Next Generation Gravity Mission design activities within the MAGIC -Mass Change and Geoscience International Constellation

Luca Massotti, Alexandra Bulit, Ilias Daras, Bernardo Carnicero Domínguez, Olivier Carraz, Kevin Hall, Arnaud Hélière, Günther March, Valentina Marchese, Philippe Martimort, Kyle Palmer, Gonçalo Rodrigues, Pierluigi Silvestrin, and Neil Wallace

EGU23-14482, 25/04/2023, VIENNA, AT (Virtual)

ESA UNCLASSIFIED – For ESA Official Use Only

State of the art: mass change from gravity

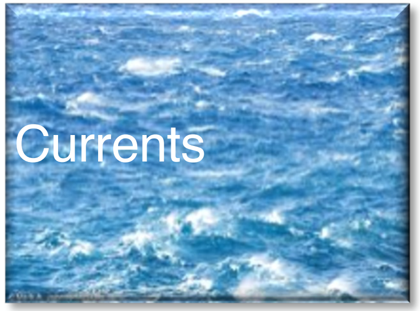

Drought


Ice mass loss


Earthquake


Flood

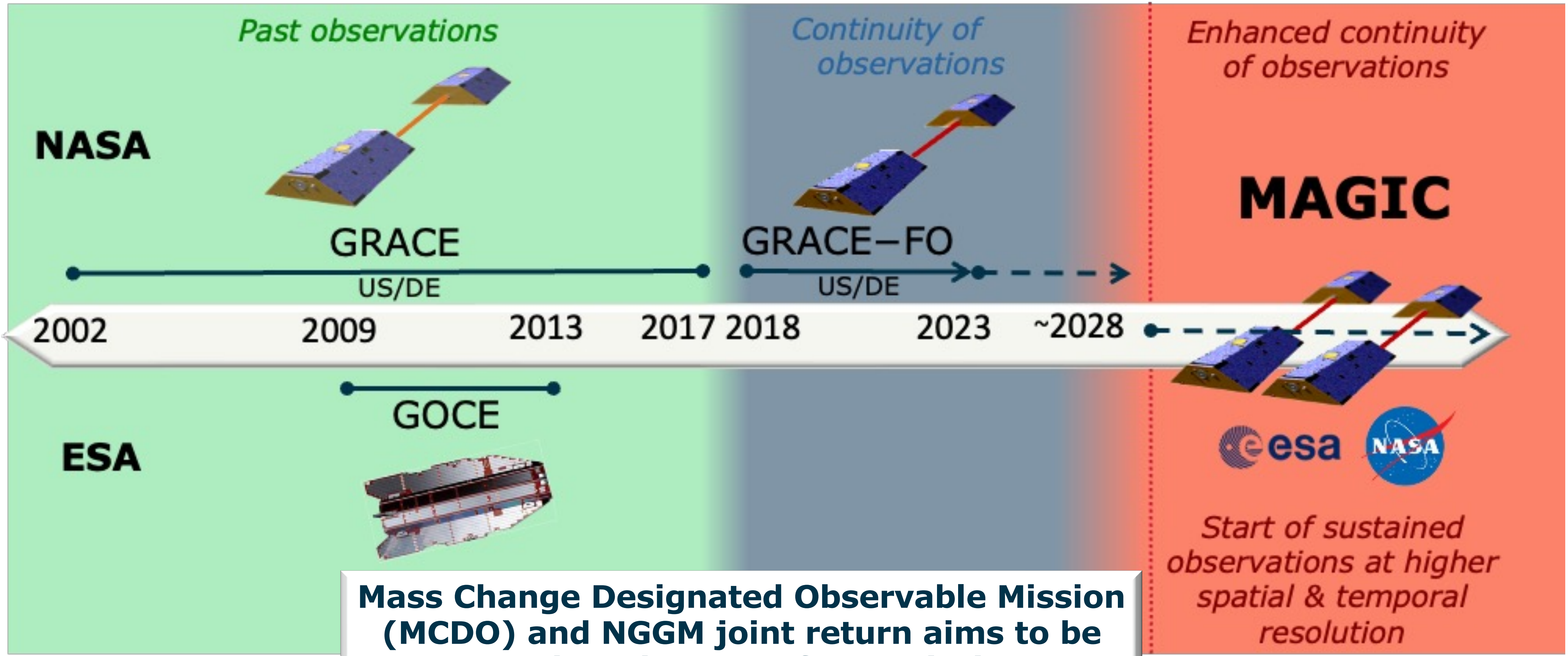

Land uplift


Currents


Water use


Sea level rise

ESA & NASA cooperation – MAGIC Joint Mission



Past observations

Continuity of observations

Enhanced continuity of observations

NASA

GRACE

US/DE

GRACE–FO

US/DE

MAGIC

2002 2009 2013 2017 2018 2023 ~2028

GOCE

ESA

Start of sustained observations at higher spatial & temporal resolution

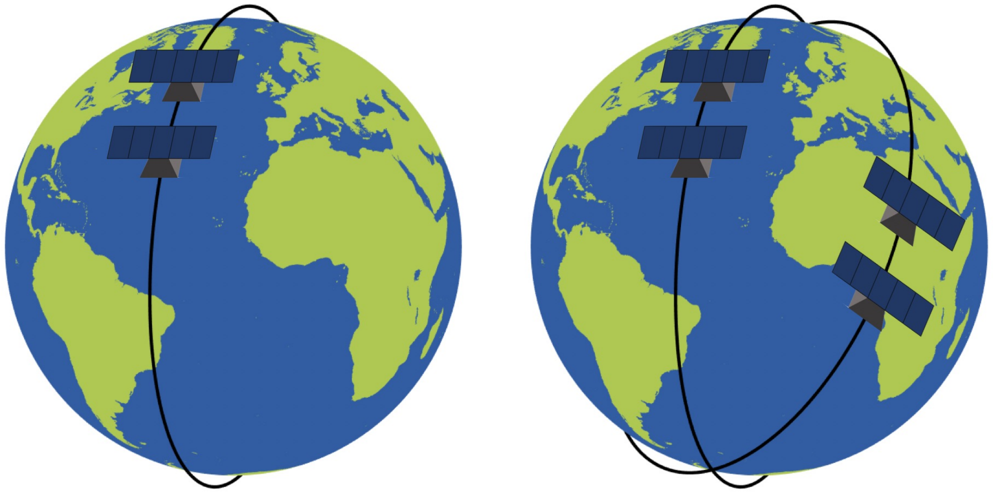
Mass Change Designated Observable Mission (MCDO) and NGGM joint return aims to be more than the sum of two missions

Mass change from gravity

MAGIC will be composed of two pairs of satellites:

- The first pair (i.e. P1) is to be implemented via a DE-US fast-paced cooperation programme to ensure continuity of observations with GRACE-FO.
- The second pair (i.e. NGGM, P2) is to be implemented via a Europe-US cooperation programme with some potential NASA in-kind contributions with target launch date compatible to maintain at least 4 years of combined operations.

P1 is expected to be flying in a **polar orbit** at about 500 km altitude while **P2** will be flying in an orbit about 400 km and 70 deg of **inclination** in a “quasi” Bender constellation configuration since P1 is not expected to control its orbit



