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Milestones in Physics (3)

Heterodyne Interferometry

René Dändliker, Honorary Member SATW and SSOM, Fellow OSA and EOS

Milestones in Physics (3)

Swiss research institutes and industries play a leading role to measure both quantities ‘time’ and ‘length’ with ever increasing accuracy, reliability and flexibility. Smart optical metrology concepts are the key to success. In the following we present from a first hand account how progress in optical interferometry and length measurement with nanometer precision has emerged.

Heterodyne Interferometry

René Dändliker, Honorary Member SATW and SSOM, Fellow OSA and EOS

I will tell you the story of heterodyne interferometry from my personal point of view and based on my own experience. In 1960 the first lasers were realized, in 1963 I got my diploma in physics from the ETH in Zürich and started my scientific career as Ph.D. student at the newly founded Institute of Applied Physics (IAP) at the University of Berne with the task of doing laser research, having no idea neither of lasers nor of optics. Together with two friends from the ETH, HP Brändli and Heinz Weber, and some other young colleagues, we had a very successful time during the following years, working on cw HeNe lasers, pulsed solid-state lasers, and nonlinear optics.

Heterodyne laser interferometry

To learn more about this new field of lasers, we organized in 1964 an International Symposium on Laser Physics and Applications [1]. H. de Lang and J. Haisma of Philips Research Center in Eindhoven reported on the polarization behavior of HeNe lasers with Zeeman splitting in an axial magnetic field, and F. T. Arecchi and A. Sona of the C.I.S.E Laboratories in Milano presented results on long distance interferometry over 120 m with a HeNe laser. A few years later, Zeeman splitting in HeNe lasers was used to stabilize the emission at the center of the Ne-transition at 632.8 nm (red light): a short Zeemann split HeNe laser emits two oppositely rotating circularly polarized components of the same longitudinal mode at slightly different frequencies due to induced dispersion, separated by about 2 MHz, which can be measured as an electronic beat frequency with a photo detector behind a linear polarizer. Thanks to their orthogonal polarizations those two optical frequencies can be separated by appropriate polarizing elements and sent independently into the two arms of a Michelson interferometer. The observed beat frequency at the interferometer output carries the optical phase difference of the two arms: **optical heterodyne interferometry was born!** During my stay at the Philips Research Laboratories from 1969 to 1970, I had the opportunity to work with this type of heterodyne interferometry. The heterodyne laser interferometer was commercialized by Hewlett Packard in 1970 and became the workhorse for linear displacement and velocity measurements in high precision machinery up to 40 m with a resolution of 1 nm and a typical accuracy of ±0.4 ppm.

Heterodyne holographic interferometry

When I moved in 1970 to work at the Brown Boveri Research Center in Baden, Switzerland, one of the main research topics was the application of holographic interferometry for object deformation and vibration measurements, as suggested first in 1965 by Powell and Stetson [2]. Deformation of the object appears as interferometric fringe patterns in the reconstructed image. Visual inspection of these interference patterns is limited to an accuracy of 0.5 fringe, or 0.25 fringe at its best. Remember: at that time no electronic storage and no digital evaluation of optical images were available since CCD video cameras and digital frame grabbers became only commercially available around 1985.
However, for quantitative deformation and vibration studies more accurate measurement and interpolation of the fringe pattern is required. Heterodyne interferometry would be the solution to measure directly the optical phase difference in the fringe pattern. Since double exposure holographic interferometry is the most common and convenient kind of holographic interferometry, we had to find a solution to store the two wave fields (before and after the object deformation) independently in the hologram, so that during reconstruction the required optical frequency difference between the two interfering light fields can be introduced. The most convenient realization is to use two different reference waves. The first experimental results obtained in our laboratory together with my two colleagues, B. Ineichen and F. Mottier, were published in 1973 [3]. The frequency offset (80 kHz) between the reconstructed light fields was produced with a rotating radial diffraction grating. The reconstructed image was scanned with a photo detector and the phase of the beat signal was measured with a conventional phase locked amplifier. The reproducibility of the phase reading was at any position within 0.2°, which corresponds to less than 1/1000 of a fringe. Further improvements and applications of heterodyne holographic interferometry are presented in volume XVIII of the book series *Progress in Optics*, edited by Emil Wolf [4].

