National Aeronautics and
Space Administration

EXPLORE EARTH

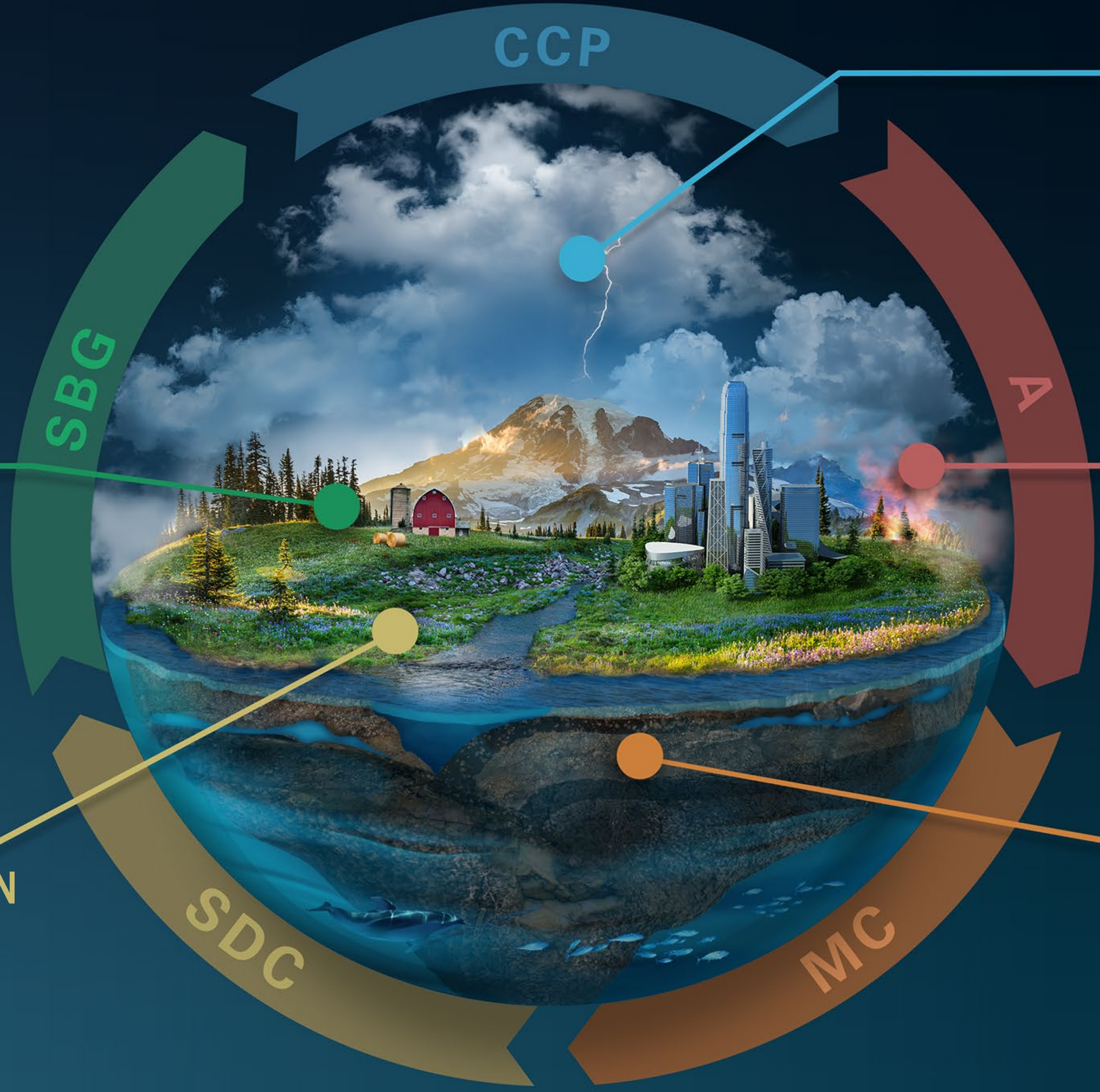
Mass Change Town Hall

Julie A. Robinson, Ph.D.
Deputy Director, Earth Science Division
Science Mission Directorate, NASA

