First Developments on Laser Metrology Technologies and Drag/Formation Control Techniques

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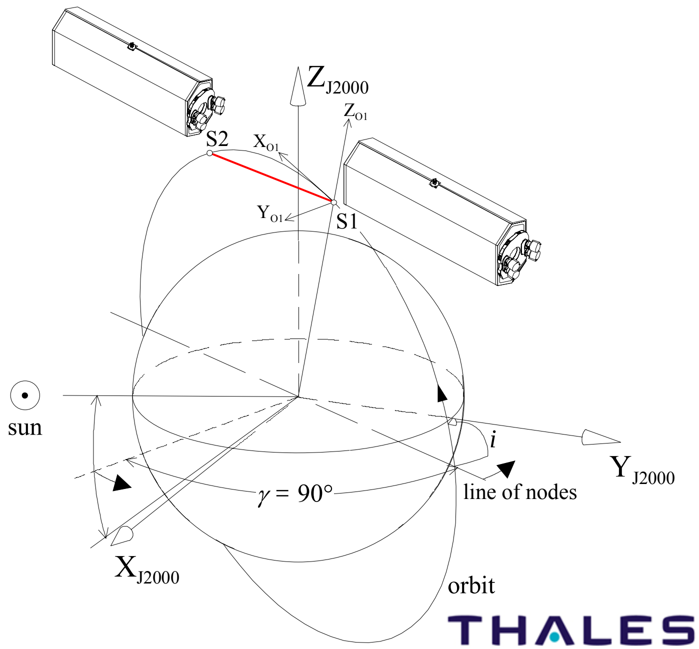
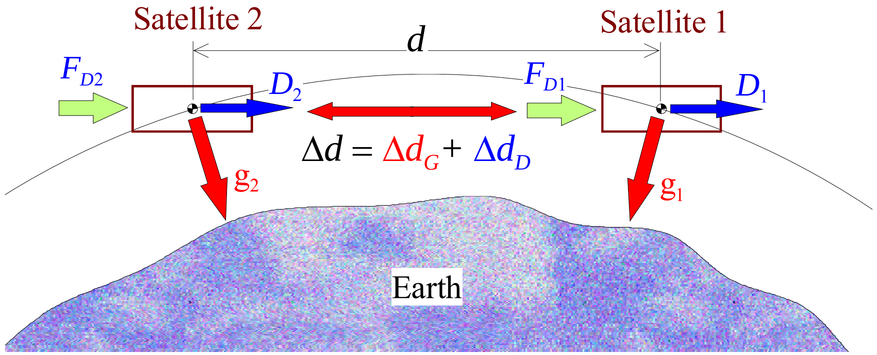
Preparatory studies for a Next Generation Gravity Mission (NGGM) have been promoted by ESA since 2003. Three of them have been performed by TAS, addressing a first ouline of the mission, a first devopment of the laser metrology for the satellite-to-satellite tracking and a first design of the drag-free and formation control systems.

Reference mission scenario considered for the metrology and drag-free/formation control systems design

- Orbit mean altitude: 325 km, circular
- Inclination: 96.78° (sun-synchronous)
- Longitude of ascending node:
  $\Omega = RA_{\odot} \pm 90°$ (dusk-dawn/dawn-dusk orbit)
- Measurement phase duration: 6 years
- Satellite formation: 2 satellites flying along the same orbital path (GRACE-like)
- Satellite attitude: Earth pointing
- Satellite-satellite distance: 10 km



Top-level requirements

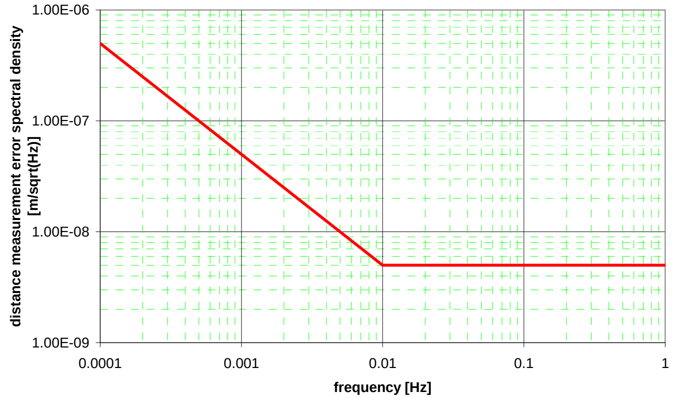


The distance variation between two satellites (Δd) is measured by a laser metrology system.

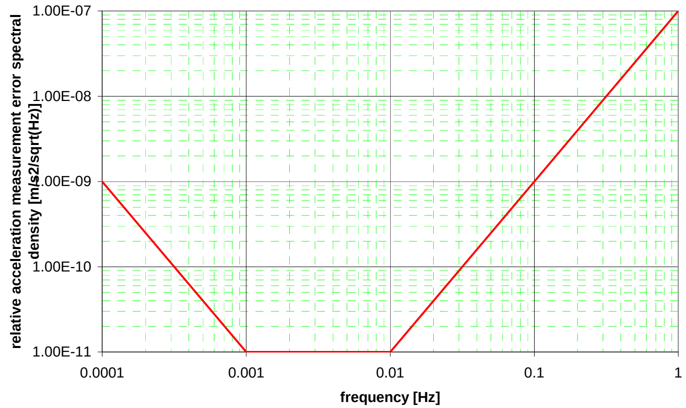
The distance variation between the satellites produced only by drag forces (Δd_D) is measured by accelerometers.

