Workshop “Galileo Galilei” (GG) and GGG lab prototype: state of the art and new possibilities”

The GG satellite mission: synthesis of the 2009 ASI Phase A2 study

Alberto Anselmi[1] and Antonio Sposito[2]

[1] ThalesAlenia Space Italia, Torino

[2] Agenzia Spaziale Italiana, Roma

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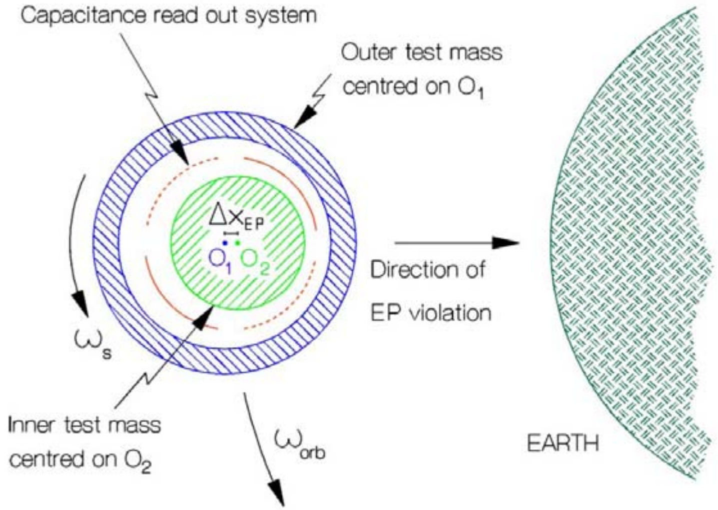
Experiment principle

Weak Equivalence Principle: "in a gravitational field, all test particles at the same point in space-time undergo the same acceleration"

- Gravity locally equivalent to accelerated frame
- Free falling frame locally equivalent to inertial frame



Objective: 0.5 pico-m displacement between 2 rotors in supercritical rotation

- equilibrium position very close to the rotation axis, reducing the otherwise destructive effects of centrifugal forces.
- weakly suspended fast spinning rotor tends to spin around its center of mass, i.e. it behaves like a free rotor
- Signal of known frequency, known direction

Fast spin (60 rpm)

- Needed for supercritical rotation
- Modulation of the signal
- Most perturbing effects (e.g. due to spacecraft mass anomalies, non-uniform thermal expansion, parasitic capacitances, etc.) are DC because the entire system is spinning
- Reduction of 1/f noise

Lab apparatus in principle the same as space apparatus. In space:

- Factor of 1000 improvement because of stronger driving force (whole Earth gravity)
- Factor of 1000 improvement because of smaller perturbing forces