“In-line”

“Bender”

Joint mission challenges

- **Long-term monitoring** is a prerequisite for deriving reliable trend estimates. The longer the time series, the better positioned we are to providing answers to questions of ice mass loss, sea level rise, groundwater depletion, and natural hazards. A climatology (<30 years) is important for climate applications and satellite gravity data derived indexes (e.g. for flood or drought).

- **Increase of spatial resolution** is required to properly monitor important catchment basins that are either smaller than, or at the resolution limits of, current space gravimetric missions. This allows a better “closure” of the water cycle. This is also important for specific ice, ocean and solid Earth applications.

- **Increase of temporal resolution**, in combination with short latencies (day-few days), will facilitate near real-time applications and services with direct applicability, e.g., in water management and evaluation of flood risk, issues of coastal vulnerability, etc. It will also lead to improvements at longer periods (month, season, trend, ..) by capturing and estimating short period solutions reducing aliasing effects.

- **Consistent and homogeneous quality products for a given period (important for services and science):** existing missions have changing ground track patterns resulting in variable quality products, so a controlled constellation is desired.

System design status and Phase A studies

The **NGGM Phase A** is currently running an “ **extension** ” phase (**8 months**) approaching the **Delta - Preliminary Requirement Review** of the satellite design proposed by two consortia in competition.

