Towards a Suspension Platform Interferometer for the AEI 10 m Prototype Interferometer

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Abstract. Currently, the AEI 10 m Prototype is being set up at the Albert Einstein Institute in Hannover, Germany. The Suspension Platform Interferometer (SPI) will be an additional interferometer set up inside the vacuum envelope of the AEI 10 m Prototype. It will interferometrically link the three suspended in-vacuum tables. The inter-table distance will be 11.65 m. The SPI will measure and stabilise the relative motions between these tables for all degrees of freedom, except roll around the optical axis. In this way, all tables can be regarded as one large platform. The design goal is $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ differential distance stability between 10 mHz and 100 Hz.

1. Introduction

Currently, the AEI 10 m Prototype is being set up at the Albert Einstein Institute in Hannover, Germany. As with other prototypes in the gravitational wave community, the purpose of this prototype is to prove and develop new techniques for future generations of gravitational wave detectors. Furthermore, the AEI 10 m Prototype [1] will probe at (and later beyond) the standard quantum limit (SQL) of interferometry and will be a testbed for geodesy and LISA [2] related experiments.

The AEI 10 m Prototype is housed inside an L-shaped, ultra-high vacuum envelope of 11.65 m arm length (measured from tank centre to tank centre). Each of the three vacuum tanks will contain a seismically isolated optical table of dimension 1.75 m by 1.75 m. The table design is a modified version of the HAM-SAS table tested at LASTI [3]. This design provides excellent passive and independent seismic isolation at the resonant frequencies of the optics suspension system in both vertical and horizontal directions by use of geometric anti-spring filters [4] and inverted pendulums [5]. However, the optical tables will still move slightly relative to each other.

This residual differential motion of the tables is too large for the experiments planned for GRACE follow-on, to be conducted in the AEI 10 m Prototype facility. For GRACE follow-on tests, two of the tables will act as satellites. The goal of these tests is to show that the GRACE

follow-on interferometer can resolve changes in the satellite distance smaller than $2.5\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ between $10\,\mathrm{mHz}$ to $100\,\mathrm{mHz}$, increasing with $1/f$ when going from $10\,\mathrm{mHz}$ to $1\,\mathrm{mHz}$ [6]. To demonstrate this, the prototype tables will be moved by a well-defined amount. It is obvious that the relative motion between the tables has to be smaller than the GRACE follow-on goal. This sets the requirement on the residual relative motion between the in-vacuum optical tables to $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ between $10\,\mathrm{mHz}$ to $100\,\mathrm{mHz}$, increasing with $1/f$ when going from $10\,\mathrm{mHz}$ to $1\,\mathrm{mHz}$ and $10\,\mathrm{nrad}/\sqrt{\mathrm{Hz}}$ for angular deviation in the same frequency range. To realise this, all three in-vacuum tables will be linked interferometrically by a so-called Suspension Platform Interferometer (SPI). The SPI will measure the residual table motions and apply the appropriate feedback to stabilise the table distances via coil-magnet actuators.

The SPI can be beneficial for other projects in the AEI 10 m Prototype. For example, reducing residual motion of suspended mirrors in the quantum-measurement experiment [1] would help lowering the required actuator power and thus its electronic noise. Hence, we set the requirement of the SPI to be $100\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ relative displacement noise up to $100\,\mathrm{Hz}$. Due to this constraint, and the fact that we can benefit from in-house knowledge gained during LISA Pathfinder development [7], we decided to choose a heterodyne Mach-Zehnder interferometer configuration for the Suspension Platform Interferometer.

The idea of stabilising relative displacements is not new within the gravitational wave community. It was first proposed by Ronald Drever in 1987 [8]. He suggested to set up an ancillary interferometer above the measurement interferometer (MIFO). This so-called suspension point interferometer is locked to the injected laser. It will reduce the residual motions of the mirrors and thus, ease the lock acquisition of the MIFO. This idea was experimentally tested by Yoichi Aso, who demonstrated $40\,\mathrm{dB}$ noise reduction of a Fabry-Perot interferometer below $1\,\mathrm{Hz}$, down to $0.1\,\mathrm{Hz}$ [9]. The experiment coming closest to the AEI 10 m Prototype SPI is the metrology testbed depicted in [10]. In this experiment the relative longitudinal and yaw motions between two hexapods separated by $1\,\mathrm{m}$ were measured by use of three homodyne Michelson interferometers. The longitudinal displacement was stabilised down to $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ at $1\,\mathrm{mHz}$.