Dec. 13, 2022

EARTH SYSTEM OBSERVATORY

INTERCONNECTED CORE MISSIONS



CLOUDS, CONVECTION AND PRECIPITATION

Water and Energy in the Atmosphere

SURFACE BIOLOGY AND GEOLOGY

Earth Surface & Ecosystems

AEROSOLS

Particles in the Atmosphere

SURFACE DEFORMATION AND CHANGE

Earth Surface Dynamics

MASS CHANGE

Large-scale Mass Redistribution

EARTH SYSTEM OBSERVATORY

INNOVATION & COMPETITION
EARTH EXPLORER MISSIONS

Greenhouse Gases

Ozone and Trace Gases

Atmospheric Winds

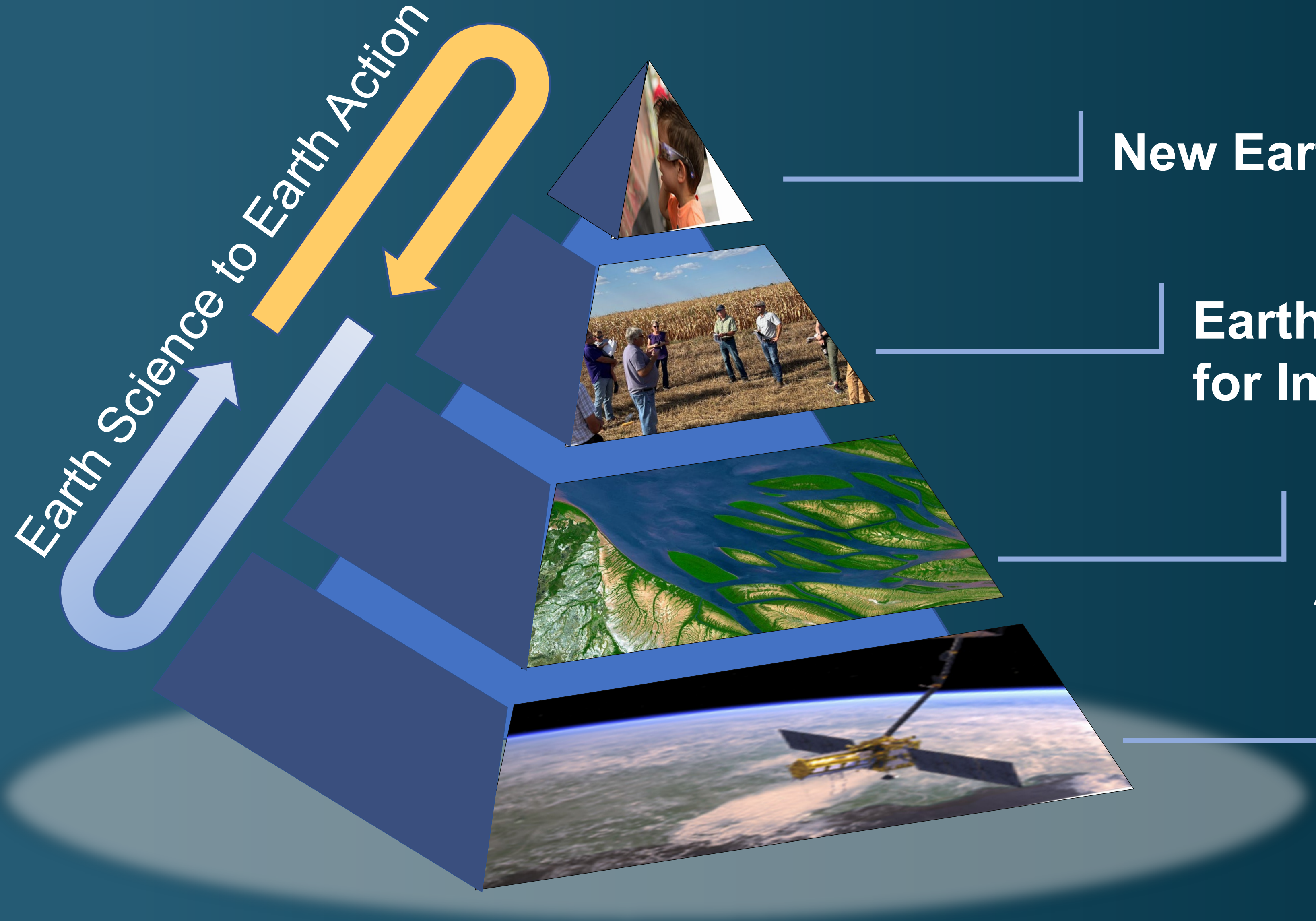
Ice Elevation

Snow Depth and Water Content

3D Ecosystem Structure

Ocean Surface Winds and Currents

NASA Earth Action Strategy



New Earth Information Center

Earth Action Solutions for Impact

Earth System Science & Applications Incubation

Earth System Observations

NASA EARTH

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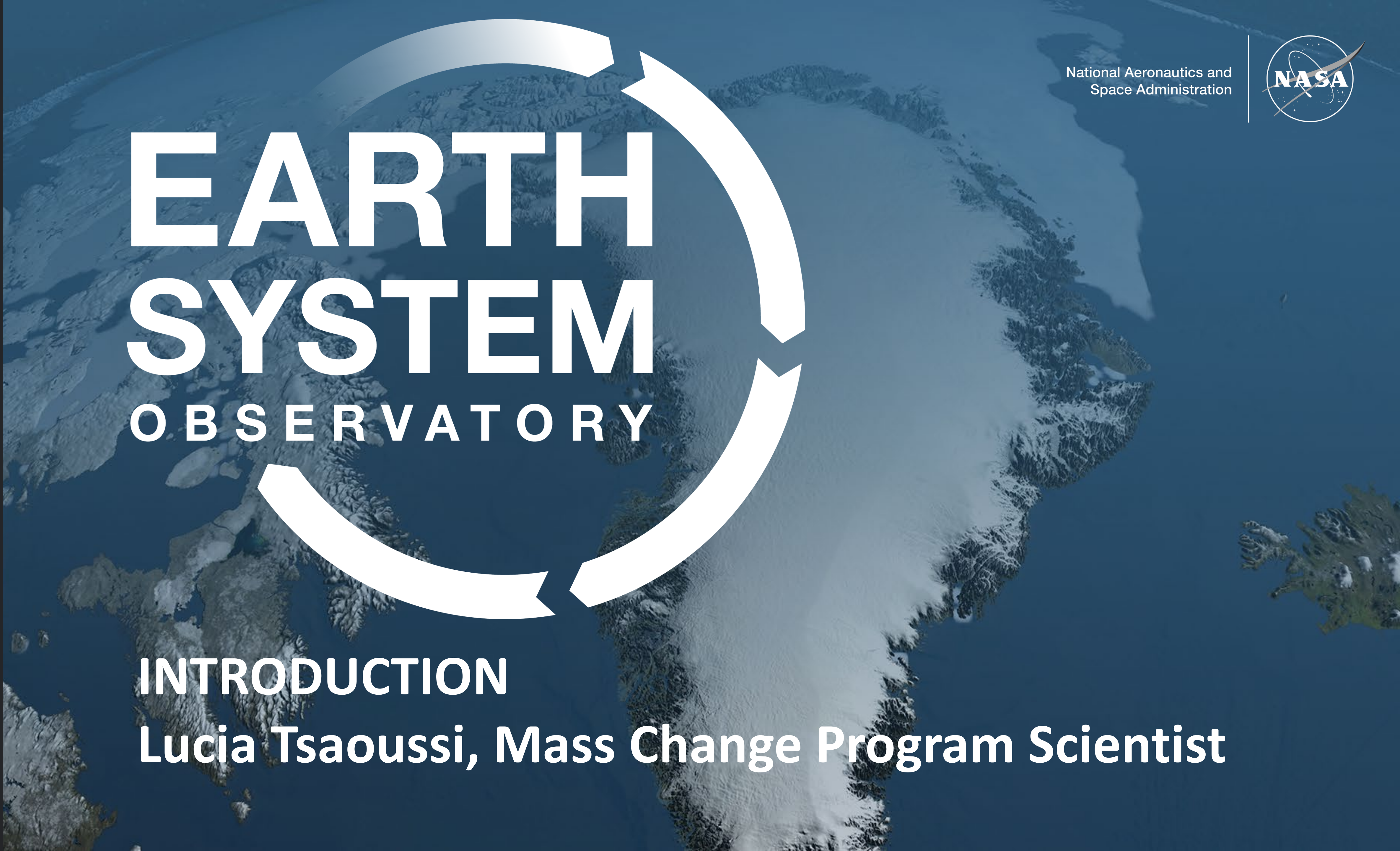
MASS CHANGE TOWN HALL

