International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ESA Activities and Perspectives on Laser Tracking Instrument for NGGM/MAGIC Mission

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127776X · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2689654

ESA Activities and Perspectives on Laser Tracking Instrument for NGGM/MAGIC Mission

Olivier Carraz *[a], Luca Massotti [b], Aaron Strangfeld [b], Kai-Cristian Voss [c], Kolja Nicklaus [c], Gerhard Heinzel [d], Vitali Müller [d], Arnaud Heliere [b], Anne Ferri [c], Marina Kaufer [c], Johanna Flock [c], Mark Herding [c], Bailey Allen Curzadd [c], Markus Weller [c], Bernardo Carnicero Dominguez [b]
[a]RHEA for ESA, European Space Agency, ESA/ESTEC Keplerlaan 1, PO Box 299 NL-2200 AG Noordwijk, The Netherlands; [b]European Space Agency, ESA/ESTEC Keplerlaan 1, PO Box 299 NL-2200 AG Noordwijk, The Netherlands; [c]SpaceTech GmbH, Seelbachstraße 13, D-88090 Immenstaad, Germany; [d]Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institut) and Institut for Gravitational Physics, Leibniz Universität Hannover, Callinstraße 38, D-30167 Hannover, Germany

ABSTRACT

In the past twenty years, gravimetry missions have demonstrated a unique capability to monitor not only major climate-related changes of the Earth directly from space like quantifying the melting of large glaciers and ice sheets, global sea level rise, continental draught, major flooding events, but also effects of large earthquakes and tsunamis. To respond to the increasing demand of the user community for sustained mass change observations at higher spatial and temporal resolution, ESA and NASA are coordinating their activities and harmonizing their cooperation scenarios in an implementation framework, called MAGIC (MAss change and Geosciences International Constellation). This builds upon the heritage from the GOCE, GRACE and GRACE-FO missions as well as on-going pre-developments on laser–ranging interferometry in preparation for the Next Generation Gravity Mission (NGGM). The new Laser Tracking Instrument (LTI) is being developed by the industrial lead SpaceTech GmbH with scientific lead at Albert Einstein Institute under contract to ESA. To consolidate the performance of the mission concept and the technological and programmatic feasibility of the entire mission, technology risk-retirement activities will be conducted to achieve Technology Readiness Level (TRL) 5/6 for the LTI at the end of Phase B1 and TRL 6 at the Instrument Unit level at the end of Phase A.

Keywords: Laser interferometry, Laser ranging, Gravity, NGGM

1. INTRODUCTION

In the past twenty years, gravimetry missions have demonstrated a unique capability to monitor not only major climate-related changes of the Earth directly from space - quantifying the melt of large glaciers and ice sheets, global sea level rise, continental draught, major flooding events, but also effects of large earthquakes and tsunamis. Adding to fundamental knowledge about the Earth, NGGM [1] will also provide essential climate variables (ECV) for ground water, mass balance of ice sheets and glaciers as well as heat and mass transport, as already demonstrated by successful missions like GOCE [2], GRACE [3] and GRACE Follow-On (GRACE-FO) [4].

To respond to the increasing demand of the user community for sustained mass change observations at higher spatial and temporal resolution [5], ESA and NASA are currently coordinating their activities and are harmonizing their cooperation scenarios in an implementation framework, called MAGIC (MAss change and Geosciences International Constellation).

Programmatic discussions between ESA and NASA have already started in early 2020 to identify the most suitable scenario for the implementation of the mission, with the aim of leveraging key technological developments as well as technical and scientific expertise available in Europe and the US. This effort builds upon the heritage of GOCE, GRACE and GRACE-FO missions as well as on-going pre-developments on laser–ranging interferometry in preparation for NGGM.

