Initial Calibration and Stability Results from the LiCAS RTRS FSI System *

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Abstract

The Linear Collider Alignment and Survey (LiCAS) Rapid Tunnel Reference Surveyor (RTRS) will survey the reference network of the ILC to a high accuracy. It will measure the position of retro-reflectors along the tunnel wall using optical techniques including Frequency Scanning Interferometry (FSI) [6] [5] [7]. The LiCAS RTRS has 2 FSI measurement sub-systems: the internal, used to measure car to car coordinates, and external FSI subsystems, used to measure the car to wall marker coordinates. An FSI length measurement system requires at least two interferometers; one has an unknown Optical Path Length Difference (OPD), and is referred to as the measurement interferometer; the other has a known OPD, and is referred to as the reference interferometer. The FSI sub-systems are required to measure the measurement interferometer OPD to micron accuracy. For FSI to measure to the required accuracy, the reference interferometer requires an Optical Path Length Difference (OPD) to be known to the micron level. The reference interferometer's length must also be stable to the micron level over long periods of time. The design of the reference interferometer, external and internal FSI subsystem are described along with the reference interferometer thermal stabilisation study. The initial results of the calibration of the LiCAS reference interferometers and initial stability of the internal and external FSI subsystems are also discussed.

INTRODUCTION

Frequency Scanning Interferometry

The intensity of an FSI interferometer is given by given by [1].

$$I = I_1 + I_0 cos(\phi + \phi_0), \tag{1}$$

where ϕ is the phase difference of the two arms of the interferometer, given by

$$\phi = 2\pi D\nu(t)/c, \tag{2}$$

* Work supported by STFC in the LC-ABD collaboration and by the Commission of the European Communities under the 6th Framework Programme Structuring the European Research Area, contract number RIDS-011899.

where D is the OPD of the measurement interferometer and $\nu(t)$ is the frequency of the laser.

In an FSI system, the frequency of the laser is changed to find an unknown optical path length difference (OPD). The intensity output of the interferometer varies in a sinusoidally with laser frequency, with one oscillation referred to as an interference fringe. The LiCAS laser tunes linearly with wavelength not frequency.

If equations (1) and (2) are combined, we find equation (3) for time defendant part of the FSI intensity;

$$I = I_0 cos(2\pi D\nu_{(t)}/c). \tag{3}$$

From this it would be expected that D could be determined if ν_t is known or could be found. This is not easily possible due to the non-linear frequency tuning of the laser. To solve this problem a reference interferometer with a precisely known OPD is added to the system. The laser is split and passed into both reference and measurement interferometer simultaneously. The advantage of this is that as both of the interferometers have the same laser and thus the same frequencies, this means that equation (2) is valid for both interferometers. This can then be used to show;

$$\phi = D\phi_{ref}(t)/D_{ref}. \tag{4}$$

Now equation (1) combined with equation (4), yields the following time dependence;

$$I = I_0 cos(D\phi_{ref}(t)/D_{ref}). \tag{5}$$

The phase of the reference interferometer is extracted using phase extraction techniques (see [3]). If the intensity of the measurement interferometer is plotted against the reference interferometer extracted phase, the angular frequency is given by

$$\omega = D/D_{ref}. \tag{6}$$

The angular frequency is determined using spectral analysis (see [3]) and the unknown distance D is determined.

FSI SYSTEM DESIGN

The FSI system is made up of several subsystems:

- The Reference Interferometer

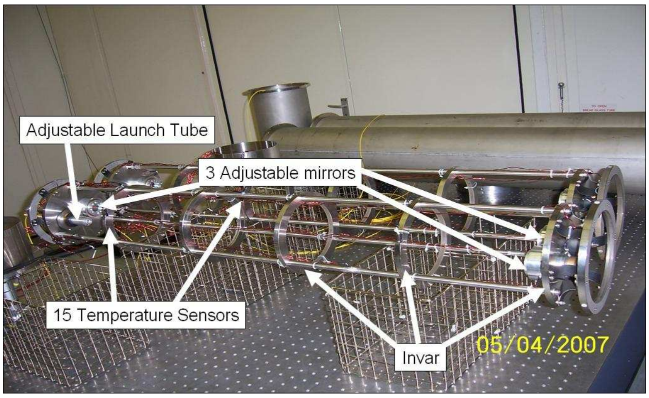

Figure 1: Photo of the two LiCAS reference interferometers under construction in oxford