Subtracting (Δd_D) from (Δd) the distance variation produced by the gravity acceleration is obtained: $\Delta d_G = \Delta d - \Delta d_D$

Top-level requirement on satellite-satellite COM distance variation measurement



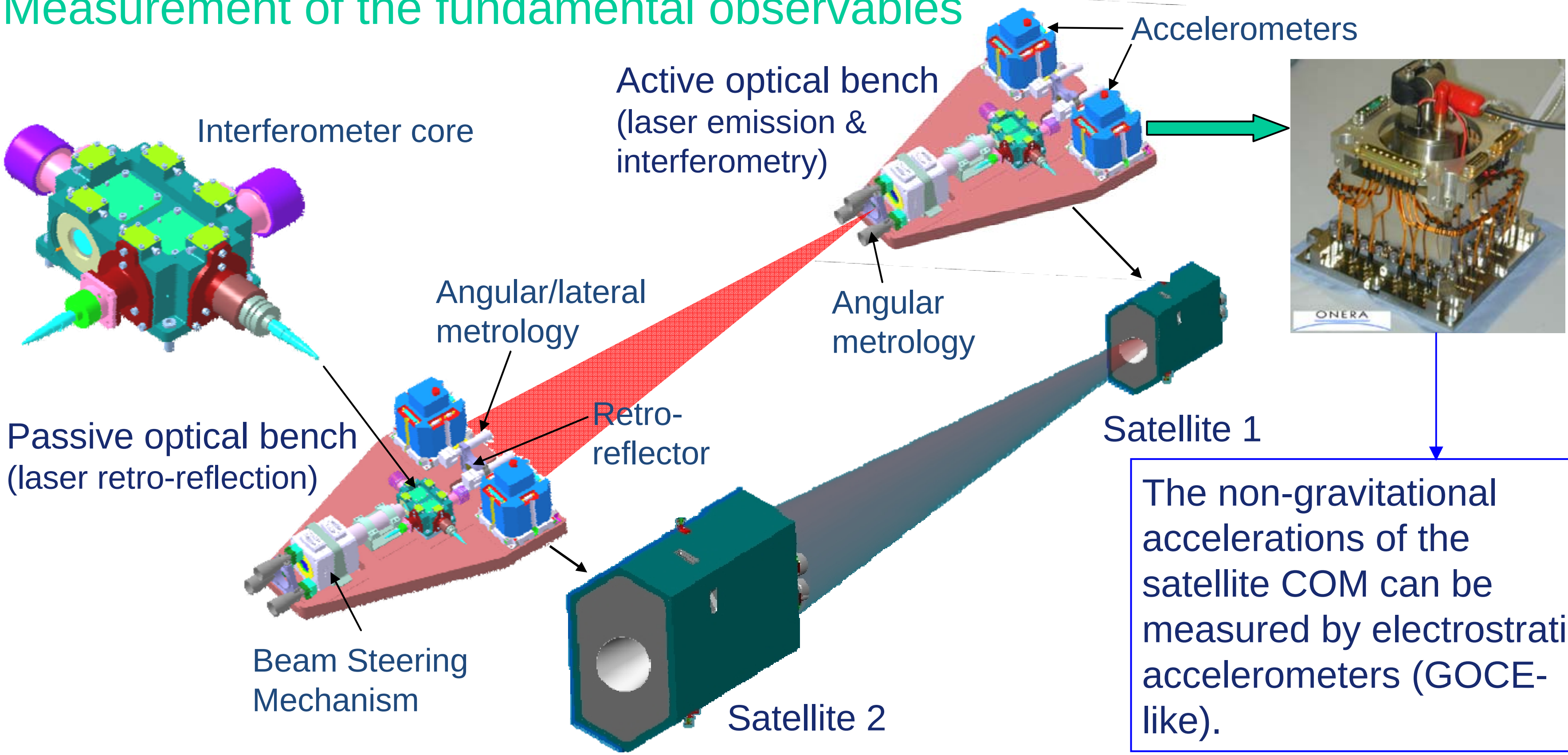
Top-level requirement on relative non-gravitational acceleration measurement



A measurement system with such performances operating in the reference mission scenario can provide a geoid height variation resolution = 0.1 mm/year at $\ell = 200$.

