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

Luca Massotti, Antonio Caiazzo, Bernardo Carnicero Dominguez

Clean Space Industrial Days, 13/10/2022, ESA-ESTEC

Mass change from gravity

- Since 2011 ESA and NASA explore potential cooperation on a possible cooperation on a future gravity mission under the umbrella of the Joint Programme Planning Group (JPPG) established between NASA and ESA for cooperation in the field of Earth Observation

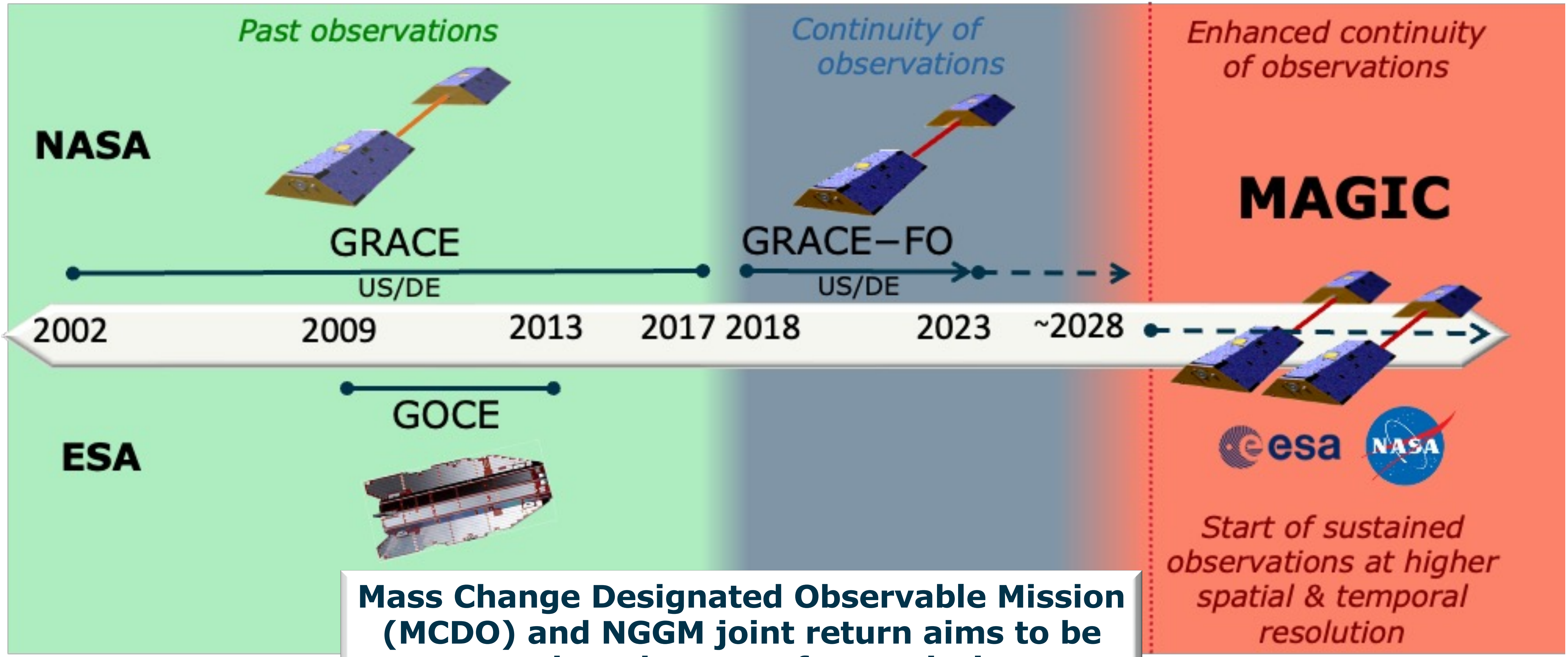
- In 2013 a NASA/ESA Interagency Gravity Science Working Group with US and European scientists produced a report indicating a possible future cooperation scenario for a mass change mission

- The two agencies articulated a strong interest in exploring joint future mission in writing: ESA letter February 15, 2019, NASA letter February 27, 2019 and NASA letter November 15, 2019.

- A joint Mission Requirements Document (MRD) v1 is established by the Ad-hoc Joint Science Study Team (AJSST) and the current Joint Mass Change Mission Expert Group (JMCMEG) with US and European scientists.

- The Mass change And Geosciences International Constellation (MAGIC) is foreseen as a joint ESA/NASA mission based on NASA's Mass Change Designated Observable (MCDO) and ESA's Next Generation Gravity Mission (NGGM).

