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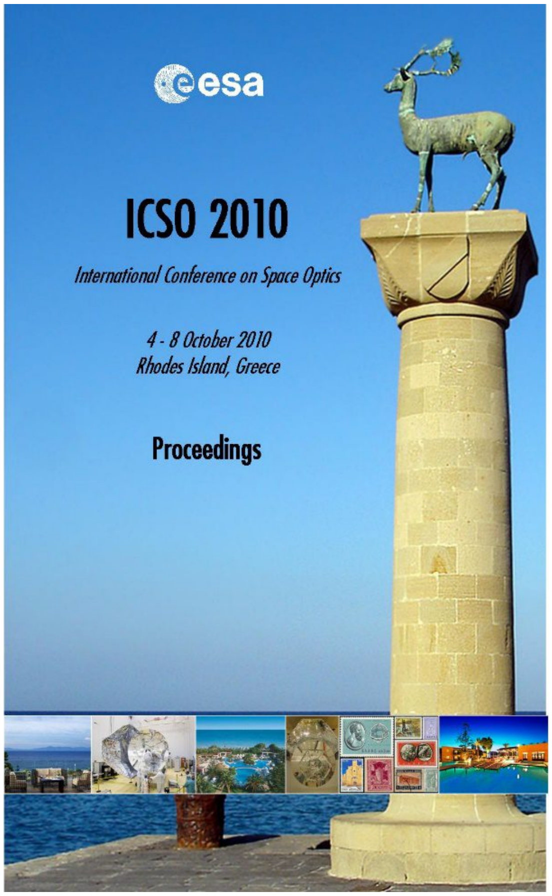

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DUAL ABSOLUTE AND RELATIVE HIGH PRECISION LASER METROLOGY

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ABSTRACT

Design, integration, test setup, test results, and lessons-learnt of a high precision laser metrology demonstrator for dual absolute and relative laser distance metrology are presented. The different working principles are described and their main subsystems and performance drivers are presented. All subsystems have strong commonalities with flight models as of LTP on LISA Pathfinder and laser communication missions, and different pathways to flight models for varying applications and missions are presented. The setup has initially been realized within the ESA project "High Precision Optical Metrology (HPOM)", originally initiated for DARWIN formation flying optical metrology, though now serves as demonstrator for a variety of future applications. These are sketched and brought into context (PROBA-3, IXO onboard metrology, laser gravimetry earth observation missions, fundamental science missions like LISA and Pioneer anomaly).

I. INTRODUCTION

In recent years applications of inter-spacecraft laser interferometers have been studied for a variety of applications like

- Absolute distance metrology for acquisition and control of precise formation flying in the tens of micron accuracy range as for DARWIN and TPF
- Relative distance metrology in tens of nanometers as for next-generation gravity missions like NGG and GRACE-II
- Relative distance metrology in the picometer range for LISA Pathfinder and LISA
- and finally laser communication, though not a direct metrology

Starting from the requirements for simultaneous absolute and relative laser distance metrology, initiated for the DARWIN mission, a versatile dual absolute and relative laser metrology system based on super-heterodyning [1] (see next section) has been developed. Its subsystems can be tailored to a variety of further applications.

For the laser metrology demonstrator, the initial specs have been set as:

- Operational measurement distance range: 0-250 m, resulting in the use of an afocal telescope and a passive retro-reflector corner cube
- Unambiguous distance range of +- 25 mm, asking in case of super-heterodyning [1] for a synthetic wavelength of 100mm, corresponding to 3 GHz offset
- Absolute accuracy within +- 32 µm 1-σ at 10 Hz of the true value, including statistical noise, nonlinearities on OPD scan, and static biases
- For the specific case of superheterodyning interferometry, this corresponds to a relative accuracy of better than 0.32 nm, not taking into account frequency drifts
- Longitudinal drift velocities up to 50 mm/sec are to be respected by design as worst case, asking for better than 1 ns synchronization time error for the selected dual phasemeter approach and appropriate electrical filter bandpasses to deal with Doppler shifts of the laser carrier

A side goal of this activity has been to assess purely fiber-based beamcombiners and polarisers, and to understand their specific pros and cons for high-precision laser metrology.