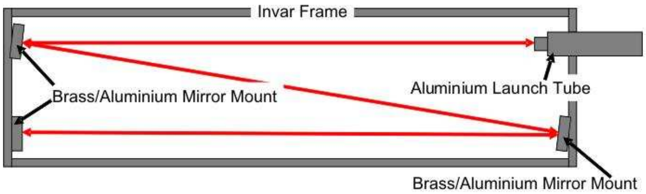

Figure 2: Sketch of a LiCAS Reference Interferometer

- The External FSI subsystem
- The Internal FSI subsystem

The following sections describe the design and function of these systems.

Reference Interferometer Design

The reference interferometer is a folded path Fizzeau interferometer with an OPD of approximately 6m (figure 1 and 2). The main bars of the interferometer, the end plates and the rings are made of invar. The three mirrors are held in brass half spheres which are mounted in aluminum cones. These mirrors can be pointed in two dimensions to allow the interferometer to be aligned. There is also a movable launch tube. The length of this launch tube can be adjusted during the thermal calibration process, for example, if the interferometer's OPD coefficient of thermal expansion (CTE) is positive, the launch tube can be moved into the interferometer to reduce the CTE to zero. There are also 15 temperature sensors placed throughout the interferometer.

External FSI Subsystem Design

The external FSI system is responsible for determining the 3D position of a reference network marker with respect to a measurement unit. A measurement unit has 6 FSI lines all monitoring the same retro reflector (figure 4); figure 3 shows a photo of an installed unit, in which 5 of the 6 lines are visible along with a retro reflector. The FSI lines are bare fibers; there is no collimation or beam splitters. From the lengths measured by all 6 FSI lines; the retro reflector can be reconstructed using multilateration [4].

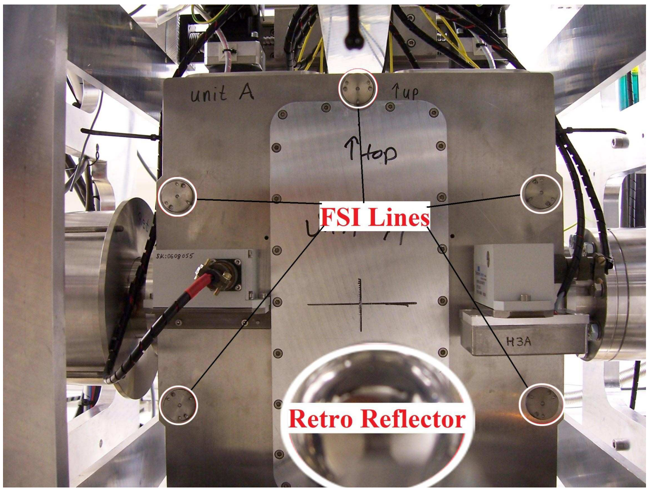

Figure 3: Photo of the a LiCAS unit installed observing a retro reflector

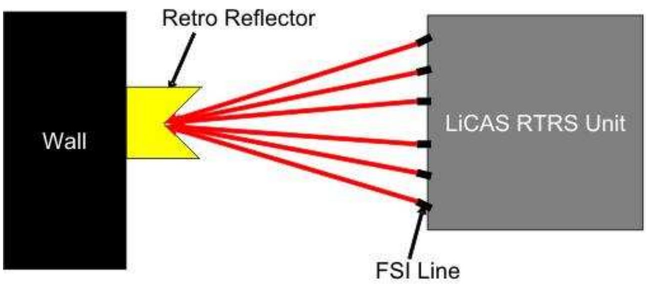

Figure 4: Sketch of External FSI System

Internal FSI Sub-System Design

The internal FSI systems are responsible for measuring the distance from one unit to the next. A unit has 6 collimated fibers with beam splitters attached (figure 5) to the collimators. Each of the 6 FSI lines monitor one of 6 retro reflectors mounted on the next measurement unit (figure 6 and 7).

REFERENCE INTERFEROMETER CALIBRATION

We require a reference interferometer which is stable to the micron level. The two different types of calibrations required for the reference interferometer: length calibration and thermal calibration, are described in the following two sections.