ESA & NASA cooperation – MAGIC Joint Mission



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, with some potential ESA in-kind contributions.

- 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

MAGIC

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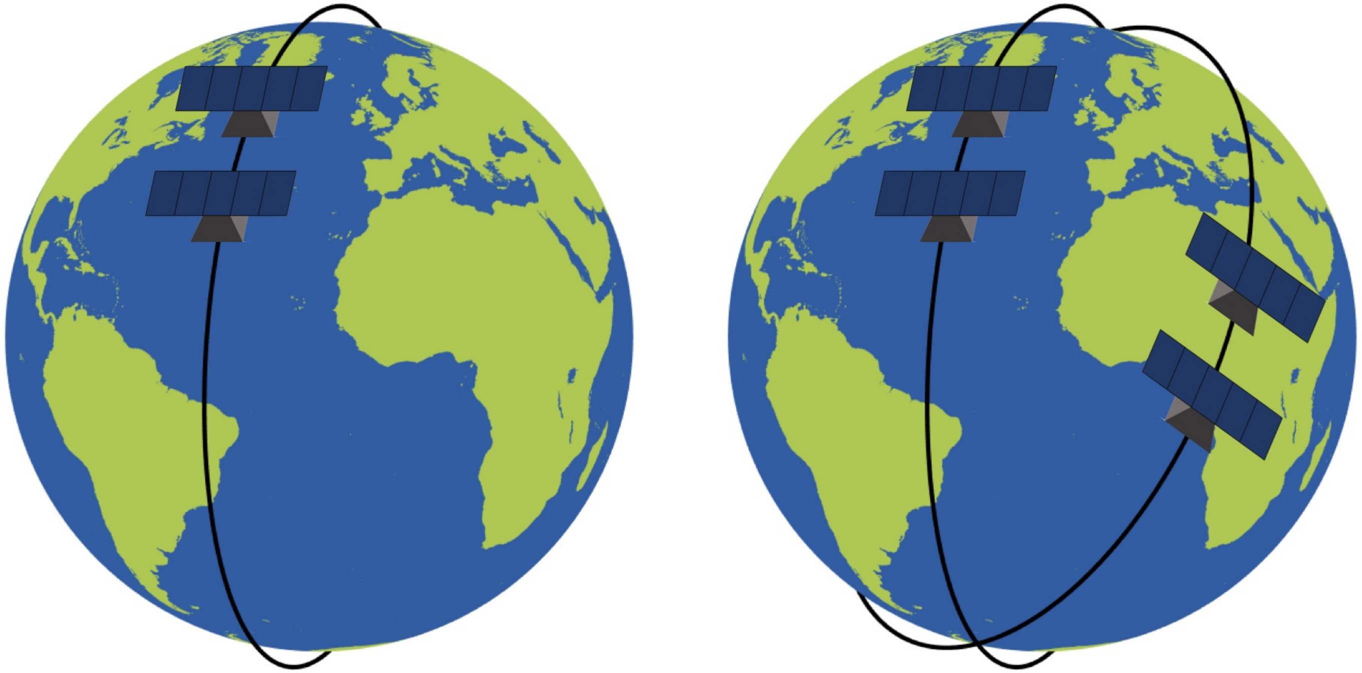
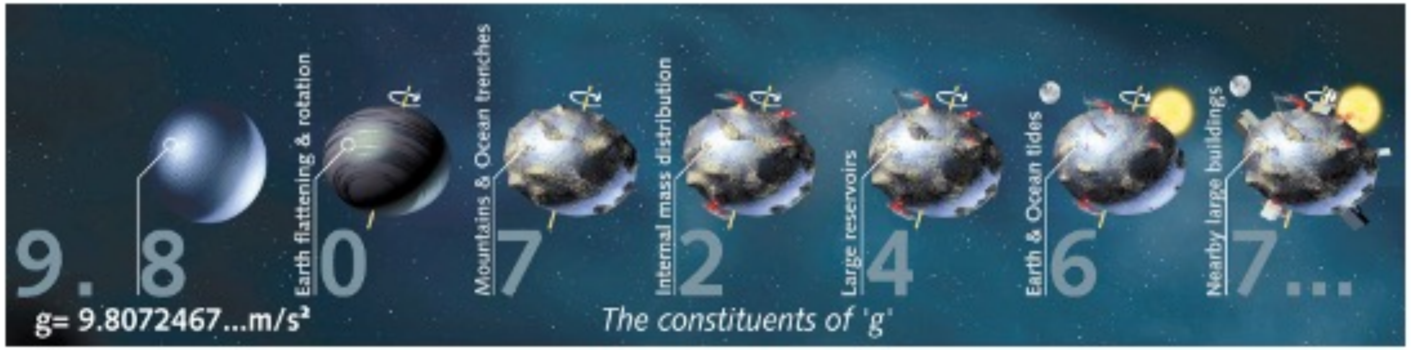


