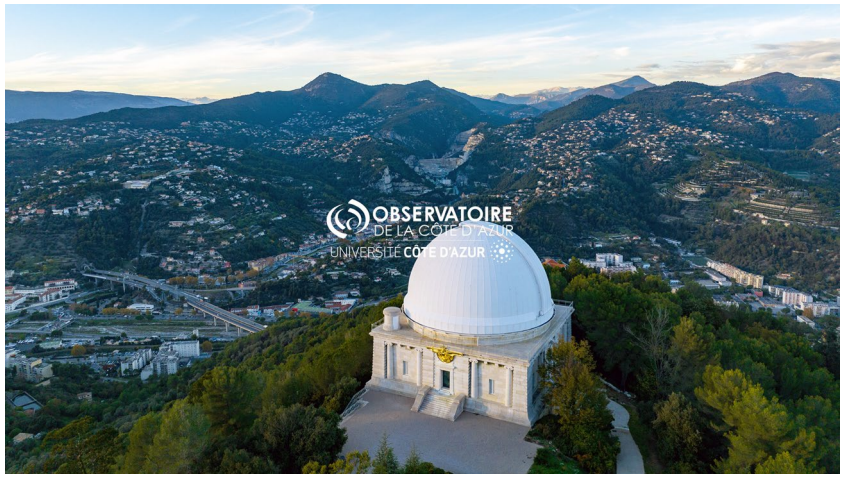
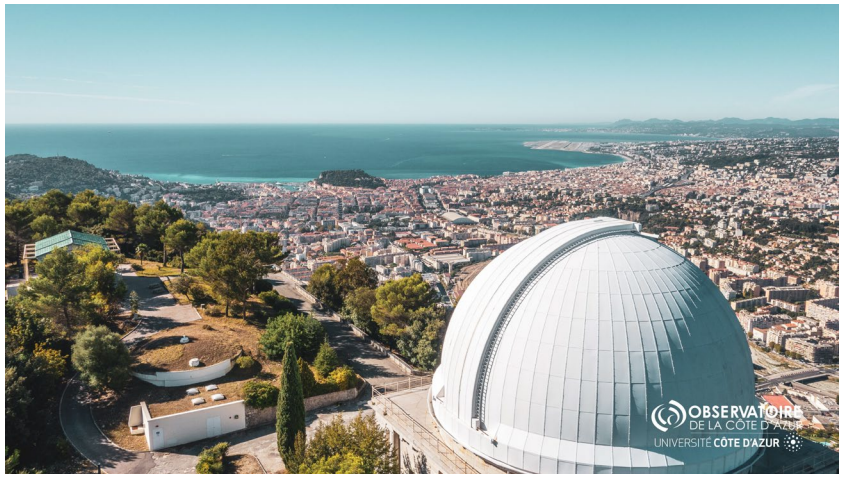




Photoreceivers for laser interferometry in space – LISA mission

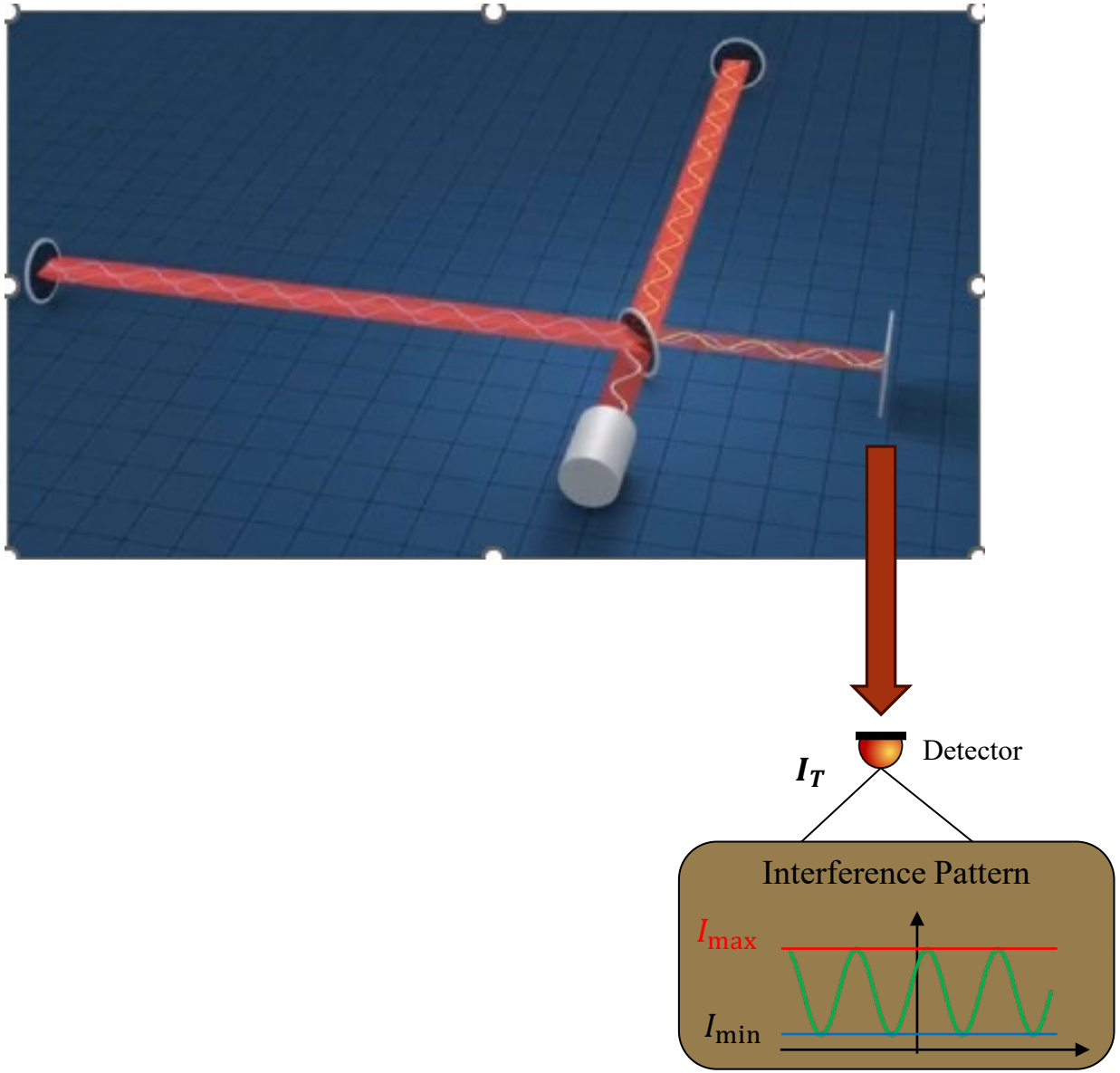
Nicoleta Dinu-Jaeger / Laboratoire ARTEMIS/ CNRS - Observatoire de la Côte d'Azur - UniCA
COMET, Opto-electronics detectors for scientific space applications, ISAE-SUPAERO, 13.06.2024