Reference Interferometer Length Calibration

The reference interferometer's length (L_{ref}) needs to be known to the sub-micron level. To determine L_{ref} experi-

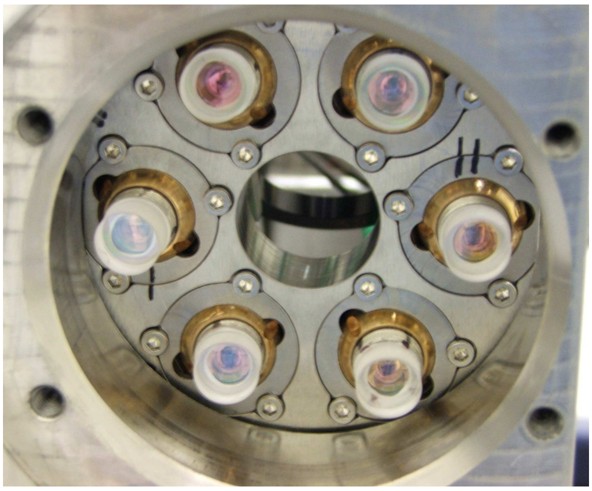

Figure 5: Photo of the mounted internal FSI launch optics

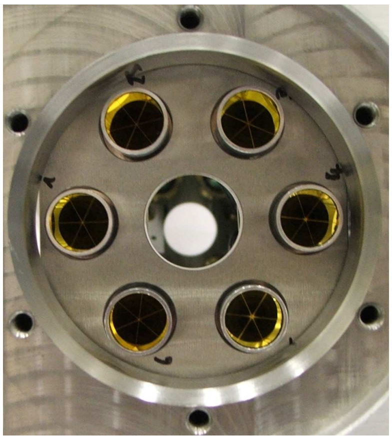

Figure 6: Photo of the mounted internal FSI retro reflectors

mentally, a motion stage on which two retro reflectors are mounted back to back was used. One retro reflector is monitored by a collimated FSI line; the other is monitored by a laser tracker. The collimated FSI line and the laser tracker were set up to be as collinear as possible. The motion stage was moved to a series of positions: at each position the FSI system measured the length ratio ($Lratio = \frac{L_{stage}}{L_{ref}}$) of the the stage interferometer to (Lref) and the laser tracker measured, ΔL, the displacement of the stage with respect to the stage initial position (Linitial). The length ratio is expressed by equation 7 and can be rearranged to give equation 8 . Equation 8 states that, the gradient in a plot of ΔL vs Lratio

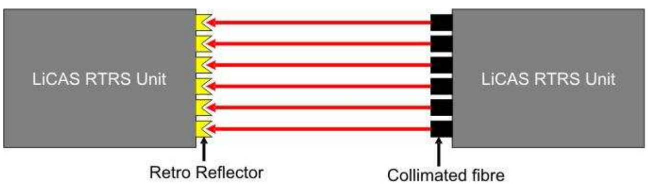

Figure 7: Sketch of the Internal FSI System

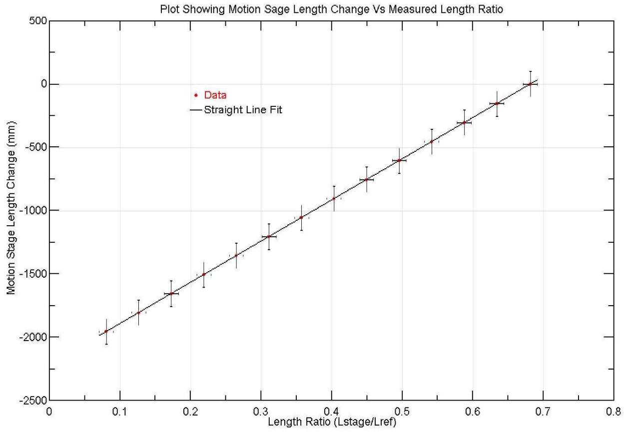

Figure 8: Data from length calibration experiment with fit results. Note: error bars are magnified by 10000

