Heterodyne interferometry with a frequency comb - the cornerstone of optical very long baseline interferometry?

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RÉSUMÉ. *Nous présentons un concept visant à améliorer l'interférométrie hétérodyne grâce à l'utilisation du peigne de fréquence récemment couronné par le Prix Nobel. Ce peigne de fréquence permet de stabiliser des lasers avec une précision typique de* 10^{-17} *ce qui surpasse les systèmes actuels basés sur des horloges au Césium. Ceci permettra alors de stabiliser les oscillateurs locaux des receveurs hétérodynes utilisés en astronomie avec une précision absolue de quelques* 10^{-4} *Hz. Des peignes de fréquences indépendants, situés dans différents observatoires, pourraient permettre de stabiliser des lasers au* CO_2 *utilisés comme oscillateurs locaux. Ceci transférerait le concept d'interférométrie à grandes bases du domaine radio/submillimétrique à l'infrarouge. Cette technologie pourrait ouvrir la voie à l'utilisation de bases supérieures à 100 m et pouvant atteindre plusieurs 100 km.*

ABSTRACT. *We present a new concept for the enhancement of heterodyne interferometry taking advantage of the frequency comb recently decorated with the Nobel Prize. The frequency comb allows stabilizing lasers to typically* 10^{-17} *surpassing the presently best such systems based on Cesium fountains. This will allow to stabilize the local oscillators in astronomical heterodyne receivers absolutely to a few times* 10^{-4} *Hz in the N-band. Independent frequency combs at different observatories can be used to stabilize* CO_2*-lasers as local oscillators to port the idea of Very Long Baseline Interferometry (VLBI) from the radio/submm domain into the infrared regime. This could be the enabling technology for baselines beyond several 100 m up to many 100 km.*

MOTS-CLÉS : *interférométrie stellaire, interférométrie hétérodyne, VLBI, peigne de fréquence, horloges au Césium*

KEYWORDS: *stellar interferometry, heterodyne interferometry, frequency comb, VLBI, Cesium fountain*

1. Introduction

Over the last decade, astronomical observations with interferometers have come of age producing a number of very interesting scientific results notably with the VLTI [1, 2]. As envisioned in 1983 by Lena [3], Michelson/Fizeau amplitude interferometry so far prevailed over intensity and heterodyne interferometry and provided the majority of scientific results. Intensity interferometry suffers from the lack of phase information and a low sensitivity, and heterodyne interferometry combines a modest sensitivity with a limitation to basically the N-band.

Our new concept for heterodyne interferometry takes advantage of the frequency comb recently decorated with the Nobel Prize [4]. Due to the extremely high stability of the frequency emitted by the laser, individual local oscillators at different observatories could be phase locked to frequency combs porting the idea of Very Long Baseline Interferometry (VLBI) from the radio/submm domain into the infrared regime. This could be the enabling technology for baselines beyond several 100 m up to many 100 km when a physical link between the telescope is close to impossible.

2. Principle of Heterodyne Interferometry

In amplitude interferometry the coherence function of the celestial source is determined by having the stellar light collected with two individual telescopes interfere with itself, hence *homodyne* detection. The contrast and phase of the subsequent fringe pattern represents the modulus and phase of the coherence function. The technical challenge is to ensure optical path differences (OPD) smaller than the coherence length of the observed spectral bands by using Delay Lines. In order to have reliable measurements of the coherence function the OPD needs to be controlled within fractions of the wavelength setting tight limits to the performance of the Delay Lines. The necessity of a Delay Line and optical systems to interfere the light requires a close vicinity of the two telescopes limiting the baselines and, thus, the angular resolution. However, the baseline can be as long as several 100 m if optical fibres are used to transport the light [5].

Heterodyne interferometry relies on interfering the stellar light with the light of a local oscillator, basically a monochromatic laser, producing a beat signal with a frequency in the radio range. Knowing amplitude and phase of the local oscillator, the amplitude and phase of the original stellar light are now in the beat signal. The advantage is that OPDs can be adjusted electronically and that a sophisticated Delay Line system is not required. The disadvantage is the limited sensitivity since only light from a very narrow spectral band around the frequency of the laser contributes to the beat signal

While heterodyne detection is the standard detection method from the submillimeter to the radio spectrum there has been only one heterodyne interferometer in the infrared, the Infrared Spatial Interfero-meter (ISI) [6]. Designing the ISI, the CO_2-lasers that are used as local oscillators had proven not to be sufficiently stable in frequency what converts into random phase variations. This requires optical locking of the two local oscillators to achieve a phase stability of a few degrees. The necessary optical systems between the telescopes, prevent an arbitrarily long baseline.

3. Principle of the Frequency Comb

Frequency combs have been used for more than 20 years to measure e.g. atomic fine-structure. To make it a widespread technique for optical frequency metrology a number of improvements were introduced [4].