Outline

- Laser interferometry
  - Tiny distance variation measurements
- Scientific space missions using laser interferometry
- LISA mission, photoreceivers & ARTEMIS activities
- Future scientific missions using laser interferometry
  - Next generation photoreceivers

Laser interferometry

- Michelson interferometer



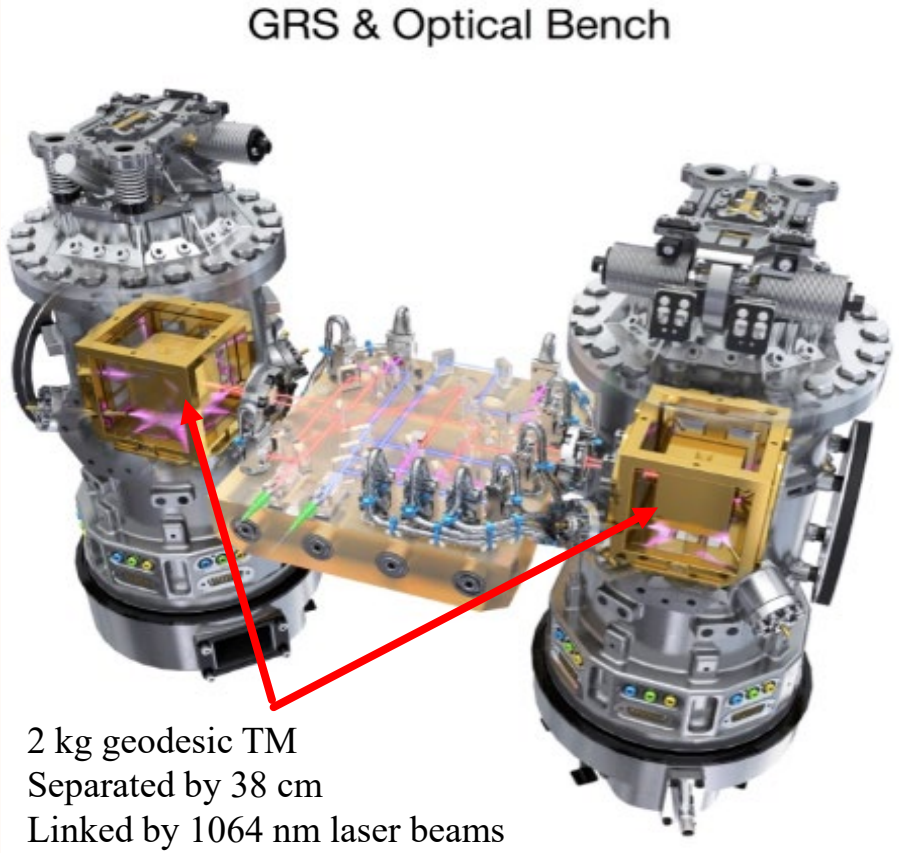
- Optical signal detection and Phase measurement

$$I_T = \underbrace{I_1 + I_2}_{I_{DC}} + \underbrace{2\sqrt{I_1 I_2}\cos\left(2\omega t + \frac{2\pi}{\lambda}\cdot 2\Delta L\right)}_{I_{AC}}$$

