Superheterodyne Laser Metrology for the Very Large Telescope Interferometer (VLTI)

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Abstract – Specific observations with the Very Large Telescope Interferometer (VLTI) require a highly accurate laser metrology system to monitor, along several hundred meters, the internal optical path followed by the stellar light. This metrology system involves a careful management of the laser beam within the VLTI as well as an accurate phase detection scheme. This paper describes results obtained on a phase meter prototype, developed to demonstrate sub-nm resolution and nm level accuracy, based on super-heterodyne detection. A description of a full-scale test foreseen at the VLT observatory is included.

1 INTRODUCTION

The Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO) will enable the coherent superposition of stellar beams coming from two or more telescopes. The purpose of the Phase Referenced Imaging and Micro-arcsecond Astrometry facility (PRIMA) within the VLTI is to enable simultaneous interferometric observations of two stellar objects that are separated by up to 1 arcmin.

The principle of phase-referenced observation is illustrated in Fig. 1. A bright reference star is fed into a primary beam combiner to stabilize the fringe motion induced by atmospheric turbulence, by actuating the Delay Lines over an optical stroke of up to 120 m. In this way long integration time can be used on a nearby faint science object. In these conditions, the optical path difference seen by the science object, OPD_S, observed on a secondary beam combiner, is given to a first order by

$$OPD_S \approx \mathbf{B} \cdot \Delta\mathbf{S} + \Delta L \quad \text{for } OPD_R = 0, \qquad (1)$$

where **B** represents the distance between the telescopes, **ΔS** is the objects angular separation, and ΔL is the internal optical path difference between the reference and science objects. OPD_S can be fine-tuned using Differential Delay Lines over an optical stroke of about 60 mm. Knowing B and by measuring independently OPD_S and ΔL, an image of the science object can be reconstructed (Phase-referenced imaging) or the star separation measured (Narrow Angle Astrometry).

Therefore a metrology system is required to monitor ΔL with an accuracy goal of 5nm to possibly reach Narrow Angle Astrometry measurements at the 10 microarcsec level [1]. This metrology system will be based on superheterodyne laser interferometry associated with a careful management of the laser beam within the VLTI.

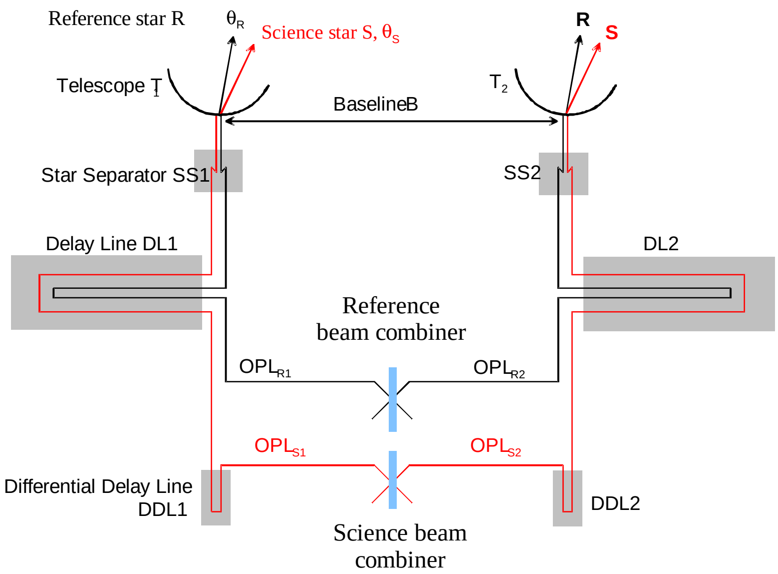

Figure 1: Schematic description of the PRIMA facility of the VLTI.

2 SUPERHETERODYNE DETECTION

Heterodyne detection is a powerful method to achieve high resolution fringe interpolation. The metrology of PRIMA will be composed of two standard heterodyne interferometers, the first one for the reference object, and the other one for the science object. In order to avoid any crosstalk between the two interferometers, two different frequency shifts f_1 = 650 kHz and f_2 = 450 kHz are chosen, and a frequency offset Δν = 80 MHz is generated between the two interferometers. After ac coupling, the two detected interference signals are of the form

$$I_{mes,1}(t) = I_1 \cos(2\pi f_1 t + \phi_1) \text{ and } I_{mes,2}(t) = I_2 \cos(2\pi f_2 t + \phi_2), \quad (2)$$

with

$$\phi_1 = \frac{4\pi\ \nu}{c} L_1 \ and\ \phi_2 = \frac{4\pi\ (\nu + \Delta\nu)}{c} L_2, \quad (3)$$

where L_1, L_2 are the internal optical path difference for the science and reference interferometer, respectively. The value of interest for the PRIMA metrology is the internal differential optical path difference $\Delta L = L_1 - L_2$. Although the individual