AGU 2022 – 13 DECEMBER 2022



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INTRODUCTION

Lucia Tsaoussi, Mass Change Program Scientist

Mass Change Mission Collaboration

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- Mass Change is 1 of 5 Designated Observables in the 2017 Decadal Survey
  - NASA and International partners are collaborating to implement the next gravity/mass change mission
- The goal of the agencies is to materialize the Bender constellation, shown to meet science and societal objectives described in 2015 paper (Pail et. al.) and by the IUGG Expert Panel *
  - The agencies built on a successful legacy of previous missions: GRACE & GRACE-FO by NASA and DLR, and GOCE by ESA
  - The project will report today on their status and plans
- MC is one of the four missions of the Earth System Observatory (ESO).
  - NASA works to integrate the ESO missions by leveraging engineering, science, data systems and applications capabilities
    - ESO integration will enable multi-disciplinary and interdisciplinary research, and augment the missions' community of practice

Pail, R., Bingham, R., Braitenberg, C. *et al.* Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society. *Surv Geophys* **36**, 743–772 (2015). https://doi.org/10.1007/s10712-015-9348-9

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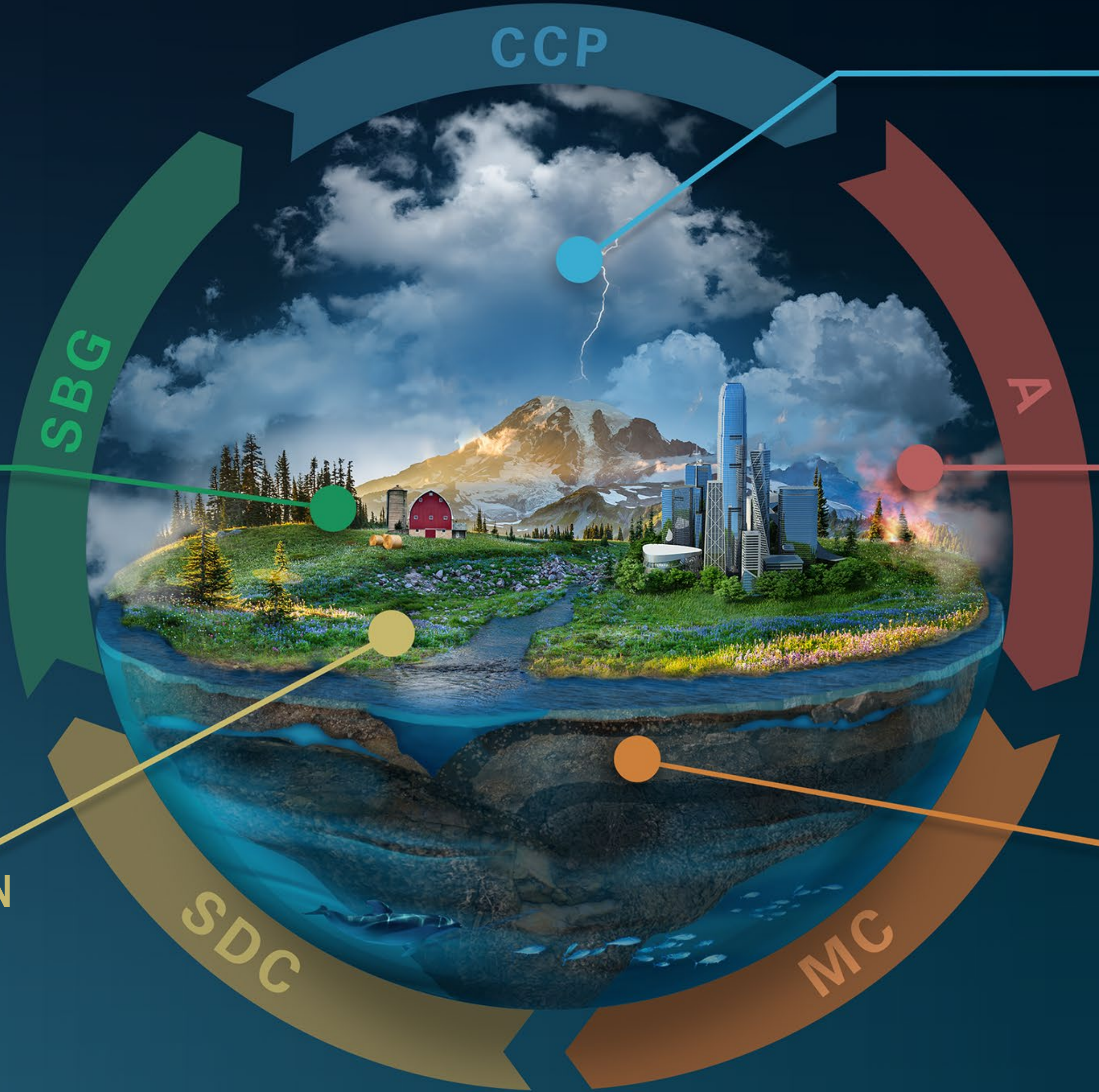
INTERCONNECTED CORE MISSIONS