2. Optical layout of the Suspension Platform Interferometer

The optical layout of the SPI (see Fig. 1) consists of two parts: the modulation bench and the measurement bench. The modulation bench containing the laser is located outside the vacuum system. Since the mismatch of the arm lengths in each Mach-Zehnder MIFO is about $22\,\mathrm{m}$ the free running laser frequency needs to be stabilised. In order not to let frequency noise limit the SPI sensitivity, we are aiming to reduce the position noise due to frequency fluctuations to $10\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at $10\,\mathrm{mHz}$, resulting in a frequency stability better than $128\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at $10\,\mathrm{mHz}$. We chose an iodine-stabilised Nd:YAG laser with a wavelength of $1064\,\mathrm{nm}$, which is commercially available [11]. On the modulation bench the laser light is split into two paths and modulated at the heterodyne frequency by two AOMs. The heterodyne frequency has been chosen to be around $20\,\mathrm{kHz}$ in order to provide a control bandwidth up to $100\,\mathrm{Hz}$. The light is then coupled into two $20\,\mathrm{m}$ long polarisation-maintaining single-mode optical fibres. These are fed through into the vacuum system towards the measurement bench. In order to not be limited by thermal expansion, all optics on the measurement bench will be bonded [12] onto a baseplate made of the ultra-low expansion material Clearceram®-Z HS, with a coefficient of thermal expansion of $(0.0 \pm 0.2) \cdot 10^{-7}\,\mathrm{K}^{-1}$ [13].

The measurement bench consists of three interferometers: the reference interferometer (RIFO), and two MIFOs. The RIFO is used to cancel all noise individually picked up along each path starting from the very first beam splitter (labelled BS in Fig. 1) on the modulation bench, ending at the recombination beam splitter (labelled RBS in Fig. 1) of the RIFO. Furthermore, the RIFO defines the point to which the phase information gained at the MIFOs is compared.
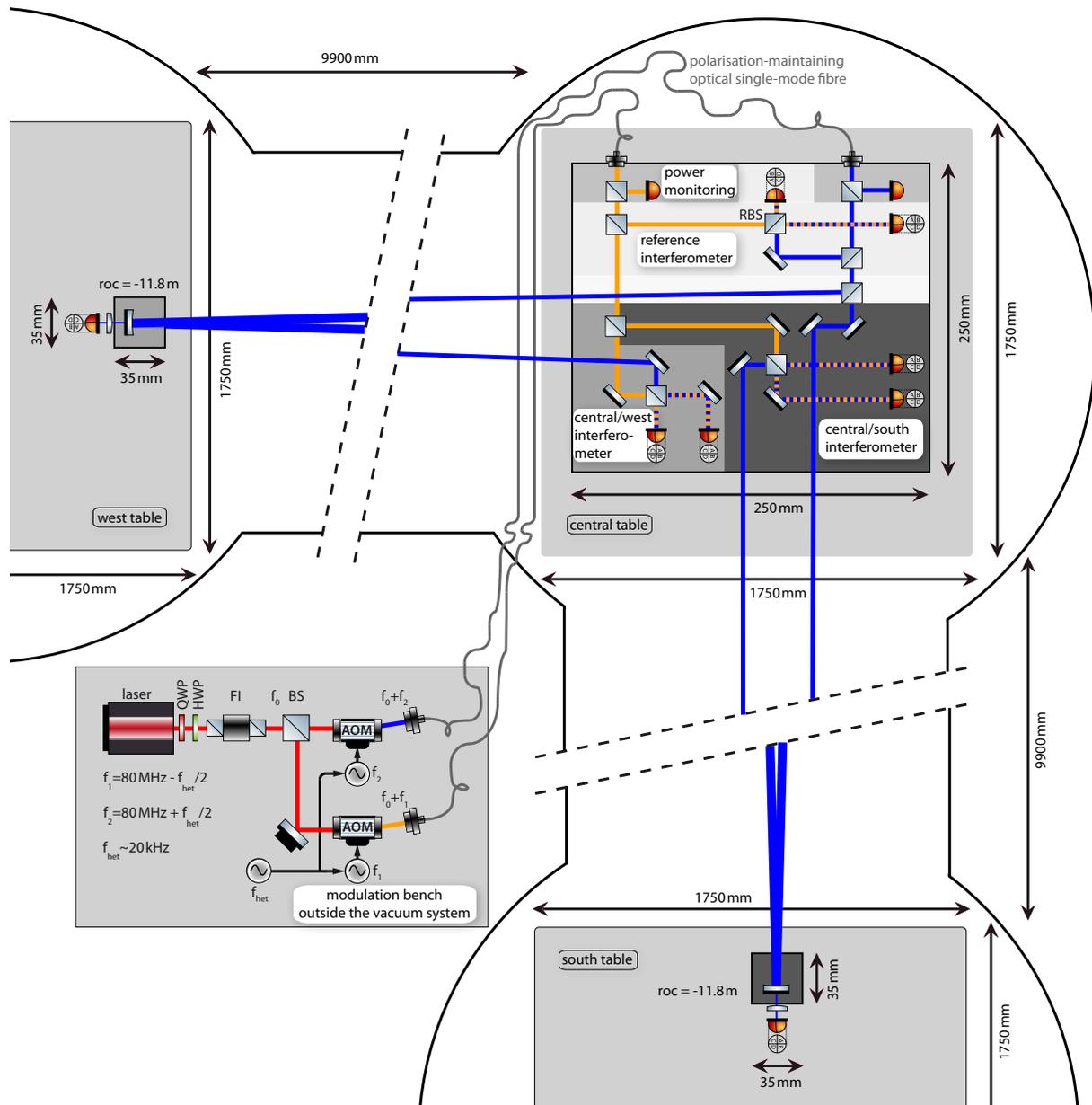
Figure 1. Schematic setup of the SPI. The reference beam is drawn in orange, the measurement beam in blue. For illustration purposes, position and size of the in-vacuum baseplates do not correspond to their real positions. Due to the small footprint of the baseplate (and overall height of 50 mm) it is still possible to place e.g. the suspended beam splitter of the SQL interferometer in the centre of the central table.

