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
- 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

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 spheres for compensating sphere center movements
- Full coverage of sphere using second mechanism
- Setup in vacuum chamber on air-cushion dampers

Simulation

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

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 m (19 px)

Post Processing:

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

Methods for circle profile reconstruction from differential measurements:

Fourier-space reconstruction approach or

\[ \varphi(\theta) = \varphi_0(\theta) - \sum_{i=0}^{n} A_i \cos(i \theta) \]

\[ \varphi(\theta) = \sum_{i=0}^{n} A_i \sin(i \theta) \]

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

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 completed 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

\[ \text{Fig 1: Different concepts for GRS configurations.} \]  
\[ \text{Fig 2: Measurement setup in the vacuum chamber.} \]  
\[ \text{Fig 3: Schematic of the optical setup.} \]  
\[ \text{Fig 4: Test mass support with two mechanisms (elevation, azimuth) to rotate the sphere.} \]  
\[ \text{Fig 5: Simulated results of path length contribution by optical system (tilt-to-length)} \]  
\[ \text{Fig 6: Correction of a circle profile measurement by a fitted 2D (X-Y) linear correction.} \]  
\[ \text{Fig 7: Instrument noise: Amplitude spectral density of path-length measurements for a resting sphere.} \]  
\[ \text{Fig 8: Performance of differential measurement for one exemplary circle profile.} \]  
\[ \text{Fig 9: Preliminary measurement of a complete sphere surface, covering a range >2pi in elevation angle} \]  
\[ \text{Fig 10: Visualisation of all circle profiles measured over different evaluations.} \]  

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