CLOUDS, CONVECTION AND PRECIPITATION

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Large-scale Mass Redistribution

MASS CHANGE

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OPENING REMARKS

Bernie Bienstock, Mass Change Project Office

MASS CHANGE

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AGENDA

Welcome	Julie Robinson / NASA HQ
Introduction	Lucia Tsaoussi / NASA HQ
Opening Remarks	Bernie Bienstock / JPL, Caltech
Overview	Mike Gross / JPL, Caltech
DLR – P1 Status	Michael Nyenhuis / DLR
ESA – P2 Status	Ilias Daras / ESA
Science	David Wiese / JPL. Caltech
Mission Implementation	André Girerd / JPL. Caltech
Summary	Mike Gross / JPL. Caltech
Community Discussion / Questions	Moderated by David Wiese / JPL. Caltech

MASS CHANGE

Mass Change Development

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- Mass Change (MC) DO study began in October 2018
- Continued through 2019, 2020, until May 2021 – hosted town halls at the past 3 AGUs
- Developed the SATM, including vetting by the community
- Defined architecture classes, with science value metrics for each
- Studied predicted life of GRACE-FO to meet the continuity requirements of the DS
- Assessed technology readiness, risks and maturation plans
- Identified potential international partnerships and began dialogues with each
- Produced a comprehensive final report in July 2021, summarized in AGU publication*

* Wiese, D., Bienstock, B., *et al*. The Mass Change Designated Observable Study: Overview and Results,
AGU Earth and Space Science, Volume 9, Issue 8, August 2022,
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022EA002311

Identified High-Level Architectures

The MC study team analyses included:

- NASA Headquarters (HQ) guidance and constraints
- Decadal Survey (DS) recommendations
- Community input
- Technology readiness
- High-level cost estimates
- International partner interest, capabilities, and readiness

The highest-value architectures were identified to

- Provide acceptable levels of DS recommended science, as judged by the community
- Include technology elements that can be matured within the MC timeframe

MASS CHANGE

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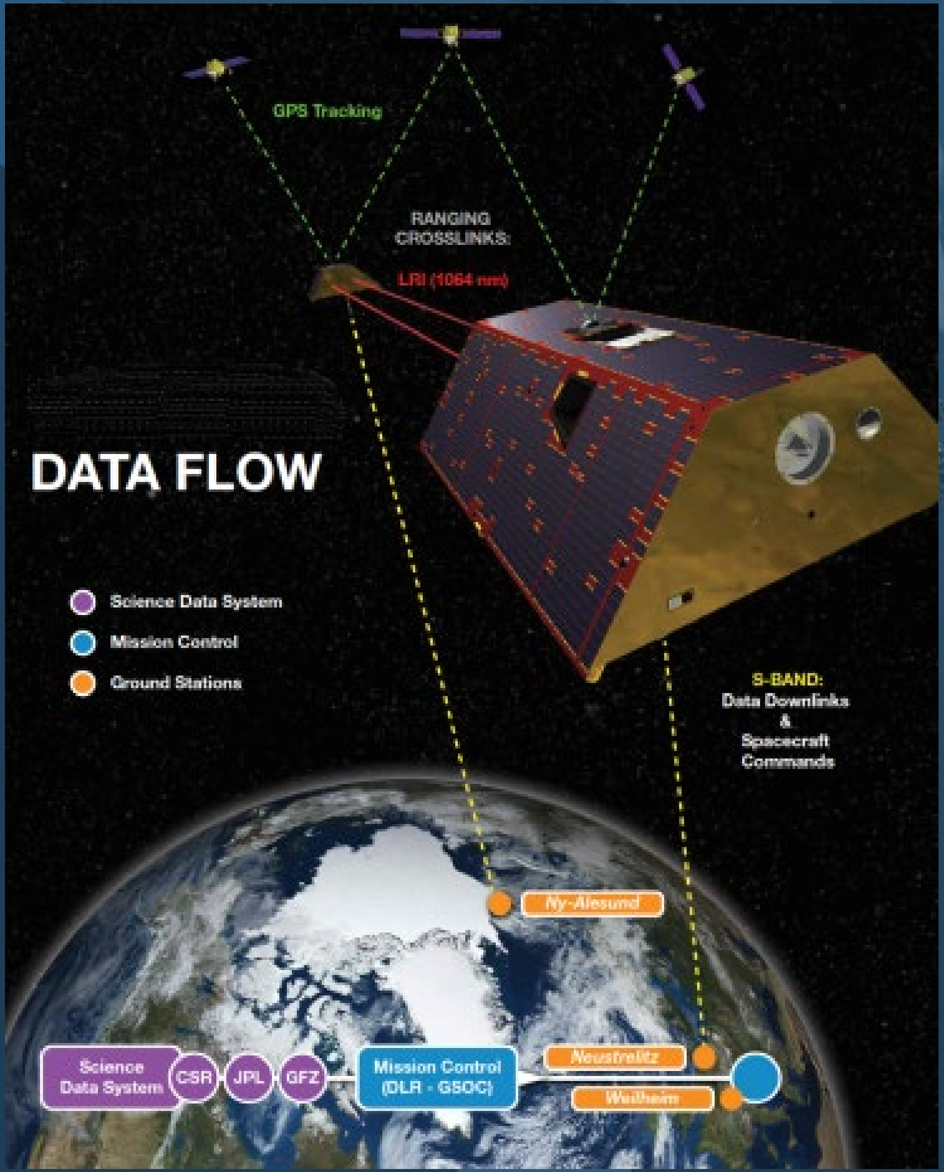
OVERVIEW

