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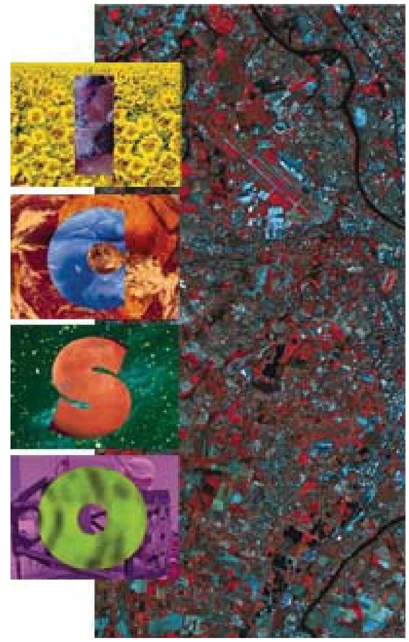

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ABSOLUTE METROLOGY FOR SPACE INTERFEROMETERS

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ABSTRACT *- The crucial issue of space-based interferometers is the laser interferometric metrology systems to monitor with very high accuracy optical path differences. Although classical high-resolution laser interferometers using a single wavelength are well developed, this type of incremental interferometer has a severe drawback: any interruption of the interferometer signal results in the loss of the zero reference, which requires a new calibration, starting at zero optical path difference. We propose in this paper an absolute metrology system based on multiple-wavelength interferometry.*

1. INTRODUCTION

The DARWIN mission of ESA, which is devoted to the search of terrestrial exoplanets, requires an accuracy of a few nm over baselines longer than 50 m. The current concept consists of 6 telescopes in a hexagonal configuration and a central beam combiner[1]. The telescope array will operate in a nulling mode, to enable the search for a planet around the star. The current concept does foresee a local GPS with cm accuracy for positioning the free flyer telescopes, and short delay lines in the central unit for optical path compensation.

The requirements for the LISA project (ESA/NASA), devoted to the detection and observation of gravitational waves, are even more stringent: a picometer laser metrology is required to monitor the relative displacement between three spacecrafts forming an equilateral triangle. The distance between any two spacecrafts is as long as 5 million kilometers.

The crucial issue of stellar interferometers is therefore the laser interferometric metrology systems to monitor with very high accuracy optical path differences. Classical high-resolution laser interferometers using a single wavelength are well developed, and could be combined with a calibration of the zero optical path difference (zero-*OPD*) to fulfill the requirements for stellar interferometry. However, this type of incremental interferometer has a severe drawback: any interruption of the interferometer signal results in the loss of this zero reference, which requires a new calibration. If the optical path difference can be determined rather absolutely than incrementally, the calibration of the zero-*OPD* is not required any more, or is at least substantially simplified. Furthermore, absolute metrology would not require an uninterrupted process any more. An absolute metrology is therefore of interest for ground-based and space-based stellar interferometers. For space-based interferometers, it should allow to control accurately the position of all spacecrafts relative to each other.

2. ABSOLUTE METROLOGY

Absolute distance measurement with submicrometer accuracy cannot be covered by classical interferometry or by current time-of-flight technology. Multiple-wavelength interferometry (MWI) is, as classical interferometry, a coherent method, but it offers greater flexibility in sensitivity by appropriately choosing the two different wavelengths. Indeed, the use of two different wavelengths,

λ_1 and λ_2, permits the generation of a synthetic wavelength $\Lambda = \lambda_1\lambda_2/|\lambda_1 - \lambda_2|$, much longer than the two individuals optical wavelengths. This method thus makes it possible to increase the range of non-ambiguity for interferometry. Absolute distance measurement can be performed using MWI, possibly in combination with time-of-flight distance measurement. Multiple-wavelength interferometry can be operated also in a wavelength tuning mode[2]. Instead of one phase measurement for a fixed separation $\Delta\lambda = \lambda_1 - \lambda_2$ of the two wavelengths, the phase can be monitored while tuning the wavelength difference $\Delta\lambda$ between the two sources.

2.1 Multiple-wavelength interferometry with fixed synthetic wavelengths

In this case, multiple-wavelength interferometry can be combined with a commercially available time-of-flight (TOF) technique (e.g. Distomat, Leica) which allows a coarse measurement of the distance with 1 mm accuracy. Then, a chain of synthetic wavelengths can be used to determine the number of optical wavelength λ in the distance L. Finally, the optical fringe is interpolated to achieve 5 nm accuracy. Table 1 shows a possible measurement procedure. This technique has the advantage to enable simultaneous measurements at Λ_1, Λ_2 and λ. However, it requires at least 3 lasers.

