WE LOOK AFTER THE EARTH BEAT

GG studies at TAS-I: state of the art

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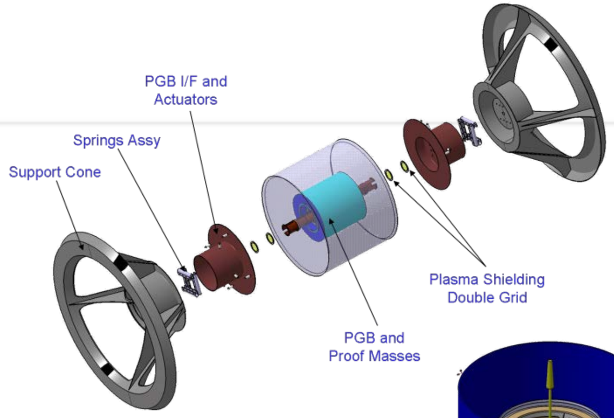
INRIM, 24-10-2014

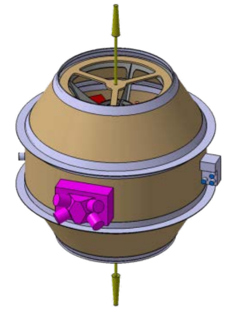
GG@ThalesAleniaSpace

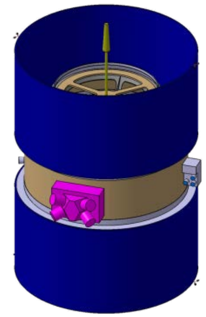
- 1996 Early experiment concept presented to ESA HQ
  - Industrial support on satellite & drag-free control concepts
- 1998 ASI small satellite call
  - Prime Contractor of industrial Phase A study (1998, updated 2000)
  - Equatorial orbit, Pegasus launch
- 2001-2002 ASI study update
  - Sun-synchronous orbit (SSO), Dnepr launch
- GG included in ASI's 2006-2008 *Piano Spaziale Nazionale*
  - Prime Contractor of Advanced Phase A Study (A2), 2008-2009
  - Equatorial orbit, Vega launch
- 2011 NASA Explorer AO (JPL/ASI)
  - Support to preparation of project proposal
  - SSO, Taurus launch
- 2012 ESA Small Satellite call
  - Support to preparation of scientific proposal
  - SSO, Vega piggyback launch / Cold-gas proportional thrusters

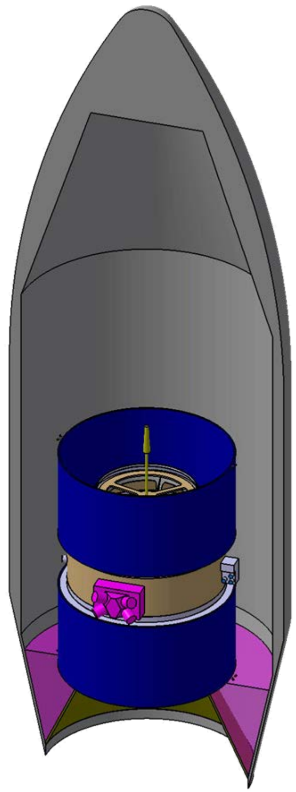
2009 ASI Phase A2 Study

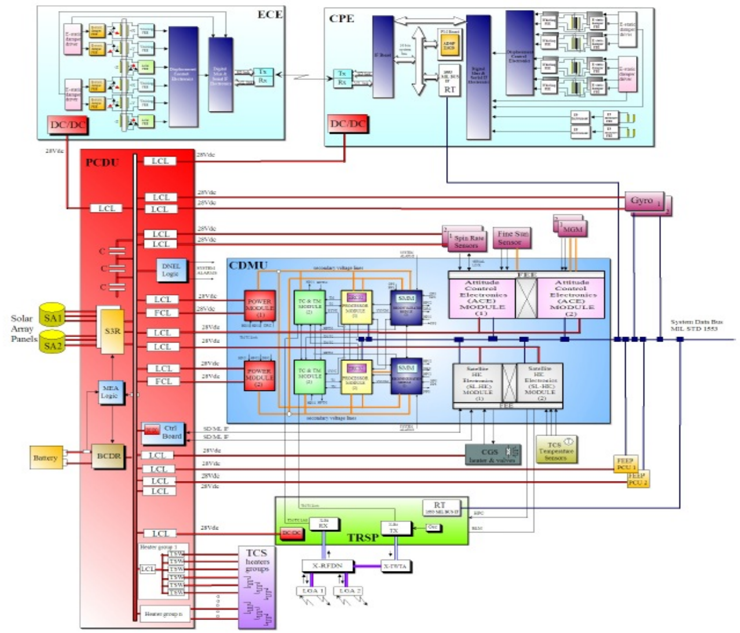
- 3 TAS-I centres + 4 subcontracting companies + 2 scientific institutes involved
  - TAS-I Torino-Milano-Firenze
  - ALTA, ALTEC, DTM, SILO
  - INRIM, Polytechnic School of Torino
- 14 permanent members of the TAS-I study team
- 30 documents submitted to the Preliminary Requirements Review
- 3 custom-built software simulators
- 1 working breadboard of spin sensor











