

**GRUPPO DI GRAVITAZIONE SPERIMENTALE – IAPS - INAF**

# **IL GRUPPO DI GRAVITAZIONE**

**PRESENTAZIONE PER LE AUDIZIONI INAF 2022**

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**20 Maggio 2022**

# INTRO SCHEDA GG-IAPS

Schede figlie	Acronimo	Coordinatore
BC-1 Italian Spring Accelerometer - missione spaziale ESA/BepiColombo	ISA-BC	francesco.santoli
Accelerometry for Galileo Enhancement and Science	AGES	francesco.santoli
Galileo for Science 2.0	G4S_2.0	david.lucchesi
Italian Spring Accelerometer - Moon Seismometer	ISA-MS	roberto.peron
Liquid Actuated Gravity	LAG	massimo.visco
High Accuracy Accelerometer - missione spaziale ESA/JUICE	HAA-JUICE	marco.lucente
Satellite Test of Relativistic Gravity	SaToR-G	david.lucchesi
Lunar Laser Ranging	LLR	roberto.peron
Measurement of Environmental and Relativistic In-orbit precessions	METRIC	roberto.peron
Gravimetro Aereo Intelligente	GAIN	francesco.santoli

# **CHI SIAMO E COSA FACCIAMO**

# UNA STORIA COMUNE DI ESPERIENZE E COMPETENZE

## Origini, anni '70

Il gruppo di Gravitazione Sperimentale inizia la sua attività all'interno del Laboratorio Plasma Spazio (LPS) del CNR negli anni settanta del secolo passato, sotto la direzione di **Guido Pizzella** ed **Edoardo Amaldi**

## L'antenna risonante

Nella sede di Frascati, viene installata un'antenna per la **rivelazione di onde gravitazionali** a barra risonante criogenica da 300 kg. Il segnale meccanico dell'antenna viene letto da **un trasduttore elettromeccanico** inizialmente piezoelettrico e successivamente capacitivo, amplificato da **dispositivi a basso rumore** e analizzato con **algoritmi per l'estrazione di deboli segnali immersi nel rumore**.

## Anni '80

Per iniziativa di Franco Fuligni e Valerio Iafolla, inizia lo sviluppo di un **accelerometro per uso spaziale** che si avvale dell'esperienza maturata nella ricerca delle onde gravitazionali.

## Anni 2000

All'inizio degli anni 2000 David Lucchesi porta all'interno del gruppo l'attività **di misure di Relatività Generale con i satelliti LAGEOS inseguiti da terra con raggi laser**.

## 2003

Il gruppo ha **sviluppato**, in collaborazione con l'industria, l'**accelerometro ISA** della missione **BepiColombo** e ne gestisce direttamente le operazioni in volo dal momento del **lancio nel 2018**.

## 2008

Dal gruppo è scaturito uno spin-off: AGI Assist in Gravitation and Instrumentation.

# UN GRUPPO, DUE ANIME

## Competenze scientifiche

- Relatività Generale e teorie alternative della gravitazione, fisica dell'interazione gravitazionale, onde gravitazionali, meccanica celeste e astrodinamica, geodesia
- Tecniche di analisi dati (serie temporali, identificazione sorgenti di rumore, ecc.)
- Modelli perturbativi per forze non gravitazionali
- Determinazione Orbitale di Precisione con i sistemi S/W Geodyn II (NASA-GSFC) e Bernese GNSS Software (AIUB)

## Competenze tecnologiche e ingegneristiche

- Progettazione meccanica, termica ed elettronica (analogica e digitale)
- Prototipazione e realizzazioni meccaniche ed elettroniche
- Tecnica di laboratorio per metrologia meccanica, elettronica, vuoto, criogenia e controllo termico
- Gestione strumentazione spaziale
- Pipeline per il trattamento, la distribuzione e l'archiviazione dati
- Metodologie di sviluppo tecnologico (DDV)
- Ingegneria di sistema

Queste **competenze**, unite alla disponibilità delle **strutture di calcolo**, di un **laboratorio** ampio ed attrezzato e delle altre **facilities** dello IAPS, permettono al gruppo di svolgere **tutte le fasi della ricerca sperimentale**: ideazione, progettazione e realizzazione degli esperimenti e successivamente elaborazione ed interpretazione dei risultati.

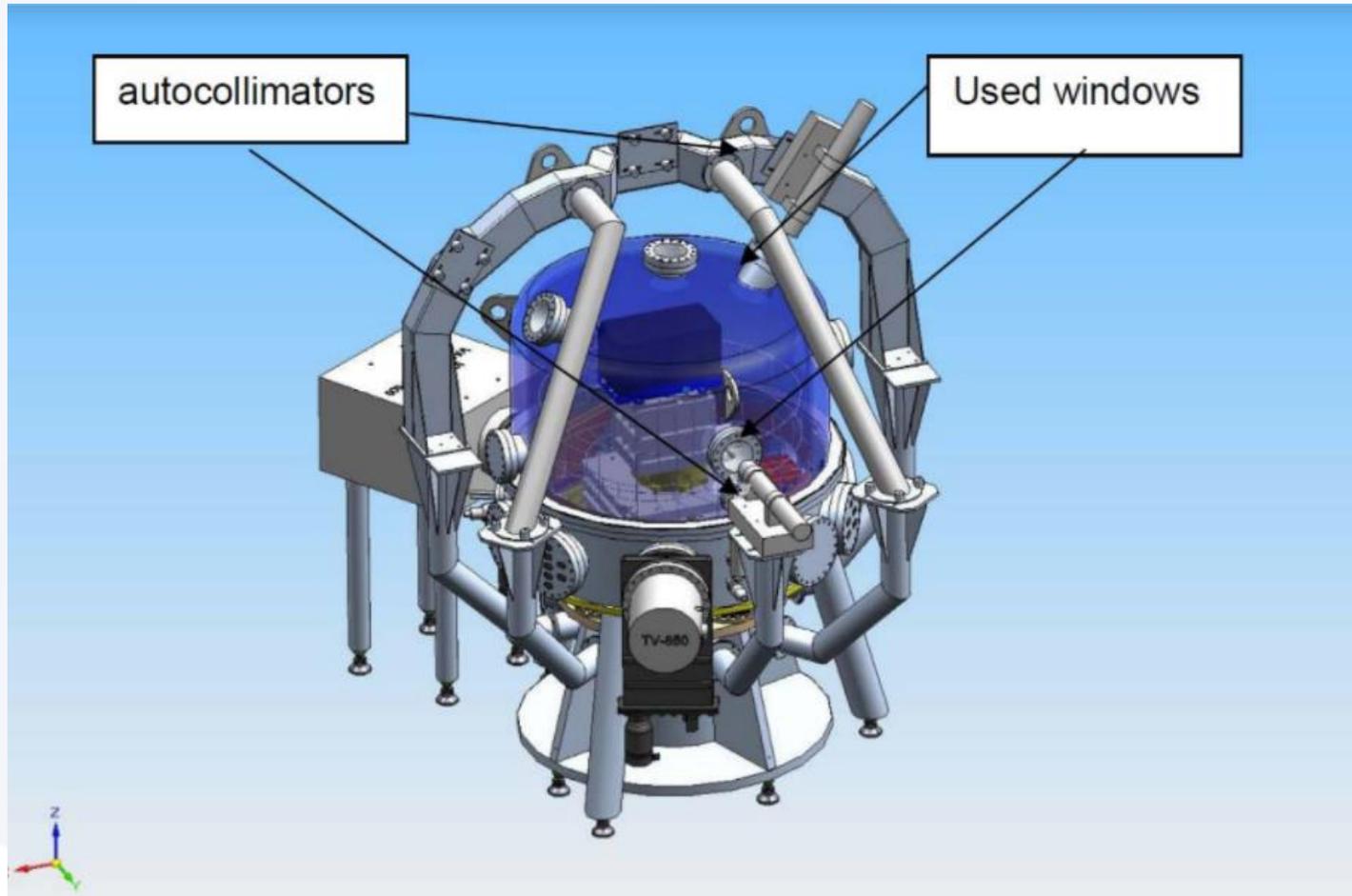
# IL LABORATORIO



- MAIV elettronica
- AIV meccanica
- Criogenia
- Vuoto
- Trattamenti termici
- Torre di caduta
- Calibrazione di accelerometri (funzione di risposta, allineamenti, sensibilità alla temperatura)
- Monitoraggio sismico e gravimetrico

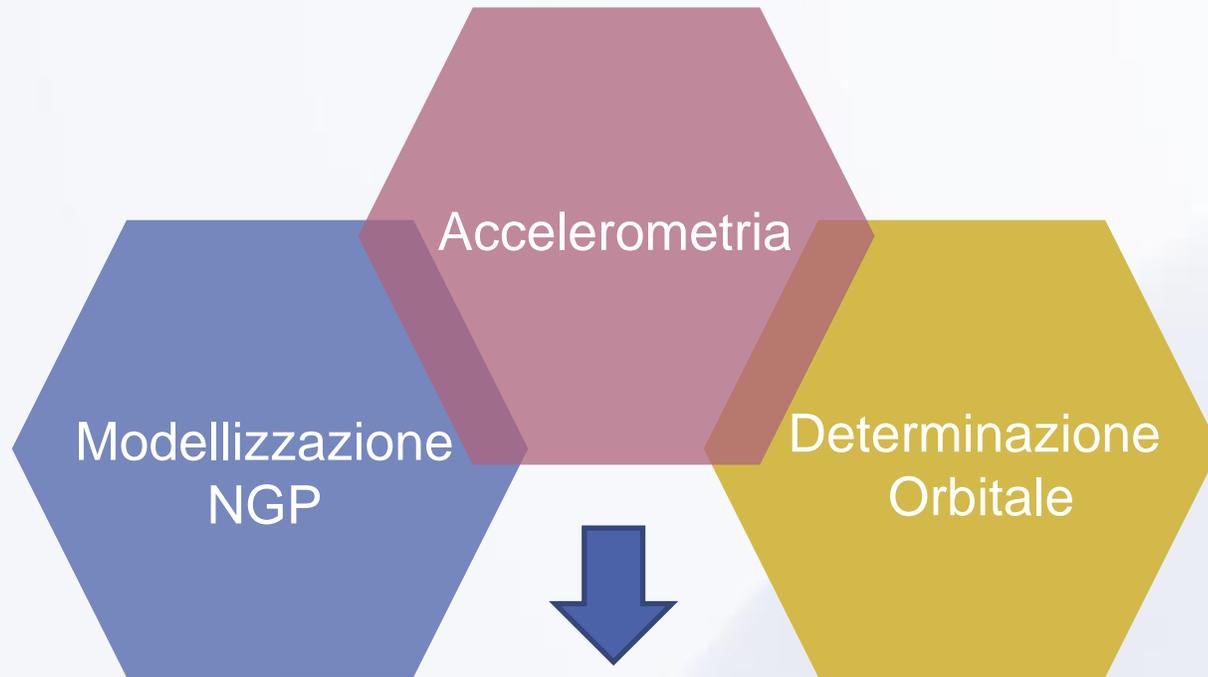
# IL LABORATORIO

## MTGSE - MECHANICAL AND THERMAL GROUND SUPPORT EQUIPMENT



- Proprietà ASI, sviluppata per ISA e HAA
- Camera TV (10-6/10-8 mbar) con 2 cold plate.
- Volume interno ca. 600 l
- Movimentazioni (tip-tilt, rotation stage)
- Autocollimatori.
- Facility di utilità per caratterizzazione di accelerometri alta sensibilità.
- Previsto uso per test a lungo termine di ISA FS.
- Ambiente pulito (classe 100.000)
- Basamento e struttura esterna per scambiatori di calore, da realizzare.
- Attualmente presso TAS-I, verrà trasferita in IAPS. Finanziamento da ASI per trasferimento: 50 k€