Technique	Unambiguity range	Resolution ($\delta\phi = 2\ /200$)
Distomat DI2002 (Leica)	> 1 km	1 mm
2λ-interferometry, Λ_1 = 5 mm	2.5 mm	12 µm
2λ-interferometry, Λ_2 = 50 µm	25 µm	120 nm
1λ-interferometry, λ= 1 µm	500 nm	2.5 nm

Table 1: Example of multiple-wavelength interferometry combined with time-of-flight technique

2.2 Variable synthetic wavelength

If the phase ϕ of the variable wavelength Λ is monitored during the wavelength tuning, the 2π cycles can be counted and the total phase difference is known absolutely. This allows now an absolute determination of the ranging distance L. The evaluation of the ranging distance from ϕ requires the exact knowledge of the wavelength tuning. This may be determined with the help of an additional Michelson interferometer with an exactly known, calibrated optical path difference L_{cal}[2,3]. The phases of the measuring and reference interferometer will be given by

$$\phi = 4\pi\frac{\Delta\nu}{c}L \text{ and } \phi_{cal} = 4\pi\frac{\Delta\nu}{c}L_{cal}. \tag{1}$$

The distance is then found to be $L = L_{cal}\Delta\phi/\Delta\phi_{cal}$.. A possible solution consists of using two-wavelength interferometry (TWI) with variable synthetic wavelength and classical incremental interferometry. The TWI system should allow to determine the number of optical wavelengths. During the frequency chirping, the possible variation of the OPD can be monitored using the incremental interferometer. Table 2 shows a possible configuration

Technique	Resolution ($\delta\phi = 2\ /200$)
Variable synthetic wavelength, $\Delta\nu$ = 1.5 THz	500 nm
Incremental interferometer (λ = 1 µm)	2.5 nm

Table 2: Example of MWI with wavelength tuning mode

This technique has the advantage to be simpler. However, the continuous tunability which is required (> 1 THz) may be very difficult to obtain with commercially available lasers. In addition, the measuring time for the absolute metrology will be limited by the tuning rate of the laser. This system may however be of interest to recover the order of the optical fringe when the incremental interferometer is interrupted.

2.3 Sources

In any case, one of the optical wavelengths has to be stabilized and known with a very high accuracy (< 10^{-11} to obtain nm accuracy over 100 m). In order to achieve this day-to-day reproducibility, absolute frequency stabilization is mandatory. Depending on the interferometer concept, the requirement on the coherence length may be very stringent (> 100 m).
In the case of MWI with fixed wavelengths, the different wavelengths must be stabilized with respect to each other with high accuracy. This can be done with the help of a common reference length in the form of a Fabry-Pérot resonator. Absolute accuracy is obtained by stabilizing the Fabry-Pérot with respect to a frequency stabilized master laser[4], e.g. a laser stabilized on an atomic absorption line, as shown in Fig. 4. A new concept of a multiple-wavelength source was developed recently for which the calibration of the different synthetic wavelengths is obtained by beat-frequency measurements[5,6]. This concept may be useful to stabilize and calibrate synthetic wavelengths between 1 mm and 200 mm. Smaller synthetic wavelengths can be achieved by using two lasers which are frequency stabilized on different absorption lines.

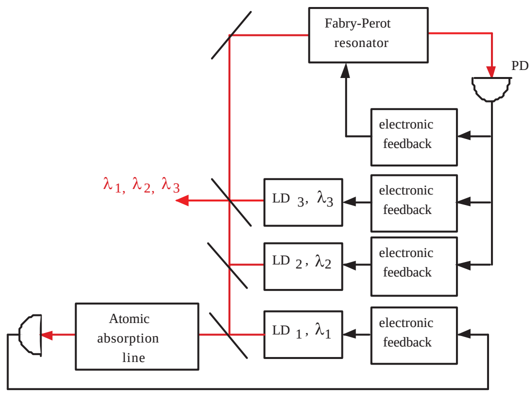

Figure 4: Example of multiple-wavelength source.