- Allow to measure tiny (µm to pm) variation of distances over long distances (km to Mkm)

Laser interferometry in space physics experiments

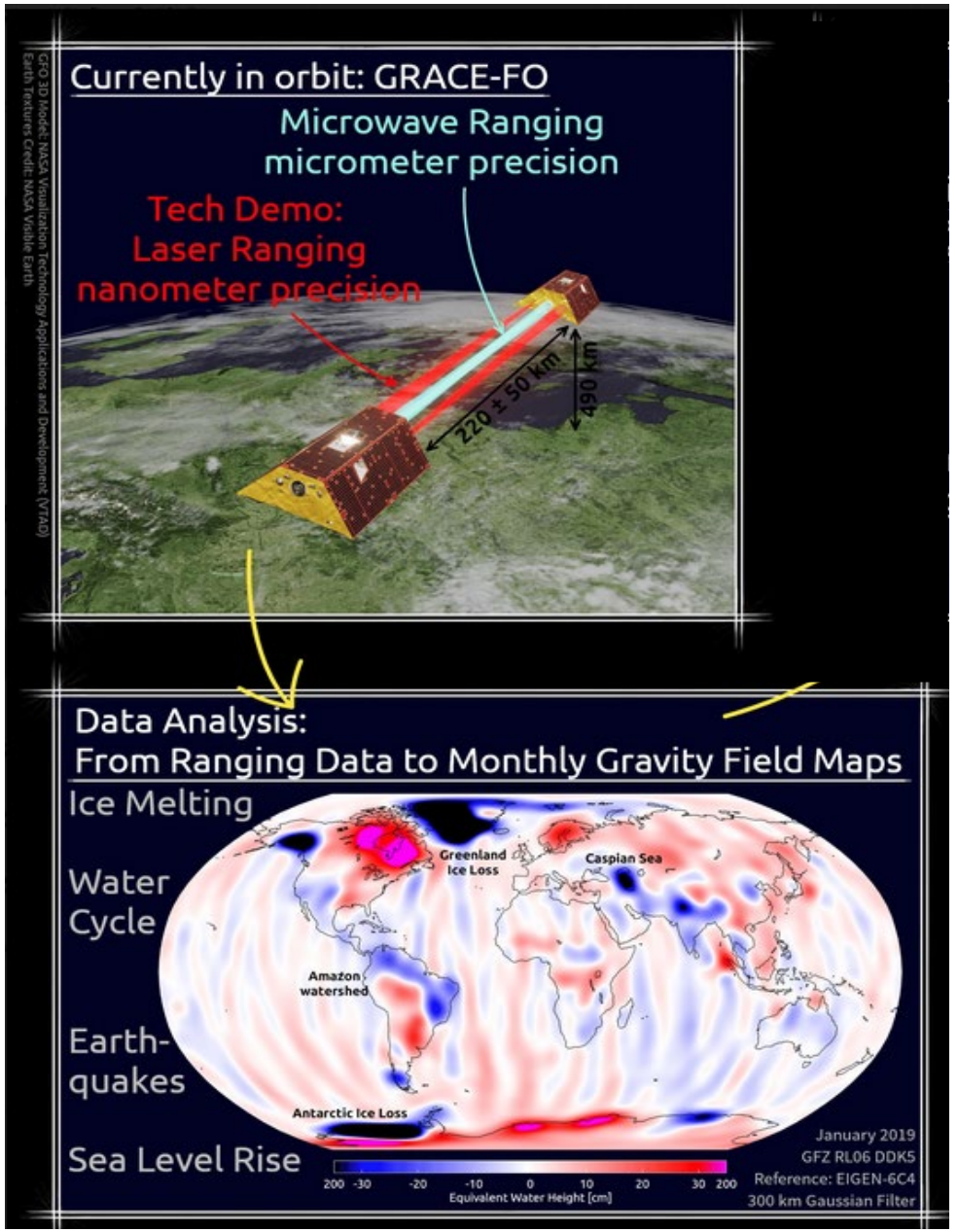
- LISA Pathfinder
  - 180-days mission 2016 - 2017
- Objectif
  - LISA mission precursor to test free-falling mass technology using laser interferometry
- One satellite
  - 2kg geodesic TM, 2 kg, 4 cm, 38 cm distance
- High performance measurements, 2x better than requirements
  - Differential acceleration noise: ~5.2 fm s-2/√Hz, f ∈ (0.7 – 20) mHz
  - Displacement readout noise: ~35 fm/ √Hz, f > 60 mHz



