Phase A Activities Insights and User/Mission Requirements for NGGM as a Mass-change and Geosciences International Constellation (MAGIC)

ASI WS di consultazione della comunità scientifico/applicative sulla missione ESA NGGM/MAGIC

26 January 2021

Luca Massotti, Roger Haagmans, Pierluigi Silvestrin,

Background

Over the past years discussions between ESA and NASA led to a strong interest in exploring a joint future mission, as noted in various communications (ESA letter February 15, 2019, NASA letter February 27, 2019 and NASA letter November 15, 2019).

The agencies have cooperated in preparing a **Mission Requirement Document** (available via ASI) and defining science study activities. A Joint Expert Group, co-led by NASA HQ and ESA, will support the definition of jointly agreed user and science needs.

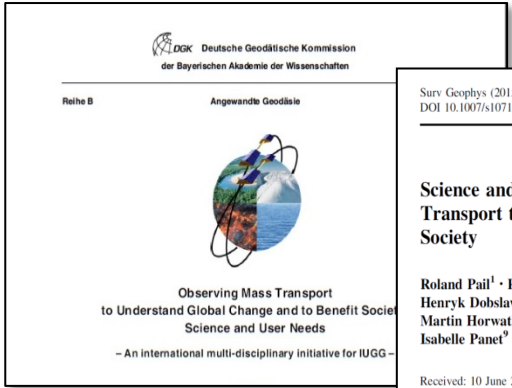
Global User Community Activities

Two User Community Workshops in 2007, Noordwijk, NL and 2009, Graz, AT

IUGG 1st resolution in 2011 and letter to Space Agencies in 2012

Global User Community Science Team (IUGG, IAG, GGOS)

ESA-NASA
Interagency Gravity Science Working Group

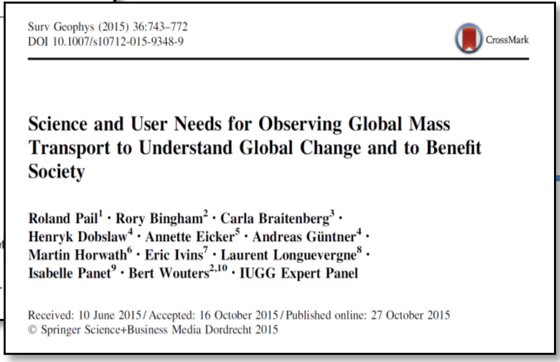


DGK Deutsche Geodätische Kommission
der Bayerischen Akademie der Wissenschaften

Reihe B Angewandte Geodäsie

Observing Mass Transport
to Understand Global Change and to Benefit Societ
Science and User Needs

– An international multi-disciplinary initiative for IUGG –



Surv Geophys (2015) 36:743–772
DOI 10.1007/s10712-015-9348-9

CrossMark

Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society

Roland Pail[1] · Rory Bingham[2] · Carla Braitenberg[3] · Henryk Dobslaw[4] · Annette Eicker[5] · Andreas Güntner[4] · Martin Horwath[6] · Eric Ivins[7] · Laurent Longuevergne[8] · Isabelle Panet[9] · Bert Wouters[2,10] · IUGG Expert Panel

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Towards a sustained observing system for mass transport to understand global change and to benefit society

NASA/ESA Interagency Gravity Science Working Group (IGSWG)

12 May 2016

Doc. nr.: TUD-IGSWG-2016-01

Explore possibilities for cooperation on future gravity satellite constellation concepts …

Through coordination of ongoing and planned activities

Post GOCE & GRACE-FO mission:
community urging to implement long-term gravity constellation

UGGI

IUGG

International Union of Geodesy and Geophysics

Resolutions

ADOPTED BY THE COUNCIL
AT THE XXVI GENERAL ASSEMBLY
PRAGUE, CZECH REPUBLIC
(22 JUNE – 2 JULY 2015)

- ✓ IUGG (**Int. Union of Geodesy and Geophysics**) embodies all geophysical and geodetic disciplines
- ✓ Represents about 100,000 users worldwide,
- ✓ Resolution 2 is the only resolution which makes explicit mention of satellite missions → GRACE (FO), GOCE & Swarm

Resolution 2:

Future Satellite Gravity and Magnetic Mission Constellations

*The **International Union of Geodesy and Geophysics***

Considering

- The interest and need of the IUGG scientific community to understand processes of global mass transport in the Earth system, and the interaction among its subsystems including continental hydrology, cryosphere, atmosphere, ocean and solid Earth, in order to close the global water budget and to quantify the climate evolution of the Earth,
- The long lead time required to bring an earth observation system into operation,

Acknowledging

- The experience acquired in the last decade within the IUGG in analyzing data from dedicated satellite missions such as CHAMP, GRACE, GOCE and Swarm for the purpose of estimating the gravity and magnetic fields and their time variations,
- The clear expression of need from the user communities so far, and the definition of joint science and user requirements for a future satellite gravity field mission constellation by an international working team under the umbrella of IUGG,

Noting

- The need for a long-term sustained observation of the gravity and magnetic fields and related mass transport processes of the Earth beyond the lifetime of GRACE and the GRACE Follow-On planned for the 2017 - 2022 period, and beyond the lifetime of Swarm, currently 2013 to 2018,
- The demonstrated need for satellite constellations to improve temporal and spatial resolution and to reduce aliasing effects,

Urges

International and national institutions, agencies and governmental bodies in charge of supporting Earth science research to make all efforts to implement long-term satellite gravity and magnetic observation constellations with high accuracy that respond to the aforementioned need for sustained observation.

Previous studies & documents:


DGK Deutsche Geodätische Kommission
der Bayerischen Akademie der Wissenschaften

Reihe B Angewandte Geodäsie Heft Nr. 320

Observing Mass Transport
to Understand Global Change and to Benefit Society:
Science and User Needs

– An international multi-disciplinary initiative for IUGG –

edited by
Roland Pail

with contributions of

Rory Bingham, Carla Braitenberg, Annette Eicker, Martin Horwath, Eric Ivins, Laurent Longuevergne, Isabelle Panet, Bert Wouters, Gianpaolo Balsamo, Melanie Becker, Decharme Bertrand, John D. Bolten, Jean-Paul Boy, Michiel van den Broeke, Anny Cazenave, Don Chambers, Tonie van Dam, Michel Diament, Albert van Dijk, Henryk Dobslaw, Petra Döll, Jörg Ebbing, James Famiglietti, Wei Feng, Rene Forsberg, Nick van de Giesen, Marianne Greff, Andreas Güntner, Jun-Yi Guo, Shin-Chan Han, Edward Hanna, Kosuke Heki, György Hetényi, Steven Jayne, Weiping Jiang, Shuanggen Jin, Georg Kaser, Matt King, Armin Köhl, Harald Kunstmann, Jürgen Kusche, Thorne Lay, Anno Löcher, Scott Luthcke, Marta Marcos, Mark van der Meijde, Valentin Mikhailov, Christian Ohlwein, Fred Pollitz, Yadu Pokhrel, Rui Ponte, Matt Rodell, Cecilie Rolstad-Denby, Himanshu Save, Bridget Scanlon, Sonia Seneviratne, Frederique Seyler, Andrew Shepherd, Tony Song, Wim Spakman, C.K. Shum, Holger Steffen, Wenke Sun, Qiuhong Tang, Virendra Tiwari, Isabella Velicogna, John Wahr, Wouter van der Wal, Lei Wang, Hua Xie, Hsien-Chi Yeh, Pat Yeh, Ben Zaitchik, Victor Zlotnicki

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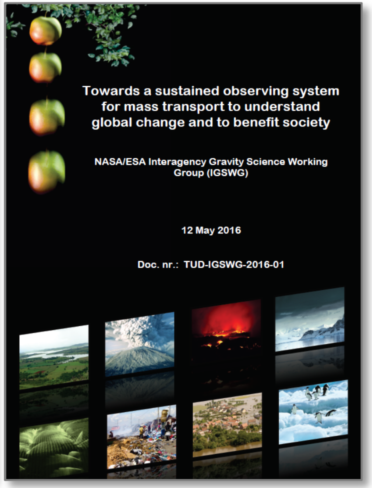
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12 May 2016

Doc. nr.: TUD-IGSWG-2016-01


Proposal Reference Number: CEE9/019

e.motion²

Earth System Mass Transport Mission²

Proposal for Earth Explorer Mission EE-9

In Response to
Call for Proposals for Earth Explorer Mission EE-9
(ESA/EXPLORER/EE-9 November 2015)
by the

e.motion² Team

June 2016


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Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)

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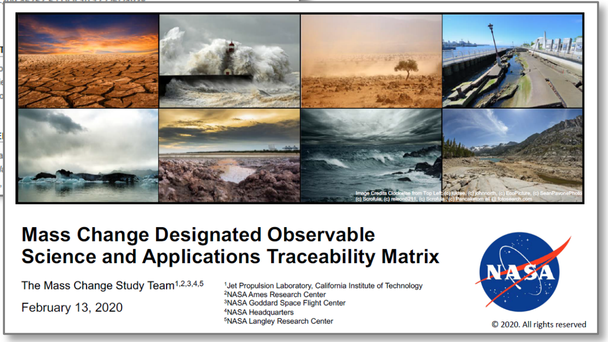
Mass Change Designated Observable
Science and Applications Traceability Matrix

The Mass Change Study Team[1,2,3,4,5]

February 13, 2020

[1]Jet Propulsion Laboratory, California Institute of Technology
[2]NASA Ames Research Center
[3]NASA Goddard Space Flight Center
[4]NASA Headquarters
[5]NASA Langley Research Center

