THE LICAS RAPID TUNNEL REFERENCE SURVEYOR – THE STATUS AFTER COMMISSIONING *

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Abstract

The Rapid Tunnel Reference Surveyor (RTRS) is a prototype robotic system for surveying the reference network in the International Linear Collider (ILC). After four years of development the RTRS has been installed in a tunnel at DESY. Nearly all subsystem commissioning is complete and initial measurement runs were performed. We review the design criteria of the RTRS, discuss the currently achieved performance [1] [2] and present plans for calibration. We discuss new developments in our analysis software [3] and present an improved understanding of the systematic errors and their dependence on the accuracy of the calibration processes. Last we suggest improvements and simplifications for the next generation RTRS.

INTRODUCTION

Particle physicists from around the globe are convinced that an international linear collider with a luminosity of $2 \times 10^{34} cm^{-2} s^{-1}$ will bring us new insights into the most fundamental questions in physics. This luminosity is 10,000 times that obtained with the SLC, the worlds highest luminosity linear collider to date. The necessary ultra low emittance can only be maintained throughout the 100km of beam line if all elements are accurately aligned. In the main linacs the required reference network survey accuracy stands at 200 (500) microns in the vertical (horizontal) direction over distances of 600m. The LiCAS-RTRS aims to provide a reference network survey to this accuracy.

The very long length of ILC beam lines mandates a rapid survey system to keep the costs of machine down-time and survey manpower at an acceptable level. The current RTRS prototype will be used to develop such rapid and robotic survey methods. It is to be understood as a research and development platform for measurement and survey techniques in long straight tunnels. A user system for the actual ILC survey is expected to be significantly smaller and less complex than the current prototype. We will describe some of the differences in the last section of this paper.

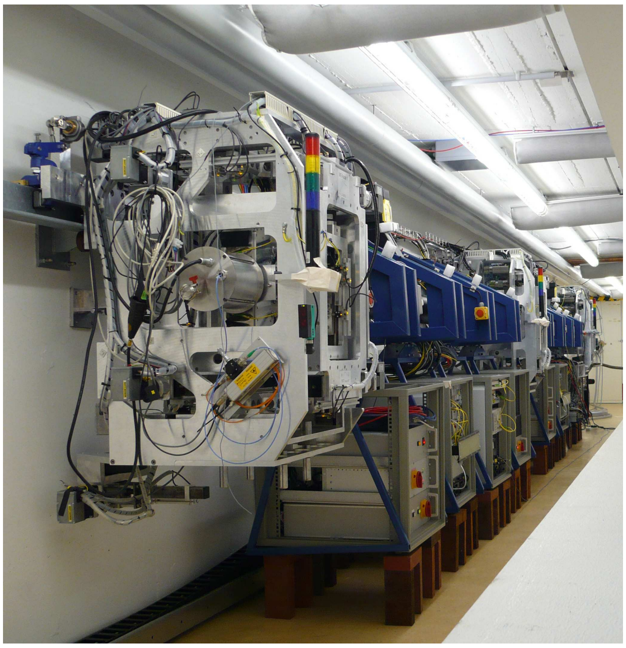

Figure 1: The prototype RTRS after commissioning in the DESY test tunnel (Jan. 2008). The electronics crates in the service cars have temporarily been supported by metal bricks during an analysis of vibration sources.

While the current project focuses on the technically most challenging problem of the long distance reference survey, it is conceptually straight forward to include any automatic survey instrument on board the RTRS, reference it against the RTRS internal measurement systems and use it for a fully automatic survey collider components.

Figure 1 shows a photograph of the prototype RTRS in the test tunnel at DESY.

DESIGN CONSIDERATIONS

Below we list important design objectives for a highly accurate survey instrument for large scale accelerators and the way in which we address them. Details of the RTRS measurement system have been described previously in [7] [8].