1995: GG proposed to ESA

1995-96: first Alenia studies

- Oct. 96: presentation to ESA/FPAG

1997: GG proposed to ASI

1998: First ASI Phase A study

- Dec. 98:ASI Workshop on small satellite mission studies

2001: Add-on study: GG in SSO

2004: Start of GGG lab experiment

2007: GG Phase A2 RFP

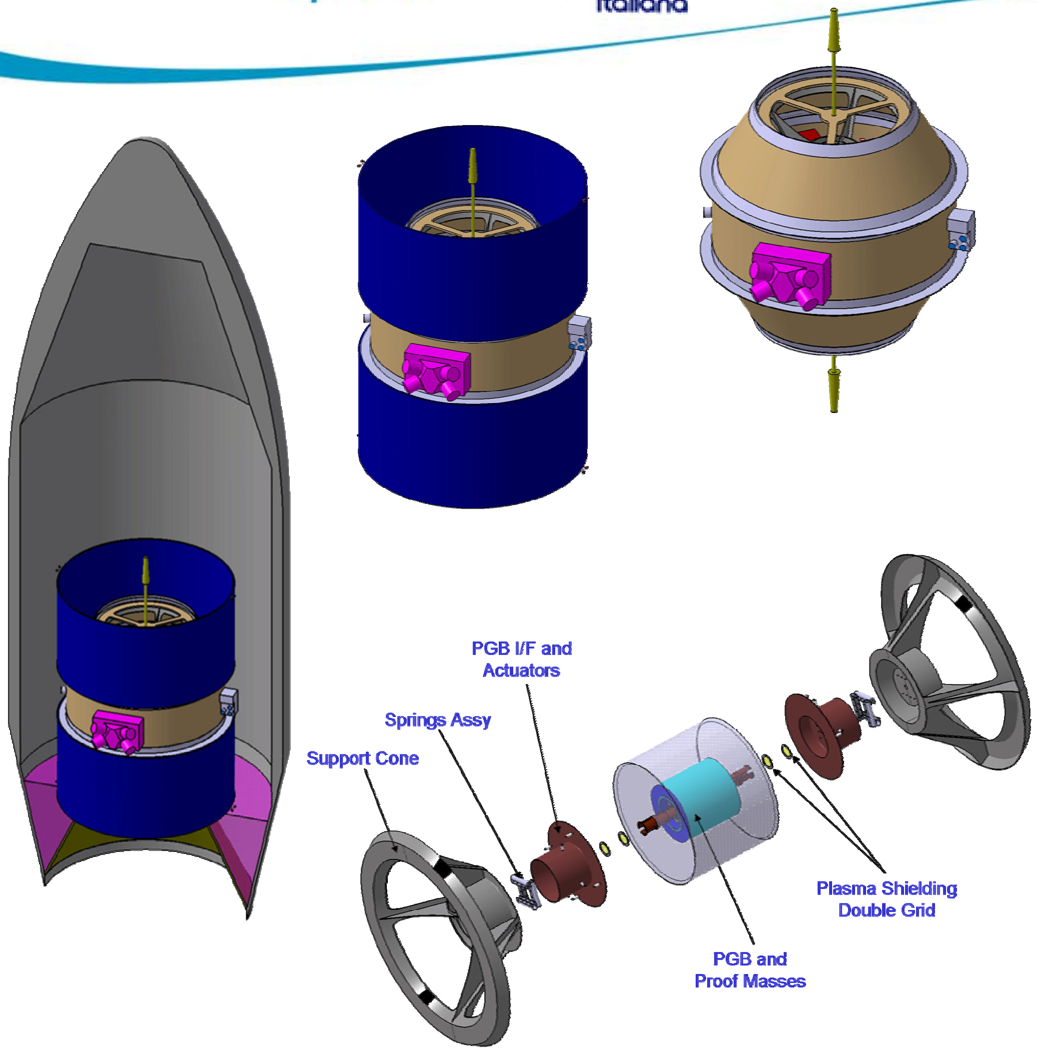
2008-09: GG Phase A2 study

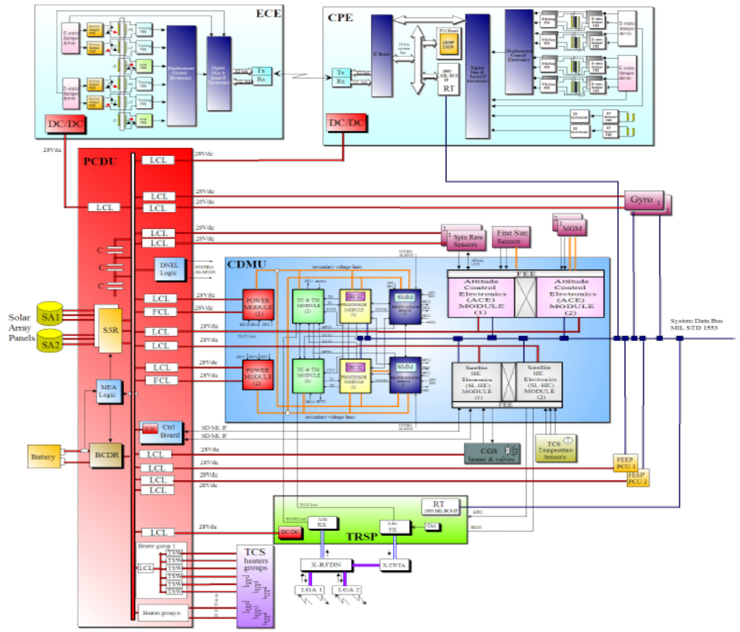
- Development of GG simulator

2009 Phase A2 Study

- **Kick-off 16.09.2008, Final Presentation 18.06.2009**
- **6 project meetings, 3 reviews**
- **3 TAS-I centres + 4 subcontracting companies + 2 scientific institutes involved**