OPD L_1 and L_2 can reach 130 m, the differential OPD ΔL is limited to 60 mm. The individual measurements of the phases ϕ_1 and ϕ_2, suffer from several drawbacks: (i) Simultaneous measurements are mandatory to obtain the desired accuracy on the differential optical path difference interferometry, because of the speed of the delay lines (5 mm/s); (ii) the integration times must be relatively short because of the fast variations of ϕ_1 and ϕ_2; (iii) the phase noise caused by the frequency fluctuations of the laser source can be high, because of the large OPD. Superheterodyne detection, initially developed for two-wavelength interferometry [2], can be used to access directly the phase difference $\phi_1 - \phi_2$. Indeed, by mixing electronically the two interference signals and by band-pass filtering around $f_1 - f_2$, we obtain a signal

$$I_{mes}(t) = I_{12} \cos[2\pi(f_1 - f_2)t + \phi_1 - \phi_2], \tag{4}$$

which depends now only on the phase difference

$$\phi_1 - \phi_2 = \frac{4\pi\ \nu}{c}\Delta L - \frac{4\pi\ \Delta\nu}{c} L_2\,. \tag{5}$$

The first term depends only on the differential optical path difference. However, the second term is sensitive to the individual optical path difference L_2 of the reference interferometer. Since $\Delta\nu$ can be chosen small, the phase difference is not very sensitive to L_2. However, since the delay line of the VLTI can move over several meters during the observation, we have to take this phase variation $\delta\phi$ into account. For that purpose, the displacement δL_2 must be monitored with a moderate accuracy (sub-mm accuracy) using the individual interference signal $I_2(t)$.

Superheterodyne detection has several advantages: (i) It allows a more direct measurement of the differential optical path difference; (ii) the phase measurement can be performed with a longer integration time by averaging over many cycles since the phase difference $\phi_1 - \phi_2$ varies much slower than the individual phases; (iii) the phase noise of the demodulated signal is much lower than the one of the individual heterodyne signals, provided that the same laser is used for both interferometers. Indeed, the fluctuations of the phase difference are less important than the fluctuations of the individual phases, since the phase noises of the individual heterodyne signals are correlated.

3 PHASE-METER PROTOTYPE

The electronic prototype for superheterodyne phase detection is shown in Fig. 2. It consists of four photodetectors, two superheterodyne modules and a digital phase-meter. The left side of Fig. 3 shows a picture of the four VME boards constituting the prototype. The system was designed to enable nm accuracy with optical powers as low as a few 10 nW.

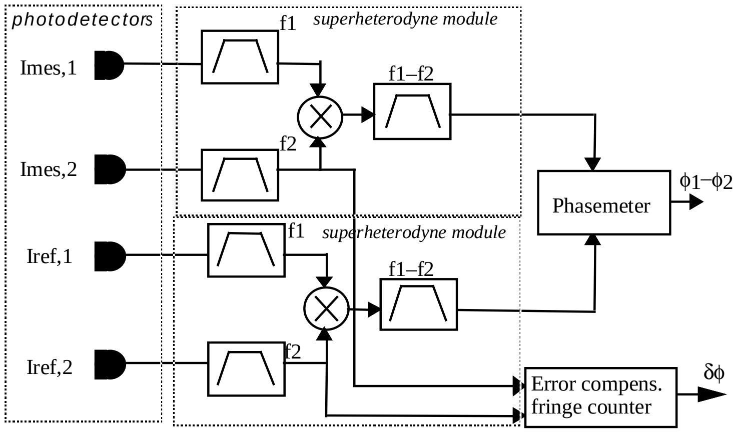

Figure 2: Concept of the superheterodyne phase detection system.