II. Design and MAIT

The demonstrator has been split into two different model classes. Where space heritage of units is given, these have been realized on breadboard level to reduce development costs and to add the possibility of easy comparison of design variants by substituting off-the-shelf components. New application specific subsystems are being built on engineering model EM level to give flight model development a good head-start.

Superheterodyning

The original design driver for selecting superheterodyning [1] has been that for white-light stellar interferometers on separated spacecraft (DARWIN, TPF) the absolute distance as well the relative velocity have to be both controlled.

Both metrologies can simultaneously be measured by well-known superheterodyning interferometry [1] where two relative heterodyne laser metrology subsystems with laser frequencies at fixed offset are simultaneously read out in two separate phasemeters. This principle has been selected and breadboarded within the Astrium HPOM 1&2 studies for ESA, and has been a candidate demonstrator instrument for PROBA-3.

The principal setup is depicted in figure 1 and consists of:

- One Nd:YAG laser at λ1=1064 nm (or 3 10^5 GHz), stabilized to molecular lines of an Iodine cell [1]
- A second Nd:YAG laser operating at λ2 with a frequency offset of 3 GHz, locked through a PLL

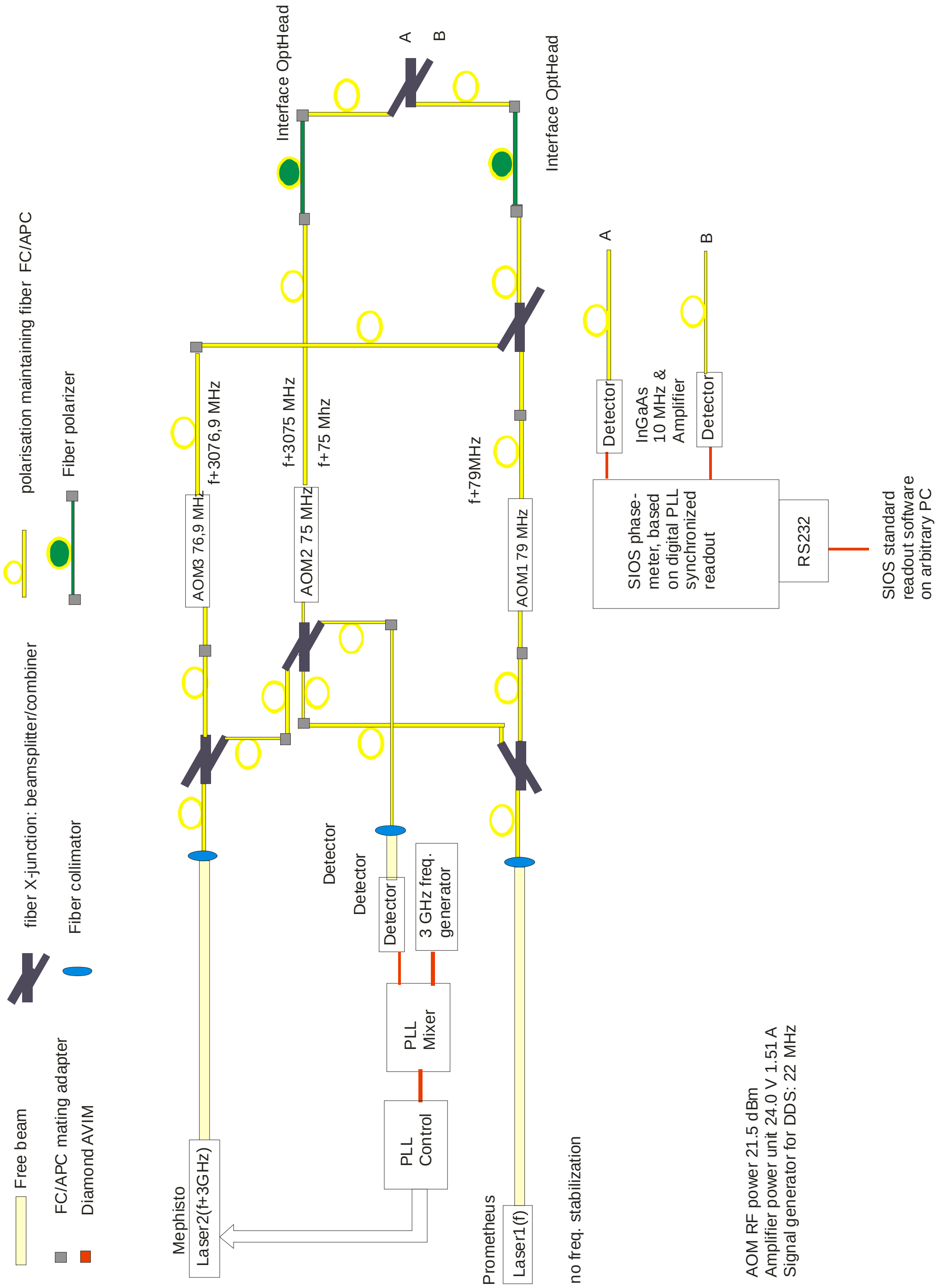

Fig. 1.: Design schematic of laser locking subsystem, super-heterodyning subsystem, and initial dummy test setup

