# STABILIZATION OF THE ILC FINAL FOCUS USING INTERFEROMETERS

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*Abstract*

We are developing a system of interferometers to measure relative motion between two objects (for example, the two final focus quadrupoles of a linear collider) to a few nanometers. Two instruments are under development in the John Adams Institute at the University of Oxford : A distance meter to measure length changes and a straightness monitor to measure perpendicular shifts. We will present the technique, results and resolutions of our distance meter prototype. We also examine the applications of interferometers at the ILC.

## INTRODUCTION

Interferometric measurements are routinely made with nanometre resolution over sub-millimetre dynamic ranges[1]. Here the aim is to combine traditional interferometry at nanometre precision with long range Absolute Distance Interferometry techniques, (which offer micron precision over tens of metres[2]), in the same fibre-coupled interferometer design. At one end of the interferometer is a launch head (which transmits and receives light) and a reflector at the far end. Interferometers of this design will be deployed as distance meters, in geodetic grids[1] arranged for precise monitoring of relative motion of accelerator components. Each end of an interferometer therefore is part of a grid node.

Straightness monitors measuring transverse motions are needed to monitor both positions and rotations. We plan to develop both distance meters and a straightness monitor in Oxford, but this paper will concentrate solely on the distance meter. Several prototype designs for the distance meter are currently being tested at Oxford. The target system has nanometre resolution, with a dynamic measurement range of several metres and a readout rate between 100 Hz and 1 kHz. Such a system would be ideal for monitoring the relative stability of critical magnets in the Beam Delivery System (BDS) of the International Linear Collider (ILC).

The ILC final focus quadrupoles will be several metres apart and must maintain relative vertical alignment to less than 10 nm for optimum luminosity collisions at the Detector Interaction Point. The monitoring of the relative positions of the two final focus quadrupole magnets is the most challenging measurement, requiring nanometre resolution from both the straightness monitor and the distance meter.

[1] A geodetic grid is also known as a network.

### *ATF at KEK*

We are building a setup at the Accelerator Test Facility (ATF) at KEK, comprising a network of distance meters to measure the relative position of two beam position monitors (BPM)s. The network shown in Figure 1, performs the same job as a straightness monitor[2]. The network is designed to constrain the six degrees of freedom of an intermediate reference triangle, (running along a ceiling girder and down to a floor node), with respect to three nodes attached to a carbon fibre frame which supports the SLAC-BPM. These constraints require nine distance meters. Similarly, nine distance meters are used to relate the position of the KEK-BPM to the reference triangle, for a total of 21 distance meters in the network. The primary

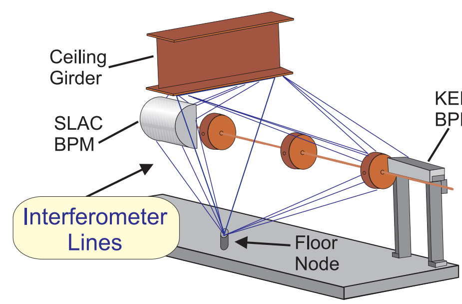


Figure 1: A schematic drawing of the proposed ATF geodetic network, for monitoring relative movement between two sets of beam position monitors (BPMs). The axial line between the BPMs represents the beam pipe.

aim is to measure the relative vertical displacement of the KEK-BPM with respect to the SLAC-BPM. The sensitivity of the network to vertical displacements increases with increasing height of the reference triangle; hence to maximise sensitivity the traingle stretches from floor to ceiling. All distance meter launch heads are in the nodes of the reference triangle, so that the lighter, more compact reflectors are in the BPM network nodes.

Network performance was simulated using Simulgeo[3] an opto-geometric simulation package. The input assumptions included a distance meter resolution and stability of 1 nm. The predicted resolution is 20 nm for the vertical component of relative positions of the BPMs.

Experiments at the ATF will test the performance of our distance meter and network designs, which can be com-

[2] A straightness monitor consists of a collimated laser beam acting as a straight line reference, with respect to which, transverse motions are measured. Here a straightness monitor is excluded by lack of a direct line of sight.

pared, both with simulation and with independent measurements of vertical displacements by each BPM with respect to the electron beam, (with a resolution of tens of nanometres). The set-up will also be use used to test active stabilisation algorithms, by moving the BPMs to maintain a fixed relative position.