“In-line” “Bender”

Mass distribution and mass transport

Gravity reflects the **mass distribution** of the Earth



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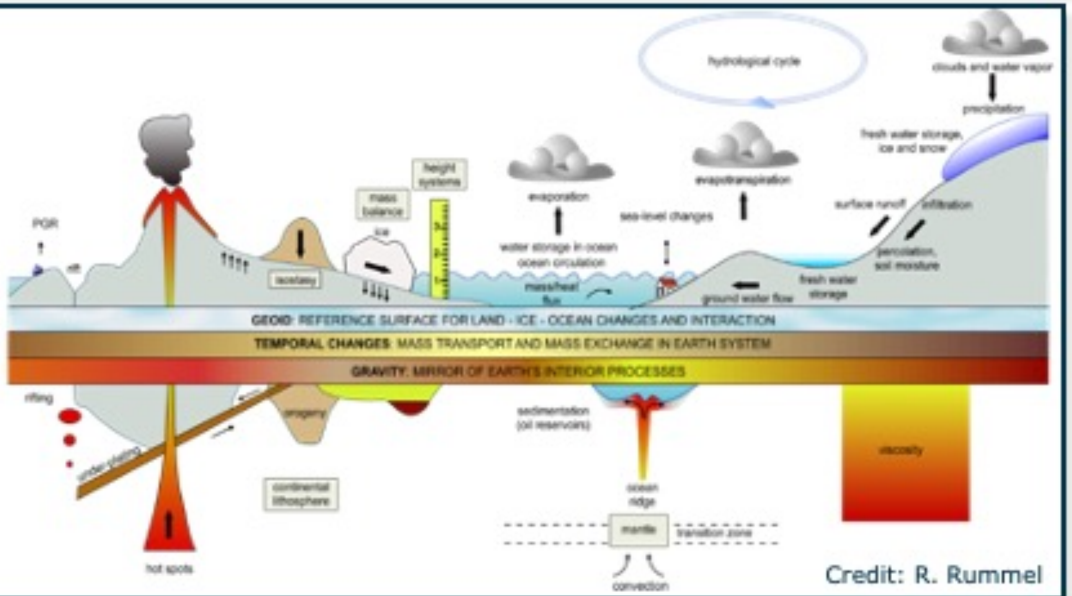
Mass RE-distribution (=transport) causes variations in the gravity field.

On short time scales, mass transport is mostly caused by water transport.



Credit: R. Rummel

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.

Background

More than a decade of ESA system and technology studies on the subject of the NGGM

Title	Epoch	Prime / Main SubCos	Purpose and main achievements
Laser Doppler Interferometry Mission for Earth's Gravity Field	2004 - 2005	TASI INRIM	System and instrument concept study
Laser interferometry high precision tracking for LEO	2007-2009	TASI INRIM	Proof of concept of the measurement principle (retro-reflector concept) • Laser interferometer prototype • Angular/lateral metrology breadboard • Beam Steering Mechanism breadboard (CCN 1)
System support to laser interferometry tracking technology development for gravity field monitoring	2007-2010	TASI Turin Polytechnic	System concepts • Investigation on electric propulsion technology and first tests of mini-RIT on NanoBalance facility (CCN1, 2)
Assessment of a Next Generation Mission for Monitoring the Variations of Earth's Gravity	2009 - 2012	TASI/ADS (DE)	System definition study • Extended Study of the "Pendulum" Option (CCN1)
Next Generation Gravity Mission: AOCS Solutions and Technologies	2012-2014	TASI Turin Polytechnic	Control design and algorithm study • 4-tier control design (formation/orbit control/drag-free control/attitude control)
Miniaturised Gridded Ion Engine Breadboarding and Testing for Future Earth Observation Missions	2013-2019	ASL(D) TASI subCo	Wide thrust range [50µN to 2500µN] mini ion engine for NGGM drag-free and attitude control • Thruster optics and 2000h life test
Assessment of Satellite Constellations for Monitoring the Variations in Earth's Gravity Field	2013-2019	Munich Uni. TASI consultant	Geophysical applications and anti-aliasing (Earth tides)
High Stability Laser (HSL1 & HSL2)	2011-2019	STI FHG ILT, NPL,ADS(D)	High stability laser with fibre amplifier for interferometric earth gravity measurements • Laser source & driver • Laser Stabilization Unit (Cavity)
Consolidation of the System Concept For the Next Generation Gravity Mission	2015-2020	TASI STI	System study update • Trade-off of Transponder and retroreflector concepts
Development of the Lateral Angular Metrology for NGGM	2017-2019	TASI INRIM	APMS/LAME breadboard
Development of an Acceleration Insensitive, Thermal Noise Mitigated OSRC Engineering Model	2017-2019	ADS(D) STI, NPL, Sodern …	Optical Stabilizing Reference Cavity breadboard
Proof-of-concept test for retroreflector interferometer for NGGM	2019-ongoing	STI, TASI, INRIM	Optical bench design and breadboard tests (retroreflector concept)