The metrology system

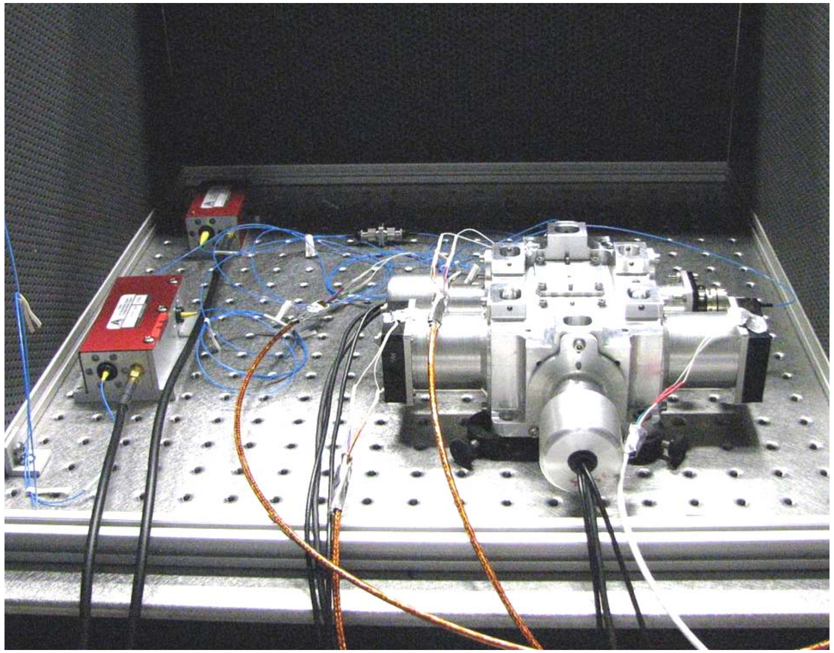
Measurement of the fundamental observables



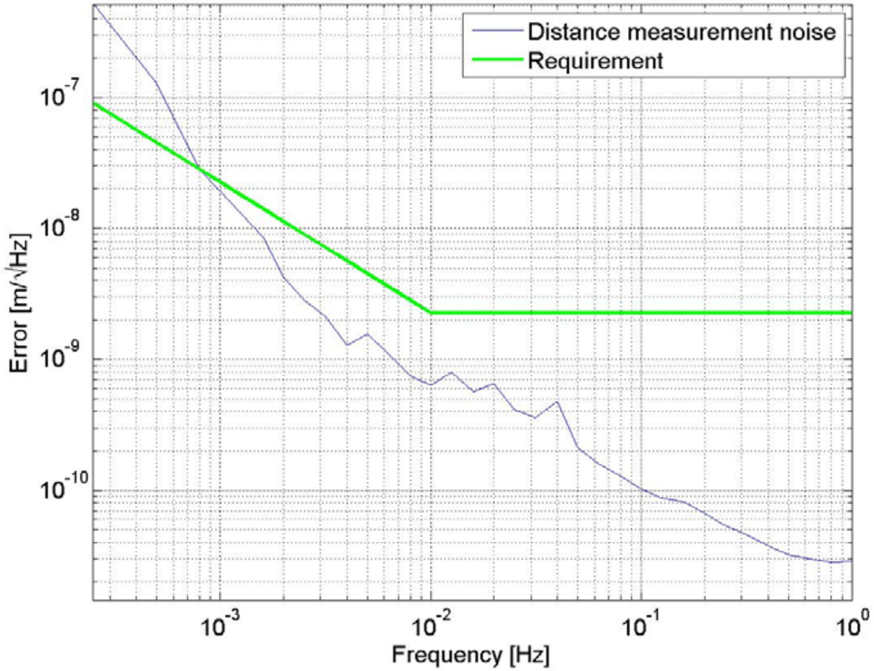
The non-gravitational accelerations of the satellite COM can be measured by electrostatic accelerometers (GOCE-like).

- **Distance variation metrology**: Michelson-type heterodyne laser interferometer (Nd:YAG 1064 nm laser, 750 mW optical power) with chopped measurement beam, complemented by Angle/Lateral Displacement Metrology, Beam Steering Mechanism.
- **Working range of the laser interferometer**: up to 100 km.
- **Satellite relative velocity tracking capability**: up to 15.9 m/s.

Laser interferometer performance test



Laser interferometer breadboard prepared for the intrinsic noise test (measurement of a constant distance).

