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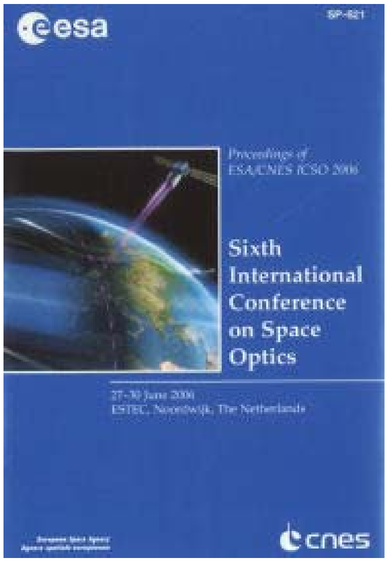

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HIGH ACCURACY ABSOLUTE DISTANCE METROLOGY

Bas L. Swinkels[1], Nandini Bhattacharya[1], Ad L. Verlaan[2], and Joseph J.M. Braat[1]
[1]Delft University of Technology, the Netherlands, Email: b.l.swinkels@tudelft.nl
[2]TNO, Delft, the Netherlands

ABSTRACT

One of ESA's future missions is the Darwin Space Interferometer, which aims to detect planets around nearby stars using optical aperture synthesis with free-flying telescopes. Since this involves interfering white (infra-red) light over large distances, the mission is not possible without a complex metrology system that monitors various speeds, distances and angles between the satellites. One of its sub-systems should measure absolute distances with an accuracy of around 70 micrometer over distances up to 250 meter. To enable such measurements, we are investigating a technique called frequency sweeping interferometry, in which a single laser is swept over a large known frequency range. Central to our approach is the use of a very stable, high finesse Fabry-Pérot cavity, to which the laser is stabilized at the endpoints of the frequency sweep. We will discuss the optical set-up, the control system that controls the fast sweeping, the calibration and the data analysis. We tested the system using long fibers and achieved a repeatability of 50 micrometers at a distance of 55 meters. We conclude with some recommendations for further improvements and the adaption for use in space.

1. INTRODUCTION

In the next few years a number of space missions will be carried out that consist of multiple satellites that fly in close 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 Space Interferometer, which will be launched by ESA around 2014 and is aimed at detecting planets around nearby stars. It consists of up to 6 free-flying telescopes and a central satellite that interferometrically combines the collected light to obtain an angular resolution that is higher than achievable with a single telescope. The interferometric detection poses very high demands on the satellite pointing and the stability of the mutual distances. To observe the 'white-light' fringes, it is necessary that the optical path length experienced by the starlight is equal along the different paths from telescopes to beam combination to within a fraction of the wavelength. This is not possible without a complex metrology system that monitors all the distances, angles and velocities in the system. [1] 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 micronewton thrusters. Our research focuses on the possible implementation of the sub-system that should measure the absolute distance between two satellites with high accuracy. For Darwin the required accuracy would be slightly better than 100 micrometers over a distance of up to 250 meters.

Several techniques are possible for measuring absolute distances, such as pulsed time-of-flight measurements, various high frequency modulation schemes and interferometric methods. Many of these are not truly absolute measurements, but rather a scheme were several systems with decreasing synthetic wavelengths are cascaded to resolve ambiguities. One proposed scheme for Darwin is to use 2-wavelength interferometry to do the high resolution measurement and use a local GPS-like system to determine the integer number of synthetic wavelengths. The accuracy of the latter system is limited to several centimeters, which is thus also the lower limit of the synthetic wavelength. If a high accuracy distance measurement is required, this translates to a very high phase resolution.

We are currently studying a technique that is a truly absolute and uses only a single tunable laser, which is called frequency sweeping interferometry.[2, 3] The technique basically works by sweeping a tunable laser over a well known frequency difference. The total phase difference observed is then directly proportional to the optical path length difference in the

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interferometer. This method does not suffer from the ambiguity problem described above, so we can choose the synthetic wavelength as small as possible, limited only by the mode-hop-free range of the laser. We can thus achieve a similar accuracy with much lower requirements on the phase resolution. Another obvious advantage is the fact that only a single laser is used.