The new Laser Tracking Instrument (LTI) is being developed in a so-called LTI pre-development activity under contract to ESA by the industrial lead SpaceTech GmbH in Immenstaad and the scientific lead Albert Einstein Institute in Hannover. The now converging design is based on a trade-off between several previous ESA development activities and the Laser-

*olivier.carraz@ext.esa.int; phone +31 71 565 3714; esa.int

Ranging Interferometer (LRI), a US-GER technology demonstrator on GRACE-FO. The LTI consists of the following main units:

- An Instrument Control Unit (ICU) that includes phasemeter, processor and electronics
- A Laser Head Unit (LHU) consisting of a narrow linewidth Non-Planar Ring Oscillator (NPRO) laser at 1064nm wavelength with control electronics,
- A Laser Stabilisation Unit (LSU), made of a very stable optical cavity and associated coupling optics (optics arm)
- An interferometer Optical Bench Assembly (OBA),
- An off-axis Retroreflector Unit (RRU).

The objective of the LTI pre-development activity is to design, manufacture and test all the units that make up the LTI in a representative environment to reach TRL 6 (Engineering Model) at the end of the Phase A System Studies. Subsequent procurement activities will include the assembly and testing of a full instrument demonstrator for functional and performance verification with the aim of achieving TRL5/6 for the LTI at the end of Phase B1.

The description of the overall pre-development activity is presented, with particular emphasis on the redundancy concept and functionality of the individual units.

2. NGGM TOP LEVEL MISSION AND LTI REQUIREMENTS

The main objective of the NGGM mission is defined in the Mission Requirements Document (MRD) [6] and is the long-term monitoring of the temporal variations of Earth's gravity field at high resolution in time (3 days) and space (100 km). The objectives of the mission are:

- to measure and monitor the mass change and improve current estimations of ground-water storage, soil moisture, water balance closure, global change impacts on water cycle, to provide the capability to raise extreme events warning (e.g. drought, flood).
- to measure and monitor the cryosphere mass balance, the global and regional sea level, the Glacial Isostatic Adjustment (GIA), including the estimation of mass changes for ice sheet and glaciers.
- to provide mass and sea level change and heat estimates for oceanography to improve tidal and ocean circulation models. Such information will also serve as critical input to operational oceanography and marine forecasting services as well as sea ice monitoring in the polar oceans.
- to measure and monitor the mass change on Earth's deep interior properties and dynamics, Earth's crust under internal or external forcing, including observations for improvements in natural resources exploitation and assessment of effects of geohazards (e.g. earthquakes, tsunamis and volcanic activities).
- to measure and monitor the mass change and its trends for climate change applications.
- to provide measurements of mass change for ground-water storage and global change impact on water cycle applications for extreme events warnings and soil moisture.
- to provide measurements of mass change for estimations of cryosphere mass changes including ice sheet and glaciers.
- to support monitoring applications of geo-hazards (including moment magnitude (Mw) 8 earthquakes and Mw 7 as target) over few hundred kilometers areas and deep interior properties and dynamics over large spatial scales (e.g. 6.000 km) for estimating body tides at millimeter accuracy.
- to provide measurements of thermosphere neutral density and wind.
- to provide new atmospheric parameters to separate atmospheric signals from the mass variation measurements.

The baseline mission scenario to achieve these goals is a satellite mission consisting of two pairs of satellites in a so-called Bender configuration [5][7]. One pair flies in a polar orbit with an inclination of about 90°, a second pair flies with an inclination of 65-75°, at an altitude between 395 km and 415 km and with a distance of about 220 km between the two satellites of each pair. The heterodyne laser interferometer is foreseen as the main instrument. The top-level requirements for the laser interferometer were derived as part of the study: Table 1 lists the key mission parameters, the expected satellite environment and the main LTI performance requirements that form the basis for the mission design.

