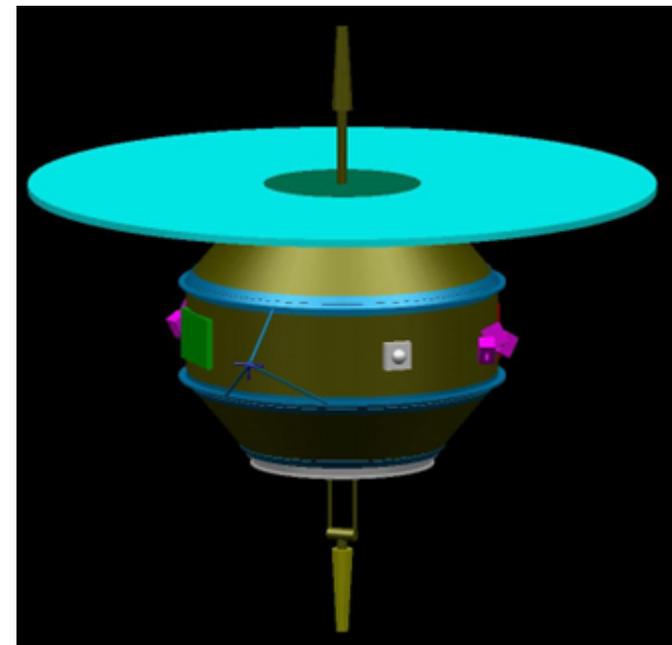
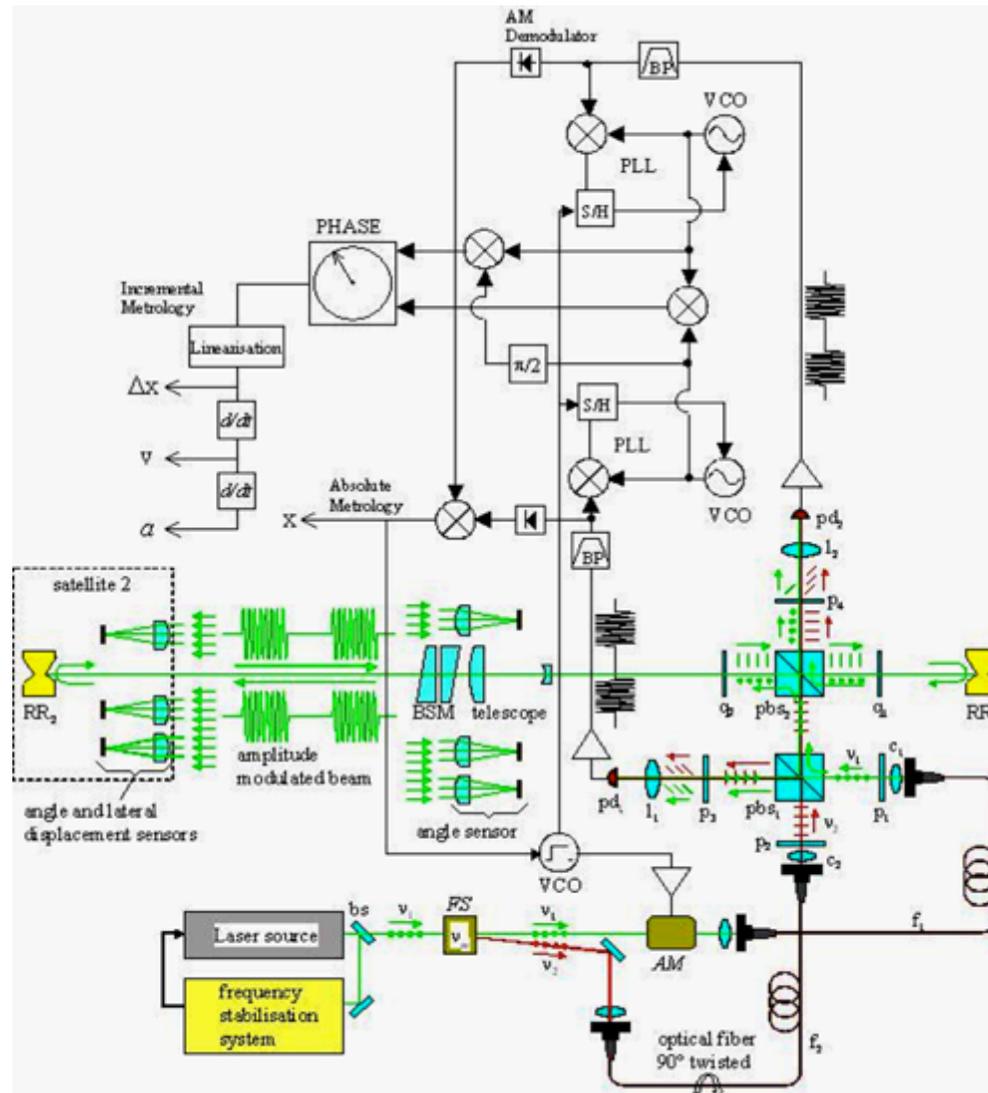


Research activity at INRIM relevant for GG



Outline

- Capacità di progettazione, realizzazione e misura
 - Misure meccaniche e termiche
 - Misure interferometriche
 - Altre attività
- Interferometro (laser gauge) per GG
 - Limiti degli interferometri
 - Soluzioni possibili

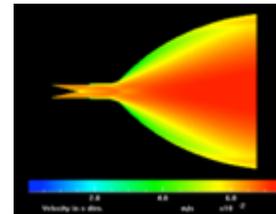
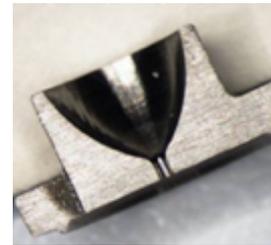
Realizzazioni meccaniche

- Tradizione ultraventennale di progettazione, modellizzazione meccanica e fisica e realizzazione di prototipi per applicazioni spaziali.

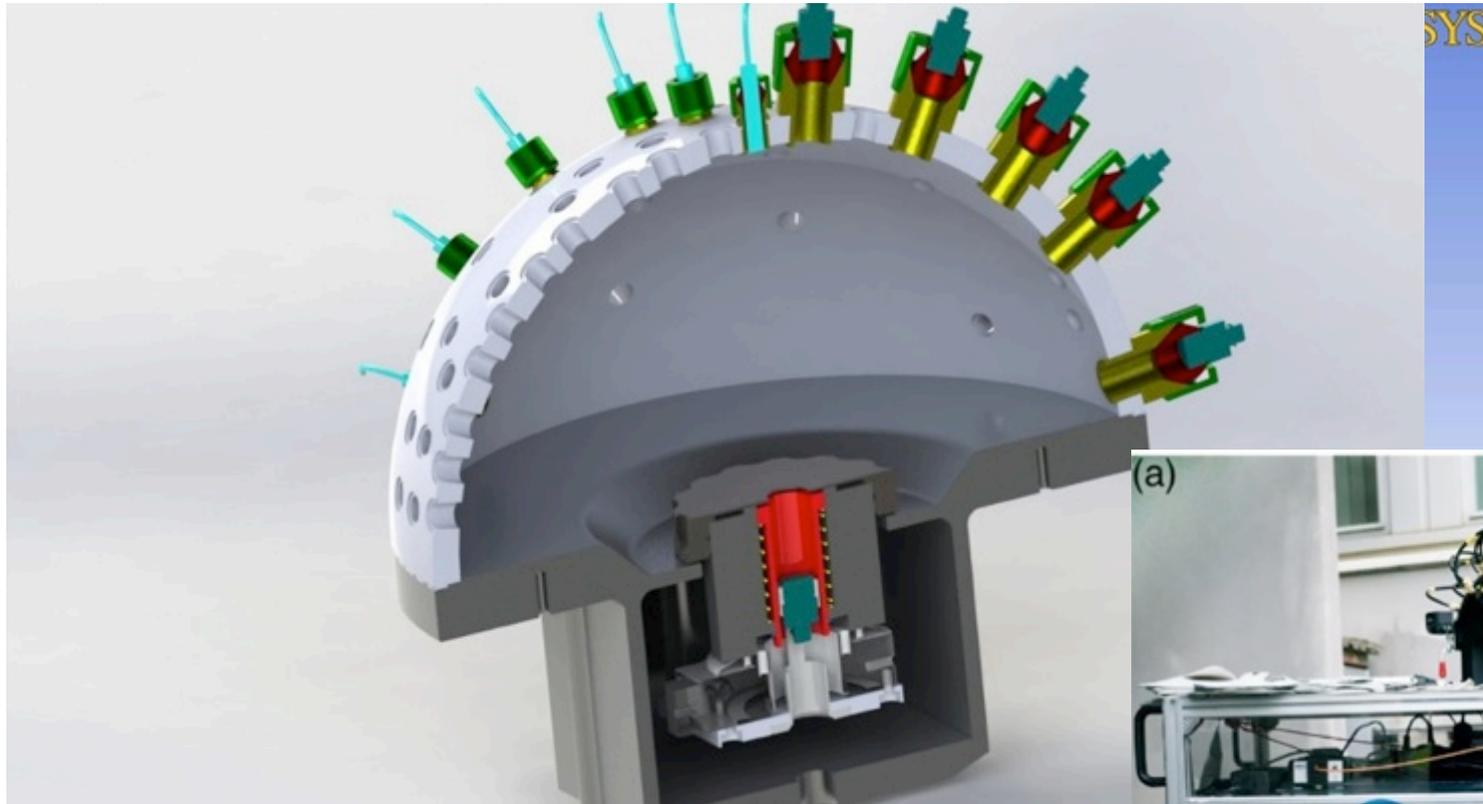
Mechanics Division: > 20 years research activity for space missions

Mechanics division has worked in tight collaboration with TAS (former Alenia Space), ASI and ESA for the development of methods, sensors and actuators. Some examples are:

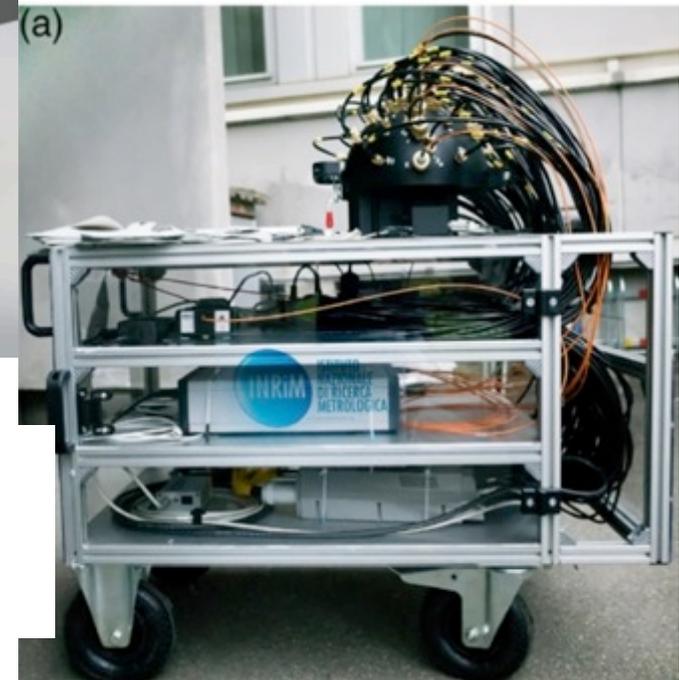
- Picometer stabilization of mirrors for astrometry (GAIA)
- Development of piezo valve and nozzles for gas thrusters
- Optical balances for sub μN thruster characterization (Nanobalance)
- Interferometry for synthetic aperture telescope for Earth observation (EUCLID)