Mission recap and measurement performance estimation

Two satellite pairs in '**Bender formation**'

- P1 pair near-polar + P2 pair mid-inclination
- Spacecraft design compatible with either pair
- Pearl-string formation, 220 km c.a. sat-to-sat distance

8-yr (4-yr thresh.) + 6 months comm. lifetime at constant altitude

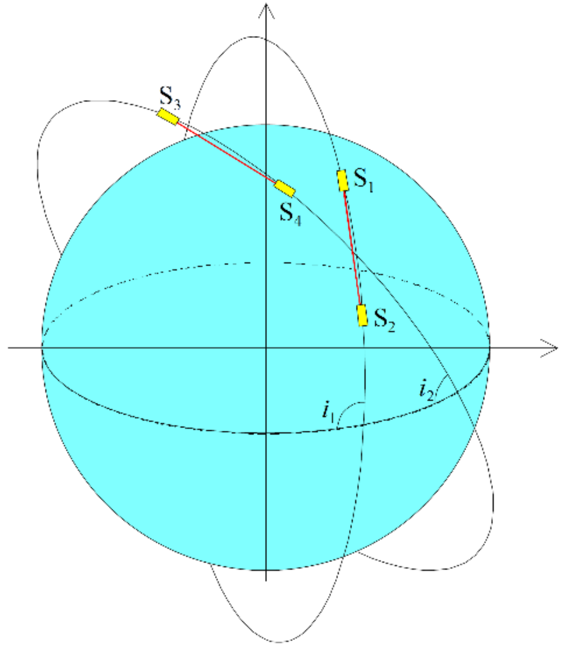
- ~400 km: minimum altitude compatible with resources

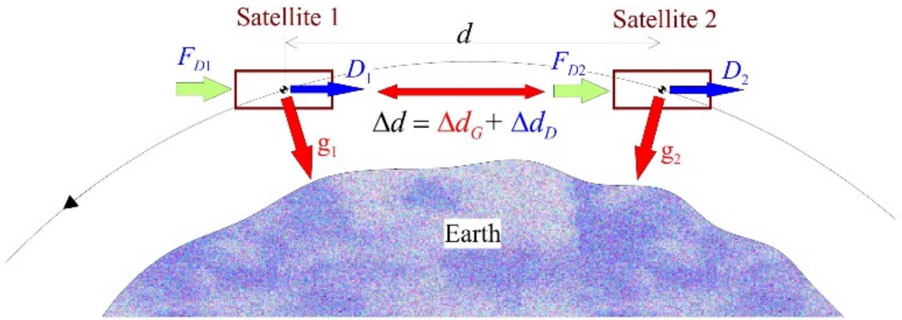
1-mm accuracy geoid

- @ 500 km spatial resolution in 3 days
- @ 150 km spatial resolution in 10 days

Laser ranging + accelerometry + POD (GNSS)

- Instrument performance budgets provided *as error PSD*
- Mission performance: *formal error propagation to SH*





Orbit design and Science Support study to MAGIC

Candidate orbit scenarios

Orbit ID	P1 Altitude [km]	P1 Inclination [deg]	P2 Altitude [km]	P2 Inclination [deg]
5d_397_70	388	89	397	70
3d_409_70	388	89	409	70
3d_402_65	388	89	402	65

- P1 is planned to drift (natural orbit decay)
- P2 will fly at its nominal initial altitude

Each orbit ID has a first part dedicated to highlight the length of the sub-weekly sub-cycle with high homogeneity (i.e., “3d” for 3 days). 5 days sub-cycle scenarios have the possibility to nearly match the same sub-cycle of the polar pair.