Table 1. NGGM mission parameters and requirements relevant for the LTI

Parameter	Value	Comment
Mission parameters and LTI requirements		
Inter-satellite distance	220 km	
Orbit height	395 km to 415 km	
Inter-satellite ranging noise	Goal: $\sigma_d = 1 \times 10^{-13}\ \mathrm{Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$ Threshold: $\sigma_d = 2 \times 10^{-13}\ \mathrm{Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$	To have the amplitude spectral density σ_d expressed in range units $[\mathrm{m\ Hz}^{-\frac{1}{2}}]$, the goal and threshold requirements shall be multiplied by the inter-satellite distance (see Fig. 1). $\mathrm{NSF}(f) = \sqrt{1+\left(\frac{10\mathrm{mHz}}{f}\right)^2}\sqrt{1+\left(\frac{1\mathrm{mHz}}{f}\right)^2}$
Mission duration	4 years to 8 years	
Satellite environment		
Thermal noise around the LTI units	ICU: $0.3\ \mathrm{K\ Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$ LSU: $0.1\ \mathrm{K\ Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$ OBA: $0.3\ \mathrm{K\ Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$ RRU: $0.1\ \mathrm{K\ Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$	
Satellite pointing error in science mode	20 µrad without steering mirror 3 mrad with steering mirror	Over 1 orbit
Satellite pointing noise	$\tilde{\theta}, \tilde{\psi} < 2\ \mu\mathrm{rad\ Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$	
LTI unit requirements/performance		
Laser wavelength	1064 nm	
Laser frequency noise	Goal: $20\ \mathrm{Hz\ Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$ Threshold:	

	$40\ \mathrm{Hz}\ \mathrm{Hz}^{-\frac{1}{2}} \times \mathrm{NSF}(f)$	

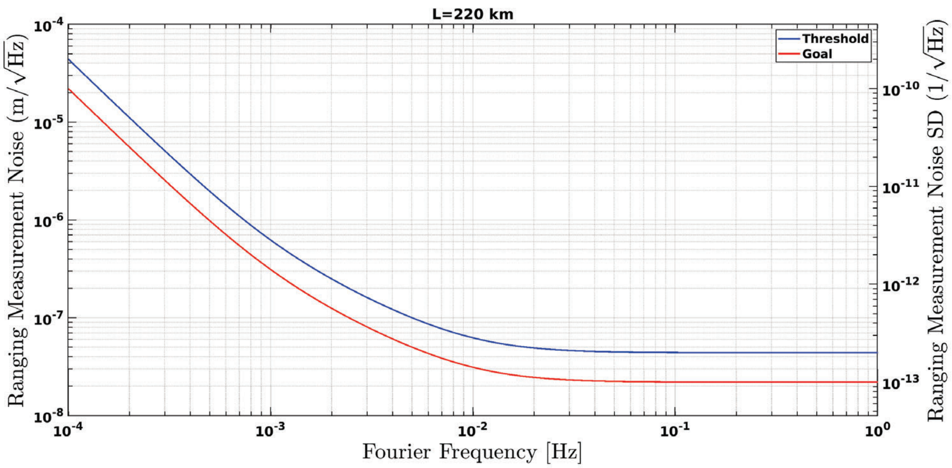
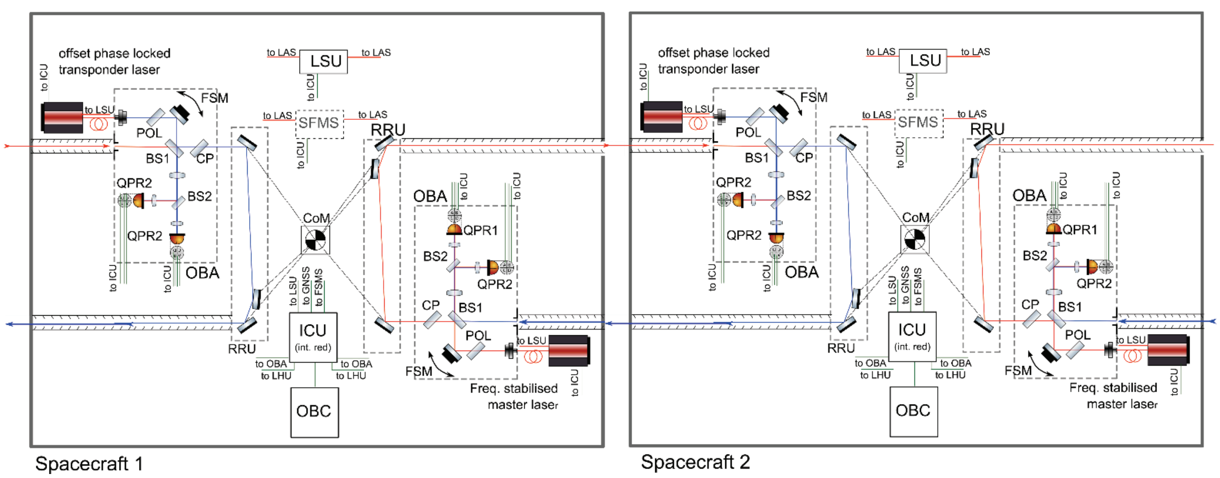


