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ABSOLUTE DISTANCE METROLOGY FOR SPACE INTERFEROMETERS

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ABSTRACT

Space interferometers consisting of several free flying telescopes, such as the planned Darwin mission, require a complex metrology system to make all the components operate as a single instrument. This metrology system consists of various sub-systems to monitor distances, angles and speeds. Our research focuses on one of these sub-systems that measures the absolute distance between two satellites with high accuracy. For Darwin the required accuracy would be in the order of 10 μm over 250 meter.

To measure this absolute distance, we are currently building a frequency sweeping interferometer. It is operated by first measuring a phase in the interferometer, sweeping a tunable laser over a known frequency interval and finally measuring a second phase. By also counting the number of fringes during the sweep it is possible to determine the absolute path length difference without ambiguities. We plan on actively stabilizing the wavelength at the endpoints of the sweep on a Fabry-Perot cavity using the Pound-Drever-Hall technique. In this way the unknown distance is directly referenced to the length of the Fabry-Perot cavity.

1. INTRODUCTION

In the next few years a number of space missions will be carried out that consist of multiple satellites that fly in formation. Examples include missions for gravitational wave detection, X-ray telescopes and synthetic aperture telescopes. Depending on the demands of the mission, a metrology system will be needed that controls the mutual distances within the formation to more or lesser precision. The background of our research is the Darwin Infrared Space Interferometer, which will be launched by ESA around 2014 and is aimed at detecting planets around other stars. It consists of 6 free-flying telescopes and a central satellite that will interferometrically combine the collected light to form 'white-light' fringes in the infrared.

The interferometric detection poses very high demands on the satellite pointing and the stability of the mutual distances. It is necessary that the optical path length experienced by the starlight should be equal along the different paths from telescopes to beam combination to within a fraction of the used wavelengths. This is not possible without a very complex metrology system that monitors distances, angles and speeds. These sub-systems will become operational in order of increasing accuracy to finally enable a science measurement. The measurements made with the various systems will be used to control the optical path length by moving a delay line and by moving the satellites with milli- and micro-Newton thrusters. Our research focuses on the possible implementation of a technique in one of these sub-systems that measures the absolute distance between two satellites with high accuracy. For Darwin the required accuracy would be in the order of several tens of micrometers over a distance up to 250 meter.

Optical techniques for measuring absolute distances can be divided in two categories: incoherent and coherent methods. Examples of the first kind are pulsed time-of-flight and continuous wave amplitude modulation methods. An advantage of these techniques is that they are not dependent on the coherence length of the used light, but only on the properties of the modulation scheme. Most of them are limited in accuracy, although some schemes approach our accuracy requirements [1]. Examples of the second type are various interferometric methods, among which multiple-wavelength interferometry and several schemes involving tunable lasers. We are currently investigating a scheme that uses only one tunable laser, which is known as frequency sweeping interferometry (FSI).

2. FREQUENCY SWEEPING INTERFEROMETRY

Frequency Sweeping Interferometry essentially uses a tunable laser and a Michelson-like interferometer. Fractional fringes are measured at the beginning and the end of the sweep and the integer number of fringes is counted during the sweep [2]. It is then possible to express the optical path length difference L in terms of a measured phase difference Φ:

$$L = \frac{\Phi}{2\pi}\Lambda = \left(N + E\right)\Lambda \,, \qquad (1)$$

with N and E the integer and a fractional fringe number. The synthetic wavelength Λ is defined as

$$\Lambda = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} \approx \frac{\lambda^2}{\Delta\lambda} \,, \qquad (2)$$

with λ_1 and λ_2 the two endpoints of the wavelength sweep. This can be simplified by substituting $\lambda_1 \approx \lambda_2 \approx \lambda$ and $\lambda_2 - \lambda_1 = \Delta\lambda$.

Measuring the phase at the beginning and the end of the sweep yields *E* and counting the integer number of fringes during the sweep yields *N*. In fact, this method can be viewed as a time-multiplexed double wavelength measurement. The advantage of FSI is that the total phase difference Φ can be measured by counting fringes during the wavelength sweep. This allows the total distance to be calculated without ambiguities. In contrast, double-wavelength interferometry only measures phase differences modulo 2π and thus needs an additional (lower accuracy) system to remove the ambiguity.

2.1 Error analysis

Error analysis of (1) and (2) yields

$$\delta L = \sqrt{\left(\Lambda \delta E\right)^2 + \left(L \frac{\delta\Lambda}{\Lambda}\right)^2} = \sqrt{\left(\Lambda \delta E\right)^2 + 2\left(L \frac{\lambda}{\Delta\lambda}\frac{\delta\lambda}{\lambda}\right)^2}, \qquad (3)$$

with *δL* the error in the length measurement, *δE* the error in the phase measurement and *δλ* the error in the wavelength at the two endpoints. It is assumed that no error is made in counting the integer *N*. Note that the first term is an absolute error and the second is a relative error, which is a factor $\lambda / \Delta\lambda$ larger than the relative wavelength error. In our case a relative wavelength stability of 10^{-11} would be required to achieve a relative measurement error in the length of 10^{-7}. This extreme stability is only necessary during the measurement. Over longer terms the demands relax to the same level as the required relative length error.

A different error arises when the optical path length changes during a measurement. An optical path length change of one wavelength would then be interpreted as a change of one synthetic wavelength. Due to the benign environment of the space vacuum we are not bothered by air turbulence, but vibrations could become an issue. Linear movement of the spacecraft should be straightforward to compensate for.