2. FREQUENCY SWEEPING INTERFEROMETRY

Frequency sweeping interferometry can be understood by considering an optical interferometer that is equipped to measure phase as a function of time. For fixed or slowly changing optical frequency ν, the phase ϕ is proportional to both the distance D and the optical frequency. Because the phase is usually measured modulo 2π, the absolute phase is unknown. By unwrapping the phase over time, however, it is possible to measure phase differences. If the light-source is a tunable laser that is swept from optical frequency ν_1 to ν_2, the difference between the phase measured before and after the sweep ϕ_1 and ϕ_2 will be

$$\phi_2 - \phi_1 = 2\pi\frac{2D\nu_2}{c} - 2\pi\frac{2D\nu_1}{c} = 4\pi\frac{D}{\Lambda}, \qquad (1)$$

with c the speed of light. This formula closely resembles the phase encountered in normal interferometry, but now with a much larger *synthetic* wavelength Λ defined by

$$\Lambda = \frac{c}{\Delta\nu} = \frac{c}{p\,\Delta\nu_{\mathrm{fsr}}} = \frac{2d}{p}, \qquad (2)$$

with $\Delta\nu = \nu_2 - \nu_1$ the frequency difference of the sweep, which should be defined very accurately. We achieve this by sweeping the laser between two different resonances of a very stable Fabry-Pérot cavity. In this way the frequency difference is fixed to an integer multiple p of the free-spectral-range $\Delta\nu_{\mathrm{fsr}}$, which causes a direct relation between the synthetic wavelength and the length of the cavity d. Reversing Eq. (1), the distance D can be calculated with

$$D = \frac{\Delta\phi}{4\pi}\Lambda. \qquad (3)$$

The length is thus directly proportional to the total phase difference $\Delta\phi = \phi_2 - \phi_1$, which can be determined by measuring the phase before and after the sweep and counting the number of fringes during the sweep. Error analysis yields the error in the length measurement δD

$$\begin{aligned}\delta D^2 =& 2\left(\frac{\Lambda}{2}\right)^2\left(\frac{\delta\phi}{2\pi}\right)^2 + \\ & D^2\left[\left(\frac{\delta\Delta\nu_{\mathrm{fsr}}}{\Delta\nu_{\mathrm{fsr}}}\right)^2 + 2\left(\frac{\nu}{\Delta\nu}\right)^2\left(\frac{\delta\nu}{\nu}\right)^2\right],\end{aligned} \qquad (4)$$

where $\delta\Delta\nu_{\mathrm{fsr}}$ is the error in calibrating the free-spectral-range, $\delta\phi$ is the error in the phase measurement and $\delta\nu$ is the error in optical frequency of the locked laser (which is caused both by the locking itself and by any drift of the cavity).

The first term is constant and depends on the error in measuring the phase at both ends of the frequency sweep, each with error $\delta\phi$. The second term scales with the distance D and depends on the calibration of the free-spectral-range and on the stability of the synthetic wavelength. As indicated by Eq. (2), the synthetic wavelength is determined by a *difference* between two large frequencies with error $\delta\nu$ each. This leads to the amplification of the error by a large factor $\nu/\Delta\nu$. Because of this, our method needs a *short term* stability (on the time scale of a single measurement) on the order of $1 \cdot 10^{-11}$, even though the required measurement accuracy is $1 \cdot 10^{-7}$. This is very challenging, but it is similar to the stability needed for measuring incremental distances with a resolution of one nanometer over a distance of 100 meters, which is needed in a different metrology system for Darwin.

One drawback of using frequency sweeping interferometry is that the technique is very sensitive to target movement during the frequency sweep. A movement over a distance of one optical wavelength would then be interpreted as a shift over one synthetic wavelength. This problem is usually solved by adding a second laser, which reduces the sensitivity to movements on the order of the synthetic wavelength itself. [4, 5] Our approach is not to add a second laser, but to solve the problem in the data analysis with a simple interpolation scheme. [6] This scheme only works if the movements are smooth on the time-scale of a measurement, which would be the case in our intended application.