While the first laser receives a heterodyning of net 4 MHz, the second laser sees a heterodyning of net 1.9 Mhz, allowing them to be filtered into separate phasemeter channels that measure phase ϕ_1 and ϕ_2 , respectively.

$$\phi_1 = 2\pi \frac{2D}{\lambda_1}, \qquad \phi_2 = 2\pi \frac{2D}{\lambda_2},$$

where D is the inter-spacecraft separation.

The difference phase $\phi_1 - \phi_2$ can be written as

$$\phi_1 - \phi_2 = 2\pi \frac{2D}{\Lambda}, \qquad \frac{1}{\Lambda} = \frac{1}{\lambda_1} - \frac{1}{\lambda_2} = \frac{1}{c_0}(f_1 - f_2) = \frac{1}{10^5 \lambda_1}$$

and corresponds to a synthetic wavelength Λ which only depends on the frequency offset between the two lasers and the performance of the frequency-locking PLL, but not on individual absolute laser stability. As the derivative of D to individual phase measurements scales with the synthetic wavelength, but not with the individual wavelengths,

$$\frac{\partial D}{\partial \phi_1} = \frac{\partial D}{\partial \phi_2} = \frac{\Lambda}{4\pi}$$

very low noise of the individual phasemeter channels is essential as well as precise timing in case of non-zero-average relative velocity. 32 micron absolute accuracy spec therefore correspond to less than 32 µm/10^5 = 0.32 nm accuracy for the phasemeter noise.

Breadboard level

Consequently three subsystems have been breadboarded:

- Laser subsystem
- Super-Heterodyning subsystem
- Phasemeter

The design schematic is provided in figure 1, whereas figure 2 shows the actual hardware.