  - TAS-I Torino-Milano-Firenze
  - ALTA, ALTEC, DTM, SILO
  - National Metrology Institute, Polytechnic of Torino
- **14 permanent members of the TAS-I (Torino) GG study team**
- **30 documents submitted to the Preliminary Requirements Review**
- **3 custom-built software simulators**
- **1 working breadboard of spin sensor**

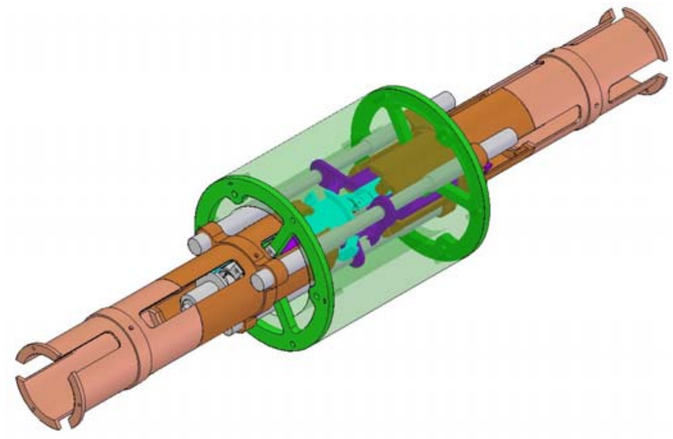
GG Technical Baseline





GG technical baseline

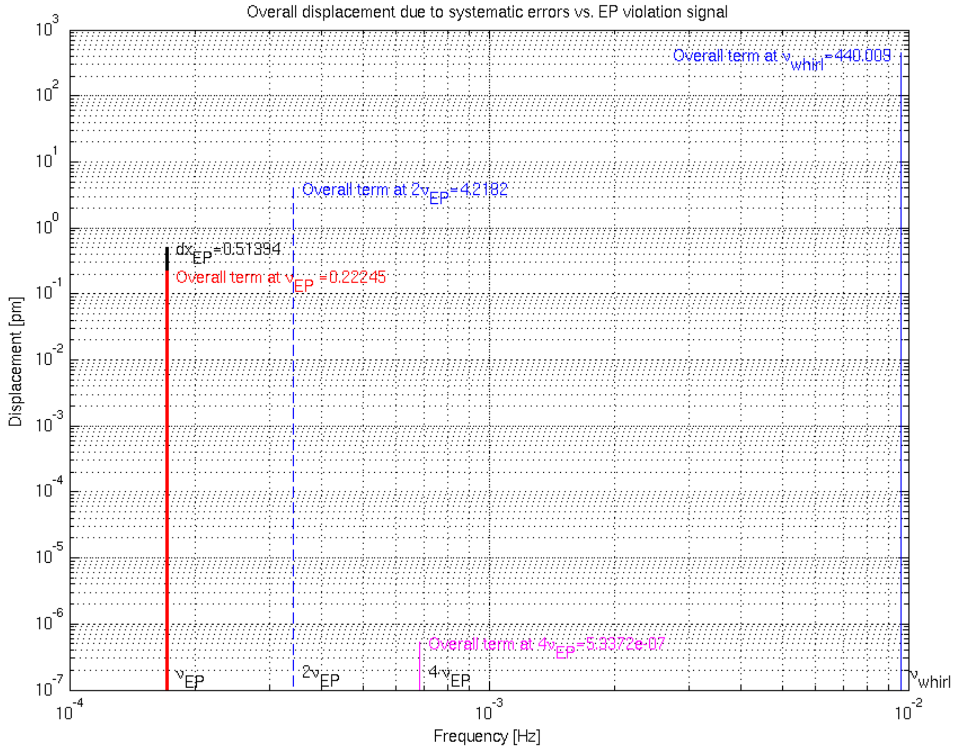
- 500 kg launch mass
- 500 W power demand
- 350 kbit/s telemetry rate
- Equatorial circular orbit, 700 km altitude
- 4 passes per day telemetry dump
- 1 year mission + 1 year extension