2 kg geodesic TM
Separated by 38 cm
Linked by 1064 nm laser beams

Laser interferometry in space physics experiments

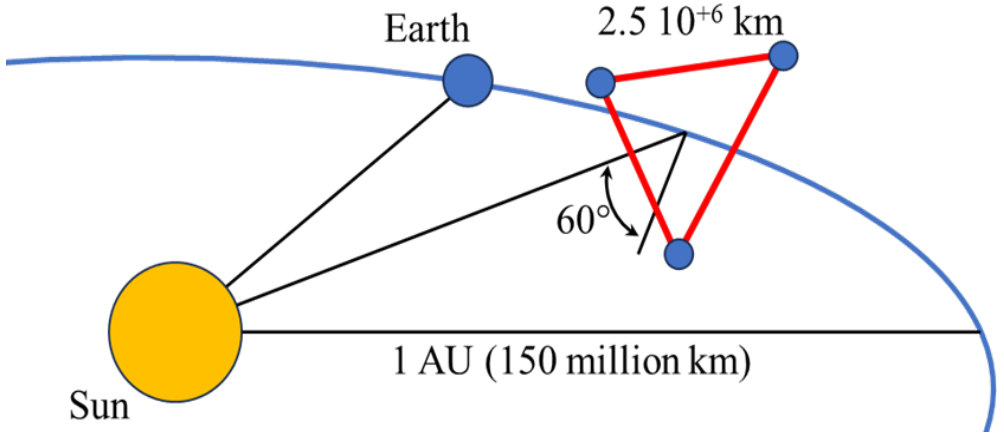
- Gravity recovery and Climate Experiment (Grace-FO) (US-Germany)
  - Two satellites in geocentric orbit since 2018
    - 220 km distance
    - 490 km altitude
  - Measure distance between satellites using laser interferometry with nm accuracy
  - Distance between two satellites is affected by Earth gravity field changes
  - Gravity field changes used to measure indicators of climate change (melting polar ice or groundwater levels)



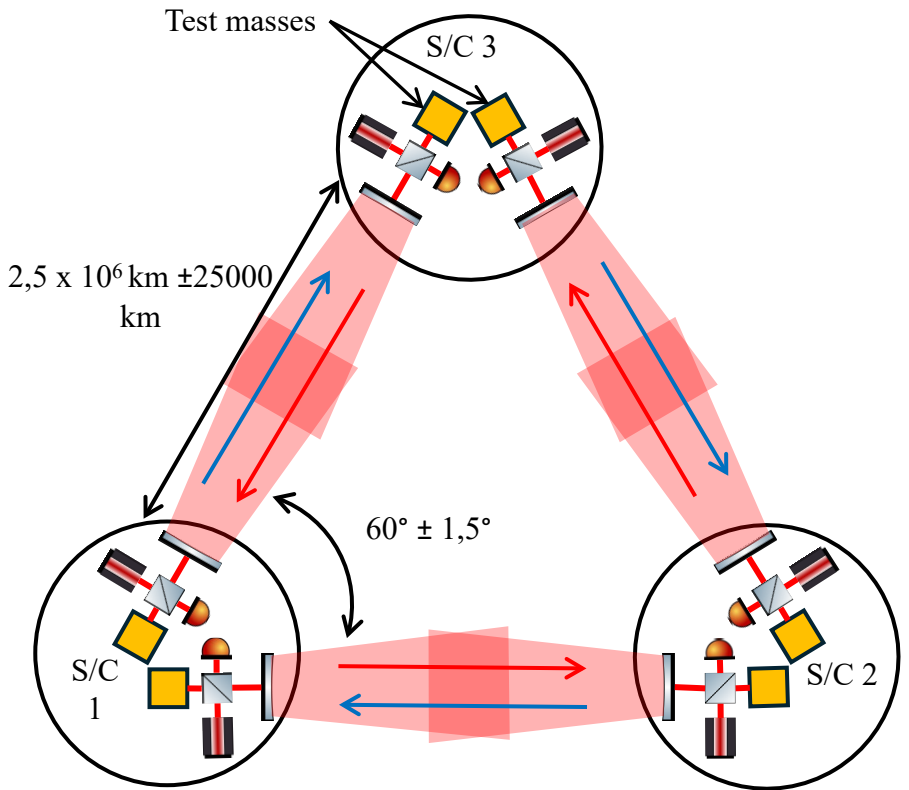
Laser interferometry in space physics experiments

Laser Interferometry Space Antenna

- First GW Observatory in space (launch 2035)
- Objectif
  - Detection of low frequency GW (0.1 – 1 Hz)