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MCDO - NASA

UNIVERSITÀ DEGLI STUDI DI MILANO ThalesAlenia Space GIS

Gravitational seismology - ESA study

IUGG

IGSWG

e.motion²

2015 2016 2017 2018 2019 2020

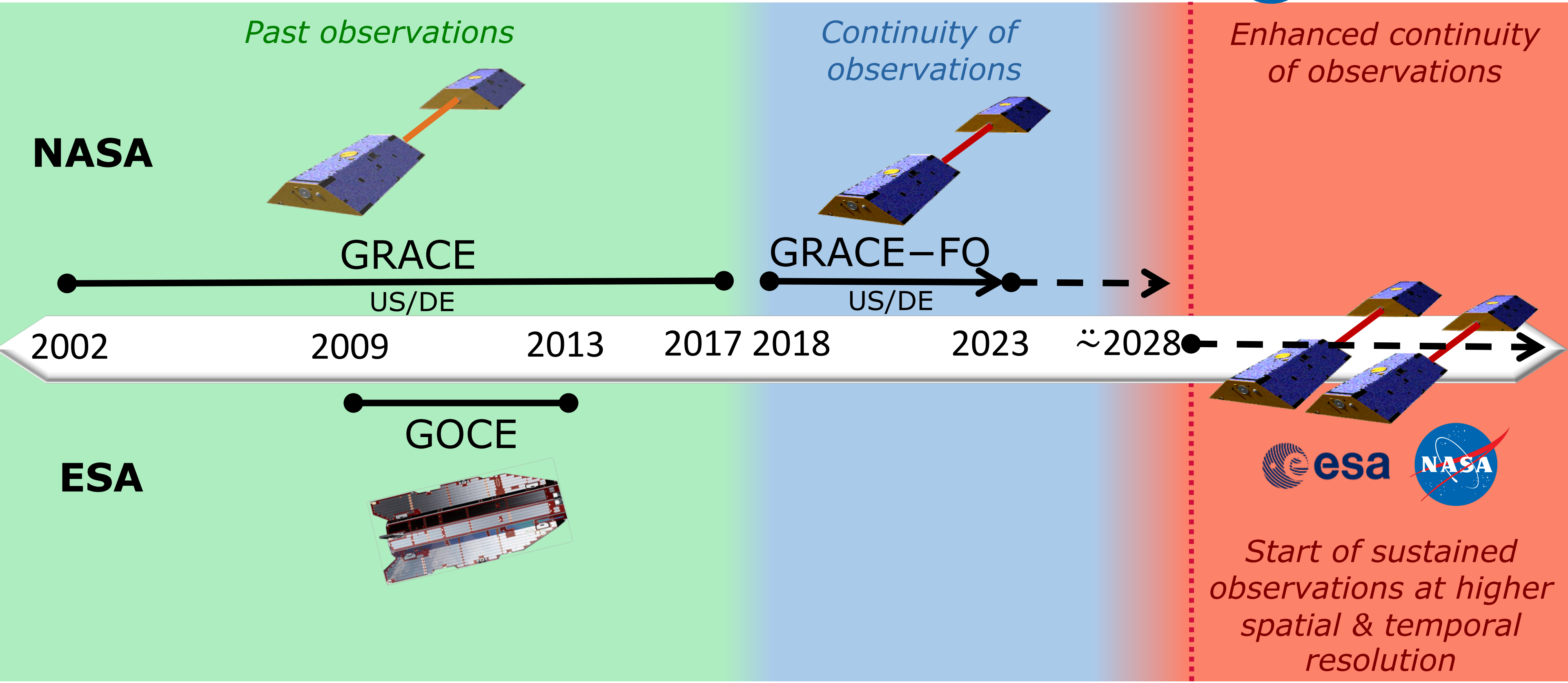
Where mass change contributes to GCOS ECVs

Domain	GCOS Essential Climate Variables
Atmospheric	**Surface:** Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget. **Upper-air:** Temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance). **Composition:** Carbon dioxide, methane, and other long-lived greenhouse gases, Ozone and aerosol, supported by their precursors
Oceanic	state, sea ice, surface current, ocean colour, Carbon dioxide partial pressure, ocean acidity, phytoplankton. **Sub-surface:** Temperature, salinity, current, nutrients, Carbon dioxide partial pressure, ocean acidity, Oxygen, tracers.
Terrestrial	River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture.

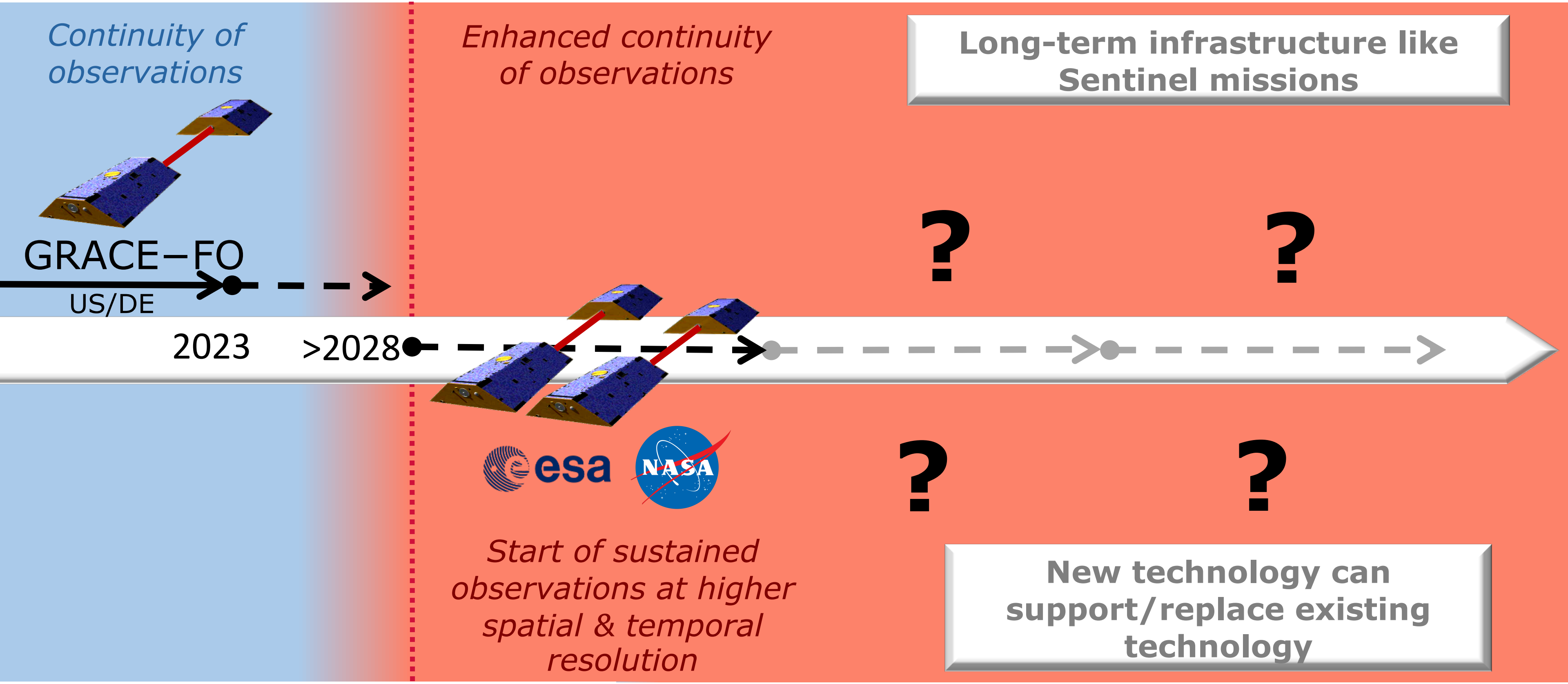
Total Water Storage (TWS) accepted as new ECV

High, medium, low contribution

ESA & NASA cooperation: MAGIC



Opportunity for long-term cooperation: beyond MAGIC



AJSST tasks

First part

Science Targets

Joint Requirements in MCDO SATM format

- MCDO SATM
- MCDO + NGGM SATM

Key questions:

- New targets/boxes?
- One for "longer term", monthly and "weekly" science/applications?
- Understand "delta" of one pair versus two pair in this format

Joint requirements in bubble plot format

- IUGG report bubble plots "longer term"
- IUGG report bubble plots "monthly"
- IUGG report bubble plots "weekly"

Key questions:

- Where does the performance of new simulations lie relative to these documents and e.g. e-motion2 proposal to ESA?

Measurement System Requirements (needed for MRD*). Note that these should be more ambitious (and agreed to by NASA and ESA) than Science Targets by definition.

Degree variance of integrated performance of measurement system (like GRACE-FO)

Key question: Should the above box be dependent on the below boxes? Answer: Probably not.

Derived following the approaches for GRACE-FO and e-motion2

Harmonise to ensure "uniform quality products"

- Sampling Periods of polar
- Sampling Periods of Lower Inclined

* MRD – Mission Requirements Document

Methodology to derive user requirements from references

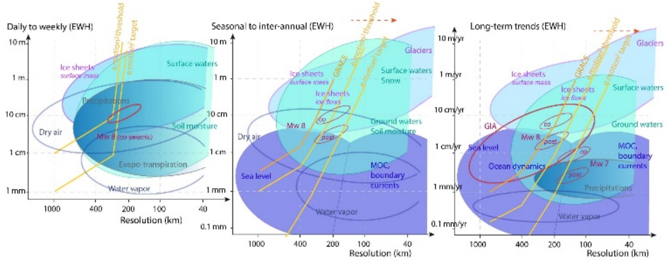
- **E.motion2 bubble plot** → Spatial resolutions [km] for the three time scales:
  - **D**aily to weekly;
  - **M**onthly to seasonal;
  - **L**ong-term.

  Thresholds and *targets* are obtained from the intersections between the yellow lines and the signal bubbles (including flection points and "unrealistic" signals).