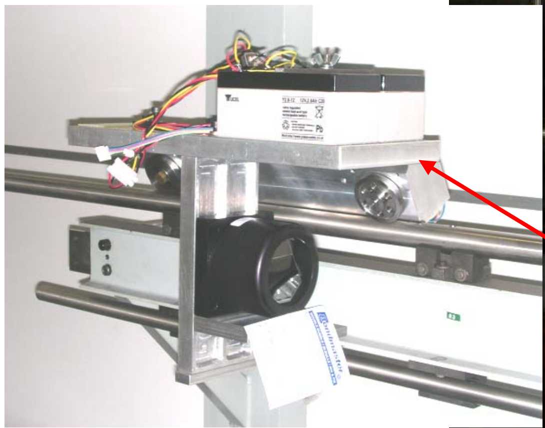


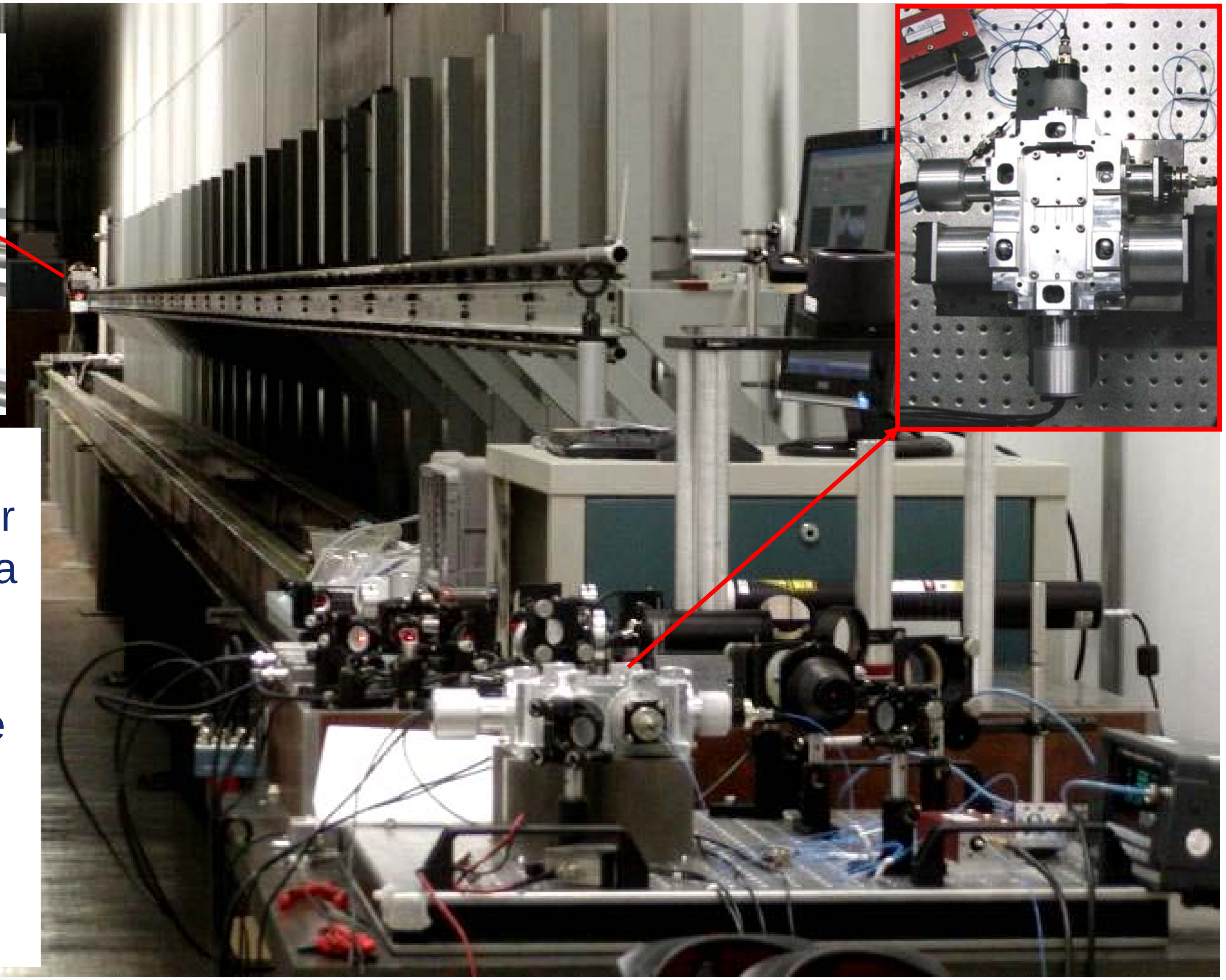
Spectral density of the distance variation measurement error obtained during the tests and compared to the requirement.

In order to achieve the specified measurement performance over a distance of 10 km, the laser frequency shall have a relative stability $\delta\nu/\nu \leq 1.4 \cdot 10^{-13}$ $Hz^{-1/2}$.

Laser interferometer performance test

Interferometer breadboard





Laser interferometer breadboard prepared for the functional test over a long distance (~90 m) with a moving target. The effectiveness of the measurement beam chopping scheme was successfully verified in this test.