- 2 concentric test masses within a vibration suppression assembly (PGB)
- 2 payload electronics units
- Capacitive sensing and detection
- 1 Hz spin
- Cold-gas attitude acquisition and spinup
- FEEP or Cold-Gas Proportional Thruster drag-free control
- High accuracy measurement of spin rate (Spin rate sensor)
- 10 launch-lock devices

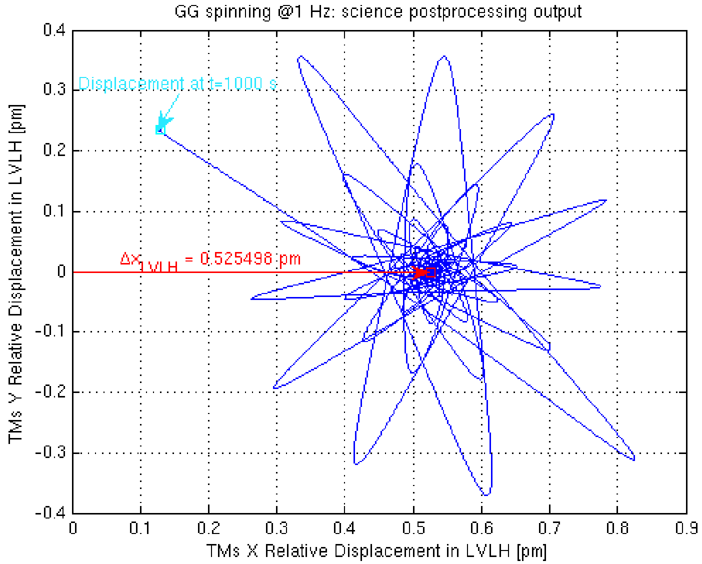
Amplitude Spectrum of EP signal and disturbing effects (affecting measurements in the XY plane) as observed in the IRF

- Signal and most effective deterministic disturbances (smallest frequency separation)
  - Most effecting disturbances at ν_{EP} well below the signal
  - One week duration of the elementary experiment ensures good frequency separation for all the competing lines, including the first line at $2 \times \nu_{EP}$



GG Software Simulator

- Spacecraft shell, PGB, TMi, TMo + dummy "reference frame" body : **27 DoFs**
- Gravity and gravity gradient are **"on"**
- Current mass/inertia properties for all bodies (including proof masses quadrupole moment)
- Orbit altitude h = 630 km to match the reference non gravitational acceleration **2×10^{-7} m/s^2**
- Stiffness reproducing PGB modes and common and differential proof masses modes in the XY plane and along Z, according to the mission requirements
- Mechanical quality factor is lowered for TMs in order to amplify whirl motion
- Environment fully modeled
- **$\eta = 10^{-17}$** for all the science simulations (science target)
- **Quadruple precision** to predict science performance of the mission



Polar plot of the differential displacement in the LVLH reference frame. After a transient, the TMs relative displacement has nearly null mean value along Y_{LVLH} and 0.525 pm mean value along X_{LVLH}