The JMCMEG and ESA MAGIC Phase A Science Support Study concluded that **inclined pair** orbits with **3 days sub-cycles** are beneficial for Near Real Time (NRT) products and emergency applications, since a homogeneous ground-track sampling of the inclined pair is essential for such services.

The ground-track **homogeneity for monthly solution** has been proven to be less critical due to the sufficiently dense global sampling achieved in 30-day periods.

System design status and Phase A studies

The **NGGM Phase A** is currently reaching the **Preliminary Requirementd Review** of the satellite design proposed by two consortia in competition.

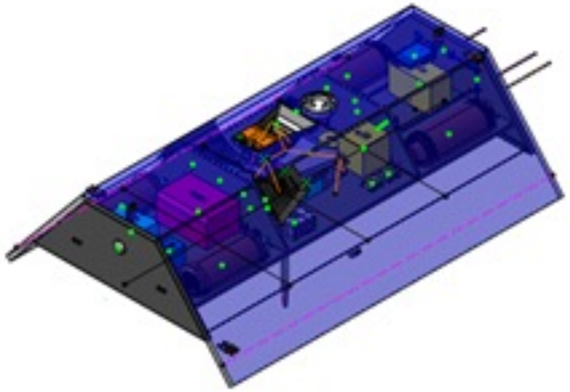
Each satellite is embarking 2 or 3 ultra-fine **accelerometers** (for redundancy and enhanced on board calibration capability) and a **Laser Tracking Instrument** (**LTI**), i.e. a Michelson interferometer in transponder configuration.

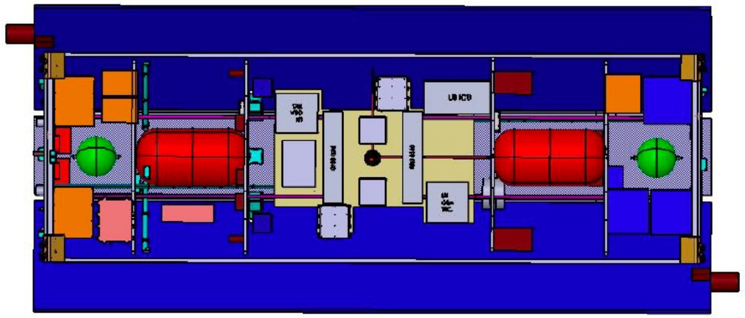
The proposed designs rely either in a **mono-** or **bi- propellant** solution to enable the complex drag-free, formation and attitude control system (i.e. DFAOCS), allowing the satellites to be tree axis stabilized and nadir pointing, to track and fine pointing to each other, and to implement drag compensation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

The actuators devoted to *lateral/cross track* and *attitude controls* are **proportional cold gas thrusters**, and those devoted to *drag compensation* are based on **electric propulsion**, aiming to cover a lifetime up to 8 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**, performed by Finite Element Analyses.

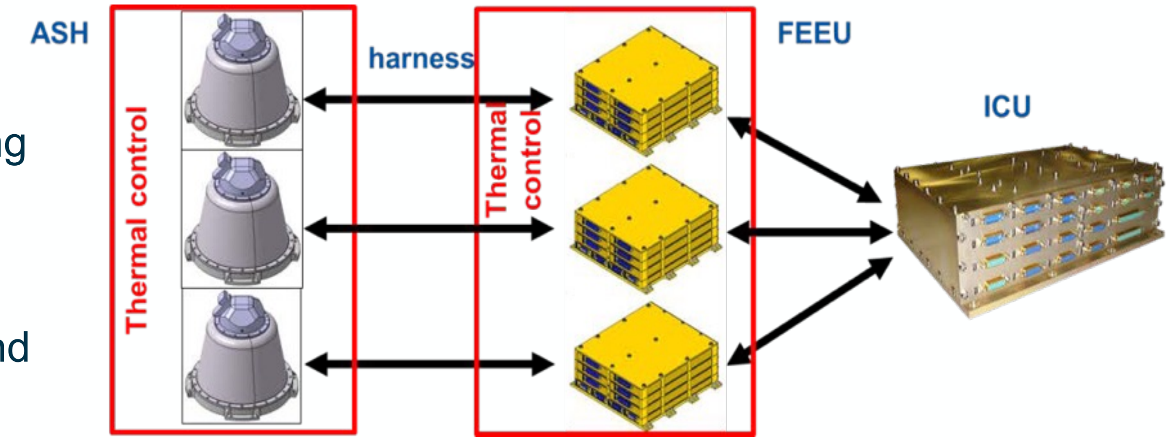
MicroSTAR accelerometers

MicroSTAR accelerometer is composed of the following units:

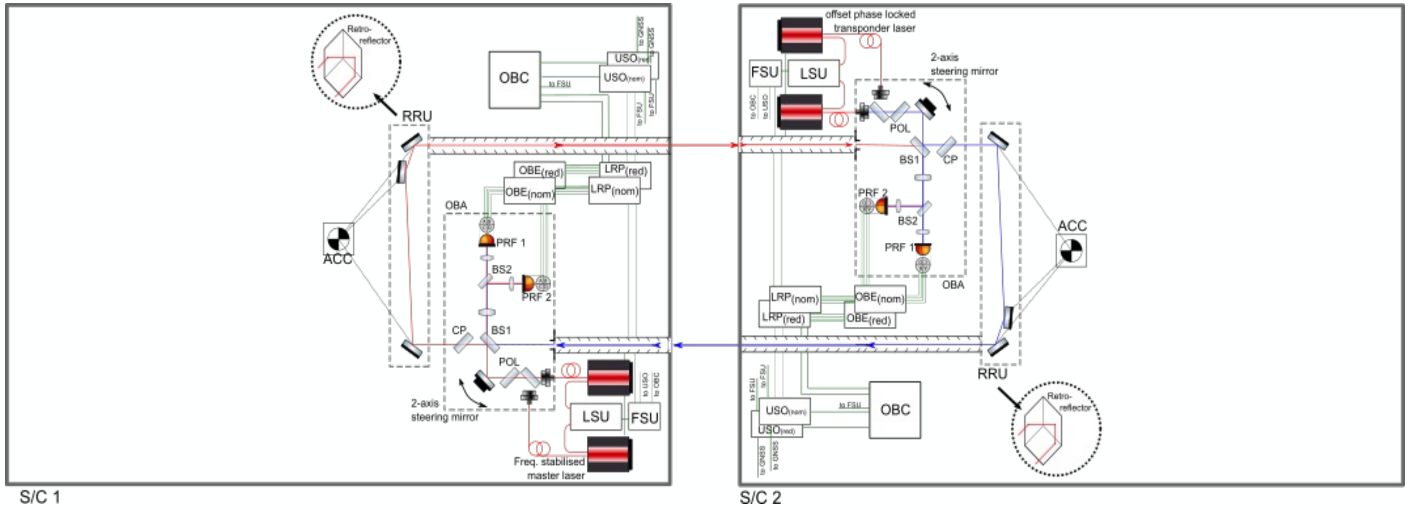
- Accelerometer Sensor Head (ASH), with the mechanical parts of the sensor, as the proof-mass and the electrode cage surrounding it;

- The Front-End Electronic Unit (**FEEU**), with the thermal sensitive analog and digital functions allowing to control the proof-mass and to provide the acceleration measurement. In case of *an analog controlled unit*, the FEEU shall also contain the analog PID controllers of the proof-mass, and the digital interface to the spacecraft On-Board Computer (OBC);

- In case of a *digital FEEU*: 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 for both the analog and digitally controlled designs; and
- In case of an *analog FEEU*: the Power Control Unit (**PCU**), with the power conversion functionalities.



Laser Tracking Instrument LTI



Partially redundant LTI concept with potential US contribution

On ESA side, technology risk-retirement activities have been started to reach the TRL 6 for the full LTI at the end of the Phase B

The LTI consists of the following main units:

- An Instrument Control Unit 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 (optics 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),
- An Ultra Stable Oscillator (USO) for precise time-tagging.

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 challenges:

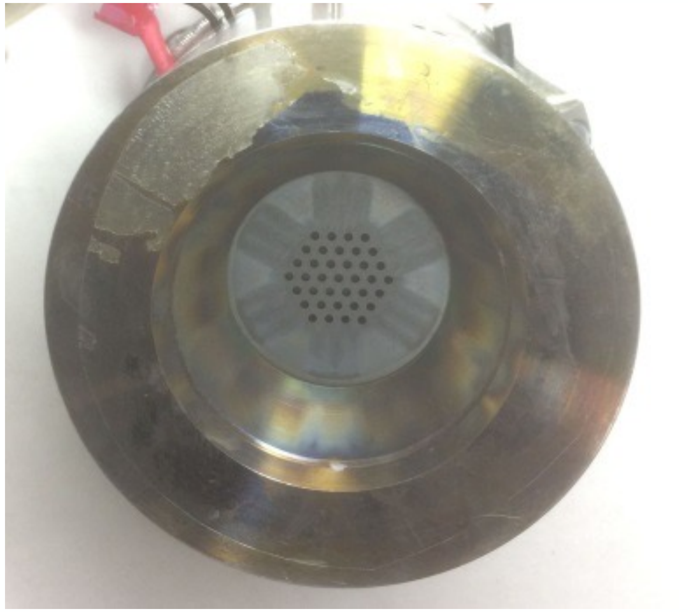
- Ultra-fine thrust control, resolution and extremely low thrust noise.
  - 1μN thrust knowledge and control resolution
  - Thrust Noise PSD / Frequency bandwidth

Thrust Noise PSD	Frequency bandwidth
≤ 30 μN/√Hz	< 3 mHz
≤ 1 μN/√Hz	30 mHz ≤ f < 10 Hz

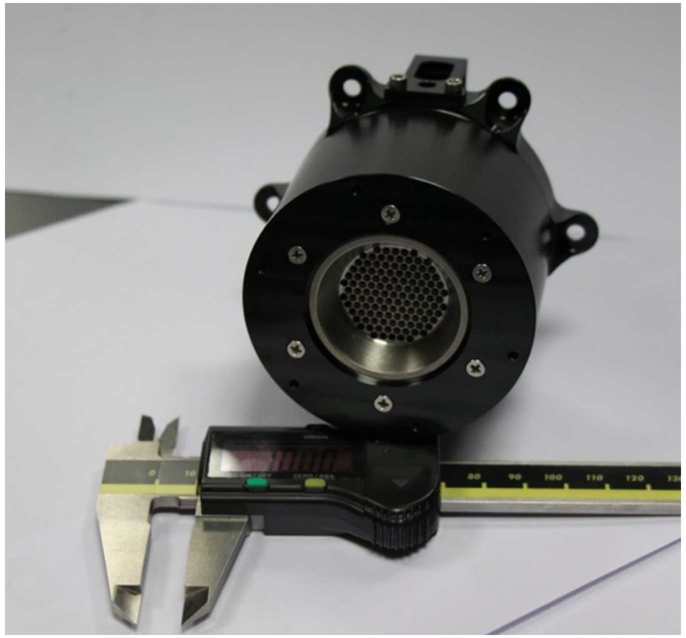
- Wide throttling ranges
  1,000:1 for attitude, 50:1 for drag compensation.
- Rapid throttling capability (>100μN.s^{-1}) to compensate for localized atmospheric density variations and swirling at higher frequencies.
- High specific impulse for ADC requirements (of the order of 2500s) and total impulse 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 **miniature gridded ion thruster** technology developed in Europe



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

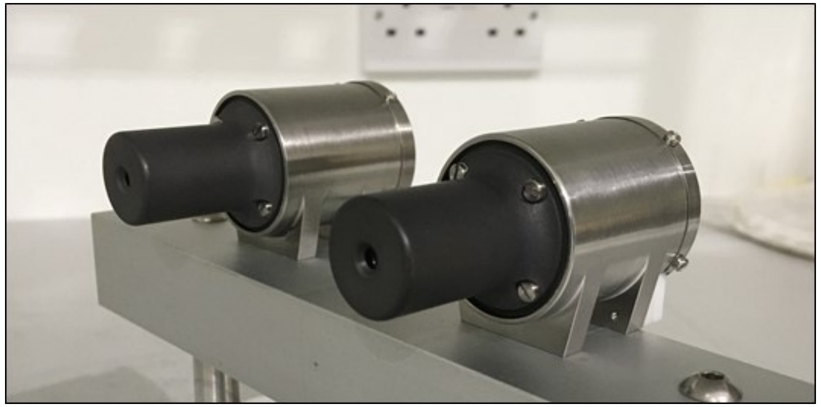


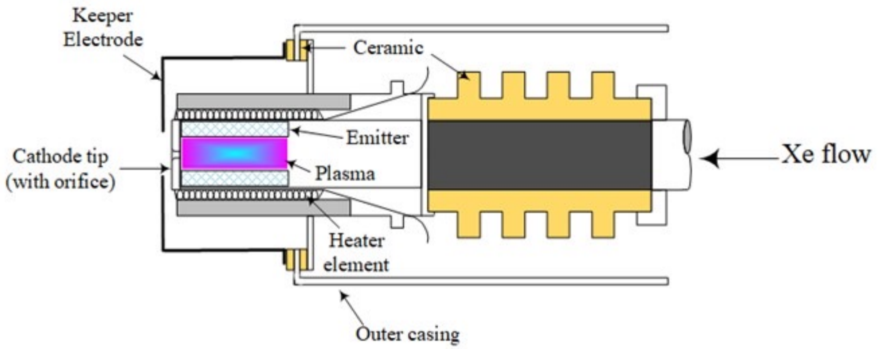
RIT-3.5 under development by Mars Space Ltd (UK).
Image courtesy of MSL and Transmit