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Control requirements

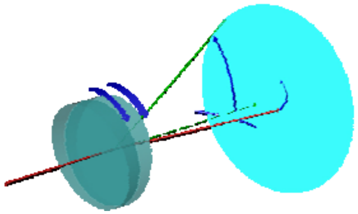
Satellite attitude control in a Local Orbital Reference Frame	Requirement
Maximum misalignment	$\phi, \theta, \psi \leq \pm 0.5°$
Alignment stability spectral density	$\tilde{\theta}, \tilde{\psi} \leq 10^{-5} \frac{rad}{\sqrt{Hz}}$
Control of the satellite angular rates about the COM	**Requirement**
Maximum angular rates	$\omega_X, \omega_Z \leq 10^{-4}$ rad/s $\omega_Y \leq 1.2 \cdot 10^{-3}$ rad/s (pitch)
Angular rate stability spectral density	$\tilde{\omega}_X, \tilde{\omega}_Y, \tilde{\omega}_Z \leq 10^{-6} \frac{rad}{s\sqrt{Hz}}$
Control of the satellite angular accelerations about the COM	**Requirement**
Maximum angular accelerations	$\dot{\omega}_X, \dot{\omega}_Y, \dot{\omega}_Z \leq 1 \cdot 10^{-6}$ rad/s^2
Angular acceleration stability spectral density	$\tilde{\dot{\omega}}_X, \tilde{\dot{\omega}}_Y, \tilde{\dot{\omega}}_Z \leq 10^{-8} \frac{rad}{s^2\sqrt{Hz}}$
Control of the satellite linear accelerations about the COM	**Requirement**
Maximum linear accelerations	$D_X, D_Y, D_Z \leq 1 \cdot 10^{-6}$ m/s^2
Residual linear acceleration spectral density	$\tilde{D}_X, \tilde{D}_Y, \tilde{D}_Z \leq 10^{-8} \frac{m}{s^2\sqrt{Hz}}$
Control of the satellite-satellite relative position	**Requirement**
S2-S1 displacement along the line joining the COMs	$\Delta d_X \leq \pm 500$ m (about the nominal distance = 10^4 m)
S2-S1 relative lateral displacement	$\Delta d_Y, \Delta d_Z \leq \pm 50$ m
Control of the laser beam pointing from S1 to S2	**Requirement**
Maximum pointing error	$\theta_B, \psi_B \leq 1 \cdot 10^{-5}$ rad
Pointing stability spectral density	$\tilde{\theta}_B, \tilde{\psi}_B \leq 10^{-7} \frac{rad}{\sqrt{Hz}}$

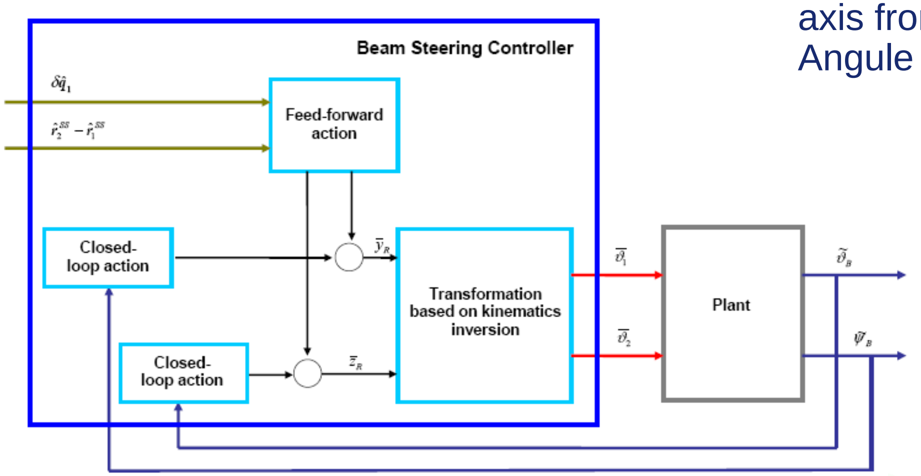
The function of the laser beam pointing (subject to stringent requirements) is assigned to a dedicate opto-mechanical system (Beam Steering Mechanism) ⇒ relaxed requirement on absolute pointing of each satellite.

The utilization of ultra-sensitive accelerometers implies to control the satellites in “drag-free” condition in position (non-gravitational liner acceleration control) and attitude (stable angles, rates).

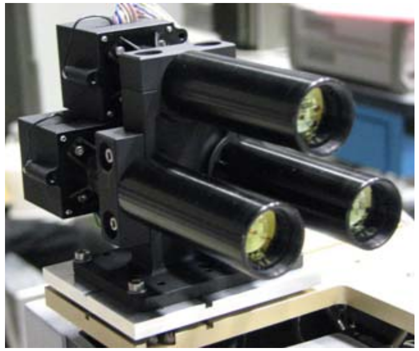
The relative position control is driven by the optical link and is not very stringent (*loose* formation).

Laser beam pointing control system

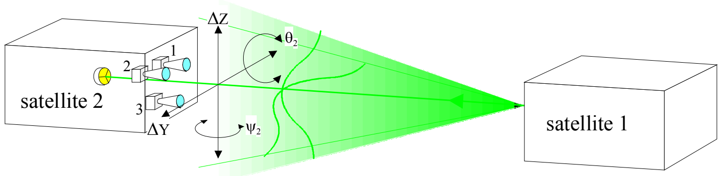




Lateral Displacement Metrology sensing the offset of the laser beam axis from Satellite 2 (integrated with Angule Metrology)