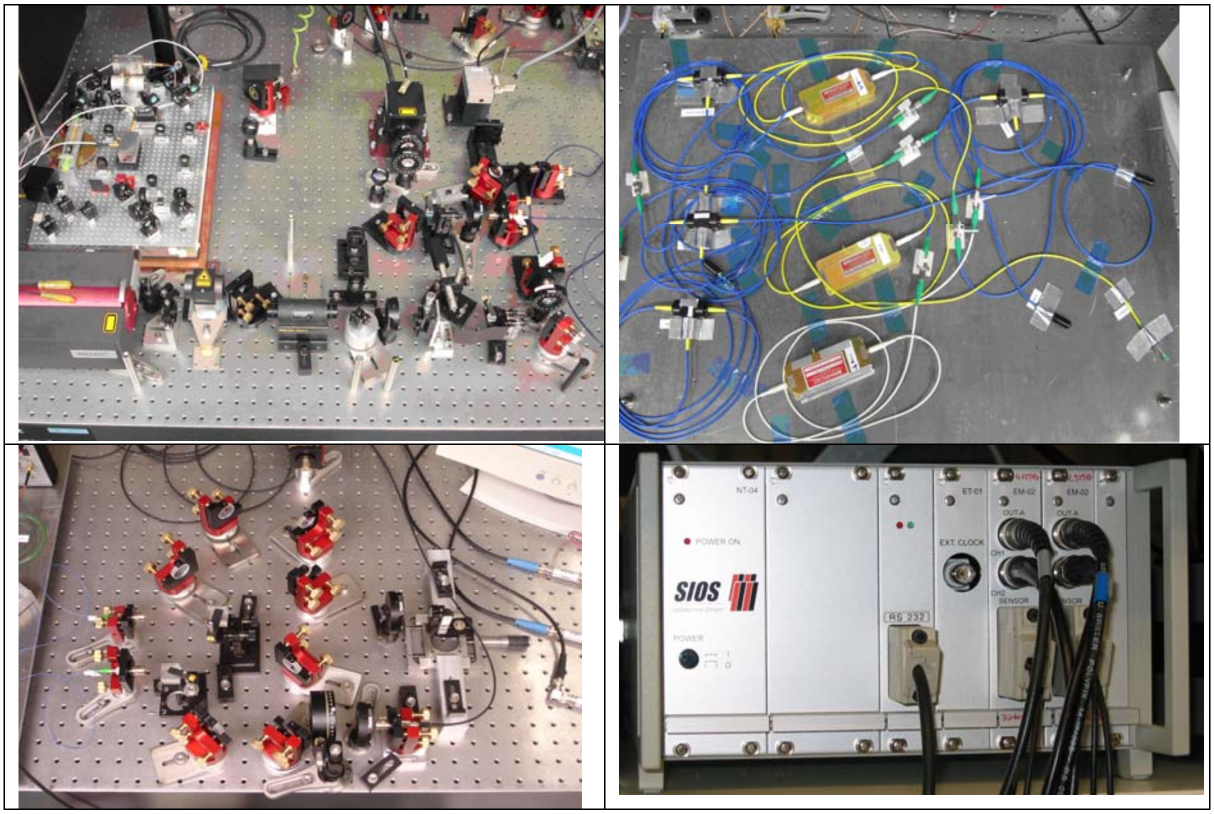

Fig. 2.: Hardware setup from top left in clock direction:
Laser subsystem and Iodine stabilization [2], Super-heterodyning subsystem, phasemeter, dummy optical head subsystem. Beam combination and polarization control have been breadboarded in three different approaches as discrete optics, fiber-pigtailed discrete components, and purely fiber-based optics

This setup will eventually be tested with an

- EM-level optical head consisting of a SiC telescope and an silica optical beam combiner bench ,
- and an Iodine stabilization breadboard [2]

in a thermal vacuum tank.

EM Engineering Model level

The optical head will be connected to the super-heterodyning subsystem and phase-meter detectors via polarisation-maintaining optical fibres with LTP flight qualification. The head holds the beam combiner bench and the telescope, which collimates the laser beam to be retro-reflected by the target spacecraft. Part of the return beam is steered towards a position sensor device for sensing the target transverse displacement. The separation of emitted and return beams minimises the backscattering towards the laser sources. The optical head has a space envelope of 245 x 180 x 140 mm and a mass less than 2 kg including baffles and cover

To withstand radiations, the optical design includes mainly silica optical parts. The structural parts are all in silicon carbide ceramic, which, in addition to its properties of stiffness, lightness and thermal conductivity, has a thermal expansion which matches the silica one. The afocal telescope has a con-focal mirror design with intermediate image plane, such that a field stop could be implemented to reject the sunlight. The magnified emitted beam has a diameter at 1/e² intensity of 20 mm. The telescope aperture is oversized to allow for lateral shifts of the return beam.

Fig. 3.: Optical head consisting of telescope on top and beam-combiner bench below central base plate. An intermediate field stop at the focus of the Dall-Kirkham is implemented allowing operation close to sun direction. The receive aperture is tolerant to lateral beam shifts.