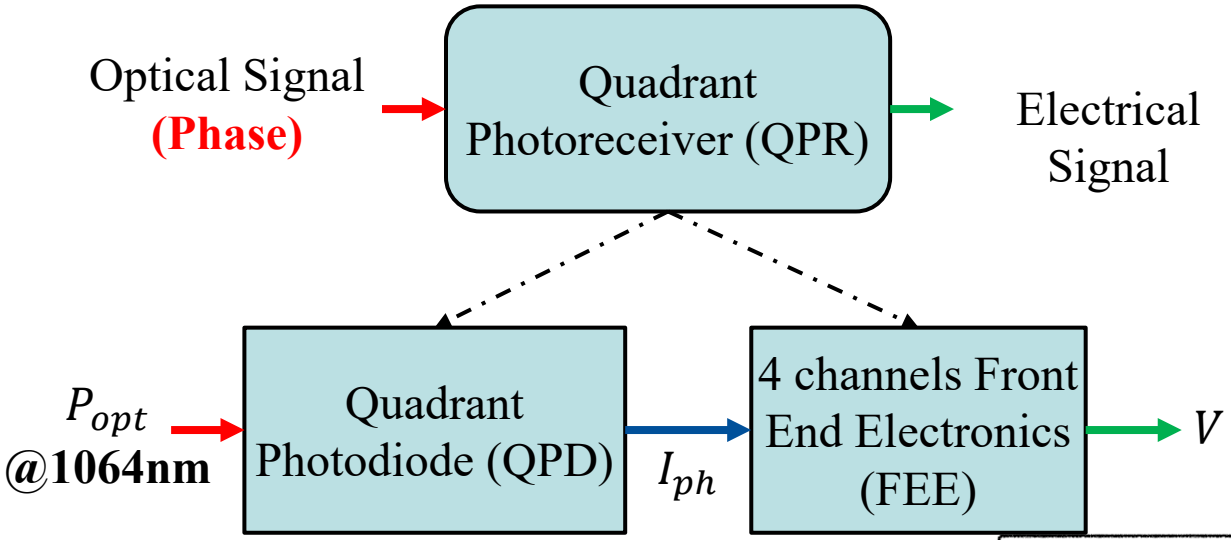


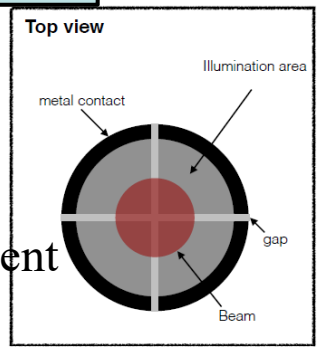
- Distance and angular variation measurements
  - L = 2.5 MKm → ΔL ≈ pm to nm (Δϕ ≈μrad)
  - Long satellite distance – weak light
    - Low noise detectors
  - Doppler effect – heterodyne interferometry
    - MHz range measurements
  - Unstable satellites – tilt-to-length coupling
    - Position and angular sensitive detectors



Photoreceivers for laser interferometry in LISA

LISA Quadrant Photoreceiver





- Quadrant Photodiode (PD)
  - Convert the optical power into a photocurrent
- Front End Electronics
  - Convert the photocurrent into a voltage
  - Amplify the signal

Requirements

- QPD Diameter: 1.5 mm (goal 2 mm)
  - Large is better to simplify alignment, but it would imply large capacitance
- QPD Gaps: 10-20 µm
  - Large gap will waste light and increase TTL coupling noise
- QPD Responsivity: > 0.7 A/W @ 1064 nm
  - QE > 80%; avoiding wasting photons which could reduce S/N ratio → LA signal: 500 pW
- QPD Low reflectivity: < 1%
  - Reflected stray light induces phase noise
- QPR Current noise: < 2 pA/√Hz
  - It requires low capacitance QPD (<10pF/segment)
- QPR Bandwidth: 2-30 MHz
  - Depends on Doppler shifts from the relative motion of the spacecrafts
- Radiation hardness, mechanical and thermal stability, lifetime…