The effects of both the increased sensitivity for wavelength errors and the ‘movement error’ can be mitigated by increasing the wavelength sweep range, but this has trade-offs in choices of laser and electronics. If these remain a problem we could change to different measurement schemes using a second laser.

3. EXPERIMENTAL

3.1 Wavelength stabilization

Methods for stabilizing the wavelength of a laser can be time-based, spectroscopic or based on a mechanical standard. Although the first two have some definite advantages, we choose to use a mechanical reference for the moment. Several related experiments [3] were done using a reference interferometer, where the lengths of both the unknown and the reference branch are measured at the same time with the same technique. Since it is hard to make a compact and stable reference interferometer longer than 10 meter (using folding mirrors), the measurement branch would be much longer than the reference in our case. This would cause the phase errors in the reference branch to dominate all other errors. We therefore chose to use a Fabry-Perot cavity instead. These are generally only a few tens of centimeters long, but using an extremely high finesse it is possible to achieve better frequency discrimination than with a much longer reference interferometer. A Fabry-Perot cavity also has the advantage of an easy to interpret spectrum for relative wavelength changes, which is sufficient in our case.

The short-term stability of a Fabry-Perot cavity can be very good, assuming operation in a vibration-free environment and in vacuum. Modest temperature stabilization will suffice if the mirror spacer is built from material with a low thermal expansion coefficient. Long-term demands are less severe, but the length calibration should be preserved from pre-launch calibration to operation in space. There are some possibilities to do in-flight calibration of the cavity length by determining the free spectral range with laser beating, but this would require a second laser.

3.1 Set-up

See Fig. 1 for a schematic overview of our set-up. Our laser is an external cavity laser diode, which can be tuned by rotating a piezo controlled grating or by changing the laser diode current. We choose to do our experiments at a wavelength of 633 *nm* for compatibility with our existing metrology experiments. The technique could however easily by adapted to more favorable wavelengths.

The tunable laser is locked to the Fabry-Perot cavity with the Pound-Drever-Hall method. This involves modulating the light with an electro-optic modulator and looking at the phase of the light reflected of the cavity. Given a sufficient bandwidth of the feedback loop, it is possible to narrow the linewidth of the laser to well below 100 Hertz [4]. Our cavity is 10 cm long and is built completely out of ultra low expansion (ULE) glass and has a finesse of 10000. It will eventually be placed in vacuum.

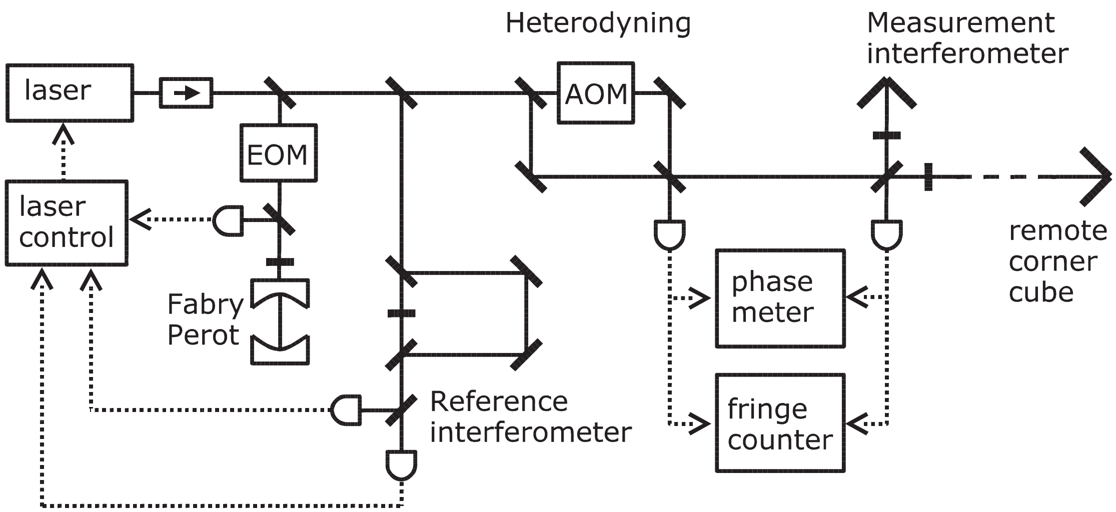

Fig. 1: Schematic overview of our Frequency Sweeping Interferometer set-up. EOM and AOM are electro- and acousto-optic modulators. The various wave-plates, (non-) polarizing beam-splitters, detectors and optical isolator have not been labeled for clarity.

To compensate for piezo nonlinearity and to monitor mode-hops and others disturbances that influence the wavelength sweep, we are also adding a reference interferometer. It should only have good short time stability. For the longer term stability and the determination of the endpoints of the wavelength sweep we will still rely on our Fabry-Perot cavity. This really relaxes the demands of the reference interferometer, which can therefore be made into a compact device using a fiber [3].

The measurement interferometer will consist of a standard Michelson-type heterodyne interferometer. The long branch will be formed by a corner cube located on the target satellite. Finally a standard heterodyne system will be used to measure the phases and count the fringes.

4. RESULTS AND CONCLUSIONS

We described the system for measuring absolute distances that we are currently building. We so far succeeded in locking the laser to the Fabry-Perot cavity, but we need to improve the bandwidth of our feedback system to really cause line-width narrowing. The cavity itself is still drifting too much, but this will hopefully be resolved once it is placed in vacuum. We also have a simple version of the reference interferometer in place, which allows us to monitor laser linewidth and other parameters. We hope to present some first results of the length measurements in the near future. We will simulate the long distances using fiber.

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