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Absolute Metrology for Stellar 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.

Keywords: Multiple-wavelength interferometry, absolute distance measurement, metrology.

1. INTRODUCTION

The purpose of the Phase Referenced Imaging and Micro-arcsecond Astrometry facility (PRIMA) within the VLTI is to enable simultaneous interferometric observations, with two or more telescopes, of a reference and a science objects that are separated by up to 1 arcmin[1,2]. For micro-arcsecond astrometry, the internal optical path difference has to be measured with an accuracy of at least 5 nm over the baseline length of the two telescopes (up to 130 m). This task requires a highly accurate interferometric metrology system. The actual concept for PRIMA does foresee a calibration procedure to avoid the need for an absolute metrology system. The zero-ΔOPD is thus calibrated by injecting the reference star in both stellar interferometers (primary and secondary). During all this calibration procedure, the laser metrology must not be interrupted to avoid the loss of the zero reference.

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[3]. 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 zero-OPD calibration 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 the zero reference, which requires a new calibration, starting at zero optical path difference. If the optical path difference can be determined rather absolutely than incrementally, the calibration of the zero-*OPD* using either an internal white-light source or stellar light is not required any more. This could simplify therefore the calibration scheme. Furthermore, absolute metrology would not require an uninterrupted process any more. For PRIMA, an absolute metrology could significantly reduce the complexity of the star separator design. For DARWIN, the absolute metrology should allow to measure accurately the position of the spacecraft, and to ensure that the telescopes fly equidistantly from the central beam combiner.

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 over 60 mm 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[4]. Instead of one phase measurement for a fixed separation $\Delta\lambda = \lambda_1 - \lambda_2$ of the two wavelengths, two phase measurements are performed before and after a change of the wavelength difference $\Delta\lambda$ between the two sources.

3.1 Multiple-wavelength interferometry with fixed synthetic wavelength

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 4 lasers.

Technique	Unambiguity range	Resolution (2π/200)
Distomat DI2002 (Leica)	> 1 km	1 mm
2λ-interferometry, $\Lambda_1 = 5$ mm	2.5 mm	12 µm
2λ-interferometry, $\Lambda_2 = 50$ µm	25 µm	120 nm
1λ-interferometry, $\lambda = 1$ µm	500 nm	2.5 nm

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

3.2 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}[4,5]. 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 with variable synthetic wavelength and classical incremental interferometry. The TWI system should allow to determine the number of optical wavelength. 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 (δφ = 2π/200)
Variable synthetic wavelength, Δν = 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 laser is interrupted.

3.3 Sources

In any case, one of the optical wavelengths has to be stabilized and known with a high accuracy (at least $8\cdot10^{-8}$ for PRIMA). 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 stringent (> 100 m).
In the case of MWI with fixed wavelengths, the different wavelengths must be stabilized with respect to each other with a 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[6], 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[7,8]. 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.

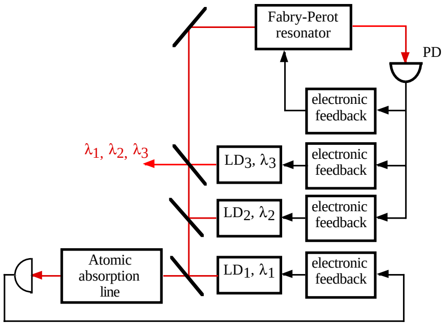

Figure 4: Example of multiple-wavelength source.

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. Lightwave). Absolute frequency stabilization can be achieved using I_2 absorption line at 532 nm and a frequency doubling crystal[9]. Smaller synthetic wavelengths (< 1 mm) could possibly be generated with an additional laser diode stabilized on the absorption lines of He at 1083 nm. Indeed, the use of one semiconductor laser at 1083 nm and one Nd:YAG laser at 1064 nm should allow to generate a synthetic wavelength of 60 µm, which is of a great interest in our application. In order to get a sufficiently large coherence length, the linewidth of the laser diode could be narrowed using a small external cavity[10].

In the case of 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) 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.

3.3 Detection technique

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., enables high-resolution measurements at arbitrary synthetic wavelengths Λ without the need for separation of these wavelengths optically. Moreover, it has been seen that this type of detection could also be used for PRIMA to access directly the differential OPD[11].
Different heterodyne frequencies are generated for each wavelength by means of acousto-optic modulator (e.g. 40 MHz and 40.1 MHz). For two-wavelength interferometry, the interference signal is therefore given by

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

which is the sum of the two heterodyne signals for the wavelengths λ_1 and λ_2, with the corresponding interferometric phases $\phi_1 = 4\pi\, L/\lambda_1$ and $\phi_2 = 4\pi\, L/\lambda_2$. Synchronous detection at the heterodyne frequency f_1 allows to determine the optical phase at λ_1. After amplitude demodulation, one gets

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

This signal at $f = f_1 - f_2$ makes it possible to measure directly the phase difference $\phi = \phi_1 - \phi_2 = 4\pi\, L/\Lambda$, which is now only sensitive to the synthetic wavelength Λ. We see therefore that the method allows to detect directly the phase difference and the optical phase without optical separation of the wavelength. This technique may be therefore of great interest for the desired absolute metrology system.