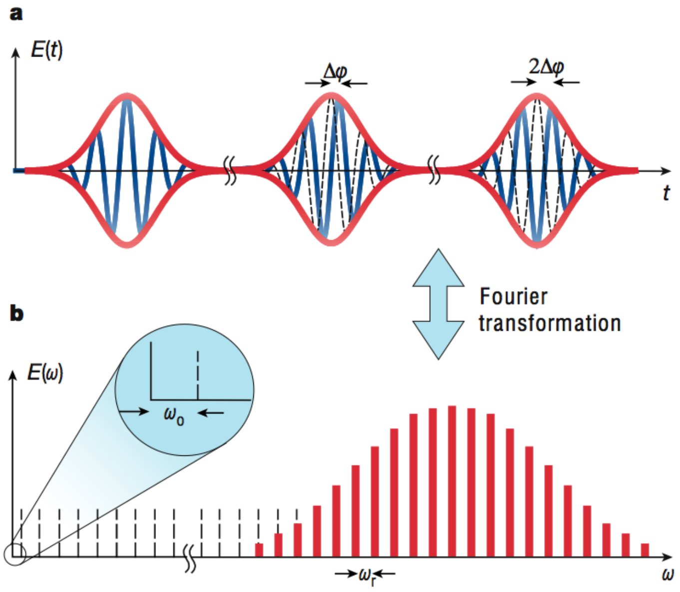

Figure 1. *Time series of pulses (a) of a mode locked laser and its spectrum (b) (Fig. from [4]) : The difference between phase and group velocity causes a phase shift* $\Delta\varphi$ *that translates into a frequency offset* $\omega_0 = \Delta\varphi/T$*, with* T *the interval between the pulses, and with the spacing of the comb* $\omega_r = 1/T$*.*

First, it was shown that the interval T between pulses, defining the mode spacing ω_r is the same across the frequency comb. Using an optical frequency interval divider (OFID), three frequencies ν_1, ν_2 and ν_3 were locked and it was checked if they obey the relation $2\nu_3 = \nu_1 + \nu_2$. It was found that the deviation from the perfect grid was less than 3 10^{-17}.

Second, by reducing the length of each pulse to about 3λ the envelope in Fig. 2b spans more than an octave making it particularly simple (using non-linear crystals for frequency doubling) to obtain the offset frequency ω_0. Determining ω_0 and ω_r the spectrum is completely defined and any difference frequency is known with high precision.

4. Benefits for Very Long Baseline Interferometry

An extremely stable laser source like the frequency comb is the key element for a heterodyne interferometer consisting of physically decoupled and, thus, arbitrarily spaced telescopes.

The frequency comb, allows stabilizing lasers to typically 10^{-17} surpassing the presently best such systems based on Cesium fountains. This in turn will allow to stabilize the local oscillators absolutely to a few times 10^{-4} Hz in the N-band with $\nu = 2.5\ 10^{13}$ Hz. Two identical such systems in different observatories will have a mutual phase drift of less than about 5 degree per minute.

The problem of interfering the amplitudes has to be tackled additionally. The question is to do it in real time through waveguides or to store the data for later processing like the VLBI.

A possible implementation plan and potential science cases are described in [7].

5. References

[1] A. Richichi, and F. Paresce, ”Harvesting Scientificc Resultus with the VLTI” ESO Messenger, **114**, 26-34, 2003

[2] M. Wittkowski et al., ”Observing with the ESO VLT Interferometer”, ESO Messenger, **119**, 14-17, 2005

[3] P. Lena, ”Aperture Synthesis in the Infrared : Prospects for a VLT”, in *Workshop on ESO’s Very Large Telescope*, ESO Conf Proc 17, Eds. J.-P. Swings and K. Kjär, 129-140, 1983

[4] Th. Udem, R. Holzwarth and T.W. Hänsch, ”Optical Frequency Metrology”, Nature, **416**, 233-237, 2002

[5] G. Perrin et al., ”Interferometric Coupling of the Keck Telescopes with Single Mode Fibers”, Science, **311**, 194, 2006

[6] D.D.S. Hale, M. Bester, W.C. Danchi. W. Fitelson, S. Hoss, E.A. Lipman, J.D. Monnier, P.G. Tuthill and C.H. Townes, ”The Berkely Infrared Spatial Interferometer : A Heterodyne Stellar Interferometer for the Mid-Infrared”, ApJ, **537**, 998-1012, 2000

[7] H.-U. Käufl and A. Glindemann, ”Optical Very Long Baseline Interferometry : The Quest for Nano-Arcsec Resolution in Astronomy ?”, these proceedings, 2006

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   Visions for Infrared Astronomy, Paris, 20-22 March 2006

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3. TITRE DE L'ARTICLE :
   Heterodyne interferometry with a frequency comb - the cornerstone of optical very long baseline interferometry?

4. TITRE ABRÉGÉ POUR LE HAUT DE PAGE MOINS DE 40 SIGNES :
   Heterodyne interferometry

5. DATE DE CETTE VERSION :
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