- *The individual measurement techniques must have high intrinsic resolution.* Absolute distance measurements through Frequency Scanning Interferom-

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* 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.

etry (FSI) and straightness measurements by Laser Straightness Monitors (LSM) are capable of sub micron accuracy over long distances. Gravity referenced tilt sensors (GRTS) can reach micro radian resolution.

- *The overall measurement concept must be highly redundant.* All measurements of the RTRS, except for the roll around the LSM beam axis (R_z) are doubly redundant. This is the reason for the four cameras of the LSM and the six internal and external FSI interferometers.
- *The system should allow for cross checks between different measurement techniques.* The LSM and internal FSI system both measure transverse rotations (R_x, R_y) and a tilt sensor also measures R_x
- *Calibration should be possible in the field and the stability of calibration should be verifiable during operation.* Later we show results from simulations of a field calibration system and point to our scheme for auto-calibration that does not require external witness measurements.
- *Calibration constants must remain stable over long periods.* The measurement units were designed to have no moving parts and are machined from a single, stress relieved cast of Invar. The reference interferometers are also made from Invar and have a mechanism for thermal expansion compensation.
- *Ambient conditions upon which calibration constants may weakly depend must be recorded and compensation of these dependencies should be possible.* The sensing unit and reference interferometers are equipped with accurately calibrated and strategically placed temperature sensors which can be used to correct for thermal expansion. The air temperature in the region of the external FSI measurements and close to all heat sources is monitored. The temperature DAQ system monitors its own temperature to correct for its own temperature drift.
- *The system should control systematic errors.* The internal optical systems operate in vacuum, avoiding refraction. The external FSI systems operate over as short a distance in air as possible. The measurement units can be mounted in two orientations that differ only by a 180 degree rotation around the x-axis, thus revealing systematic errors in wall marker height measurements. The reflection system for the LSM uses a retro-reflector and a flat mirror allowing the reflected LSM beam to be adjusted accurately anti-collinear to the incoming beam [6] The relationship between calibration and systematic errors has been studied carefully .

PROJECT STATUS

In this section we describe the construction and assembly of the measurement units, the currently achieved functionality, as well as the commissioning of the RTRS.

Measurement Unit Construction and Assembly

Each measurement unit body was machined from a single Invar-36 cast which has been stress relieved after roughing. They were precisely machined on a Bridgeport Vertical Machining Centre 1000E 22. As built measurements of critical features were done using a Wenzel LH 108 CMM. All parts of the units were ultrasonically cleaned and the units were assembled, adjusted and vacuum tested in a clean room at Oxford. Figure 2 shows photographs of the open, assembled unit from both sides.

LSM cameras were mounted onto Invar camera holders and optically surveyed using a Smart-Scope video metrology system as the CCD can not be touched. Camera-holder sub assemblies were then mounted into the units. Six internal FSI launch optics (reflectors) shown in inset a (d) in figure 2 were mounted onto an Invar holder, together with an LSM beam splitter. The holders were then mounted into the units and the pointing of each FSI launch optic was individually adjusted. PT100 temperature sensors were calibrated to 0.01K accuracy and mounted in strategic locations across the unit.

Commissioning and current functionality

In April 2007 the first systems to complete construction were the FSI reference interferometers. They were aligned and their thermal expansion compensation mechanism was adjusted in a long series of temperature ramps at Oxford until December. After shipping to DESY, a first pass of length calibration was completed in January 08. A final pass is planned for March after the thermal expansion curves have been verified.

In May 2007 commissioning of the RTRS started at DESY. Initially the vacuum, propulsion and DAQ systems were installed and tested. The measurement units followed in June. Installation of cables, fibres and auxiliary connections took one month. Commissioning of the 6-D stepper motor systems, that move the measurement units, took place over three months, as very complex limiting and synchronicity issues had to be resolved. Vacuum testing took one month.

First data was taken in November when the straightness of the rail was found to be incompatible with the clear aperture of the vacuum system. A larger aperture system is under construction and will be installed in March 2008.

The gain on all LSM cameras was manually adjusted to the beam conditions. The RTRS had all of its sensors aligned and operational for the first time in late January 2008.