Solid-state lasers emitting around 1 µm are of interest because of their high coherence length (>> 100 m). Interesting emission lines can be obtained with Nd:YAG or Nd:YLF lasers at 1047 nm, 1053 nm, 1064 nm, 1320 nm or 1340 nm. Nd:YAG lasers emitting at 1064 nm are continuously tunable over more than 50 GHz. This allows to generate synthetic wavelength larger than 5 mm. The frequency offset between two Nd:YAG lasers can be locked using a commercially available electronic system (e.g. LOLA system from Lightwave). Absolute frequency stabilization can be achieved using a frequency doubling crystal and the I_2 absorption line at 532 nm[7]. Smaller synthetic wavelengths (< 1 mm) could possibly be generated with an additional solid-state laser emitting at 1047 nm (Nd:YLF, CrytaLaser). Indeed, the use of one laser at 1047 nm and one Nd:YAG laser at 1064 nm should allow to generate a synthetic wavelength of 65 µm, which is of a great interest for our application.

In the case of the wavelength tuning mode, the most critical point is the tunability of the laser, which must be at least 1 THz. To our knowledge, only external cavity laser diodes (e.g. New Focus, Velocity Tunable Diode Laser or Photonetics lasers) can achieve such a tunability without mode hops. The fixed wavelength must also be frequency stabilized on an external reference. For the calibration of the wavelength tuning, a temperature-stabilized Fabry-Pérot interferometer (e.g. Newport Super-Cavity) with an exactly known length can act as the reference interferometer. In that case, the wavelength tuning can be determined accurately by counting the resonances at the output of the Fabry-Pérot resonator. The main drawback of external cavity laser diodes is their moderate coherence length (100 m) and their frequency noise spectrum which is usually composed of a white noise part and a 1/f noise, which is a limiting factor for long baseline interferometry[8].

2.4 Detection techniques

Signal processing is mandatory for practical applications of MWI. Several detection techniques have been proposed which are based on heterodyne or superheterodyne detection. Superheterodyne detection, introduced by Dändliker et al.[2], enables high-resolution measurements at arbitrary synthetic wavelengths Λ without the need for separation of these wavelengths optically. Different heterodyne frequencies are generated for each wavelength by means of acousto-optic modulators (e.g. 40 MHz and 40.1 MHz). For two-wavelength interferometry, the interference signal is therefore given by

$$I(t) = a_0 + a_1 \cos(2\ \ f_1 \mathrm{t} + \phi_1) + a_2 \cos(2\ \ f_2 \mathrm{t} + \phi_2), \tag{2}$$

which is the sum of the two heterodyne signals for the wavelengths λ_1 and λ_2, with the corresponding interferometric phases $\phi_1 = 4\ \ L/\lambda_1$ and $\phi_2 = 4\ \ L/\lambda_2$. After amplitude demodulation of the signal $I(t)$ one gets

$$I_{dem}(t) = a_{12} \cos[2\ \ (f_1 - f_2)t + (\phi_1 - \phi_2)]. \tag{3}$$

This signal at $f = f_1 - f_2$ makes it possible to measure directly the phase difference $\phi = \phi_1 - \phi_2 = 4\ \ L/\Lambda$, which is now only sensitive to the synthetic wavelength Λ. We see therefore that the method allows to detect directly the phase difference without optical separation of the wavelengths.

3. POSSIBLE CONCEPT

As already mentioned, the wavelength tuning mode requires an external cavity laser diode to obtain a very large range of tunability. However, the coherence length and the frequency noise spectrum of laser diodes may be limiting factors for long baseline interferometry. A solution with solid-state lasers seems to be more promising, but this requires a fixed synthetic wavelength approach. Figure 5 shows the possible concept for the source, composed of Nd:YAG and Nd:YLF lasers. Table 3 shows the corresponding chain of synthetic wavelengths. By using different heterodyne frequencies f_i for each optical frequency ν_i (i = 1,2,3), the interference signal becomes

$$I(t) = a_0 + a_1 \cos(2\ \ f_1 \mathrm{t} + \phi_1) + a_2 \cos(2\ \ f_2 \mathrm{t} + \phi_2) + a_3 \cos(2\ \ f_3 \mathrm{t} + \phi_3), \tag{4}$$

where the interferometric phases are $\phi_1 = 4\ \ L/\lambda_1$, $\phi_2 = 4\ \ L/\lambda_2$ and $\phi_3 = 4\ \ L/\lambda_3$. With appropriate bandpass filters, and with the superheterodyne technique described above, the synthetic phases $\phi_1 - \phi_2$ and $\phi_1 - \phi_3$ can be measured, as shown in Fig. 6. A bandpass filter around f_1 and heterodyne detection at f_1 will enable the measurement of the optical phase ϕ_1. These interferometric measurements should then be combined with a commercially available time-of-flight technique, e.g. the Distomat DI2002 from Leica AG.

