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METRIC

Measurement of EnvironmenTal and Relativistic In-orbit preCessions

METRIC: a mission concept for upper atmosphere mapping, gravitational physics and geodesy

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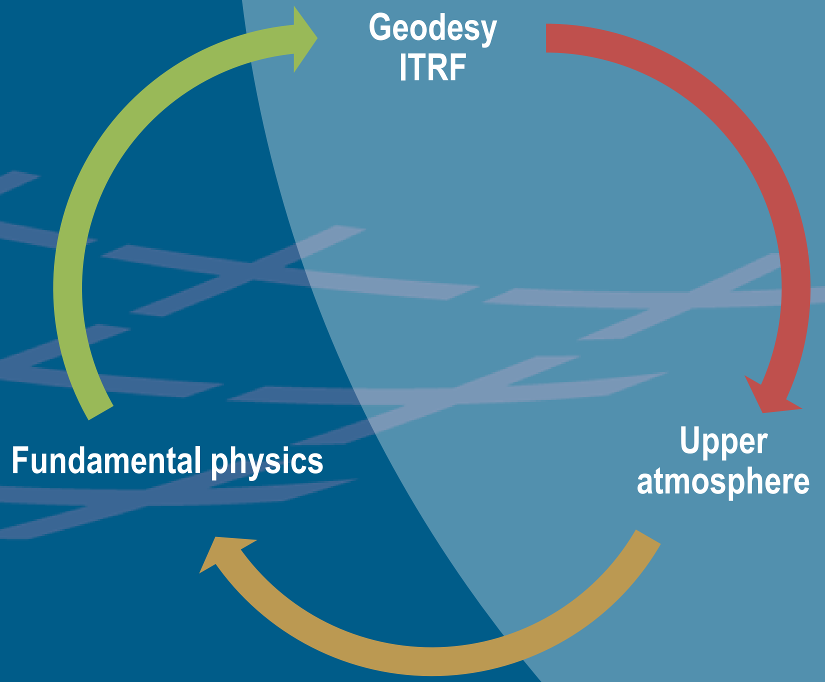
INAF Istituto Nazionale di Astrofisica · Università degli Studi di Padova 800 anni 1222-2022 · INFN Istituto Nazionale di Fisica Nucleare · CISAS G. Colombo · ISTI · Tor Vergata Università degli Studi di Roma · Politecnico Milano 1863 · ASI

METRIC scientific objectives

METRIC: Measurement of EnvironmenTal and Relativistic In-orbit preCessions

- **Upper atmosphere** Map **atmospheric density** by in-situ **acceleration measurement**, together with SLR and GNSS tracking, at altitudes of interest for satellite deorbiting, upper atmosphere modelling, orbital debris
- **Fundamental physics** Tests of **gravitation theories** in weak-field conditions through a precise measurement of **nodal and apsidal lines precession**
- **Geodesy / ITRF** Provide a space-based **core co-location site** for linking space geodetic techniques



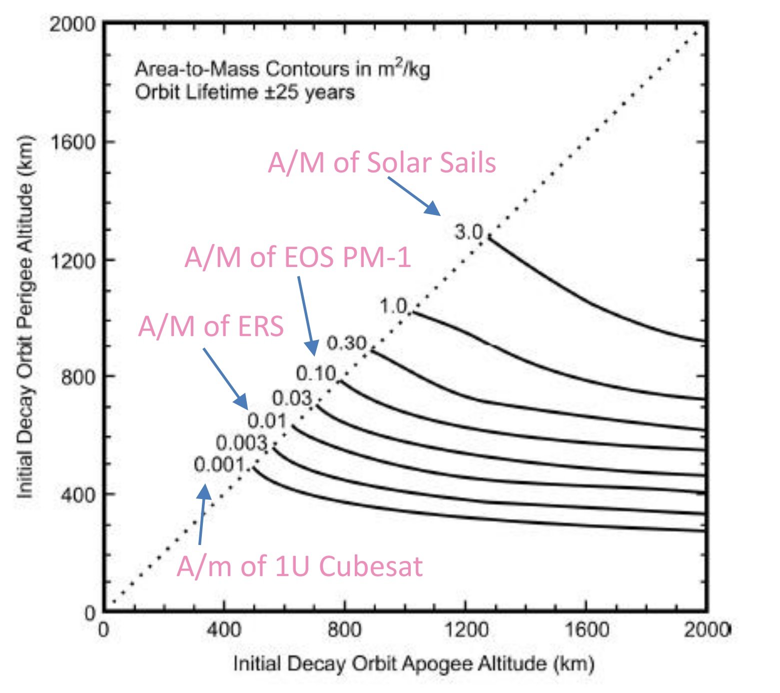
Science – Upper Atmosphere Density Mapping