# AREE DI COMPETENZA E CAMPI DI ATTIVITA'



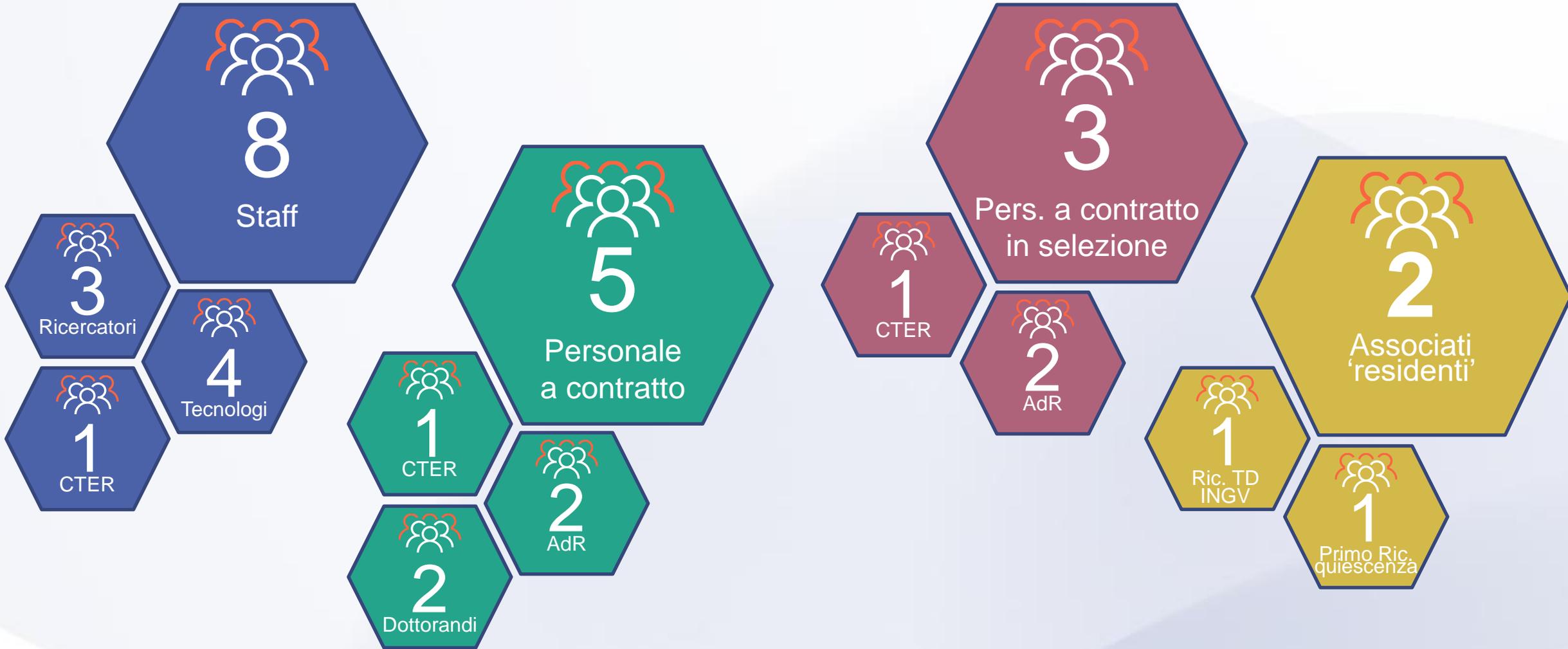
1. RSN4 (test di gravitazione), RSN5 (sviluppo e trasferimento tecnologico), RSN3 (gravimetria planetaria)
2. Ricadute in settori scientifici affini: geodesia, geofisica, navigazione.

## Trasversalità intrinseca

La gravitazione sperimentale risulta intrinsecamente trasversale tra i RSN:

- I 'test di gravitazione' appartengono al RSN4
- La gravimetria è una tecnica per la planetologia: RSN3
- Apparteniamo anche a RSN5 per il carattere sperimentale e di sviluppo strumentale.

# QUANTI SIAMO



# CHI SIAMO

Staff	Nome	Inquadramento
1	David Lucchesi	Primo Ricercatore
2	Roberto Peron	Ricercatore
3	Massimo Visco	Ricercatore
4	Francesco Santoli	Primo Tecnologo
5	Carlo Lefevre	Tecnologo
6	Marco Lucente	Tecnologo
7	Carmelo Magnafico	Tecnologo
8	Emiliano Fiorenza	CTER

Associati residenti	Nome	Inquadramento
1	Valerio Iafolla	Primo ric. quiesc.
2	Lorenzo Iafolla	Ric. TD INGV

Pers. a contr.	Nome	Inquadramento
1	Marco Cinelli	AdR
2	Alessandro Di Marco	AdR
3	Umberto De Filippis	Dottorando
4	Feliciano Sapiro	Dottoranda
5	Lino Loffredo	CTER TD

Pers. da selez.	Progetto	Inquadramento
1	AGES – G4S	CTER TD
2	ISA BepiColombo	AdR
3	ISA BepiColombo	AdR

In verde: profili tecnologici  
In rosso: profili scientifici

# PROGETTI DI RICERCA CORRENTI 1/2

Programma	Tipologia	Ruoli INAF	Aree tematiche	Collaborazione
<b>ISA BepiColombo</b>	Partecipazione a missione spaziale	<ul style="list-style-type: none"> <li>• Principal Investigator</li> <li>• Gestione operazioni</li> <li>• Calibrazioni scientifiche</li> </ul>	<ul style="list-style-type: none"> <li>• Planetologia</li> <li>• Relatività</li> </ul>	<ul style="list-style-type: none"> <li>• ESA (missione, finanziamenti)</li> <li>• ASI (finanziamenti)</li> <li>• Thales Alenia Space (partner industriale)</li> <li>• Uni Rm1 (partner scientifico)</li> </ul>
<b>G4S_2.0</b>	Analisi e misure; sviluppo tecnologico	<ul style="list-style-type: none"> <li>• Responsabilità scientifica e programmatica</li> </ul>	<ul style="list-style-type: none"> <li>• Relatività</li> <li>• Navigazione</li> <li>• Geodesia</li> <li>• Sensoristica</li> <li>• Modelli</li> </ul>	<ul style="list-style-type: none"> <li>• ASI (finanziamenti, collaborazione)</li> <li>• PoliTo (partner scientifico)</li> </ul>
<b>HAA JUICE</b>	Partecipazione a missione spaziale	<ul style="list-style-type: none"> <li>• Calibrazioni scientifiche</li> <li>• Operazioni e trattamento dati TBD</li> <li>• Collaborazione scientifica TBD</li> </ul>	<ul style="list-style-type: none"> <li>• Planetologia</li> <li>• Relatività</li> </ul>	<ul style="list-style-type: none"> <li>• Thales Alenia Space (partner industriale, finanziatore)</li> <li>• Uni Rm1 (partner scientifico)</li> </ul>
<b>GAIN</b>	Sviluppo tecnologico	<ul style="list-style-type: none"> <li>• Attività sperimentale</li> </ul>	<ul style="list-style-type: none"> <li>• Machine learning</li> <li>• Sensors fusion</li> <li>• Gravimetria</li> <li>• Prospezioni geologiche</li> </ul>	<ul style="list-style-type: none"> <li>• INGV (partner scientifico)</li> <li>• Regione Lazio (finanziamenti)</li> </ul>

# PROGETTI DI RICERCA CORRENTI 2/2

Programma	Tipologia	Ruoli INAF	Aree tematiche	Collaborazione
<b>SaToR-G (LARASE)</b>	Analisi dati 'spaziali' per misure di fisica fondamentale	<ul style="list-style-type: none"><li>• Responsabile scientifico</li></ul>	<ul style="list-style-type: none"><li>• Test di gravitazione in campo debole</li><li>• Modelli perturbativi</li><li>• Determinazione orbitale</li></ul>	<ul style="list-style-type: none"><li>• INFN (gestione)</li><li>• Uni Tor Vergata</li><li>• ISTI/CNR</li><li>• Osservatorio di Yebes</li></ul>
<b>LAG</b>	Esperimento a terra	<ul style="list-style-type: none"><li>• Responsabile locale Tor Vergata</li><li>• Modellazione delle interazioni</li></ul>	<ul style="list-style-type: none"><li>• Test di gravitazione in laboratorio</li></ul>	<ul style="list-style-type: none"><li>• INFN sez. Napoli e Tor Vergata (finanziamento e collaborazione)</li><li>• Università Napoli</li><li>• Uni Tor Vergata</li></ul>
<b>AGES</b>	Sviluppo tecnologico	<ul style="list-style-type: none"><li>• Responsabilità scientifica e programmatica</li></ul>	<ul style="list-style-type: none"><li>• Sensoristica</li><li>• Navigazione</li><li>• Geodesia</li></ul>	<ul style="list-style-type: none"><li>• ESA (finanziamenti)</li><li>• Thales Alenia Space (subco industriale)</li></ul>

# **OBIETTIVI E RISULTATI SCIENTIFICI E TECNOLOGICI**



# SATOR-G + LARASE

## TOP LEVEL GOALS

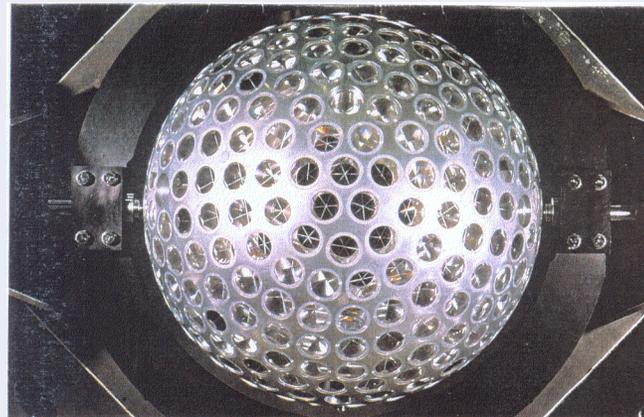
The predictions of **GR** on the orbits of **geodetic satellites**, which play the role of **test masses**, will be compared with those of **ATG** both metric and non-metric in their essence



Parameter	Unit	Symbol	LAGEOS	LAGEOS II	LARES
Semi-major axis	km	a	12 270.00	12 162.08	7 820.31
Eccentricity	-	e	0.0044	0.0138	0.0012
Inclination	deg.	i	109.84	52.66	69.49
Radius	cm	R	30.0	30.0	18.2
Mass	kg	M	406.9	405.4	383.8
Area/Mass	m <sup>2</sup> /kg	A/M	6.94×10 <sup>-4</sup>	6.97×10 <sup>-4</sup>	2.69×10 <sup>-4</sup>



LAGEOS (NASA, 1976)



LAGEOS II (ASI/NASA, 1992)



LARES (ASI, 2012)

# SATOR-G + LARASE

These satellites are tracked with very high accuracy through the powerful **Satellite Laser Ranging (SLR)** technique

The **SLR** represents a very impressive and powerful technique to determine the round-trip time between Earth-bound laser Stations and orbiting passive (and not passive) Satellites

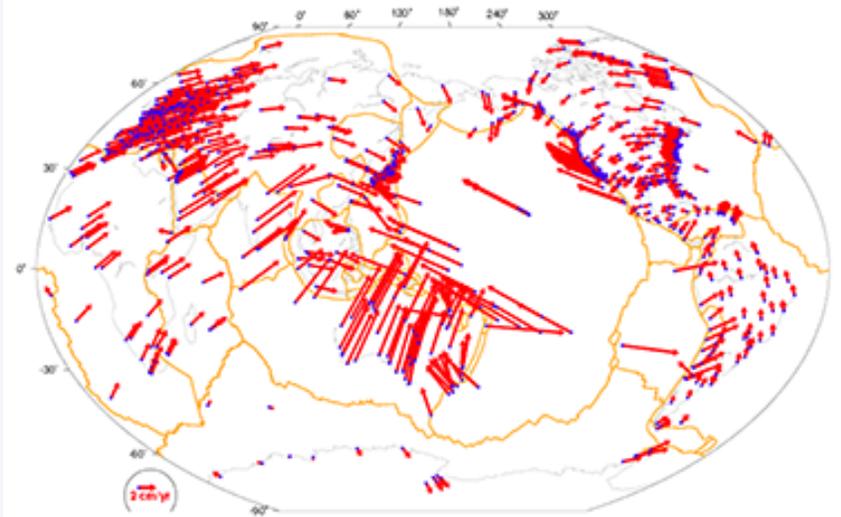
The time series of range measurements (full rates and normal points) are then a record of the motions of both the end points: the Satellite and the Station

