MARVEL (Mass And Reference Variations for Earth Lookout): high-low SST laser link

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& the MARVEL Team

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MARVEL – OBJECTIFS SCIENTIFIQUES

Dans sa configuration nominale, MARVEL a pour but d'atteindre en une mission unique deux objectifs scientifiques majeurs et complémentaires :

- **Surveillance des changements de masse dans le système terrestre avec une grande précision**
- **Réalisation, au niveau mm, du référentiel terrestre – ITRF.**

Bénéfices scientifiques :

- **Géodésie**: champ de gravité variable, orbitographie précise, système de référence, niveau de la mer (grâce à une orbitographie précise)
- **Hydrologie**: évolution de la teneur totale en eau sur les continents, évaluation des stocks d'eau disponibles, prévision de la sécheresse
- **Cryosphère**: gains et pertes de masse des calottes glaciaires polaires et des glaciers, contribution à l'élévation du niveau de la mer
- **Océanographie**: évaluation des transferts de masse entre l'océan et les continents (échelles mondiale et régionale)
- **Géophysique**: signature des grands tremblements de terre
- **Climat**: estimation du déséquilibre énergétique de la Terre, transferts de masse d'eau en réponse au changement climatique
- **Rebond postglaciaire**: mesure de sa composante gravitationnelle, contraintes d'observation

Basic Concepts

❖ Nominal configuration:

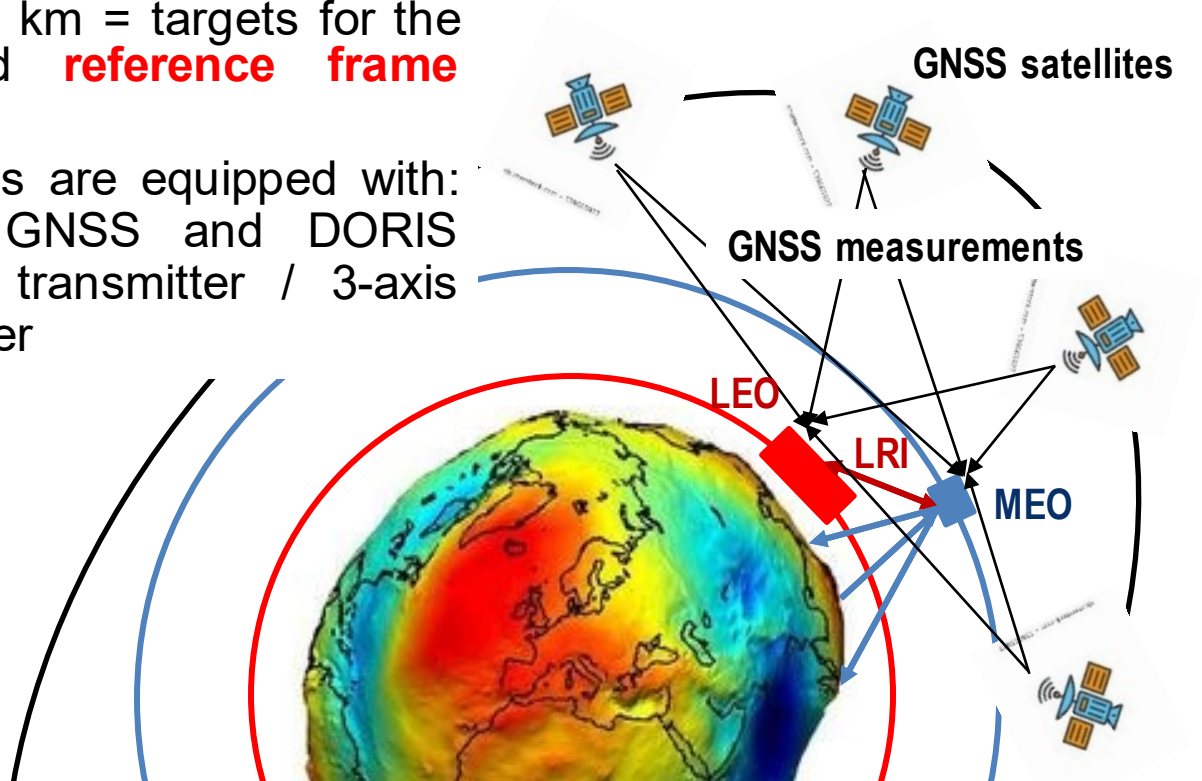
- **LEO** constellation (min. 1 satellite) in polar orbit at ~ 400 km **= Gravity field sensor**

  The low satellite(s) is equipped with: laser ranging device with pointing system / 3-axis accelerometer / GNSS receiver