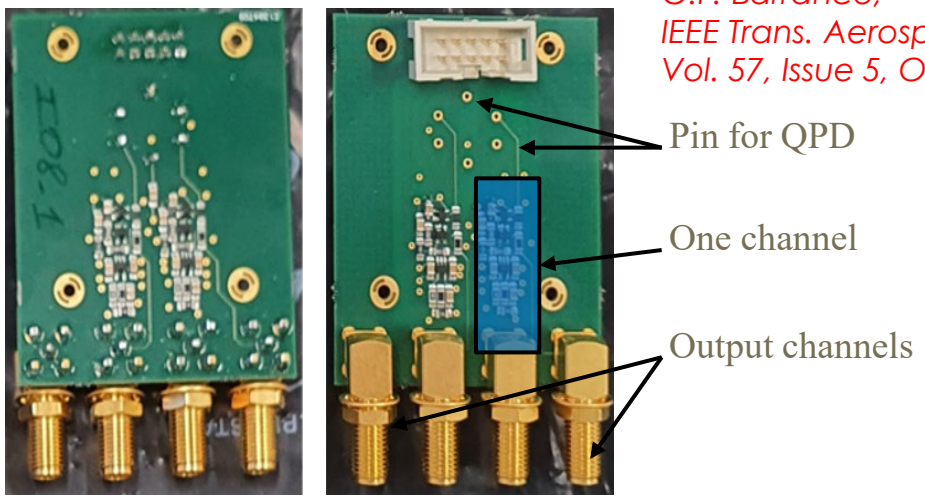
LISA QPD InGaAs status

Ref	Manufacturer/ Supplier	Material Type	Diam (mm)	Interquadrant Gap (µm)	R (A/W) @ 1064 nm	Individual quadrant capacitance (pF)	Vbias (V)	Idark (nA)@ 5V Room T	Cut-off fréquence (MHz)	NEP max (W/√Hz)	Package	Reference
G6849-01	Hamamatsu	InGaAs	1	30	0.683	25-40 pF (@1V, 1MHz) 15.5pF @ 5V, 15 MHz	5	0.2	120	$4x10^{-14}$	TO5	Hamamatsu datasheet Meas CPPM, QPD ZIFO
G6849	Hamamatsu	InGaAs	2	100	0.683	100-160 pF (@1V, 1MHz)	5	0.6	30	$6x10^{-14}$	TO5	Hamamatsu datasheet
G6849SPL2 AR@1064nm	Hamamatsu	InGaAs	3	100	0.683	800 - 2000 (@1V, 1MHz)	5	1 - 7	5	$1x10^{-13}$	TO-8	Preliminary Hamamatsu datasheet
FCI-Q1000 used Grace-FO mission	OSI Optoelectronics	InGaAs	1	45	0.69 (QE 80%)	25	5	15		$1.2x10^{-14}$	TO5 ou TO8	OSI datasheet FCI-InGaAs-Qxxx
FCI-Q3000	OSI Optoelectronics	InGaAs	3	45	0.69	225	5	2-100		$2.5x10^{-14}$	TO5 ou TO8	OSI datasheet FCI-InGaAs-Qxxx
First low noise QPD for LISA mission	Discovery Semiconductor	InGaAs/InP Dual-depletion region	1	20		2.5	5	140			TO3	
	Discovery Semiconductor	InGaAs	2	25		10	5	550				
Low noise QPD for LISA mission	Hamamatsu	InGaAs	1	20	0.8 (QE 92%)	6 (@5V, 10 MHz)	5	1.5			TO5	P.Colcombet PhD Thesis
Low noise QPD for LISA mission	Hamamatsu	InGaAs	1.5	20	0.8 (QE 92%)	11 (@5V, 10 MHz)	5	0.5			TO5	P.Colcombet PhD Thesis
Low noise QPD for LISA mission	Hamamatsu	InGaAs	2	20	0.8 (QE 92%)	16 (@5V, 10 MHz)	5	0.5			TO5	P.Colcombet PhD Thesis
Low noise QPD for LISA mission, 1st run	NL Bright Photonics & Smart Photonics	InGaAs	1.5	20	0.82 (QE 95.5%)	6	20	0.1			TO8	P.Colcombet PhD Thesis
Low noise QPD for LISA mission, 2nd run	NL Bright Photonics, VIGO Photonics, Cezamat, Helia Photonics	InGaAs	1.5 - 2	20		< 6						

LISA QPR Front End Electronics (FEE) status

- Discrete components FEE
  - Main specifications
    - Quad channel DC coupled, transistor-based low noise TIA
    - Based on commercial components with hi-reliability versions
    - TIA DC & AC gain: 30 kΩ
    - Input current noise < 2 pA/√Hz @ 3-30 MHz AC band
  - New design under development

AEI Hannover, DE

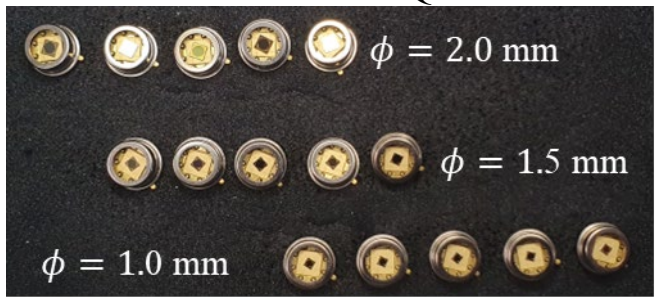


G.F. Barranco, IEEE Trans. Aerospace & El. Sys. Vol. 57, Issue 5, Oct. 2021

- Specific design ASIC FEE
  - Main specifications
    - Quad channel TIA in 1.2 V domain
    - Low noise and high linearity
    - Independent 10 -100 kΩ AC gain control
    - Independent 2.5 – 5 kΩ gain control
    - Input current noise < 2 pA/√Hz @ 3-30 MHz AC band
    - TID tolerance up to 1 kGy
    - SEL tolerance 80 MeV.cm^2/mg