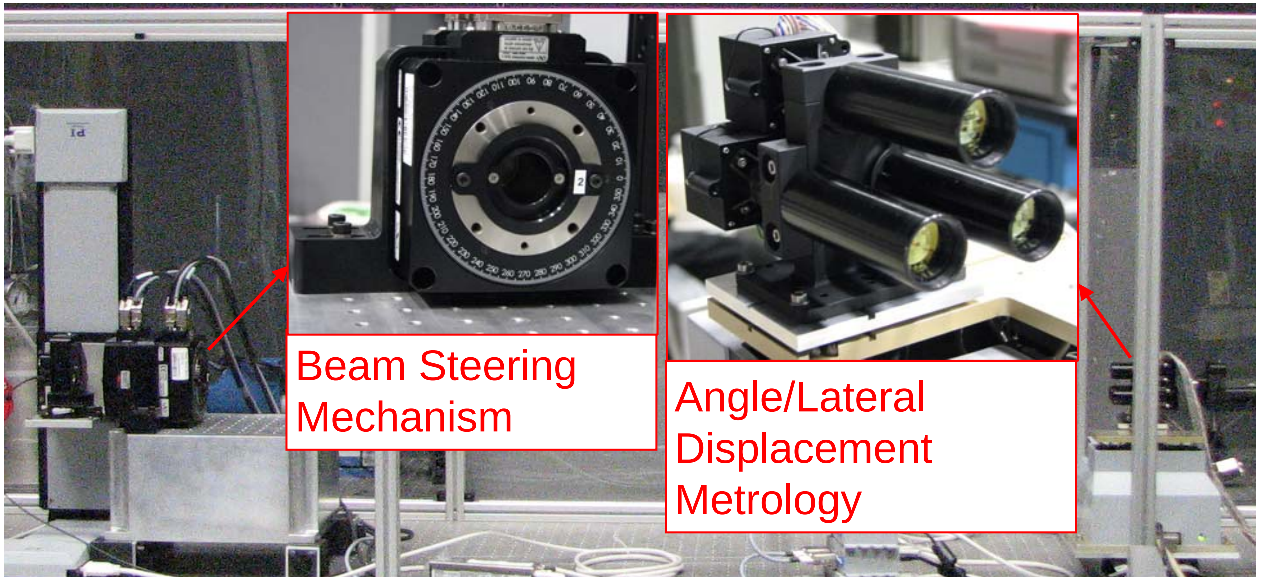
Beam Steering Mechanism (BSM) changing the orientation of the outgoing beam



- The mis-pointing of the laser beam at Satellite 2 are measured by the Lateral Displacement Metrology and transmitted to Satellite 1 via inter-satellite link.
- The rotation angles of the BSM prisms are computed using the inverse kinematics from the lateral displacements measurements (feed-back action).
- A feed-forward action, fed by the S1-S2 relative position and by the S1 attitude measurements, is also implemented (mainly effective for the first optical link acquisition).

Laser beam pointing control test

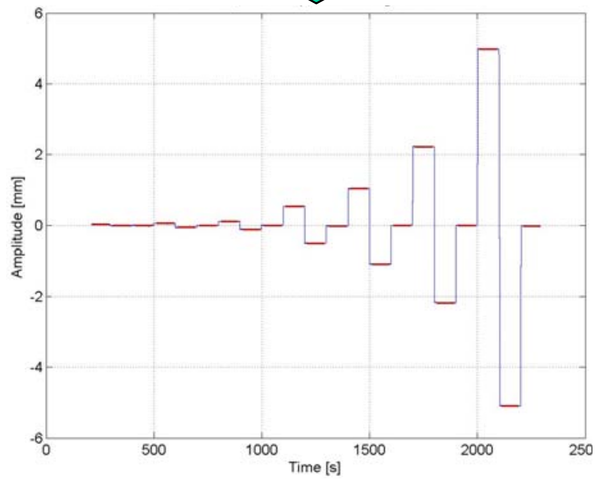
Breadboard of the Beam Steering Mechanism and of Lateral Displacement Metrology prepared for the performance test



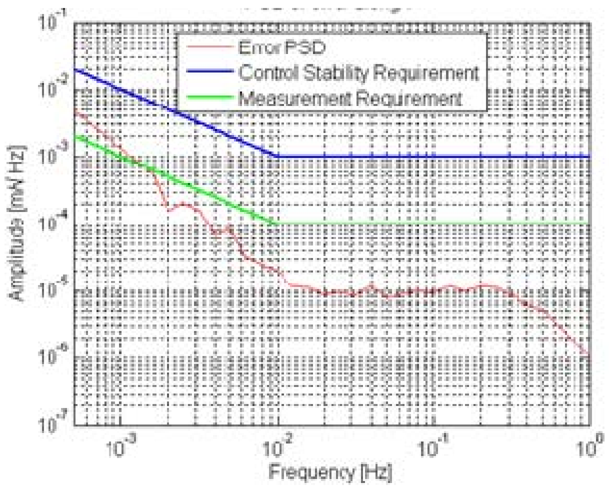
Open-loop test of the Lateral Displacement Metrology.

Lateral displacement steps (from ±50 μm to ±5 mm) measured by the optical metrology at 10 Hz.

Max. measurement error: 0.25 mm Max. measurement noise: 14 μm 1σ.



Closed-loop test of the laser beam pointing control system (BSM driven by the Lateral Displacement Metrology measurements). Laser beam pointing stability results.