- **Goal** Accurate measurements of **atmospheric drag** in the altitude range where it affects **satellite lifetimes** **(Peron & Lorenzini 2014)**

- **Issues**
  - Satellites in the range 450-1200 km of altitude may or may not violate the **25-year deorbit guideline** depending on ballistic coefficient and solar activity

  - Knowledge of **atmospheric density** and its dependency on varying solar and geomagnetic activity is still affected by large uncertainties, especially in upper-LEO **(Pardini+ 2001, 2006, 2010, 2012)**

S/C lifetime 25 years: NASA, 1995

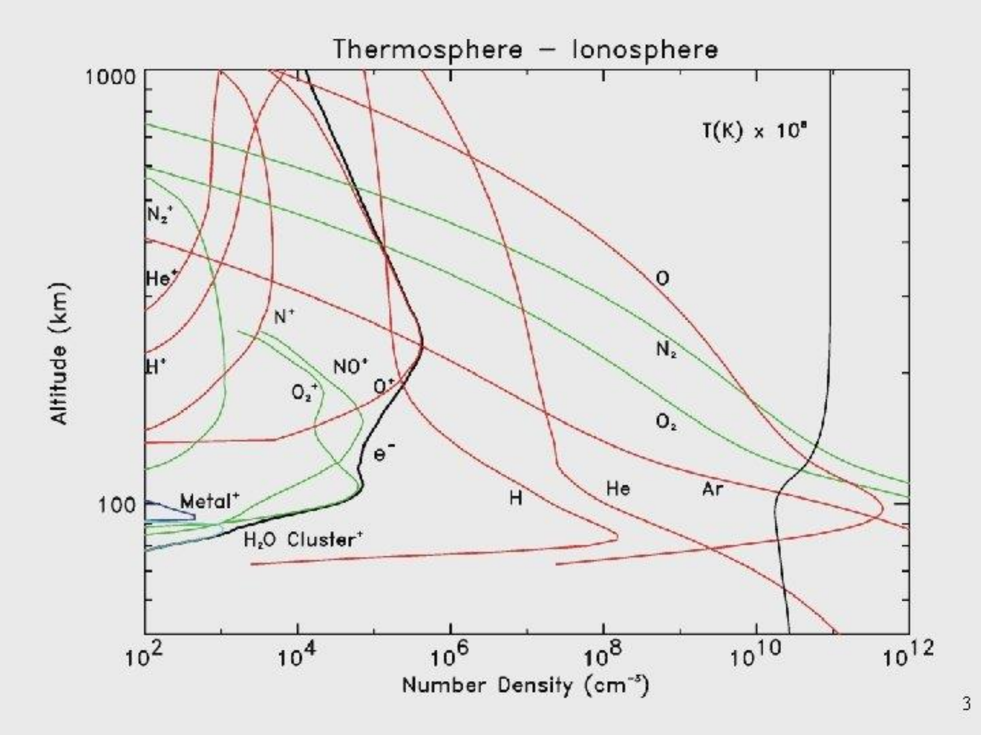


- **Returns** Improved knowledge of atmospheric density and its variability in LEO will benefit the **estimate of satellites lifetimes** and the **accuracy of conjunction assessments**. Any progress in the field will lead to a reduction of **collision avoidance maneuvers**, saving **propellant**, improving **safety**, mitigating the problems related to **orbital debris**

Science – Upper Atmosphere Density Mapping

- **Issues** In the altitude range 500-1200 km the atmospheric composition changes, also in response to varying solar activity: atomic oxygen (O), the dominant species in low LEO, progressively gives way to helium (He) and atomic hydrogen (H)