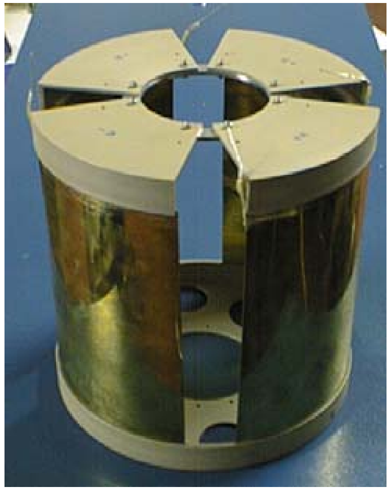
Specification of experiment requirements developed as part of this study

Ultimate test by analysis (S/W simulator)

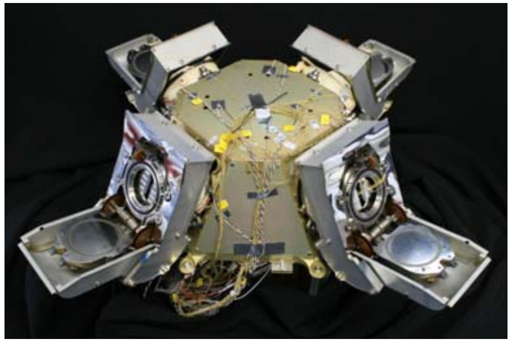
- Cannot be tested on ground at required sensitivity

Technology requirements:

- Soft springs, precise machining, mass balancing: demonstrated in the lab
- Capacitive readout: state of the art
- Spin rate measurement (1E-5 fractional accuracy): functioning breadboard available
- Drag Free Control:
  - constrained by design to same requirements as LISA Pathfinder (qualification ongoing)
  - GOCE heritage
- Charge control: test masses are grounded by springs; local charges (patch effects) can be measured on the ground (demonstrated in the lab)
- Cleanliness: baking of "hydrogen-rich" test mass (high density polyethylene); outgassing of experiment chamber allowed by design