The only remaining issues are the installation of some air temperature sensors, the mounting of one reference in-

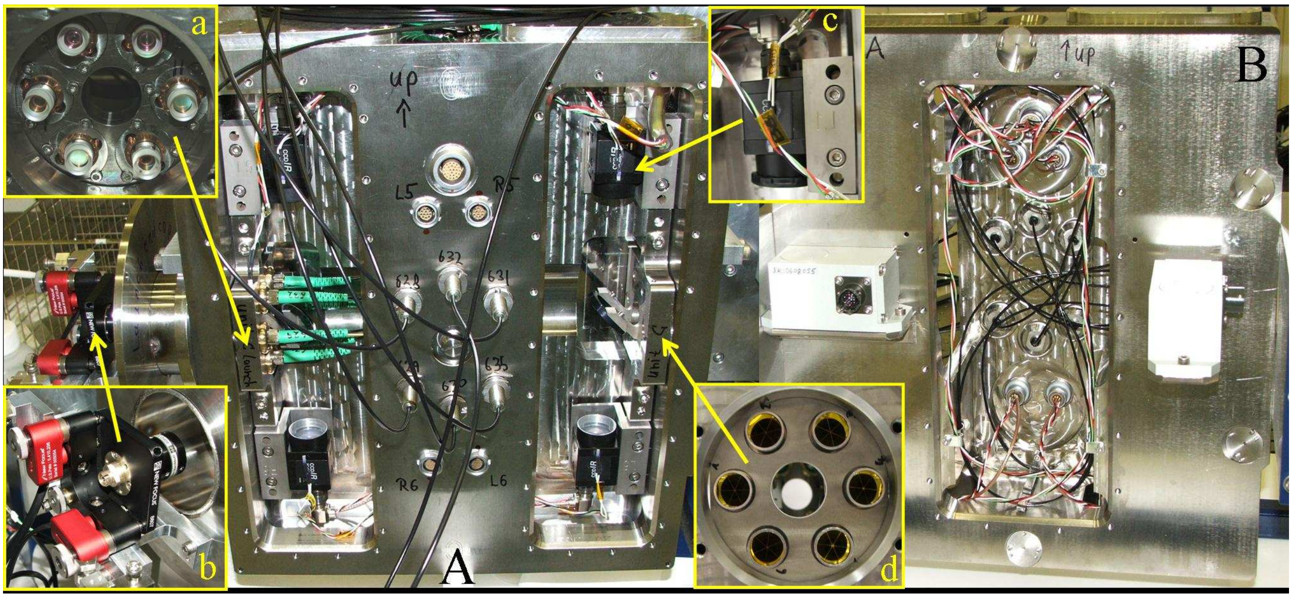

Figure 2: Photographs of measurement unit C. Part A) unit from tunnel side. Internal sensing systems, and vacuum feedthroughs for 6 FSI fibres, 4 LSM cameras and temperature sensors can be seen. Part B) unit from the wall side. Tilt sensors and 6 external FSI launch points (two covered by insets) are shown. Insets: a) internal FSI collimators; b) LSM launch optics on pico motor c) LSM camera with PT100 on Invar camera holder d) internal FSI retro reflectors

terferometer onto the RTRS and the installation of the upgraded vacuum system.

MEASUREMENT PERFORMANCE

A 90 hour long data taking run of the entire RTRS under stationary conditions was performed at beginning of February. The aim was to determine the stability and resolution of the sensing systems and to improve the long term stability of the DAQ system. So far only data from the LSM and FSI systems have been analysed and no cross-system correlations have been performed. We present here extracts from these analyses and point the reader to [2] and [1] for details about the FSI and LSM systems respectively. It has to be noted that during this run the air conditioning system in the tunnel had failed and the external air temperature rose by nearly 10 degrees.

LSM

In an earlier run the LSM had detected fast oscillations of the LSM beam, believed to be caused by vibration of the LSM launch optics. We have purchased a new LSM collimator for installation in late February. To eliminate the DAQ systems, computers and power supplies as the drivers of these vibrations the electronics crates were lifted off the service cars and temporarily supported on metal bricks as can be seen in figure 1.