3. EXPERIMENTAL

To evaluate the frequency sweeping interferometry technique, we built a breadboard-style set-up, see Fig. 1 for an overview. More details about the setup were discussed previously in [7]. The laser source is an external cavity laser diode with a wavelength of 633 nm. It is able to scan without any mode-hops over more than 80 GHz, but we usually limit our measurements to scans of about 21 GHz due to some limitations in our electronics. As a reference for our distance measurement, we use a very stable Fabry-Pérot cavity. It is constructed entirely out of ultra-low expansion glass (ULE), has a finesse of 10000 and a free-spectral-range of 1.5 GHz. The cavity is placed in a small vacuum tank, since the free-spectral-range is dependent on the refractive index of the medium between the mirrors. In our measurement scheme, the tunable laser is repeatedly scanned up and down between two resonances of this Fabry-Pérot cavity.

At the endpoints of the sweep, the laser is locked to a resonance using the Pound-Drever-Hall technique, in which an error signal is fed back directly to the high frequency current modulation input of the laser. [8] The whole process of sweeping, searching for and locking to a resonance is done under control of a digital signal processor (DSP). The DSP is able to monitor changes in optical frequency by analyzing the signals of a simple unbalanced, homodyne *reference* interferometer. The output of the DSP drives the piezo input of the laser. See Fig. 2 for a plot of the signals captured by the DSP during one complete cycle of sweeping up and down. We thus have created a light-source with an optical frequency that is tuned very accurately in a trapezoidal pattern.

The final part of our setup is the so called *measurement* interferometer, which contains the unknown distance that should be measured. In this interferometer, we can insert long polarization maintaining fibers to simulate long distances in the lab. This allows us to measure at a number of discrete path lengths up to 110 meter (equivalent to a distance of 55 meter). Also included is a delay line to measure with a varying distance. The phase in this interferometer is measured using a heterodyne scheme, for which the optical frequency in one of the arms is shifted by using an acousto-optic modulator (AOM). The light is interfered twice: once with two short paths to provide a reference signal and once with a short path and the long unknown path to provide the measurement signal. Both signals, which oscillate roughly at the heterodyne frequency, are recorded by a high frequency detector. The phase difference between the two signals corresponds to the interferometric phase we want to measure. These two signals are recorded directly by two fast counters. The difference between the two counts yields the coarse value of the phase in integer number of fringes, without any need for unwrapping. To also measure the phase with a resolution much better than 2π, the signals are electronically mixed to a much lower frequency, to allow detecting the time of the zero-crossings with a second pair of counters. The coarse measurement is able to track large phase differences with a speed of more than 10^5 fringes per second, while the fine measurement can measure the phase at the end-points of the sweep with a resolution of better than $2\pi/1000$. The coarse and the fine measurement can be combined to unwrap the phase.

In the data-analysis we can obtain two different measurements from the phase data: By evaluating the phase difference measured during the frequency sweep, the absolute distance can be calculated using Eq. (3). Simultaneously, the phase measured at one of the ends of the frequency sweep can be interpolated to yield the phase that would be measured in a conventional single-wavelength interferometer. If this wavelength is known, we can use it to obtain a incremental distance measurement.

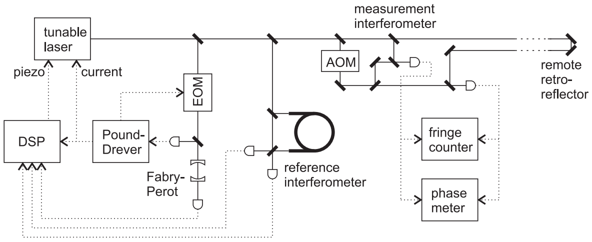

Figure 1. Overview of the experimental setup.