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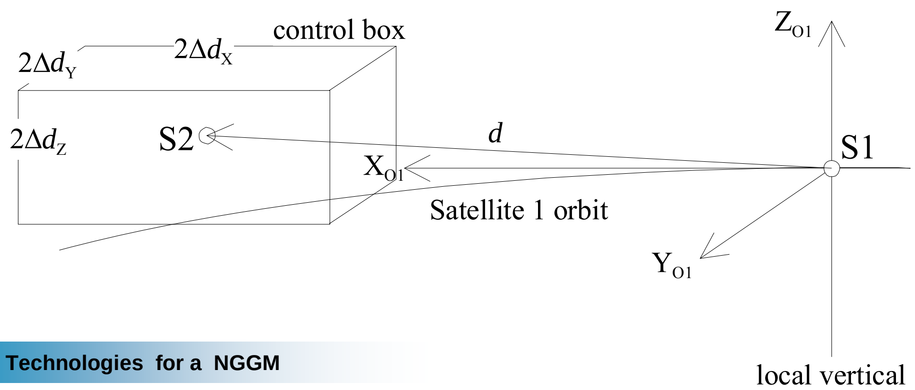
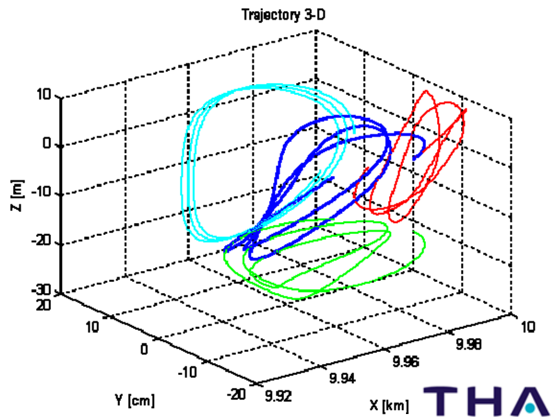
Formation and drag control challenges

- The formation control must keep the position of the Satellite 2 relative to Satellite 1 bounded within the "control box":
  1. **without interfering with the scientific measurements (the satellites must be "free" to move under the effect of the gravity field over time scales of 1000 s);**
  2. **without spoiling the drag-free environment (i.e. the formation control accelerations must fulfil the drag-free requirement too);**
  3. **minimizing the thrusters use (in terms of dynamic range, propellant consumption), by avoiding the compensation of the periodic, differential gravitational perturbations not driving the satellite outside the control box, and the accelerometers differential bias/drift (to be estimated and subtracted from the commands sent to the ion thruster by the drag-free loop).**
- The drag-free control must reduce the non-gravitational accelerations of the two satellites without compensating the formation control accelerations.





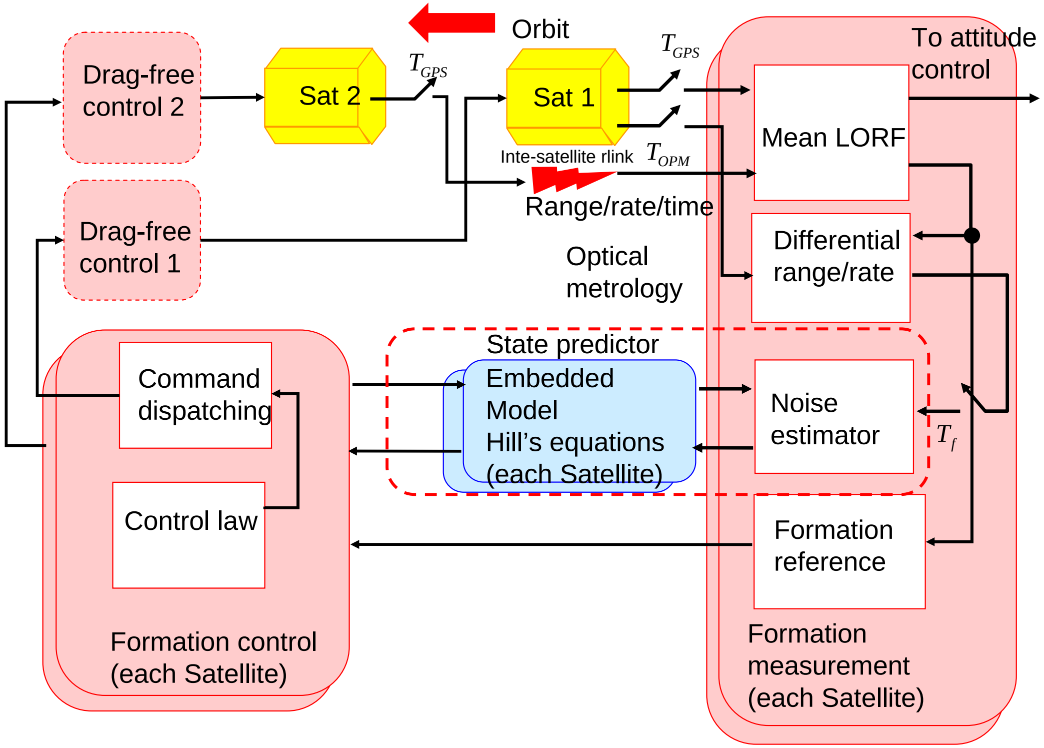
Formation and drag-free control architecture

Formation control: Outer, lower BW loop (<1 mHz), providing the reference acceleration profile which is tracked by the drag-free control.

Drag-free control:

inner, wider BW loop (upper frequency ~0.8 Hz).

