Differential common path interferometry for picometre surface metrology

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Motivation

Future gravitational wave research missions would benefit from spherical gravitational reference sensors (GRS):

- Single GRS design
- Fully suspension-free operation possible
- Strongly reduced actuation-crosstalk acceleration noise due to fewer actuated degrees of freedom.
- Strongly reduced tilt-to-length coupling

Challenges:

- Surface deviations part of the measurement path, requires compensation of the surface map
- On-flight or a-priori surface map determination
- Understanding of tilt-to-length effects at pm scale required

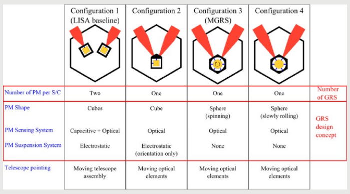

Fig 1: Different concepts for GRS configurations. [Gerardi.2014]

Fig 2: Measurement setup in the vacuum chamber.

Experimental test bed

- Symmetrical heterodyne interferometer in differential configuration
- 3 interferometers based on Nd:YAG lasers with AOM for frequency shift
- 2 beams sample in Differential configuration (x1/x2) with an azimuthal beam separation of 56 mrad
- Fixed-reference interferometer for recording lateral position (x) of sphere for compensating sphere center movements
- Full coverage of sphere using second mechanism
- Setup in vacuum chamber on air-cushion dampers

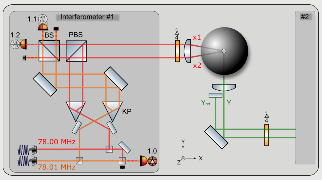

Fig 3: Schematic of the optical setup. Beams (X1-X2) are in symmetrical differential configuration.

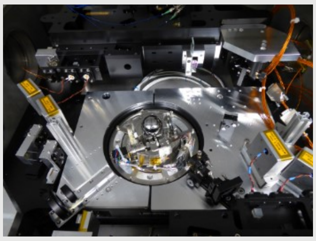

Fig 4: Test mass support with two mechanisms (elevation, azimuth) to rotate the sphere.

Simulation

- Position of the sphere is impacted by error movements of rotation stages and its eccentricity (total residual ± 3 µm)
- Measurement is geometrically influenced by the shape (~ 50nm / µm) of the and additionally by driving tilt-to-length effects in the optical system (~ 1nm / µm)
- Currently a 2D linear correction fit on the measurement based on the sphere position is proposed

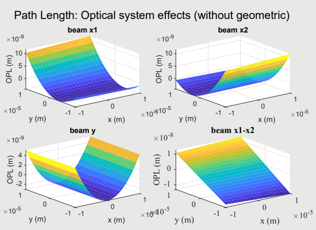

Fig 5: Simulated results of path length contribution by optical system (tilt-to-length)

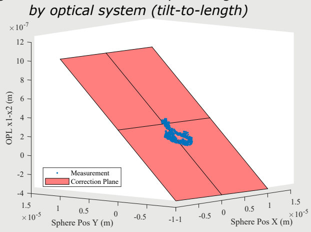

Fig 6: Correction of a circle profile measurement by a fitted 2D (X-Y) linear correction.

Measurement and Processing

- Interferometer zero stability < 10 pm for relevant measurement path (x1 - x2)
- Per-pixel repeatability of measurement < 2nm

- Measurement shows 200 great circles at different elevations, each with 8192 pixels along azimuth direction
- Circles were recorded at 5 deg/s and low-pass filtered (6 Hz) resulting in an effective spatial resolution of 290 µm (19 px)

Post Processing:

- Integration over the beam distance between the two differential arms (x1 - x2)

Methdos for circle profile reconstruction from differential measurements:

→ Fourier-space reconstruction approach or

$$x(\theta) = l_{X1} - l_{X2} = s(\theta) - s(\theta + \theta_b)$$

$$x(\theta) \xrightarrow{\mathcal{F}} X = S + S \cdot e^{-j\omega\theta_b}$$

$$S = \frac{X}{1+\epsilon - e^{-j\omega\theta_b}} \xrightarrow{\mathcal{F}^{-1}} s(\theta)$$

→ Discrete reconstruction approach

- Combination of several circle profiles into a sphere map by a elevation mechanism
- Data shows repetition along elevation after full rotation and mirror of sphere's second dome

- Stitching of several circles along elevation axis intersection and mapping into spherical coordinates.

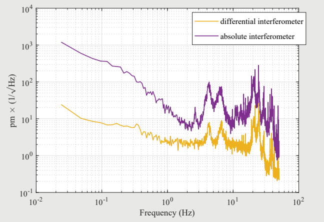

Fig 7: Instrument noise: Amplitude spectral density of path-length measurements for a resting sphere.

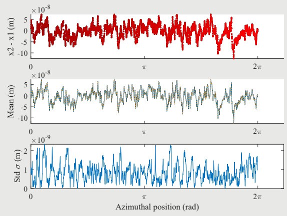

Fig 8: Performance of differential measurement for one exemplary circle profile. (Middle: Mean, Bottom: Deviation).

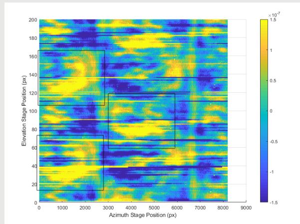

Fig 9: Preliminary measurement of a complete sphere surface,covering a range >2pi in elevation angle

Conclusions

- A concept of reconstructing circle profiles and sphere surfaces along a sphere using point interferometers has been proposed.
- Advantage of the method is high suppression of common path errors in the symmetrical differential interferometer path, combined with a compensation for non-common path errors.
- Two integration methods are demonstrated and reconstruction over complete sphere has been shown.
- Very high accuracy of differential measurement below nanometers repeatability was demonstrated
- Integration method very sensitive to periodic errors (1/rev), which tend to get amplified

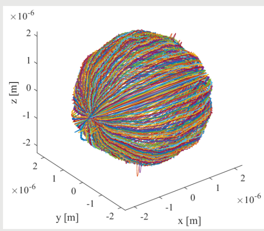

Fig 10: Visualisation of all circle profiles measured over different evaluations.

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