Figure 3 shows histograms of the vertical (y) and horizontal (x) coordinates from the first camera in the beam on car-1 over a period of 40h during which only little systematic drift (from the temperature changes) occurred. There is a noticeably larger RMS in the horizontal direction which has not been observed under laboratory conditions. We believe this is a vibration problem which we will investigate further.

Over long time scales we observe rotational motion of the measurement unit in car-1 (the LSM launch co-moves with car-1). This is observed by both car-2 and car-3. Car-3 observes twice the beam motion of car-2. This is consistent with an angle drift of the launch optic.

The above results have been obtained using single Gaussian fits to the two, 1-D, row and column projections of the images. This is likely to result in systematic errors when a camera observes two beams simultaneously in significantly different locations. This is indeed the case on many cameras despite of the anti-reflection coating on the CCD face plates and is believed to come from the uncoated inner surface of the face plates or from the CCD surface itself. An image of two beams on CCD can be seen in figure 4. We have developed a new fitting software that performs two dimensional fits of multiple beams.

We have also developed two methods for in situ calibration of the LSM components. Only the geometrical offsets of the CCD cameras were considered as calibration parameters so far. The scale and orientation of the CCD pixel rows and columns were not yet calibrated. This will happen only once the LSM and the FSI system get calibrated together because the FSI reference interferometer brings a separately calibrated length scale into the combined calibration process and is thus expected to improve scale determination very significantly. In figure 5 we show the expected accuracy and resolution of the LSM calibration procedure using a laser tracker as a witness. We have also

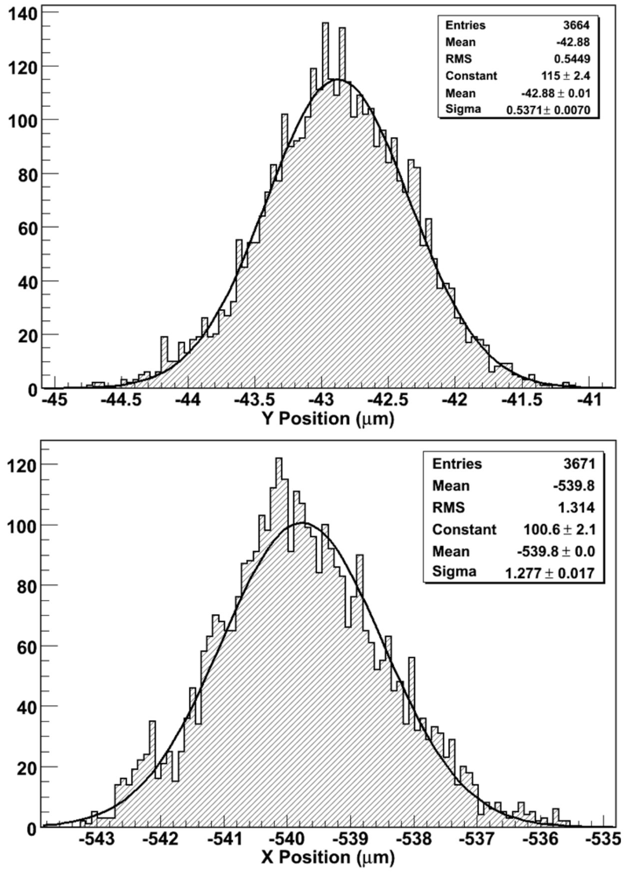

Figure 3: Histograms of the vertical (y) and horizontal (x) positions on camera zero on car-1 over 40 hours.