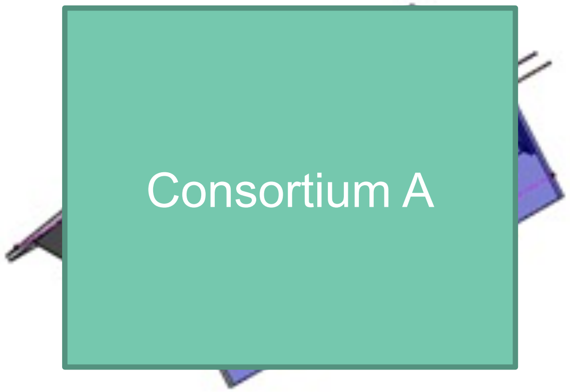
Each satellite is embarking 3 ultra-fine **accelerometers** (for redundancy and enhanced on board calibration capability) and a **Laser Tracking Instrument** (**LTI**), i.e. a Michelson interferometer in transponder configuration.

The proposed designs rely in a **mono-propellant** solution to enable *drag-compensation*, formation and attitude control system (i.e. DFAOCS), allowing the satellites to be tree-axis stabilized and nadir pointing, to track and fine pointing to each other, and to implement drag compensation for minimizing the disturbances on the accelerometer instruments.

The actuators devoted to *lateral/cross-track drag compensation* and *attitude control* are **proportional cold gas thrusters**, and those devoted to *drag compensation* are based on **electric propulsion**, aiming to cover a lifetime up to 7.5 years.

Several baseline and back-up thruster options have been presented and are under evaluation

System design status and Phase A studies

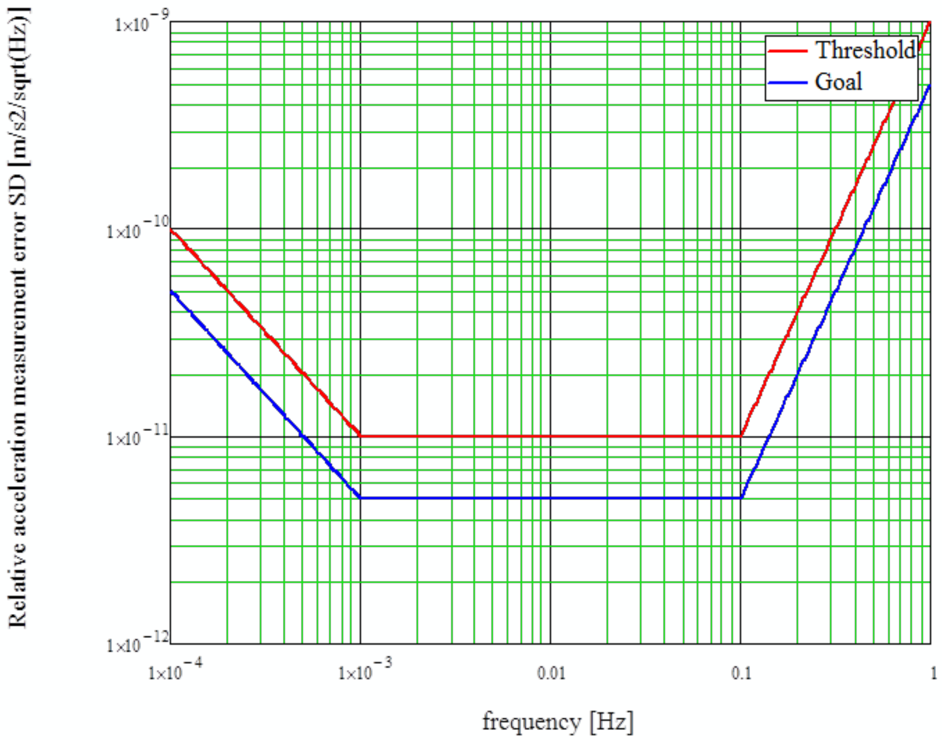


Concepts based on two spacecraft mounted on a **central dispenser**, and being supported at discrete points, for release once in-orbit. These configurations are tailored to meet the available *launch mass*, *launch volume* as well as the **natural frequency and inertia requirements** specified by the launch vehicles User Manuals.

The design of the spacecraft and dispenser were supported by detailed **Finite Element Analyses**. This allowed their verification for stiffness and strength, as well as the derivation of the dynamic environment of the payload units and the propulsion sub-system.