During the following years after 1979, when I had moved to establish a research activity in applied optics at the newly founded Institut de Microtechnique at the Université de Neuchâtel, Switzerland, the experimental improvements and the theoretical limitations of two-reference-beam holographic interferometry was further investigated by R. Thalmann for his Ph. D. thesis (1986). Contrary to laser interferometry with a Michelson interferometer, holographic interferometry of solid objects works with a non-cooperative target, i.e., scattered light from a rough surface, giving rise to speckles in the image of objects. The statistical properties of interference detection in speckled images and the resulting phase errors were theoretically and experimentally investigated [5].

Meanwhile, around 1985, CCD video cameras and digital frame grabbers became available for image processing and evaluation. For moderate accuracy and spatial resolution, quasi-heterodyne techniques (phase-stepping) had been developed, which allow electronic scanning of the image by photodiode arrays (CCDs) or TV cameras and computer assisted digital phase evaluation [6]. Quasi-heterodyne holographic interferometry with TV detection is nearly as simple as standard double-exposure holography, and it does not require any special instrumentation apart from a video electronic data acquisition system. Therefore, it was also used in commercial equipments. That was for me the end of heterodyne holographic interferometry. An overview of the state of art in 1994 of two-reference-beam holographic interferometry is given in [7].

Heterodyne interferometry for measuring microvibrations

When I just arrived at Neuchâtel in 1978, we were asked to measure the in-plane vibration amplitude of quartz resonators for the watch industry. These resonators are a few millimeters in size, oscillate typically at 32 kHz and the mechanical amplitudes are in the sub-micrometer range. Heterodyne interferometry was the method of choice. However, the object is not a mirror, the laser light is scattered by the rough surface, giving rise to speckles. Heterodyne interferometry for measuring microvibrations was investigated theoretically and experimentally by J.-F. Willemin for his Ph. D. thesis (1984). The equipment consists of two different parts, the optics, which has to be adapted to the object and the movement to be measured, and the electronic signal processing. The light source is typically a 633 nm HeNe laser with a few mW output power. In-plane as well as out-of-plane displacements and vibrations of objects with diffusely scattering surfaces are measured in real time. Microvibrations with amplitudes down to 1 nm and frequencies up to 5 MHz were analyzed at a spatial resolution of 35 µm.

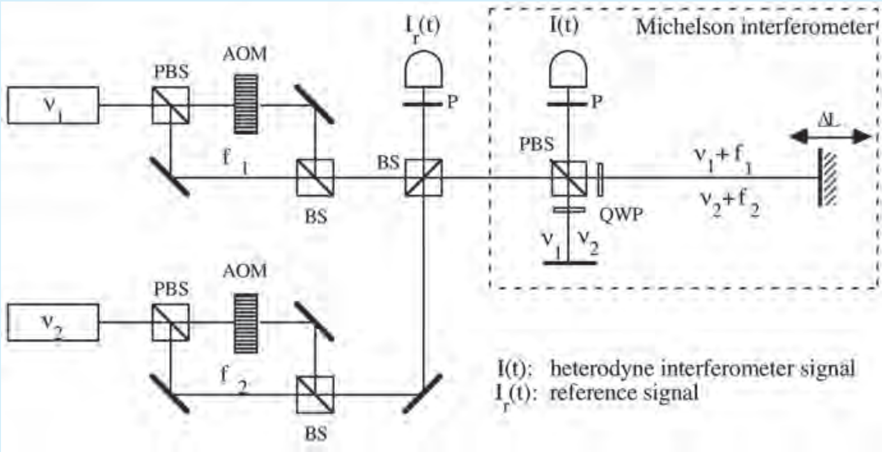
In collaboration with S. M. Khanna and C. J. Koester at the College of Physicians & Surgeons of the Columbia University, New York, we developed a noninvasive optical system for the study of the function of inner ear in living animals [8]. The objects whose vibration is to be measured (e.g., individual hair cells in the organ of Corti) are small (about 10 µm) and the reflectivity very low (about 0.001%). The confocal laser interferometer has a spot size of about 2 µm and a sectioning depth of about 20 µm. It is integrated into a white light optical sectioning microscope, which allows to visualize individual cells of the organ of Corti. Thanks to the heterodyne detection gain (reference beam power about 0.1 mW), the detection is shot-noise limited, even for very low collected light power from the object. The heterodyne signal is analyzed with a commercial low noise FM demodulator in the range of 10 Hz to 100 kHz. With an illumination power of 50 nW in the focal spot, which is below the damage threshold for the cochlear cells, the vibration sensitivity is better than 1 pm (for 1Hz bandwidth.)