3.1 Photodetectors

Photodetectors were designed and manufactured to obtain a bandwidth of several MHz, a high voltage sensitivity and low-noise operation. InGaAs photodiodes and low noise transimpedance stages were used for that purpose. A bandwidth of 10 MHz was obtained for a voltage sensitivity of 0.88 V/µW. The noise-equivalent-power (NEP) was found to be 0.2 $pW/Hz^{0.5}$, which is very close to the Johnson noise limit given by the load resistor of the photodiode at 20°C (0.15 $pW/Hz^{0.5}$).

3.2 Superheterodyne modules

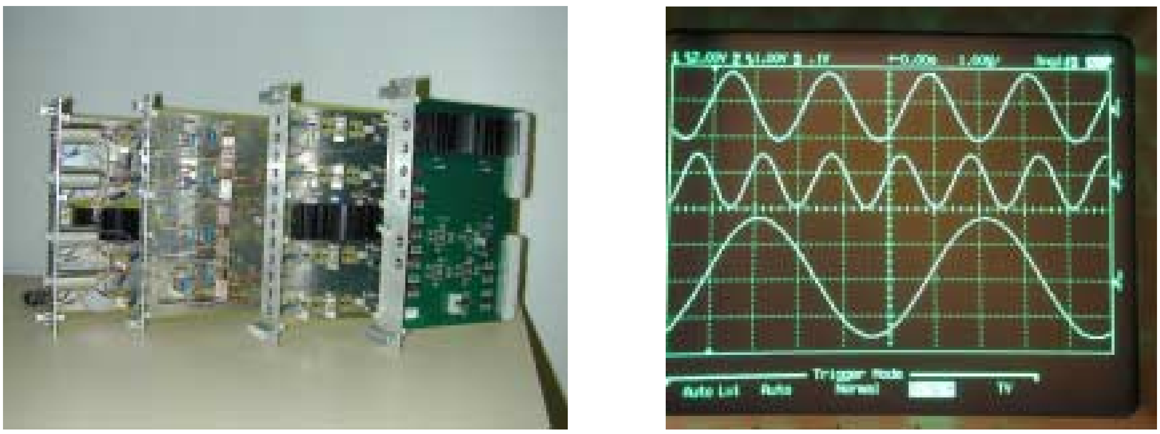

Figure 3: Picture of the VME boards (left) and picture of the heterodyne and superheterodyne signals on the oscilloscope (right).

One VME board containing two superheterodyne modules was designed and manufactured. Each module is composed of input bandpass filters around 450 kHz and 650 kHz, a frequency mixer, and an output bandpass filter around 200 kHz. It was found that the phase shifts introduced by the input bandpass filters are critical, since the tracking of the delay lines will change slightly the heterodyne frequencies. Therefore, care has been taken to minimize these phase shifts. Electrical tests showed that the phase variations introduced by the module are smaller than 0.6 deg. Preliminary optical tests have been performed by means of a Nd:YAG laser emitting at 1.32 µm (Lightwave series 125), and four fiber pigtailed acousto-optic modulators (IntraAction AOMs), to generate the heterodyne frequencies f_1 = 650 kHz and f_2 = 450 kHZ. Figure 3 shows a picture of the two individual heterodyne signals at 450 kHz and 650 kHz, and the obtained superheterodyne signal at 200 kHz.

3.3 Digital phase-meter

The concept of the digital phase-meter is described in Fig. 4. The sinusoidal reference and probe signals are first converted in square signals by means of limiting amplifiers, and are then fed to a logic circuit. The measurement principle consists of measuring the time interval between the leading edges of the reference and the probe signals.