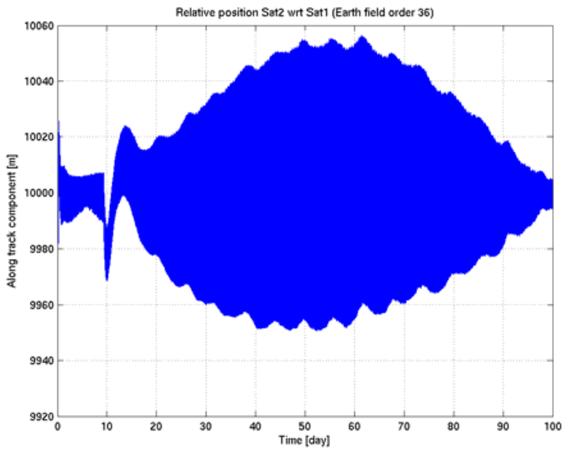
Formation control commands shared between the two satellites.

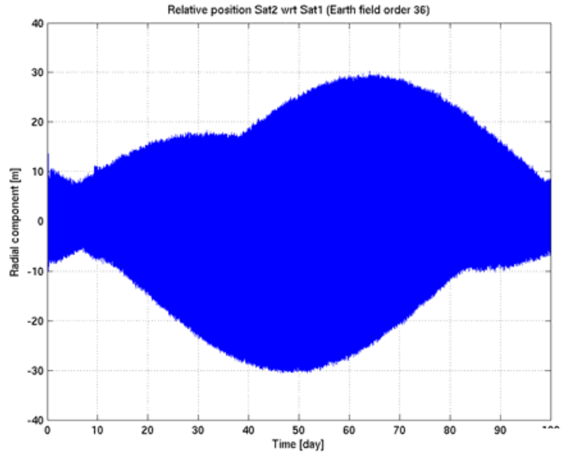


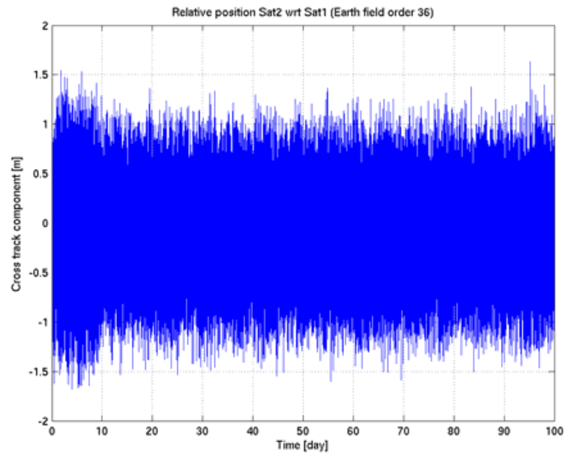
The relative position/velocity of the satellites is obtained from the GPS (in absolute and differential modes) augmented by the laser interferometer. The accelerometer bias is estimated from the effect produced on the orbits and on the relative motion of the two satellites, and is subtracted from the drag-free command to the thrusters.

Formation and drag control

Formation and drag-free control numerical simulations results



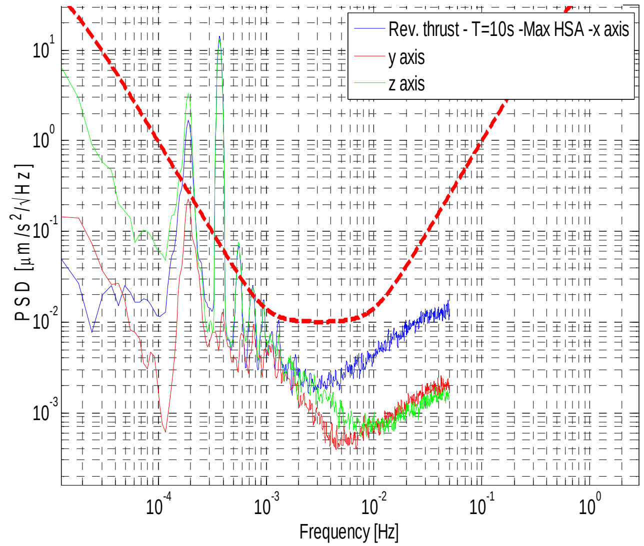




Relative Position of the Satellite 2 wrt the Satellite 1 over 100 days with Formation Control ON.

Included perturbations: gravity field up to degree/order 36; accelerometers differential bias and drift.

Spectral densities of the commanded formation control accelerations: the drag-free requirement is fulfilled in the measurement band 1÷100 mHz



Thrusters for the formation, drag attitude control

Among the various thruster technologies reviewed, the “miniaturized” Radio-Frequency Ion Thrusters (mini-RIT) developed by University of Giessen/ASTRIUM appear the most promising ones for the NGGM. For an in-line satellite formation, two thruster typologies are necessary: main thrusters for the along-track drag force compensation and formation control; lateral thrusters for the cross-track drag force compensation, formation and attitude control.

To cope with the large variation of the drag forces encountered in a long duration mission, especially in periods of high solar activity, the thruster dynamic range shall be at least 40 (~0.44 to 17.6 mN for the main thrusters; ~0.05 to 2 mN for the lateral thrusters). Moreover, a high specific impulse is required throughout the whole dynamic range for minimizing the propellant consumption. A characterization campaign of these thrusters on the Nanobalance test facility of TAS-I is planned to take place in 2010.