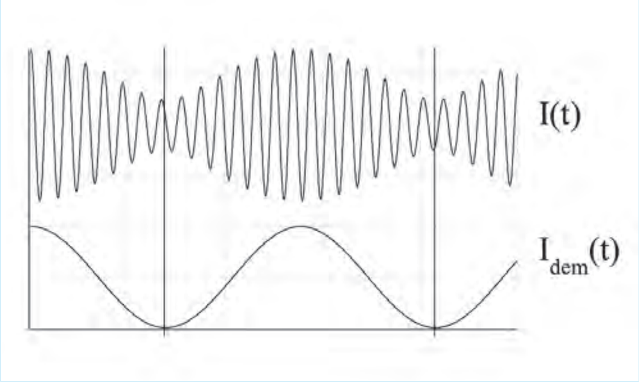
Super-Heterodyne for Multiple-Wavelength Interferometry

Laser (heterodyne) interferometry allows to measure displacements or distances up to at least 10 m by interferometric techniques. However, absolute distance measurement with a resolution of better than 0.1 mm over several meters cannot be covered by classical interferometry or by current time-of-flight metrology. Multiple-wavelength inter-

1. Super-heterodyne Detection

R. Dändliker, R. Thalmann, D. Prongué, Opt. Lett., ***13****, 339-341 (1988)*





Super-heterodyne detection enables high-resolution measurements at arbitrary synthetic wavelengths $\Lambda = \lambda_1 \lambda_2/|\lambda_1-\lambda_2|$ without the need for interferometric stability at the optical wavelengths λ_1 and λ_2, or separation of these wavelengths optically. The optical setup consists of two heterodyne interferometers with laser sources of the optical frequencies ν_1 and ν_2 for the two wavelengths λ_1 and λ_2, and several beam-splitters (PBS polarizing and BS non-polarizing) to separate and recombine the different paths. For each wavelength (optical frequency), slightly different heterodyne frequencies f_1 and f_2 are generated by the acousto-optical modulators AOM (typically f_1=40.1 MHz and f_2=40.0 MHz). Because f_1-f_2 is chosen small compared with f_1 and f_2, the detector output has the form of a carrier-suppressed amplitude-modulated signal

$$I(t) = a_0 + a_1\cos(2\pi f_1 t + \phi_1) + a_2\cos(2\pi f_2 t + \phi_2).$$

After amplitude demodulation, one gets a sinusoidal signal

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

at the frequency f_1-f_2= 100 kHz which is equivalent to the heterodyne interference signal for the synthetic wavelength Λ, with $\phi = \phi_1 - \phi_2 = 4\pi\Delta L/\Lambda$. The phase accuracy of the super-heterodyne detection is better than $2\pi/200$.

ferometry (MWI) is, as classical interferometry, a coherent method, but it offers great flexibility in sensitivity by an appropriate choice of the different wavelengths. Indeed, the use of two different wavelengths, λ_1 and λ_2, permits to generate a synthetic wavelength $\Lambda = \lambda_1\lambda_2/|\lambda_1-\lambda_2|$, much longer than the two individual optical wavelengths (***Infobox 1***). This method thus makes it possible to increase the range of non-ambiguity for interferometry and to reduce the sensitivity of the measurement. Moreover, this technique is also applicable to rough surfaces. My interest in MWI was triggered in 1987 by a request of ESTEC, the European Space Research and Technology Centre, for a study and evaluation of a metrology concept for large structures in space. In the context of this study the concept of super-heterodyne MWI was developed [9] and in 1987 a corresponding patent was deposited by our industrial partner Wild Heerbrugg AG. Super-heterodyne detection permits to measure the phase difference of two optical frequencies that cannot be resolved by direct optoelectronic heterodyne detection.