- **IUGG Table 1-1** → Accuracy [cm *or* cm/yr]. Values from the table are interpolated. Each thematic field has its own spatial resolutions (from bubble plot) and accuracy is estimated from IUGG interpolated values. **IGSWG** specific requirements are also included for a few signals.

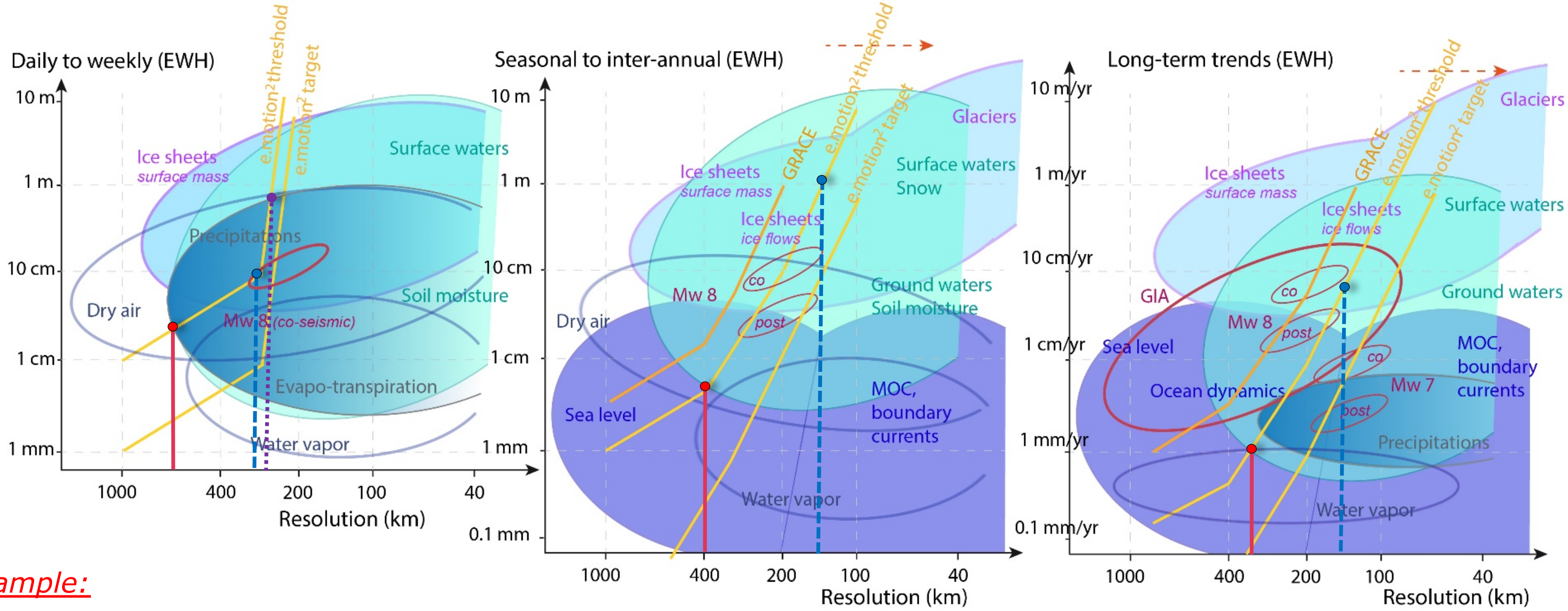
- **Assumption:**
  - ➢ Seasonal to inter-annual → Monthly
  - ➢ **IUGG 1-day is "Daily to weekly"**

- **Inclusion of MCDO requirements**



Mission	Temp. res.	Performance				
		Spat. res.	Equivalent Water Height (EWH)	Geoid	Gravity anomaly	Gravity Gradient
GRACE	1 month	800 km (d/o 25)	7.5 mm / 0.75 mm/yr	0.15 mm / 0.015 mm/yr	0.25 µGal / 0.025 µGal/yr	10 µE / 1 µE/yr
		400 km (d/o 50)	25 mm / 2.5 mm/yr	0.25 mm / 0.025 mm/yr	1 µGal / 0.1 µGal/yr	0.1 mE / 0.01 mE/yr
		200 km (d/o 100)	0.5 m / 5 cm/yr	2.5 mm / 0.25 mm/yr	25 µGal / 2.5 µGal/yr	5 mE / 0.5 mE/yr
Scen. 1	1 month	800 km (d/o 25)	1.5 mm / 0.15 mm/yr	0.03 mm / 3 µm/yr	0.05 µGal / 5 nGal/yr	2 µE / 0.2 µE/yr
		400 km (d/o 50)	5 mm / 0.5 mm/yr	50 µm / 5 µm/yr	0.2 µGal / 0.02 µGal/yr	20 µE / 2 µE/yr
		200 km (d/o 100)	10 cm / 1 cm/yr	0.5 mm / 0.05 mm/yr	5 µGal / 0.5 µGal/yr	1 mE / 0.1 mE/yr
		150 km (d/o 133)	50 cm / 5 cm/yr	1 mm / 0.1 mm/yr	10 µGal / 1 µGal/yr	5 mE / 0.5 mE/yr
		100 km (d/o 200)	5 m / 0.5 m/yr	10 mm / 1 mm/yr	200 µGal / 20 µGal/yr	50 mE / 5 mE/yr
Scen. 2	1 month	800 km (d/o 25)	0.15 mm / 0.015 mm/yr	3 µm / 0.3 µm/yr	5 nGal / 0.5 nGal/yr	0.2 µE / 0.02 µE/yr
		400 km (d/o 50)	0.5 mm / 0.05 mm/yr	5 µm / 0.5 µm/yr	0.02 µGal / 0.002 µGal/yr	2 µE / 0.2 µE/yr
		200 km (d/o 100)	1 cm / 0.1 cm/yr	0.05 mm / 0.005 mm/yr	0.5 µGal / 0.05 µGal/yr	0.1 mE / 0.01 mE/yr
		150 km (d/o 133)	5 cm / 0.5 cm/yr	0.1 mm / 0.01 mm/yr	1 µGal / 0.1 µGal/yr	0.5 mE / 0.05 mE/yr
		100 km (d/o 200)	0.5 m / 0.05 m/yr	1 mm / 0.1 mm/yr	20 µGal / 2 µGal/yr	5 mE / 0.5 mE/yr
Scen. 3	1 day	800 km (d/o 25)	15 mm	0.3 mm	0.5 µGal	20 µE
		400 km (d/o 50)	50 mm	0.5 mm	2 µGal	200 µE
Scen. 4	1 day	800 km (d/o 25)	1.5 mm	0.03 mm	0.05 µGal	2 µE
		400 km (d/o 50)	5 mm	0.05 mm	0.2 µGal	20 µE

E.motion² bubble plots – Spatial resolution definition



E.motion², Earth System Mass Transport Mission², Proposal for Earth Explorer Mission EE-9 (CEE9/019), June 2016.

Example:

	Signal	Daily to weekly	Monthly to Seasonal	Long-term trends
Threshold-a	**Hydrology**	600 km	400 km	350 km
Threshold-b		300 km	150 km	150 km
Threshold-c		280 km	-	-

IUGG Table 1-1 – Accuracy definition

Th.-a Th.-b Th.-c

Hydrology

Daily to weekly

Th.-a	Th.-b	Th.-c
600 km	300 km	280 km

Monthly to seasonal

Th.-a	Th.-b	Th.-c
400 km	260 km	-

Long-term trends

Th.-a	Th.-b	Th.-c
350 km	150 km	-

Thematic field	Time scale D: Daily to weekly M: Monthly L: Long-term trend	Threshold: Resolution & Accuracy [EWH]	Target: Resolution & Accuracy [EWH]
Hydrology	**D**	Threshold-a: 600 km @ **3.2 cm** Threshold-b: 300 km @ **5.9 cm** Threshold-c: 280 km @ **6.0 cm**	Threshold-a: 600 km @ **0.3 cm** Threshold-b: 300 km @ **0.6 cm** Threshold-c: 280 km @ **0.6 cm**
	M	Threshold-a: 400 km @ **0.5 cm** Threshold-b: 260 km @ **4.8 cm**	Threshold-a: 400 km @ **0.05 cm** Threshold-b: 260 km @ **4.8 cm**
	L	Threshold-a: 350 km @ **0.1 cm/yr** Threshold-b: 150 km @ **5.0 cm/yr**	Threshold-a: 350 km @ **0.01 cm/yr** Threshold-b: 150 km @ **0.5 cm/yr**

Process for all science objectives

This procedure is repeated to consolidate all requirements related to science questions formulated for *hydrology, cryosphere, ocean, solid earth and climate*.

A **S**cience **T**raceability **M**atrix (SATM) is build to keep track of the origin of specific requirements.