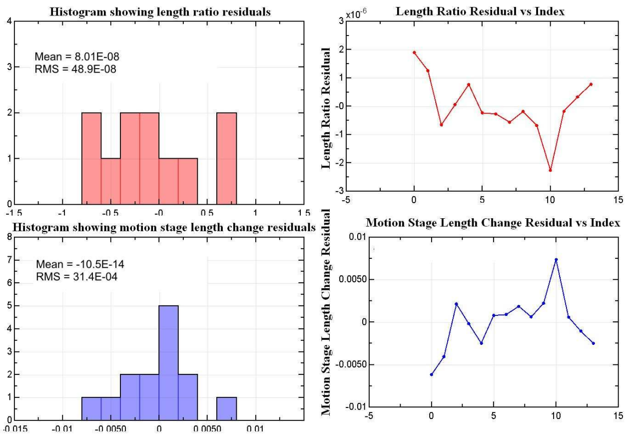

Figure 9: The residues of the fit and data from figure 8

is equal to Lref.

$$L_{ratio} = \frac{L_{initial} + \Delta L}{L_{ref}}. \quad (7)$$

$$\Delta L = L_{ratio} L_{ref} - L_{initial}. \quad (8)$$

Plot 8 shows that from an initial test of the length calibration experiment. The errors on length ratio data were found as the RMS of the five consecutive measurement. Their errors were of the order 1E-6. The error on ΔL were estimated from the laser tracker specifications as 10μm. Plot 8 also shows the straight line fit to the data with the error bars magnified by a factor of 10000.

The residuals between the data and the fit in figure 8 are shown in figure 9. Figure 9 shows that the residuals for the length ratio and ΔL have RMS spreads of 4.9E-7 and 3.1μm respectively. The RMS spreads are smaller than expected. This shows that there is a correlation between the errors, which gives an increased accuracy in the fitting.

The slope from the straight line fit is 3.2521901m +/- 3μm. The experiment will be repeated with the following improvements to reduce the errors: taking smaller steps

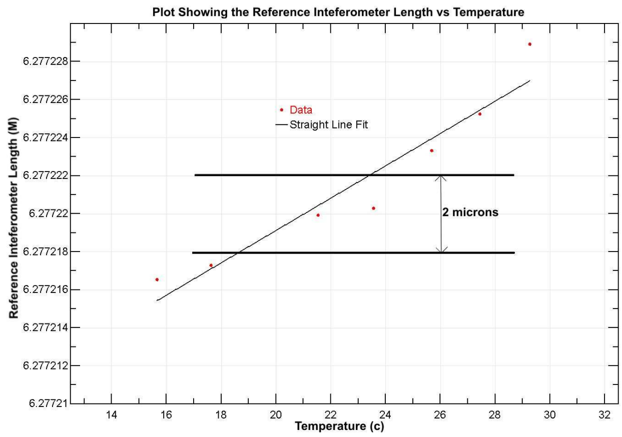

Figure 10: Data From the first pass of the thermal calibration of one of the LiCAS reference interferometers

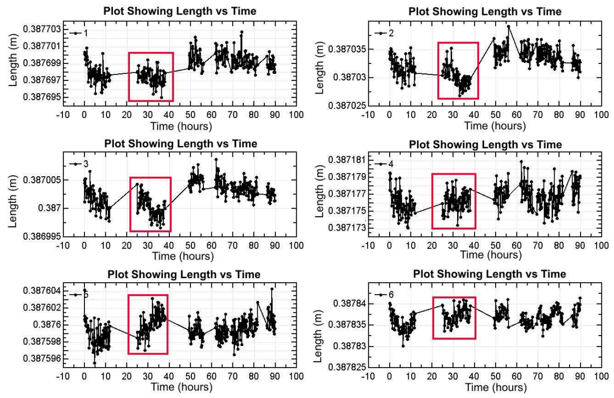

Figure 11: Lengths measured by external FSI system over a 90 hour period. Regions of interest are marked

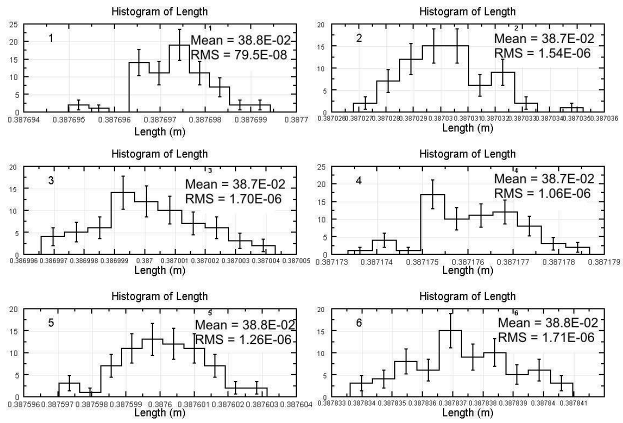

Figure 12: Histogram of lengths measured by external FSI system over a 14 hour period

along the motion stage, repeating these measurements multiple times, covering the optical path to reduce air turbulence and improving the collinearity of the laser tracker and FSI measurement.