Further improvements and applications were studied by Y. Salvadé for his Ph. D. thesis (1999). Laser diodes locked to different lines of a passive frequency comb using a Fabry-Perot resonator allows one to obtain an absolute calibration of the synthetic wavelengths through electronic beat-frequency measurements. Experimental results show that a calibration of the synthetic wavelength in the millimeter range with an accuracy of better than 10^{-5} is feasible (***Infobox 2***). After a discussion with T. W. Hänsch (Nobel Prize in Physics 2005) at Theo Tschudi's 60th birthday party in Darmstadt, he invited me to present a paper on MWI for absolute distance measurement at the IQEC 2002 in Moscow. I presented the concept of using an active comb spectrum of a mode-locked laser instead of a Fabry-Perot resonator comb (***Infobox 3***). In 2006, this concept was experimentally verified [10]. Experimental results demonstrated the generation of a **90 µm** synthetic wavelength (frequency difference of 3.3 THz) calibrated with an accuracy better than 0.2 parts in 10^{-6}. Since the phase accuracy of the super-

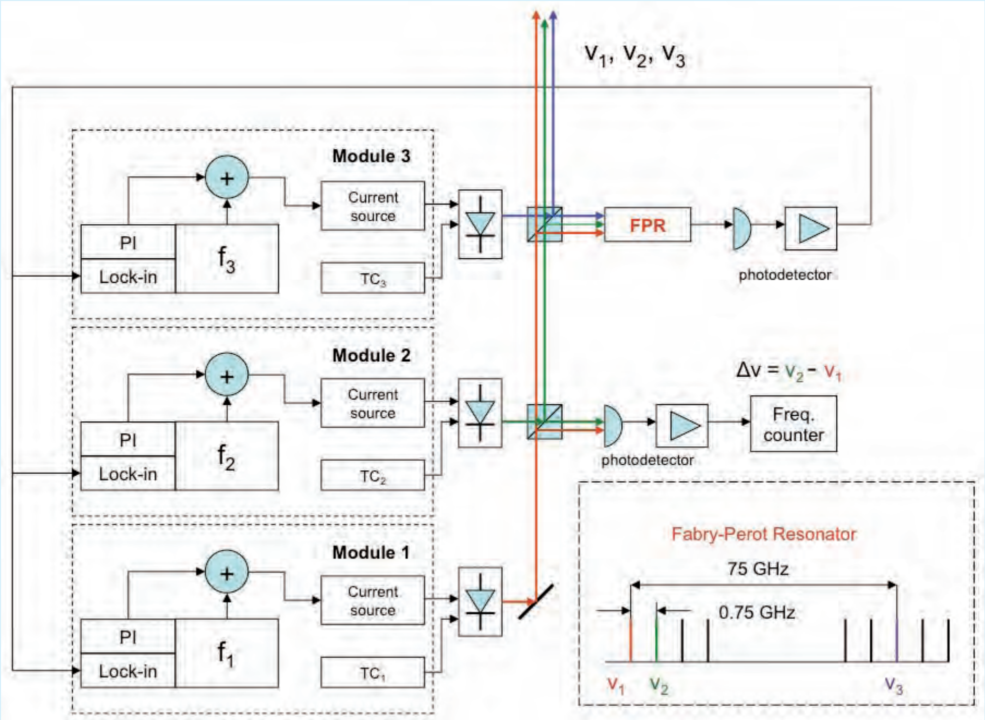
2. Calibrated Multiple-Wavelength Source using a Passive Frequency Comb