The internal accommodation was verified by performing **thermal analyses** of the orbital environment, involving detailed Thermal Mathematical Models. These thermal analyses not only serve as reference for assessing the compatibility with the thermal specifications of the different units, but also provide the thermal maps employed on the prediction of the **Thermo-Elastic Distortions (on-going)**, performed by Finite Element Analyses.

Instrument Performance Requirements - Accelerometers



The accelerometer has been designed to meet the top-level relative non-gravitational acceleration measurement error requirement (figure to the left).

NGGM technology pre-development activity: focus on the adaptation of the ONERA's **MicroSTAR** **accelerometer** to fulfil the NGGM's needs and specifications.

Main objectives:

- consolidate and propose a detailed accelerometer design based on heritage capable of meeting the NGGM requirements;
- procure, manufacture and test in a representative environment the units comprising the accelerometer design for NGGM. *and*
- In addition, technology developments to raise the TRL of the full accelerometer to TRL 6 have been initiated.

Sensor improvement: beyond GOCE acc. performances

Objectives:

- Low-frequency noise of the accelerometer (below 1 mHz) improved wrt GOCE
- Performance shall be identical along the 3 directions (3 ultra-sensitive axis), but limited in the axis where the thin discharge wire is located -> cubic proof mass
- Accelerometer to support 3 linear + 3 angular drag compensation
- Proof mass translational and rotational measurements are used for satellite attitude control

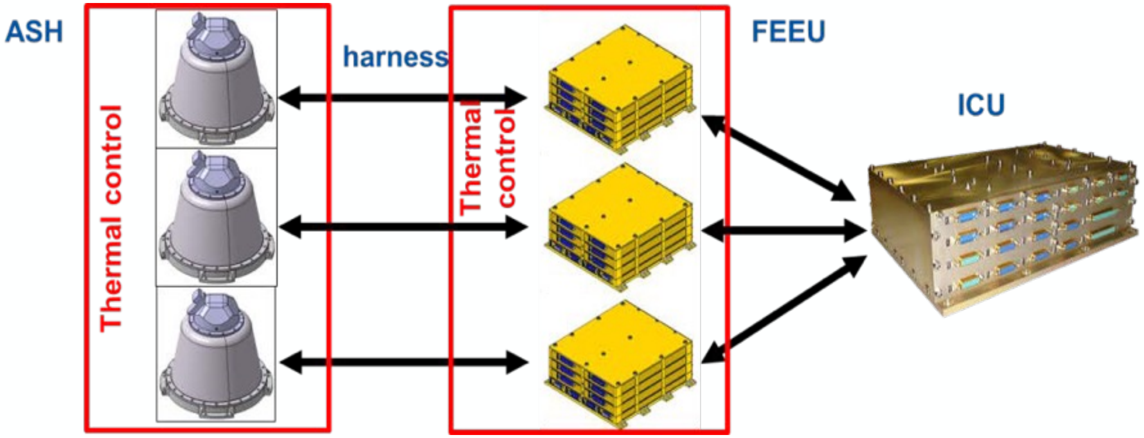
Performance improvement is possible adjusting several parameters:

- Shape and mass of the proof-mass: an heavier and cubic proof-mass can potentially push the performance along the three axes closer to the 10^{-13} $m/s^2/Hz^{1/2}$ noise floor;
- Increasing the gap between proof-mass and electrodes;
- changing the material and the stiffness property of the proof-mass grounding wire, for discharging purposes;
- read-out electronics re-design, for decoupling the measured translational and rotational motion of the proof-mass.