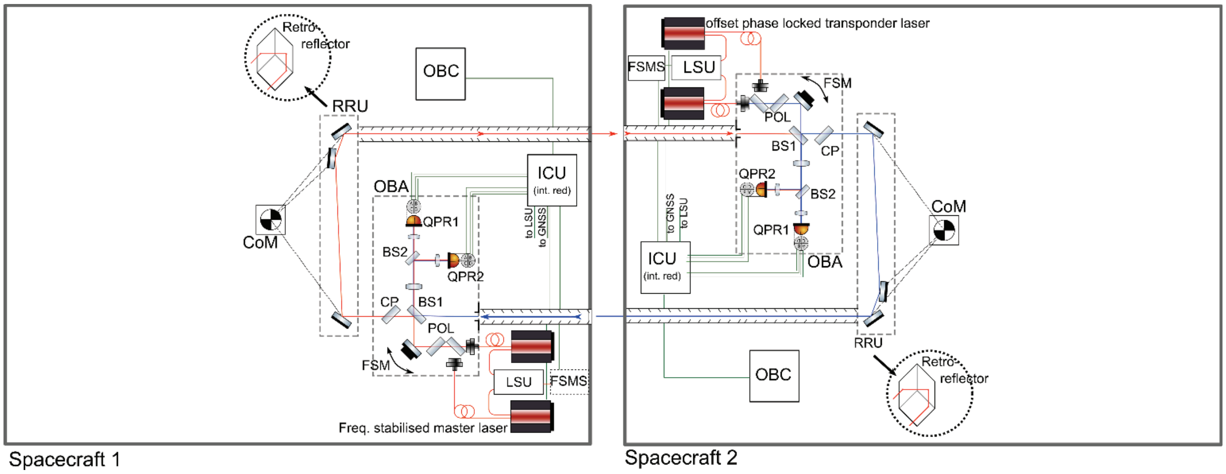
Figure 1. Amplitude spectral density of the goal (red) and threshold requirements (blue) of the inter-satellite distance variation. As reference, the performance at L=220 km inter-satellite distance is given on the left vertical axis.

3. LTI IMPLEMENTATION SCHEMES: OFF-AXIS TRANSPONDER CONCEPT WITH FULL AND PARTIAL REDUNDANCY

At the beginning of the LTI pre-development, two concepts were initially studied, namely the off-axis transponder scheme as applied in GRACE-FO [8] and the enhanced retroreflector scheme, already investigated in former NGGM studies [9][10]. At the end of the first part of the activity, in conjunction with the Phase A studies, it was agreed to select the transponder concept. However, two options are still under study, which is related to the redundancy philosophy.
The two redundancy scheme concepts are depicted in Figure 2.



(a)



(b)

Figure 2. Concept of the laser tracking instrument in off-axis transponder configuration: (a) with full redundancy; (b) with partial redundancy. Figure taken from [12]

In the transponder LTI, the laser head on satellite 1 is locked to the cavity ("Master Laser"), providing 25 mW of single mode single frequency signal to the optical bench. On the second spacecraft, the laser frequency is offset-looked to the first laser by some MHz ("Slave Laser").

