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Frequency drift interferometry for coherent stray light measurement on the LISA space instrument, Laser Interferometer Space Antenna

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Context :

Coherent stray light is inherently a pitfall in many respects. Its measurement at the system level can pose difficulties on an assembled system, in which, for example, it is often no longer possible to introduce any instrumentation for measuring the scattered light.

The purpose of our work is to develop a general method for measuring stray light at the system level, allowing us to determine the different sources of stray light within the system to be tested, whatever its origin, and the corresponding stray light fraction. We will then implement the demonstrator for the measurement of stray light in the unit (called MOSA, for Moving Optical Sub-Assembly) of emission-reception and interferometry of the laser links of the LISA space mission (Laser Interferometer Space Antenna) for the detection of gravitational waves.

Method:

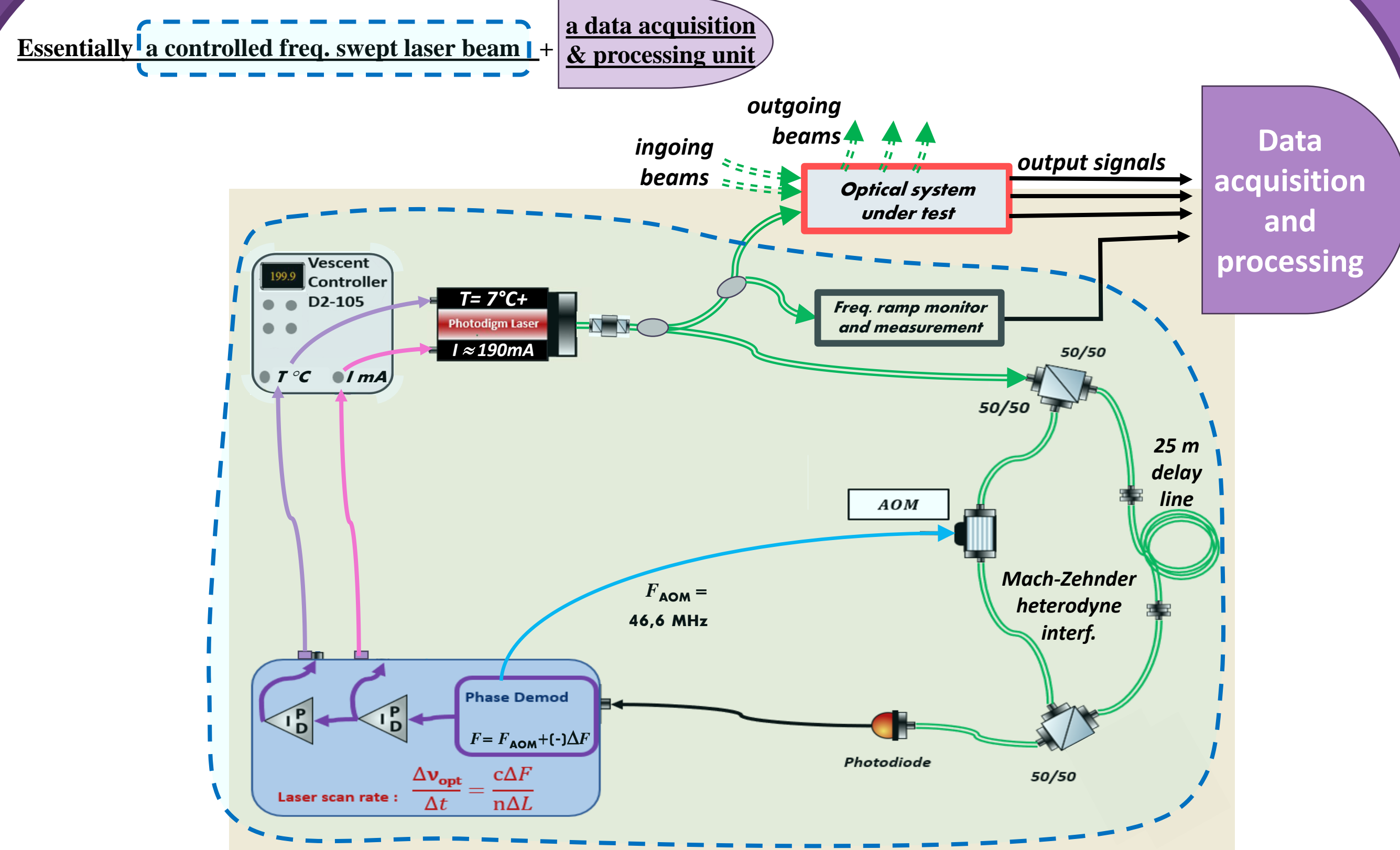
We use a single-mode laser source in which optical frequency is swept over time and inject this beam into the optical system under test. During the optical frequency scan, we record all the outgoing signals (both optical and electrical). If one or more of these signals show a fringe-like behavior, in the frequency spectrum, this modulation is interpreted as due to the presence of a stray light amplitude, interfering with the nominal light amplitude. The nominal/SL optical path difference (OPD) is retrieved from the frequency of these interference fringes (f_{itf}), as in coherent reflectometry, using:

$$f_{itf} = \frac{\Delta L \Delta \nu_{opt}}{c \Delta t}$$

where $\Delta L = L_{SL} - L_{nom}$, the Stray Light to nominal OPD, and $\frac{\Delta \nu_{opt}}{\Delta t}$ the frequency scan rate

We Fourier-transform the recorded photo signals to retrieve the list [SL amplitude vs. OPD] of the different SL contributions. Requirements for MOSA stray light tests: noise floor in fractional SL amplitude < $2.2 \cdot 10^{-6}$ and OPD resolution < 2 mm.

The SL-OGSE instrumentation :

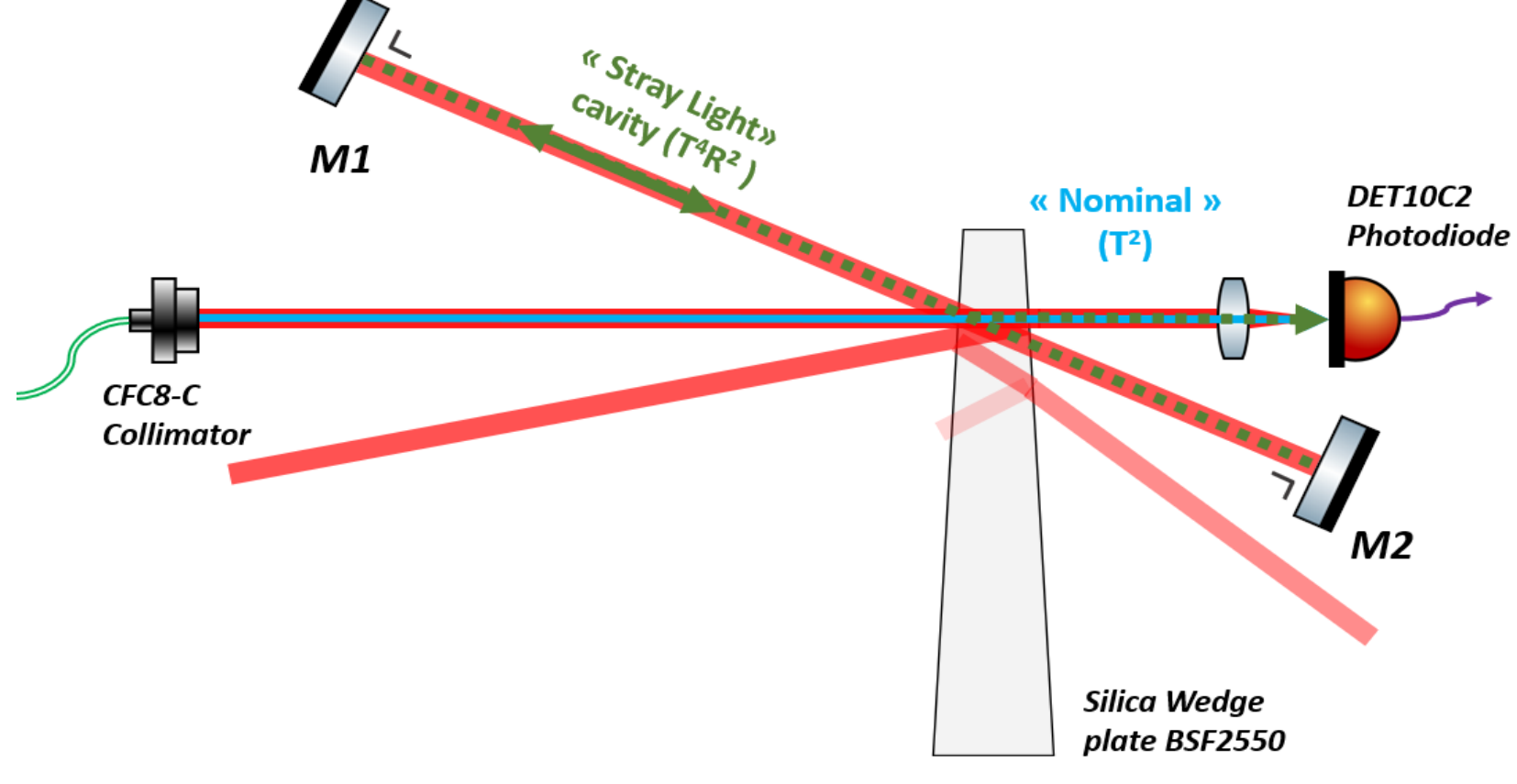


- Frequency swept laser:** 1064,5 nm fibered laser diode to be swept over at least 1 nm ($\Delta \nu_{opt} = 265$ GHz) allowing a resolution of 2 mm on the OPD SL/nominal (1 mm on the position of the stray light source). Our Photodigm laser can be scanned over 522 GHz by current and temperature control.
- Frequency Ramp Control:** Offset phase-locked loop that achieves linear optical frequency drift ($\frac{d\nu_{opt}}{dt} = Cte$) using an unbalanced fibered heterodyne Mach-Zehnder interferometer ($\frac{d\nu_{opt}}{dt} = \frac{c\Delta F}{n\Delta L_{MZ}}$). We obtain a frequency scan rate of 5.10 GHz/s for a demodulation frequency offset of $\Delta F = 577,90$ Hz, and for the unbalance $n\Delta L_{MZ} \approx 33$ m introduced by a fiber of 25 m in the Mach-Zehnder interferometer. (ref¹)
- Frequency Scan rate measurement:** Measurement of the beat frequency between the frequency swept laser and a fixed frequency 1064,5 nm laser diode. (ref²)

Calibrator: A fibered interferometer (ring cavity with $\Delta L_{calib} = 1$ m) containing two 1,55 μ m 20 dB optical attenuators (inside) to check the quality of the frequency ramp by doing a real-time interference measurement simultaneously with the MOSA tests.

MOSA simulator: Free space setup where stray light contributions with known OPD and amplitude are used to test the efficiency and accuracy of our demonstrator. The bench is composed of a silica wedge plate allowing us to generate multiple reflections/transmissions in $R \approx 4\%$ at $T=1-R$ (SL beams), mirrors M1 and M2 reflecting the stray beams: some reflections finally reach the photoreceiver placed on the nominal beam and thus appear as "stray light contributions". In our case :

- Nominal beam: First transmission at the output of the wedge (T^2)
- Stray Light beam: Power ratio $T^2 R^2 \Delta L_{MIM2} = OPD$ M1-M2 = **1,4022m**
- Cavity M1-M2 : Echoes of the SL beam every ΔL_{MIM2} , power ratio after each round trip: T^2 (if we ignore the beam divergence)