Capacitance bridge plates



FEEP thruster cluster

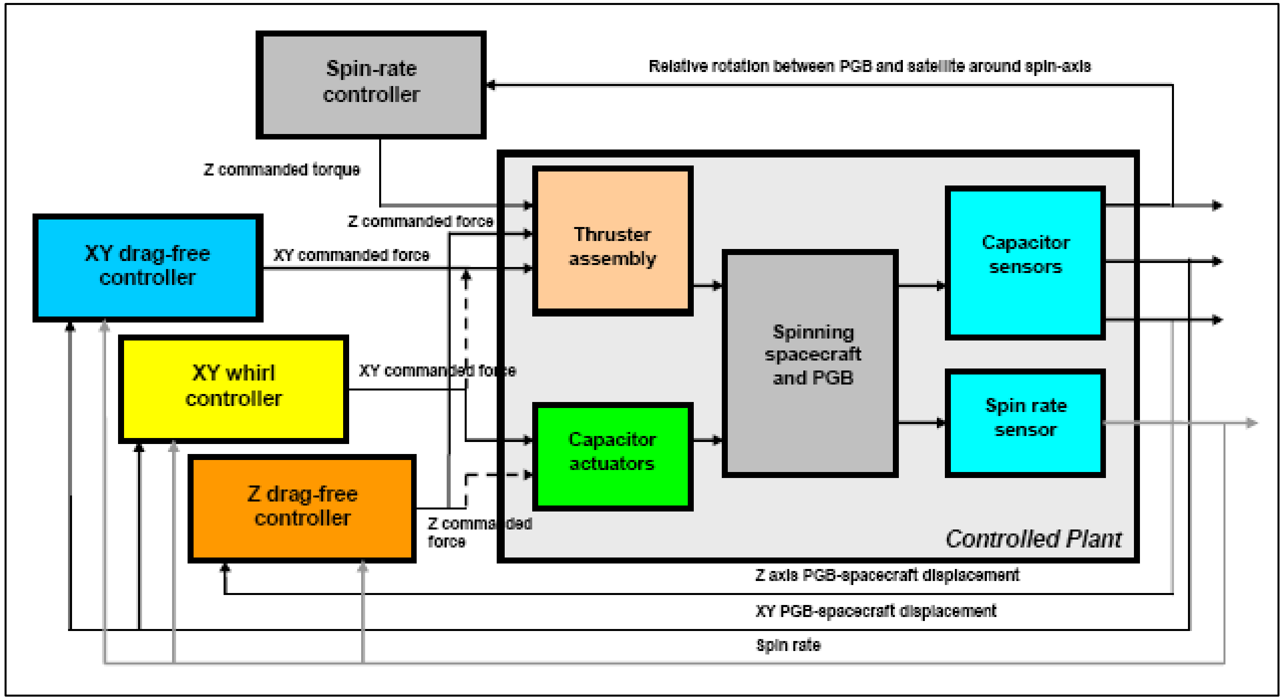
Four control loops

X-Y drag control the most demanding

- Rejection greater than 1/50,000 at 1Hz
- Accounting for response time of the available thrusters (> 30ms).

Control solution based on the integration of a sort of notch filter

- actually, to model periodic drag, a harmonic oscillator in the state observer



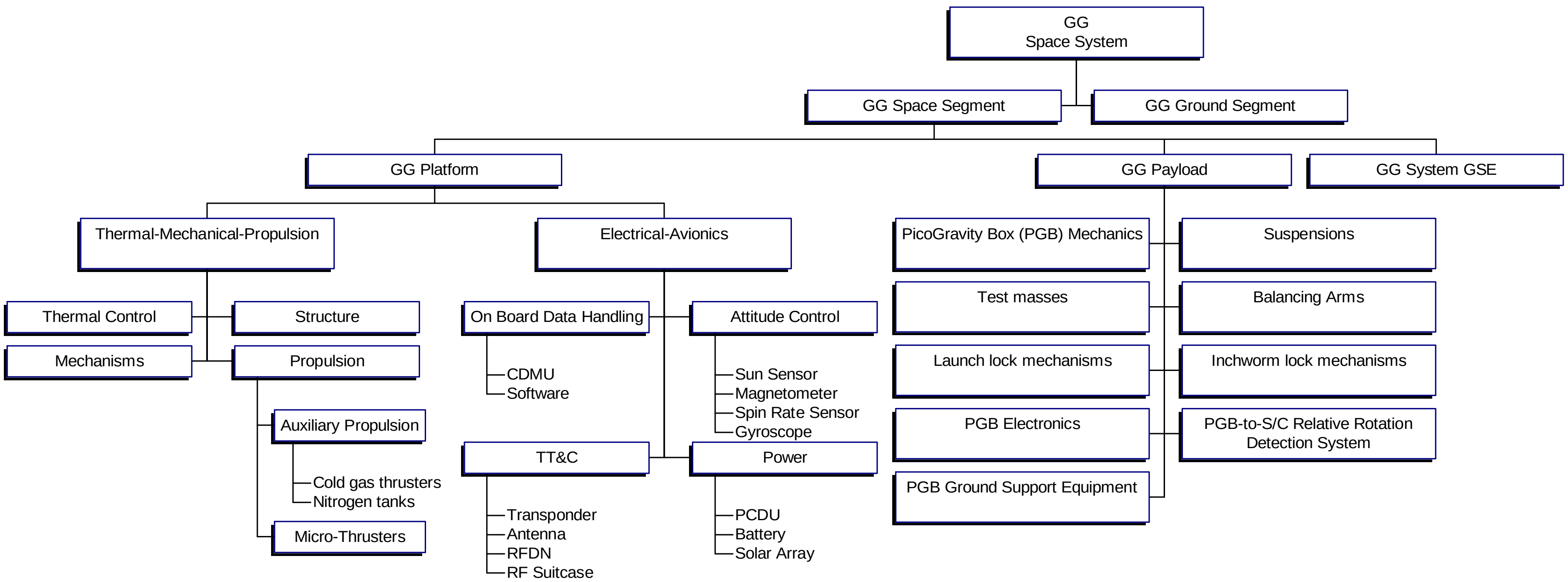
All controllers designed according to state-space approach based on state observer and gain feedback functions