<table>
<tr><td colspan="5">Spatial resolutions and temporal scales associated to gravity changes
Science and Applications Traceability Matrix (SATM)
Current status Vs. MCDO Vs. Joint constellation (MAGIC)</td><td colspan="3">References: IUGG-interpolated, IUGG specific requirement, DS+MCDO, IGSWG, Grav. Seismo.; Wiese et al. 2016, Metivier & Conrad, 2008; Marquart et al.,2005 + Dumberry, 2010
N.A. = Not Applicable/Not Available (e.g. due to lack of measurements/capabilities)</td></tr>
<tr><td rowspan="4">Thematic field</td><td rowspan="4">Signal</td><td rowspan="4">Time scale (D: Daily to weekly; M: Monthly (Seasonal to inter-annual); L: Long-term trend)</td><td>Current state of the art (e.g. GRACE, GRACE-FO)</td><td>MCDO</td><td colspan="3">Joint constellation (MAGIC)</td></tr>
<tr><td rowspan="3">Resolution & Accuracy</td><td rowspan="3">Resolution & Accuracy</td><td colspan="2">Resolution & Accuracy</td><td rowspan="3">Scientific/societal Questions & Objectives</td></tr>
<tr><td>Threshold</td><td>Target</td></tr>
<tr></tr>
<tr><td>Hydrology</td><td>Ground-water storage</td><td>D</td><td>N.A.</td><td>N.A.</td><td>Threshold-a: 600 km @ 3.2 cm;
Threshold-b: 300 km @ 5.9 cm;
Threshold-c: 280 km @ 6.0 cm</td><td>Target-a: 600 km @ 0.3 cm;
Target-b: 300 km @ 0.6 cm;
Target-c: 280 km @ 0.6 cm</td><td>Q: H1, H2, H3, CL2;
O: H-1a, H-</td></tr>
</table>

Overall user requirements: Science and Applications Traceability Matrix

				Goal: 3 km @ 1.0 cm			H2-c; H-3a; CL-2a
		L	1000 km @ 1.0 mm/yr	TBD	Threshold-a: 350 km @ 0.1 cm/yr; Threshold-b: 150 km @ 5.0 cm/yr	Target-a: 350 km @ 0.01 cm/yr; Target-b: 150 km @ 0.5 cm/yr; Target-c: 200 km @ 0.1 cm/yr	
Cryosphere	Cryosphere mass balance	D	N.A.	N.A.	N.A.	N.A.	Q: C1, C2, C3, CL2; O: C-1b; C-2a, C-2b, C-2d, C-2e; C3-a; CL-2a, CL-2b
		M	200-500 km @ 4.0-5.0 cm	Baseline: 300 km @ 4.0 cm; Goal: 100 km @ 1.0 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr	
	Global and regional sea level	D	N.A.	N.A.	N.A.	N.A.	Q: C1, C2, CL1, CL2; O: C-1a, C-1c; C-2a; CL-1a, CL-1b; CL-2a
		M	300 km @ 1.5 cm	Baseline: 300 km @ 1.5 cm; Goal: 100 km @ 1.5 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr	
	GIA	D	N.A.	N.A.	N.A.	N.A.	Q: C1, C2, CL2; O: C-1a, C-1c; C-2a; CL-2a, CL-2b
		M	300 km @ 2.5 cm	Baseline: 300 km @ 2.5 cm; Goal: 200 km @ 1.0 cm	Threshold-a: 250 km @ 5.5 cm; Threshold-b: 150 km @ 50.0 cm	Target-a: 250 km @ 0.55 cm; Target-b: 150 km @ 5.0 cm; Target-c: 200 km @ 1.0 cm	
		L	350 km @ 1 cm/yr	TBD	Threshold-a: 170 km @ 2.6 cm/yr; Threshold-b: 130 km @ 15.0 cm/yr	Target-a: 170 km @ 0.26 cm/yr; Target-b: 130 km @ 1.5 cm/yr; Target-c: 150 km @ 0.2 cm/yr	
		D	N.A.	N.A.	N.A.	N.A.	

Science Requirements vs. Simulations (so far)

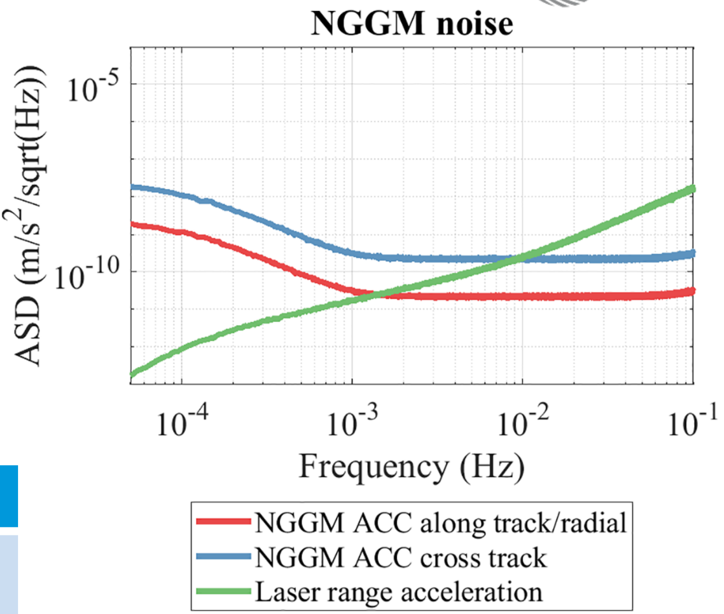
- Simulations based on the following publication:

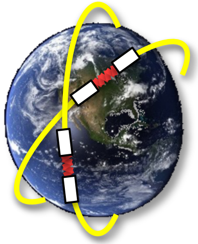
  " Anna F Purkhauser, Christian Siemes, Roland Pail, Consistent quantification of the impact of key mission design parameters on the performance of next-generation gravity missions, *Geophysical Journal International*, Volume 221, Issue 2, May 2020, Pages 1190–1210, https://doi.org/10.1093/gji/ggaa070"
- Dual pair simulations vs. threshold science requirements
- Cumulative degree RMS plots
- Scenario deltas:
  - ✓ Altitude: 350 km / 500 km
  - ✓ Noise: Nominal / Instrument-Noise-Only
  - ✓ Temporal: Daily - Weekly / Monthly / Long-term

Simulation details

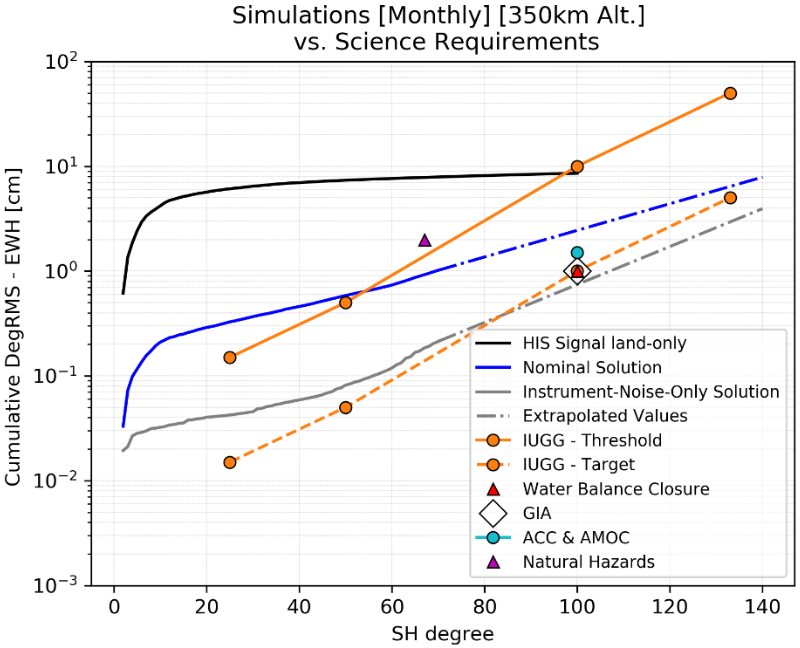
- Solutions include the HIS global signal
- Raw solutions not post-processed
- Weekly solutions of d/o 70 co-parameterized with daily solutions of d/o 15
- 100km inter-satellite distance

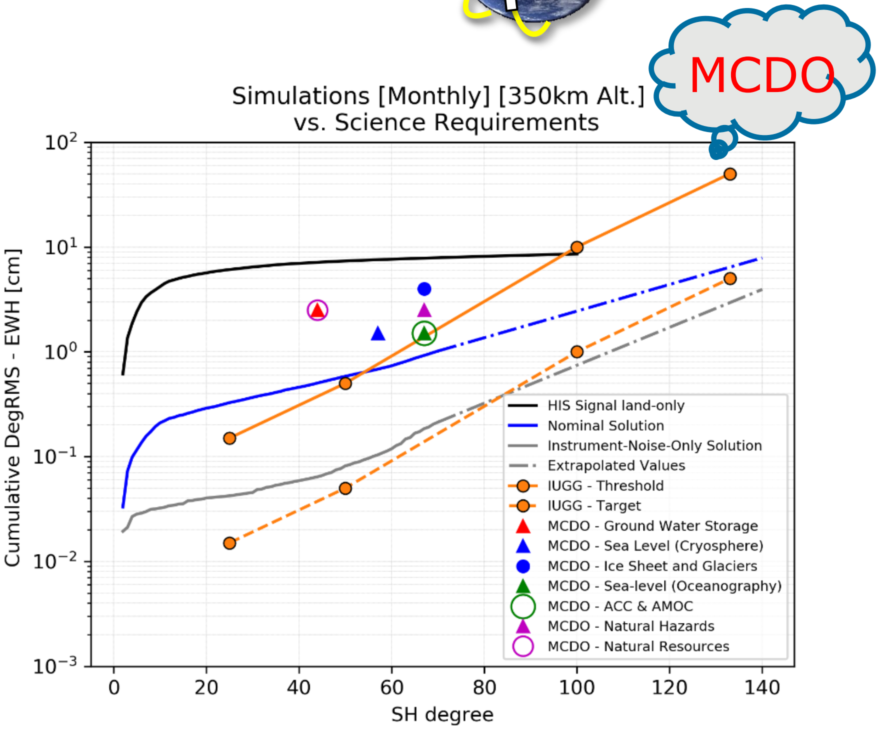
Nominal Solution	Instrument Noise Solution
• NGGM-type instrument noise • AO de-aliasing model errors • OT model errors • HIS residual temporal aliasing error	• NGGM-type instrument noise



