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. Our research focuses on one of its 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 exploring the frequency sweeping interferometry technique. Its measurement principle is to first measure a phase in the interferometer, sweep a tunable laser over a known frequency interval and finally measure 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. The wavelength at the endpoints of the sweep is stabilized on a Fabry-Perot cavity. 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. For most of these, a metrology system that controls the formation with high accuracy is an essential component to achieve the science measurement. 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 complex metrology system that monitors all the distances, angles and velocities in the system. 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 lengths by moving delay lines and by steering 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 of up to 250 meter.

Several techniques are possible for measuring absolute distances. Some of them are incoherent, such as pulsed time-of-flight and some high frequency modulation schemes. Other methods are coherent and use various interferometric methods. Among these are 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).

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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 [1]. It is then possible to express the optical path length difference L in terms of a measured phase difference Φ:

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

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

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

with λ_1 and λ_2 the two endpoints of the wavelength sweep. This can be simplified by substituting $\lambda_2 - \lambda_1 = \Delta\lambda$ and assuming that $\lambda_1 \approx \lambda_2 \approx \lambda$. This synthetic wavelength is exactly equal as the one encountered in conventional double-wavelength interferometry. In fact, FSI can be viewed as a time-multiplexed double-wavelength measurement.

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 this way, the total phase difference Φ can be determined, which yields the absolute distance L without any 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

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

with δL the error in the length measurement, δE the error in the phase measurement and $\delta\lambda$ 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 vacuum in space we are not affected by air turbulence, but vibration sensitivity 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 [2] 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. Compared to a spectroscopic reference, 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.
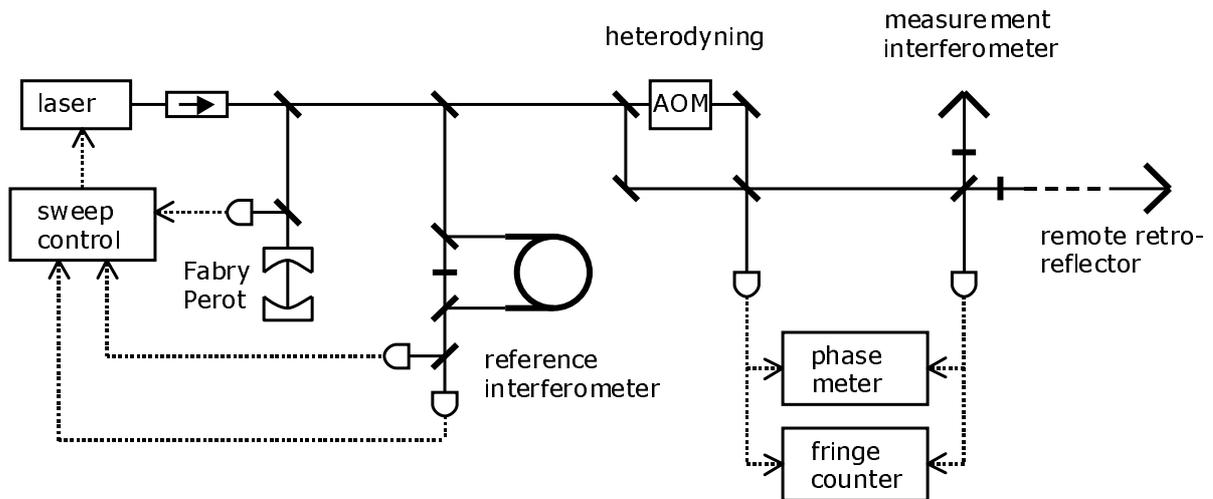

Fig. 1: Schematic overview of our Frequency Sweeping Interferometer set-up.

3.2 Set-up

See Fig. 1 for a schematic overview of our set-up. The 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 endpoints of the wavelength sweep are defined by locking the laser to a Fabry-Perot cavity with the Pound-Drever-Hall method. This involves modulating the light with an electro-optic modulator and detecting the light reflected from the cavity. Mixing this signal with the modulation frequency yields an error signal that has a very steep slope at the frequency of a cavity resonance. Given sufficient bandwidth of the feedback loop, it is possible to narrow the linewidth of the laser to well below 100 Hertz [3]. 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.

To compensate for piezo non-linearity and to monitor mode-hops and others disturbances that influence the wavelength sweep, we are also implementing 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 rely on the Fabry-Perot cavity. This really relaxes the demands of the reference interferometer, which can therefore be made into a compact device using a fiber [2].

The fast part of the feedback (laser current) will be completely analog, but we plan on using a digital signal processor (DSP) for the slow part (piezo). In this way it will be possible to seamlessly switch between locking to the cavity and sweeping monitored by the reference interferometer.