Reference Interferometer Thermal Calibration

For thermal calibration two interferometers are required: one interferometer is held at a constant temperature while the temperature of the second interferometer is changed in an environmental chamber. The interferometer with the changing temperature is the one being calibrated. When the interferometer under calibration has come to thermal equilibrium, its length ratio with respect to the other interferometer is measured. This is repeated at several temperatures. From the data, a CTE for the interferometer can be determined. With the CTE of the interferometer known, the launch tube can be adjusted to compensate for the thermal expansion. This is repeated until adjustments become too small to be reliably implemented. After adjustment the experiment is repeated to verify the residual CTE of the interferometer, which can later be used for off line thermal corrections to the length.

The first stage of launch tube adjustment has been completed and the second stage is on going. A first pass of CTE verification suffered due to an air conditioning failure which meant the interferometer acting as reference was not maintained at a constant temperature. The data for this first pass is shown in figure 10 along with a straight line fit. It can be seen that even though the interferometer acting as reference was thermally unstable, that the data points are within 1μm of the line.

INITIAL FSI STABILITY RESULTS

The LiCAS-RTRS was set up to allow a stability study of the subsystems. During the stability study the train's rail clamps were applied and the electronic crates mechanically detached from the RTRS and placed in steel bricks to reduce vibration. Data was then taken every 10 minutes for approximately 90 hours.

The next 2 subsections show the results for the internal and external FSI systems during the stability study.

Initial External FSI Stability Results

The three LiCAS units monitored their respective retro reflectors throughout the experiment. The lengths measured during the 90 hour period are shown in figure 11. A histogram covering the time period 26-40 hours of figure 11 is shown in figure 12. From the histogram in figure 12 we can see that the precision of the FSI line length measurements ranges from 0.78μm to 1.71μm. Note that during this time period some of the FSI lines measured a significant, systematic distance change which is why some of lines have an appearant lower precision than others.

The lengths from the external FSI system can be combined to reconstruct the reference marker's positions. The reconstruction gives the x,y,z, position of the marker with respect to the measurement unit. The results shown for the

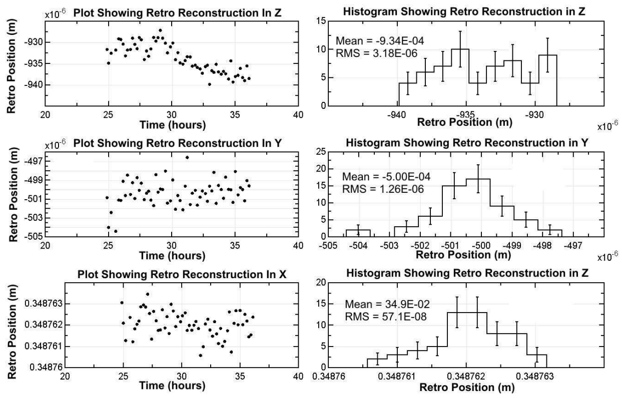

Figure 13: Reference marker reconstruction over a 14 hour period along with the histograms of that data

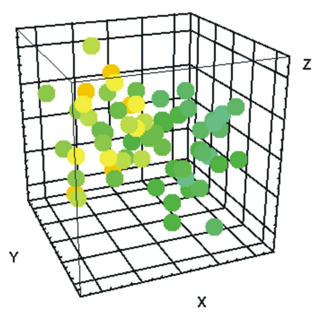

Figure 14: 3D reference point reconstruction, colour indicates time with yellow early and green late

reconstruction in figure 13 are for the same 26-40 hour time period used in figure 12. Figure 13 shows that the reference marker is moving during this time period. This is also seen in the 3D reconstruction plot shown in figure 14. From figure 13 the marker reconstruction precision can be estimated to be of the order 1.3μm.