- **MEO** constellation (min. 2 satellites) in polar orbit at ~ 7000 km = targets for the LEO satellites and **reference frame determination**

  The MEO satellites are equipped with: SLR reflector / GNSS and DORIS receivers / VLBI transmitter / 3-axis micro-accelerometer

MEO measurements to ground stations: SLR / DORIS / VLBI

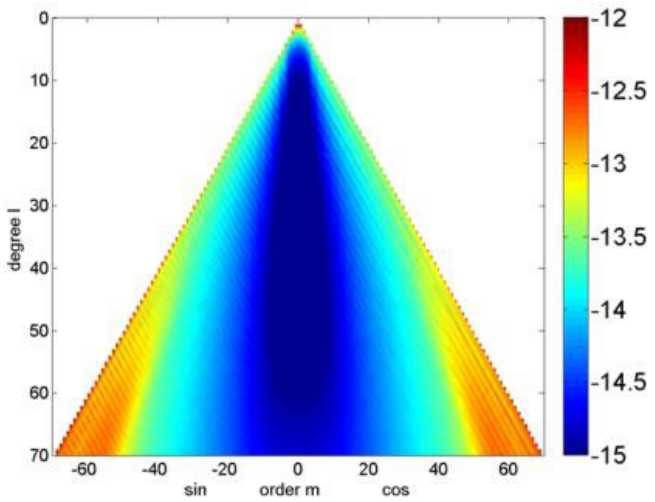


Gravity field sensor

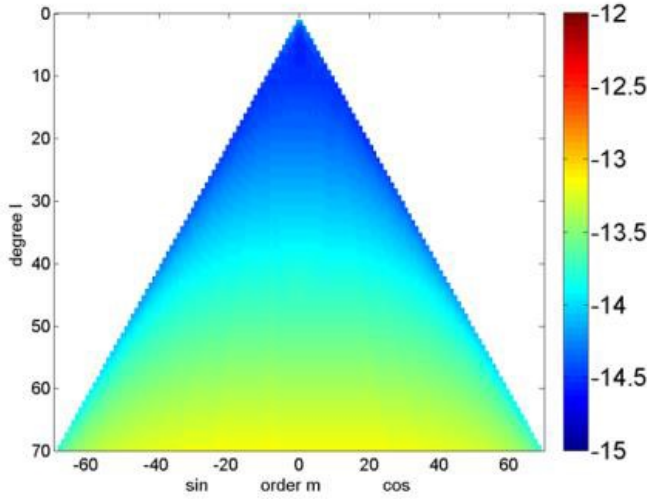
Compared to along-track low-low ranging formations (GRACE & GRACE-FO), the improved detection of mass transfers within the Earth system is expected through the **high-low laser link** between the two constellations:

➔ Observation of the **radial** component of gravity-induced orbit perturbations

➔ **Error structure close to isotropic:**



GRACE-type error structure



MARVEL-type error structure

(MOBILE proposal for EE-10, Pail et al. 2018)

Alternative configurations

- We also propose two alternative (and less costly) configurations, where only the first goal is fully reached.
- In any case, the goal of monitoring mass change with enhanced precision is attained through the use of high-low SST laser tracking.

- **"Nanosat version":**
  - **LEO:** identical to nominal configuration
  - **MEO:** 2 or more "nU" polar-orbiting **nanosatellites** at 7000 km equipped with: SLR reflector / GNSS receiver / AOCS.

- **"GNSS version":**
  - **LEO:** identical to nominal configuration
  - **MEO: GNSS satellites** are used as reference targets for the LEO satellite, provided they are equipped with adapted SLR reflectors

Scientific and Measurement Performance

- Numerical simulations have been performed by Pail et al. (2019) in the framework of the MOBILE proposal to ESA/EE-10. Below are some results of these simulations.

1. Instrument-only errors
   - LEO altitude: 350 km / Realistic noise applied to the LRI and ACC measurements / 28-day solutions for different configurations (2 MEO – 1 LEO, 3 MEO – 1 LEO, 2 MEO – 2 LEO)
   - The Atmosphere/Ocean/Hydrology/Ice/Solid_Earth (AOHIS) curve is in black, the expected performance of the GRACE-FO mission is in red