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. We will use either long fibers or a delay line to simulate the long distances in the lab.
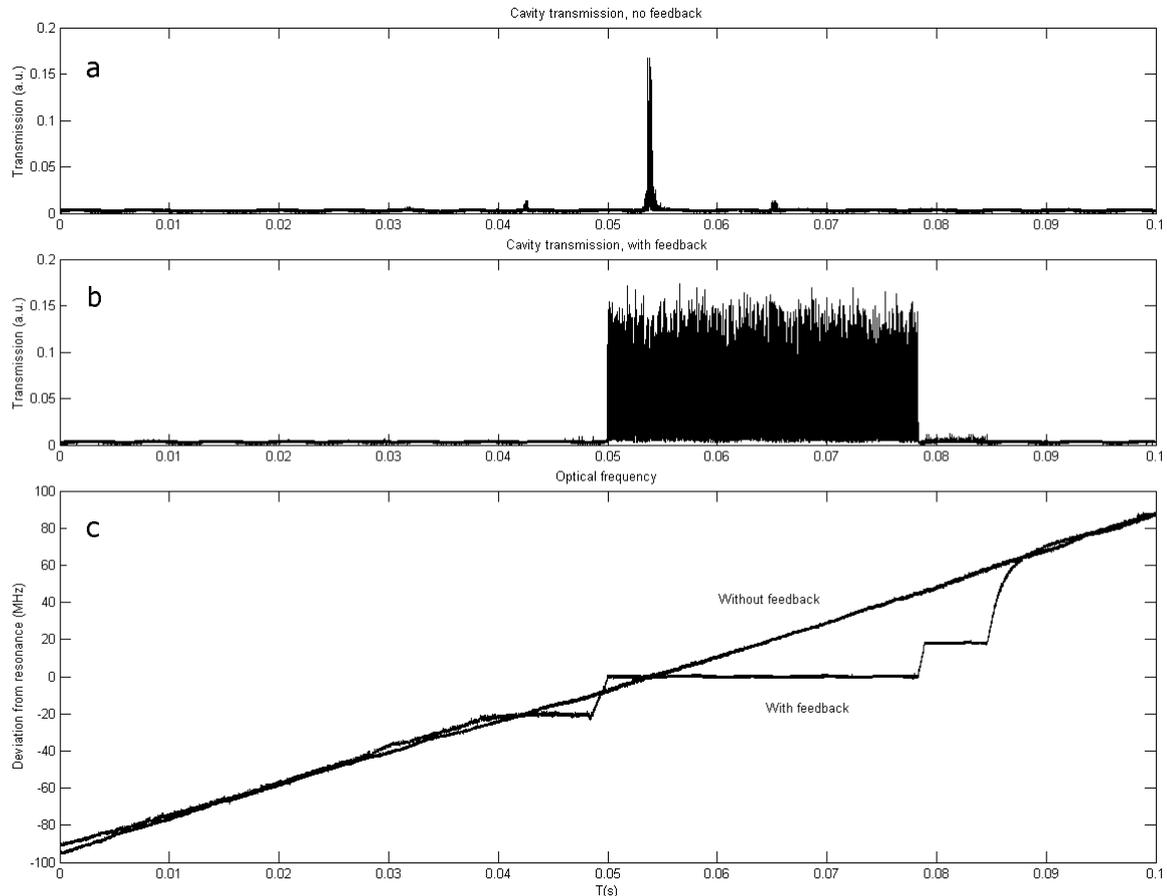

Fig. 2: Locking the laser to the Fabry-Perot cavity. a) Cavity transmission, no feedback. b) Cavity transmission, with feedback. c) Change in optical frequency as observed with reference interferometer, with and without feedback. Locking is confirmed by the transmission of the cavity, as well as the central plateau in frequency (the smaller plateaus are 'anti-locking' to the modulation sidebands).

4. RESULTS

So far we did the basic characterization of the laser system, including the mapping of the mode-hop behavior. We measured a mode-hop free range of 15 GHz. This might be improved later with the laser under control of a DSP-controller, which could simultaneously tune the piezo and the laser diode current.

We achieved initial laser locking, which is shown in Fig. 2. In this case the laser is scanned past the Fabry-Perot cavity resonance with the piezo, while the fast part of the feedback (laser current) is used for feedback. The optical frequency change, as observed with the reference interferometer, shows the locking with a flat tableau. The transmission of the cavity however shows that the laser does not experience any linewidth narrowing. The transmission signal falls all the

way back to zero, indicating that the linewidth of the laser is still larger than the cavity resonance (150 kHz). This should be improved by optimizing the electronics.

We also did some first stability measurements by beating our stabilized diode laser with a commercial stabilized Helium-Neon laser. The observed drift rates are still too high. This can be explained because the cavity is filled with air, which has a refractive index that varies as a function of temperature and pressure. This should be solved in the near future when we put the cavity in a vacuum chamber.

Recently we received polarization maintaining fibers with lengths up to 50 meter to simulate the long distances. Temperature drift is reduced by putting the fibers on top of a big metal block and shielding the whole reference interferometer with an insulating box. In future we want to use even longer fibers.

5. CONCLUSIONS AND OUTLOOK

We described the system for measuring absolute distances that we are currently building. We did some initial testing of the laser and have built up half of the set-up. We succeeded in locking the laser to the Fabry-Perot cavity, but we still need improvements by optimizing the electronics and placing the cavity in vacuum. We also have implemented the reference interferometer, which allows us to monitor the locking and tuning behavior of the laser. We hope to present some first results with medium length fibers in the near future. Building of the heterodyne measurement interferometer and testing with long fibers is in progress.

ACNOWLEDGEMENTS

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