- In use at TAS-I since several years
- GOCE the latest application

FEEP status

No	Parameter	Unit	Value	FEEP status
1	Maximum thrust	µN	>=150	Thruster is designed and currently being qualified for a maximum thrust of 150 µN. Command capability is, at present, greater than 204.8 µN, and thrust up to 540 µN was recorded during one test
2	Max thruster response time	ms	40	Current response time (for 60 µN step from 0 to 60 µN) is about 80 to 150 ms, (depending on thrust and up or down command), with command frequency at 10 Hz. Step response can be improved up to 30-40ms reducing internal delay, fall time, by biasing minimum thrust (e.g. working with thrust higher than 70 µN) and/or adding some internal dissipation.
3	Resolution (quantization)	µN	24	Thruster/PCU are designed and currently being qualified for a thrust resolution of 0.1 µN
4	Max noise	µN/√Hz	18	The thruster is being qualified for 0.03µN/√Hz (range 0.006 to 5 Hz)
5	Scale factor error	%	12	PCU allows scale factor correction and re-calibration with a 12 bit resolution (individual command correction). Requirement is not deemed critical.
6	Update command rate	Hz	10	Already available for Lisa Pathfinder
7	Total impulse	Ns	4500	Thruster is designed vs. a requirement of 2900 Ns (Lisa Pathfinder). Life test (on QM) will be performed up to 1100 Ns (with possible extension to higher total impulse). Analysis will be performed to predict EOL performance. At present, > 1000 Ns were verified at EM level.
8	Minimum thrust	µN	<=10	Thruster is designed and currently being qualified for a minimum thrust of 0.3 µN.
9	Vector stability	rad	0.17	For thrust greater than 10 µN is always met.
10	Centrifugal acceleration	g	<4.4	Not met by current design. Modification of thruster design, and, in particular, of tank position and shape, to minimize hydrostatic head will permit to achieve the requirement.

- TAS-I + Team of Small Italian companies (ALTEC, ALTA, DTM, SILO) + scientific institutes (PoliTo, INRIM)
- 4-yr development plan
- 70M€ estimated cost-at-completion (excluding launch)



Programme Schedule

ID	Task Name
1	**GG planning**
2	GG phase B K.O. - T0
3	GG Preliminary Design Review (PDR) - Start C/D
4	GG Critical Design Review (CDR)
5	GG Proto-Flight Model TRR - Start System I&T
6	GG Flight Acceptance Review (FAR)
7	GG Launch Readness Review (LRR)
8	**Payload phases B/C/D**
9	PGB Kick Off
10	Flight PGB Design
11	Flight PGB Development & Testing
12	Flight PGB ready for I&T on Satellite
13	**GG platform phase B**
14	System I/F Consolidation
15	Units and S/S draft specification
16	GSE adaptation/definition for GG
17	**GG phase C/D**
18	GG Equipments / SS Detailed Specification
19	GG Platform Equipment Procurement
20	GG PT structure Procurement (including H/N & propulsion)
21	GG PT Non Standard Items Development Models
22	GG GSE procurement
23	GG SW Development & Test
24	ATB adaptation for GG
25	GG SW testing on ATB
26	GG Platform I&T and functional test (incl. FEEP)
27	GG PGB Integration and Functional Verifications
28	GG System Testing
29	Environmental Test (TV/TB, Mechanical, EMC)
30	GG ready for Launch Campaign
31	**GG phase E**
32	Launch Campaign
33	GG ready to Launch
34	GG Launch