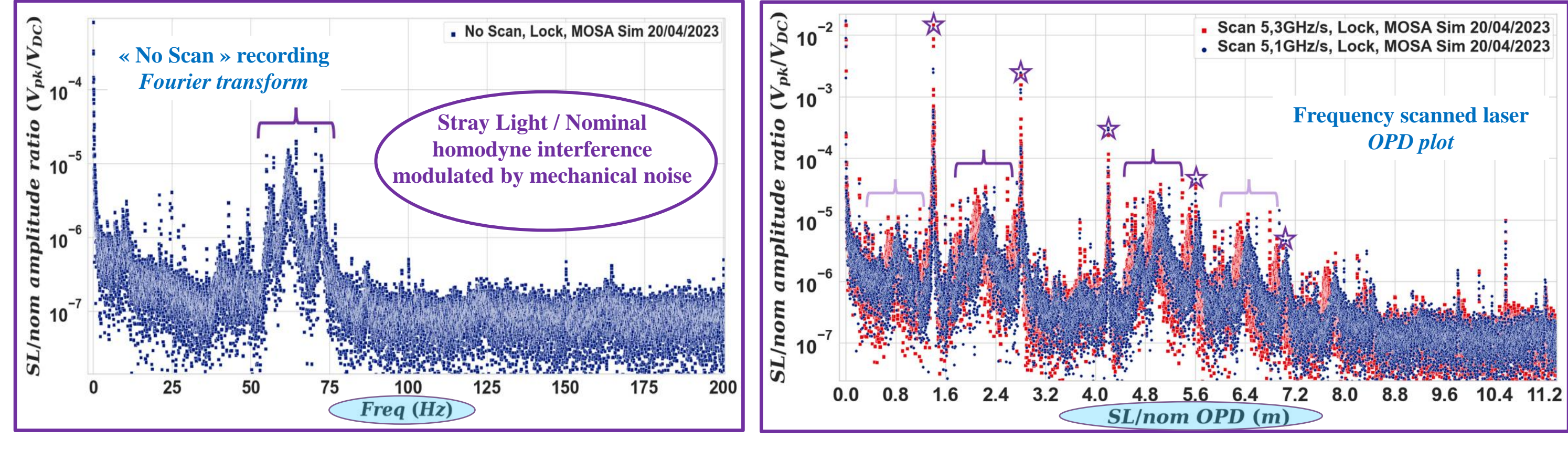


Results on the MOSA simulator's tests:

Main parameters of the stray light measurement :

- Fractional electrical amplitude between the nominal beam ($V_{DC} = 3,1$ V) and the stray light beams: $A_{itf}(V_{pk})/A_{nom}(V_{DC})$
- Optical path difference between the nominal beam and the stray light beams: **OPD ΔL_{tot}**
- Frequency scan rate of the laser: **5,10 GHz/s** (~510 GHz / 100 s.) and **5,30 GHz/s** (~530 GHz / 100 s.)

Spectra of the MOSA Sim photoreceiver:

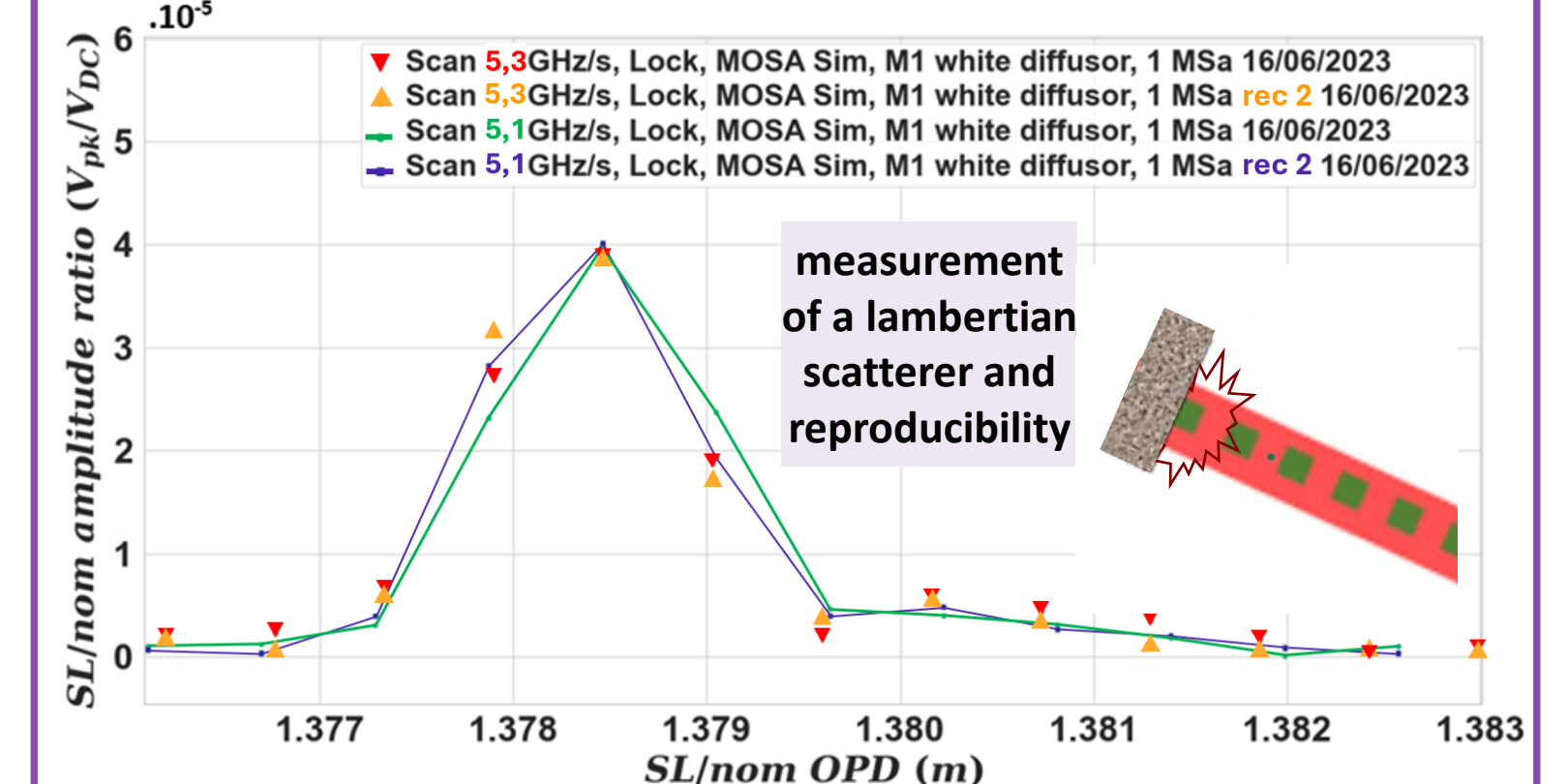