The optical setup on the OBA routes the beam from the fibre collimator to a beam splitter (BS), which splits the beam into one part that is sent to the other spacecraft (via the retroreflector) and one part that is guided to the quadrant photoreceivers (QPR). The imaging optics in front of the photoreceivers image the exit of the fibre collimator and the OBA entrance aperture onto the

photoreceivers, thereby minimizing the effect of beam walk due to beam angle changes as well as phase errors due to diffraction effects of the baffles and entrance aperture. The compensation plate (CP) minimizes the ranging noise introduced by the beam splitter (BS) under pointing noise. Only the BS and CP are in the direct measurements path, in which any path length noise (thermally or pointing driven) directly couples into the ranging performance. The noise of all other optical elements (from fibres to BS and BS to photoreceivers) is strongly suppressed due to common-mode effects.

The received beam from the other spacecraft with a power of about 1-3 nW enters the optical bench and is reflected at the beam splitter and imaged onto the photoreceivers.

The heterodyne signal (the beat between the local oscillator and the received beam from the other spacecraft) is read out from the 4 elements of the photoreceivers, preamplified and processed in the phasemeter of the Instrument Control Unit (ICU). The phase variation delivers the relative distance change of the spacecraft to each other, which is the main science signal. The phase difference of the individual quadrant delivers the pointing information to the other spacecraft, used to drive the attitude control system of the satellite to µrad accuracy.

The off-axis retroreflector (RR) with its vertex in the Centre of Mass (CoM) of the spacecraft routes the beam around the CoM, thereby enabling the distance measurement from CoM to CoM of the two spacecraft. It needs to provide a beam co-alignment (incoming to outgoing beam) of less than 40 µrad and a low temperature dependency of the vertex position to enable the required ranging performance.

At the second spacecraft (with the laser in slave mode), the identical instrument configuration is implemented, but differing on the two S/Cs with respect to the flight direction. The received signal from the first spacecraft is used to offset lock the local laser by some MHz and also to point the second spacecraft to the first spacecraft (by use of the DWS signal). Apart from the mode of operation of the LH, the operation principle is as on spacecraft 1.

4. LTI ENGINEERING MODEL (EM) UNITS DESCRIPTION

The LTI EM consists of several main units on each satellite, individually placed in the spacecraft (S/C):

- ICU
- LHU

- the Laser Stabilization Unit (LSU), an optical cavity, to stabilize the laser in frequency,
- the Scale Factor Measurements System (SFMS) or Scale Factor Unit (SFU) for measurement of the absolute laser frequency,
- the Ultra-Stable Oscillator (USO), which may be replaced by an Oven Controlled Crystal Oscillator (OCXO) as clock signal, provided by the Global Navigation Satellite System (GNSS) receiver,
- OBA
- RRU

It is completed by a set of optical baffles to reduce straylight and ensure a clear optical aperture, optical fibers between the LHU, LSU and OBA as well as the electrical harness.

ICU:
The exact configuration of this ICU has yet to be decided. It shall include several sub-units, mainly:

- **The Laser Ranging Processor (LRP)**

The primary function of the LRP is to measure the phase of the laser interferometer signal from the photoreceiver, since phase changes are proportional to separation changes between the two orbiters. It also is used to control the laser frequency, either by phase locking the local laser to the incoming light or by stabilizing the laser frequency to the optical cavity. The LRP also controls the angle of the steering mirror and, if necessary, performs the search required to establish the optical link. Each satellite will have two LRP sub-units, one nominal and one redundant sub-unit, but only one will be in operation at a time.

- **Optical Bench Electronics (OBE):**

The OBE provides power to the steering mirror and the photoreceiver and provides signal conditioning between the photoreceiver and the LRP. For the steering mirror, it includes a current driver and the electronics for angle measurement, as well as analogue electronics for controlling the mirror position to a preset position with a PID controller. Each satellite will have two OBE sub-units, one nominal and one redundant sub-unit, but only one will be in operation at a time.