E. Zimmermann, Y. Salvadé, R. Dändliker, Opt. Lett, ***21****, 531-533 (1996)*

Laser diodes locked to different lines of a passive frequency comb using a Fabry-Perot resonator allows to obtain an absolute calibration of the synthetic wavelengths through electronic beat-frequency measurements. The block-diagram shows the realization of a calibrated three-wavelength source. It consists of three laser diodes, LD_1, LD_2, and LD_3, operating at the frequencies ν_1, ν_2, and ν_3, respectively. Two of them (LD_1 and LD_2) are stabilized on two consecutive resonances of a common stable Fabry–Perot resonator (FPR) used as frequency discriminator. In our experiment, the FPR had a free spectral range (FSR) of 750 MHz ($\nu_{21} = \nu_2 - \nu_1 = 0.75$ GHz). The corresponding beat frequency of 750 MHz is detected and measured by a frequency counter with electronic accuracy. The third laser diode (LD_3) is tuned from ν_1 to ν_3 over N resonances of the FPR. The frequency difference $\nu_{31} = \nu_3 - \nu_1 = N\,\nu_{21}$ is then known with the same accuracy as the electronically calibrated beat frequency ν_{21}. For N = 100, we obtained $\nu_{31} = 75$ GHz, which yields a synthetic wavelength of $\Lambda = 4$ mm. Experimental investigations were performed with commercial GaAlAs monomode laser diodes. For the locking of the laser frequencies on the desired resonances of the FSR, a portion of the light from the different lasers is launched into the FPR. The center frequencies of the lasers are brought, by means of temperature tuning (TC), near a resonance peak of the FPR at which the feedback loop is closed. To permit the stabilization of the laser sources, the optical frequency of the diodes is modulated by a modulation of the injection current at $f_1 = 10$ kHz, $f_2 = 40$ kHz, and $f_3 = 50$ kHz. The excursion of the optical frequency is approximately 1 MHz, which is much less than the resonance width of the FPR. These frequency modulations are then transformed by the FPR into intensity modulations, which are detected and synchronously demodulated with the lock-in amplifiers to yield the error signal for the feedback loop.

Experimental comparison with a HP laser interferometer prove that the electronic calibration of the synthetic wavelength of $\Lambda = 4$ mm is feasible with an accuracy better than 10^{-5}, although the corresponding beat-frequency (75 GHz) is well beyond the range of electronic photodetectors.

With the reported three wavelength source it is possible to measure distances without ambiguity within 0.2 m with a resolution of better than 10 µm.



heterodyne detection is better than 2π/200, this synthetic wavelength allows to resolve the optical wavelength of 1.3 µm (Nd:YAG) and to reach therefore nanometer accuracy.

Another special application of super-heterodyne laser interferometry has been developed for the Very Large Telescope Interferometer (VLTI) of ESO (European Southern Observatory) at Paranal [11]. Specific observations with the 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 an accurate phase detection scheme. For the required accuracy of 5 nm over a differential optical path of 100 mm we have developed a high-resolution laser metrology system based on super-heterodyne detection.

From Optical Wavelength to Frequency

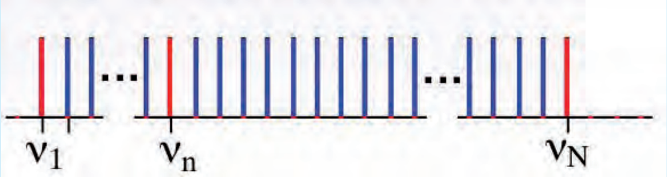
In classical optical interferometry fringes are observed and light is characterized by its wavelength. In 1960 the meter definition was based on the wavelength of the orange-red emission line of the Krypton-86 atom in vacuum. But only the advent of highly coherent and stable cw lasers allowed to measure electronic beats (MHz) of optical frequencies and direct optoelectronic detection of the interference phase by heterodyne laser interferometry (commercialized 1970). Interferometry is phase, and phase is related to frequency. Contrary to the wavelength, the frequency is independent of the refractive index of the medium and frequencies can be measured with very high accuracy by counting periods (definition of the second by the frequency of atomic clocks). Arthur L. Schawlow (Nobel Prize in Physics 1981) stated therefore: "**Never measure anything but frequency!**", which means 560 THz instead of 532 nm for visible light. Since 1999 optical frequency metrology has become reality, using frequency-comb spectra together with optoelectronic beat frequency and heterodyne detection [12].

Acknowledgment: My thanks go to Bernhard Braunecker who suggested the subject and supported me in the writing with many helpful comments.