- **Issues** These varying dominant species interact in a different way with the substances of satellite surfaces, leading to changing accommodation and drag coefficients



- **Goal** Improving the knowledge of accommodation coefficients, as a function of altitude and solar activity

- **Returns** This may lead to better drag coefficient estimates and more accurate modelling of the atmospheric drag perturbation above 500 km

Science – Fundamental Physics

Relativistic corrections to geocentric equations of motion – IERS Conventions (2010)

The test of the **equation of motion** for a massive body in a given gravitational field remains an important tool in the quest for a unified description of the fundamental interactions in the physical universe

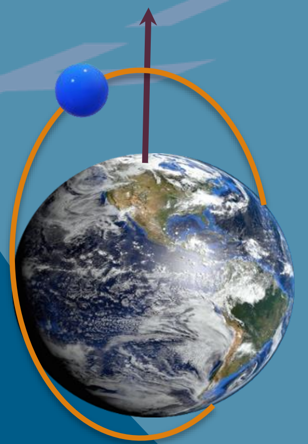
$$\Delta\ddot{\vec{r}} = \frac{GM_E}{c^2 r^3}\left\{\left[2(\beta+\gamma)\frac{GM_E}{r} - \gamma\dot{\vec{r}}\cdot\dot{\vec{r}}\right]\vec{r} + 2(1+\gamma)(\vec{r}\cdot\dot{\vec{r}})\dot{\vec{r}}\right\} + (1+\gamma)\frac{GM_E}{c^2 r^3}\left[\frac{3}{r^2}(\vec{r}\times\dot{\vec{r}})(\vec{r}\cdot\vec{J}) + (\dot{\vec{r}}\times\vec{J})\right] + \left\{(1+2\gamma)\left[\dot{\vec{R}}\times\left(\frac{-GM_S\vec{R}}{c^2 R^3}\right)\right]\times\dot{\vec{r}}\right\},$$

Effect	Ratio to J_0
Schwarzschild	$10^{-9} – 10^{-10}$
Lense-Thirring	$10^{-11} – 10^{-12}$
De Sitter	$10^{-11} – 10^{-12}$

	METRIC	LAGEOS
e	5.2×10^{-2}	4.43×10^{-3}
$\dot{\omega}_{Schw}$	12.5	3.28
$\dot{\Omega}_{LT}$	0.153	0.0309
$\dot{\omega}_{LT}$	~ 0	0.0314
$\dot{\Omega}_{dS}$	0.0176	0.0176
$\dot{\omega}_{Yuk}$	(0.144)	(0.0819)

Relativistic secular precession rates (arcsec/year)

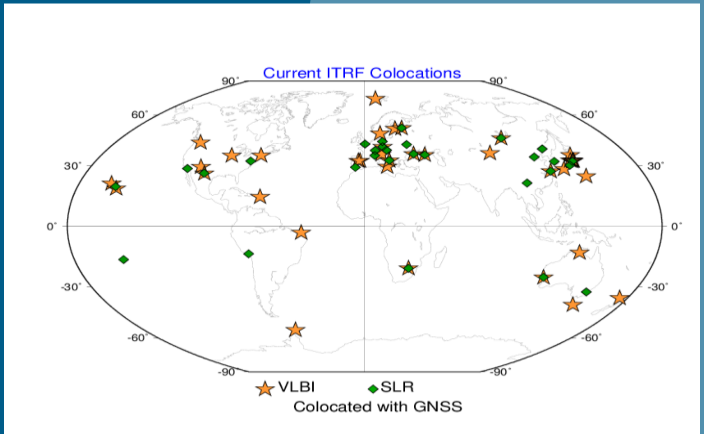
Advantages of a **polar** or **quasi-polar orbit**: strong suppression of competing **Newtonian gravitational signal**



450 x 1200 km polar orbit

Science – Geodesy

SLR & VLBI are critical for the ITRF frame definition : origin (SLR), scale (SLR & VLBI), but their co-locations (< 10 sites) are poorly distributed



- The ITRF is fundamentally based on **co-locations** of 2 or more instruments operating at the same site, and with terrestrial ties available
- Almost all SLR, VLBI and a large number of DORIS stations are co-located with GNSS
- → **GNSS links together SLR, VLBI & DORIS networks**
- But more than 50 % of tie discrepancies are larger than 5 mm, caused mainly by **technique systematic errors**