Thanks to the accurate modelling (of both gravitational and non-gravitational perturbations) of the orbit of these satellites — approaching 1 cm in range accuracy — we are able to determine their Keplerian elements with about the same accuracy

The precision of the measurement depends mainly on the laser pulse width (about  $1 \cdot 10^{-10}$  s —  $3 \cdot 10^{-11}$  s)

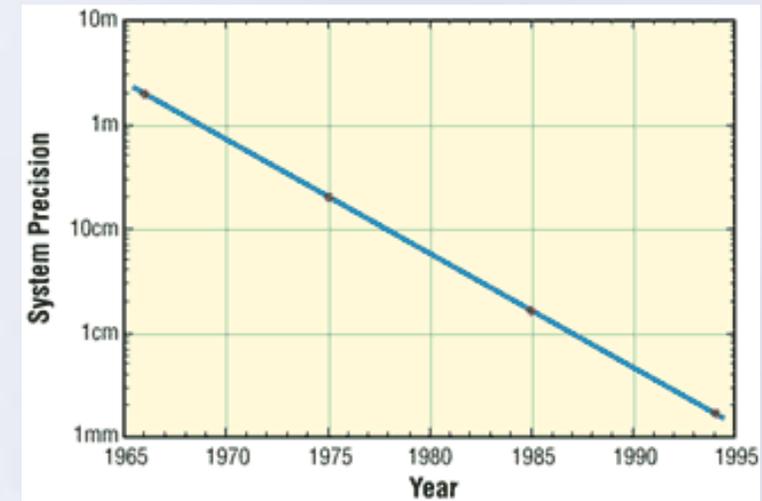


# SATOR-G + LARASE



With respect to this external and quasi-inertial frame it is then possible to measure the absolute positions and motions of the ground-based stations, with an absolute accuracy of a few mm and mm/yr

The normal points have typically precisions of a few mm, and accuracies of about 1 cm, limited by atmospheric effects and by variations in the absolute calibration of the instruments. In this way the orbit of LAGEOS satellites may be considered as a reference frame, not bound to the planet, whose motion in the inertial space (after all perturbations have been properly modelled) is in principle known



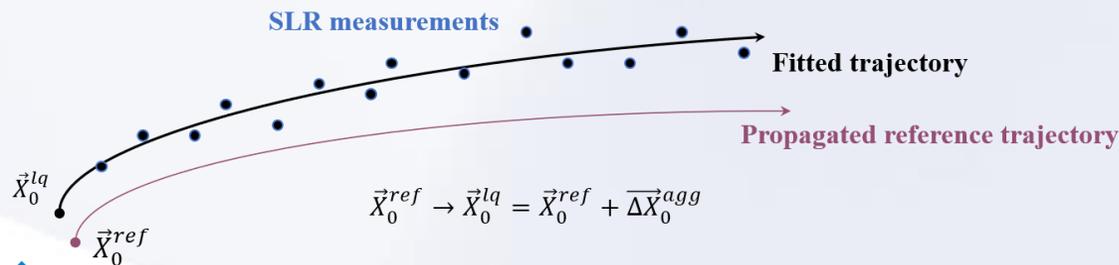
# SATOR-G + LARASE

## PRECISE ORBIT DETERMINATION

Two software are used for the Precise orbit Determination (POD):

- GEODYN II (NASA/GSFC)
- SATAN (NSGF, UK)

1. From a least squares fit of the tracking data by means of an appropriate dynamic model, the estimate of the state vector of the satellite at the beginning of 7-day arcs is obtained
2. Then from an appropriate comparison between the state vector estimated at the beginning of each arc with the state vector estimated at the beginning of the previous arc but propagated at the same epoch, the residuals in the orbital elements are obtained



### Orbits:

$$\frac{d}{dt} \vec{x} = f(\vec{x}, t, \vec{\alpha}) \quad \text{Differential equation}$$

$$\begin{cases} \vec{x} \in \mathbb{R}^\ell \\ \vec{\alpha} \in \mathbb{R}^m \end{cases} \quad \begin{array}{l} \text{State vector (position and velocity, ...)} \\ \text{Models dynamic parameters (C}_{20}, \text{Cr, ...)} \end{array}$$

$$\vec{x}(t_0 = \vec{x}_0 \in \mathbb{R}^\ell) \quad \text{Initial condition at a given epoch: } \ell = 6 + \dots$$

$$\vec{x} = \vec{x}(t, \vec{x}_0, \vec{\alpha}) \quad \text{General solution for the orbits (integral flow)}$$

### Observations:

$$C = C(\vec{x}, t, \vec{\beta}) \quad \text{Observation function, } \vec{\beta} \in \mathbb{R}^n \quad \text{kinematic parameters}$$

$$R_i = O_i - C_i = O_i - C(\vec{x}(t_i), t_i, \vec{\beta}) = \sum_j \frac{\partial C_i}{\partial P_j} \delta P_j + \delta O_i \quad Q(\vec{R}) = \frac{1}{q} \vec{R}^T \vec{R} = \frac{1}{q} \sum_{i=1}^q R_i^2$$

Table 2. Models currently used, within the LARASE research program, for the analysis of the orbit of the two LAGEOS and LARES satellites. The models are grouped in gravitational perturbations, non-gravitational perturbations and reference frames realizations.

Model For	Model Type	Reference
Geopotential (static)	EIGEN-GRACE02S/GGM05S	[84,90,91]
Geopotential (time-varying, tides)	Ray GOT99.2	[92]
Geopotential (time-varying, non tidal)	IERS Conventions 2010	[89]
Third-body	JPL DE-403	[93]
Relativistic corrections	Parameterized post-Newtonian	[88,94]
Direct solar radiation pressure	Cannonball	[46]
Earth albedo	Knocke-Rubincam	[63]
Earth-Yarkovsky	Rubincam	[56,64,65]
Neutral drag	JR-71/MSIS-86	[50,51]
Spin	LASSOS	[42]
Stations position	ITRF2008	[95]
Ocean loading	Schernek and GOT99.2 tides	[46,92]
Earth Rotation Parameters	IERS EOP C04	[96]
Nutation	IERS A00	[97]
Precession	IAU 2000	[98]

# SATOR-G + LARASE

## MAIN SCIENTIFIC RESULTS OF LARASE



An important aspect of our activities lies in continuously improving the dynamic model of the orbits of satellites, in particular the models related to:

1. Non-Gravitational perturbations
2. Gravitational perturbations

This activity of development of perturbative models, in particular for non-gravitational forces, constituted one of the major results of **LARASE**, beyond the significant measurements obtained in the field of fundamental physics, and still constitutes a salient activity that characterises the current **SaToR-G** experiment

The **LARASE** results:

1. Reconstruction of the internal structure of the two **LAGEOS** satellites and of **LARES**: mass and moments of inertia
2. Spin model for the three satellites: general and averaged
3. Thermal model of the three satellites: general and averaged
4. Neutral drag model for **LARES**

M. Visco, D. Lucchesi, *Review and critical analysis of mass and moments of inertia of the LAGEOS and LAGEOS II satellites for the LARASE program*. Adv. in Space Res. 57, 044034 doi:10.1016/j.asr.2016.02.006, 2016

M. Visco, D. Lucchesi, *Comprehensive model for the spin evolution of the LAGEOS and LARES satellites*. Phys. Rev. D 98, 044034 doi:10.1103/PhysRevD.98.044034, 2018

Pardini, C.; Anselmo, L.; Lucchesi, D.M.; Peron, R. *On the secular decay of the LARES semi-major axis*. Acta Astronautica 2017, 140, 469–477. doi:10.1016/j.actaastro.2017.09.012

# SATOR-G + LARASE

## MAIN SCIENTIFIC RESULTS OF LARASE

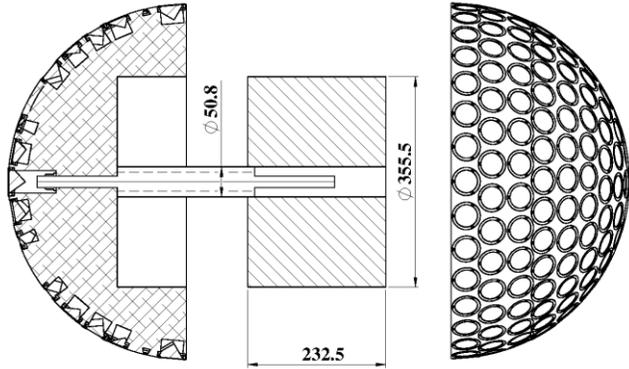


Table 1  
Materials used for the construction of the two LAGEOS satellites (Cogo, 1988) and their nominal densities.

Satellite	Material density $\rho_n$ (kg/m <sup>3</sup> )		
	Hemispheres	Core	Stud
LAGEOS	AA6061 2700 <sup>a</sup>	QQ-B-626 COMP.11 8440 <sup>a</sup>	Cu-Be 8230 <sup>b</sup>
LAGEOS II	AlMgSiCu UNI 6170 2740 <sup>c</sup>	PCuZn39Pb2 UNI 5706 8280 <sup>c</sup>	Cu-Be QQ-C-172 8250 <sup>c</sup>

<sup>a</sup> ASM International Handbook Committee (1990).

<sup>b</sup> Bauccio (1993).

<sup>c</sup> It is the value calculated in Cogo (1988) starting from the measured averaged composition.

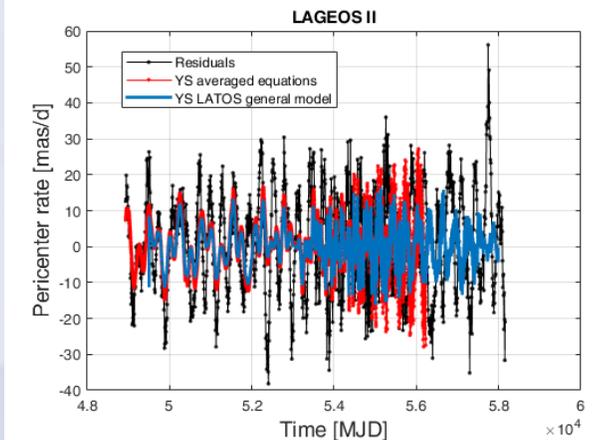
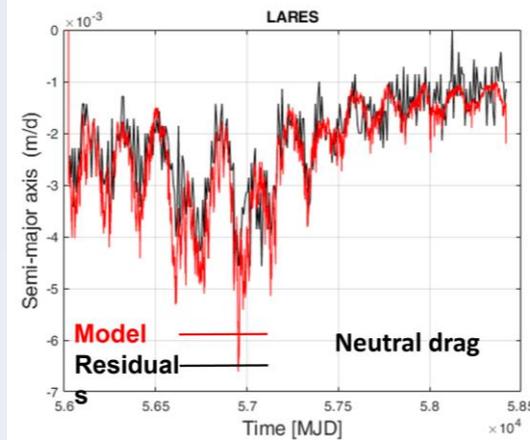
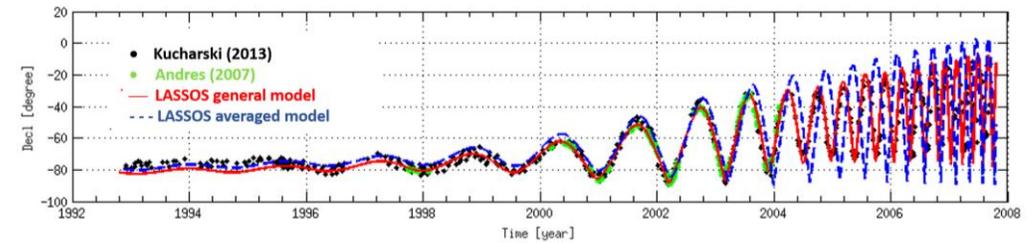
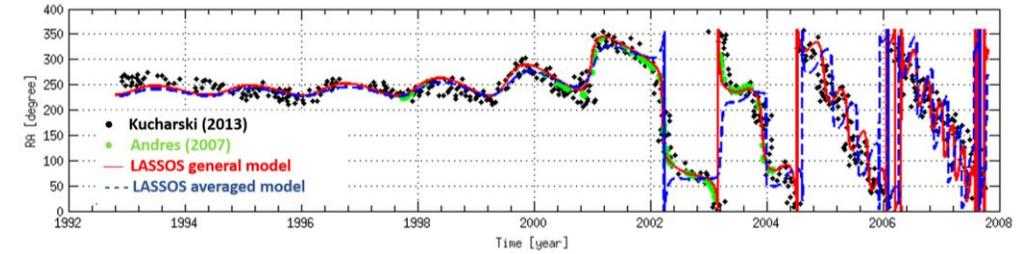
Table 1. Principal moments of inertia of LAGEOS, LAGEOS II and LARES in their flight arrangement.