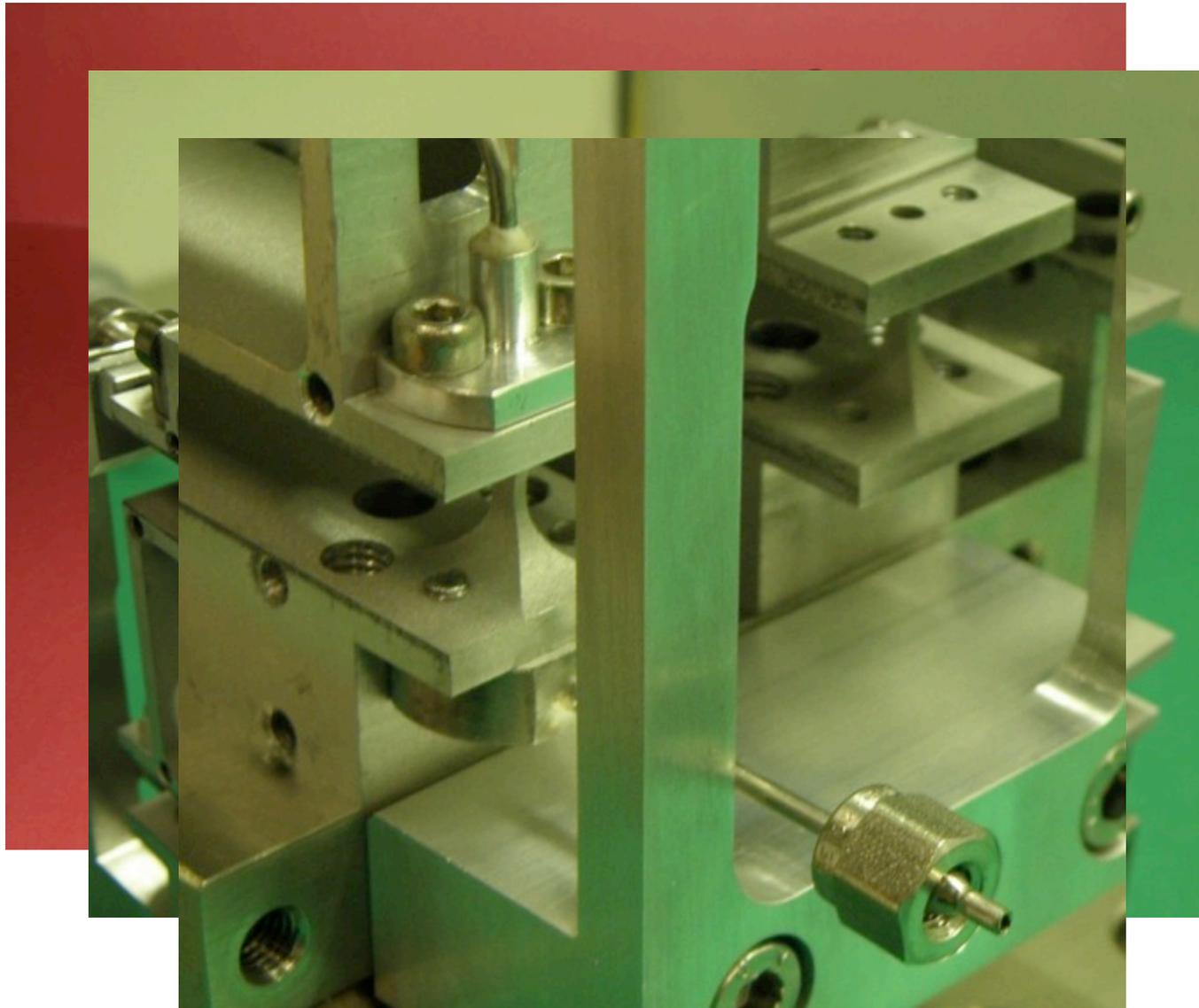
Realizzazioni meccaniche



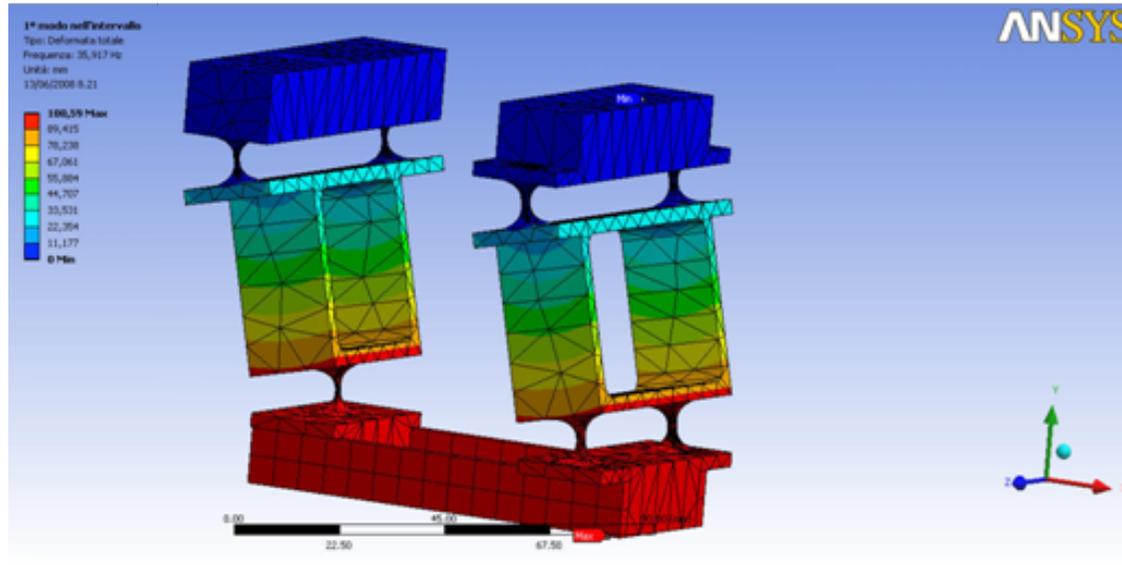
Spettrogoniometro per la misura di riflettanza di foglie
come reference per l'osservazione della terra dallo
spazio



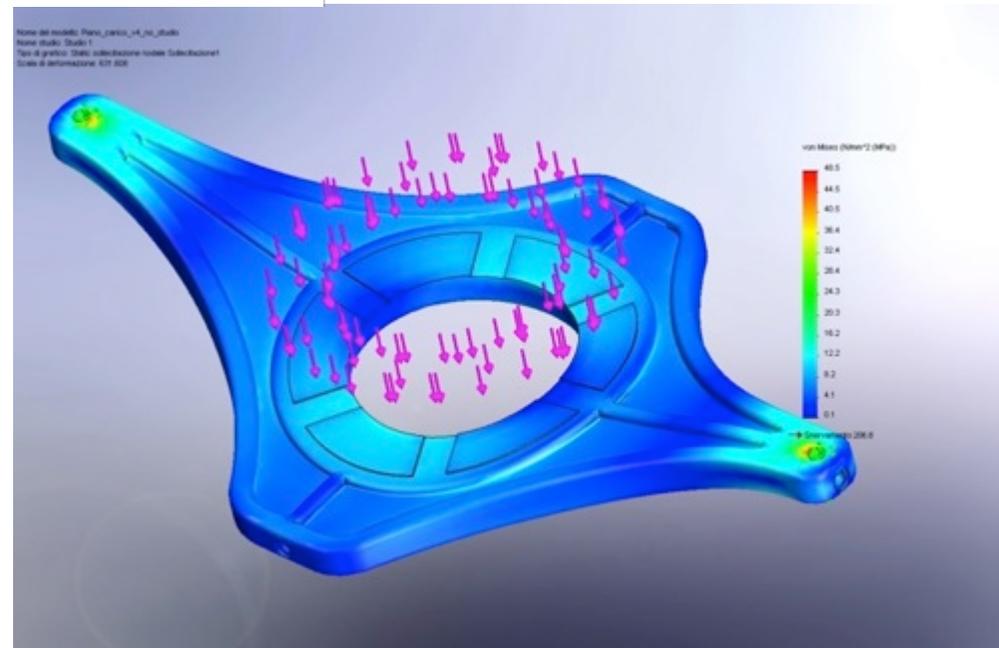
Realizzazioni meccaniche



Progetto e modellizzazione



Studio delle deformazioni elastiche e modi di risonanza con modelli agli elementi finiti



Micro-Thrusters per satelliti scientifici

Tecnologia: *cold-gas thrusters*

“Gas freddo”: il gas viene accelerato tramite un processo puramente fluidodinamico, senza reazioni chimiche

Impiego: microspinte per controllo di assetto di satelliti

Controllo proporzionale della spinta grazie a valvole a controllo piezoelettrico sviluppato presso INRIM

Simulazione del flusso interno all’ugello e quindi calcolo delle prestazioni tramite sviluppi dell’equazione di Boltzmann =>

Direct Simulation Monte Carlo ($0.1 < Kn < 100$)

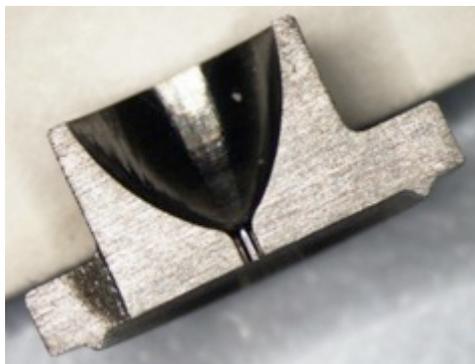
Range da meno di 1 μN a 1 mN e oltre;
Risoluzione inferiore a 1 μN

Elevata risposta in frequenza

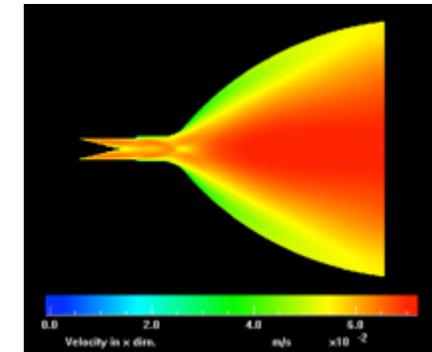
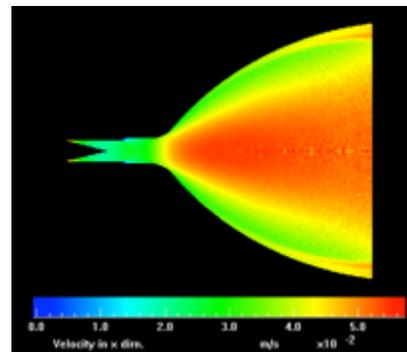
Operativi su GAIA, montati su μSCOPE e LISA PF



Thruster integrato per satellite GAIA



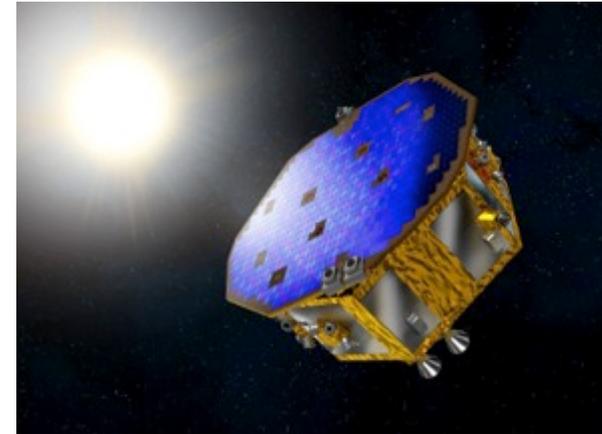
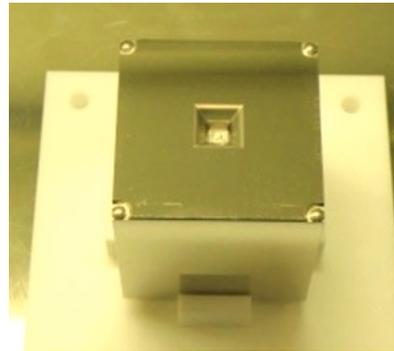
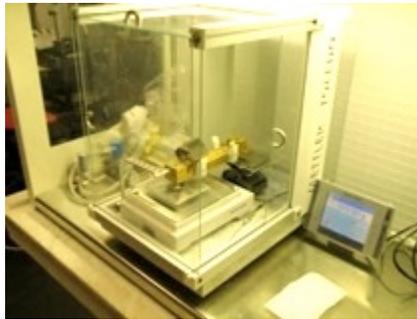
Ugello sezionato



Mappe di velocità a diverse portate

Caratterizzazione metrologica

- **Massa** (es. LISA PATHFINDER – ESA (2007-2011))
 - Densità
 - Omogeneità
 - Suscettività magnetica



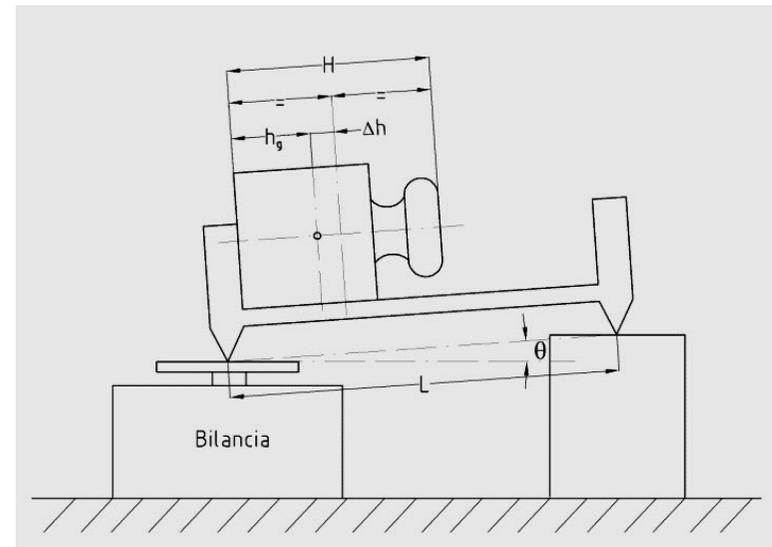
Sensori inerziali: N. 2 cubi 46 x 46 mm di Oro – Platino, 73% Au, 27% Pt. Massa circa 2 kg

Massa (incertezza 50 μg)

Densità tramite pesata idrostatica (incertezza relativa $< 5 \times 10^{-6}$)

Centro di massa tramite weighbridge (incertezza $< 1 \mu\text{m}$)

Suscettività magnetica (misura fattibile)

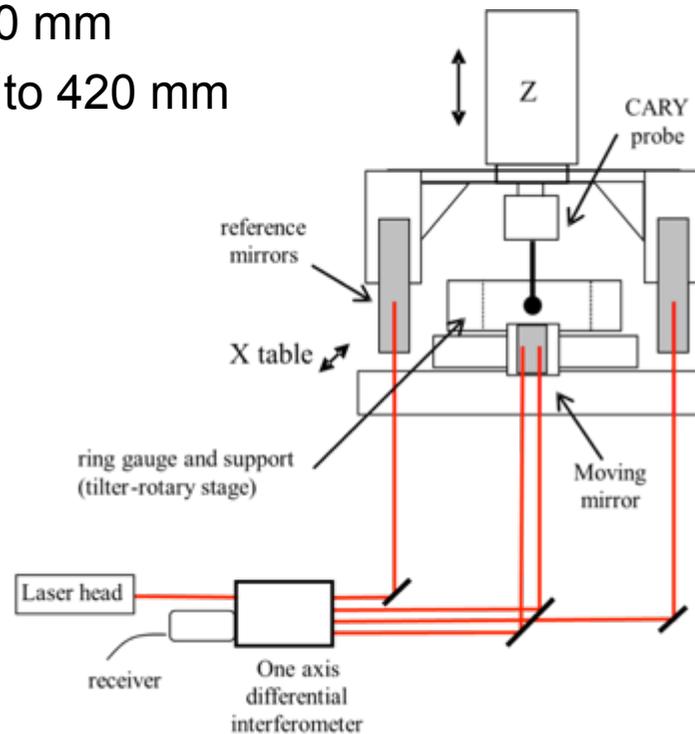


Caratterizzazione metrologica

- **Misure dimensionali**
 - Forma
 - Diametro
 - Rotondità

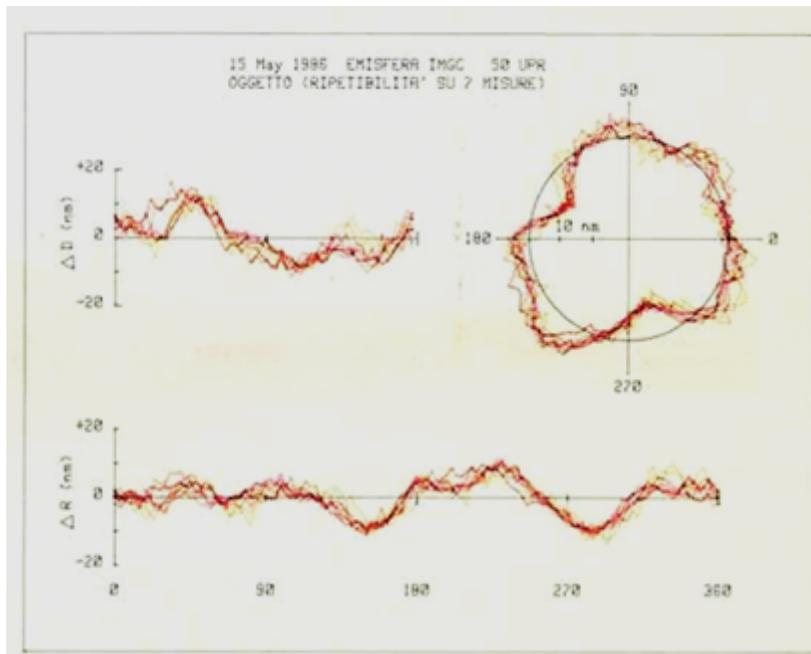
Diametri

- Misure di diametro e di rettilineità con controllo interferometrico
- Incertezza sul diametro 35 nm
- Lateral: 200 mm
- Vertical: 100 mm
- Axial: up to 420 mm