Initial Internal FSI Stability Results

Measurement unit 3 monitored the retro reflectors on unit 2 during the stability run. The lengths measured are shown in figure 15, only 5 lines are shown due to a failure of one of the lines. The plot shows that the units are moving apart. To study the precision of the internal FSI lines; the lengths measured in line 1 were subtracted from the other lengths. The result of this subtraction is shown in figure 16.

One region of interest in figure 16 is in the region 20-30 hours where there is a sudden jump in the lengths measured by all of the lines with respect to line 1. This jump is largest in line 4, then reduced in line 3 and further reduced in lines 2 and 6. This shows that the unit has gone through a sudden rotation and a simplified calculation shows that this rotation is approximately 16 μrad. A second region of interest in

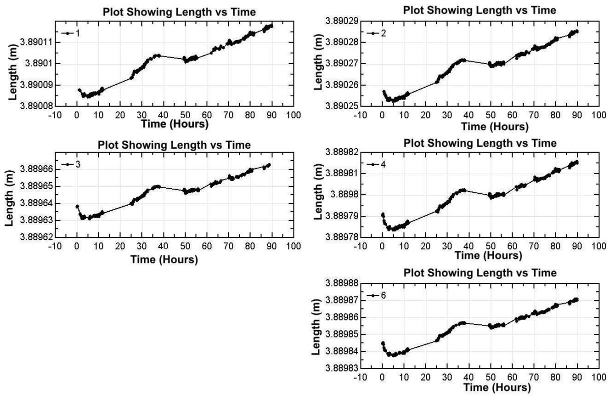

Figure 15: The lengths measured by the internal FSI on car 3 during a 90 hour period

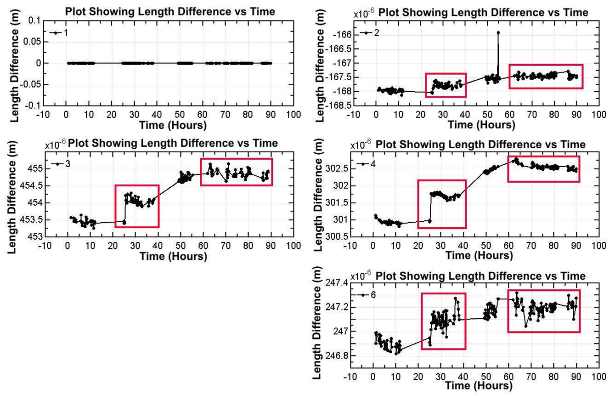

Figure 16: The lengths measured by the internal FSI on car 3 with the lengths of line 1 subtracted during a 90 hour period. Regions of interest are marked

figure 16 are the last 30 hours which are relatively stable, making it suitable for a study of the precision of the internal FSI system. The lengths measured during the last 30 hours were histogramed and are shown in figure 17. The RMS for the lines vary between 45nm and 102nm, which is a measure of the precision of the internal FSI system.

CONCLUSION

The LiCAS reference interferometer's are under calibration. The evidence to date indicate that the reference interferometer lengths can be determined to the micron level. From the initial stability tests on the external FSI system, the precision is shown to be at the micron level, and external marker reconstruction precision is of the order of 1.3 μm. External marker reconstruction is expected to be improved through better analysis techniques and through calibration of the external FSI launch point positions. The initial stability tests of the internal FSI system shows precision at the 50-100 nm level.

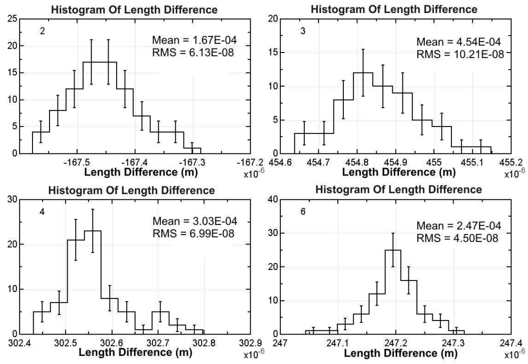

Figure 17: Histogram of the lengths measured by the internal FSI on car 3 with the lengths of line 1 subtracted during a 30 hour period

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