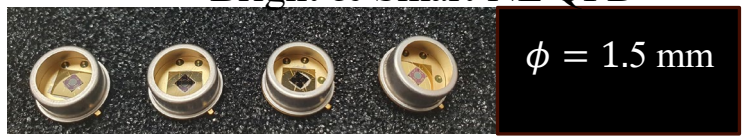
LISA QPD radiation degradation studies

Hamamatsu JP QPD

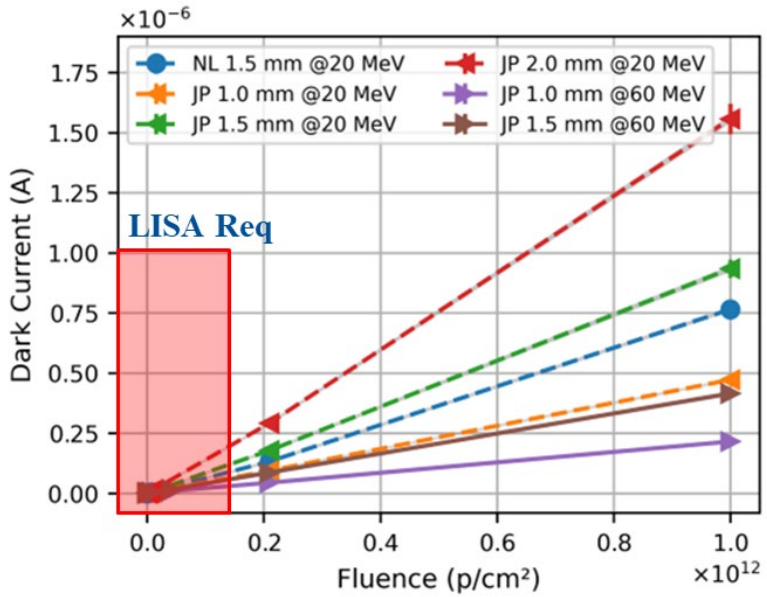


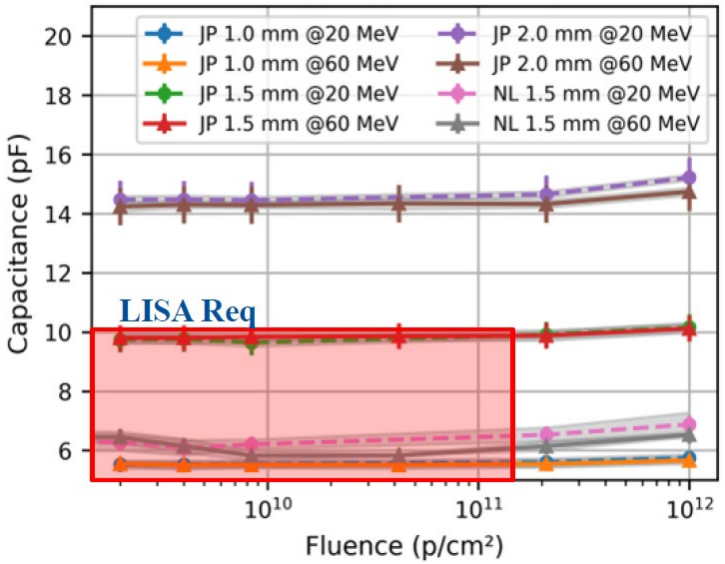
- Objectives
  - Validate the special design $In_{0.53}Ga_{0.47}$ As QPD for LISA mission (large diam, low capacitance) (JP & NL) under LISA space radiation environment
- OCA/ONERA/CAL collaboration / P. Colcombet PhD Thesis