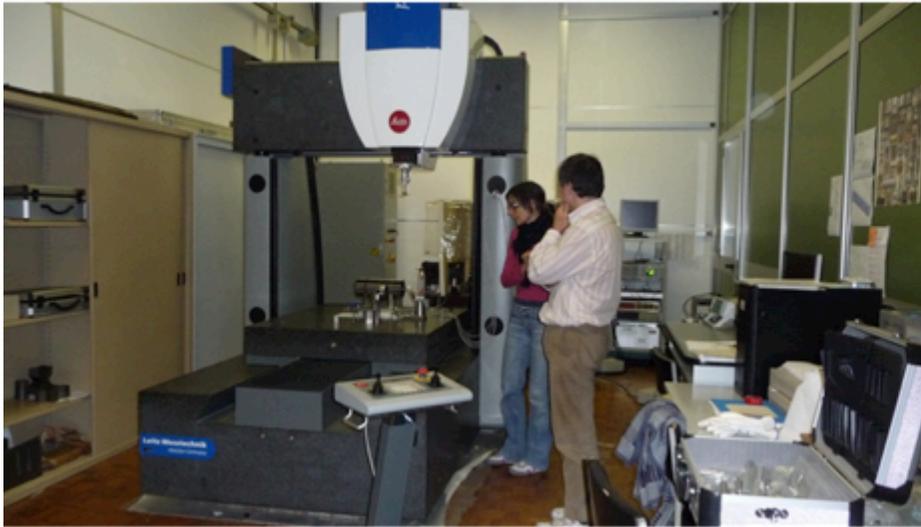


Rotondità

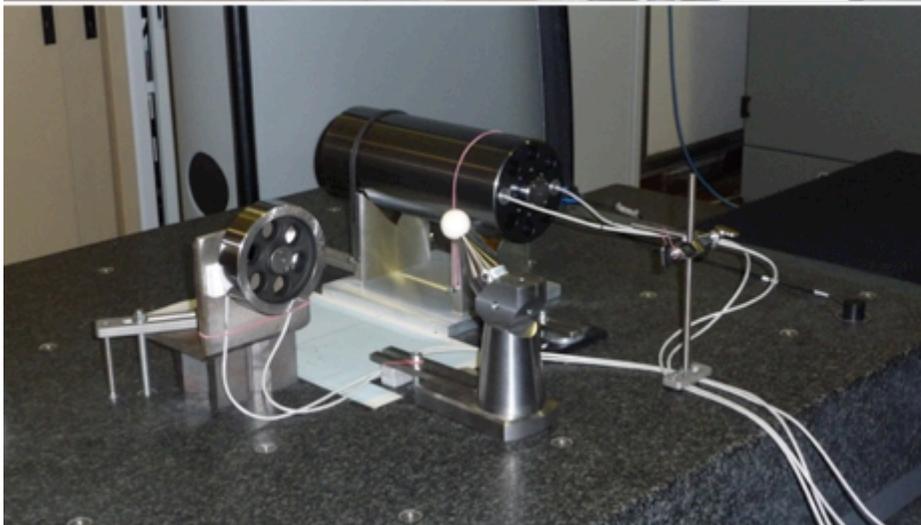
Misure di rotondità (scostamento massimo dal cerchio dei minimi quadrati) con incertezza di 7 nm



CMM



CMM: Leitz PPM-C 12107
Volume di lavoro: $(12 \times 10 \times 7) \text{ dm}^3$
MPE: $0,6 \mu\text{m} + 1,7 \cdot 10^{-6} L$

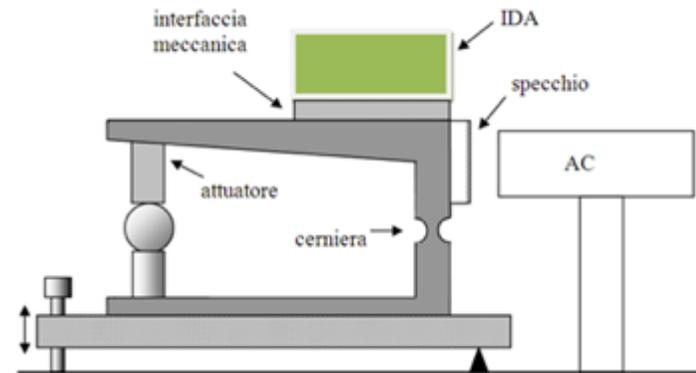


Esempio: taratura delle aree delle sezioni rette di un pistone tuffante (fornisce la riferibilità al gasometro INRIM, duplicato in Brasile)

	Nominale	Incert. estesa, U	Incert. percent, $U\%$
Diametro	120 mm	$1,5 \mu\text{m}$	$13 \cdot 10^{-6}$
Area	11 310 mm ²	0,28 mm ²	$25 \cdot 10^{-6}$

Altre capacità di misura

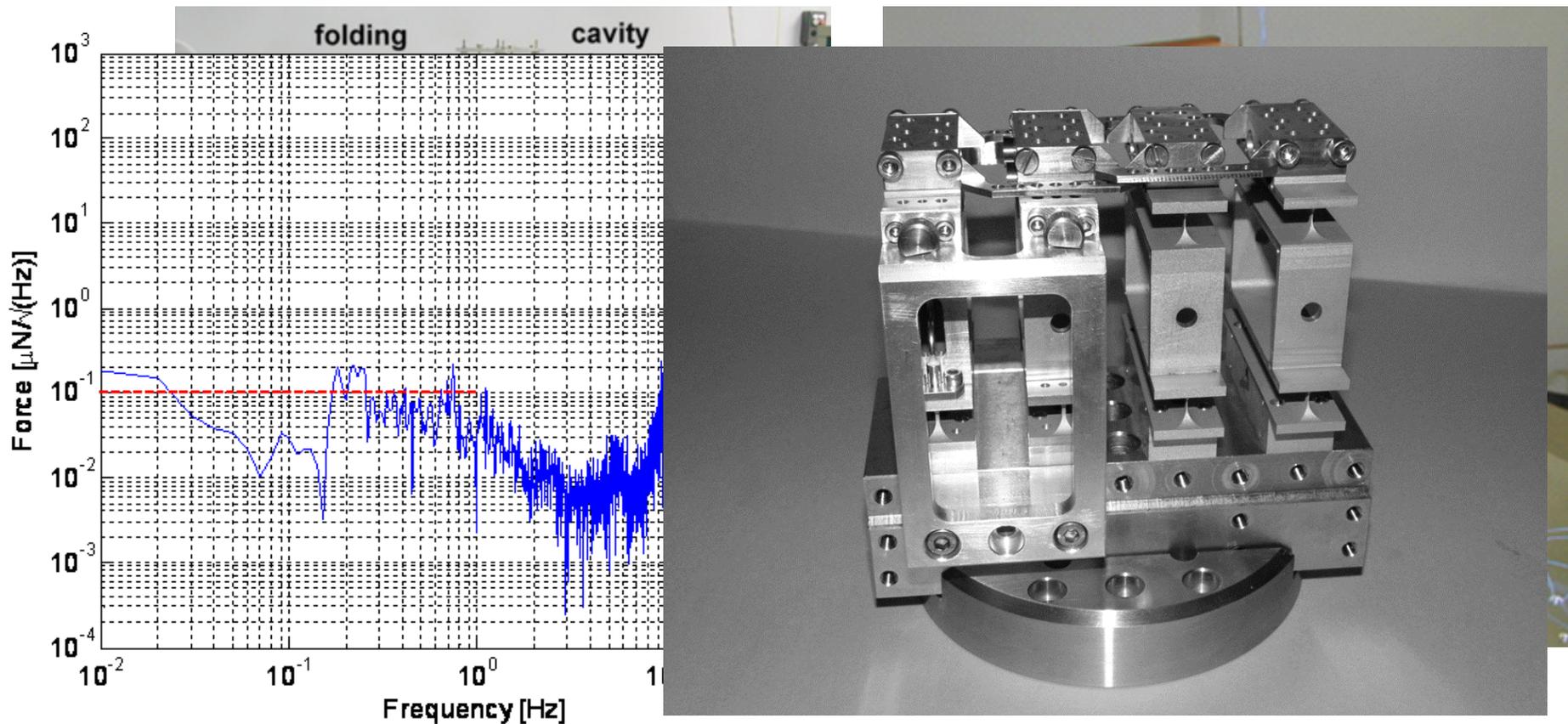
Taratura di accelerometri utilizzando generazione di nano angoli con incertezza relativa di 10^{-5}



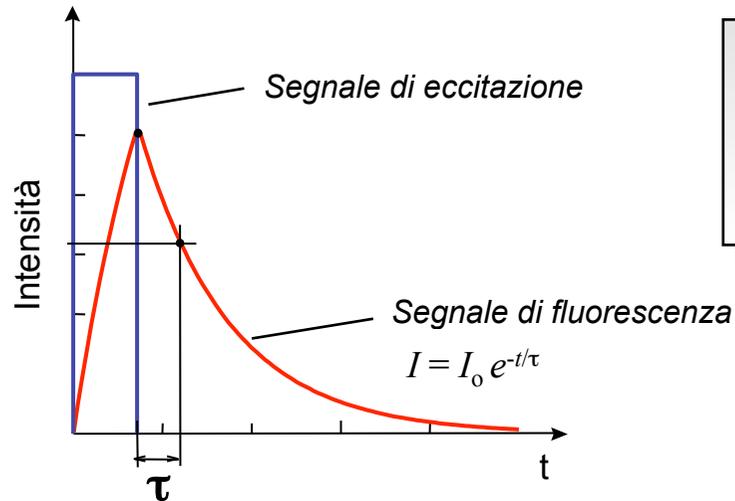
- High accuracy accelerometers for gravimetric space missions are calibrated through nano-radian angle generators
- A contract with Thales Alenia Space is for the calibration of the spring accelerometers (ISA) to be installed onboard the Bepi Colombo mission

Altre capacità di misura

- Misure di spinta per micro-thruster



Termometria a fibra ottica basata sui fosfori



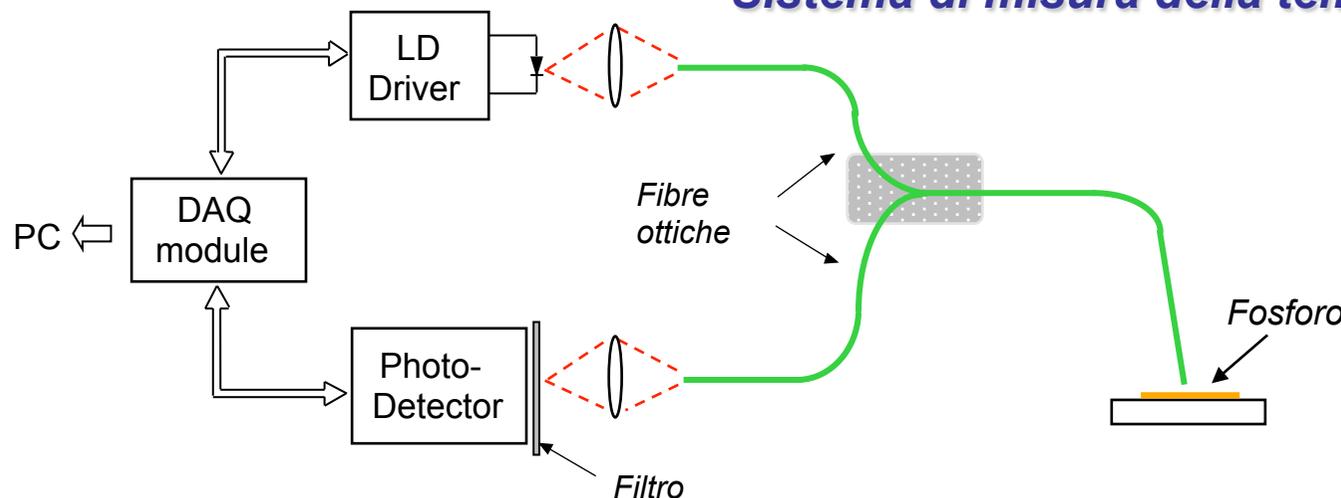
Il tempo di vita τ può essere misurato inviando al fosforo un segnale di eccitazione impulsato di lunghezza d'onda opportuna e osservando la diminuzione dell'intensità in funzione del tempo dall'istante in cui cessa l'eccitazione.

$$I = I_0 e^{-t/\tau} \quad \text{dove:} \quad \tau = f(T)$$

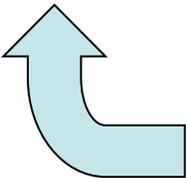
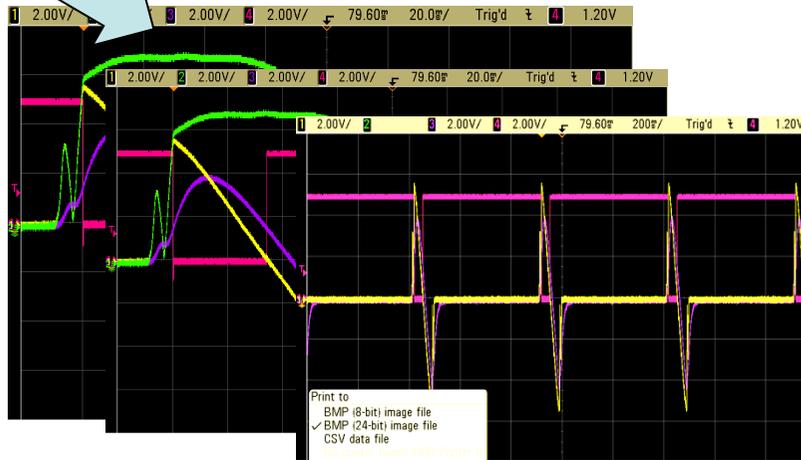
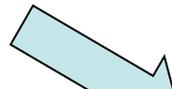
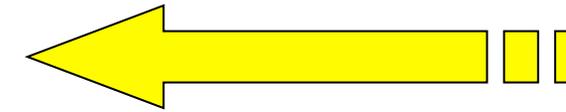
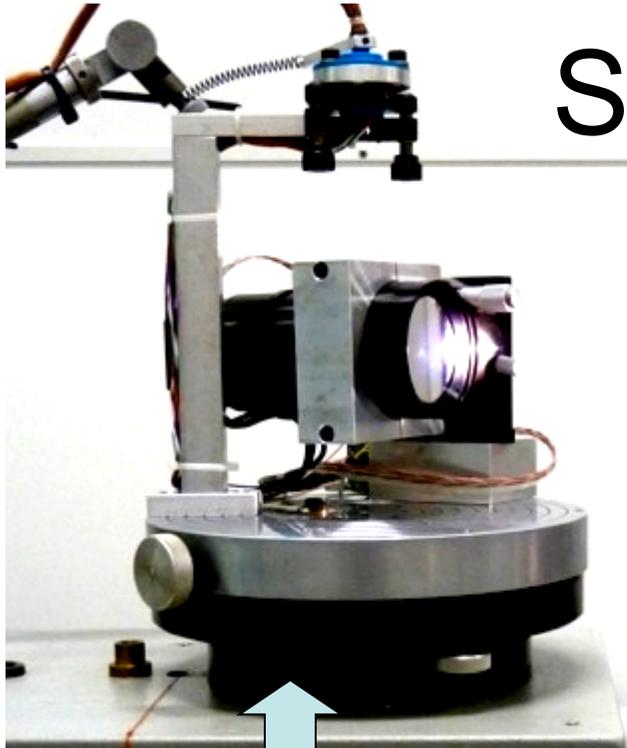
➔ si ricava la temperatura T