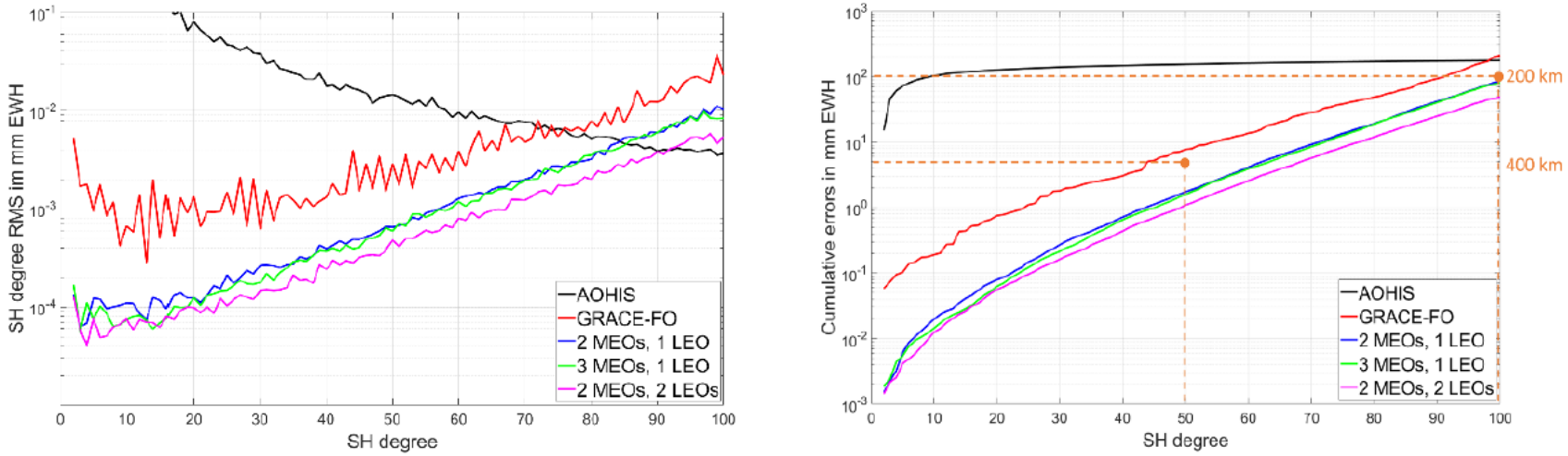


Figure 2-5: Degree (error) standard deviations (left) and cumulative signal/error standard deviations (right) of full AOHIS signal (black) and different mission scenarios, when including only instrument errors. The threshold science requirements for 400 km (SH degree 50) and 200 km (SH degree 100) are included in orange color.

Scientific and Measurement Performance

- The figure shows that a mission with the specified instrument performance is below the threshold requirements even for the minimum configuration of 2 MEOs and 1 LEO (blue curve).

2. <u>Simulation including the HIS aliasing errors</u>

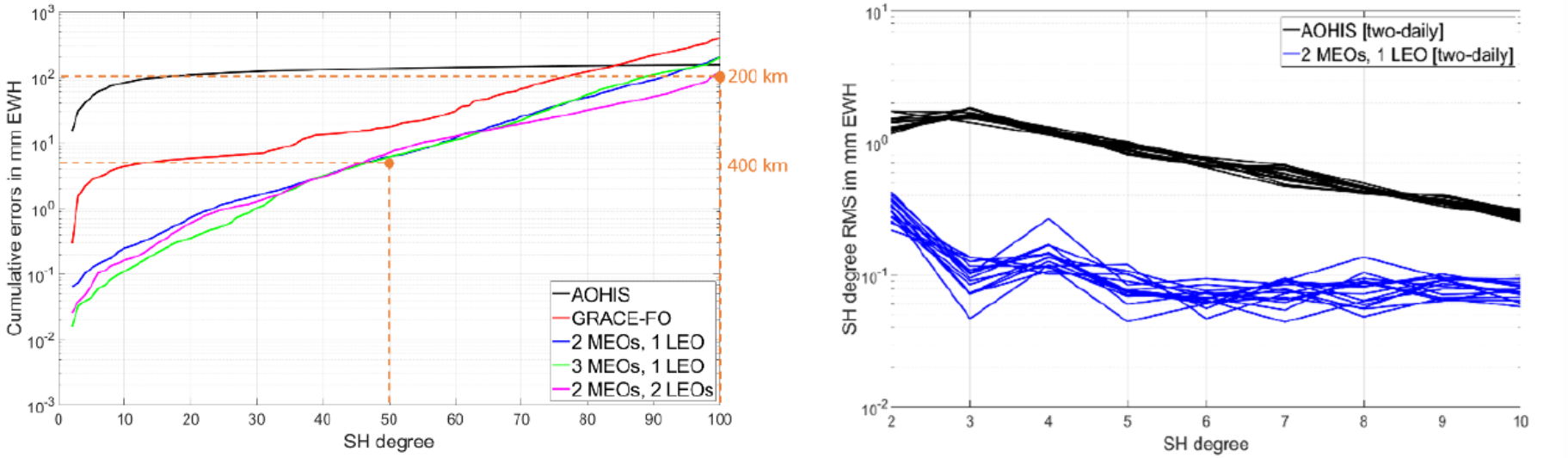


Figure 2-6: *Cumulative degree (error) standard deviation (left) when including instrument and HIS aliasing errors (left); degree standard deviations of 2-daily gravity field solutions resolved up to SH degree 10 when including and recovering the full AOHIS signal (right).*