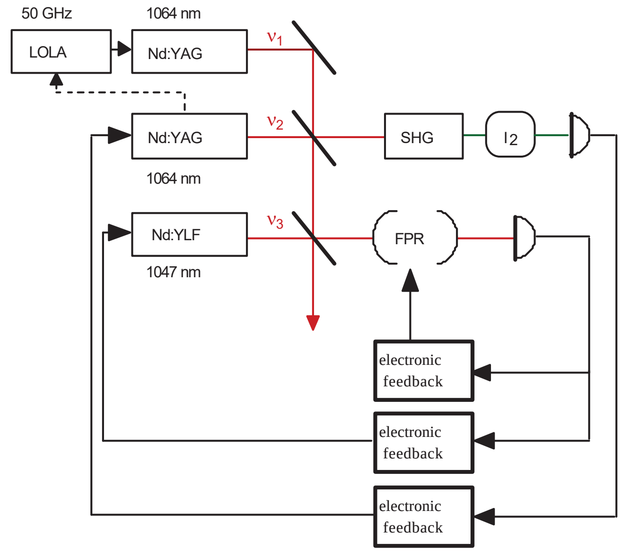

Figure 5: Possible concept for the multiple-wavelength source. LOLA: laser offset locking system (Lightwave); SHG: second-harmonic generator; FPR: Fabry-Pérot resonator; I_2: iodine cell.

Technique	Unambiguity range	Resolution ($\delta\phi = 2\ \ /200$)
2λ-interferometry, $\Lambda_{12} = 6$ mm	3 mm	15 µm
2λ-interferometry, $\Lambda_{13} = 65$ µm	32.5 µm	162 nm
1λ-interferometry, $\lambda_1 = 1.064$ µm	532 nm	2.6 nm

Table 3: Multiple-wavelength interferometry with synthetic wavelengths Λ_{12} generated with the laser-offset locking technique and Λ_{13} generated with $\lambda_1 = 1064$ nm and $\lambda_3 = 1047$ nm.

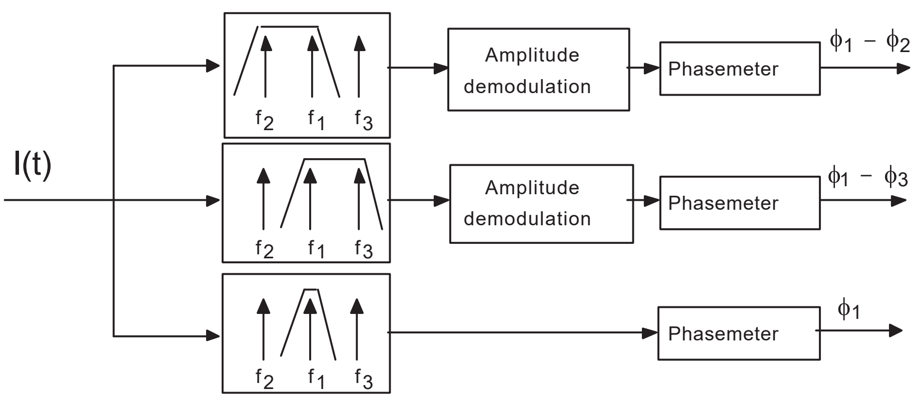

Figure 6: Heterodyne and superheterodyne detection scheme.

4. CONCLUSION

We exposed different solutions for an absolute metrology based on multiple-wavelength interferometry. The availability of highly coherent lasers around 1 µm should allow to generate a chain of synthetic wavelengths, in order to achieve absolute distance measurements with a few nm accuracy. An absolute metrology system based on multiple-wavelength interferometry could bring substantial advantages for the Darwin mission, since it could control the hexagonal configuration of the spacecrafts and ensure that the telescopes fly equidistantly from the central beam combiner.

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