Satellite	Moments of Inertia (kg m <sup>2</sup> )		
	$I_{zz}$	$I_{xx}$	$I_{yy}$
LAGEOS	$11.42 \pm 0.03$	$10.96 \pm 0.03$	$10.96 \pm 0.03$
LAGEOS II	$11.45 \pm 0.03$	$11.00 \pm 0.03$	$11.00 \pm 0.03$
LARES	$4.77 \pm 0.03$	$4.77 \pm 0.03$	$4.77 \pm 0.03$

## LArase Satellites Spin mOdel Solutions (LASSOS)

## LArase Thermal mOdel Solutions (LATOS)

Spin Orientation:  $\alpha, \delta$



# SATOR-G + LARASE

## MAIN SCIENTIFIC RESULTS OF LARASE



1. A precise and accurate measurement of the total relativistic advancement ( $\varepsilon$ ) of the pericenter of **LAGEOS II** (mainly produced by the Earth's **Gravitoelectric** field), with consequent constraints on alternative theories of gravitation

$$\varepsilon_{meas} - 1 = (-0.12 \pm 2.10) \cdot 10^{-3} \pm 2.5 \cdot 10^{-2}$$

$$\begin{cases} \varepsilon_{GR} = 1 \\ \varepsilon_{New} = 0 \end{cases}$$

2. A precise and accurate measurement of the precession ( $\mu$ ) of the node of the orbits of the two **LAGEOS** and of the **LARES** produced by the Earth's **Gravitomagnetic** field

$$\mu_{meas} - 1 = 1.5 \times 10^{-3} \pm 7.4 \times 10^{-3} \pm 16 \times 10^{-3}$$

$$\begin{cases} \mu_{GR} = 1 \\ \mu_{New} = 0 \end{cases}$$

From the 1st measurement the following constraints were derived:

1. On the combination of the **PPN** parameters  $\beta$  and  $\gamma$  of **General Relativity**
2. On the intensity  $\alpha$  of a **Yukawa-like** potential on a scale  $\lambda$  of about 1 Earth radius
3. On **non-symmetric** theories of gravitation
4. On **torsional** theories of gravitation



$$\epsilon_{meas} - 1 = (-0.12 \pm 2.10) \cdot 10^{-3} \pm 2.5 \cdot 10^{-2}$$

### Summary of the constraints obtained

TABLE XVIII. Summary of the results obtained in the present work; together with the measurement error budget, the constraints on fundamental physics are listed and compared with the literature.

Parameter	Values and uncertainties (this study)	Uncertainties (literature)	Remarks
$\epsilon_{\omega} - 1$	$-1.2 \times 10^{-4} \pm 2.10 \times 10^{-3} \pm 2.54 \times 10^{-2}$	...	Error budget of the perigee precession measurement in the field of the Earth
$\frac{ 2+2\gamma-\beta }{3} - 1$	$-1.2 \times 10^{-4} \pm 2.10 \times 10^{-3} \pm 2.54 \times 10^{-2}$	$\pm(1.0 \times 10^{-3}) \pm (2 \times 10^{-2})^a$	Constraint on the combination of PPN parameters
$ \alpha $	$\lesssim  0.5 \pm 8.0 \pm 101  \times 10^{-12}$	$\pm 1 \times 10^{-8b}$	Constraint on a possible (Yukawa-like) NLRI
$C_{\oplus LAGEOS II}$	$\leq (0.003 \text{ km})^4 \pm (0.036 \text{ km})^4 \pm (0.092 \text{ km})^4$	$\pm(0.16 \text{ km})^{4c}; \pm(0.087 \text{ km})^{4d}$	Constraint on a possible NSGT
$ 2t_2 + t_3 $	$\lesssim 3.5 \times 10^{-4} \pm 6.2 \times 10^{-3} \pm 7.49 \times 10^{-2}$	$3 \times 10^{-3e}$	Constraint on torsion

<sup>a</sup>From the preliminary estimate of the systematic errors of [166] for the perihelion precession of Mercury.

<sup>b</sup>From [167] with Lunar-LAGEOS *GM* measurements.

<sup>c</sup>From [5] and based on a partial estimate for the systematic errors.

<sup>d</sup>From [7] and based on the analysis of the systematic errors only.

<sup>e</sup>From [168] with no estimate for the systematic errors.

PPN →

Yukawa →

ATGs →

D. Lucchesi, R. Peron, *LAGEOS II pericenter general relativistic precession (1993-2005): Error budget and constraints in gravitational physics*. Phys. Rev. D 89, 082002, doi:10.1103/PhysRevD.89.082002, 2014

# SATOR-G + LARASE

## MAIN SCIENTIFIC RESULTS OF LARASE: YUKAWA-LIKE LONG-RANGE FORCE

A Yukawa-like parameterization seems general at the lowest order interaction and in the non-relativistic limit, independently of a:

- **Scalar** field with the exchange of a spin-0 light boson
- **Vector** field with the exchange of a spin-1 light boson
- **Tensor** field with the exchange of a spin-2 light boson



$$|\alpha| \cong |(0.5 \pm 8) \cdot 10^{-12} \pm 101 \cdot 10^{-12}|$$

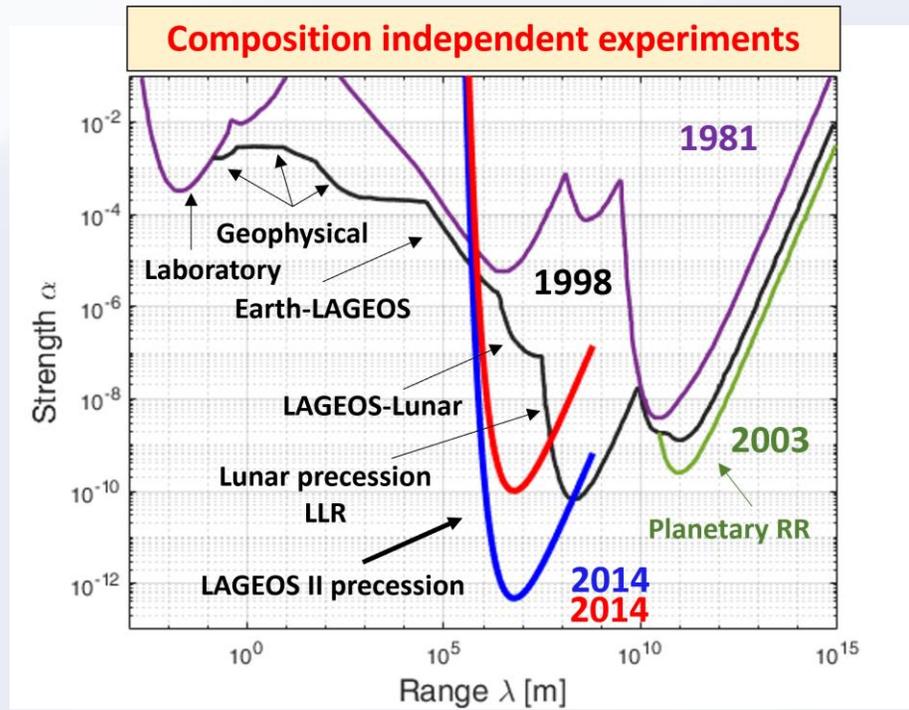
$$V_{yuk} = -\alpha \frac{G_\infty M_1}{r} e^{-r/\lambda}$$

$$\alpha = \frac{1}{G_\infty} \left( \frac{K_1}{M_1} \cdot \frac{K_2}{M_2} \right)$$

$$\lambda = \frac{h}{\mu c}$$

$M_1$  = Mass of the primary source;  
 $M_2$  = Mass of the secondary source;  
 $G_\infty$  = Newtonian gravitational constant;  
 $r$  = Distance;

$\alpha$  = Strength of the interaction;  $K_1, K_2$  = Coupling strengths;  
 $\lambda$  = Range of the interaction;  $\mu$  = Mass of the light-boson;  
 $h$  = Planck constant;  $c$  = Speed of light



Previous limits with LAGEOS's from GM measurements:

$$|\alpha| < 10^{-5} \div 10^{-8}$$

$$|\alpha| \cong 5 \cdot 10^{-13}$$

$$|\alpha| \cong 1 \cdot 10^{-10}$$

$$\lambda \cong 6,081 \text{ km} \approx 1R_\oplus$$

D. Lucchesi, R. Peron, LAGEOS II pericenter general relativistic precession (1993-2005): Error budget and constraints in gravitational physics. Phys. Rev. D 89, 082002, doi:10.1103/PhysRevD.89.082002, 2014

# SATOR-G + LARASE

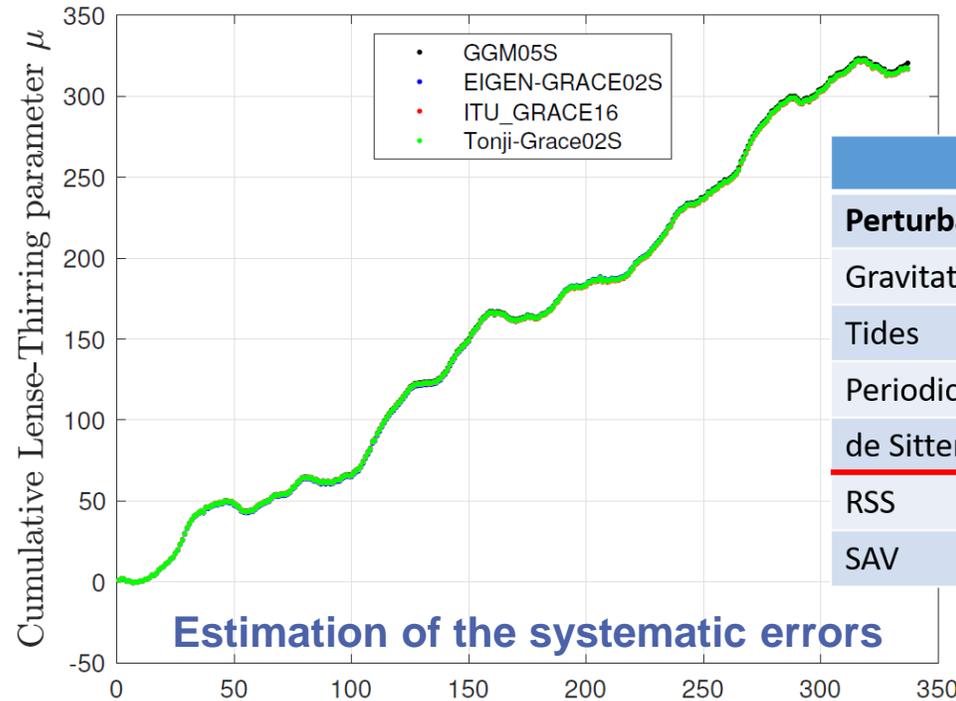
## MAIN SCIENTIFIC RESULTS OF LARASE: FROM THE NODES MEASUREMENTS



$$\mu_{meas} - 1 = 1.5 \times 10^{-3} \pm 7.4 \times 10^{-3} \pm 16 \times 10^{-3}$$