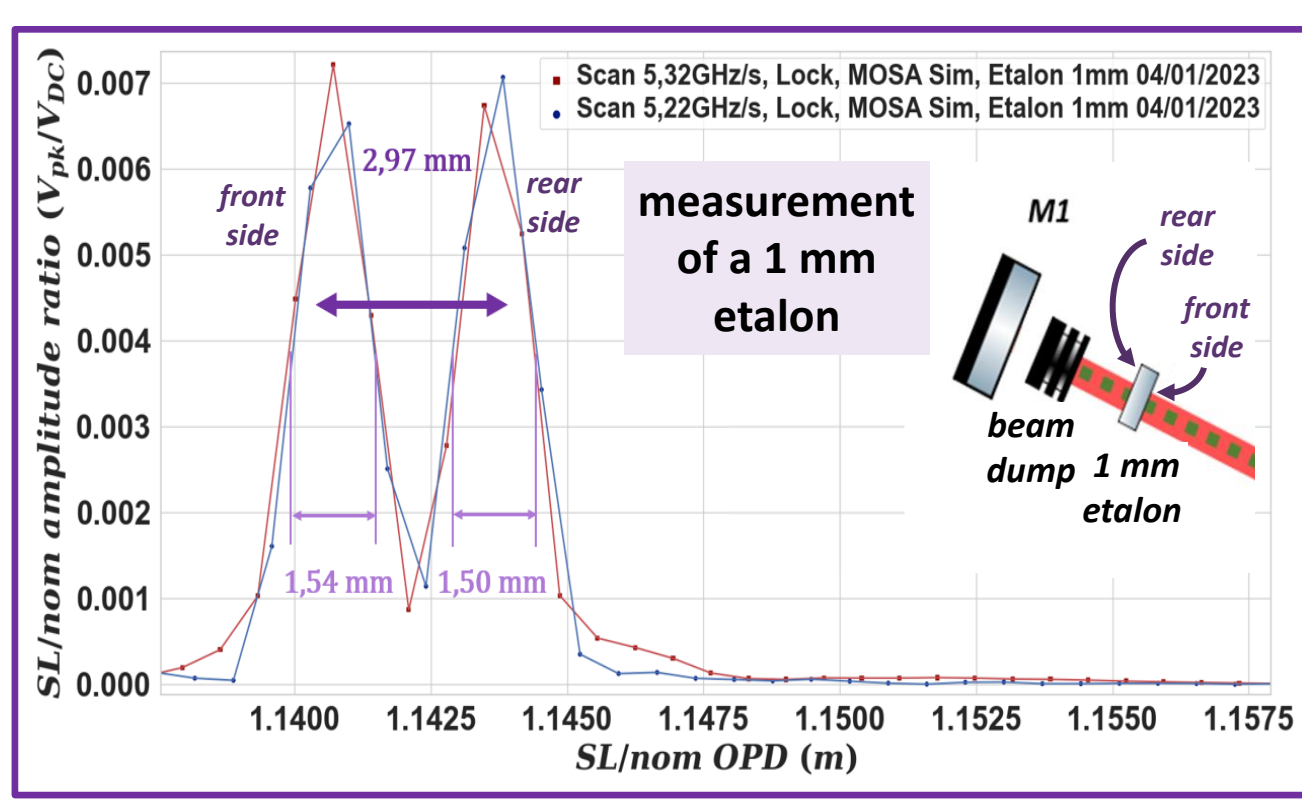