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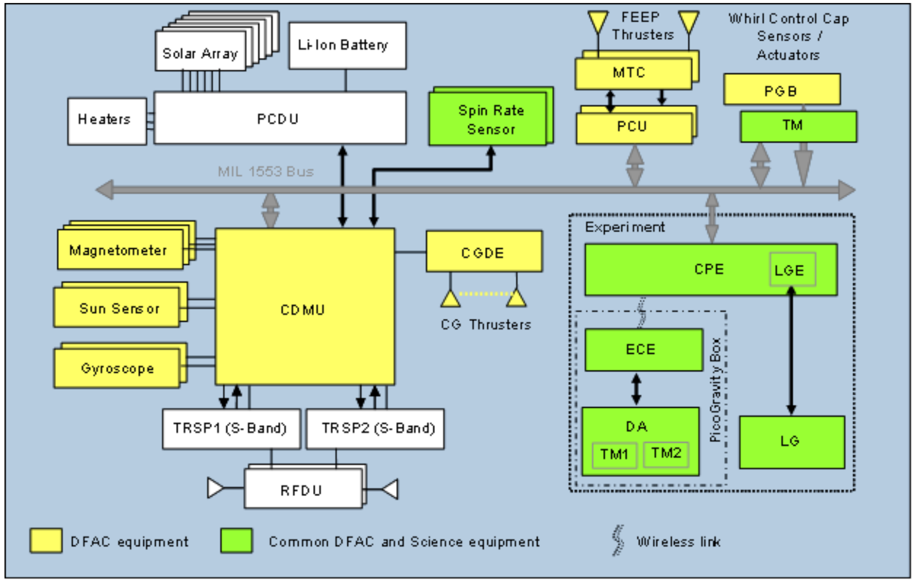
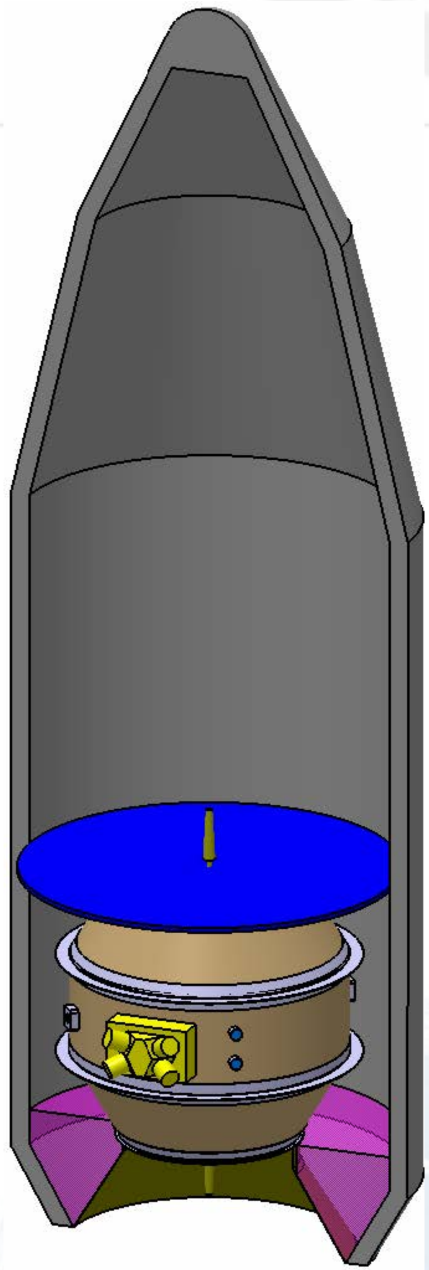
THALES ALENIA SPACE INTERNAL

Ref.:

Developments since 2009

- Sun-synchronous orbit & null checks
- Laser gauge measurement (M. Shao, JPL)
- Hydrogen-rich test mass
- Cold-gas proportional thrusters (GAIA heritage)

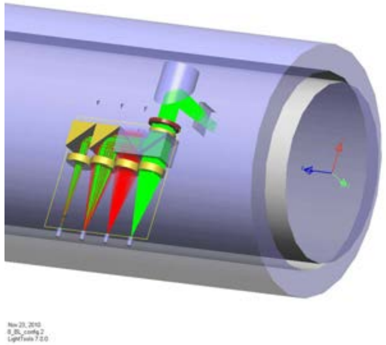




GG SSO Configuration

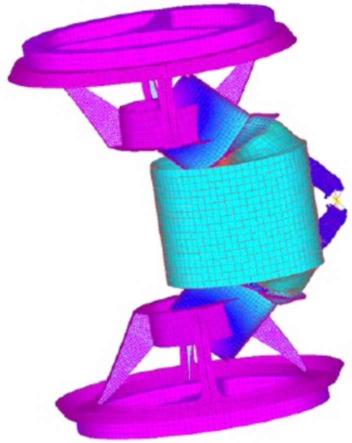
GG technical baseline

- 2 concentric test masses within vibration suppression assembly (PGB)
- 2 payload electronics units
- Capacitive test mass control
- Laser-gauge sensing and detection
- 1 Hz spin
- Cold-gas thruster (bang-bang) attitude acquisition / spinup /re-orientation
- Cold-gas thruster (proportional) drag-free control
- High accuracy measurement of spin rate (Spin rate sensor)
- 10 launch-lock devices
- 500 kg launch mass, 500 W power demand, 350 kbit/s telemetry rate
- Circular sun-synchronous orbit, 630 km altitude, 9-month mission

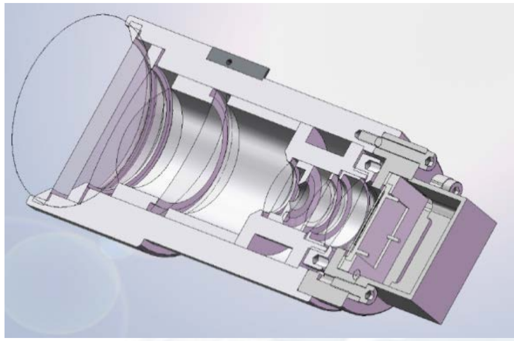


Laser gauge concept (M. Shao, JPL)

Cold-gas microthruster (Selex Galileo)



Test mass lock finite-element model (DTM)



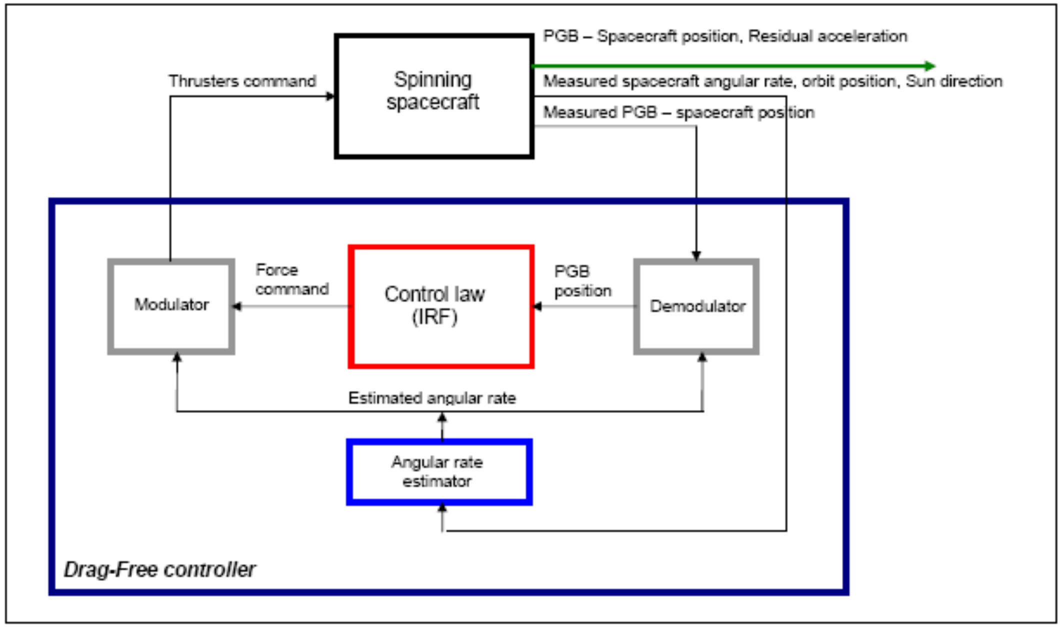
Spin rate sensor (TAS-I, SILO, INRIM)