3. 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: (i) An interruption of the laser beams would not cause a loss of the zero-reference any more, since the optical path differences are directly measured absolutely; (ii) the delay lines could be pre-positioned faster, using the *a-priori* knowledge of the OPD. (iii) it could lead to an accurate determination of the baseline length.

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The Mitaka optical/infrared Array, MIRA-I.2

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Abstract

We present the overview and the current status of a stellar interferomter, MIRA-I.2. It is a prototype for developing advanced techniques required to obtain the scientific data with accuracy better than 1%, and it consists of two siderostats with a baseline of 30m, In order to avoid the degradation of the quality of data, MIRA-I.2 is equipped with offset telescopes, vacuum delay lines, and tip-tilt star tracker system from the beginning. We plan to investigate the factors which reduce fringe visibility and to achieve the objective in three years.

1 Introduction

The Mitaka optical/InfraRed Array (MIRA) project, of which the purpose is to construct a modern stellar interferometer in Japan, started in 1994. Though the first interferometer of the project, MIRA-I.1[1, 2], was a small interferometer, which consists of two 25cm coudé telescopes and a baseline of 4m, it achieved good results in the control system; fringe tracking system[3] and tip-tilt star tracker system. After the observation of the fringes of 9 stars and measurement of the diameter of α Tau, we closed MIRA-I.1 and begun to construct advanced interferometer, MIRA-I.2 [4].

Though the control system of the MIRA-I.1 achieved which high unity gain frequency ($\sim$100Hz), the accuracy of the measured fringe visibility was not high. One of the causes was the dispersion of air. Because the MIRA-I.1 uses broadband (800nm$\pm$200nm) light, difference of the thickness of the air through which the two beams pass degrades the measured visibility. In order to avoid this problem, vacuum delay lines are adopted in several interferometers[5]. To make use of the narrow band filter is another way to reduce the effect of dispersion. Low systematic visibility was also a problem. Shadows of the spiders which support the secondary mirror of the coudé telescope distorted the beam pattern and reduce the visibility. Concerning this problem, offset telescopes are proved to be useful to increase the visibility in radio interferometers. Another problem was the discrepancy of the tilt of two beams. Though MIRA-I.1 is equipped with the tip-tilt star tracker system, the dancing of the stellar image caused

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by the air turbulance was too large and it degrades the visibility. Therefore we intend to improve the servo system. In order to avoid these problems and to achieve the high quality data, MIRA-I.2 is equipped with the vacuum delay lines, offset telescopes, and tip-tilt star tracker system from the beginning.

The infrastructures of MIRA-I.2 are almost completed. Using this interferomter, we plan to measure the diameter of 50 stars with accuracy better than 1% in three years.

2 Overview of the MIRA-I.2

2.1 Layout

A schematic view of the MIRA-I.2 is shown in Fig. 1. MIRA-I.2 has two siderostats of which the diameter is 30cm in the north and the south domes. The beam radius of stellar light reflected by the siderostat is reduced to 6 times smaller by the offset telescope. Then it is bent by a tip-tilt mirror in each dome. Next, the ray passes through the vacuum pipes and goes into the center room which is located 12m apart from the south dome and 18m from the north dome. Then two beams are directed to the laboratory through the vacuum pipes.

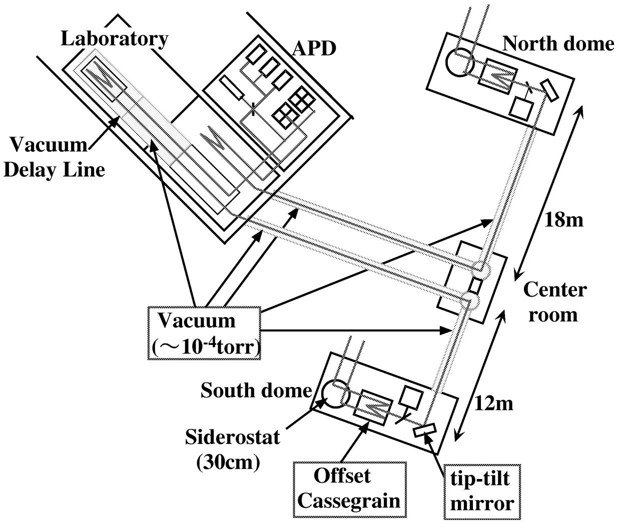

Figure 1: Schematic view of the MIRA-I.2

In the laboratory, the rays go into the vacuum delay line, which is set on the large optical bench. The length of the vacuum delay line is about 6m and a dynamic range of the delay-line cart is 4m. After the vacuum delay line, the beams are led to another optical bench where the beam intensities, tilt of the wave front, and the interference fringes are measured by APDs.