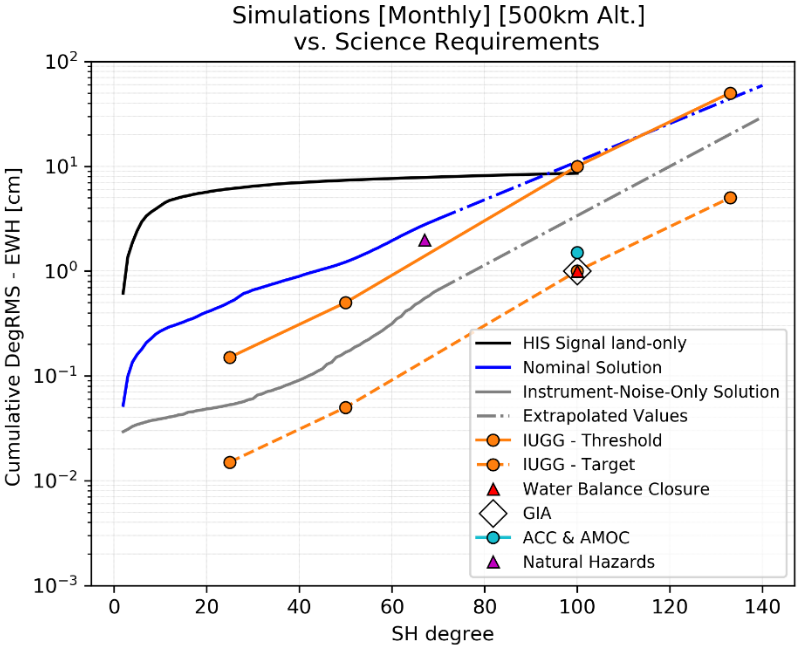


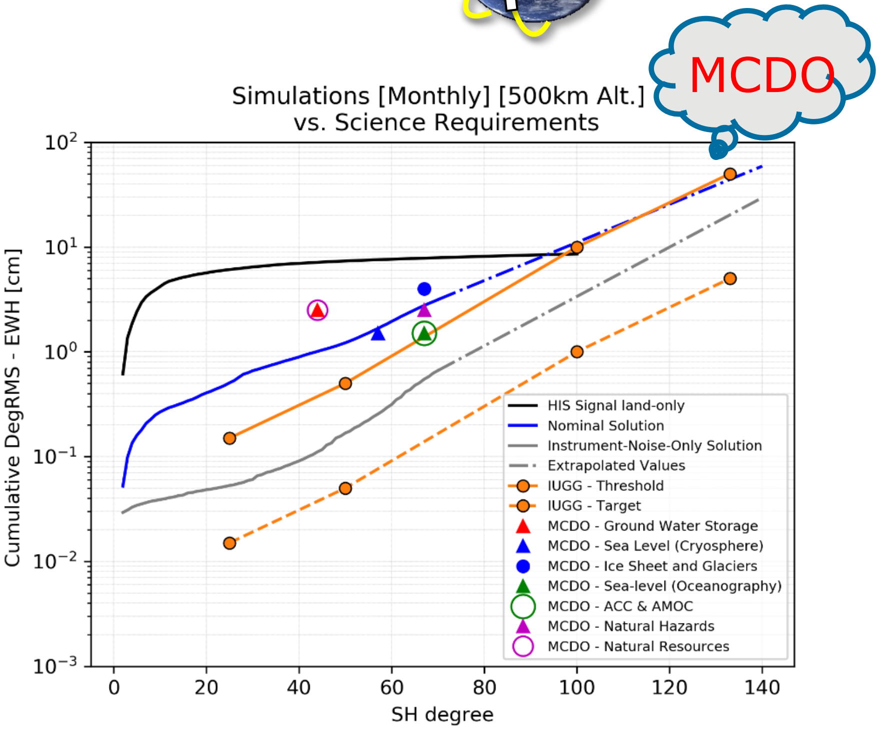
Monthly – 350 km Altitude



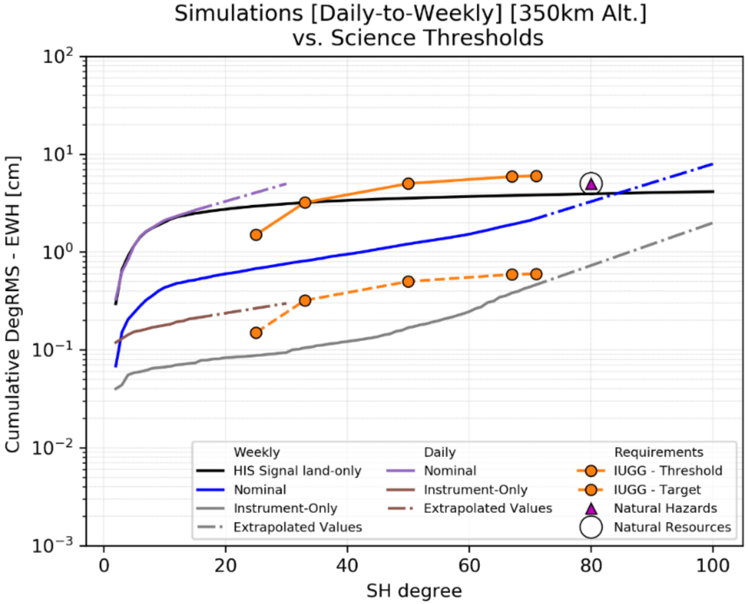


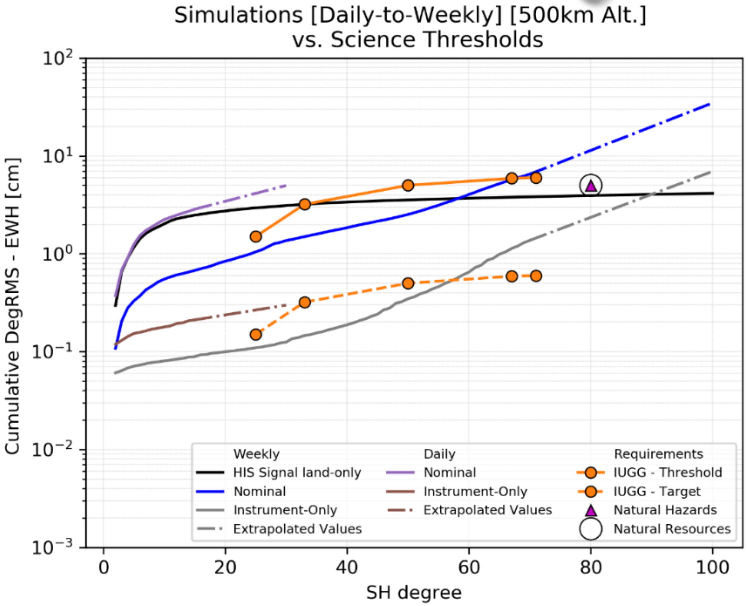
Monthly – 500 km Altitude



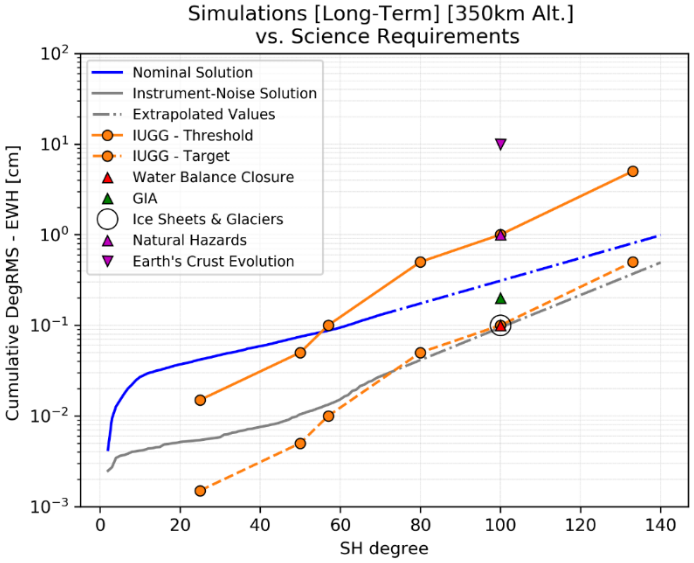


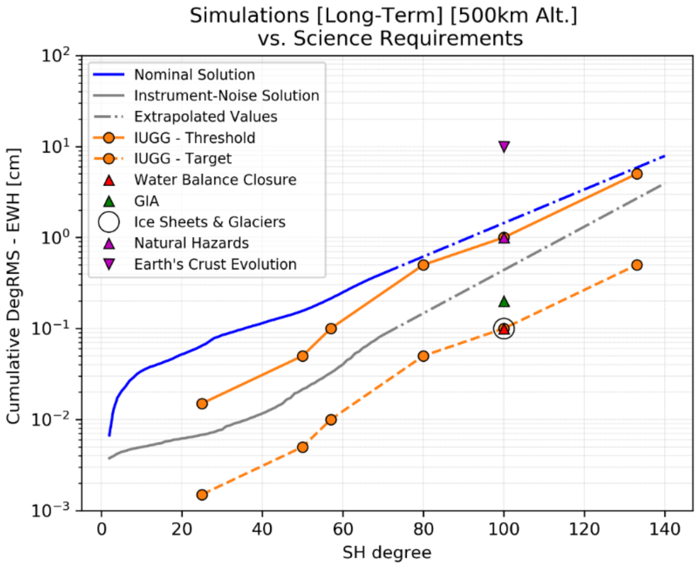
Daily-to-Weekly – 350 km and 500 km Altitude





Long Term – 350 km and 500 km Altitude





AJSST tasks

Science Targets

Joint Requirements in MCDO SATM format

- MCDO SATM
- MCDO + NGGM SATM

Key questions:

- New targets/boxes?
- One for "longer term", monthly and "weekly" science/applications?
- Understand "delta" of one pair versus two pair in this format

Joint requirements in bubble plot format

- IUGG report bubble plots "longer term"
- IUGG report bubble plots "monthly"
- IUGG report bubble plots "weekly"

Key questions:

- Where does the performance of new simulations lie relative to these documents and e.g. e-motion2 proposal to ESA?