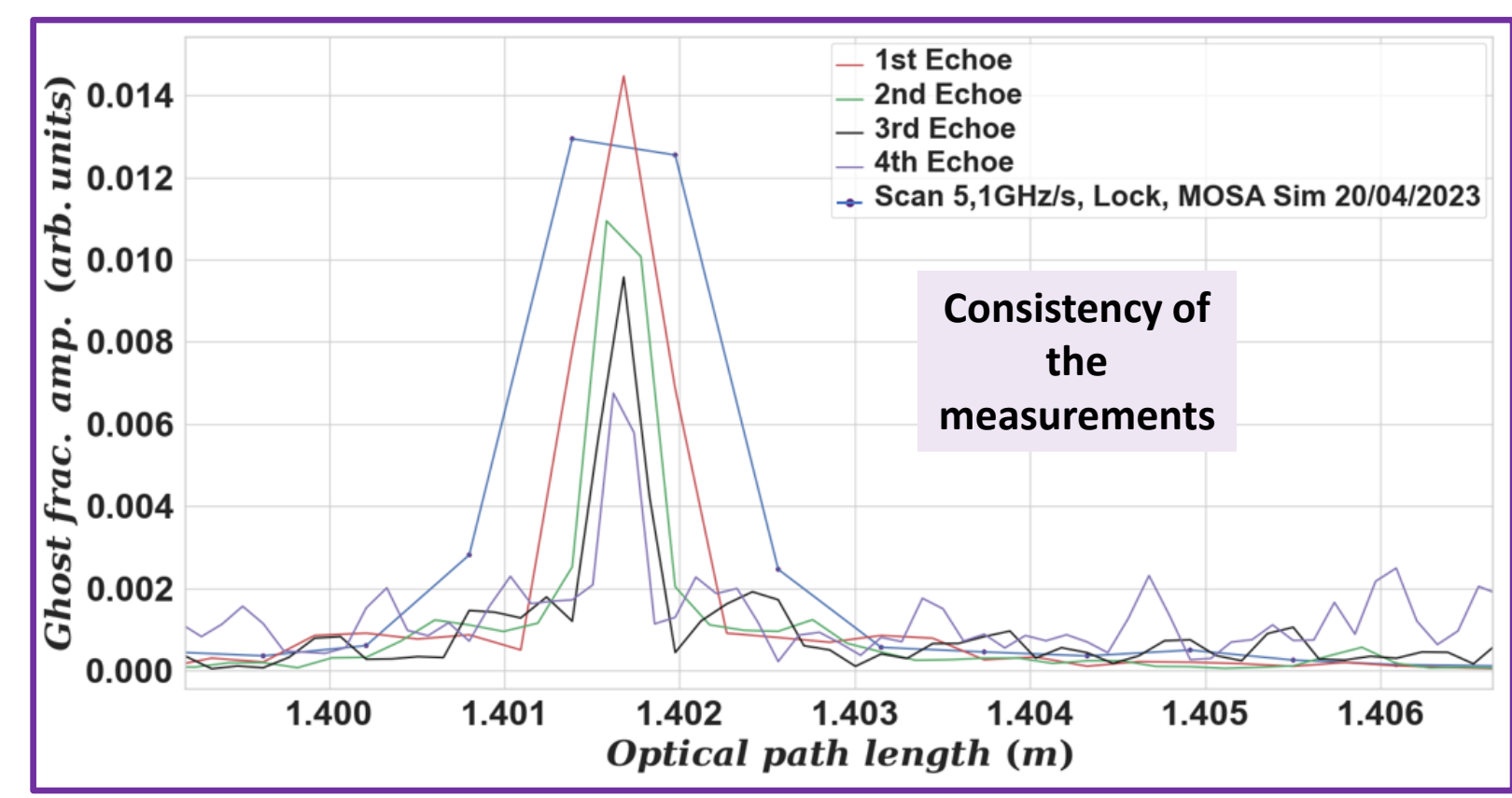