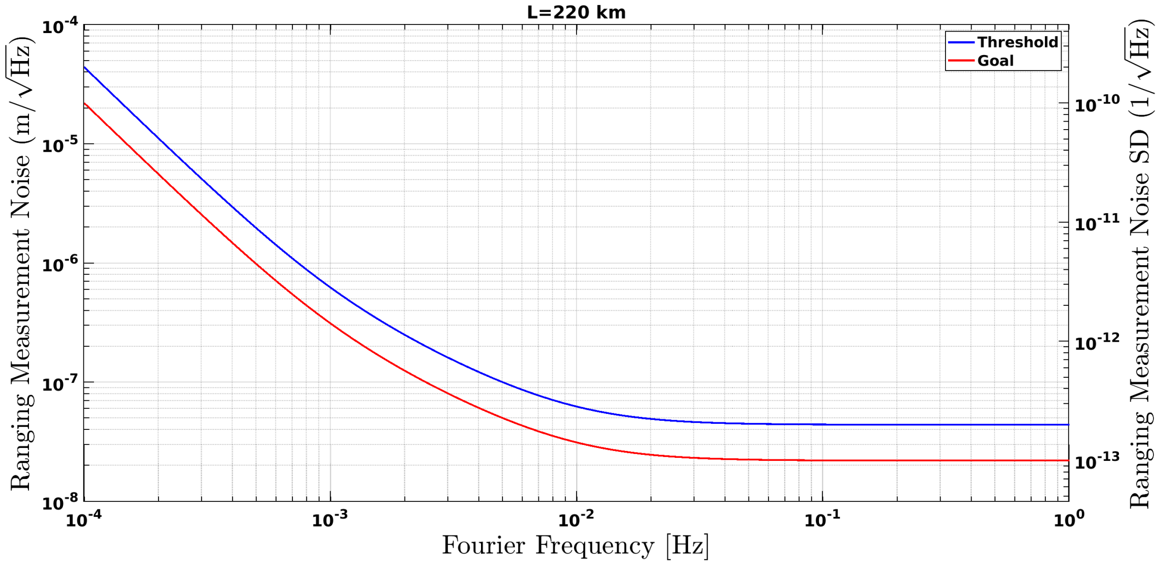
MicroSTAR accelerometers

MicroSTAR accelerometer is composed of the following units:

- Accelerometer Sensor Head (**ASH**), with the mechanical parts of the sensor, as the proof-mass and the electrode cage surrounding it;
- The Front-End Electronic Unit (**FEEU**), allowing to control the proof-mass and to provide the acceleration measurement. Digital FEEU is baselined for NGGM
- the Interface and Control Unit (**ICU**), with the software for controlling the FEEU/ASH and for interfacing with the spacecraft, including the power conversion functionalities



Instrument Performance Requirements - LTI

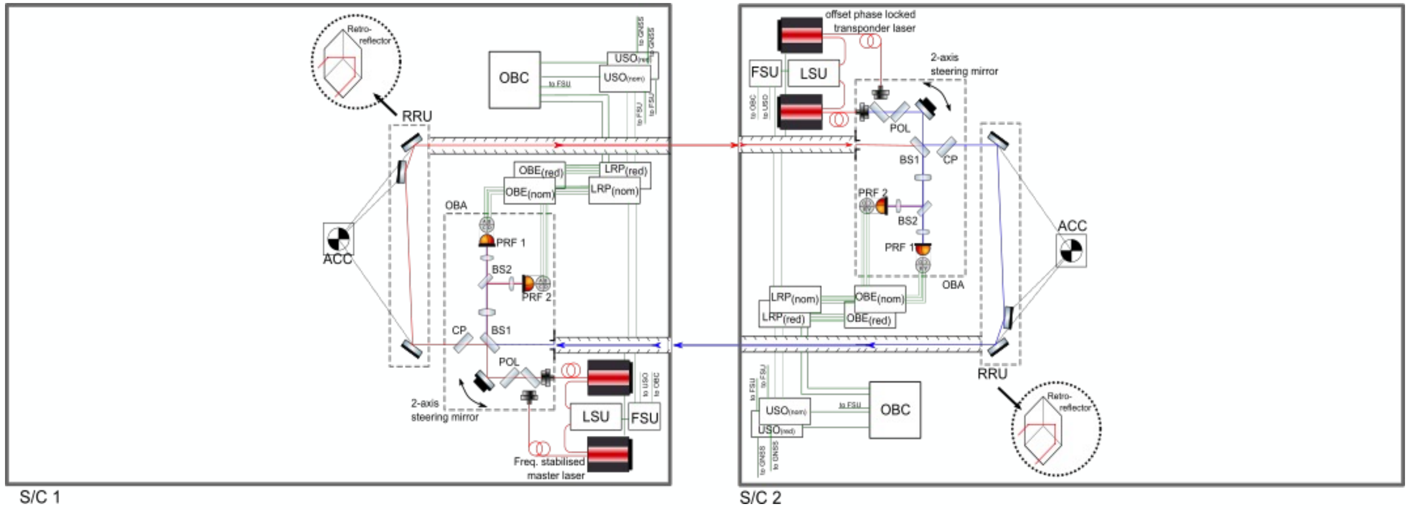


Amplitude spectral density of the goal and threshold requirements of the **inter-satellite distance variation** (as reference, the performance @ 220 km inter-satellite distance is given on the left vertical axis.