Objective:

Co-locating all four technique instruments at one **fully calibrated satellite-based platform**, a **“Core co-location site in space”** is expected to mitigate/cancel technique systematic errors and thus improves the ITRF accuracy

Credit: Z. Altamimi

Basic mission idea

Core on-board instrumentation (baseline)

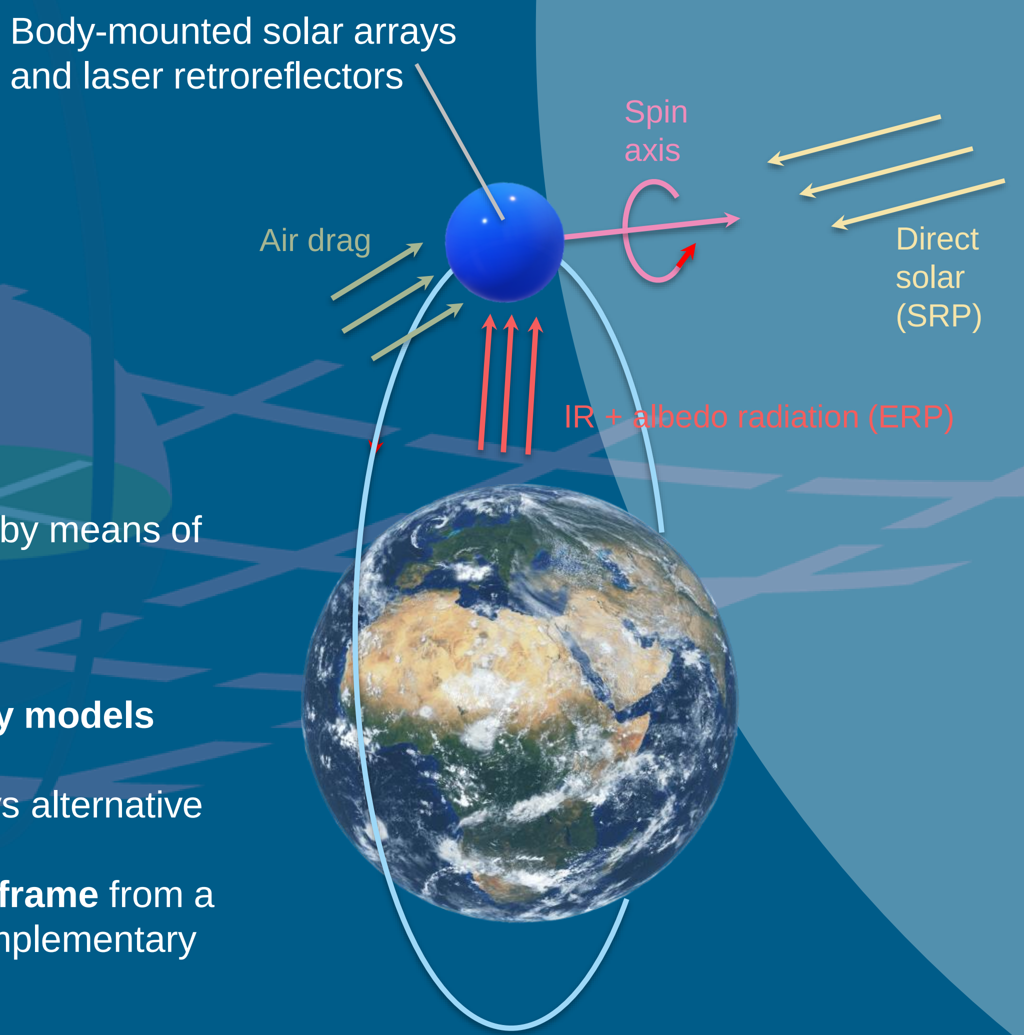
- **3-axis accelerometer** for **NGP measurement**
- Corner cube laser **retroreflectors** for **SLR**
- **GNSS** receiver
- Vacuum pressure ion-gauge