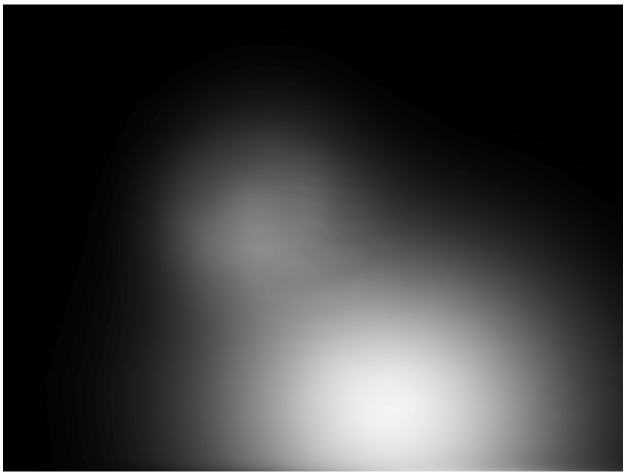

Figure 4: Two beams on an LSM camera. The dimmer beam is the reflection from the opposite camera.

developed calibration methods based entirely on internal consistency that can be used to check calibration during normal operation; see [1] for details. Similar efforts are ongoing for all sub-systems and for the overall calibration of an entire measurement unit.

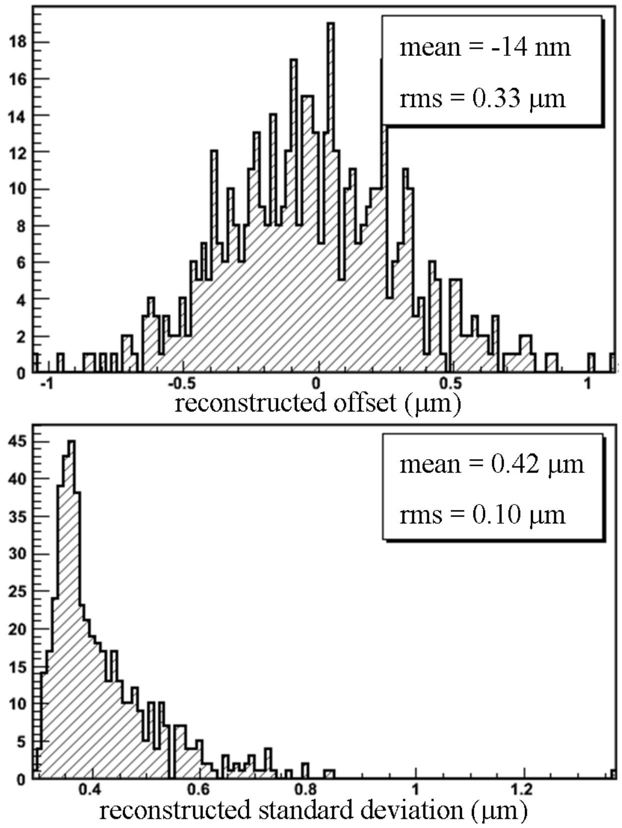

Figure 5: Histograms of the mean reconstructed vertical offsets (upper) and rms vertical offset from 500 independently calibrated LSM units (simulation). The rms of the upper plot indicates the expected accuracy, the mean of the lower plot indicates the precision of the calibration process.

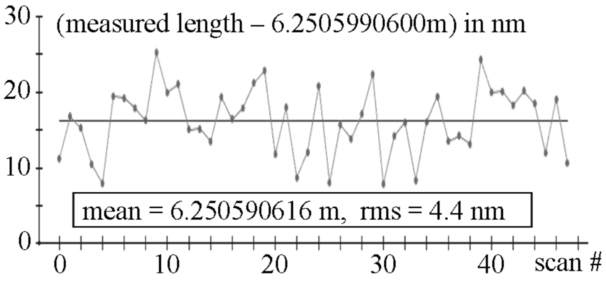

Figure 6: 15 minute time series of length measurements of the reference interferometers. The relative resolution on the optical path length is $7 \cdot 10^{-10}$

FSI

We show measurements of stability of the internal and reference FSI interferometers only. Figure 6 shows the time evolution of the optical path length difference (OPD) of reference interferometer-2 measured against interferometer-1. The relative resolution of these FSI measurements is $7 \cdot 10^{-10}$.