The LTI has been designed to meet the top-level ranging measurement noise requirement above.

The design is based on a trade-off between several former **ESA development activities** and the **Laser-Ranging Interferometer** (**LRI**), a US-German technology demonstrator embarked on GRACE-FO.

Laser Tracking Instrument LTI



Partially redundant LTI concept

The LTI consists of the following main units:

- An Instrument Control Unit (ICU) that includes a phasemeter (ICU), also called Laser Ranging Processor (LRP) in case of US contribution,
- A Laser Head Unit consisting of a narrow linewidth NPRO laser at 1064nm wavelength and with control electronics (LHU),
- A Laser Stabilization Unit (LSU), made of a very stable optical cavity (CAV) and associated coupling optics (optical arm) to stabilize the laser in frequency,
- An interferometer Optical Bench Assembly (OBA), to host the interferometer optics, with the associated Optical Bench Electronics (OBE),
- An off-axis Retro-Reflector Unit (RRU), to route the beam to the other spacecraft,
- A scale factor measurements system (SFMS) for the measurement of the absolute laser frequency, called scale factor unit (SFU/FSU): will be part of the ICU
- An Ultra Stable Oscillator (USO) for precise time-tagging, traded off against the UCXO

Propulsion subsystem

The selection and definition of the NGGM propulsion technologies and system architectures build on the heritage and lessons learned from the highly successful **GOCE** and **LISA Pathfinder** missions.

The propulsion system requirements fall into the following two categories:

- Spacecraft attitude and orbit control;
  - yaw, pitch and roll control,
  - correction of disturbance forces corss-track and radial to the orbital plane
- Atmospheric drag compensation;
  - compensation of atmospheric drag force tangential to the orbital plane (along the velocity vector).

Propulsion system requirements:

- Ultra-fine thrust control, resolution and low thrust noise.
  - 1μN thrust knowledge and control resolution

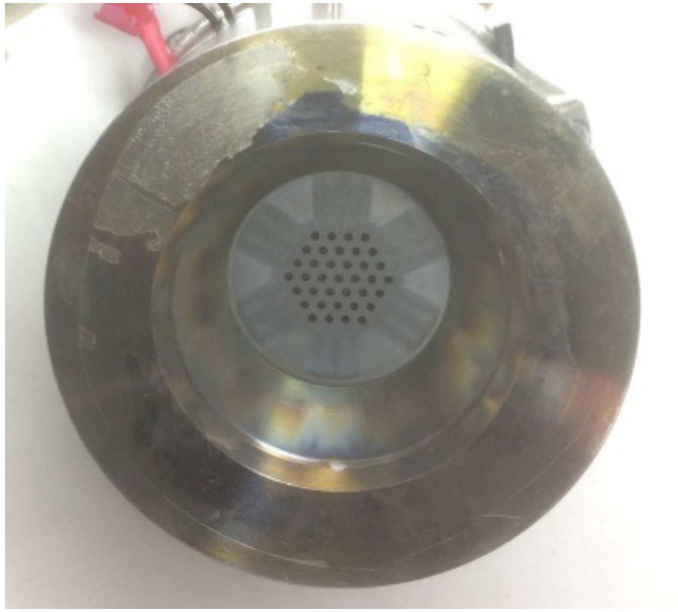
Thrust Noise PSD	**Frequency bandwidth**
$\leq 30\ \mu N/\sqrt{Hz}$	< 3 mHz
$\leq 1\ \mu N/\sqrt{Hz}$	$30\ mHz \leq f < 10$ Hz