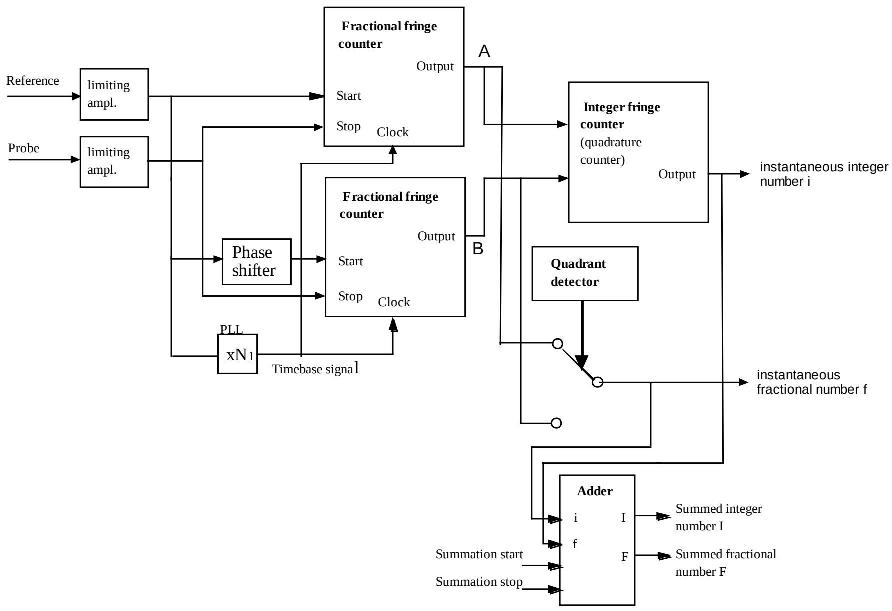

Figure 4: Concept of the digital phase-meter.

The digital phase-meter board is composed of programmable logics (Altera, MAX7000B family). The timebase signal is derived from the reference signal by a phase-locked loop, which multiplies the 200 kHz reference frequency by a factor 1024. Two measurements in quadrature are generated to avoid the problems which may happen when the phase is close to 0°. The number of 2π cycles are counted from these two quadrature signals. In addition, the board allows to average the phase over a user-defined integration time (20 µs – 0.65 s). The phase-meter board was tested with two phase-locked electrical signals. Results are shown in Fig. 5. As expected, the phase error does not exceed ±0.5 digit, that is better than 2π/1024.

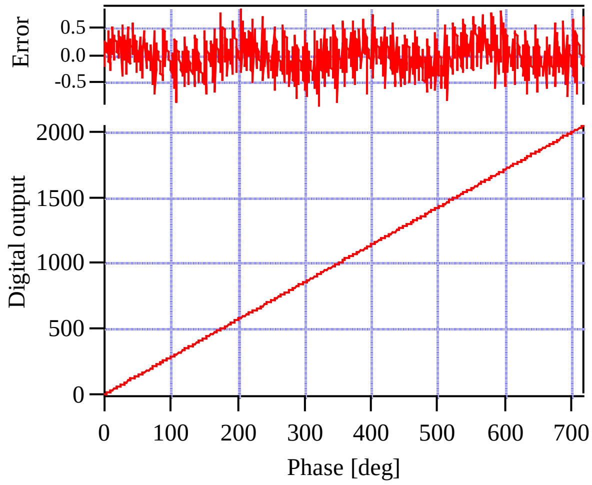

Figure 5: Electrical test of the digital board.

5 TEST CAMPAIGN AT THE VLT OBSERVATORY

The phase-meter prototype, initially tested in laboratory conditions, will be fully characterised in terms of Noise, Dynamic performance, Accuracy and Sensitivity. However, these tests must be extended to representative operating conditions at the VLT Observatory to quantify in particular the influence of the environmental conditions inside the VLTI, of the propagation length, and of the VLTI full optical train (i.e. about 20 mirrors per interferometric arm), [3]. The results will be then retro-fitted in the design of the other sub-systems of the PRIMA metrology (in particular the beam launcher, the beam combiner and the metrology end points, [1]).

The test activities will concentrate on the aspects relevant for the PRIMA metrology system:

- Quantify the amplitude and spectrum of various sources of internal OPD disturbances
- Quantify tilt errors
- Quantify polarization rotation and retardation
- Measure the noise of the metrology system in the VLTI environment (VLTI optics, long propagation path, internal seeing, Delay Lines etc....)
- Measure the laser straylight level for the required laser power determined from the above conditions.
- Measure the respective performance of the Non-polarized of the Polarized configurations [1].

In order to operate in conditions representative of the PRIMA configuration, the metrology beam will be injected in the stellar paths using “backwards” the optics of the VLTI test instrument VINCI [4]. The metrology beams will propagate through the delay lines up to the telescopes where the beam will be retro-reflected. The total optical path (return way) will be about 400 m.

Figure 6: VINCI Beam recombining optics

6 CONCLUSION

PRIMA requires a highly accurate laser metrology system to monitor, along several hundred meters, the differential internal optical path followed by the stellar light with an accuracy goal of 5 nm. This paper has presented the selected concept based on Super-heterodyne laser interferometry. A phase error better than $2\pi/1024$, i.e. 0.6 nm for λ=1.32 µm has been obtained on a prototype phase-meter. In a next step, full-scale tests will be performed at the VLTI observatory and the results retro-fitted in the design.

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