Principio di misura

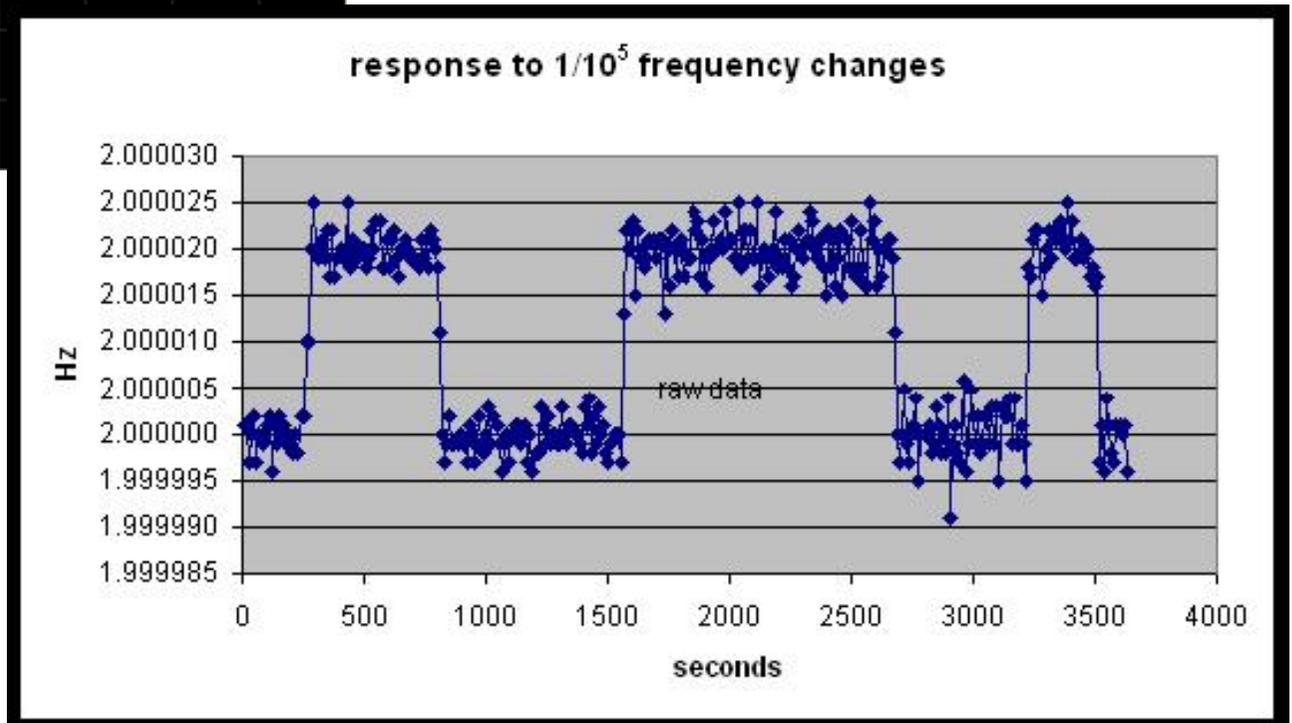
Sistema di misura della temperatura



Spin rate sensor per GG



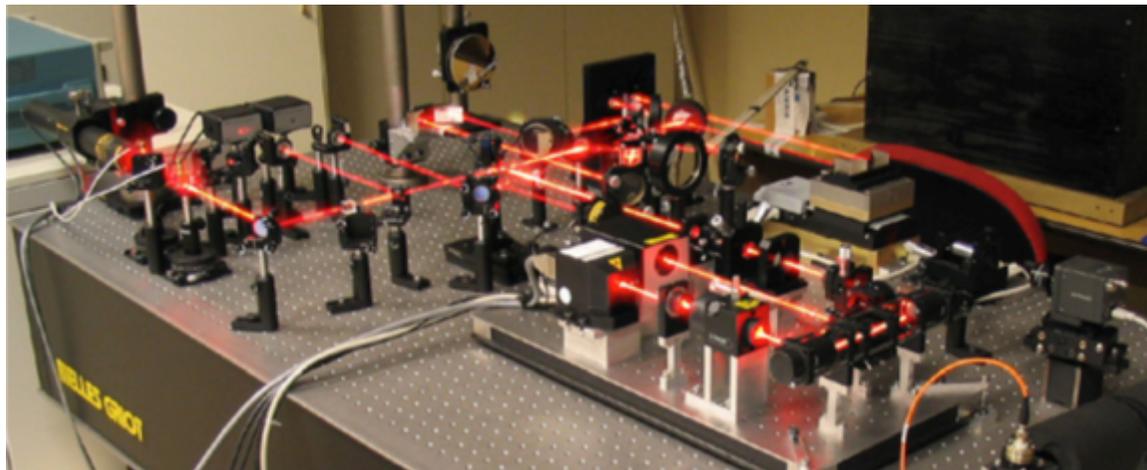
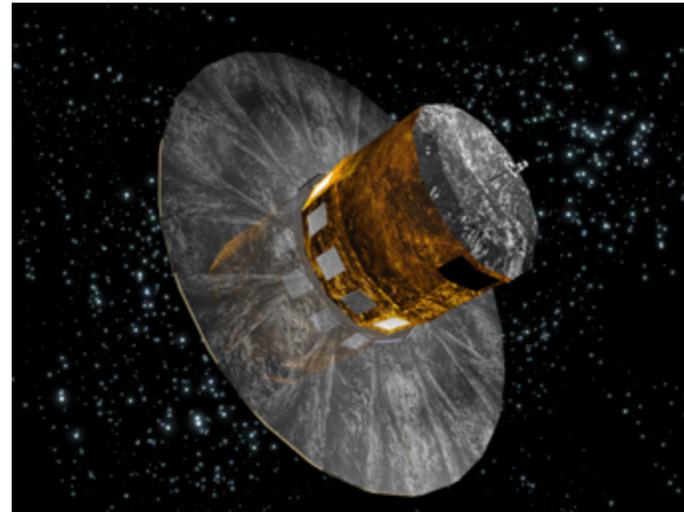
Frequency step (20 μHz) response



Misure interferometriche

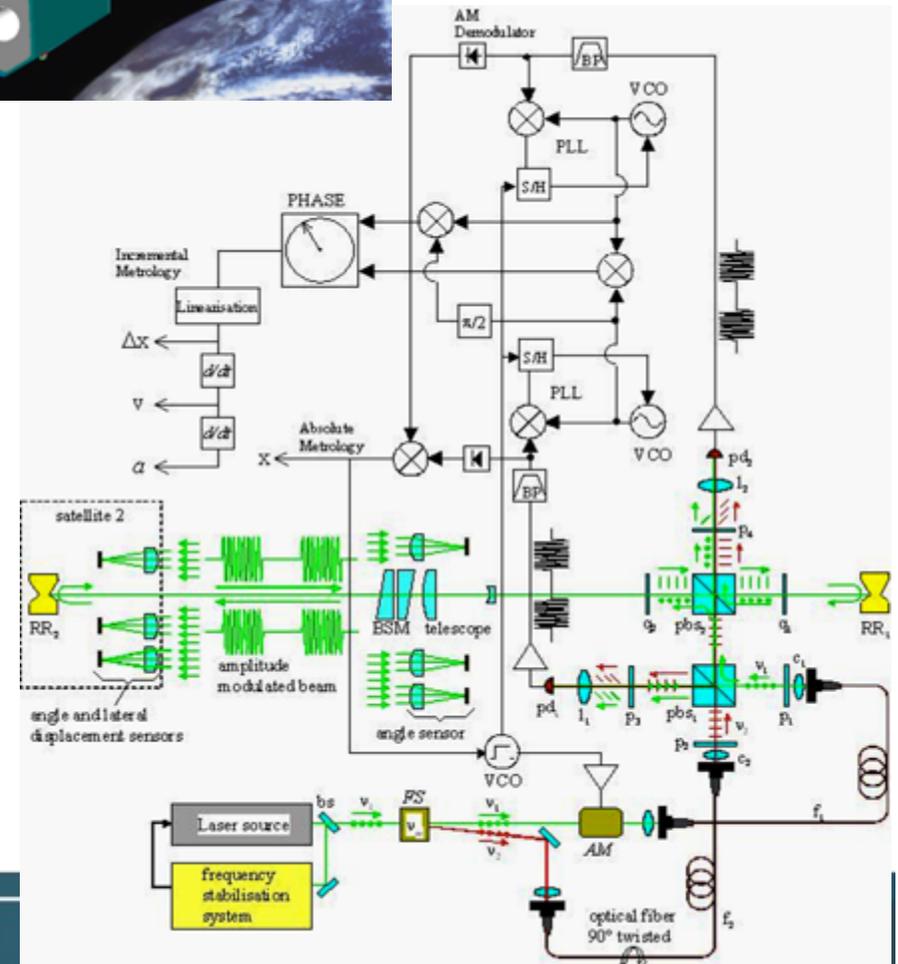
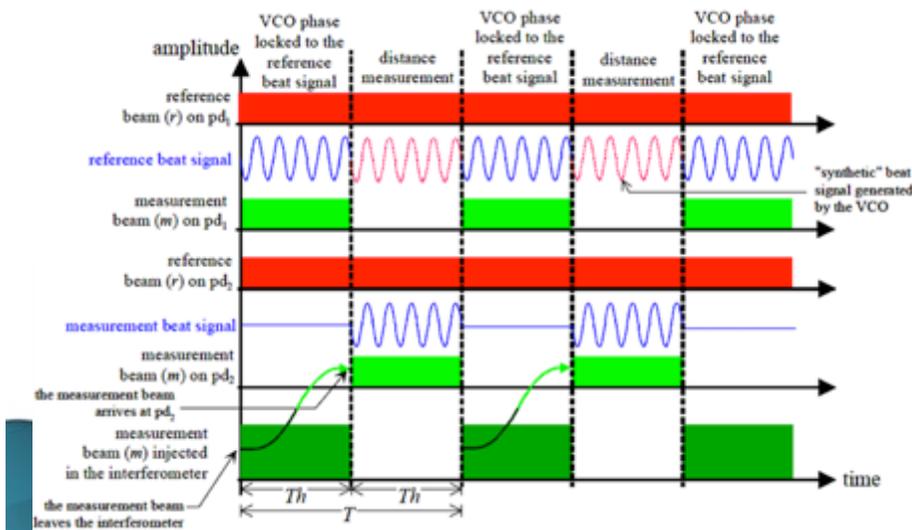
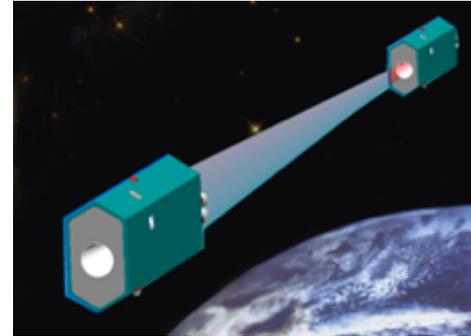
- GAIA, EUCLID, NGGM, COATS

- Picometer stabilization of mirrors for astrometry (GAIA)
- Interferometry for synthetic aperture telescope for Earth observation (EUCLID)



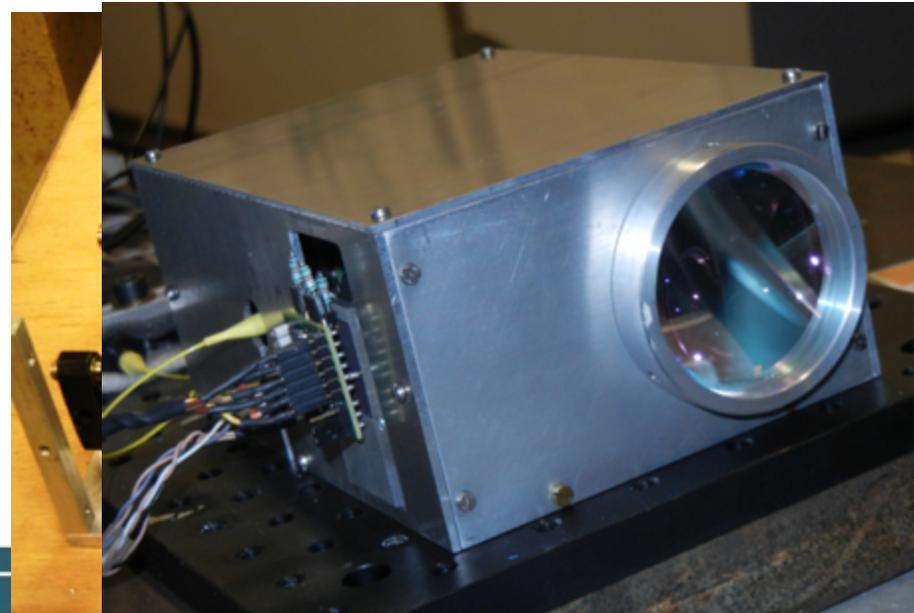
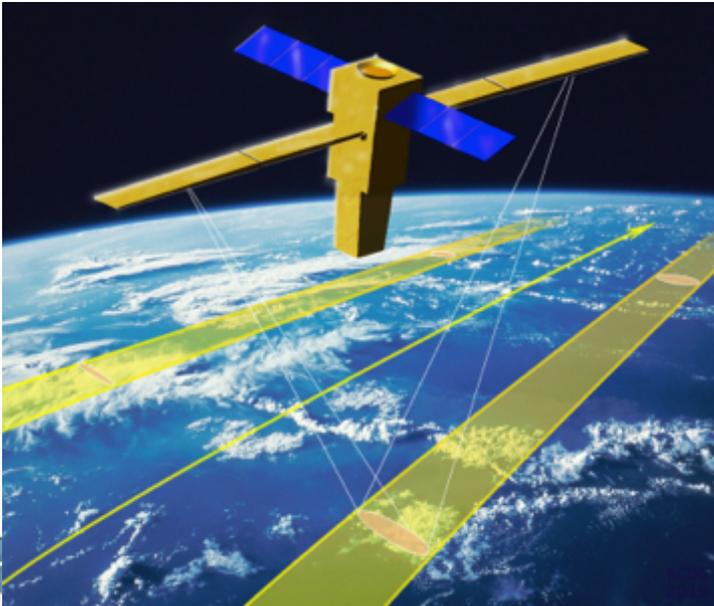
Long range interferometry for NGGM