Second part

Measurement System Requirements (needed for MRD*). Note that these should be more ambitious (and agreed to by NASA and ESA) than Science Targets by definition.

- Degree variance of integrated performance of measurement system (like GRACE-FO)

Key question: Should the above box be dependent on the below boxes? Answer: Probably not.

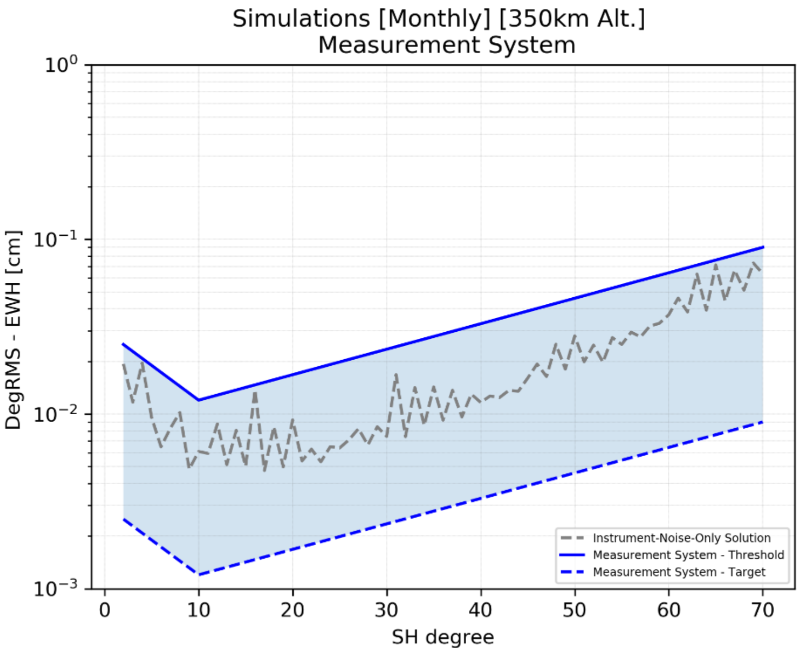
Derived following the approaches for GRACE-FO and e-motion2

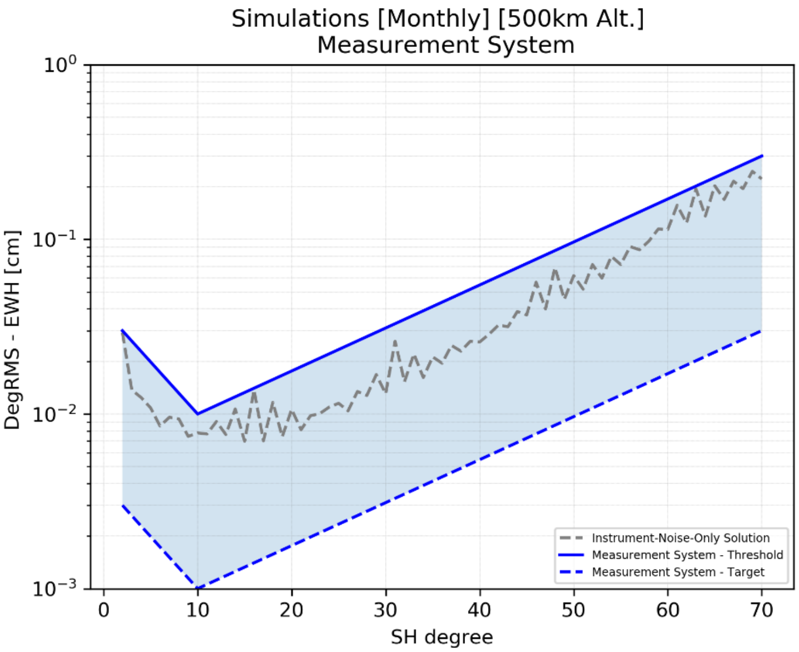
Harmonise to ensure "uniform quality products"

- Sampling Periods of polar
- Sampling Periods of Lower Inclined

* MRD – Mission Requirements Document

System Requirements





NGGM from product to instruments

The **requirements** for the SST sensor (LRI or LMI) and the accelerometer to meet the required values were derived, as presented in the table below (coloured noise).

Every mission profile belonging to a **grey box** will not meet the requirements (exe).

Sat. dist. [km] / Altitude[km]	50	100	200	300
300	>> 10	>>10	<10	<10
350	<10	<10	<1	<1
400	>1	<1	<1	<1
450	<1	<1	<1	<1
500	<1	<1	<1	<1
600	<1	<1	<1	<1

$PSD_{wn\_range} = a \cdot d$ [nm/√Hz]

where:
"a" being SST noise
"d" being intersat. distance

Sat. dist. [km] / Altitude[km]	50	100	200	300
300	o(E-12)	o(E-11)	o(E-11)	o(E-11)
350	o(E-12)	o(E-12)	o(E-11)	o(E-11)
400	o(E-13)	o(E-12)	o(E-12)	o(E-12)
450	< o(E-13)	< o(E-13)	o(E-12)	o(E-13)
500	< o(E-13)	< o(E-13)	< o(E-13)	< o(E-13)
600	< o(E-13)	< o(E-13)	< o(E-13)	< o(E-13)

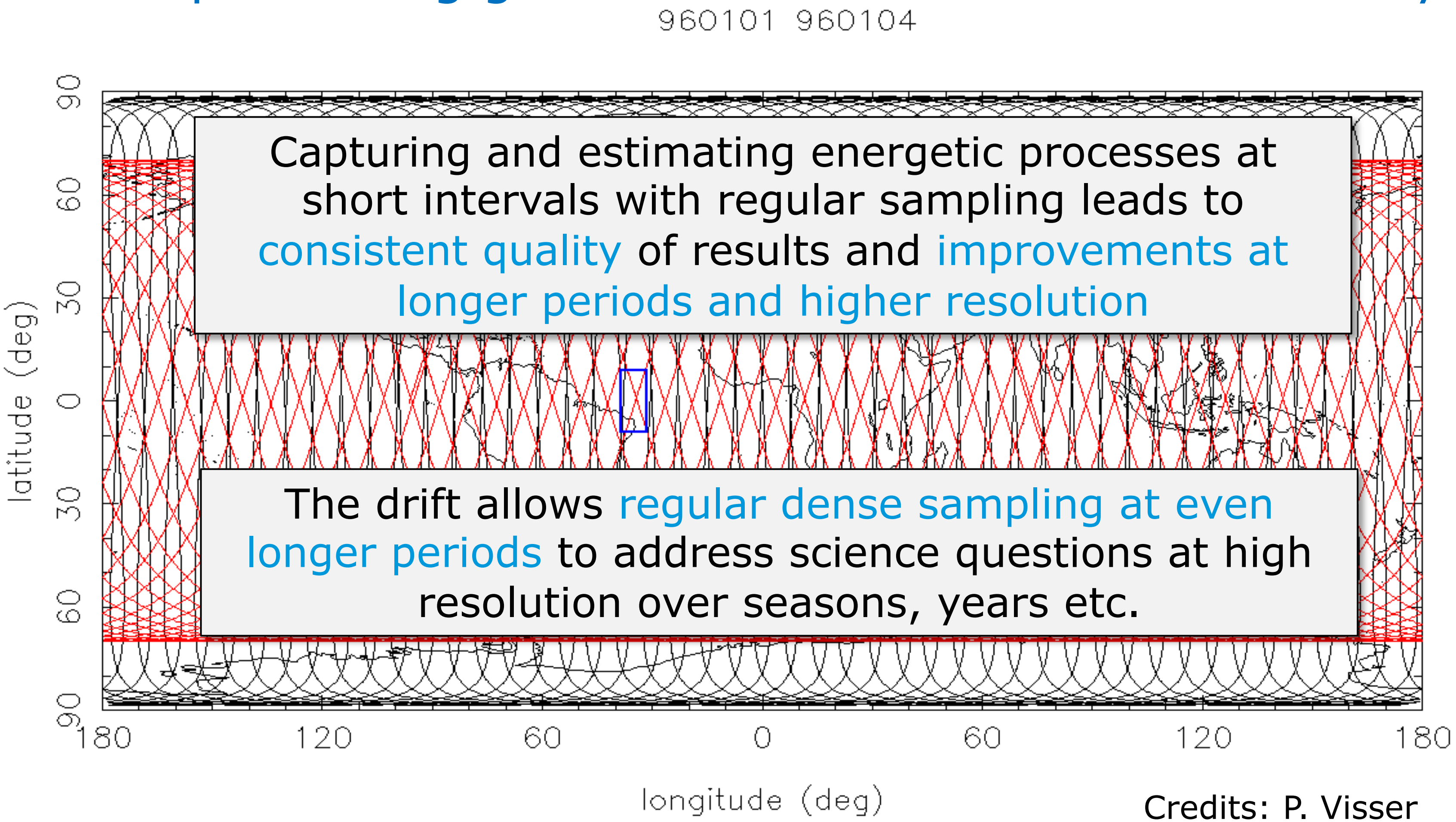
Non-gravitational differential acceleration:

$PSD_{wn\_acc} = a$ [m/s²/√Hz]
in 1 mHz < f < 100 mHz BW

3. “Optimal” design of the constellation is key to:

- capture the most demanding signals
- optimise the retrievals
- guarantees comparable quality products for the required periods (important for ECV and (near real-time) applications)
- and *requires* a degree of control of the satellites to maintain the constellation for any implementation option