2.2 Control System

Figure 2 shows the schematic view of the control system of MIRA-I.2. One of the main difference between MIRA-I.2 and MIRA-I.1 is the remote control system of the tip-tilt mirrors and the siderostats. When we use 30m baseline of MIRA-I.2, we need to transfer the control signals for the tip-tilt mirrors and siderostats over 30m. In order to establish the control system separately, we are developing it by using 6m test baseline.

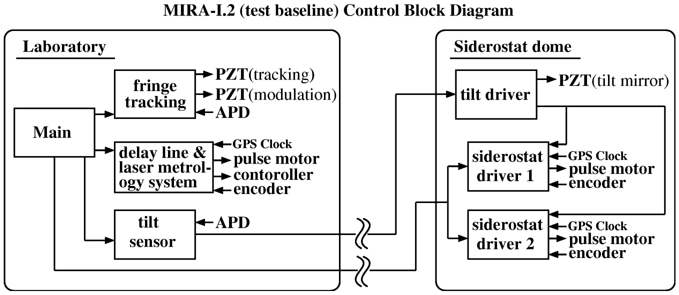

Figure 2: Control System

3 Schedule

The short-term schedule of the project is shown in Fig. 3. As we described above, we firstly use 6m test baseline in order to separate the problem caused by remote control system. Meanwhile, vacuum delay lines and other instruments are installed. We plan to obtain first fringe by using the test baseline in this autumn. Afterward, we will move the siderostats and vacuum pipes to the 30m baseline. We will rearrange the system and begin operation in winter. Other researches and developments, for example the use of narrow band filter, will start in next year.

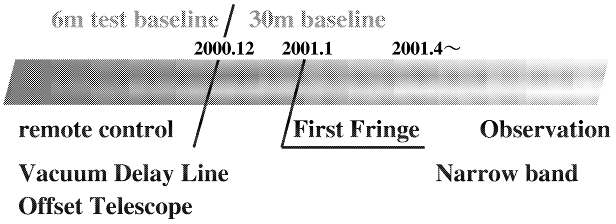

Figure 3: Short term schedule of the development of MIRA-I.2

4 Current Status

Figure 4 is a recent photograph of the site. From the left, there are north dome, center room, and south dome in a line. Behind these domes, we can see the beam combining laboratory. The vacuum pipes which connect the buildings have not been installed because they are now set at the test baseline.

Figure 4: Overview of the MIRA-I.2

Inside the laboratory is shown in Fig. 5. The delay-line cart is seen in the left and the vacuume delay line which is now under construction is seen in the right.

5 Summary

In order to achieve the highest accuracy of the system, MIRA-I.2 is equipped with several advanced instruments; vacuum delay lines, o®set telescopes, and tip-tilt star tracker system. Utilizing MIRA-I.2, we plan to evaluate and improve the performance of the system and to measure of the diameter of 50 stars with accuracy better than 1% in three years.

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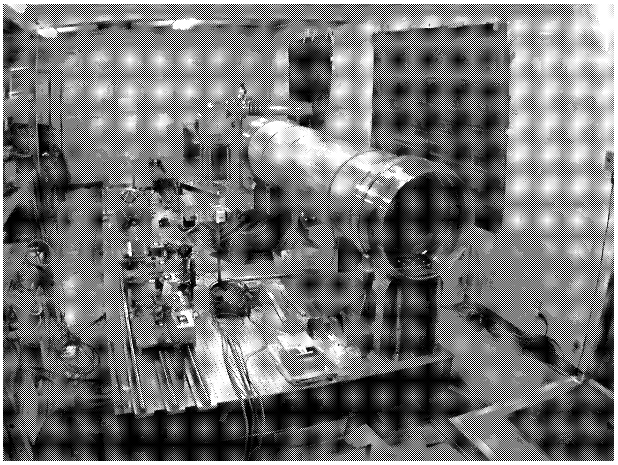

Figure 5: Photograph of the inside of the laboratory

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