- A long distance interferometer has been developed (ESA contract) for the measurement of distance of two satellites flying at low Earth orbit for the study of a post GRACE mission
- 1 nm resolution over 100 m distance has been demonstrated



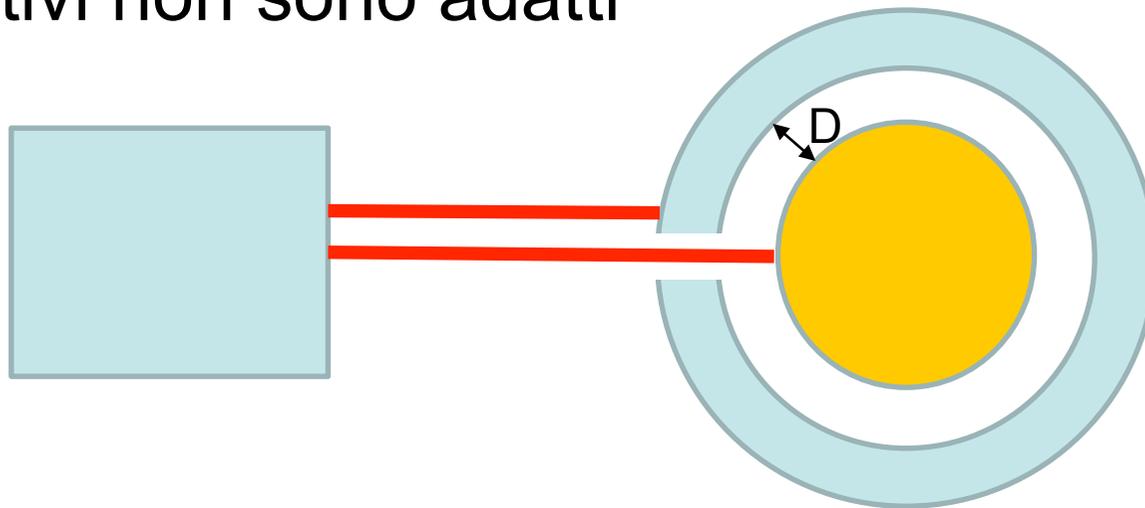
COATS: 5 DoF Telemetry and attitude sensor

- In the framework of an ESA contract a 5 degrees of freedom all optical device has been designed built and tested.
- The sensor is designed to measure relative attitude and position of remote parts of a satellite (e. g. a boom mounted antenna in a Synthetic Aperture Radar).
- Accuracy of few micrometers and sub-arcsecond resolution have been achieved at distances up to 7.5 m with a less than 1 kg device

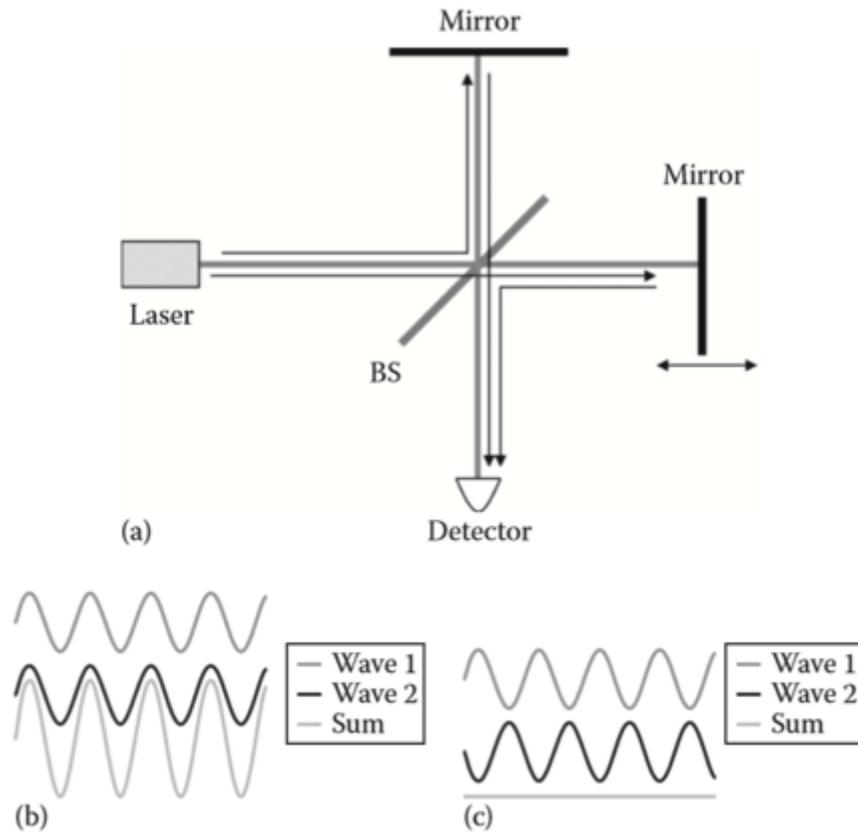


Metrologia per GG

- Misurando: variazioni di distanza tra le due masse alla frequenza di spin
- Target: $1 \text{ pm}/\sqrt{\text{Hz}}$ @ 1 Hz
- $D = 20 \text{ mm}$
- A causa della grande distanza i sensori capacitivi non sono adatti



Interferometro di Michelson



$$S = 2(1 + \cos(4\pi D/\lambda))$$

FIGURE 5.1 (a) Schematic of the Michelson interferometer. (b) Constructive and destructive interference of electromagnetic waves.

Omodina

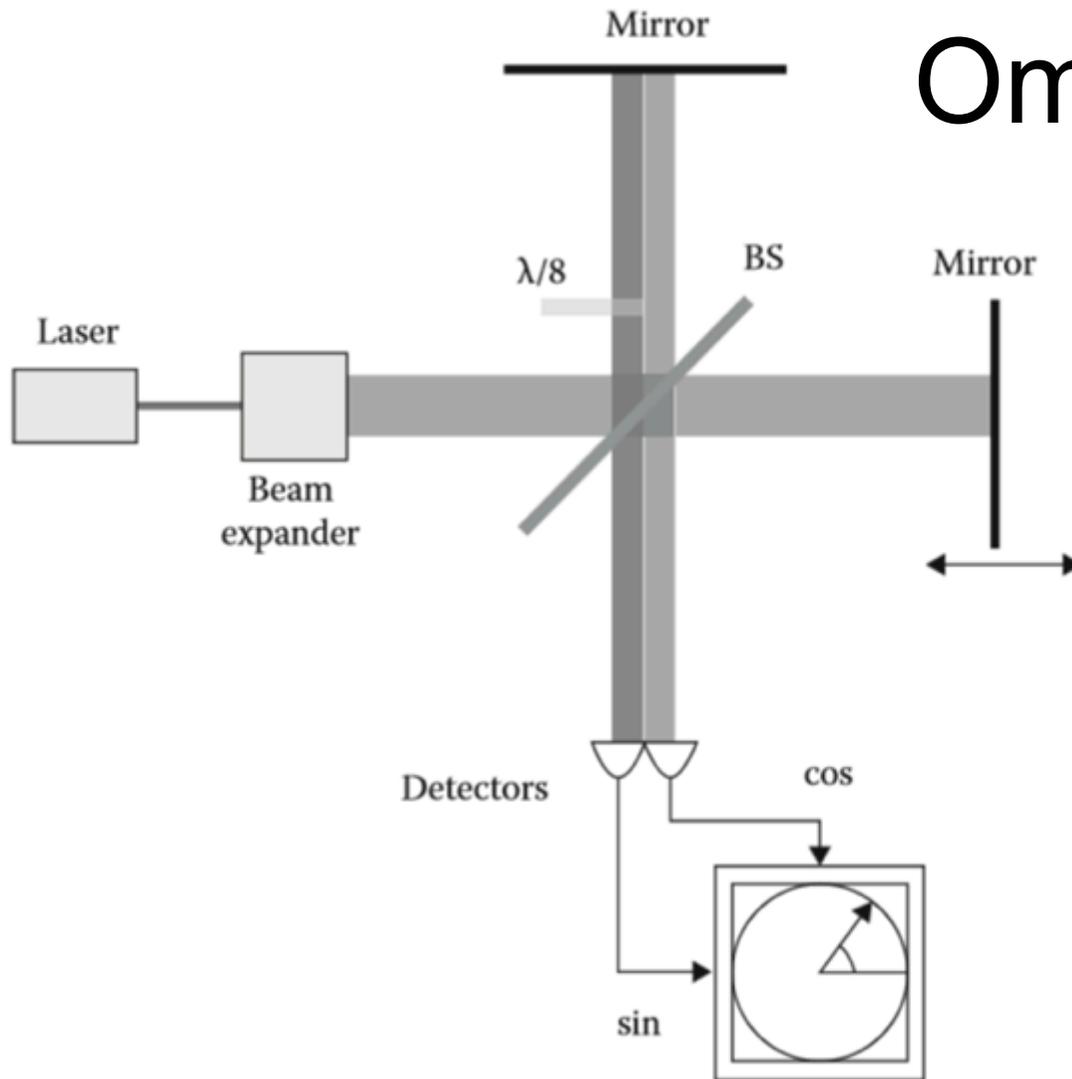


FIGURE 5.2 Practical homodyne interferometer: A retarder introduces a phase delay on one portion of the beam such that the two interference signals are in quadrature.

Polarizzazione della luce per la separazione e la ricombinazione

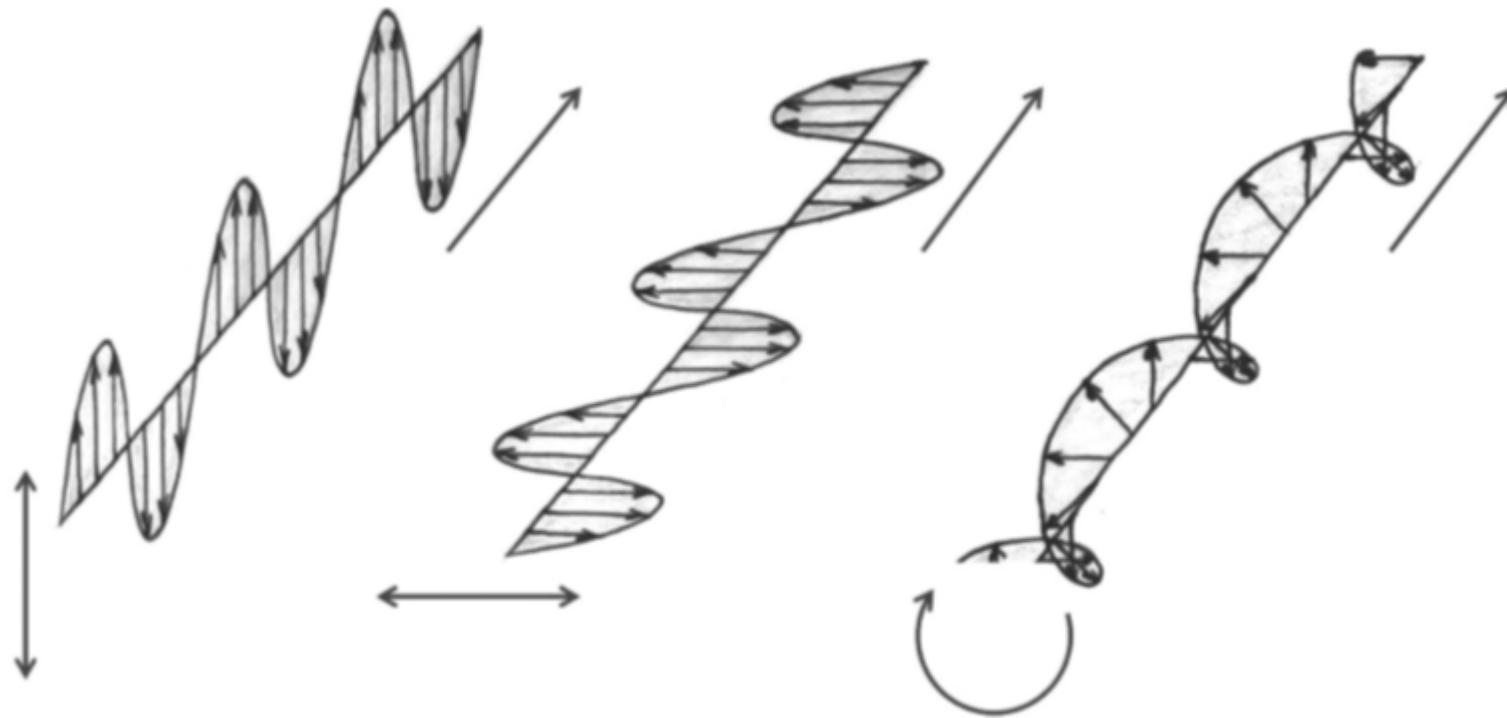


FIGURE 5.4 Vertical and horizontal linear polarized light, and quadrature combination of the two generating circular polarization.