Laser Head Unit (LHU):
The LHU provides the laser light used for laser interferometry. It follows the NPRO topology used in many ground-based precision metrology systems. It puts out approximately 25 mW of light at 1064 nanometer wavelength. Most of the light is delivered to the optical bench. A small fraction is sent to the optical cavity for laser frequency stabilization. Each satellite will have two LHU units, one nominal and one redundant unit, but only one will be in operation at a time.

Laser stabilisation unit (LSU):
The cavity in the LSU is used to stabilize the laser frequency using the Pound-Drever-Hall technique [11]. Changes in laser frequency cannot be distinguished from changes in separation between the S/C. It is expected that this will be the limiting noise source in the LTI measurement. The stability of the cavity resonance frequency is mainly determined by temperature-induced drifts in the cavity length. The LSU is redundant on instrument level, meaning that each satellite contains a cavity, but only one will be in operation at a time.

Scale Factor Measurements System (SFMS) / Scale Factor Unit (SFU):
The scale factor measurement system (SFMS) reports measurements that can be used to determine the absolute laser frequency, which is needed to convert the LTI phase measurements to a biased range. Different systems are considered such as iodine spectroscopy units or frequency combs. However, the baseline uses a scale factor unit (SFU) that applies Radio Frequency (RF) modulation tones to the cavity phase modulator to allow readout of the cavity Free-Spectral-Range (FSR), in parallel to the regular Pound-Drever-Hall readout. The FSR is a proxy for the cavity resonance frequency. The SFMS is redundant on instrument level, meaning that each satellite contains a scale factor instrument, but only one will be in operation at a time.

Ultra Stable Oscillator (USO):
Each satellite has a cold-redundant pair of Ultra Stable Oscillators (USO) that are used to drive the timers in the ICU and in the GNSS receiver. The common clock is needed to ensure accurate timing between GNSS and LTI observations. The USO may be replaced by an OCXO as clock signal provided by the GNSS receiver.

Optical Bench Assembly (OBA),
The OBA consists of the fibre-to-free space interface of the laser, means for beam clean-up, shaping and routing of the laser signal to the photoreceivers and the distant spacecraft. The OBA includes the fine steering mirror and the quadrant photoreceivers, onto which the local oscillator and the received laser beam are superposed.
The OBA contains redundant quadrant photoreceivers and beam collimators. Depending on the selected redundancy scheme (cf. Figure 2), each satellite will have one or two OBAs.

The Retroreflector Unit (RRU),
The RRU consists of a three-mirror retroreflector in a hollow corner-cube configuration with a lateral beam separation of 30 to 60 cm and with its vertex, the intersection point of the three mirror planes, located at the satellite Center of Mass (CoM). It routes the transmitted beam from the OBA to the other spacecraft. Placing the vertex of each retroreflector into each satellite's CoM enables the LTI to measure the distance variation of the CoM of the two satellites to nm accuracy without the need to have a physical mirror in the CoM, which is the preferred position of the accelerometer test mass.

5. LTI ENGINEERING MODEL UNITS STATUS

The LTI EM Units level design as well as the LTI system engineering are progressing to implement the manufacturing, assembly, integration, and tests of the units to reach TRL 6 by the end of this activity. More details on the units description will be available in the following peer-reviewed and accepted paper [12].

6. CONCLUSION

NGGM will measure Earth's gravity field and its variation in time by means of the satellite-to-satellite tracking technique, as already successfully applied on GRACE and GRACE-FO. When two satellites fly along the same orbital path with a certain separation, the leading satellite is subject to the gravitational force exerted by an overflown geographical area in advance of the trailing satellite or, equivalently, at any given time the two satellites are subject to slightly different gravitational forces. The resulting "pull" effect is a continuous variation of the distance between the centers of mass of the two satellites. The main instrument allowing the satellite-to-satellite tracking measurement is based on the Laser Tracking Instrument described in this paper.
On ESA side, technology risk-retirement activities are performed to reach the TRL 5/6 for the entire LTI at the end of Phase B1 and TRL 6 at the instrument unit level at the end of Phase A. These activities will contribute to consolidate the achievable performance of the selected mission concept as well as the technological and programmatic feasibility of the entire mission.

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