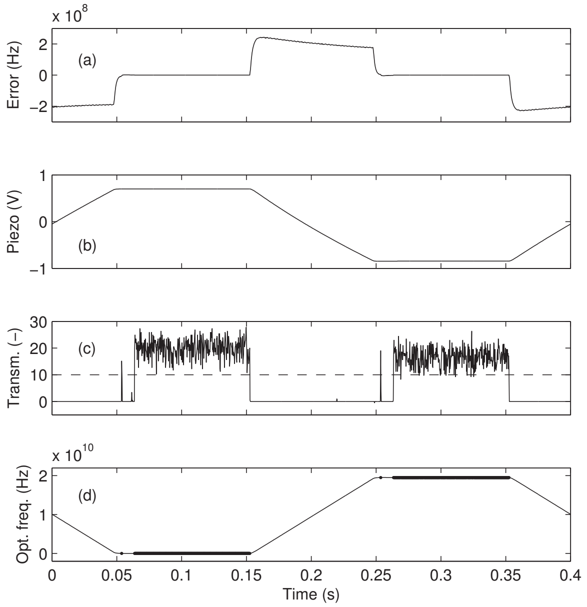

Figure 2. Signals captured by the control system during one complete cycle of sweeping over 13 free-spectral-ranges or about 19 GHz. (a) Difference between measured and intended optical frequency. This is the error signal for the control loop. (b) Voltage applied to the piezo input of the laser. (c) Transmission of the Fabry-Pérot cavity. (d) Optical frequency, dotted points indicate that the laser is locked to a resonance.

4. RESULTS

The first step in performing a measurement is to calibrate the free-spectral-range of the Fabry-Pérot cavity, since it forms the reference standard for our distance measurement. This is achieved by recording the optical frequency of a large number of resonances using an optical wave-meter, which itself is calibrated using a Helium-Neon laser at the national standard bureau. Even though the resolution of the wave-meter is limited, we are still able to perform a calibration with a relative accuracy of $2 \cdot 10^{-5}$ by tuning the laser over more than 2 THz. The free-spectral-range also appears to be constant over this range to within the resolution of the wave-meter. Although the relative accuracy of the calibration is worse than the intended accuracy of our method (around $1 \cdot 10^{-7}$), it is good enough for our initial test measurements. For a final implementation of our method, the free-spectral-range should probably be calibrated by locking the laser to various resonances and beating it with a reference laser that has a well known optical frequency.

As explained before, we are able to simultaneously obtain both an absolute and a relative distance measurement from our data. We can thus perform an *internal* comparison by looking at the difference between the two measurements. The relative measurement will have an accuracy of several nanometers. Compared to the absolute measurement, which has an accuracy of several micrometers, it can thus be considered to be a a *truth* measurement. A few error sources might be common mode to both measurements, so they would not show up in the comparison. Most errors, however, have a very different effect on both measurements, so it is still a very useful tool in evaluating the performance of the absolute measurement. It would of course be better to perform an *external* comparison of the method by simultaneously measuring a distance with a truly independent, high accuracy distance measurement (see e.g. [9]), but this was not available.

See Fig. 3 for the results for a typical measurement at 110 meters path length, during which the delay line was repeatedly moved by a few centimeters. The top graph shows a comparison of the absolute and relative measurement, which are overlapped by fitting the offset of the relative measurement. The bottom graph shows the residuals. Similar measurements are performed with different lengths of fiber in the measurement interferometer to evaluate the error as a function of the distance. The obtained standard deviation of the residuals as a function of distance can be approximated by $\delta D^2 = (D \cdot 1.0 \cdot 10^{-6})^2 + (10 \cdot 10^{-6})^2$, so our distance measurement has a relative error of 1 part per million and a fixed error of 10 micrometers. Comparing this with Eq. (4), the distance error can be explained by a phase error of around $\delta\phi = 2\pi/1000$ and an error in the optical frequency at the end-point of 15 kHz. Both are effective errors, based on a larger number of phase readings taken during a few tenths of a second that are used in the calculation of a single distance. The calibration error is probably much larger than the observed relative error, but it should be constant and will thus not show up in our limited test. In preliminary experiments, we already showed the effectiveness of our algorithm to compensate movement induced errors. [6]

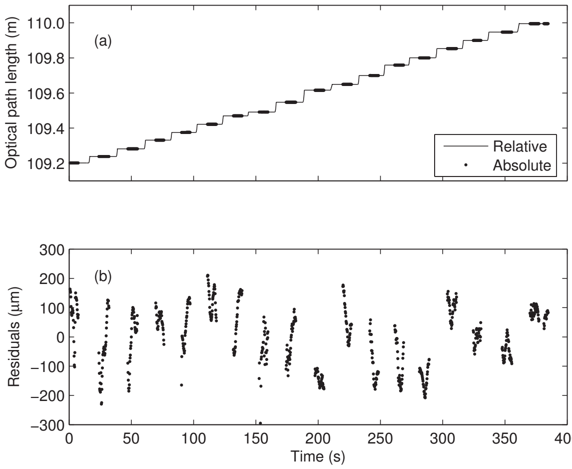

Figure 3. Absolute distance measurement with 110 meter path length. (a) Comparison of absolute and relative measurement. (b) Residuals, the standard deviation is 100µm.