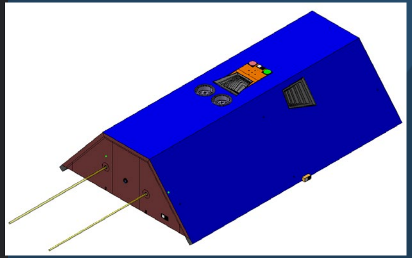
Mike Gross, Mass Change Project Manager

Mature Mass Change (MC) Mission Concept

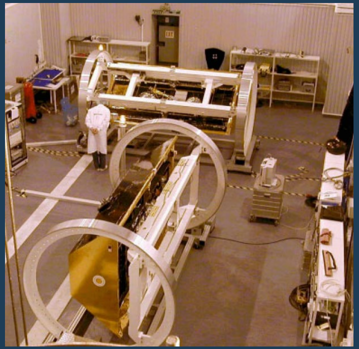
- Implementation and operation architecture is same as GRACE/GRACE-FO
- Division of responsibilities between US (NASA) and Germany (DLR) is the same as GRACE-FO
- Launch is currently planned for Late 2027/Early 2028
- Continuity of the gravity record is fundamental



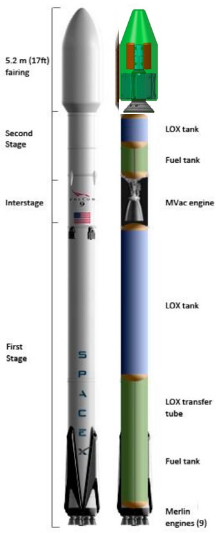
MC and GRACE-FO Architectures are Nearly Identical