To determine the resolution of the internal FSI system we show In figure 7 the differences of distances measurements

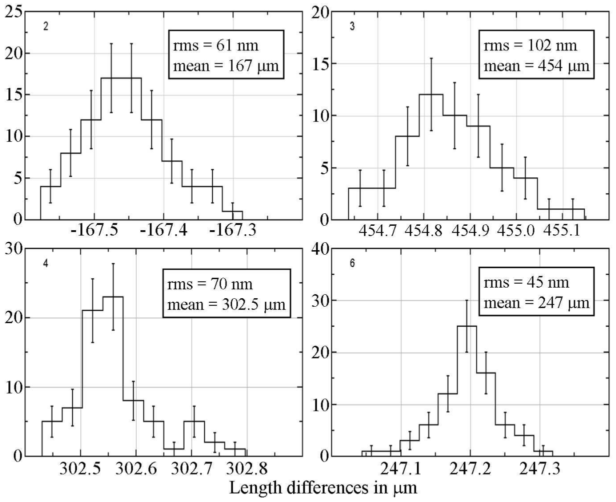

Figure 7: Histograms of the differences of the length measured by the internal FSI lines from car-3 to car-2 over a period of 30 hours

from car-3 to car-2 over 30 hours. The length differences are insensitive to translational drift between the two cars. The RMS varies from 45 to 102 nm which is more than 10 times better than anticipated.

ANALYSIS AND SIMULATION

We have studied the effects of calibration errors on the systematic measurement errors of the RTRS [3] using the Simulgeo [9] package. It has become clear that the systematic errors scale quadratically with the number of train stops and that a longer train with larger car-to-car separation is needed to improve the expected systematic errors. We have changed our baseline configuration for an ILC style RTRS from 6 cars with 5m car-to-car separation to 4 cars and 25m separation. Figure 8 shows the simulated systematic errors with the new configuration, assuming that all calibration constants can be determined with an accuracy of 1μm (μrad). When the calibration accuracy drops to 5μm (μrad) the vertical (horizontal) systematic errors grow to 280μm (320μm) indicating that the required calibration accuracy lies between 1 and 5 μm. The LSM simulations shown in figure 5 indicate that this level of accuracy can be achieved.

In parallel to our Simulgeo studies we are developing Gauss-Markov models and associated solvers for all our measurement and calibration processes. In these models the measurement process is described by: $F(X_e, X_i) = A \cdot (X - X_0) + F_0$, where F are the measurements (CCD spot positions, FSI lengths, tilt angles) that generally depend non-linearly on the internal and external unknowns X_i and X_e but have been linearly approximated through the design matrix $A = \partial F / \partial X$. We iteratively find a solution for X starting from X_0 in a way that minimises the quadratic differences between the measurements and the model. We would like to point out that, although Gauss-Markov models will provide the best linear estimator of X they do so only if the measurements contain no systematic errors. We therefore also maintain analysis methods using ray-tracers [1] which minimise the full non-linear problem. The Gauss-Markov models will help us to:

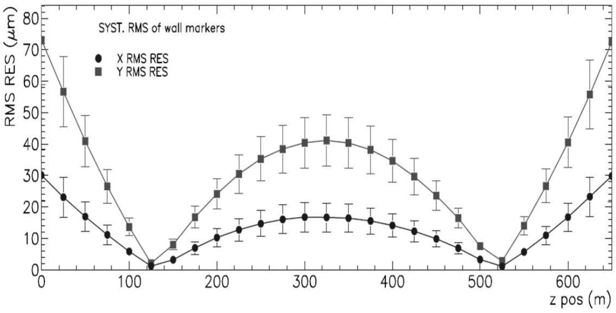

Figure 8: Systematic errors of the new baseline configuration RTRS over 600m tunnel length

- determine calibration constants. Certain conceptual limitations do not allow Simulgeo to simulate and analyse calibration experiments.
- determine wall marker co-ordinates from very long tunnel surveys. Due to its general purpose nature, Simulgeo uses large amounts of memory that limit the maximum size network that can be analysed.
- improve understanding of the measurement and calibration processes through study of the design matrices
- develop optimised and efficient solvers for our analysis problems
- consider non diagonal error matrices

In figure 9 we show the minimal design matrix A for the self-calibration process of a single LSM unit. The LSM is moved through at least six different positions and measures the beam on all CCD cameras. From these measurements the internal geometry of the LSM can be reconstructed. We will use many more positions for self-calibration to improve the precision of the process.