Drag-free control

- Four control loops (X-Y drag, Z drag, X-Y whirl, spin rate)
- X-Y drag 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 (harmonic oscillator in the state observer)
- All controllers designed according to state-space approach based on state observer and gain feedback functions (GOCE heritage)

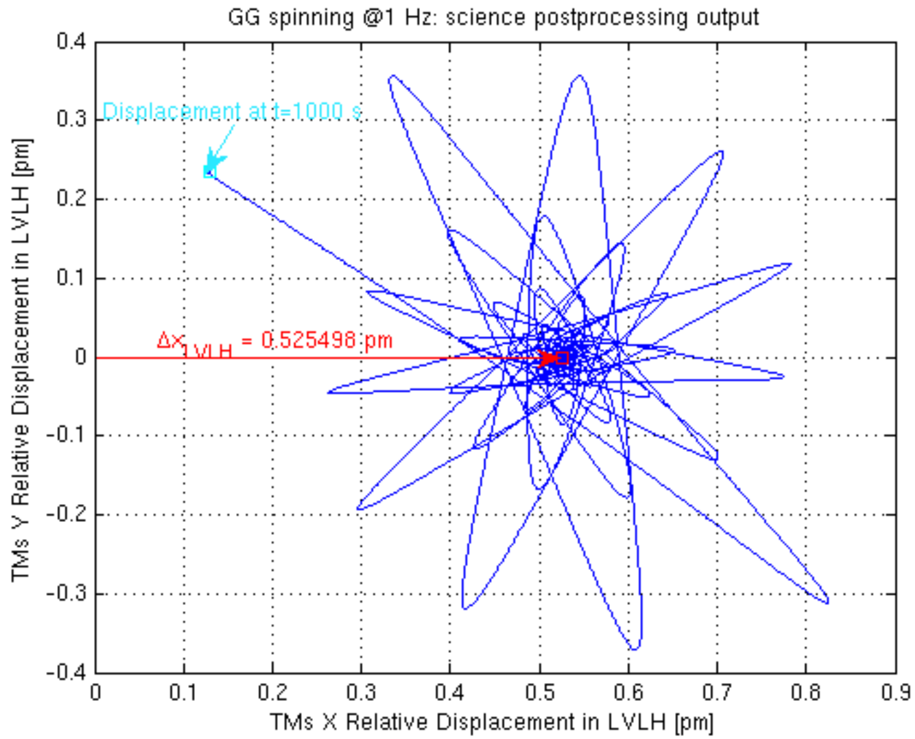
Microthruster requirements

Parameter	Unit	Value	Comments
Maximum thrust	µN	≥150	50% margin
Max thruster response time	ms	40	@ commanded step (up and down) ≥ 60 µN
Resolution (quantization)	µN	24	TBC, not critical
Max noise	µN/√Hz	18	Around 1Hz
Scale factor error	%	12	Peak
Update com rate	Hz	10	TBC
Total impulse	Ns	4500	20 % margin
Minimum thrust	µN	≤10	TBC
Vector stability	rad	0.17	Peak, at 60 µN
Centrifugal acceleration	g	<4.4	20 % margin, 0.75m spacecraft radius