At the later, ATF2, there will be a quadrupole focus reducing the beam spot size to 35 nm in the vertical. To monitor a focusing magnet, we need to develop a more compact interferometric straightness monitor, to overcome space limitations, with improved vertical resolution. The target is to be able to measure with nanometre resolution inside an available space of less than one meter (in the vertical). Such an instrument will be tested at ATF2.

## INTERFEROMETER PRINCIPLES

Interferometers discussed here use amplitude division[4] of light into two arms, to produce a signal on a photodetector, given by

$$I \quad = \quad B + A\cos\theta \tag{1}$$

The phase term can be expanded as

$$\theta \quad = \quad \left(2\pi\frac{\nu\mathcal{D}}{c} + \theta_0\right) \tag{2}$$

where $B$ and $A$ are the background and sinusoidal amplitudes respectively, $\mathcal{D}$ is the OPD between the arms of the interferometer, $\nu$ is the optical frequency of the light and $\theta_0$ a general offset phase.

Distance measurements using Frequency Scanning Interferometry (FSI) [5] (typically with sub-micron precision) will be combined with Fixed Frequency Interferometry (FFI) to make displacement measurements of nanometre precision.

### *Frequency Scanning Interferometry : FSI*

Given equation 2 for the phase of an interferometer signal, if the OPD or the optical frequency are increased, the phase of the signal increases. The respective increase required in each parameter, to shift the phase by $+2\pi$ is given by these relations

$$\begin{aligned} \Delta\nu_{2\pi} &= \frac{c}{\nu}(=\lambda) \\ \Delta\mathcal{D}_{2\pi} &= \frac{c}{\mathcal{D}} \end{aligned} \tag{3}$$

In any interferometer measurement, both $\nu$ and $\mathcal{D}$ change, to affect the phase $\theta$. In FSI the aim is to change $\nu$ rapidly and smoothly while sampling interferometer intensity data and processing numerically to obtain the corresponding interferometer phase shift $\Delta\theta$. The change of frequency can be determined precisely by reference to frequency standards[6] or more typically by measuring the corresponding phase change in a reference interferometer, illuminated by the same tunable laser and read out simultaneously. The ratio of measured OPD to reference OPD is approximately the ratio of induced phase shifts in each interferometer.

However any OPD change during the frequency scan, $\delta\mathcal{D}$ has a significant impact on precise measurements of the phase shift. The phase shift is in error by $\delta\mathcal{D}(\nu/\Delta\nu)$, where the factor $\nu/\Delta\nu$ is typically greater than 100. For given operational conditions, the faster the laser is tuned, the smaller this error will be. This error could be eliminated by independent monitoring of the OPD changes, using a second laser, not available in the tests discussed below. The system, shown in Figure 2 used fibres to connect a tunable laser to the distance meter under test and a reference Michelson interferometer. Throughout the system, all fibres were single-moded, terminated in angle polished ends to supress reflections. Without such precautions, unintended optical paths would have been present.

## DEMONSTRATION SYSTEM

A single laser system was set up, to test distance meters suitable for both FSI and FFI. A prototype distance meter was assembled to test a launch head design, suitable for FSI and FFI measurements. Here, only FSI measurements were made.

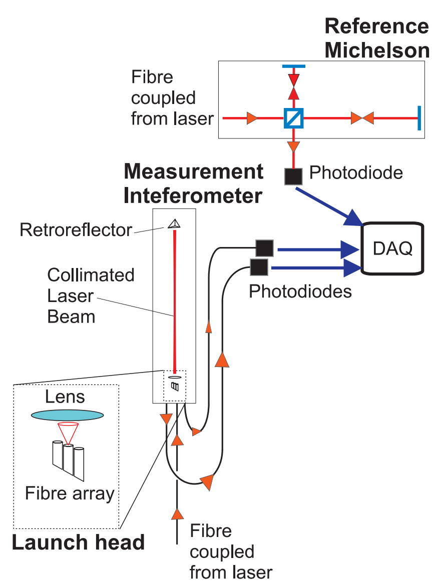


Figure 2: The measurement and Michelson reference interferometers of the demonstration set-up. Both interferometers are fibre coupled to a tunable laser, to generate sinusoidal fringes on the readout photodiodes.