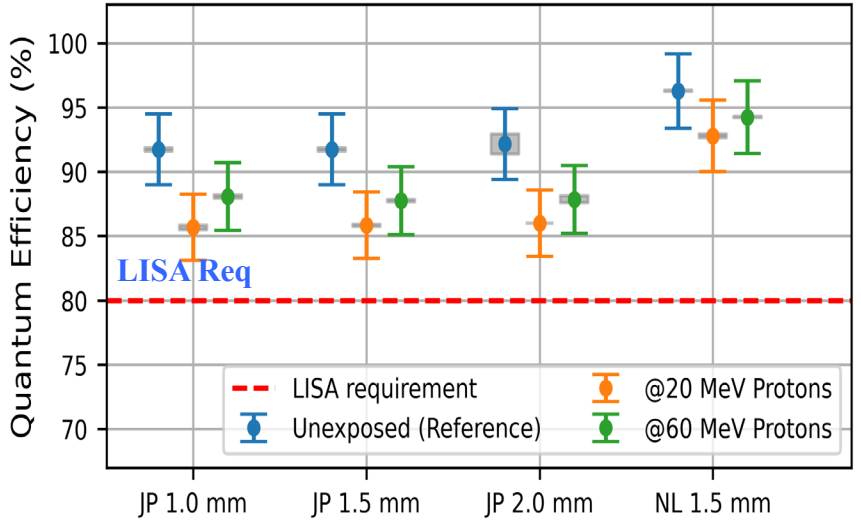
Bright & Smart NL QPD



RADECS 2023, IEEE TNS 2024
P. Colcombet PhD Thesis

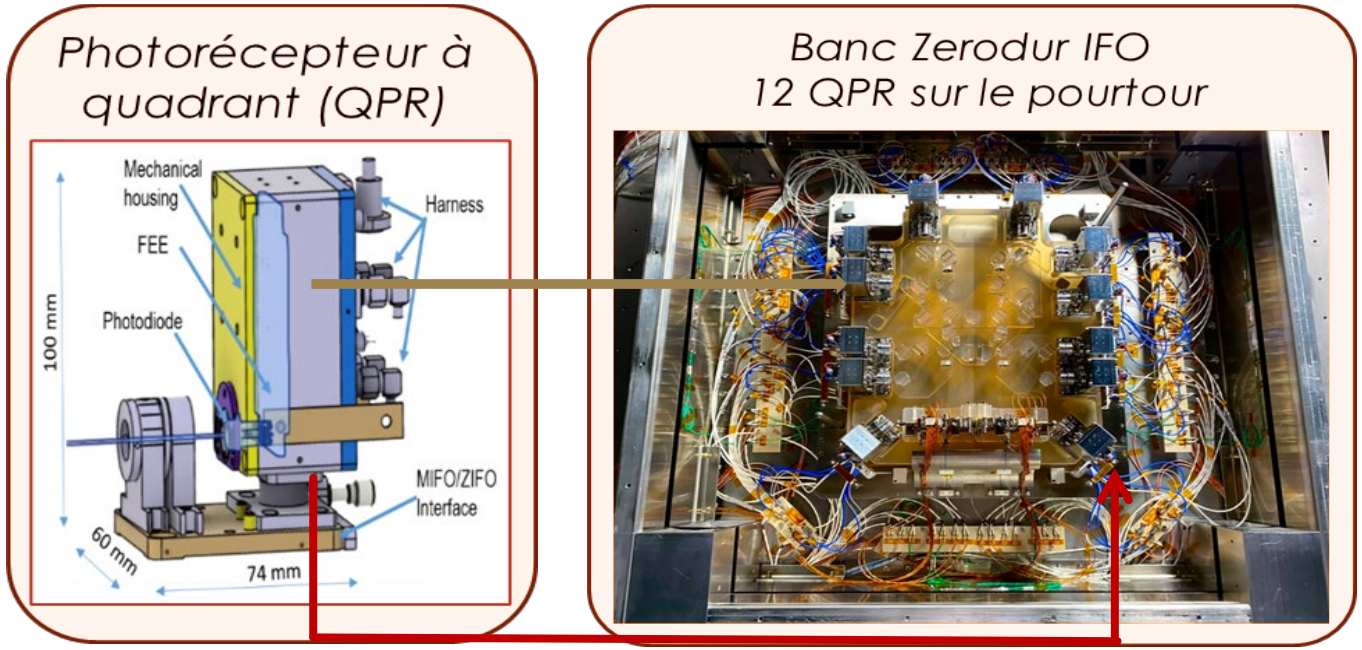


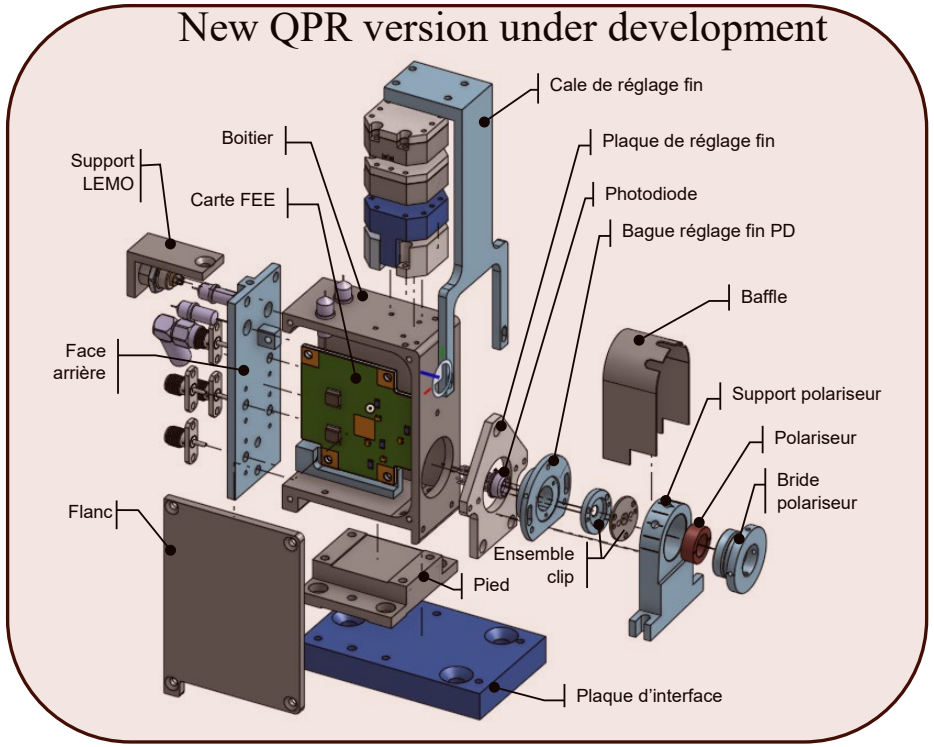




QPR developments for LISA OGSE & AIVT

- Objectives
  - Performance validation of the LISA interferometric system
  - Measurement of optical path length variation of ~ 10 pm, 30 mHz to 1 Hz
- LISA France collaboration
  - APC, OCA/ARTEMIS, CEA, SYRTE, CPPM + industries
  - CNES coordination
- OCA/ARTEMIS responsibility
  - Design, realization, validation and tests of Photoreceivers for ultra-stable OGSE for the LISA interferometric heart AIV tests





What next?

- ESA & NASA MAGIC joint mission
  - ESA/NASA: Mass Change Designated Observable (MCDO)
  - ESA: Next Generation Gravity Mission (NGGM)
    - laser interferometry @ λ = 1064 nm