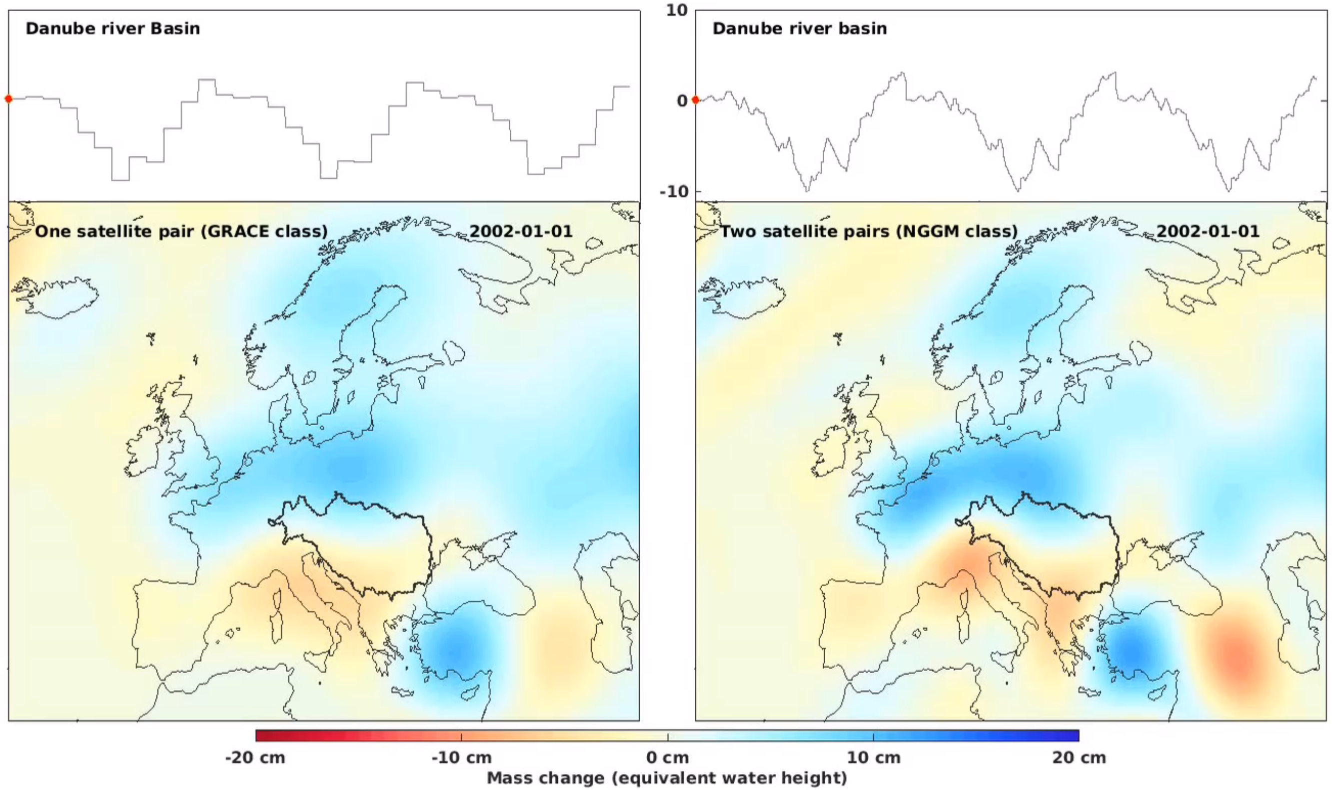
Example drifting ground tracks → Eastward near 3 days



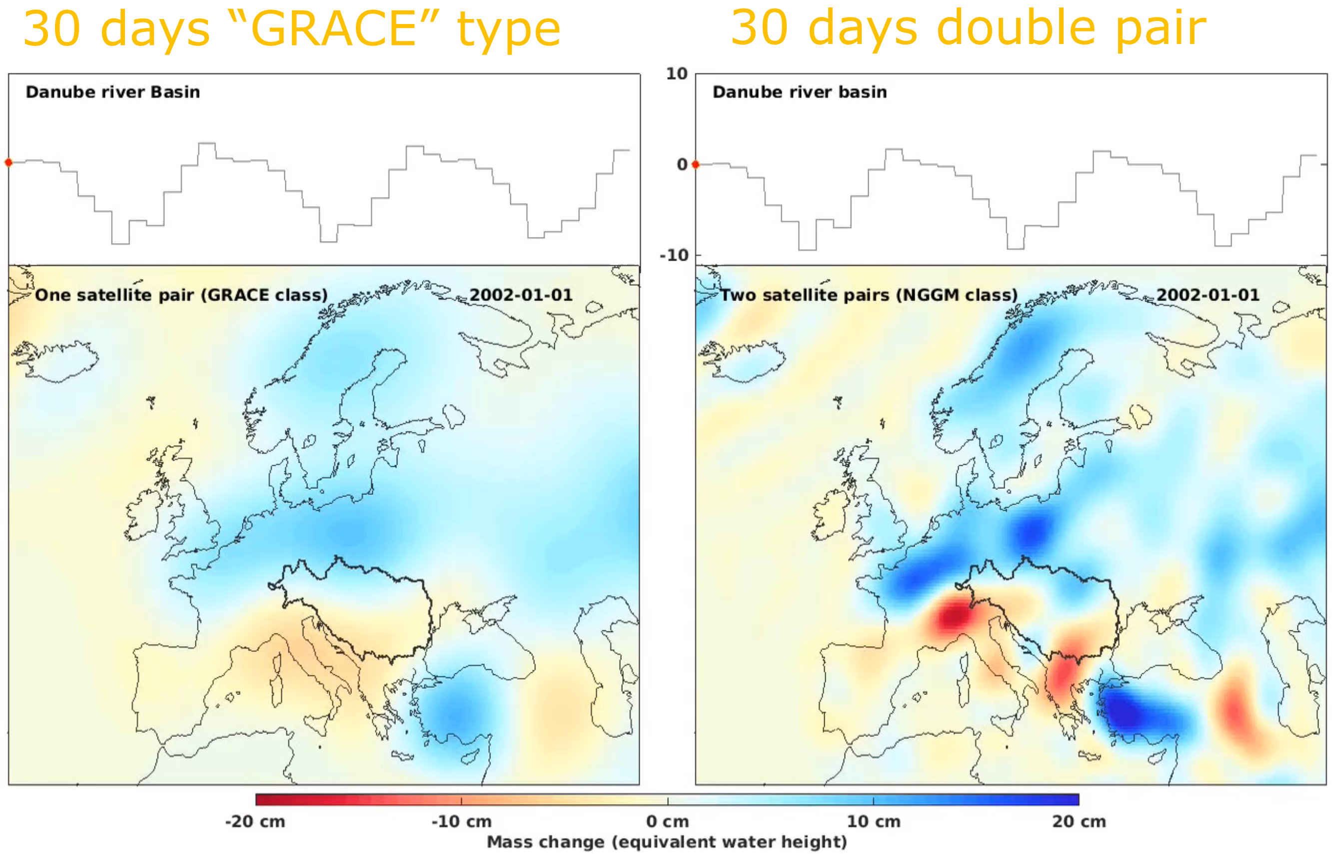
Credits: P. Visser

Example of simulation results over Europe

30 days "GRACE" type | 3 days double pair

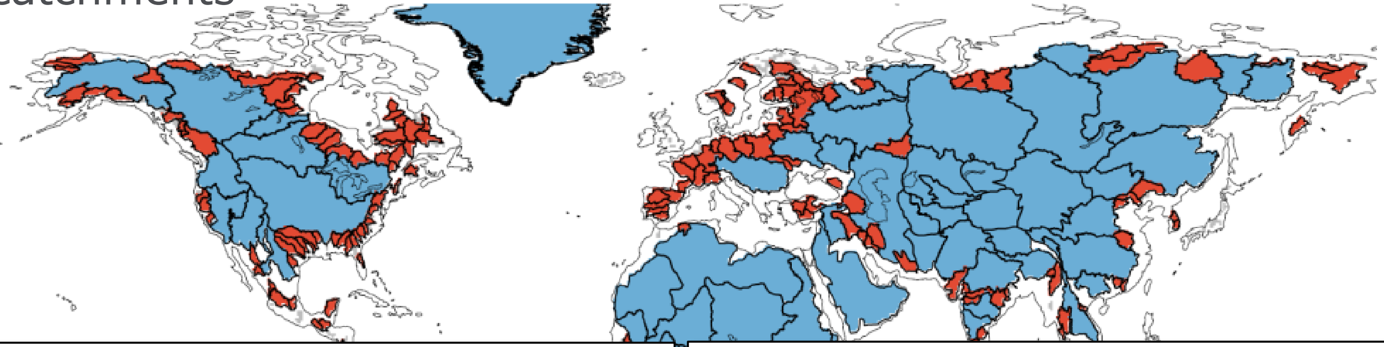


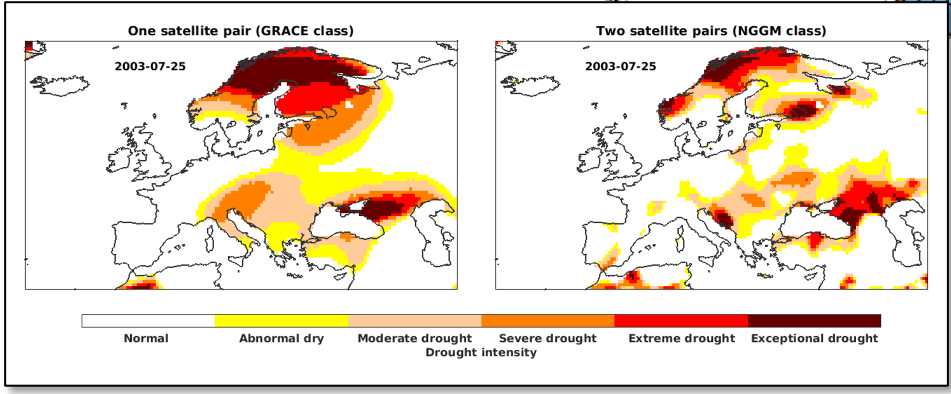
Example of simulation results over Europe