The telescope is of Dall-Kirkham type with primary mirror off-axis closely hyperbolical (f/D~0.7) and a spherical secondary mirror.

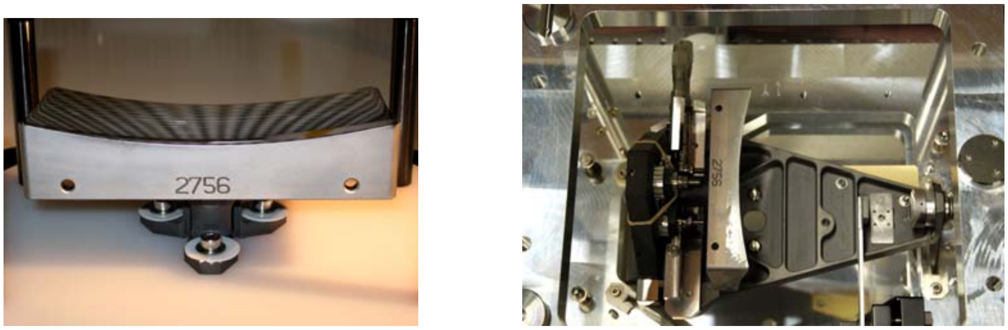

Fig. 4.: Aspherical off-axis primary mirror f/D = 0.7 (left) and telescope in alignment tool frame (right)

The beam-combiner bench is based on 50-50% silica beam-splitter plates with the same thickness to balance the interfering paths. The beams have a diameter at 1/e² irradiance of 2.5 mm. The space envelope of the mini-interferometer including collimating and focusing lenses is 100 x 100 x 25 mm.

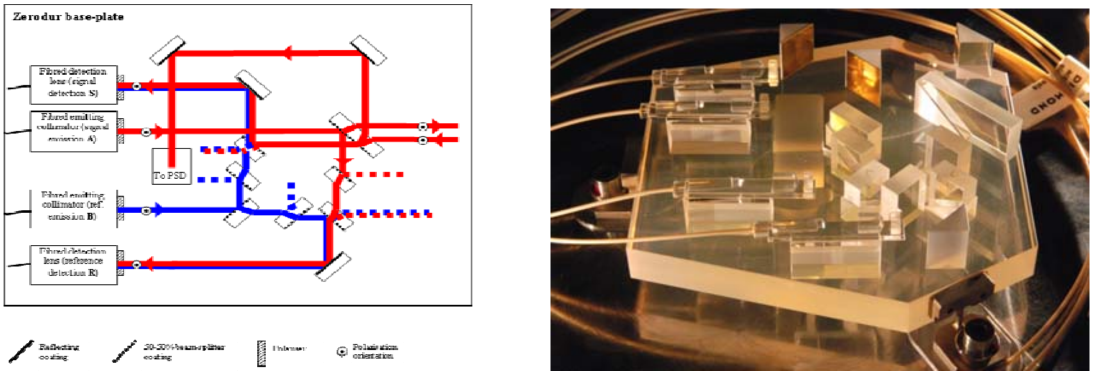

Fig. 5.: Balanced beam-combiner scheme (left) and as built ultra-stable all-silica all-glued (right) from Kylia

III. TEST RESULTS

Stand-alone tests of breadboard

Building up the system with discrete optics as well as with pigtailed free-beam combiners, the setup has turned out to be performing just like “plug and play”. A noise level of 12 µm 1-σ noise was measured “indefinitely”, corresponding to below 0.1 nm noise per phasemeter channel, insensitive to stimulated temperature fluctuations of several K. This is recorded in figure 6, showing very good long-time stability.

Surprisingly using fused fiber-splitters a significant temperature correlation of about 70 µm /K was observed in the heterodyning subsystem, independent from specific setup of optical head and polarisation cleaning. This could not be explained by first-order theory but must be a higher order effect.