The launch head of the distance meter under test consisted of a 12 way MT connector held in front of a lens ($f = 25$ mm). The MT connector holds a dozen single-mode optical fibres 250 $\mu$m apart, in a parallel array. One fibre was connected to the laser as the launch fibre, with neighbouring fibres read out using one photodetector each.

The short arm of the interferometer was formed by reflection from the far side of the lens, (with the near side anti-reflection coated). The launch head was aimed at a target retroreflector to form the distance meter.

With this design each launch head fibre can be read out for a separate FSI measurement of the same distance meter. For FFI measurements, separate read out fibres would provide complementary phase measurements, which would be combined to monitor nanometre changes in the OPD.

Here we recorded 17 FSI scans in six minutes, using two readout channels and the reference Michelson. For each scan, the signals were sampled on an ADC at 1MSample/s, for 5 seconds, with a laser tuning rate of 5 nm/s. To reduce processing time, in this initial study, a fifth of the samples recorded in each scan were used for the analysis; described below.

First, signals from the reference Michelson were fitted to determine the change in reference phase as a function of time. The (unwrapped) reference phase provided a mapping from laser frequency to each sample time. Distance meter samples were then paired up with the corresponding reference interferometer phase. These data pairs were used to produce a Lomb Periodogram[7, 8] in OPD, with the OPD scale converted to length using the known reference OPD (4.7 m), see (Figure 3).

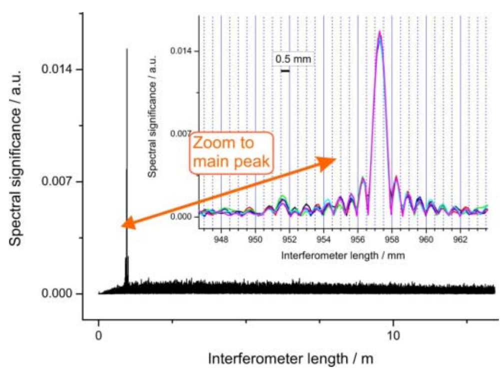


Figure 3: A Lomb periodogram, indicating the significance of OPDs in the distance meter interference signal. The main peaks in the inset are from subsequent scans.

A spectral peak[3] for the distance between launch head and reflector, was fitted to obtain the centroid for each scan. The fitted lengths for the main peaks in the Lomb periodograms are shown in Figure 4. The offset between the lengths in the two channels, has a mean value of $20.6\ \mu$m. This is a geometric effect of the $750\ \mu$m separation, between the fibres of the measured channels, at the launch head.

The variation from scan to scan is dominated by the common mode effect of OPD drift. This will be reduced in an

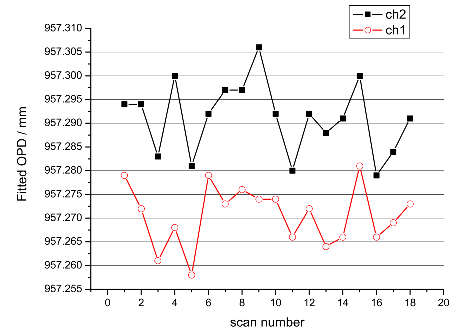


Figure 4: Repeated OPD measurements from two channels of a prototype distance meter.

evacuated system, while the remaining effects can be corrected using a fixed frequency laser (see above).

The RMS of the residual difference mode signal[4] is the effective resolution of the distance meter for absolute measurements. In this initial test, this resolution was $3.9\ \mu$m, approaching the intended micron resolution. The resolution is expected to improve after more detailed analysis using more samples from each scan.

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[3] Every pair of reflecting surface produces a term in the interference signal of equation 1. The distance meter is designed to maximise the reflection from the launch head and retroreflector and minimise all spurious reflections from elsewhere.

[4] Divided by $\sqrt{2}$ for the two channels.