Strategy

- **Polar eccentric orbit** **(preliminary: 400/450 km x 1200 km)**
- Tracking with at least two **space geodetic techniques**
- **Virtual drag-free** spacecraft through acceleration data
- Modulation of acceleration signal via **slow spin**
- Separation of atmospheric drag and solar radiation pressure is achieved by means of acceleration measurement near apogee

International context

- **Upper atmosphere** Strong need for **reliable upper atmosphere density models** (satellite lifetime, collision avoidance maneuvers)
- **Fundamental physics** Testing the law of **gravitation** (general relativity vs alternative theories)
- **Geodesy / ITRF**: Requirement of a more accurate **terrestrial reference frame** from a host of disciplines (astronomy, navigation, Earth System sciences) – Complementary and synergistic with the ESA GENESIS programme

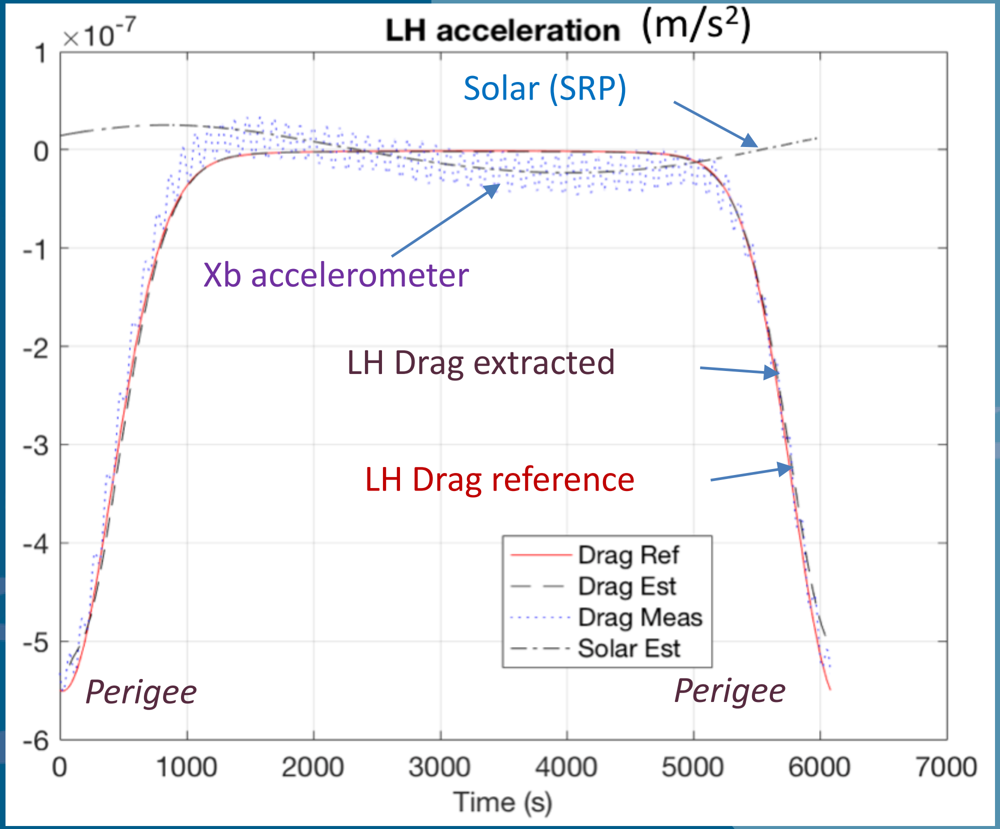


Atmospheric drag vs solar radiation pressure

The proposed strategy enables a clear separation between atmospheric drag and solar radiation pressure:

- Drag overpowers solar acceleration below an altitude of ~ 600 km (close to perigee)
- Solar radiation pressure is > 20 times stronger than drag at 1200 km of altitude (close to apogee)
- Direct solar radiation acceleration on a sphere can be modelled accurately and has a long time scale
- Earth radiation acceleration is variable on a shorter time scale but it acts in the local vertical (LV) component in phase quadrature with respect to the major atmospheric drag component along local horizontal (LH)