GG Software Simulator

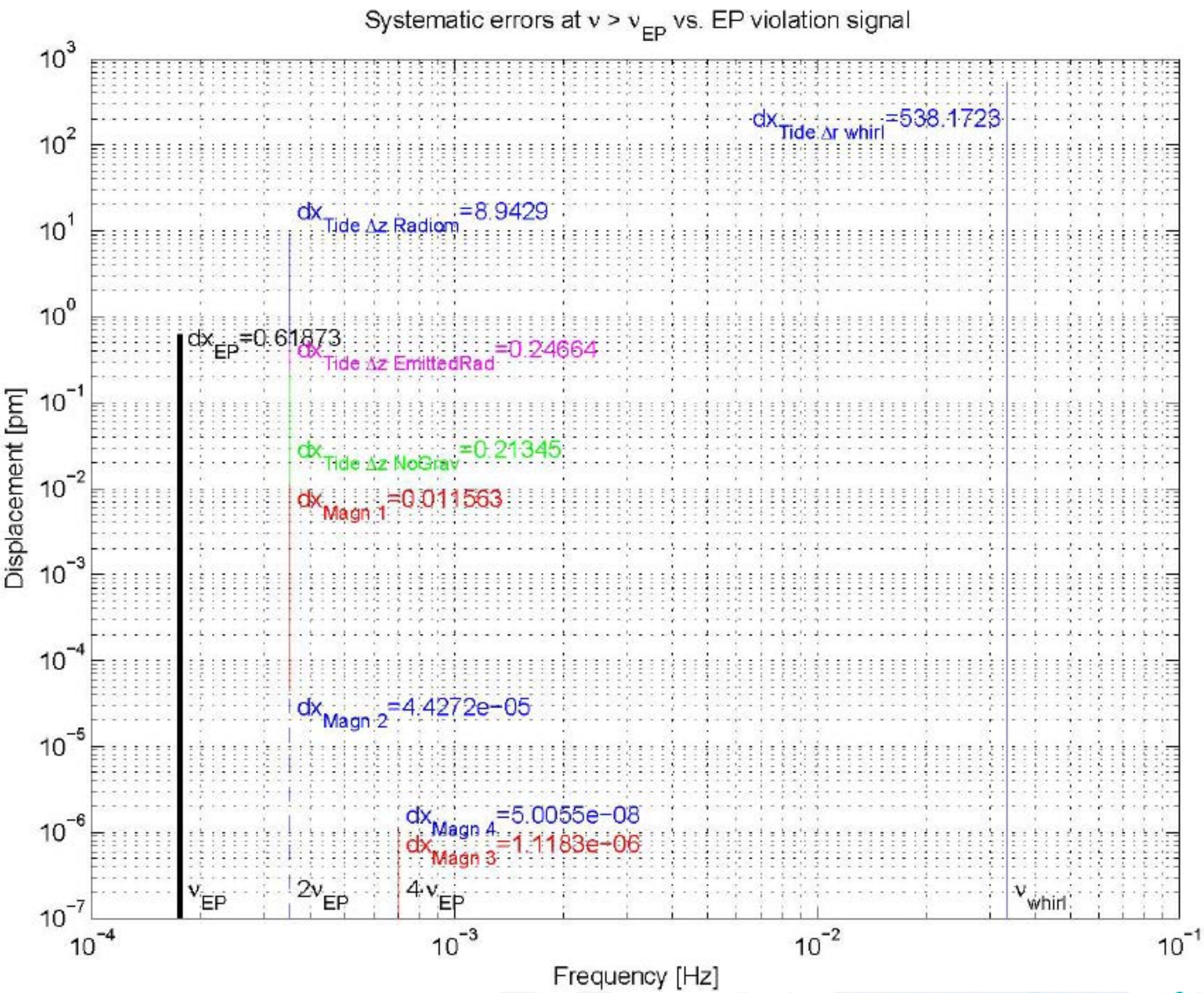
- 27 DOFs (Spacecraft shell, PGB, inner TM, outer TM + dummy “reference frame” body)
- Gravity and gravity gradient
- Current mass/inertia properties of all bodies (including proof masses quadrupole moment)
- Orbit altitude matching the reference non gravitational acceleration 2×10^{-7} m/s²
- Stiffness reproducing PGB modes and common and differential proof mass 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
- $\eta = 10^{-17}$ (science target) in all science simulations
- Quadruple precision to predict science performance of the mission



Polar plot of the differential displacement in the local vertical – local horizontal reference (LVLH) 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}

GG error budget

- Simulated EP violation signal Δx_{EP} = 0.6 *pm* at orbit frequency
- Systematic error sources at signal frequency include:
  - Earth's coupling to quadrupole mass moments of the TMs (same frequency and phase)
  - Direct radiometer effect due to infrared radiation from Earth (same frequency and phase)
  - Residual drag effect (same frequency, has a component with same phase)
  - Electric patch effects between TMs (have low frequency variation and component at signal frequency
- Twice-orbit-*f* terms are larger in magnitude but can be distinguished in post-processing



