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Swept heterodyne correlation for long-baseline stellar interferometry

Félix Gudín¹, Nicolas Forget¹

¹. Université côte d'azur, CNRS, Institut de Physique de Nice, 17 rue Julien Lauprêtre, 06200 Nice, France

Heterodyne detection of thermal light relative to a common phase reference is fundamental to heterodyne stellar interferometry. This technique allows for the reconstruction of information about stellar diameters and circumstellar environments by correlating signals from multiple telescopes without the requirement to stabilise the optical path of the ultra-weak stellar light. Pioneering work by Charles Townes and collaborators in the thermal infrared [1] demonstrated the power of this technique, achieving extreme angular resolutions on the order of a few tens of milliarcseconds ($\approx 0.2 \mu\text{rad}$) at $10.6 \mu\text{m}$. However, extending this approach to optical wavelengths faces a significant bottleneck: an inherently low [2] signal-to-noise ratio (SNR), limited by (1) the narrow detection bandwidth of electronic detectors ($< 50 \text{ GHz}$) with regards to the bandwidth of thermal sources and (2) the shot-noise fluctuations of the single-frequency reference laser.

In this talk, we present a new detection approach based on a chirped mode-locked femtosecond laser: heterodyne detection using highly chirped broadband pulses that form a cyclic, pseudo-continuous swept source. This novel local oscillator enables (1) broadband detection, (2) high-resolution spectroscopy (multi-GHz), and (3) parallel detection with simple wavelength demultiplexers. As a preliminary result, we demonstrate an all-fiber single-channel heterodyne detection of an attenuated SLED source over a bandwidth of 12 nm at $1.55 \mu\text{m}$, resulting in a detection level compatible with astronomical fluxes with short integration times (10-100 ms).

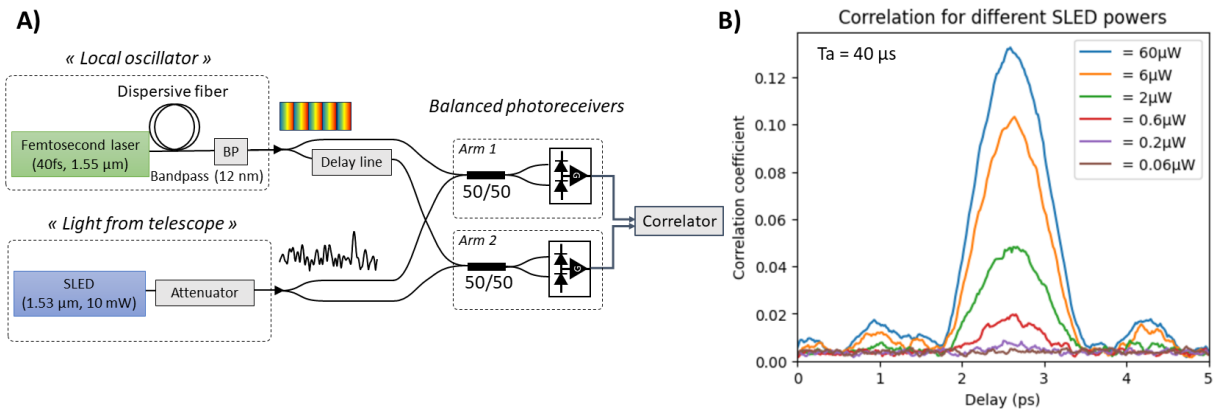


Fig. 1 A) Setup of broadband heterodyne detection using a chirped pulse train as the local oscillator. An artificial star is created using an attenuated superluminescent diode (SLED). This prototype is built with telecom-grade, single-mode, polarization-maintaining fibers. The B) Measured correlations for a decreasing power of the artificial star until the correlation signal reaches the noise level. The power values are measured at the input of balanced photodiodes. Each measurement point is the correlation between two balanced signals, sampled with an acquisition time of $40 \mu\text{s}$.

The swept source is built from an Erbium mode-locked oscillator with a repetition rate of 80 MHz . The pulses are first spectrally filtered to match the bandwidth of the SLED (12 nm), and stretched to 12.5 ns by a long dispersive single-mode fiber. The resulting instantaneous bandwidth is of 3.7 GHz . A simplified two-arm heterodyne interferometer is constructed (**Fig.1 A**) from commercial polarization-maintaining fiber components. Each arm includes a broadband 50/50 beam splitter and a 22-GHz amplified balanced detector. The two beat notes are digitalized by a 30-GHz oscilloscope and the correlation between the two arms is computed numerically. By varying the optical path lengths between the two arms, we retrieve the interferometric signal (fringe visibility and coherence length, **Fig.1 B**) of the SLED source for various input light levels. The detection limit of 200 nW for a $40 \mu\text{s}$ acquisition time is a promising result. By applying a square-root scaling factor, increasing the integration time to 40 ms will lower the detection limit down to $< 7 \text{ nW}$, which is the expected optical flux of a star like Betelgeuse ($\alpha \text{ Orionis}$) collected by a ground-based twin telescope with 1-meter mirrors.

This work demonstrates that swept heterodyne interferometry based on telecom components might provide a pathway to overcome the sensitivity bottleneck at a reasonable cost and to operate, coherently, arrays of optical telescopes with hectometric or kilometric baselines.

Example References

- [1] 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 Berkeley Infrared Spatial Interferometer: A Heterodyne Stellar Interferometer for the Mid-Infrared," *Astrophys. J.* 537, 998–1012 (2000)
- [2] M.A. Johnson, C.H. Townes, "Quantum effects and optimization of heterodyne detection", *Optics Communications*, Volume 179, 183-187 (2000)