This is indeed a very accurate measurement

### Lense-Thirring effect measurement: frame dragging



	$\delta\mu_{sys} [\%]$
<b>Perturbations</b>	<b>cum. resid.</b>
Gravitational field	<b>1.0</b>
Tides	<b>0.6</b>
Periodic effects	<b>0.3 (1.0)</b>
de Sitter effect	<b>0.3</b>
RSS	<b>1.2 (1.6)</b>
SAV	<b>2.2 (2.9)</b>

### Errors @ 95% CL

Rate (mas/yr)	LAGEOS	LAGEOS II	LARES
$\dot{\Omega}_{LT}$	30.67	31.50	118.48

Model	$\mu \pm \delta\mu$	$\mu - 1$
GGM05S	$1.0053 \pm 0.0074$	+ 0.0053
EIGEN-GRACE02S	$1.0002 \pm 0.0074$	+ 0.0002
ITU_GRACE16	$0.9996 \pm 0.0074$	- 0.0004
Tonji-Grace02s	$1.0008 \pm 0.0074$	+ 0.0008

$$\dot{\Omega}_{LT} = \frac{2G}{c^2 a^3} \frac{J_{\oplus}}{(1 - e^2)^{3/2}}$$

D. Lucchesi, M. Visco, R. Peron, et al., A 1% Measurement of the Gravitomagnetic Field of the Earth with Laser-Tracked Satellites. Universe 6, 139, doi:10.3390/universe6090139, 2020

# SATOR-G + LARASE

## SATOR-G GOALS



From the analysis of the orbits of the satellites it is possible to obtain a whole series of gravitational measurements with consequent constraints on different theories of gravitation. Among the main measures we can consider:

- Constraints on long-range interactions
- **PPN** parameters and their combinations:  $\beta$ ,  $\gamma$ ,  $\alpha_1$ ,  $\alpha_2$
- Relativistic precessions and non-linearity of the gravitational interaction
- **EEP** and **Nordtvedt effect**
- ...

Looking at the effects on the orbits of artificial satellites allows us to test **GR** vs. other **metric theories**, in their deeper aspects, related to the curvature of spacetime, motion on geodesics and field equations

The goal is to provide **precise** and **accurate** measurements, in the sense of a **robust** and **reliable** evaluation of the systematics errors, in order to obtain significant constraints for the different theories

# SATOR-G + LARASE

## SATOR-G PRELIMINARY RESULTS

$$\mu_{meas} - 1 = 1.5 \times 10^{-3} \pm 7.4 \times 10^{-3} \pm 16 \times 10^{-3}$$



Constraints to scalar-tensor theories

- An interesting case is that of **Extended Gravity (EG)** theories, where:

$$\square R \rightarrow f(R)$$

$$\square R \rightarrow f(R, R_{\alpha\beta}R^{\alpha\beta})$$

$$\square R \rightarrow f(R, R_{\alpha\beta}R^{\alpha\beta}, \phi)$$

$$S_{GR} = \frac{1}{16\pi G} \int R \sqrt{-g} d^4x + S_{ng}$$

$$S_{BD} = \frac{1}{16\pi G} \int \left( \phi R - \frac{\omega}{\phi} g^{\alpha\beta} \phi_{,\alpha} \phi_{,\beta} \right) \sqrt{-g} d^4x + S_{ng}$$

$$S_{EG} = \frac{1}{16\pi G} \int \left( f(R, R_{\alpha\beta}R^{\alpha\beta}, \phi) - \frac{\omega}{\phi} g^{\alpha\beta} \phi_{,\alpha} \phi_{,\beta} \right) \sqrt{-g} d^4x + S_{ng}$$

S. Capozziello, G. Lambiase, et al., *Constraining models of extended gravity using Gravity Probe B and LARES experiments*. PRD 91, 044012, 2015

Where  $\phi$  is a scalar field and  $\omega$  represents the dimensionless Dicke's coupling constant: it is tested by the experiments

$$\dot{\Omega}_{LT}^{EG} = - \frac{1 + m_Y r + (m_Y r)^2}{e^{m_Y r}} \dot{\Omega}_{LT}^{GR}$$

$$\dot{\Omega}_{grav} = \dot{\Omega}_{LT}^{GR} + \dot{\Omega}_{LT}^{EG}$$

$$m_Y > 1.9 \times 10^{-6} m^{-1}$$

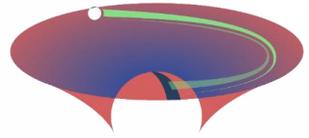
→ Introduces effective masses:  $m_R, m_\phi, m_Y$

$Y = R_{\alpha\beta}R^{\alpha\beta}$  curvature invariant

D. Lucchesi, L. Anselmo, M. Bassan, et al., *Testing Gravitational Theories in the Field of the Earth with the SaToR-G Experiment*. Universe 7, 192, <https://doi.org/10.3390/universe7060192>, 2021

# SATOR-G + LARASE

## SATOR-G PRELIMINARY RESULTS



SaToR-G

Constraints to torsion theories

Torsional theories are characterised by non-symmetric affine connections:

$$\mu_{meas} - 1 = 1.5 \times 10^{-3} \pm 7.4 \times 10^{-3} \pm 16 \times 10^{-3}$$

$$\square \quad \Gamma_{\beta\gamma}^{\alpha} \neq \Gamma_{\gamma\beta}^{\alpha}$$

$$S_{\beta\gamma}^{\alpha} = \frac{\Gamma_{\beta\gamma}^{\alpha} - \Gamma_{\gamma\beta}^{\alpha}}{2}$$

Tensor that describes the torsion phenomena

$t_1, t_2, t_3, w_1, w_2, w_3, w_4, w_5$  torsion parameters that must be constrained by measurements

$$\dot{\Omega}_{tor} = \langle \dot{\Omega}^{LT} \rangle_{sec} \left[ -\frac{w_2 - w_4}{4} \right] + \langle \dot{\Omega}^{dS} \rangle_{sec} \left[ \frac{t_2}{2} \right]$$

March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., Constraining spacetime torsion with LAGEOS. Gen. Relativ. Gravit., 43, 3099–3126, 2011

$$-0.36 < w_2 - w_4 < +0.44$$

From a previous measurement of the Lense-Thirring effect with an estimated error budget of about 10%

Ciufolini, I.; Pavlis, E.C. A confirmation of the general relativistic prediction of the Lense-Thirring effect. Nature, 431, 958–960, 2004

D. Lucchesi, L. Anselmo, M. Bassan, et al., Testing Gravitational Theories in the Field of the Earth with the SaToR-G Experiment. Universe 7, 192, <https://doi.org/10.3390/universe7060192>, 2021

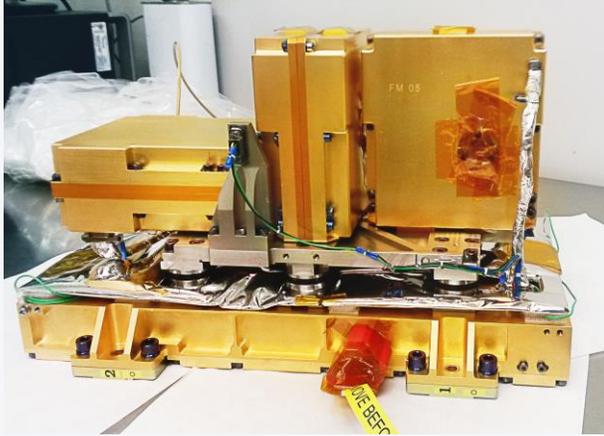
$$\dot{\Omega}_{tor} = \langle \dot{\Omega}^{LT} \rangle_{sec} \left[ -\frac{w_2 - w_4}{4} \right]$$

$$\dot{\Omega}_{grav} = \dot{\Omega}_{LT}^{GR} + \dot{\Omega}_{dS}^{GR} + \dot{\Omega}_{tor}$$

$$w_2 - w_4 = -0.006 \pm 0.064$$

# ITALIAN SPRING ACCELEROMETER - BEPICOLOMBO

## OBIETTIVI SCIENTIFICI



ISA - Italian Spring Accelerometer, è l'accelerometro ad alta sensibilità a bordo del Mercury Planetary Orbiter (MPO) della missione ESA BepiColombo.

Misurando le accelerazioni non gravitazionali agenti sulla sonda, permetterà di considerare (a posteriori) l'MPO come 'massa test' in moto su una geodetica dello spazio-tempo.



All'interno degli esperimenti di RadioScienza, ISA contribuirà allo studio del campo gravitazionale, dello stato rotazionale di **Mercurio** e ad eseguire verifiche della **Relatività Generale (parametri PPN)** con accuratezze mai raggiunte prima (specie per il parametro di Eddington  $\gamma$ ).

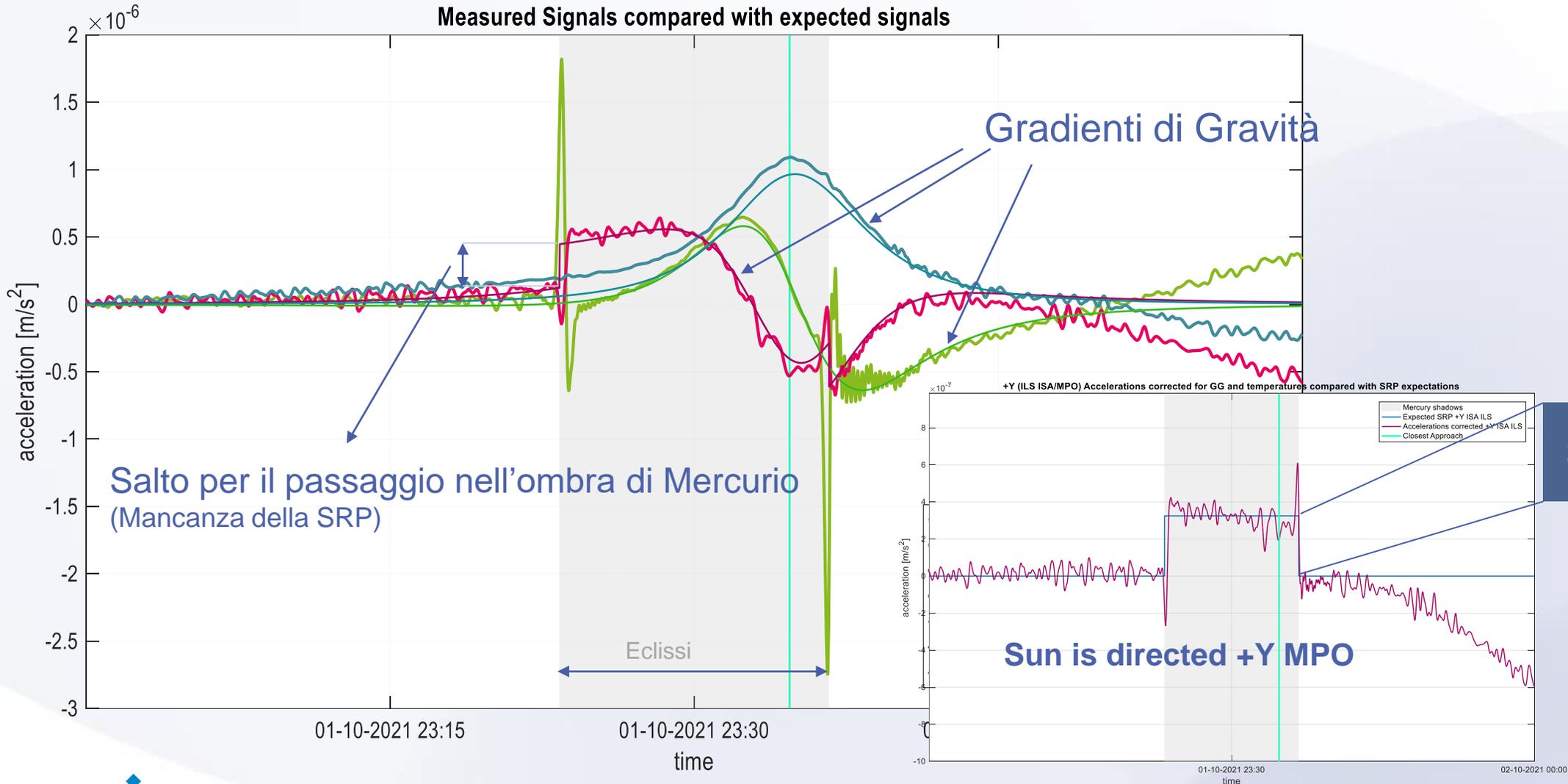
ISA è il primo accelerometro ad alta sensibilità ad aver fatto misure a bordo di una sonda nello spazio interplanetario.