3. Calibrated Multiple-Wavelength Source using an Active Frequency Comb

The following figure shows the system layout parameters as proposed by R. Dändliker at the IQEC 2002, Moscow, leading to small synthetic wavelengths ($\Lambda \approx 60$ µm).

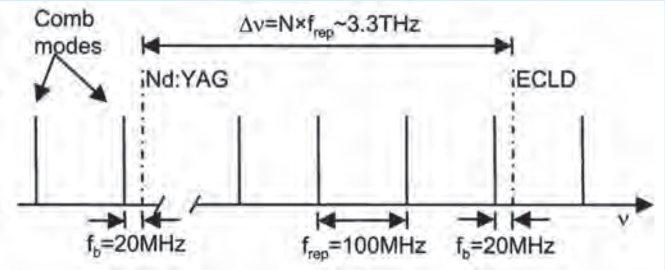
Spectrum of a mode-locked cw fs laser
Example: $\delta\nu = \nu_2 - \nu_1 = 500$ MHz
$\nu_n - \nu_1 = 10^2\,\delta\nu = 50$ GHz $\Longrightarrow \Lambda_n = 6$ mm
$\nu_N - \nu_1 = 10^4\,\delta\nu = 5$ THz $\Longrightarrow \Lambda_N = 60$ µm



This layout was later modified and experimentally verified by N. Schuhler, Y. Salvadé, S. Lévêque, R. Dändliker, R. Holzwarth, Opt. Lett., **31**, 3101-3103 (2006):

An active frequency comb is based on a fs mode-locked laser, whose repetition rate, f_{rep}, defines exactly the frequency separation $\delta\nu$ between two adjacent modes of its frequency spectrum. Several cw lasers can be locked to different modes of the comb by beat frequency measurements and electronic phase locked loops. The stability of the laser frequency separation is determined entirely by the relative stability of the frequency reference used to control the repetition rate of the fs laser. To cancel the frequency drift of the comb, either the comb can be self-referenced or one of the lasers can be locked onto a molecular transition and the comb locked to that laser through control of the comb offset.

The tunable two-wavelength source consists of a Nd:YAG laser ($\lambda_1 = 1.319$ µm), an external cavity laser diode (ECLD, $\lambda_2 \approx 1.3$ µm), and finally a mode-locked fiber laser (Menlo Systems TC-1500). A 10 MHz frequency reference with a relative uncertainty of $<10^{-11}$ is provided to the comb by a radio-controlled master clock synchronized to the carrier frequency of the Swiss time signal (HBG), which is derived from an atomic clock. This reference is used by the TC-1500 to generate two sub-references (100 MHz and 20 MHz) with the same relative uncertainty. The concept of the mutual stabilization of the lasers is as follows: one comb mode of the mode-locked fiber laser is locked to the master Nd:YAG laser, and the ECLD is locked in turn to another comb mode. In practice, the repetition rate is phase locked to the 100 MHz reference signal by changing the pump power of the fs laser. For each cw laser, the beat signal f_b with the closest mode of the frequency comb is detected and phase locked to the 20 MHz signal. The frequency comb is stabilized on the Nd:YAG laser by controlling the length of its cavity. The ECLD is locked to the comb by tuning its injection current. To prove the feasibility, we directly operated with a small synthetic wavelength of $\Lambda \approx 90$ µm ($\Delta\nu \approx 3.3$ THz). Experimental comparison with a calibrated 5529A HP laser interferometer (accuracy ± 0.02 ppm) prove that synthetic wavelengths as small as 90 µm can be generated with an accuracy better than 0.2 parts in10^6 (0.2 ppm). Since the phase accuracy of the super-heterodyne detection is better than 2π/200, this synthetic wavelength allows to resolve the optical wavelength of 1.3 µm (Nd:YAG) and to reach therefore nanometer accuracy. Using frequency-comb spectra together with opto-electronic beat-frequency and heterodyne detection, optical frequency metrology has become reality.