5. ADAPTATIONS FOR SPACE USE

Adapting our measurement method for use in space requires a number of modifications. One obvious requirement is to shrink to experiment that presently covers half an optical table into a compact, robust and light-weight package. One solution would be to implement the whole setup in fiber-optics. Most of the components can be replaced by fiber-pigtailed versions, except for the beam-launcher and the Fabry-Pérot cavity, which still require bulk optics. See Fig. 4 for a possible implementation.

Most of the individual components used in our setup have been, or are in the process of being space qualified for other missions. The most critical part will be the tunable laser. This should benefit from work done for cold atom experiments, see e.g. [10]. A second laser might have to be included for redundancy. The reference interferometer, which we use mainly in the control system to monitor the sweeping of the laser, could be implemented as an all-fiber Mach-Zehnder interferometer. It could even be removed completely if the tuning behavior of the laser is known well enough.

The design of the Fabry-Pérot cavity and the laser stabilization should benefit from work undertaken for the LISA mission, in which similar techniques are used to achieve extreme frequency stability. [11] Unique to our method is that we need to calibrate the free-spectral-range of the cavity. This could be done by calibrating the cavity on the ground and assuming that it is still valid after launch. A better method would be to calibrate the cavity in space with a modulation technique as in [12]. Alternatively, our sweeping technique could be used with a spectroscopic standard instead of a cavity. This introduces a different set of challenges, such as temperature stabilization of the standard and using Doppler-free spectroscopy to achieve the required resolution in optical frequency. The spectrum of the standard should be such, that the peaks are clearly identifiable and that they are located at a proper separation that coincides with the maximum tuning range of the laser.

A common design pattern in interferometry is to keep the laser source and the various modulators separate and feed the light by fiber-optics to a small beam-launch head. We could use a similar approach for our all-fiber solution. A beam-launcher usually consist of a small optical bench in which the light is collimated and sent to a remote corner-cube. The reflected is then collected and interfered with a local beam on a photo-diode. Since the distance to be measured can be several hundred meters long, the beam should probably be expanded to several centimeters to prevent any losses from diffraction. These design issues are almost independent from the particular distance measurement technique, so we could make use of work done in other projects. [1, 13]

One big advantage of operation in space is the lack of some external disturbances, which makes the testing on earth more challenging than the actual measurements in space. First of all, there are no problems associated with the refractive index of air, so turbulence induced errors are no longer an issue. The level of vibrations should also be very low, since this is already a requirement for the white-light interferometry in Darwin's science mission. Finally, all the path length changes will be very smooth, since Darwin consist of spacecraft of several hundred kilos pushed around by millinewton thrusters. This is ideal for our movement error correction algorithm.

6. CONCLUSIONS

We demonstrated measuring absolute distances with high accuracy using the frequency sweeping interferometry technique. Best results obtained so far are a repeatability of 100 micrometers at 55 meter, but additional testing is still needed. Currently, the accuracy appears to be limited by some problem in the laser locking. We expect that by solving this and increasing the frequency sweep range to around 150 GHz, it should be possible to increase the resolution by almost an order of magnitude. More details on our setup and our final measurement results will be published in the near future.

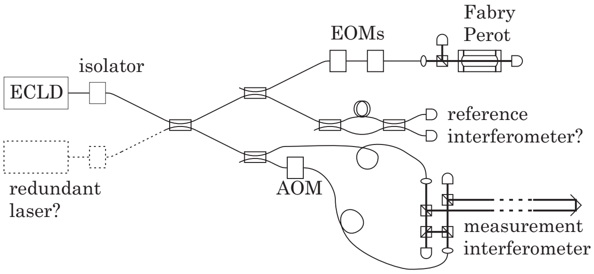

Figure 4. Proposed all-fiber implementation of our frequency sweeping interferometer. A redundant laser and the reference interferometer are optional. The measurement interferometer could be duplicated, so that a single laser and control system can be used to measure multiple distances simultaneously.

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