Le sue prestazioni sono confrontabili a quelle dei migliori accelerometri per uso spaziale.



# ITALIAN SPRING ACCELEROMETER - BEPICOLOMBO

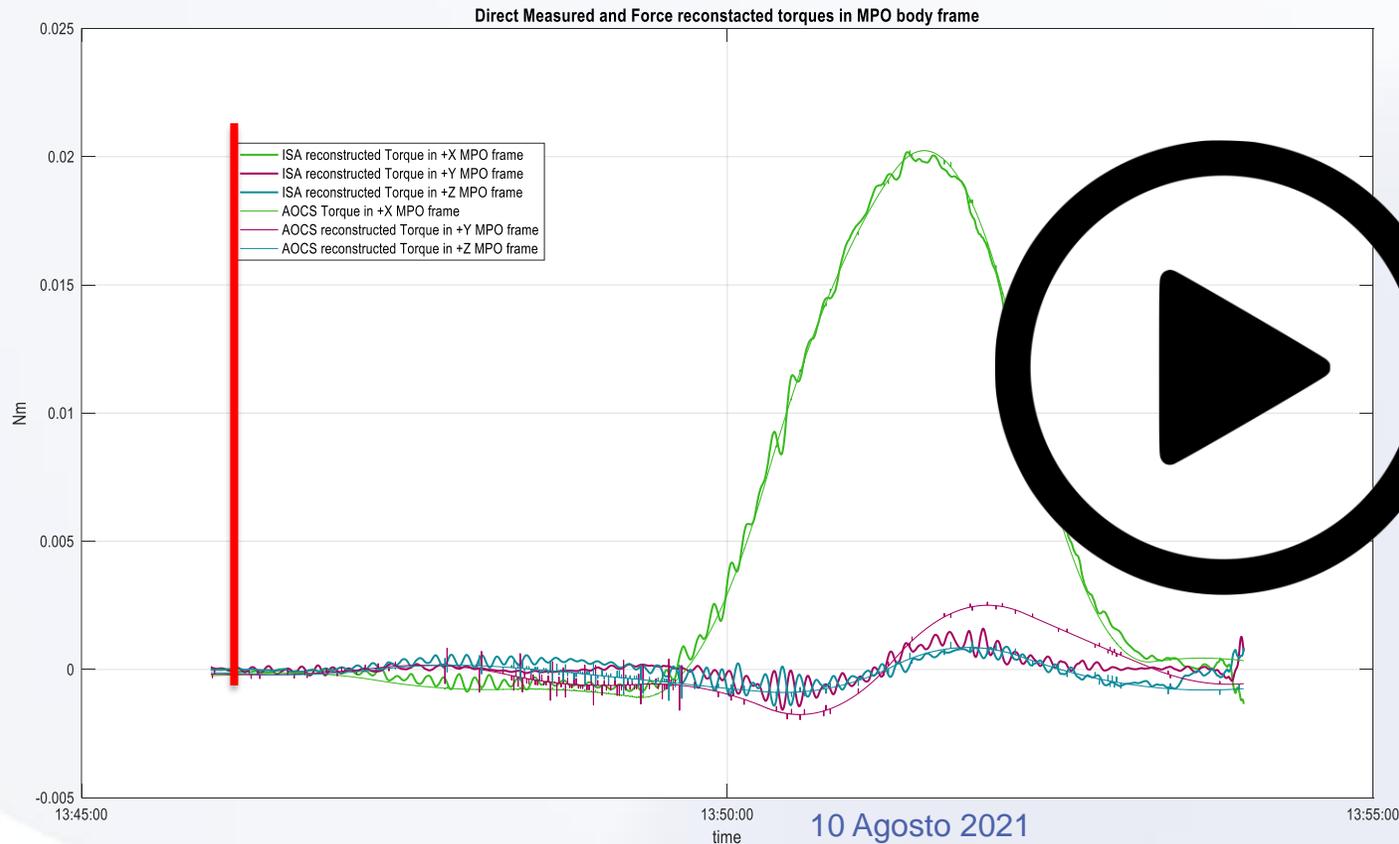
## RISULTATI DAL FLYBY#1 CON MERCURIO



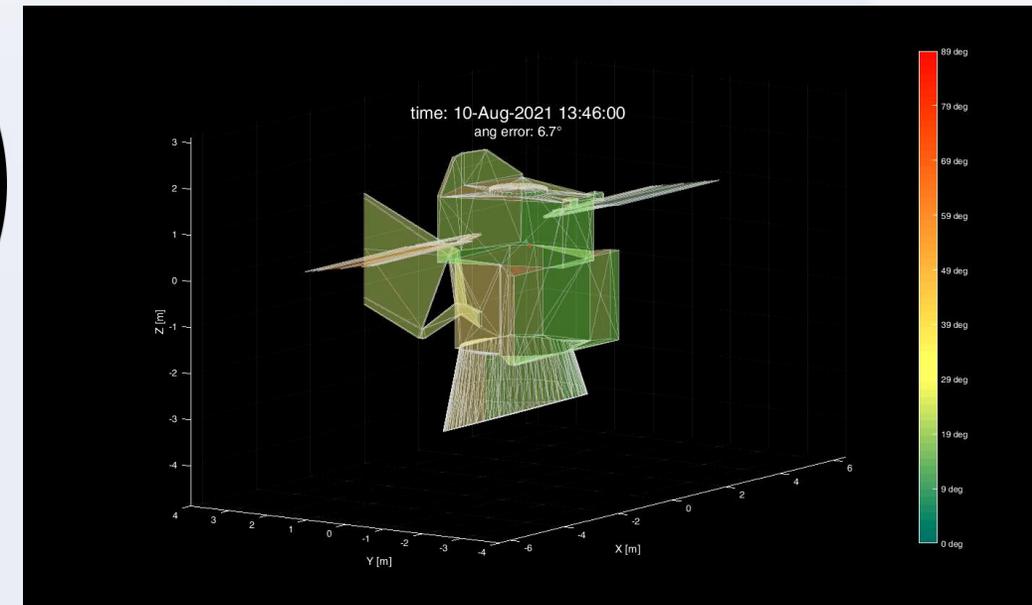
# ITALIAN SPRING ACCELEROMETER - BEPICOLOMBO

## RISULTATI DAL FLYBY#2 CON VENERE

$$\vec{T} = \vec{b} \times \vec{F}_{MPO}$$



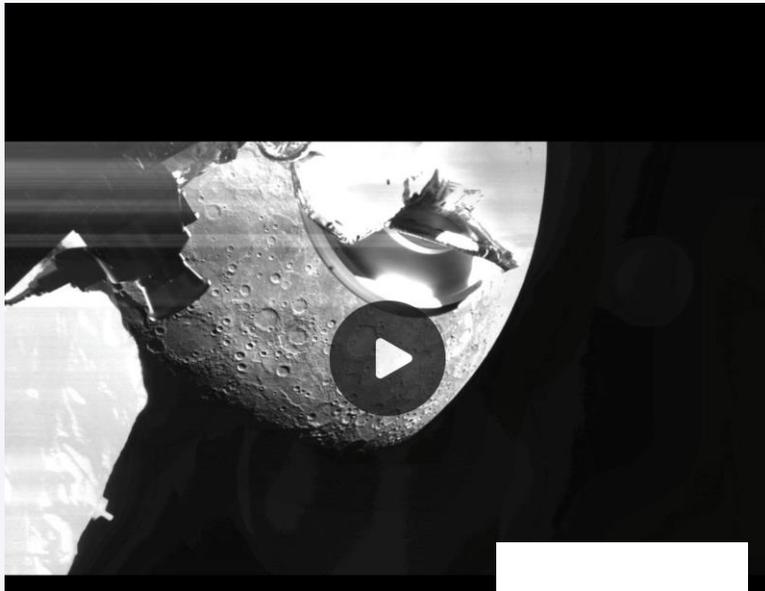
Evoluzione delle forze esterne applicate al satellite misurate da ISA e dei loro punti di applicazione stimati grazie alla comparazione con le coppie applicate dal controllo d'assetto del satellite



# ITALIAN SPRING ACCELEROMETER BEPICOLOMBO

## RISULTATI DAL FLYBY CON MERCURIO - OUTREACH

L'accelerometro si è distinto anche per i risultati di **outreach** delle sonificazioni dei suoi dati



14324 VIEWS

→ | X

SCIENCE & EXPLORATION

### Feeling a close Mercury flyby

15/10/2021 14323 VIEWS 43 LIKES 459927 ID 00:00:18

🇬🇧

LIKE DOWNLOAD

DETAILS RELATED

This section of BepiColombo Monitoring Camera imagery is set to an audio soundtrack that corresponds to the accelerations experienced by the spacecraft following the closest approach.

→ | X

SCIENCE & EXPLORATION

### How a spacecraft 'feels' a planetary flyby

15/10/2021 27873 VIEWS 89 LIKES 459925 ID 00:00:25

🇬🇧

LIKE DOWNLOAD

DETAILS RELATED

How a spacecraft 'feels' a planetary flyby

Caption: A spectrogram visualising the effects of the 1-2 October 2021 Mercury flyby on the ESA/JAXA BepiColombo

27873 VIEWS

# ITALIAN SPRING ACCELEROMETER BEPICOLOMBO



## PUBBLICAZIONI PRINCIPALI E IN PREPARAZIONE

- ❑ *ISA investigations during BC second Venus swing-by* (in preparazione)
- ❑ *ISA rendez-vous at its first Mercury swing-by* (in preparazione)
- ❑ F. Santoli, E. Fiorenza, C. Lefevre, D. M. Lucchesi, M. Lucente, C. Magnafico, A. Morbidini, R. Peron, V. Iafolla, **“ISA, a High Sensitivity Accelerometer in the Interplanetary Space - Updates after the Near-Earth Commissioning Phase of Italian Spring Accelerometer – ISA”**, Space Sci Rev (2020) 216:145, <https://doi.org/10.1007/s11214-020-00768-6>
- ❑ V. Mangano, et al., **“BepiColombo Science Investigations during Cruise and Flybys at the Earth, Venus and Mercury”**, Space Sci Rev (2021) 217:23, <https://doi.org/10.1007/s11214-021-00797-9>
- ❑ A. Genova, et al. **“Geodesy, Geophysics and Fundamental Physics Investigations of the BepiColombo Mission”**, Space Sci Rev (2021) 217:31, <https://doi.org/10.1007/s11214-021-00808-9>
- ❑ M. Lucente, C. Lefevre, E. Fiorenza, C. Magnafico, F. Santoli, V. Iafolla, **“Calibration of ISA accelerometer sensing axes for the BepiColombo mission”**, Planetary and Space Science, Volume 211, 2022,105396, ISSN 0032-0633, <https://doi.org/10.1016/j.pss.2021.105396>
- ❑ F. Santoli, V. Iafolla, E. Fiorenza, C. Lefevre, D. M. Lucchesi, M. Lucente, C. Magnafico, R. Peron, **“The ISA accelerometer for BepiColombo: data processing and operations”**, 5rd IEEE Metrology for Aerospace (MetroAeroSpace), Roma, Italy, June 20-22, 2018

# GALILEO FOR SCIENCE

## G4S\_2.0: GOALS

The **Galileo for Science (G4S\_2.0)** project, funded by **ASI**, aims to perform a set of measurements in the field of **Gravitation** with the two **Galileo-FOC** satellites on **eccentric orbits** and taking advantage of the accuracy of their on-board **atomic clocks**

The **high level goals** of the project are:

1. A new measurement of the **Gravitational Redshift**
2. A measurement of the **General Relativity precessions** on the orbits of the satellites
3. Constraints on **Dark Matter**
4. Realise a pure **Relativistic Positioning System**
5. Detection of **Gravitational Waves** with the **Galileo-system**

Other **fundamental goals** of the project are:

1. To develop new and more accurate models for the **Non-Gravitational Perturbations**
2. To develop a new **accelerometer concept** for a next generation of Galileo satellites

On-going activities focus on the following main topics:

1. On-board clock-bias data analysis on existing data: in view of the **GRS** measurement and of the constraints on the existence of **Dark Matter**
2. Models for the **NGPs**: in particular for the direct solar radiation pressure
3. Precise Orbit Determination with SLR data
4. Development of a new **accelerometer**: with the main aim of reducing **low frequency thermal problems**

# GALILEO FOR SCIENCE

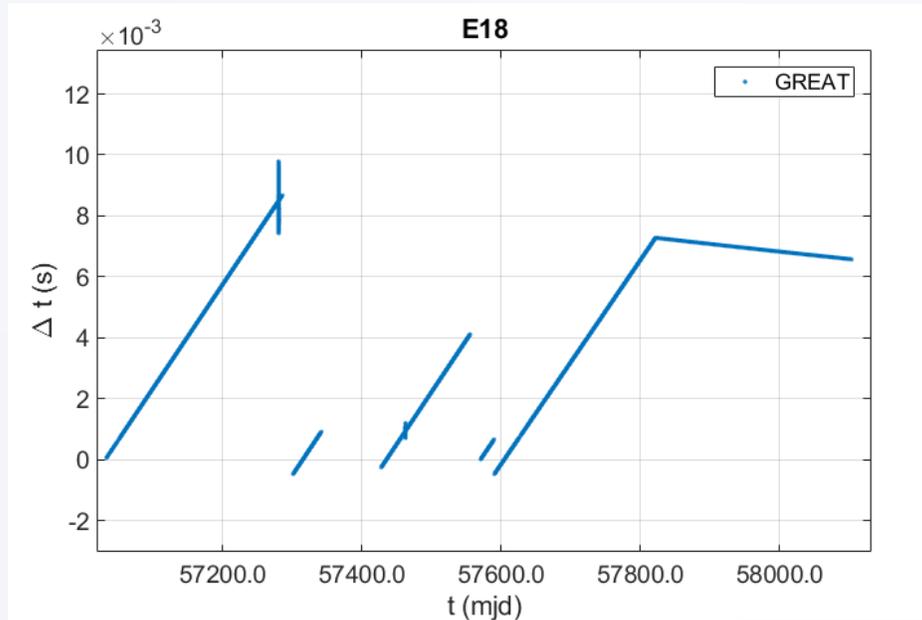
## RESULTS: CLOCK-BIAS DATA ANALYSIS GSAT-0202

GREAT project results:

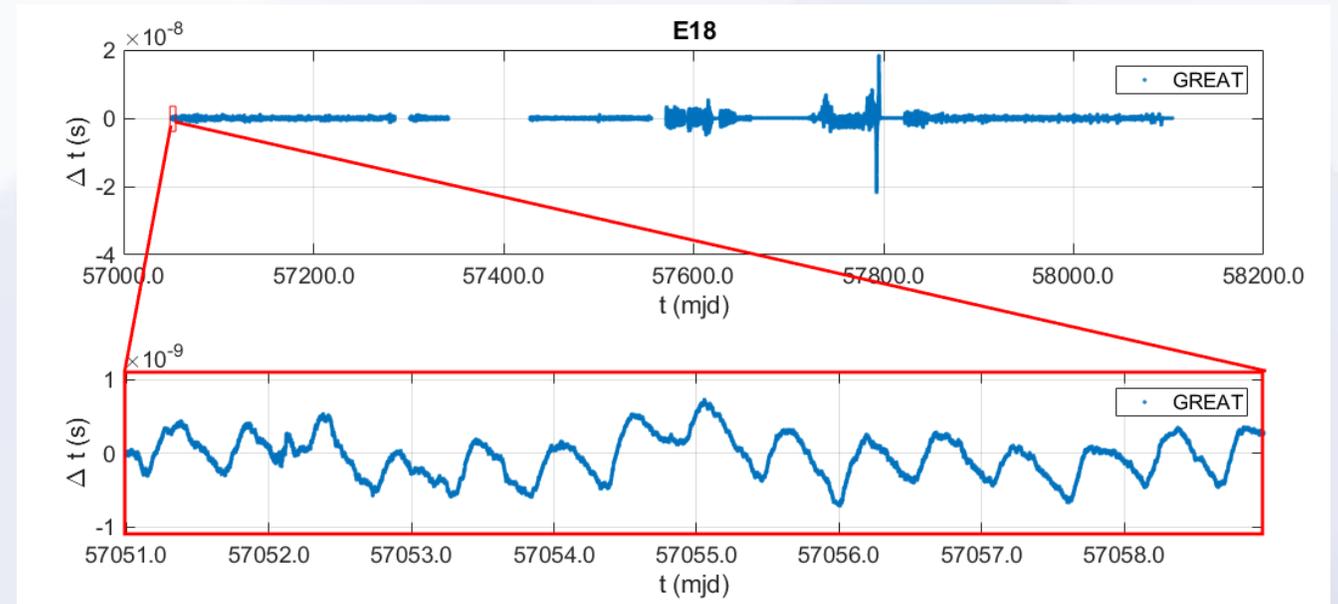
$$\alpha = (0.19 \pm 2.48) \times 10^{-5} \quad \text{P. Delva, et al., Phys. Rev. Letter, 121, 231101 (2018)}$$

$$\alpha = (4.5 \pm 3.1) \times 10^{-5} \quad \text{S. Herrmann, et al., Phys. Rev. Lett., 121, 231102 (2018)}$$

Raw clock-bias from ESOC clock solution



"Corrected" clock-bias



$$y_\alpha = -(1 + \alpha) \frac{GM_\oplus}{rc^2}$$

$\alpha = 0$  in GR

Goal

$$|\alpha| \leq 2 \times 10^{-5}$$

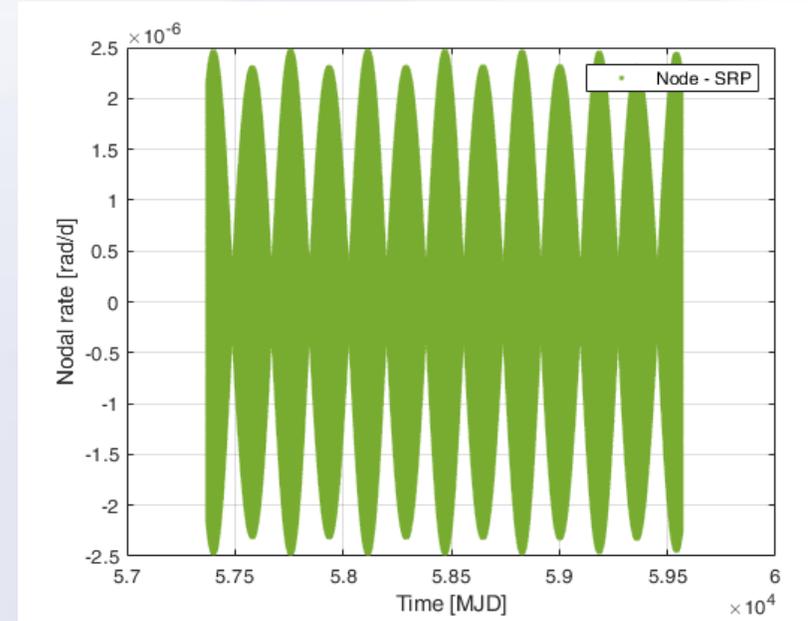
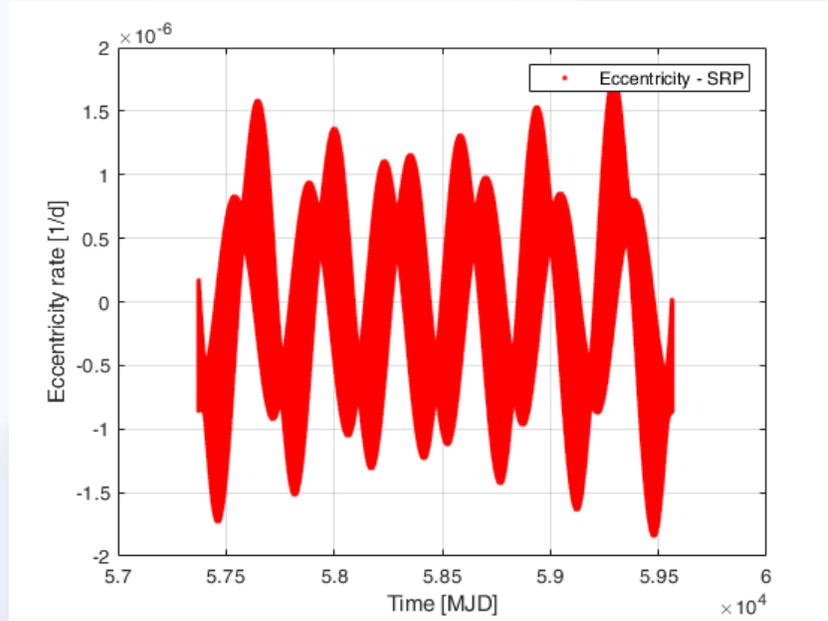
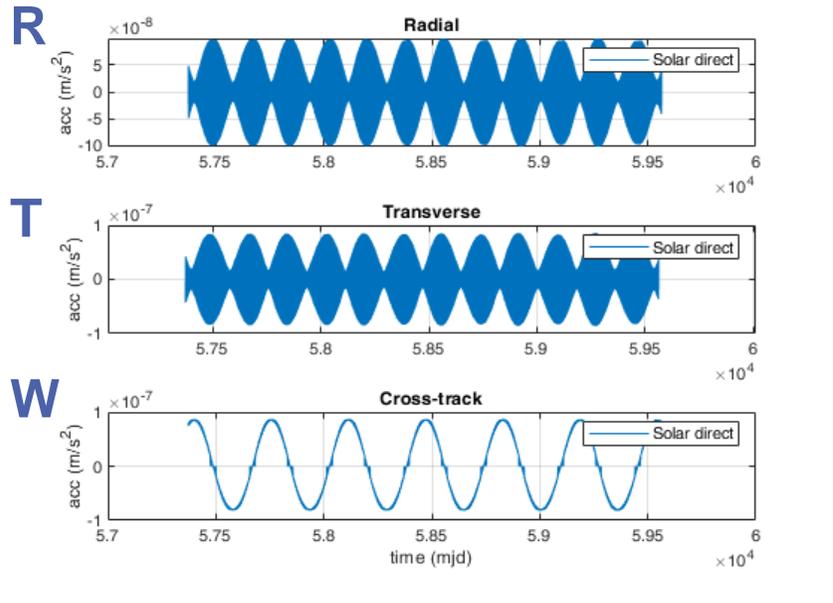
# GALILEO FOR SCIENCE