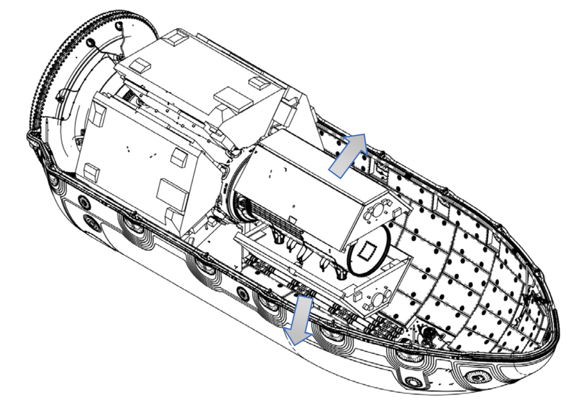
Satellite



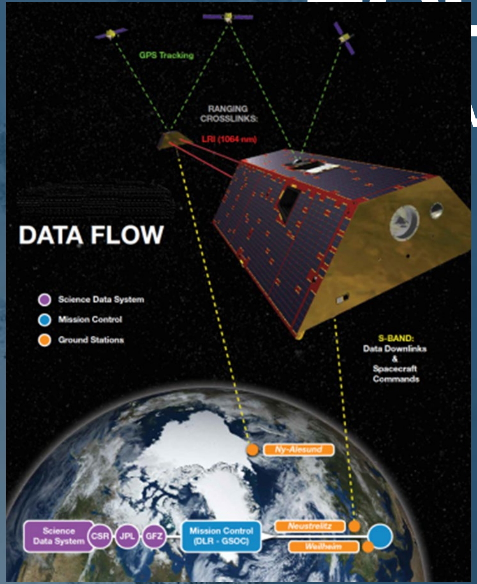
Integration & Test



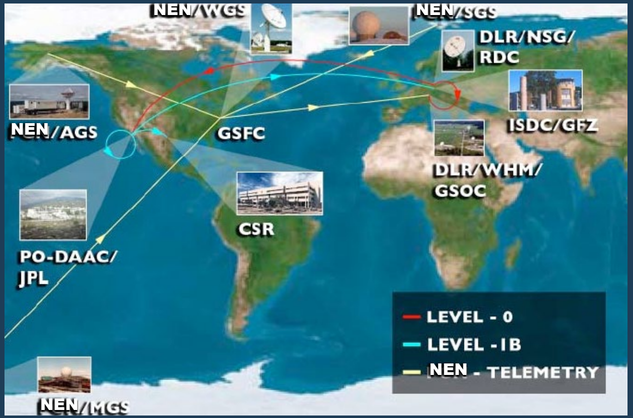
Launch



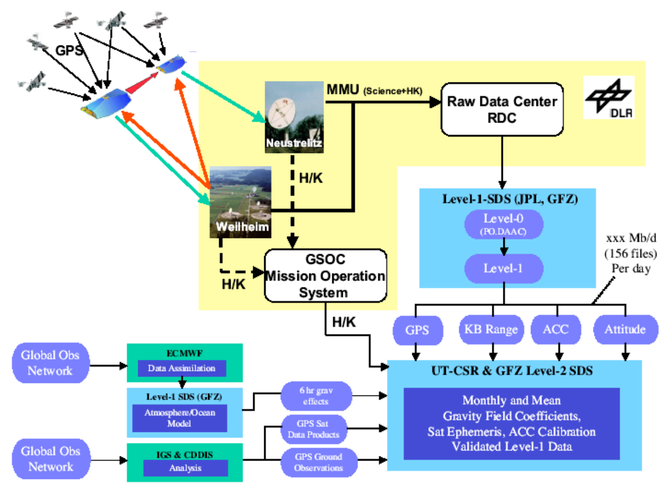
Dispensing



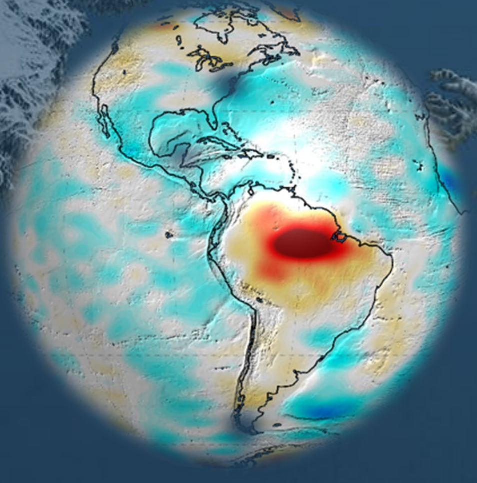
Operation



Ground Stations and Data Flow



End-to-End Information System



Science

Project Implementation Maturity Beyond Typical for Phase-A

- MC currently has baselined the same satellite-satellite tracking implementation as GRACE-FO
  - Laser Ranging Interferometer (LRI) replaces Microwave Ranging Instrument
  - Gravity fields derived from LRI tech demo on GRACE-FO are consistent with those derived from MWI, while offering improved performance at high frequencies (Pie et al., 2021; Peidou et al, 2021; Ghobadi-Far et al., 2020)
- Approaches to ACC redundancy will be assessed in Phase A, including potential contribution from ESA
- Major Project Milestones (all are current estimates and might change)
  - System Requirements Review/Mission Design Review (SRR/MDR) - March 2023
  - Preliminary Design Review (PDR) – February 2024
  - Critical Design Review (CDR) – April of 2025
  - Assembly, Integration and Test (AIT) – October 2026
  - Launch – Currently planned for Late 2027/Early 2028.

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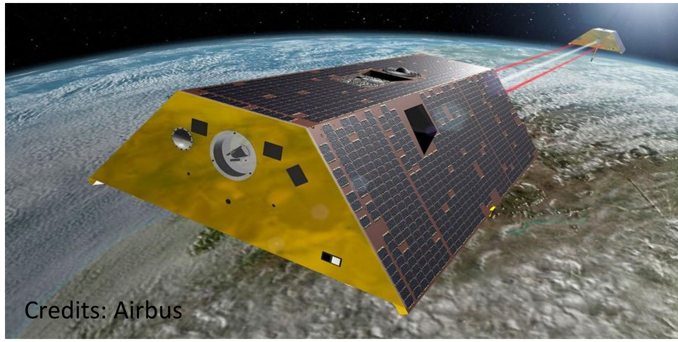
DLR – P1 STATUS

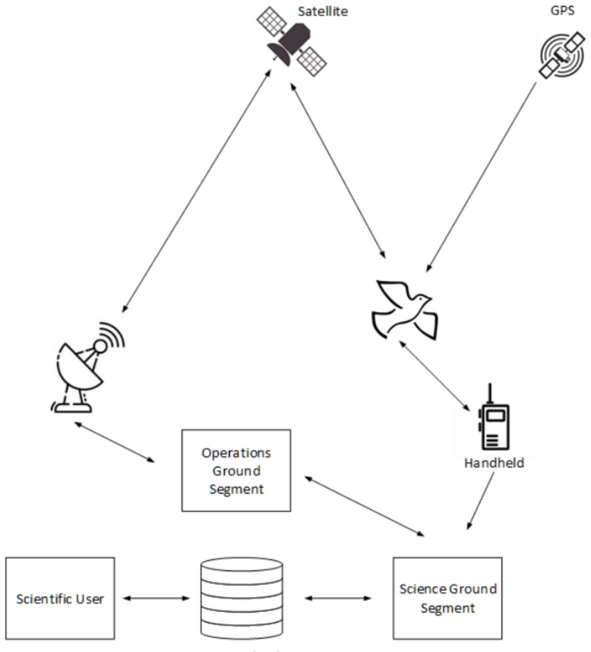
Michael Nyenhuis,
DLR Mass Change Project Manager

Continue US-D partnership on mass transport monitoring

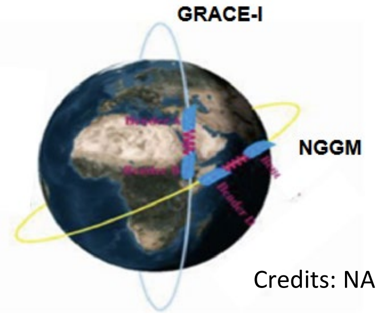
- Germany shares NASA's ambitions to continue **mass transport monitoring** as **one of five top priorities in EO for the next decade** highlighted in the NASA Earth Science Decadal Survey Report.
- To continue the **very successful technological and scientific GRACE/GRACE-FO partnership** Germany initially proposed a **joint US-D MC/GRACE-I mission** combining
  - a quickly realized single-pair **GRACE-FO successor** based on redundant LRI SST with launch in 2027 into a polar orbit to guarantee **data continuity**, and
  - an (optional) **ICARUS payload** (International Cooperation for Animal Research Using Space) which globally monitors animal movements as biodiversity indicator.
- Germany supports **NGGM*** in the Mission of Opportunity element of ESA's FutureEO program as the **second component of a double pair mission** (P1/P2 staggered approach).