Acceleration – LH comp.	Range (m/s^2)	Remarks
Neutral Drag	-1×10^{-9} to -5.5×10^{-7}	The "signal" for atmo. drag
Solar Radiation Pressure	-2.5×10^{-8} to 2.5×10^{-8}	Removed through measurement at apogee
Satellite spin motion	2.7×10^{-6}	At coning motion frequency and is filtered out

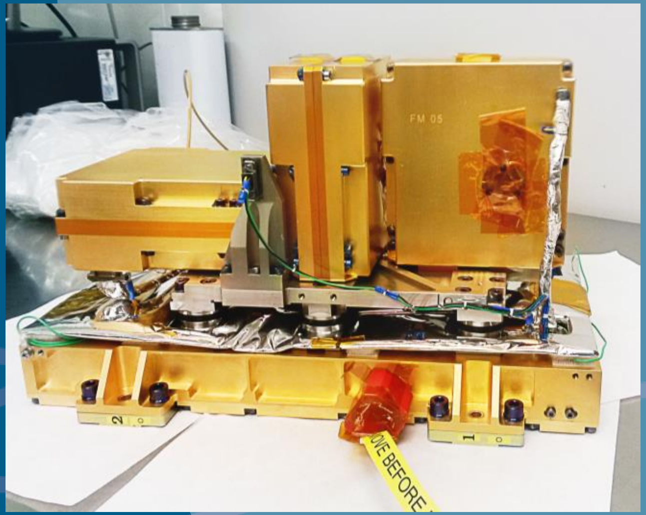


Adapted from **Lorenzini & Peron 2018**

Accelerometer

Heritage

- Original instrument concept developed at INAF-IAPS:
  - Mass-spring sensitive element with electrostatic read-out and actuation systems
  - Three-axial configuration
- ASI-INAF-TAS-I scientific payloads developed for ESA missions:
  - **ISA (Italian Spring Accelerometer)** is operating onboard **BepiColombo**
  - **HAA (High Accuracy Accelerometer)** will fly onboard **JUICE**
- Know-how @INAF-IAPS about:
  - On-ground and in-flight calibration
  - In-flight operations management
  - Data handling, archiving and analysis



METRIC accelerometer requirements:

- Signal dynamics: 10^{-6} m/s^2
- Measurement band: 10^{-4} – 10^{-1} Hz
- Precision: 10^{-10} m/s^2

ISA/HAA performance (as reference):

Signal dynamics	3×10^{-6} m/s^2
Measurement band	3×10^{-5} – 10^{-1} Hz
Precision	10^{-8} m/s^2 for signal amplitude ≤ 3×10^{-6} m/s^2
Noise floor	3×10^{-8} m/s^2/√Hz @f > 10^{-4} Hz

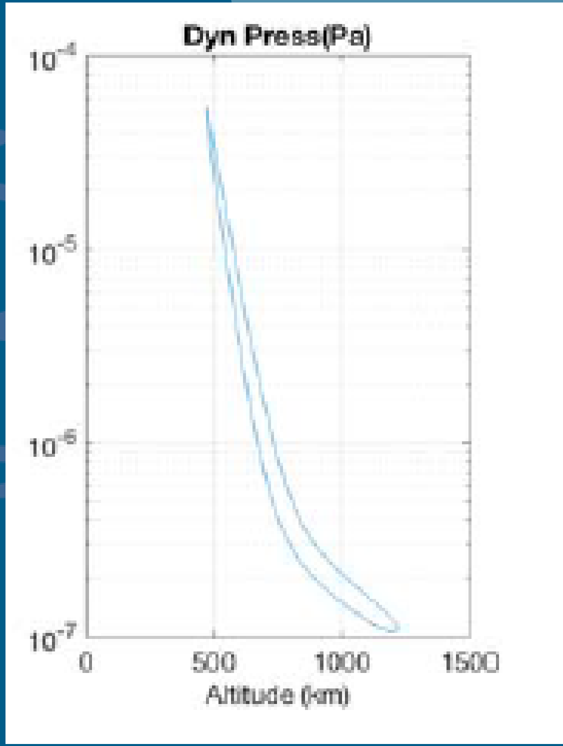
METRIC requires about 2 orders of magnitude improvement over ISA; this is considered achievable relying on ongoing development activities (INAF-TAS-I cooperation)