THALES ALENIA SPACE INTERNAL

Technology readiness

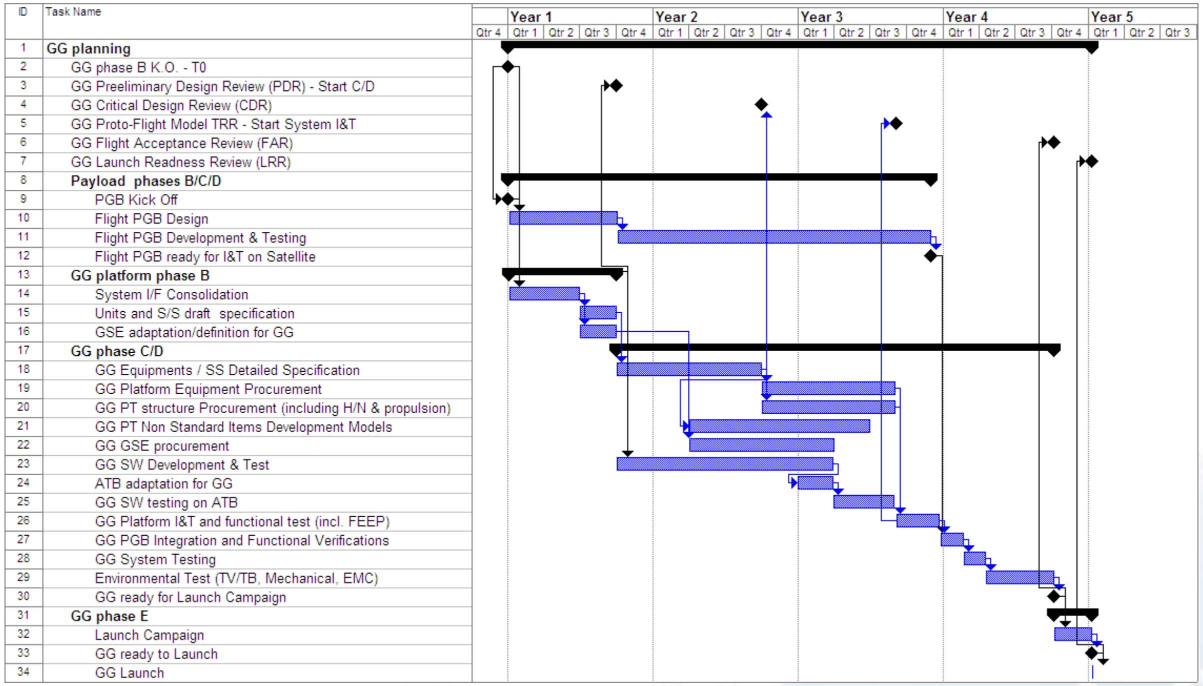
- Detailed specification of experiment requirements developed as part of 2009 ASI study
- Ultimate test by analysis (S/W simulator)
  - Cannot be tested on ground at required sensitivity
- Technology requirements
  - Soft springs, precise machining, mass balancing: demonstrated in the lab
  - Capacitive test mass control & readout: state of the art
  - Laser gauge: state of the art components
  - Spin rate measurement (10^{-5} fractional accuracy): functioning breadboard available
  - Drag Free Control:
    - constrained by design to same requirements as LISA Pathfinder & Microscope
    - GOCE heritage
  - Charge control: test masses are grounded by springs; local charges (patch effects) 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

Element	TRL	Heritage
PGB (payload)	4	GGG
Laser gauge (payload)	6	SIM
Payload Launch Lock mechanisms	6	LISA Pathfinder
CDMU	9	GOCE
Basic SW	9	GOCE
Sun Sensors	8	Selex-Galileo Smart Sun Sensor
Magnetometer	8	IAI TAMAM
Gyroscope	8	Honeywell MIMU /Northrop Grumman LN200/ Northrop Grumman microFors
Spin Rate Sensor	4	Breadboard designed, manufactured and tested as part of 2009 ASI study
Solar Panel technology	9	GOCE
Battery	9	GOCE
PCDU	9	SICRAL, Atlantic Bird 1, SICRAL 1B, Gaia
Transponder	9	GOCE
S-band LGAs	9	ATV
RFDN	9	GOCE
Thruster System	8	LISA PF qualification
Cold Gas Proportional Thruster System	8	GAIA qualification
Auxiliary Cold Gas Thruster System	9	Various market products
GCT tanks	9	Various market products
Harness	9	Various satellite projects
Thermal Control	9	Standard technology, dedicated application
Structure	9	Standard technology, dedicated application

Development approach

- Small-sat approach
  - small dedicated project team, modular architectures, in-house development of application software, direct involvement of PI and subcontractors in the project team, technically competent project management, streamlined documentation

- Sat-level protoflight approach plus flat test bench and simulators
- Structural-thermal model of experiment cage
- Qual-models of new equipment
- 4-yr development plan from Phase B to launch



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