Credits: Airbus

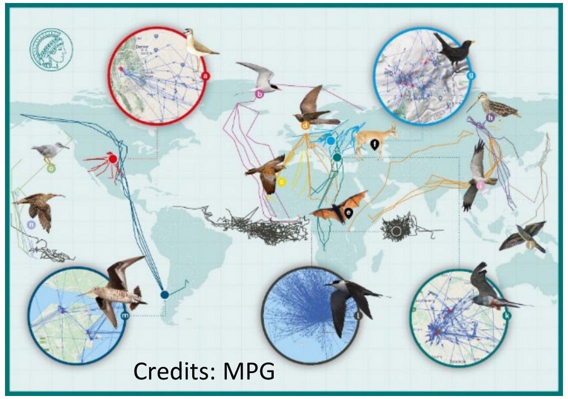


Credits: STI



Credits: NASA/JPL

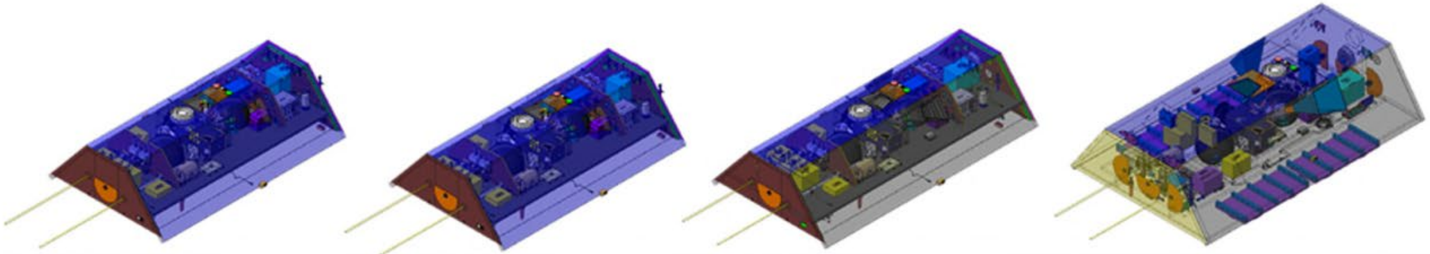
* NGGM = Next Generation Gravity Mission

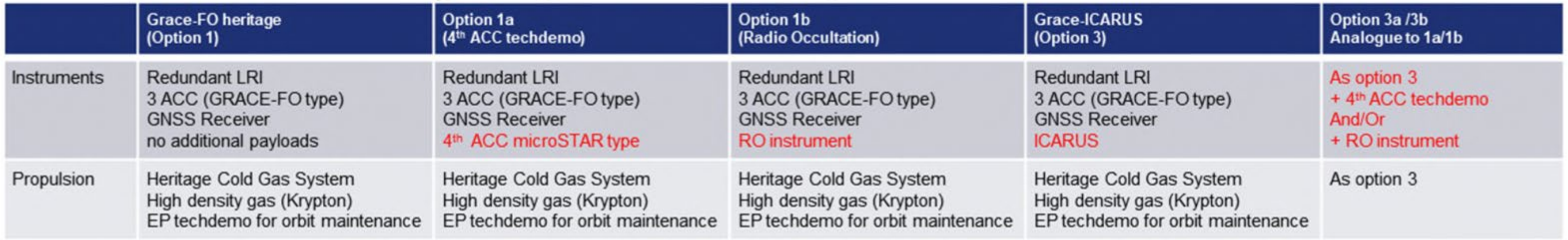


Credits: MPG

MC/GRACE-I Phase A study results (Apr-Sep 2022)

Detailed Mission Analysis (funded by BMBF, Lead by GFZ, supported by DLR, close collaboration with NASA/JPL and ESA)





	Grace-FO heritage (Option 1)	Option 1a (4th ACC techdemo)	Option 1b (Radio Occultation)	Grace-ICARUS (Option 3)	Option 3a /3b Analogue to 1a/1b
Instruments	Redundant LRI 3 ACC (GRACE-FO type) GNSS Receiver no additional payloads	Redundant LRI 3 ACC (GRACE-FO type) GNSS Receiver 4th ACC microSTAR type	Redundant LRI 3 ACC (GRACE-FO type) GNSS Receiver RO instrument	Redundant LRI 3 ACC (GRACE-FO type) GNSS Receiver ICARUS	As option 3 + 4th ACC techdemo And/Or + RO instrument
Propulsion	Heritage Cold Gas System High density gas (Krypton) EP techdemo for orbit maintenance	Heritage Cold Gas System High density gas (Krypton) EP techdemo for orbit maintenance	Heritage Cold Gas System High density gas (Krypton) EP techdemo for orbit maintenance	Heritage Cold Gas System High density gas (Krypton) EP techdemo for orbit maintenance	As option 3