FUTURE PLANS

Drawing on the experiences gained with the current prototype we suggest a number of changes that should lead towards an optimised survey system for the ILC.

We propose an increased car-to-car spacing of 25 meters and to use 4 cars in total. This will decrease the systematic errors for long distance surveys. We will develop the necessary changes for the FSI and LSM components.

We will implement a system for dual laser FSI that makes the interferometers independent of drifts and vibrations during measurement. The DAQ for this is being developed now and the system should be tested on the RTRS

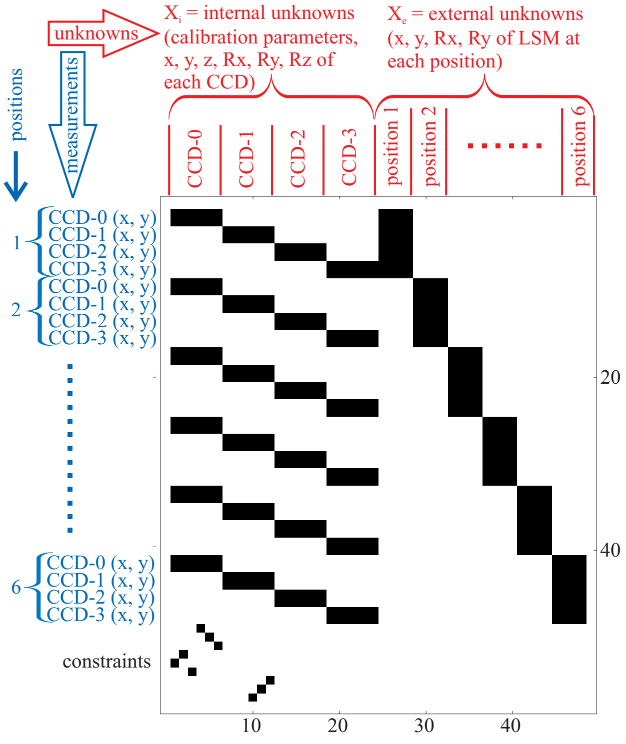

Figure 9: Design Matrix of a six position self calibration process for one LSM unit. Black entries indicate non-zero elements.

in summer 2008. We expect to significantly improve the resolution of the technique in this way.

We wish to replace the current parallel kinematics mover system with hexapod movers. These would be much stiffer, smaller and lighter and would reduce the currently observed LSM-beam vibrations. Haxapods also offer faster and larger moves than the current system.

We propose to use carbon fibre measurement units to further reduce the weight and vibration problems.

We will build improved FSI reference interferometers in the coming year. Their new features are listed here.

- use 4-fibre readout to measure instantaneous phase [4]
- introduce more beam-folding to shorten the interferometer for better handling and temperature homogeneity
- use internal liquid cooling and heating for faster and more homogeneous temperature changes during thermal calibration
- allow the interferometer to be opened along its full length for better access
- make the thermal compensation length adjustable from the outside while the interferometer is evacuated
- measure the CTE of all materials before construction This requires less dynamic range in the thermal compensation mechanism and avoids the problems associated with the often widely varying CTE of Invar.

We propose to fold the LSM cameras into a cylindrical envelope by changing the beam splitter angles. This should lead to a longer but shallower unit that can be rotated around its LSM beam axis by up to 180 degrees. Such a rotation would help to detect and correct systematic errors.

We hope to complete the measurement program with the current RTRS at DESY by August 2008 and then focus on the above improvements.

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