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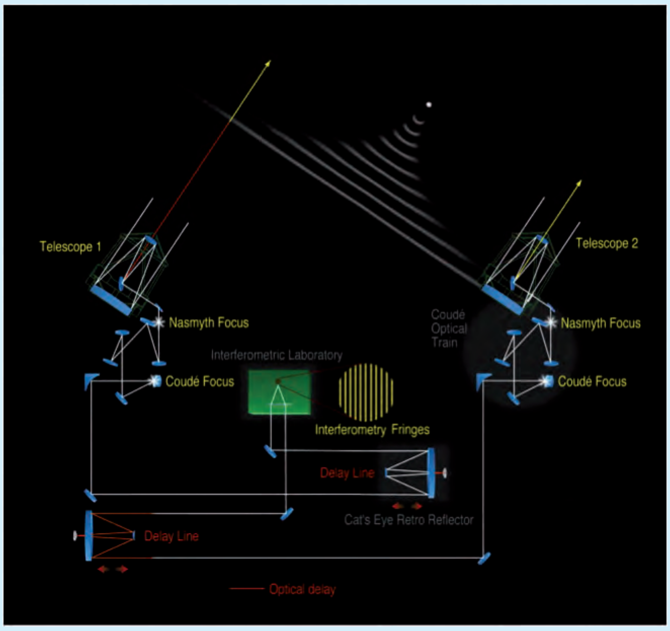
4. Astronomy

Another special application of super-heterodyne laser interferometry has been developed for the Very Large Telescope Interferometer (VLTI) of ESO (European Southern Observatory) at Paranal [11]. The VLTI allows the coherent superposition of the stellar light collected by two 8-m-diameter telescopes separated by more than 100 m. In order to achieve this, the optical paths for the light captured by the two telescopes must be equal and kept constant to within a fraction of a micron using movable optical delay lines.

The **PRIMA instrument** (Phase Referenced Imaging and Micro-arcsecond Astrometry) aims to improve the performance of the VLTI by observing at the same time as the object of interest (science object) a bright reference star close to it. The light from both objects travels through a delay line which is controlled by observing the interference fringes of the reference star and ensures the compensation of the optical path between the two telescopes. A differential delay line is then used to apply the necessary remaining compensation to the path followed by the light of the science object. In the VLTI, the light captured by two telescopes follows a train of 25 mirrors distributed along a subterranean path of approximately 200 meters, before being coherently combined. The fringe signals are affected by static optical path differences and by time-varying optical path fluctuations due to vibrations of mechanical structures, air turbulence inside the interferometer and delay line motion.

The **PRIMA laser metrology system** is being developed to monitor optical path differences and optical path fluctuations encountered by two stellar objects inside the VLTI during phase-referenced observations. The concept of the PRIMA metrology, developed by ESO in collaboration with the Institute of Microtechnology of Neuchâtel (IMT), is based on "super-heterodyne laser interferometry", where two heterodyne Michelson interferometers are operating simultaneously and have common optical paths with both observed stars through the VLTI optical train, except for the differential delay line which compensates for the position of the science object with respect to the reference star. Each interferometer arm length reaches up to 552 m (return way). The design goal is to measure the optical path difference (differential delay line, up to 120 mm) with an accuracy of 5 nm. A prototype of the laser metrology system was tested at the Paranal Observatory [*]. Because the PRIMA star separators were not yet available on the Unit Telescopes, it was not possible to propagate the metrology beams inside the VLTI optical train in two physically separated channels (i.e., four interferometric arms), as it will be during "real" PRIMA operation. Therefore the two heterodyne interferometers were common path, which corresponds to the case when the star separators will be in calibration mode. The results obtained during full-scale testing over a path of up to 520 m confirmed that the super-heterodyne assembly of the PRIMA metrology prototype is compatible with the aimed nanometer accuracy level.



However, the **final integration of the entire PRIMA instrument into the VLTI system** failed up to now. The extreme complexity of the whole system seems to require much higher precision for all optical and mechanical components in the delay lines, the beam separators and the polarizing elements to improve the differential laser interferometry. ESO and the PRIMA project group at the Observatory of Geneva are still working on solutions.

[*] S. A. Leveque, R. Wilhelm, Y. Salvade, O. Scherler, R. Dändliker, Towards nanometer accuracy laser metrology for phase-referenced interferometry with the VLTI, Proc. SPIE vol 4338, 983-994 (2003)