Eterodina

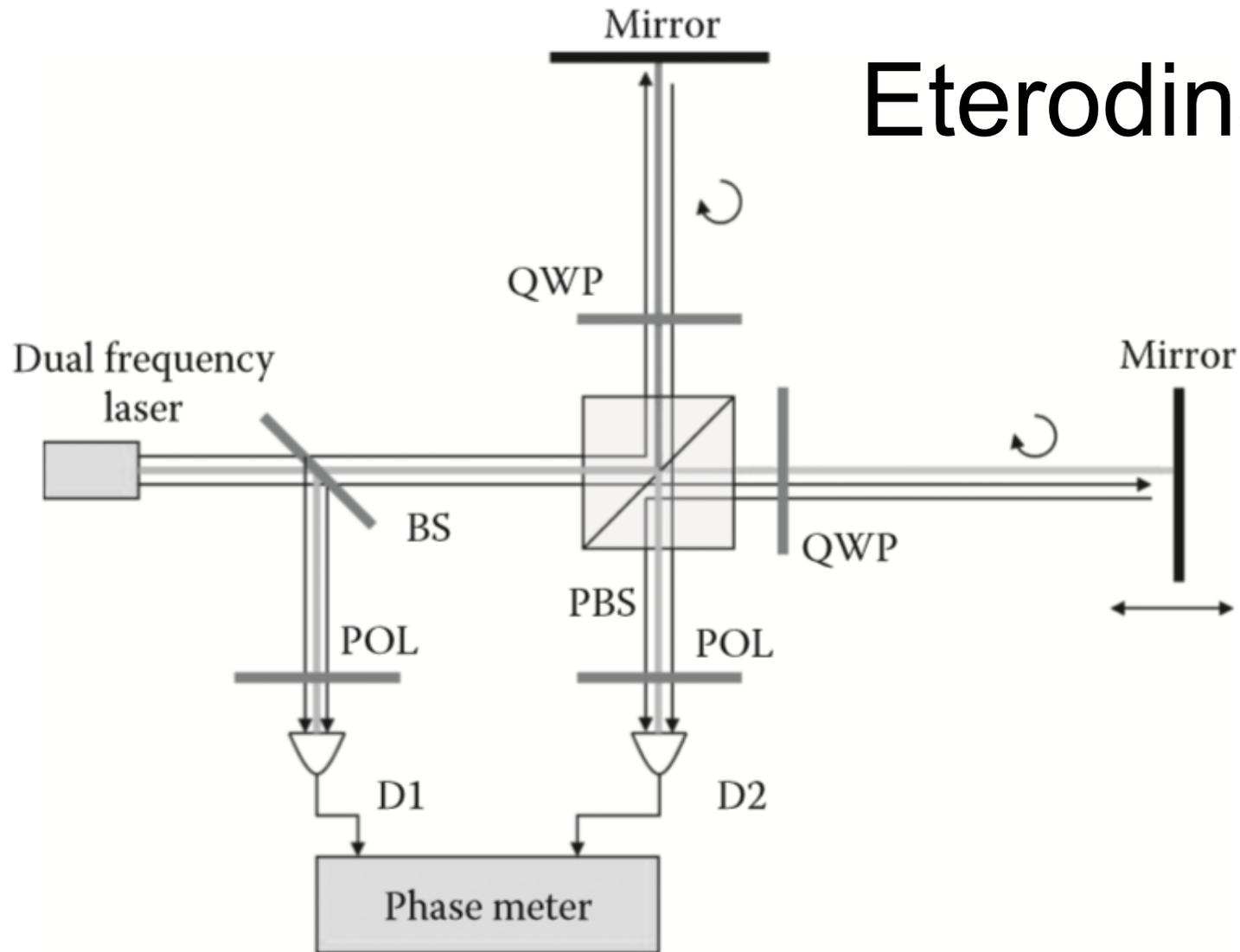


FIGURE 5.5 Heterodyne interferometer: Mirror displacement is transformed in phase delay between two beat signals.

Fabry-Perot Interferometer

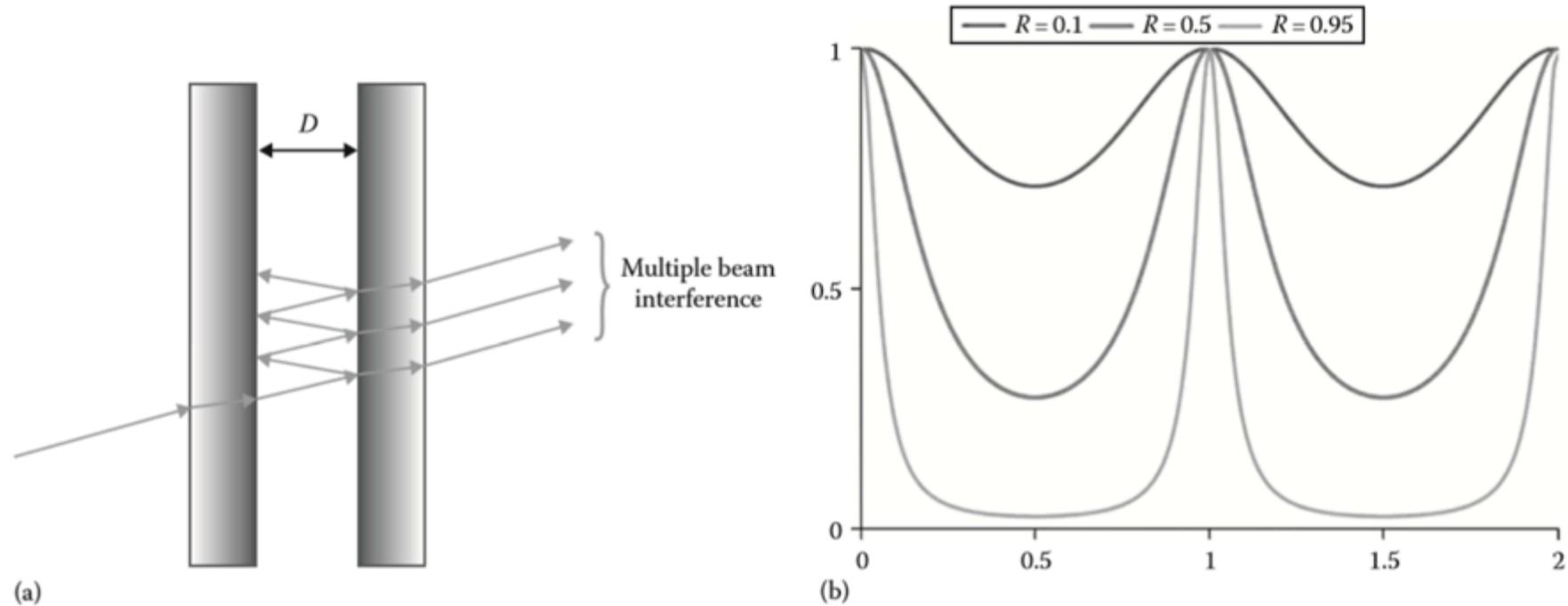
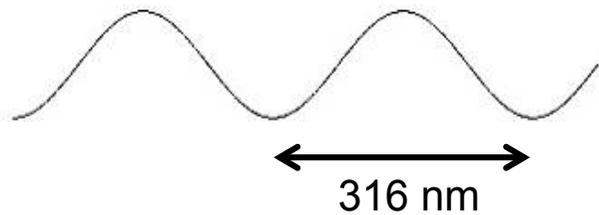
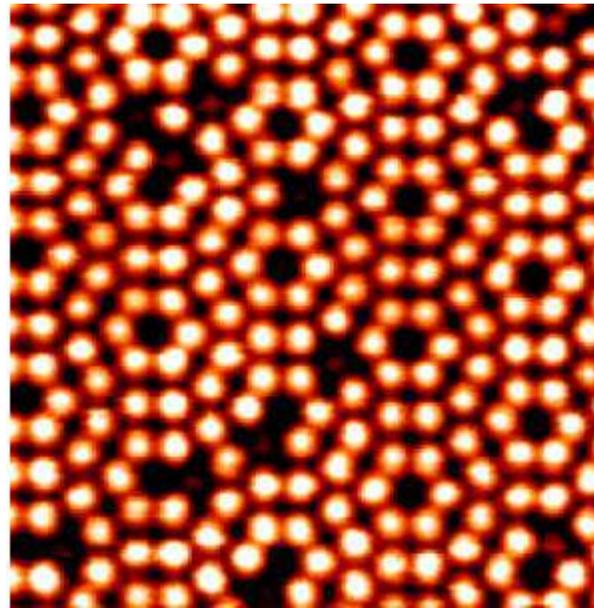
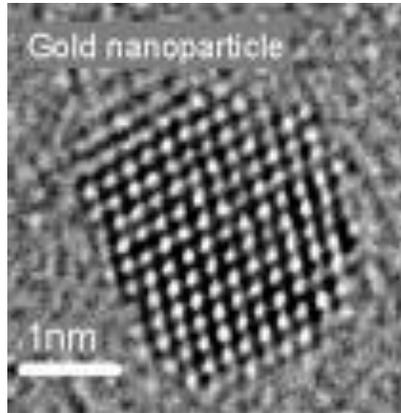


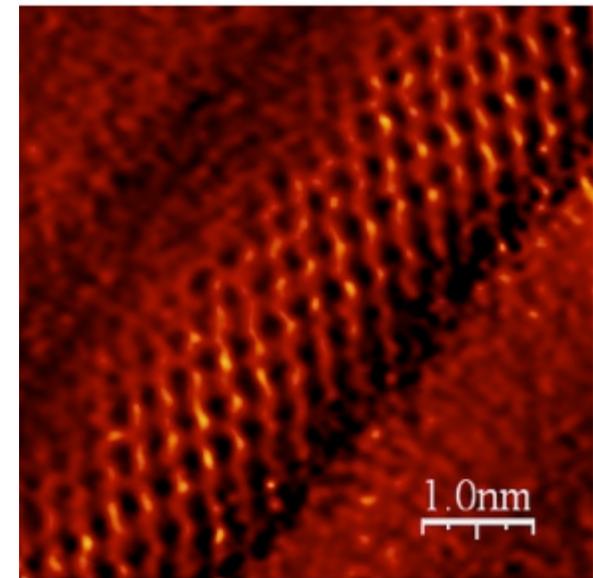
FIGURE 5.6 Fabry-Perot interferometer made from two faced partially reflecting mirrors facing each other. (a) Multiple beam interference. The transmitted power (b) is a function of the reflectivity R of the mirrors and the ratio $2D/\lambda$.

$$I_T = \frac{I_0}{1 + F \sin^2(2\pi D/\lambda)}$$

short distance interferometry



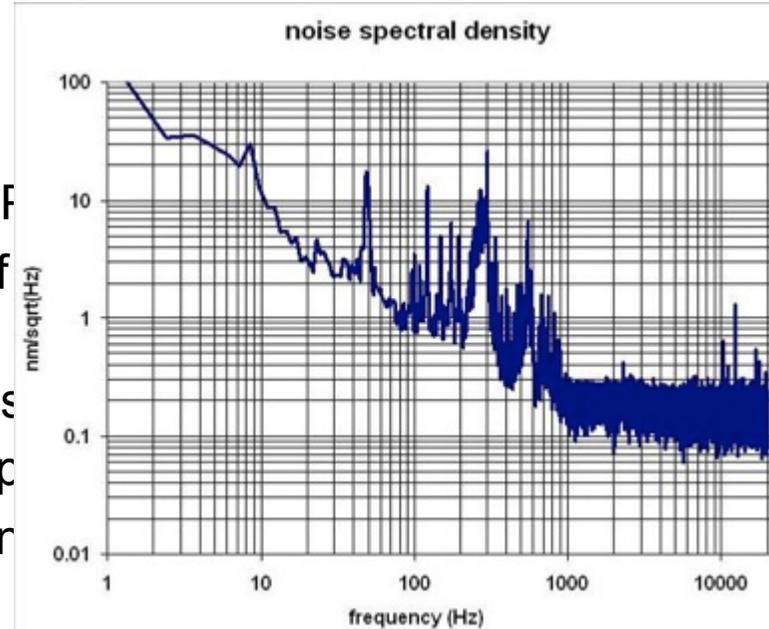
10 pm = fringe/30000 !



interferometer limits at short distance

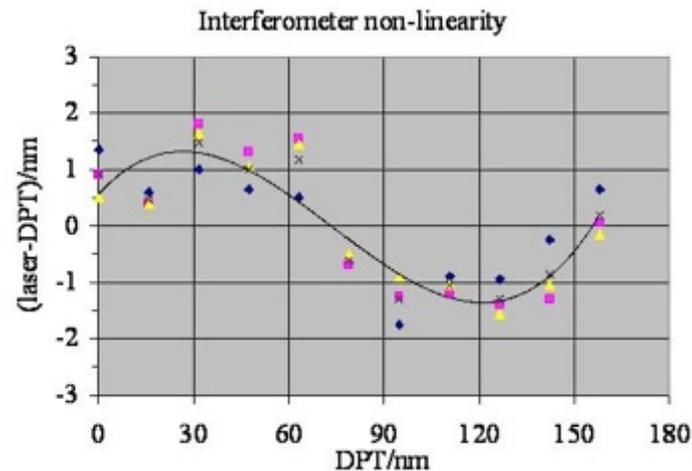
PERIODICAL (NONLINEARITY) ERRORS

- period of λ of the optical path difference (OPD)
- deviation from orthogonality and ellipticity of laser source
- finite extinction ratio of the polarizing beam splitter
- misalignment and leakage of retarder waveplate
- rotation and ellipticity induced at the reflection