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 (3)

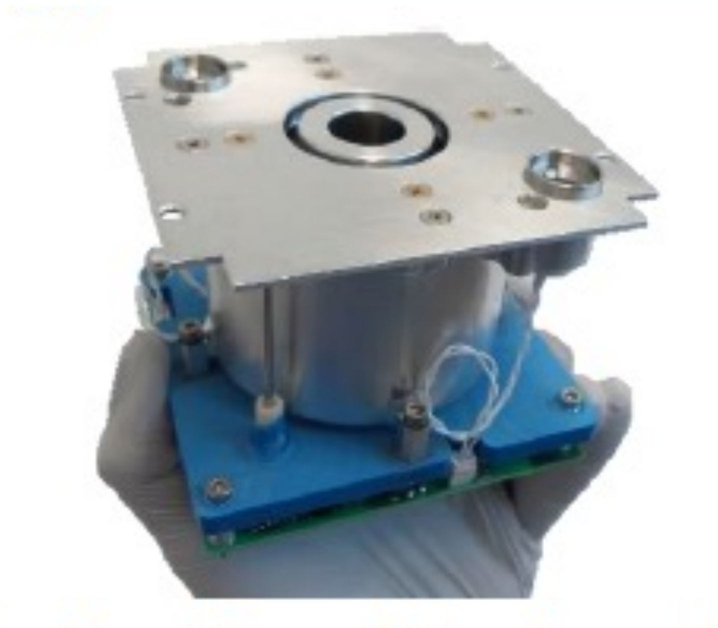
As future NGGM constellations are flown at lower altitude orbits, the **thrust** and **total impulse** requirements (and hence propellant mass) of both the *attitude and drag compensation* functions will increase, eventually to the extent that cold gas thruster technology becomes unfeasible.

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 (3)



Endurance test: > 42000 hrs

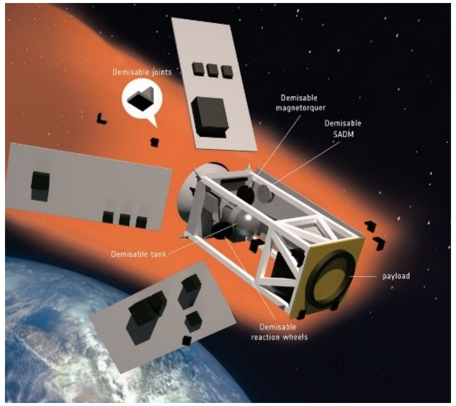
Courtesy by Enpulsion (AT)

Design4Demise

Preliminary re-entry simulations have been performed using DRAMA and following the DIVE guidelines.

Current results in terms of demisability:

- Casualty risk margin is low → it leads to the idea of using more detailed tools for re-entry simulations, in order to derive a deeper understanding of the critical elements
- Critical elements mainly identified in the payload and platform (e.g. propulsion tanks, STR baffle design) → need for demisable solutions
- A combination of D4D and D4C is definitely required to become compliant → the benefits of demise techniques and containment techniques need to be assessed, to understands which solution is optimal for each of the components/subsystems



Design4Demise

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Current results in terms of demisability:

- Limit design impact by avoiding unnecessary constraints on the design → avoid an increasing in mass and volume
- Validate separation approach → e.g. need for tests to validate separation and fragmentation conditions (e.g. radiator tiles, SA panels)
- Validate containment approach for some elements and identify design solutions → need for on-ground tests
- Some potential solutions depend on pre-developments → need to assess the current status of demisable technologies
- A clear go for the solutions that need to be baselined now is needed in Phase A.
- Requirements to subsystems need to be established now → flow down from the casualty risk requirements at system level

NGGM

- ✓ NGGM @ ESA: ***Mission of Opportunity*** candidate
- ✓ ESA-NASA: intended international cooperation for NGGM

ANY QUESTIONS?

Thanks!