Atmospheric pressure instrumentation

- **Vacuum pressure ion-gauge** Enables a more reliable extraction of atmospheric density from drag acceleration data avoiding the theoretical estimation of C_D as presently done
- **Supplier** Granville-Phillips® Series 500 Cold Cathode Vacuum Gauge

Total Pressure Meas. Range	1e-10 to 1e-2 Torr
Accuracy - Standard	1e-8 to 1e-4 Torr ± 30% (typical)
Accuracy - Calibrated Gauge	1e-8 to 1e-4 Torr ± 10%
Repeatability	1e-8 to 1e-4 Torr ± 5% (typical)
Electronics Storage Temperature	-40°C to 70°C
Electronics Operating Temperature	0 - 50°C
Bake-Out Temperature	250°C (magnets removed)
Mounting Orientation	Any
Analog Output Signal	
Output voltage (log)	0 - 11 VDC
Minimum Output Impedance	200 Ohm
Minimum Load Impedance	10k Ohm
Minimum Update Rate	40 Hz
Analog Input Signal	Input voltage 0 - 11 VDC
Power Required	13.5 - 36 VDC, <2 Watts
RS-485 Baud Rate	1200-115,200 Baud
USB Interface	Micro-AB
Set Point Relays	Max 1A@30 VDC; Min 5ma at 5 VDC, maximum ripple 1Vpp
Weight	652 grams

Small volume, mass and power consumption



Expected dynamic pressure profile along METRIC orbit

Tracking

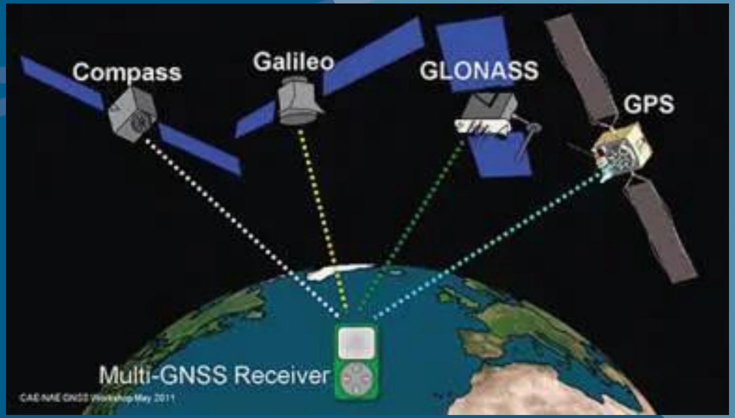
Satellite Laser Ranging (SLR)

- ILRS dedicated tracking
- Coverage: depends on stations schedule and atmospheric conditions
- Observable: range sub-cm precision
- POD: sub-dm, approaching the cm level depending on model choices


Photo by Franco Ambrico
Courtesy Giuseppe Bianco, ASI-CGS

Global Navigation Satellite System (GNSS)

- Coverage: continuous
- Observable: pseudo-range (code and phase), navigation solution
- Precise Orbit Determination (POD): sub-dm **(van den Ijssel+ 2015)**; resolved acceleration of 2×10^{-9} m/s^2 over 5-minute observables in LEO **(Kuang+ 2014)**



Retroreflector array

- Retroreflector array (LRA) to be designed and supplied by INFN-LNF, which has a vast experience in LRA for: Mars/LEO (Mars/Earth Obs, 2018+), to MEO (LARES-2, 2022), to GNSS (Galileo 2nd Generation, G2G, 2024), Moon (ESA-NASA, 2024)
- Given the relative low METRIC altitude and eccentric orbit (450 × 1200 km – preliminary), LRA technology will likely be an array of Al-coated fused silica reflectors
- Reflectors will be of COTS class, with reduced procurement time and very consolidated heritage from the same provider of the reflectors for the two LARES-2 satellites (~ 700 flight units) for ASI and for the G2G 6 + 6 satellites (several hundreds flight units) for Thales Alenia and Airbus
- LRA shape may conform to the geometric shape of the METRIC satellite (spherical LRA dome for a spherical satellite, cylindrical LRA for a cylindrical satellite, flat square LRA for a polyhedric spacecraft)
- Reflectors' detailed specs (including diameter) and total number: to be optimized on the basis of the detailed mass and geometric envelopes available to the LRA