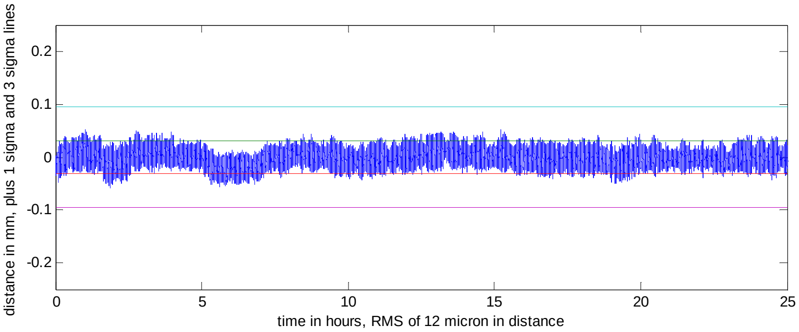

Fig. 6: Long term static distance measurement, compared to the required 1-σ (32 micron) and 3-σ lines. The distance measurement has an RMS/1-σ of 12 micron and is well in spec, and shows no correlation with room temperature fluctuations.

TV tests on EM level

Dynamic velocity and TV tests together with the EM-level optical head are soon to be started at TNO Delft, but will have to be reported in a subsequent paper. These tests will demonstrate

- Timing synchronization of the two individual phasemeter channels, to be tested with translation stages using a dynamic velocity profile. This effect is minimized by design of the phasemeter (synchronous sample and hold ADCs, internal synchronous PLL-lock)
- Longtime stability in combination with the SiC telescope, the fused silica optical beam-combiner bench, and a Zerodur-mounted reference corner cube.
- Overall temperatur sensitivity in nm/Kelvin

IV. PROGRAMMATIC PATHWAYS TO FLIGHT HARDWARE

Though the optoelectronic subsystems have been demonstrated only on breadboard level, there are clear pathways to flight representative systems:

- Flight Lasers and corresponding electronics based on NPRO Nd:YAG crystals and suitable pump-diodes have been space qualified within the LTP project and for laser communication terminals. The same applies for the AOM modulators in the heterodyning subsystem.
- Phasemeter technology has been space-qualified for LTP

- Optical bench technology and telescope are being demonstrated on EM-level, with the special challenge of working close to sun direction

Frequency stabilization is required for interferometers with large uncommon arm distance differences, the measurement error is proportional to the frequency instability at the given round trip frequency.

$$\delta D = D\frac{\delta f}{f}$$

The Aladin seed laser flight model development [3] provides an implementation of a cavity stabilization technique, though for very high performance applications ($\delta f / f = 10^{-15}...10^{-14}$) further developments of either cavity-based stabilization schemes (limited by long-time temperature control) or the Iodine stabilisation scheme used here [2] have to be further space-qualified.

The demonstrated laser frequency locking technique can directly be used for optical transponders over distances typically > 10 km, where only sub-nanoWatt optical power is received with reasonably small telescope send and receive apertures (and moderate pointing requirements). Optical transponders can receive faint laser light and return a frequency-shifted and phase locked laser beam from a second slave laser. Such optical transponder approaches are being developed and demonstrated for LISA and future earth gravimetry missions like NGG (Next Generation Gravity of ESA) and GRACE-II (NASA/DLR).

V. CONCLUSIONS AND OUTLOOK

All subsystems for high precision laser metrology in space have been demonstrated and clear pathways are defined for actual flight qualification.
As quoted earlier, future applications are numerous, including among others

- laser gravimetry earth observation missions,
- fundamental science missions like LISA and Pioneer anomaly
- precision formation flying for e.g. aperture synthesis across distinct space-craft (DARWIN/TPF)
- possibly IXO onboard metrology,
- precision control of deployed elements or measurement references

The necessary technology portfolios are available.

VI. ACKNOWLEDGEMENTS

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The laser locking system and the Iodine stabilization have been developed together with Innolight GmbH of Hanover Germany, and the phasemeter has been developed by SIOS Messtechnik GmbH of Ilmenau/Germany.
The optical head has been designed by ASTRIUM SAS, with the silicon carbide ribbed parts being sintered by Boostec Industries (Bazet, France) and the mirrors being polished by Winlight (Pertuis, France). The beam-combiner bench was manufactured by Kylia company (Paris), covering the extremely accurate and stable gluing of small components.

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