## RESULTS: BOX-WING FOR GSAT-0208 (ESA GALILEO METADATA)

### Gauss accelerations

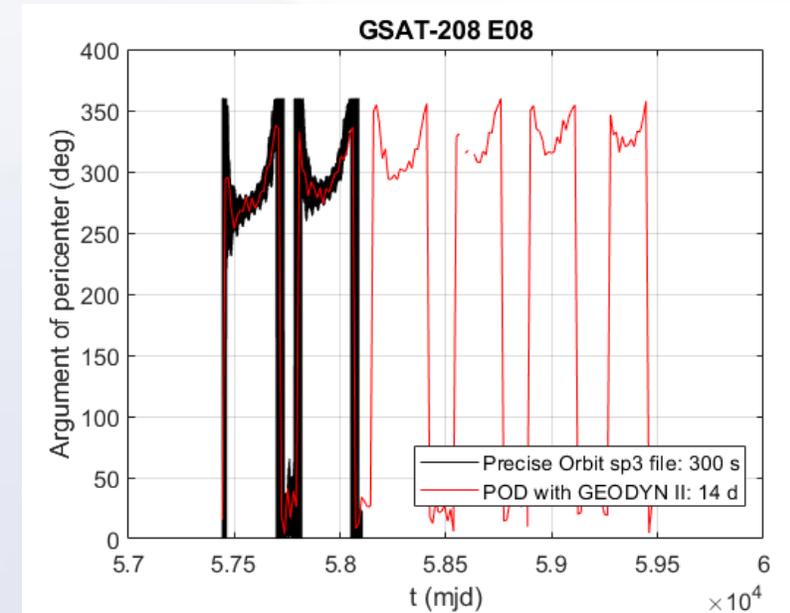
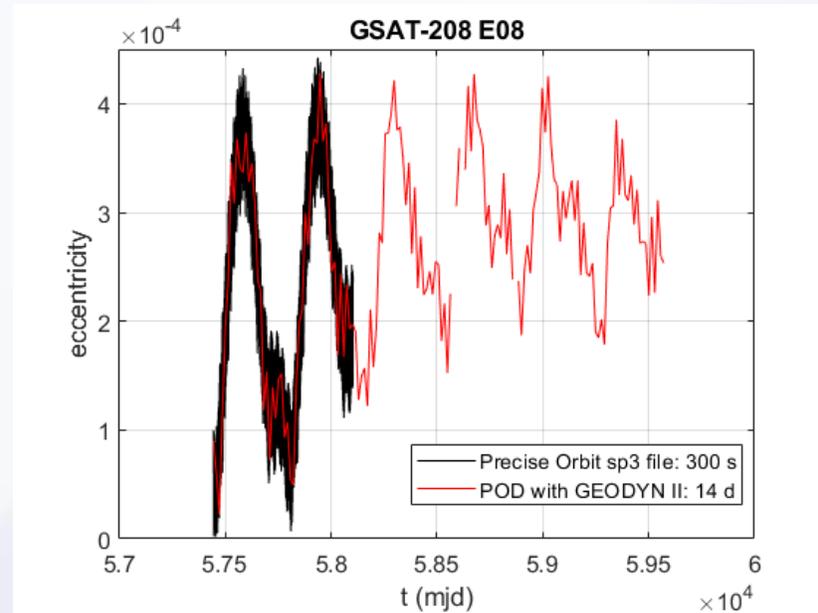
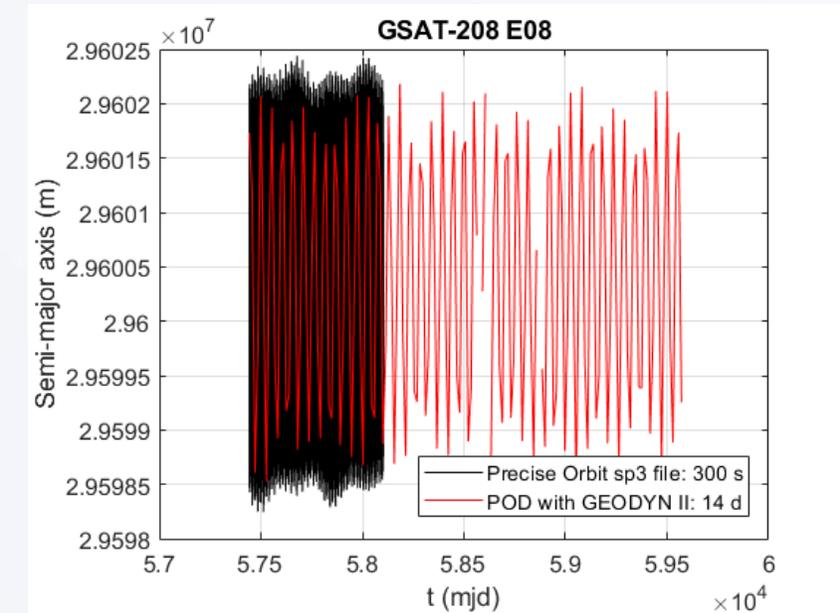
$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na} [R \sin f + T(\cos f + \cos u)]$$

$$\frac{d\Omega}{dt} = \frac{W}{H \sin i} r \sin(\omega + f)$$



# GALILEO FOR SCIENCE

## RESULTS: POD FOR GSAT-0208 VS ESA PRECISE ORBITS



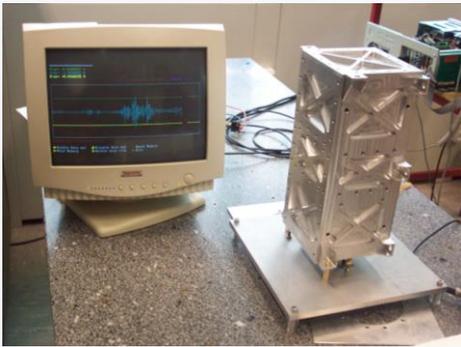
# GALILEO FOR SCIENCE

## G4S\_2.0: PUBLICATIONS

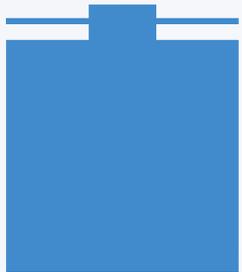
- ❑ Lucchesi D. M., et al., in Proceedings of the VI International Colloquium on Scientific and Fundamental Aspects of GNSS/Galileo, Valencia (Spain), 25-27 October 2017.
- ❑ Vespe F., et al., GALILEO for Science project (G4S): An Opportunity to Perform New Measurements in Fundamental Physics., in Scientific and Fundamental Aspects of GNSS/Galileo. 6th International Colloquium, Valencia (Spain) (2017).
- ❑ Vespe F., GALILEO for Science project (G4S): Eccentric GALILEO Satellites for General Relativistic Investigations., in 42nd COSPAR Scientific Assembly, Vol. 42 (2018) pp. H0.5–3–18.
- ❑ Sapio F., et al., The Galileo for Science (G4S 2.0) project: Fundamental Physics experiments with the Galileo satellites DORESA and MILENA, Nuovo Cimento, 2022
- ❑ Lucchesi D., et al., Fundamental Physics measurements with Galileo FOC satellites and the Galileo for Science project. Part I: a 3D-CAD and a Box Wing for modeling the effects of Non-Conservative Forces. TBP.
- ❑ Lucchesi D., et al., Fundamental Physics measurements with Galileo FOC satellites and the Galileo for Science project. Part II: a Box Wing for modeling Direct Solar Radiation Pressure. TBP.

# SVILUPPO TECNOLOGICO ACCELEROMETRI

Sviluppo ventennale ha reso il gruppo una eccellenza nell'accelerometria di precisione e un partner fondamentale nelle misure di **Radio Scienza**



2003



Prototipi ISA

Concepiti e realizzati dal Gruppo @ IFSI CNR

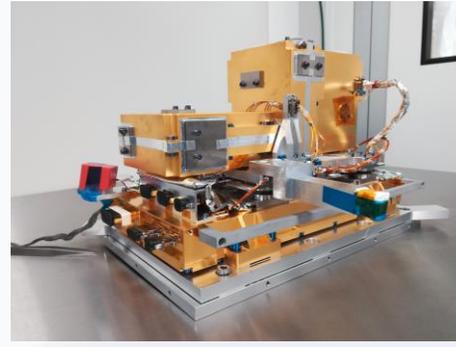


2010

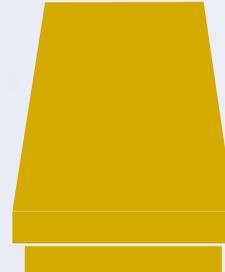


ISA FM

Banda  $3 \cdot 10^{-5} - 10^{-1}$  Hz  
Accuratezza  $10^{-8}$  m/s<sup>2</sup>

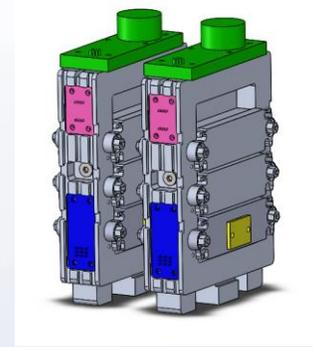


2016



HAA FM

Radhard  
Banda  $10^{-4} - 10^{-1}$  Hz  
Accuratezza  $10^{-8}$  m/s<sup>2</sup>



2022



AGES DM

Banda  $3 \cdot 10^{-5} - 10^{-3}$  Hz  
Accuratezza  $10^{-10}$  m/s<sup>2</sup>

2024

New concept

G4S

?

# **PROSPETTIVE, RISORSE E CRITICITA'**

# IMPEGNI E FINANZIAMENTI

Programma	FTE 2022	Fondi 2022 (attività INAF)	Cod. FO	Inviluppo fondi (attività INAF)	Fine programma
ISA BepiColombo	3,7	200 k€	1.05.04.29.01 1.05.04.29.06 1.05.04.03.14	5.2 M€	2030 TBC
G4S_2.0	5,3	180 k€	TBD	460 k€	2024
HAA JUICE	0,6	40 k€	1.05.04.49.02 1.05.04.49.04 1.05.04.49.07	165 k€ 1.2 M€ TBC	2022 (sviluppo) 2033 TBC (fase operativa TBC)
GAIN	1,25	25 k€	1.05.01.18.81	25 k€	2024
SaToR-G - LARASE	1,55	10 k€	INFN	115 k€	2024
LAG	0,7	2 k€	INFN	8 k€	2022 (R&D) poi fase operativa TBD
AGES	1,3	100 k€	1.05.04.03.32	500 k€ (incl. subco)	2022, possibili sviluppi TBD
<b>Totale</b>	<b>14,4</b>	<b>557 k€</b>	-	-	-

# PROSPETTIVE FUTURE

Lunar Italian Spring Seismometer

In proposta **Earth Moon Mars** per PNNR **IF**; sviluppo tecnologico di un sismometro da integrare in una futura rete geodetico/sismometrica lunare.

METRIC (Measurement of Environmental and Relativistic In-orbit precessions)

Concetto di missione presentato ad ASI; satellite in LEO con strumentazione di precisione per misure di fisica atmosferica, fisica fondamentale e geodesia.

AGES FM

Sviluppo del FM dell'accelerometro AGES, per i satelliti del sistema GNSS europeo Galileo di seconda generazione (e/o ultimo batch di prima generazione) .

Accelerometro per Genesis

Sviluppo del FM dell'accelerometro per le missioni del programma ESA GENESIS.

Lunar Laser Ranging

Fisica fondamentale e geodesia lunare basandosi su expertise sviluppata in LAGEOS (POD da tracking laser). Possibile collaborazione con INFN LNF e ASI Matera.

# CRITICITÀ

- 1. Non adeguata visibilità/peso del gruppo all'interno di INAF, dovuta a:**
  - Trasversalità delle attività il gruppo non si identifica in uno specifico RSN.
  - Molte collaborazioni con l'esterno (Università, enti ed agenzie), ma limitate collaborazioni con altri gruppi/sedi INAF.
- 2. Mancanza di personale: fattore limitante che non permette di sfruttare appieno le potenzialità del gruppo.**

**Cause:**

  - Mancanza di assunzioni di profili specifici.
  - Difficoltà a trattenere il personale dopo il periodo di formazione.

**Conseguenze:**

  - Difficoltà nel disseminare i risultati (pubblicazione, divulgazione e didattica)
  - Impossibilità di attuare i possibili progetti
- 3. Mancanza di supporto informatico centralizzato per servizi e calcoli non massivi.**

# CONCLUSIONI

- 1. Gruppo coeso e non un collage di progetti e schede.**
- 2. Attività e risultati di alto livello tecnico-scientifico in progetti originali e allo stato dell'arte.**
- 3. Collaborazioni consolidate con altri enti di ricerca e agenzie.**
- 4. Cospicuo livello di finanziamenti passati, presenti e futuri provenienti da numerose sorgenti.**
- 5. Impegni (attuali e potenziali) che richiedono un carico di lavoro del personale al limite (e in prospettiva in eccedenza) delle possibilità.**

**GRAZIE PER L'ATTENZIONE**