Extended configuration

Atomic clock

- Possibly solid-state (e.g., Cesium clock: Allan variance ~ 10^{-13} s/s)
- Scientific returns using a Doppler canceling technique: gravitational redshift measured over many revolutions

VLBI beacon

- Not trivial (i.e. considering a radio beacon at a finite distance) and must be carefully assessed, together with the observing frequency range and the network of stations tracking the satellite
- A new generation of instruments, VLBI Global Observing System (VGOS), has been established in order to meet the scientific requirements set by GGOS (i.e. an accuracy of 1 mm in station position and 0.1 mm/year in station velocity on a global scale)

Wikipedia

INAF Medicina VLBI station

Spacecraft – Preliminary estimates

Satellite characteristics at a conceptual design level

- Spherical outer shape with diameter: 50-60 cm
- Estimated overall power consumption: < 30-40 W
- Multi-junction, body-mounted solar arrays
- Satellite estimated mass range: 100 – 200 kg (inclusive of ballast to trim ballistic coefficient)
- Spin-stable: inertia tensor of S/C is non spherical and spin is around principal inertia axis
- Magnetorquers for coning control and sporadic spin trimming
- Cold gas system planned for spin-up
- **Mission duration**: ideally **11 years** (**one solar cycle**), or shorter with possible extension

TRL preliminary estimates of main elements

- Accelerometer and laser retroreflectors: ≥ 7 (tested in space in other configurations)
- Ion Vacuum gauge: 6 (commercial product to be tested for space use)
- GNSS receiver and antennas: ≥ 7 (already used in space)
- Spacecraft: 2 (presently at conceptual level)

Italian reference community

- **INAF-IAPS** High-sensitivity accelerometers development / calibration / operation (ground and space), precise orbit determination, satellite dynamics modelling, general relativity
- **INAF-IRA** Geodetic VLBI observation design / realizazion / data analysis, GNSS data analysis, local ties
- **INAF-OATo** Astronomical instrumentation modelling, data reduction and analysis algorithms, gravity theories and their experimental tests, relativistic astrometry modelling, high-performance computing, big data and numerical methods
- **UniPD-CISAS** Mission analysis, measurements in space, scientific instruments onboard accommodation
- **UniPD-DII** Contributions to satellite design
- **UniPD-GEO** GNSS data analysis, general relativity
- **CNR-ISTI** Upper atmosphere drag modelling
- **INFN-LNF** Laser retroreflectors and their accommodation
- **PoliMI** VLBI, geodesy
- **ASI-CGS** LLR, SLR, geodesy
- **YETITMOVES** GNSS data analysis
- **UniRoma2** Post-flight data analysis
- **TAS-I** High-sensitivity accelerometers space engineering and production

Outlook

Scientific objectives and mission concept

- Contribution to **three** different scientific domains
- Integration of (well) known instruments and techniques

Complementarity and synergy with ESA GENESIS programme

- **Orbit** Lower and eccentric
- **Mission duration** Should cover ideally one solar cycle
- **Geodesy / ITRF** Co-location of two/three techniques
- **NGP** Signal or (removed) noise depending on the objective (the accelerometer being one of the core instruments)
- **Spacecraft** Very compact, simple external geometry, **high-precision metrology** being a design driver

Conclusions

Essential features

- High-accuracy **accelerometer** package
- Accurate **tracking** of spacecraft
- **Polar eccentric orbit** spanning the 400/450 × 1200 km altitude range
- Spacecraft slowly spinning about an axis perpendicular to the orbital plane
- Simple spacecraft external geometry

Expected improvements to science/technology

- **Upper atmosphere** Atmospheric drag and solar radiation pressure in-situ measurement with accurate accelerometer and vacuum pressure ion-gauge over an altitude span of great interest to atmospheric science, satellite technology, orbital debris mitigation
- **Fundamental physics** A polar eccentric orbit with a clear definition of the perigee and a virtually drag-free spacecraft will lead to a precise measurement of apsidal and nodal lines precesssion
- **Geodesy / ITRF** Co-located position measurements with SLR + GNSS (+ VLBI) will provide a space-based core co-location site

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THANKS for your attention

Questions?

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