- Wide throttling ranges

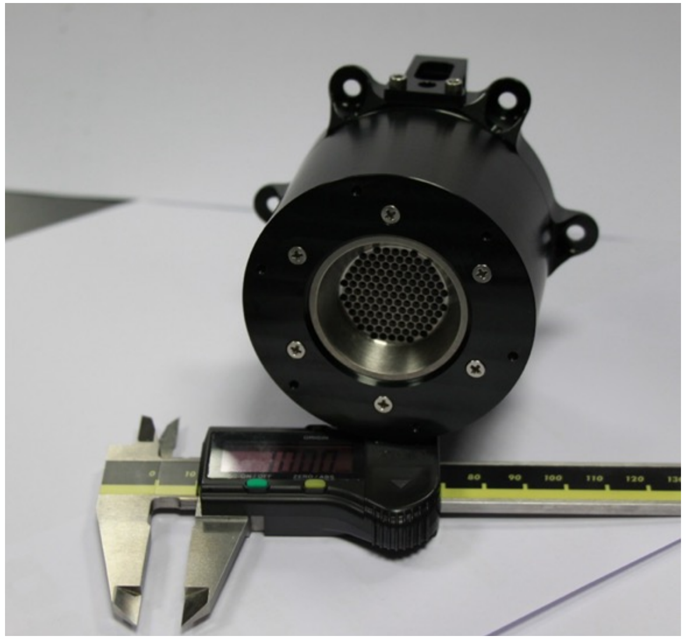
  1,000:1 for attitude, 50:1 for drag compensation.
- Rapid throttling capability (>100μN.s^{-1}) to compensate for localized atmospheric density variations and swirling at higher frequencies.
- High specific impulse for ADC requirements (of the order of 2500s) and total impulse capability (of the order of 100kNs) for the relatively large drag compensation requirements.
- Long lifetime (>70khrs) and resilience to residual atmospheric constituents, e.g. ATOX

Propulsion subsystem options and design status (1)

For the relatively high thrust and total impulse requirements of drag compensation, efforts are focusing on the application of small electric propulsion (EP) thruster technology, specifically the **miniaturized gridded ion thruster** technology developed in Europe



μRIT developed by
Ariane Group GmbH
(Germany).
Image courtesy of AGG

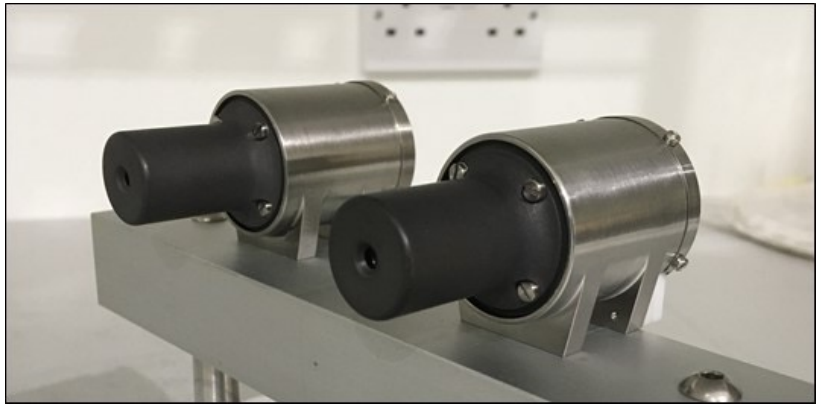


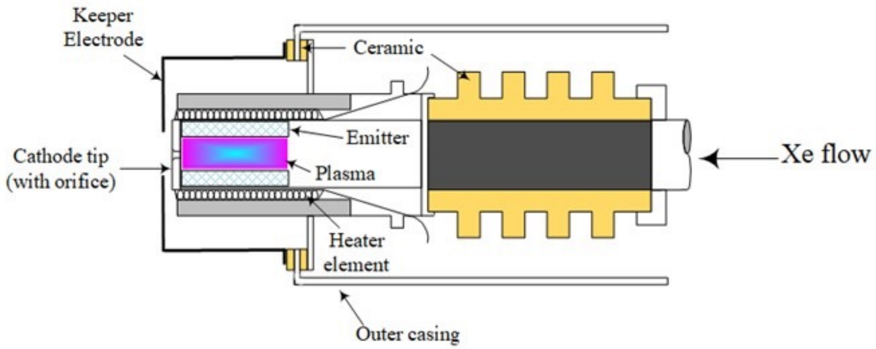
RIT-3.5 under
development by
Mars Space Ltd
(UK).
*Image courtesy
of MSL and
Transmit*

Propulsion subsystem options and design status (1)

The **neutralizer technologies** under consideration for NGGM range from propellent-less (often referred as **‘dry’ thermoionic** electron emitters, to conventional **hollow cathodes** and **RF neutralizer** technologies. The latter two technologies also employ *a flow of propellant* and therefore impact the overall specific impulse of the system, although they are of a *higher* technology readiness level (TRL) .