- The threshold science requirements are achieved for 400 km spatial resolution (SH degree 50); for 200 km (SH degree 100), the required 10 cm EWH level is crossed at degree 96 for the configuration 2 MEOs/1 LEO

Pros and Cons of Architecture

• Advantages	• Disadvantages
• Nominal configuration	
○ Mass transport observations improved by a factor at least 5 as compared to nowadays	○ Costly compared to a simple pair of satellites
○ Reference frame determination in line with the GGOS requirements	○ Technical challenge to point and to lock the LRI on a moving target
○ Modular concept: could be the first step for a sustained mass transport observing system	
○ Easy to partner	
• "Nanosat configuration"	
○ Cheaper than the nominal configuration	○ The reference frame goal is lost
○ The number of MEOs can be multiplied ➔ more continuous and more radial measurements	○ How to bring the 2 to 4 MEOs to their orbit at 7000 km ?
○ Easy to partner	
• "GNSS configuration"	
○ Cheaper than the nanosat configuration	○ The reference frame goal is lost
○ T2L2 could be embarked on GNSS to allow ps-level time transfer	○ Higher power needed for the laser
○ Precise knowledge of the GNSS orbits	
○ Multiple targets ➔ the future of Mass Change monitoring ?	

MARVEL - CONTEXTE PROGRAMMATIQUE

- 2019: "MASS CHANGE" identifiée groupe priorité 1 dans le Decadal Survey. 300 Meuros alloués : insuffisant pour la mission donc NASA recherche un partenaire pour co-construction
- **NASA / MC** : "Mass Change" : MARVEL est identifié par le JPL comme un candidat pour co-construire avec eux la future mission mass change définie dans le Decadal Survey (réunion le 6/02 CNES – JPL / réunion 24/03 CNES - NASA)
- **ESA / NGGM** : "Next Generation Gravity Mission" – dans le cadre de "Missions of Opportunity" NASA-ESA ad-hoc expert group en 2020. Phase A en 2021. ESA propose de faire un GRACE incliné pour compléter les observations de Mass Change. Pas de co-construction avec la NASA. Seulement combinaison des données de niveau 3 et plus.
- **CNES** : contexte très favorable car le CNES cherche en ce moment des coopération avec d'autres agences sur le thème des transferts de masse !!!

- **MARVEL**:

- Mission dont toutes les questions scientifiques (hormis Terre interne) sont complémentaires des questions scientifique de l'altimétrie
- Combinaison données Marvel et altimétrie ouvre la possibilité d'aborder de nouvelles questions scientifiques majeures: ex: sensibilité climatique
- Opportunité de participer avec la NASA sur Mass Change
- Potentiel de filière future à partir de Marvel: constellation type Marvel, atome froid à partir de R&T CNES.
- Un concept très modulaire (les satellites LEO peuvent être remplacés ou complétés, les satellites MEO peuvent être remplacés ou complétés par d'autres agences).


Fin

Publications

- Markus Hauk & Roland Pail (2019). Gravity Field Recovery Using High-Precision, High–Low Inter-Satellite Links, Remote Sens. 2019, 11(5), 537; https://doi.org/10.3390/rs11050537
- Daras I., Pail R. (2017). Treatment of temporal aliasing effects in the context of next generation satellite gravimetry missions. J. Geophys. Res: Solid Earth, 122(9): 7343–7362, doi: https://doi.org/10.1002/2017JB014250
- Daras I., Pail R., Murböck M., Yi W. (2015). Gravity field processing with enhanced numerical precision for LL-SST missions. 89:99-110, doi: https://doi.org/10.1007/s00190-014-0764-2
- Wiese D.N., Visser P.N.A.M., Nerem R.S. (2011). Estimating low resolution gravity fields at short time intervals to reduce temporal aliasing errors. Adv Space Res 48:1094–1107, DOI https://doi.org/10.1016/j.asr.2011.05.027
- Biancale R. et al. (2017). E-GRASP/Eratosthenes, Proposal for Earth Explorer Opportunity Mission EE-9 in response to the Call for Proposals for Earth Explorer Opportunity Mission EE-9 (ESA/EXPLORER/EE-9 rev. 1), June 2017.
- E-GRASP: http://adsabs.harvard.edu/abs/2016AGUFM.G41A1009S

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