AOM: acousto-optical modulator; BS, RBS: beam splitter, f_0: laser frequency; f_1, f_2: modulation frequencies, f_{het}: heterodyne frequency, FI: Faraday isolator, HWP: half-wave plate, QWP: quarter-wave plate, roc: radius of curvature

One of the two MIFOs measures the motion between the west and central table, the other MIFO detects the relative motion between the south and central table. It can be seen that the RIFO is located only on the central table, whereas each MIFO has one mirror mounted on the south or

west table, respectively. The position change of these end mirrors is then individually measured. The light is detected by quadrant photodiodes (QPD). Therefore, we will be able to monitor all three degrees of freedom of translation, as well as pitch and yaw. However, the sensitivity is not identical for all degrees of freedom.

In order to be able to separate linearly dependent signals, e.g. a vertical motion of a table that can be reproduced by a combination of pitch rotation and longitudinal translation; the curved end mirrors on the south and west tables will be partially transmissive. The light coming from the central table can be directly monitored on a QPD placed behind these end mirrors. Thus, we will have an additional — independent — source of information for signal separation.

3. Signal processing

The photo-currents for each QPD quadrant will be fed into a phasemeter outside the vacuum, which was originally developed for LISA Pathfinder [14]. The photo-currents are converted into voltages, the signals are then digitised, and a single-bin discrete Fourier transform is performed at the heterodyne frequency. The output values of the phasemeter for each channel are DC, real and imaginary parts of the complex amplitude of the photodiode signal at the heterodyne frequency. The argument of this complex amplitude is the phase of the signal. The phase values refer to the $\sim 20\,\mathrm{kHz}$ signal produced by the optical beat with respect to the phase of an electrical reference signal. The DC value is the light power of the two interfering beams, averaged over all QPD quadrants. The proper combination of this phase and DC information leads to four different types of values for each QPD: contrast, longitudinal phase information, differential wave-front sensing (DWS) and DC alignment signals. The contrast is a measure of how well measurement and reference laser beams interfere at the recombination beam splitter. The longitudinal phase indicates how far the tables have moved towards or away from each other. The relative angle between the wavefronts of the two interfering beams is given by the DWS signals. For the horizontal plane they are obtained by comparing the phase values of the left and right QPD sides, for the vertical plane by evaluating the phases for the upper and lower sides of the QPD. The DC alignment signals are derived in a way similar to the DWS signals, except that the evaluated signals are DC signals instead of phases. The DC alignment signals quantify how well the laser beam centre corresponds with the centre of the QPD. DC alignment signals are less sensitive than DWS signals. However, they are useful over a larger dynamic range than the DWS signals. DC alignment and DWS signals, as well as longitudinal phase information, will be used to derive error signals for the feedback control of the optical benches via coil actuators.

The phasemeter output port is an enhanced parallel port (EPP) which is currently connected to a personal computer. At a later stage, the phasemeter will be connected to a realtime Control and Data System (CDS) developed for the Advanced LIGO project [15] and adopted for the AEI 10 m control. For several reasons, it is not possible to connect the phasemeter directly to the CDS. First of all, the CDS has no parallel input port. Secondly, the phasemeter will be located as close as possible to the vacuum system, whereas the CDS is (due to infrastructural reasons) 10 m to 20 m away. However, the EPP cable length is limited to approximately 4 m. Therefore, a phasemeter interface based on a microcontroller board with an EPP input port and an ethernet output port is currently under development. Furthermore, an ethernet input port to the CDS will be implemented.

4. Status, conclusion and outlook

The SPI modulation bench has already been assembled. The measurement bench has been set up as a table-top test setup on a metal breadboard. In this particular test setup the arm length mismatch of the MIFO was about 3 m. Motions of the south and west tables were mimicked by a piezo motor-driven mirror-mount placed on two motor-driven linear stages. In this way pitch,

yaw, and longitudinal, as well as transversal motions of the end tables could be simulated. Data evaluation showed that these motions are clearly distinguishable from each other.

One of the next steps towards an SPI for the AEI 10 m Prototype will be to bond the components onto the measurement bench. The in-vacuum tables are expected to be installed in spring 2010. Following the commissioning of the first two tables, the SPI will be installed and start to stabilise their relative motion.

Acknowledgments

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