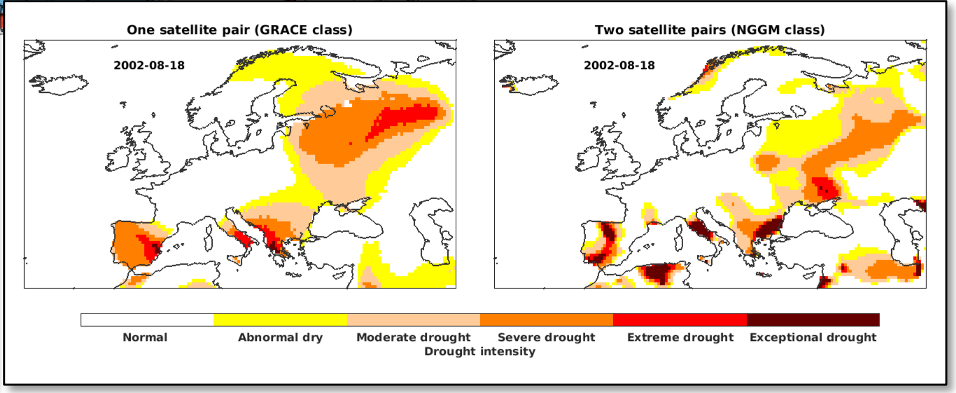


Possible results for hydrology:
better closure of the water cycle, drought and wetness indexes?

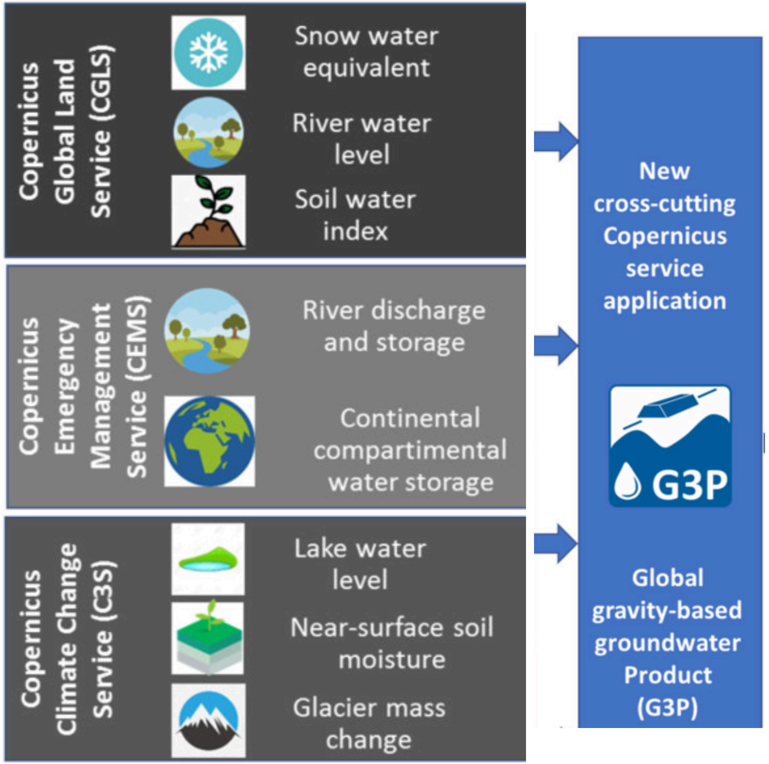
observable catchments







EC Groundwater Service and MAGIC



MAGIC will be crucial for EC groundwater service under development

4. Phase A and technology pre-developments

Background studies in ESA

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

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	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-ongoing	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 (ADDCON)	2013-2016	Munich Uni. TASI consultant	Geophysical applications and anti-aliasing (Ocean tides)
High Stability Laser (HSL1 & HSL2)	2011-ongoing	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 breadboard
Development of an Acceleration Insensitive, Thermal Noise Mitigated OSRC Engineering Model	2017-ongoing	ADS(D) STI	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)

Overview

- In this case, Phase A planning is bound by delivery of what required for decision at Ministerial Council of end 2022 to pave the way to mission implementation
- Activities for this mission include:
  - Programme steering, interactions with NASA, MS, ESA-NASA Joint Engineering Team (JET), outreach
  - Continued / expanded science support activities
  - Two parallel system studies at Phase A level
  - Technology developments: (i) within system study contracts; (ii) via dedicated contracts (see PBEO/IPC papers)
  - End-to-end performance simulators and simulation campaigns
  - Internal work (including with ESA technology experts)

Phase A Main Activities Schedule Overview

Phase A System Studies: ITT issued 18.12.20, kick-off planned in April '21. Preliminary Requirements Review (PRR) in May-June '22. End of system activities by October '22. The contracts shall include technology developments in addition to the ones below.

End-to-end simulators: at mission level, in context of science studies; at system level (i.e. up to L1 products) within the system studies above

Laser Tracking Instrument (LTI) development: RFQ being issued. Kick-off planned in March '21. Reach TRL 5 by end phase A for critical units, TRL 6 at complete LTI level by PDR.

(Enhanced MicroSTAR) accelerometer development: RFQ issued to ONERA. Kick-off planned in April '21. Reach TRL 5 by end phase A for the core + new wire (further envisaged: TRL 6 for the same items by phase B kick-off and for complete accelerometer latest by PDR)

T5 Gridded Ion Engine thruster development: RFQ issued to Mars Space Ltd. Kick-off planned in March '21. Reach TRL 5 by end phase A for neutraliser and critical items of thruster (further envisaged: TRL 6 for same items by SRR and finally for complete subsystem latest by PDR)

In-FEEP thruster development: Kick-off planned in June '21. Reach TRL 5 by phase B kick-off for critical items (neutraliser, PPU), TRL 6 for complete subsystem by PDR (assuming FEEP selected in system studies)

Phase A System Studies: Objectives, Logic,

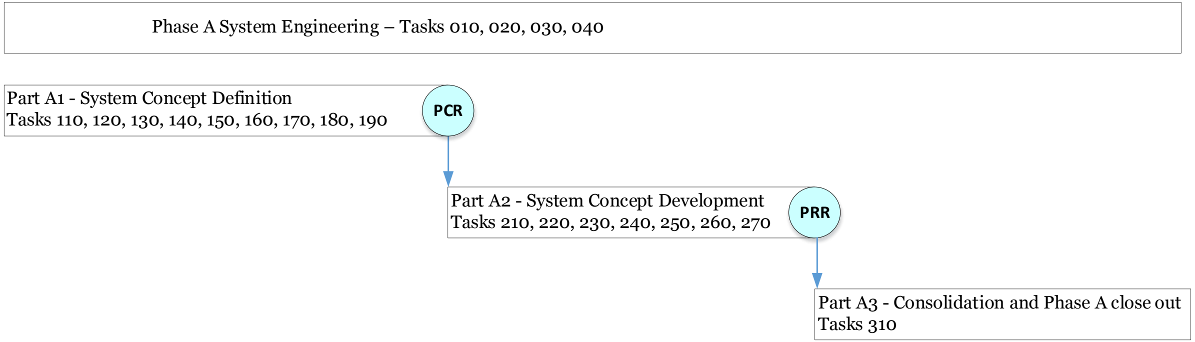
<u>Nominal payload</u>: Laser Tracking Instrument (LTI), accelerometers, GNSS receiver (latter not analysed in our studies but for accommodation)

<u>Optional payload</u> considered for accommodation, system and development implications,.. Not driving schedule/cost

Strong inter-links payload-system-constellation designs

Study includes:

- analysis of mission / system functions and requirements for all elements, end-to-end system performance simulator, launch, prototype data processing algorithms up to L1, operations and ground segment basics
- analyse of architectural scenarios at constellation and satellite level in view of cooperation with NASA
- analysis of complexity / cost with respect to e.g. lifetime



Options for orbit control / drag compensation

Key requirement: orbit control in the pair <u>and</u> among the pairs

Continuous drag compensation provides orbit control + measurement performance improvement

➔ orbit control is a must, while (continuous) drag compensation can be implemented to different extents depending on (i) targeted performance; (ii) selected orbit for the pair

We refer to 3 degree-of-freedom (DoF) drag compensation when only attitude control is performed

Options for trade-off therefore include:

- 3 DoF = attitude control only (orbit control by classical on/off thrusting)
- 4 DoF = GOCE case (along-track drag also compensated)
- 6 DoF = all forces and torques are compensated

In Phase 0, emphasis was put on most demanding/performant case: 6 DoF.

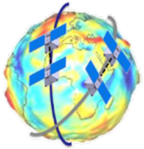
In Phase A, trade-offs will identify solution.

On/off thrusting can limit performance (cf GRACE) ➔ low-noise proportional (throttable) thrusting preferred

Options for this: cold gas type or electrical propulsion type (baseline at end Phase 0)

Mass change: the unique cross-cutting variable

- Implicitly assumed as backbone information for multiple Copernicus services (land/hydrology, climate, marine, emergency)



- Providing also the global context at medium and long term for all water related elements in atmosphere, land, ocean, ice, solid earth and thus climate
- TWS ECV and Crucial for many water cycle related ECVs in GCOS
- Unique in providing ground water information essential for water management and droughts/floods
- No operational gravity mission after GRACE-FO
- Immediate opportunities for a cross-cutting mission enabling a constellation in international cooperation