The hollow cathode technology successfully flown on the **GOCE mission** and is currently being developed for NGGM. Two examples of development neutralizers, immediately prior to diode emission, are presented below. These devices have been manufactured and have a diameter of 32mm x 66 mm long and a mass of <350 g, including a thermal isolating mounting bracket. The devices have an inherently high emission current capability and hence provide a large growth capability for subsequent constellations that could employ *multiple thrusters operating simultaneously .*





Courtesy by MSL (UK)

Propulsion subsystem options and design status (2)

For the relatively *low thrust* and *low total impulse* requirements of spacecraft attitude control, efforts are focusing on the application of more traditional, **proportional cold gas thruster** technology, such as the system flown on the LISA Pathfinder mission.

The *relatively low Isp capability* of this technology being offset by the lower total impulse requirements, power consumption and system complexity.

Propulsion subsystem options and design status for constellation evolution to lower orbits (discarded for P2)

As future NGGM constellations are flown at lower altitude orbits, the **thrust** and **total impulse** requirements (and hence propellant mass) of both the *attitude and drag compensation* functions will increase, eventually to the extent that cold gas thruster technology becomes unfeasible.

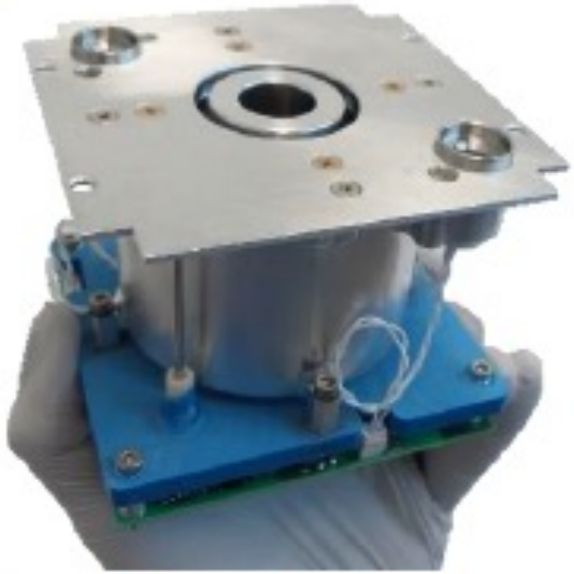
To address these longer-term needs clusters of mini-RITs can be envisaged sharing a common neutralizer to minimize system complexity.

Field emission electric propulsion (FEEP) thruster technology employing **indium** propellant is also being studied for the attitude control, where the even more rapid throttling capabilities offered by its reliance purely on electrical inputs, i.e. the performance constraints imposed by gaseous flow control techniques are eliminated, are of particular interest.

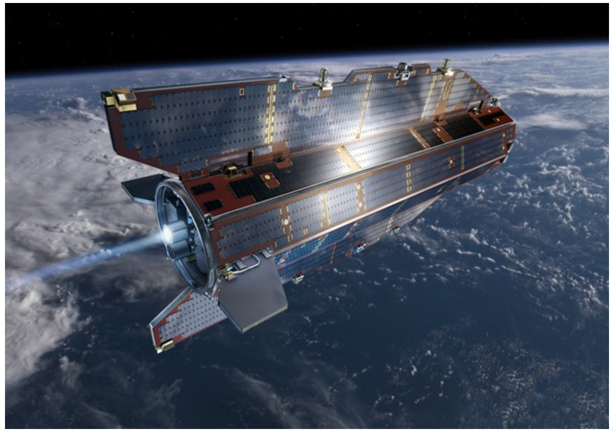
The Enpulsion indium propellant FEEP thruster unit, configured as a single 1U (100x100x100mm) standalone thruster module, is an example.
The indium propellant is stored as a **solid** in a small tank integral to the unit. When thrust is required the propellant is heated until it liquefies (approx. 160°C), at which point the liquid is drawn into the porous structure of the 'emitter crown', which includes a ring of porous metal 'needles'. A strong electric field, created by applying a high voltage between the emitter crown and a downstream surrounding electrode, forms Taylor cones of liquid indium at the apex of each needle. The enhanced electric filed at the cone tip results in the ionization and extraction of indium ions at high velocity.

Propulsion subsystem options and design status for constellation evolution to lower orbits (discarded for P2)

Courtesy by Enpulsion (AT)



Endurance test: 48000 hrs



ANY QUESTIONS ON NGGM?

Thanks!