Example fractional amplitude spectra of the photoreceiver signals recorded on the MOSA-simulator set-up. Left : Signal without a scan in frequency as a function of the Fourier frequency / Right : laser scan with OPD plot. In red (resp. blue): data obtained with an optical frequency ramp rate of 5.30 GHz/s (resp. 5.10GHz/s). Stars indicate SL peaks and brackets Stray Noise peaks.

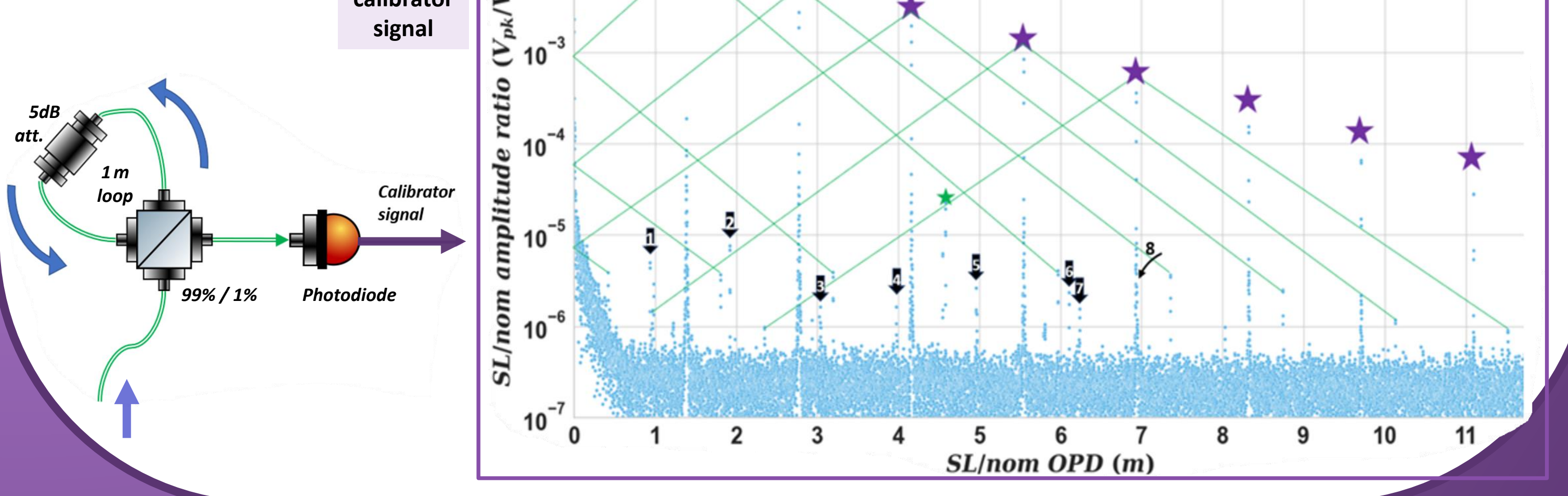
- Scans as a function of the OPD:** True SL peaks coincide (Red/Blue), whatever the scan rate (☆ SL peaks from the M1-M2 cavity)
- Mechanical noise structure (acoustic, seismic...) at $f_{mod} = 60$ Hz in the « No Scan » recording
- Amplitude loss of factor 6 in the cavity round trip due to the beam's divergence and alignment
- SL peaks modulated by mechanical noise structure at $f_{SL} \pm f_{mod}$ (dark purple bracket -> 1st SL Peak, light purple bracket -> 1st Echoe in the cavity)

OPD determination:

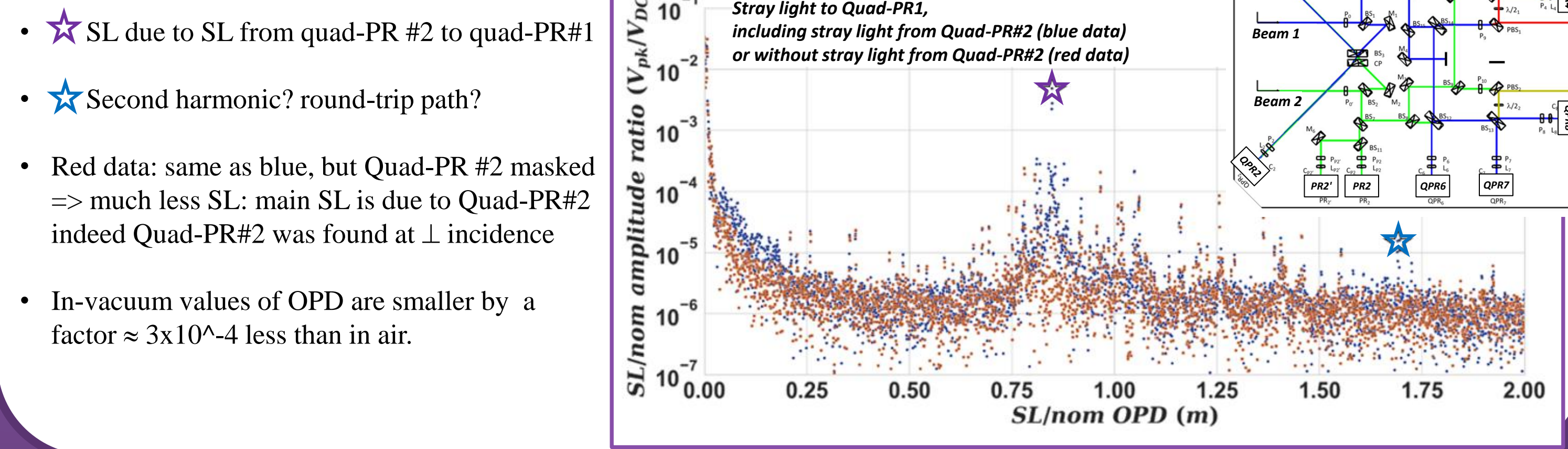
- Overlap of the N Echoes at $N \cdot \Delta L_{MIM2}$ over the main SL contribution and comparison of the peaks barycenters
- Mean barycenter at scan 5,1 GHz/s: **1,4016 m**
- Mean barycenter at scan 5,3 GHz/s: **1,4017 m**
- Max deviation with the theoretical value: **0,6 mm** on the round-trip



Monitoring of the linearity / reproducibility of the frequency ramp:



Stray Light measurement in a complex interferometer :



- ☆ SL due to SL from quad-PR #2 to quad-PR#1
- ★ Second harmonic? round-trip path?
- Red data: same as blue, but Quad-PR #2 masked => much less SL: main SL is due to Quad-PR#2 indeed Quad-PR#2 was found at \perp incidence
- In-vacuum values of OPD are smaller by a factor $\approx 3 \cdot 10^{-4}$ less than in air.

Conclusions:

Spectral analysis displays the expected stray light contributions and the SL/nominal path difference is measured, confirming device's functionality. Consistency / reproducibility / resolution are at the 0.1mm level in OPD. The two front and rear sides of a 1mm silica etalon are totally resolved. Scattered light is also observed and measured. Measurement floor at about 10^{-6} in fractional optical amplitude above ≈ 1 Hz. Improvement by normalization is under way, to subtract laser RIN. Foreign perturbations (line power pick ups, acoustic / seismic pick-up etc) are removed by two scans at two different frequency ramp rates. Presence of parasitic SL contributions coming from our fibered setup. Chromatic dispersion in the reference interferometer fibre does not affect the linearity of the frequency scan. Most significant imperfection: the polarisation wobbling in the PM fibres (adds side bands to the signals, as any perturbation does)

¹ H. Jiang, F. Kéfélian, P. Lemonde, A. Clairon, and G. Santarelli, "An agile laser with ultra-low frequency noise and high sweep linearity," Opt. Expr. 18, 3284 (2010)
² N. Chiodo, K. Djerroud, O. Acef, A. Clairon et P. Wolf, "Lasers for coherent optical satellite links with large dynamics," Appl. Opt., vol 52, pp. 7342-7351, 2013.