Coe P A, Mitra A, Howell D F and Nickerson R B 2002 A study of geodetic grids for the continuous, quasi-real time alignment of the ATLAS semiconductor tracker, *Proc. Seventh International Workshop on Accelerator alignment* SPring-8, Japan

[10] Bingham R, Botcherby E, Coe P A, Grzelak G, Mitra A, Prenting J and Reichold A 2002 The linear collider Alignment and Survey (LiCAS) Project, *Proc. Seventh International Workshop on Accelerator alignment* SPring-8, Japan

[11] Carré P 1966 Installation et utilisation du comparateur photoélectrique et interférentiel du Bureau International des Poids et Mesures *Metrologia* **2** (1) 13-23