NOISE

- detector noise
- phasemeter noise
- shot noise



Non-linearità di un interferometro

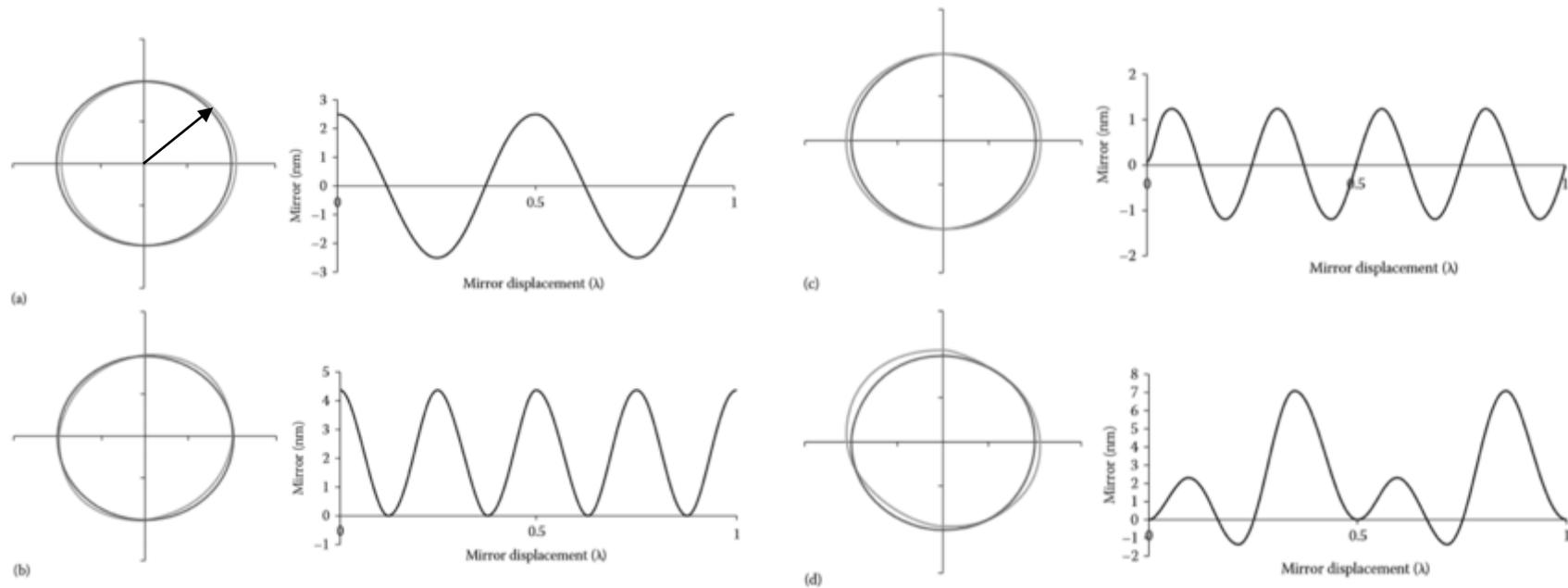
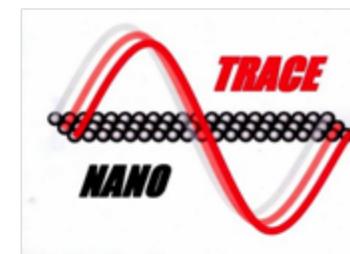


FIGURE 5.7 Effect of offset, amplitude, phase distortion on displacement evaluation errors. At the left, the distorted circle (gray); at the right, the errors in nanometers. From top left: (a) effect of 5% offset unbalance, (b) effect of 5% gain unbalance, (c) effect of 5° error with respect to perfect quadrature, (d) combination of the three.



Optical interferometry with 10 pm level accuracy: the project **Nanotrace**



•The project aimed to 10 pm accuracy of displacement metrology namely by refined optical interferometry. The challenge is an uncertainty reduction of one order of magnitude with respect to the present state of the art.

- Involved NMIs: 7
- Total work: ~ 130 MM
- Total Cost: ~ 1400 k€



2008-2011

Soluzioni per la riduzione della non-linearità

Fabry-Perot + tunable laser

$$I_T = \frac{I_0}{1 + F \sin^2(2\pi D/\lambda)}$$

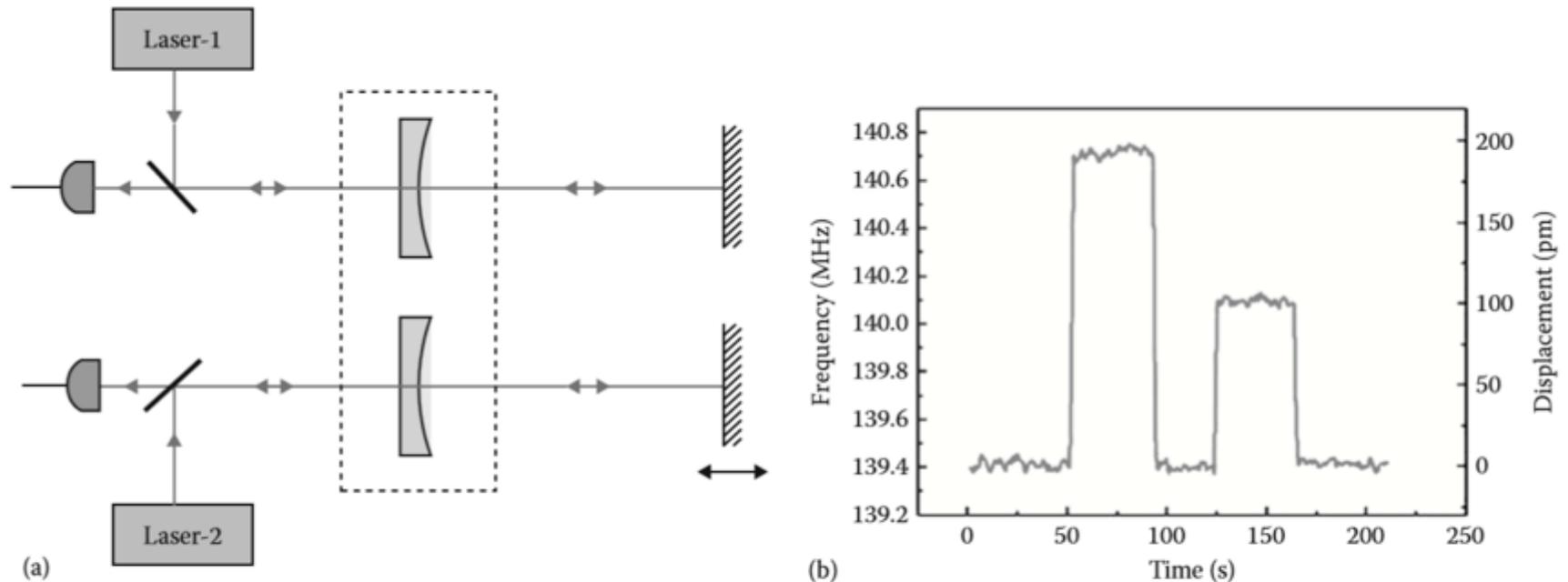


FIGURE 5.10 Differential FPI. (a) Two tunable lasers are locked to a pair of FP cavities built facing two concave mirrors in front of two flat mirrors. Measuring the frequency difference between the two lasers, the relative displacement of the two flat mirrors is obtained. (b) The movement of the mirror of an x-ray interferometer is measured with picometer resolution.

Soluzioni per la riduzione della non-linearità

Separated beams heterodyne interferometers

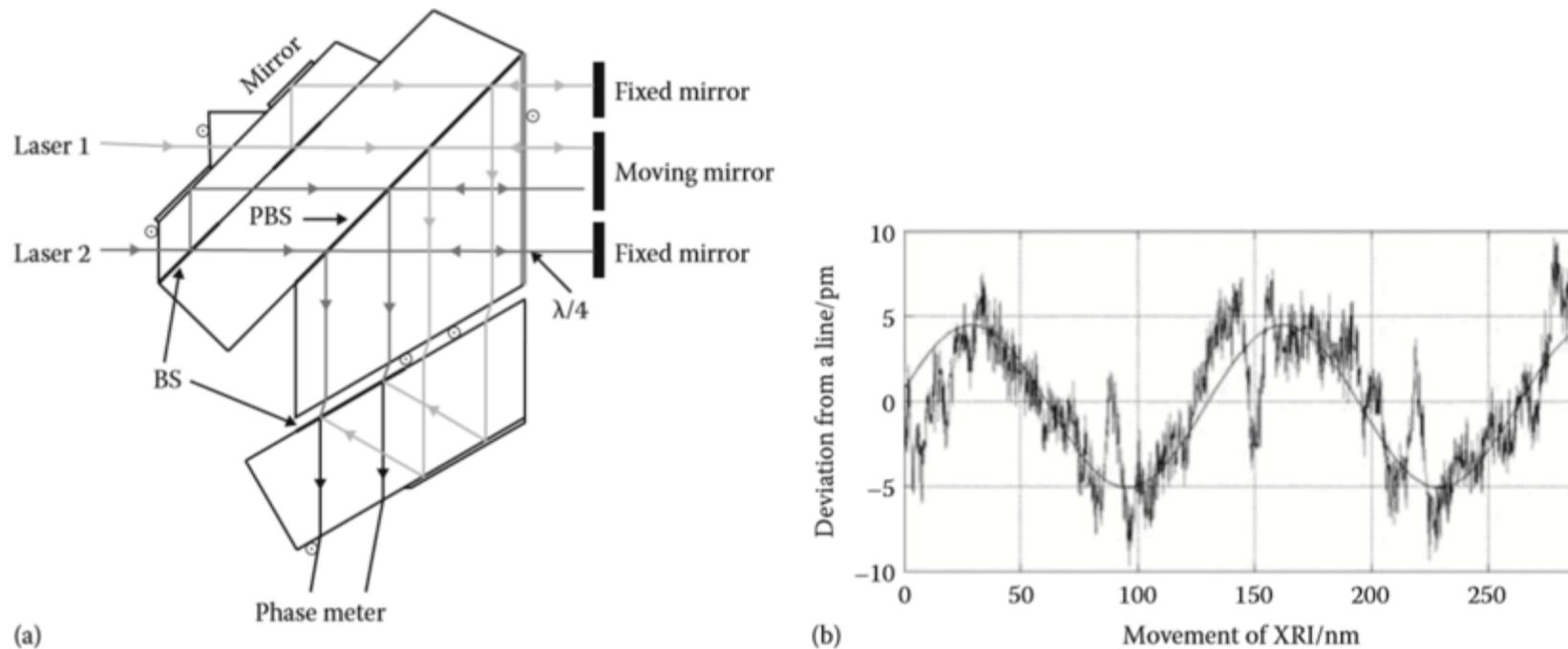
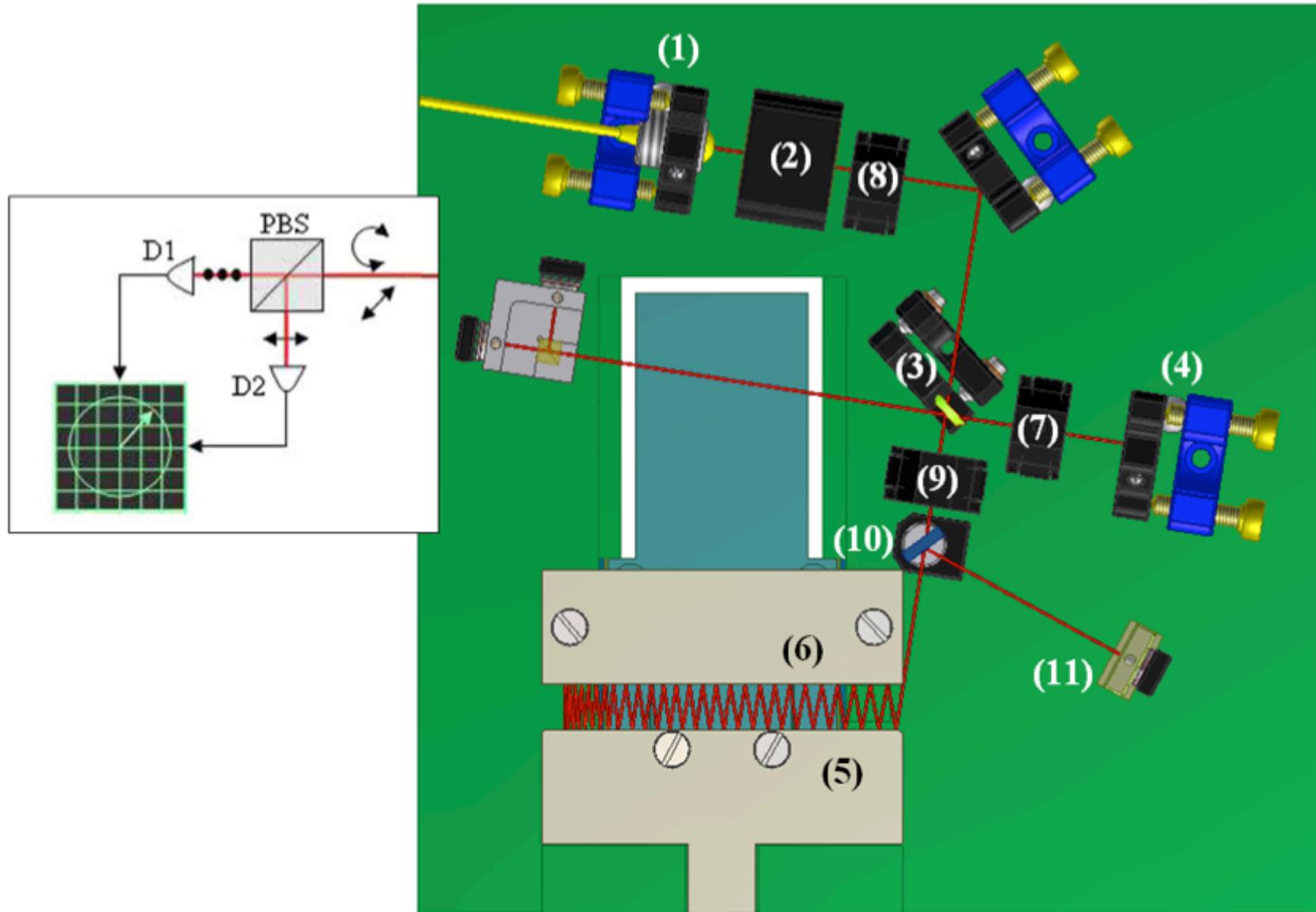
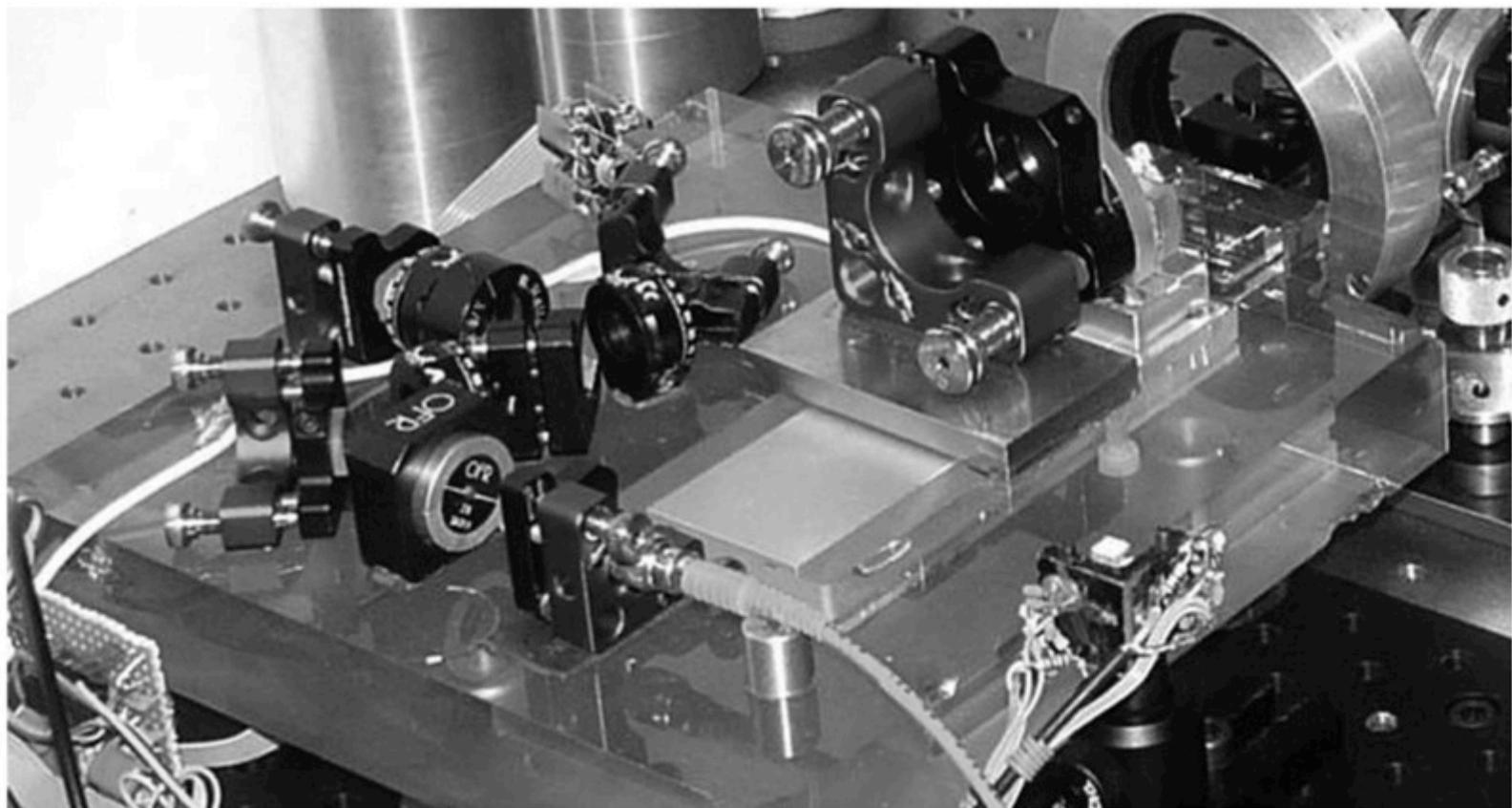


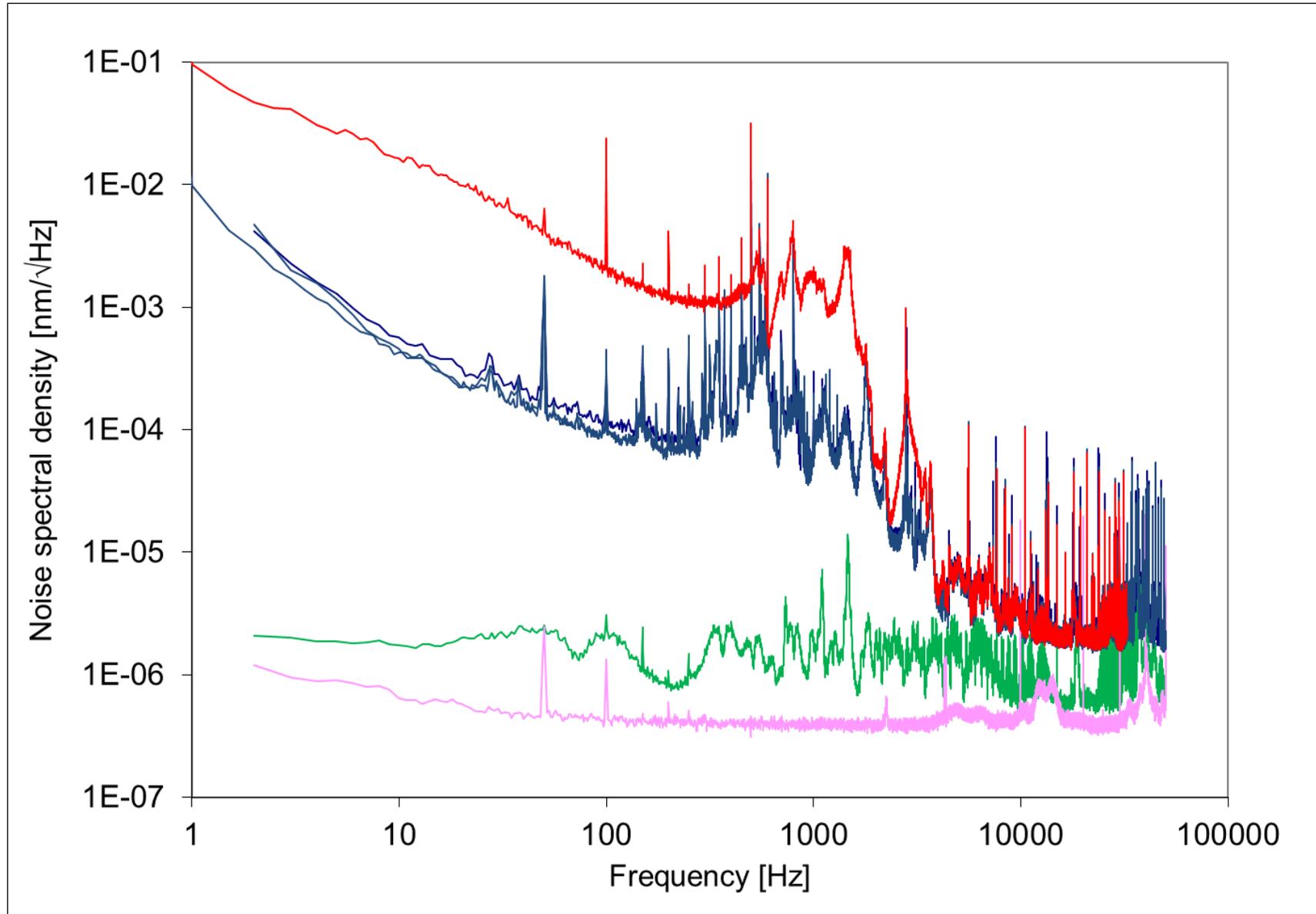
FIGURE 5.9 Separated beams heterodyne interferometer. (a) The optical BS assembly; (b) the residual errors of the interferometer showing a nonlinearity as low as ± 5 pm with $\lambda/4$ periodicity.

Multiple reflection interferometer



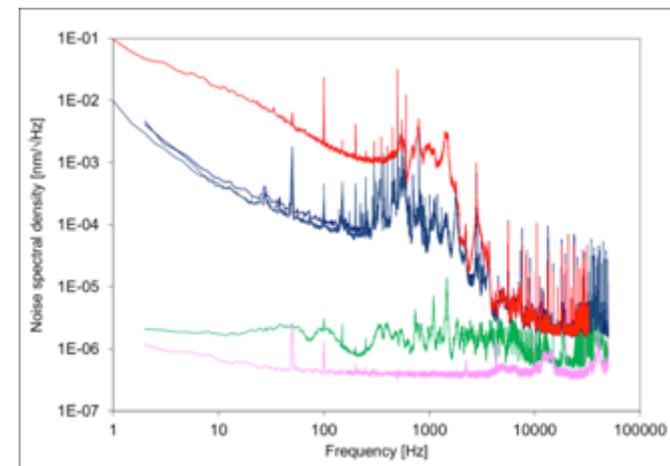
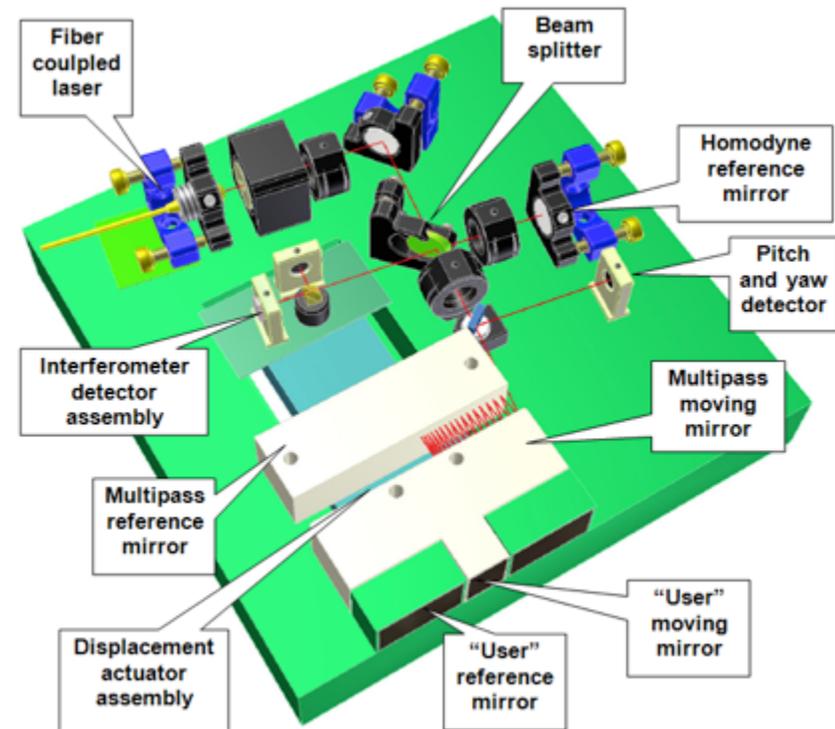


Noise of the interferometer



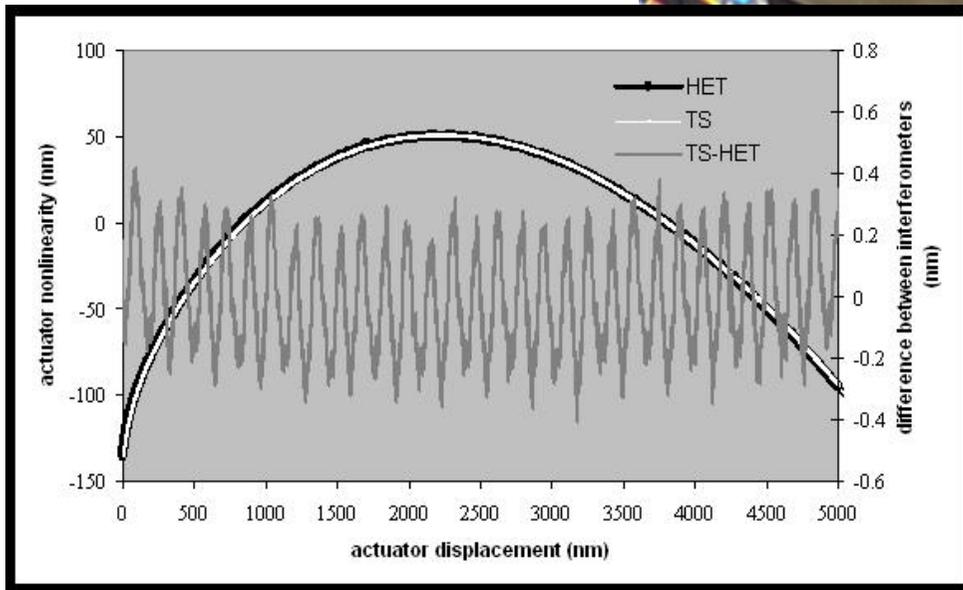
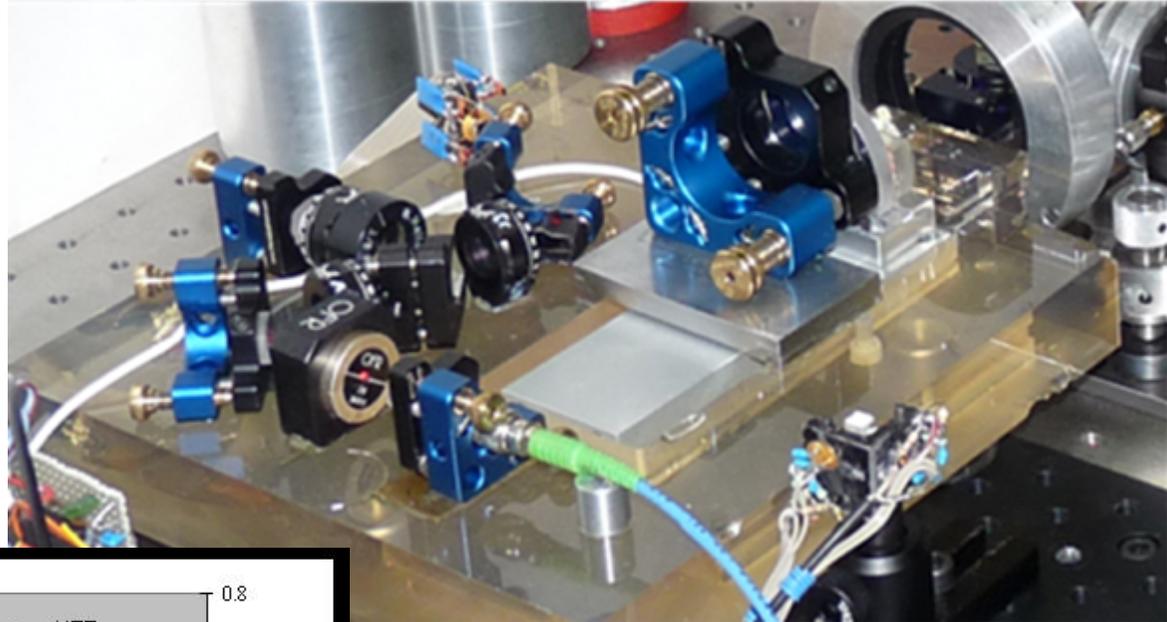
The transfer standard

- Is an actuator under the control of a multiple reflection homodyne interferometer
- The nonlinearities and the noise of the interferometer are scaled by the multiplication factor ($\sim 70x$)
- The pitch and yaw of the moving stage are actively controlled with a pentapode stage
- The front part is designed for direct comparison with differential optical interferometers
- Full range = 100 μm
- Max residual tilt = 0.1'' p.p.
- Environment limited noise < 10 pm/ $\sqrt{\text{Hz}}$
- Electronic limited noise < 10 fm/ $\sqrt{\text{Hz}}$



Characterization of an interferometer with the TS

The actuator of the TS is moved in open loop and the readings of the two interferometers are compared



The errors of the interferometer under test having 500 pm p.p. amplitude and $\lambda/4$ periodicity are measured with a resolution of few pm

**AVAILABLE FOR
COMPARISONS**



+ discussione