- Two satellites **based on GRACE-FO with technical enhancements**
  - Partly redundant LRI as SST instrument
  - Improved acceleration measurement (redundant ACCs based on GRACE-FO superSTAR or “adapted microSTAR”)
  - Heritage cold gas thrusters, potential improvements (hybrid concept with EP) discussed
- **Optional payloads**
  - ICARUS to detect animal movements (operational biodiversity monitoring in parallel to variations in the global water cycle)
  - Radio occultation (RO) instrument
- **Discarded options**
  - Low-shock cold gas thrusters
  - MicroSTAR (4th ACC) and Quantum gravity gradiometer (QGG) tech demos

MC/GRACE-I Phase A study results (Apr-Sep 2022)

Detailed Mission Analysis (funded by BMBF, Lead by GFZ, supported by DLR, close collaboration with NASA/JPL and ESA)

- Joint effort: 3 TIMs & PRR (Preliminary requirements review) co-location involving NASA/JPL and ESA
- Identified **synergies and commonalities of MC/GRACE-I and NGGM** (i.e. P1 and P2 in MAGIC) in cooperation with ESA
- Successful PRR in Sep 2022 with key recommendations:
  - Technical showstoppers have not been identified. The results of the PRR **permit the transition into Phase B**.
  - **NASA/JPL and DLR to harmonize programmatic boundary conditions** for a joint mass change mission: requirements baseline, redundancy concept (ACC/LRI), PA-approach, launcher strategy, NGGM/MAGIC framework and implementation schedule. Harmonization with ESA with regard to the MAGIC cooperation is strongly recommended.
  - To meet the expectations and needs of the scientific community for continuity and - in the frame of MAGIC - enhanced spatial / temporal resolution of mass transport products a **minimum lifetime of 5 years** (goal: 7 years) needs to be achieved.

German Parliament has approved
the budget to allow implementation of baseline option of “MC/GRACE-I” without ICARUS or RO

→ GRACE-FO re-built with enhancements and LRI as primary SST technology
→ Start of Phase B/C/D for German contributions required in 2023

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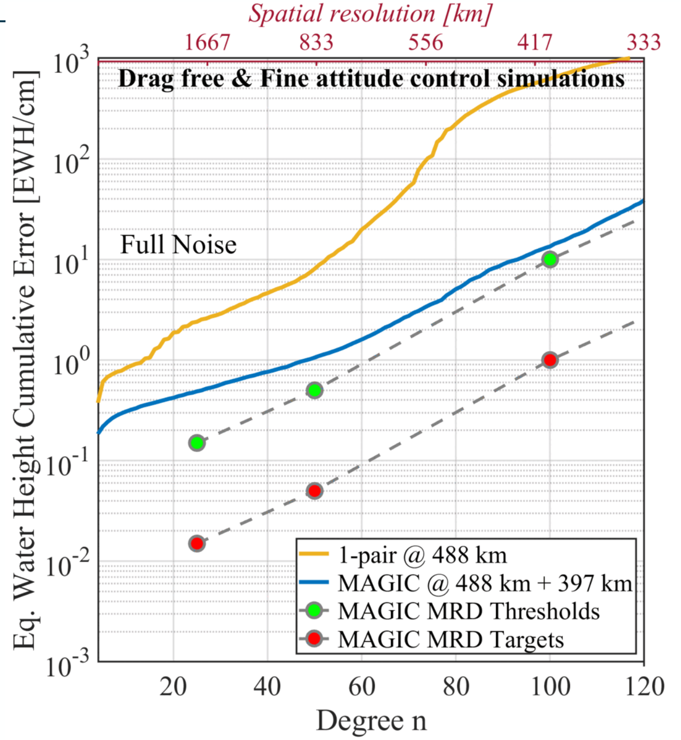
ESA – P2 STATUS

Ilias Daras,
ESA NGGM/MAGIC Mission Scientist

MAGIC *An international constellation for mass change science and applications*

- **MA**ss-change and **G**eosciences **I**nternational **C**onstellation (**MAGIC**) is the joint **NASA/ESA** two-pair “Bender-type” constellation concept based on NASA’s **MCDO** and ESA’s **NGGM** (**N**ext **G**eneration **G**ravity **M**ission).
- Enhanced continuity after **GRACE-FO** ensured to preserve climate series, per US Decadal Survey 2018
- Strong user demand expressed by **IUGG**, **IAG**, **GGOS** for improved temporal and spatial resolutions and accuracy in enhanced continuity of observations, paving the way to future sustained observations



Single-pair vs. MAGIC constellation (current assumptions) L2 performance against Measurement System and Mass Change product MAGIC MRD requirements.

- Goal is to implement a pre-operational mission with improved observations to meet science and application objectives outlined in ESA/NASA MAGIC **M**ission **R**equirements **D**ocument (**MRD**).

MAGIC *An international constellation for mass change science and applications*

First satellite pair (P1)- Mass Change / GRACE-I

- Implemented via a US-Germany fast-paced cooperation programme to ensure continuity of observations with GRACE-FO, with potential ESA in-kind contributions for a new generation of accelerometers

Second satellite pair (P2) – NGGM

- Nov. 2022 ESA’s Council at Ministerial level resolved that FutureEO-1 programme will include the start of the development of NGGM/MAGIC in cooperation with NASA

- Implemented via Europe-US cooperation programme with potential NASA in-kind contributions for a redundant Laser Ranging Instrument

- **Inclined controlled orbit** with a target altitude of **~400 km** and inclination between **65 deg** and **70 deg,** forming a **“Bender constellation”** to mitigate spatio-temporal aliasing errors

- Target launch aiming to maintain a minimum of 4 years of combined operations between P1 and P2

- **MicroSTAR** family accelerometers developed by ONERA for ESA with GOCE-like performance

- Hybrid propulsion concept: electric propulsion for orbit maintenance & drag compensation, linear cold gas thrusters for fine attitude control/drag compensation

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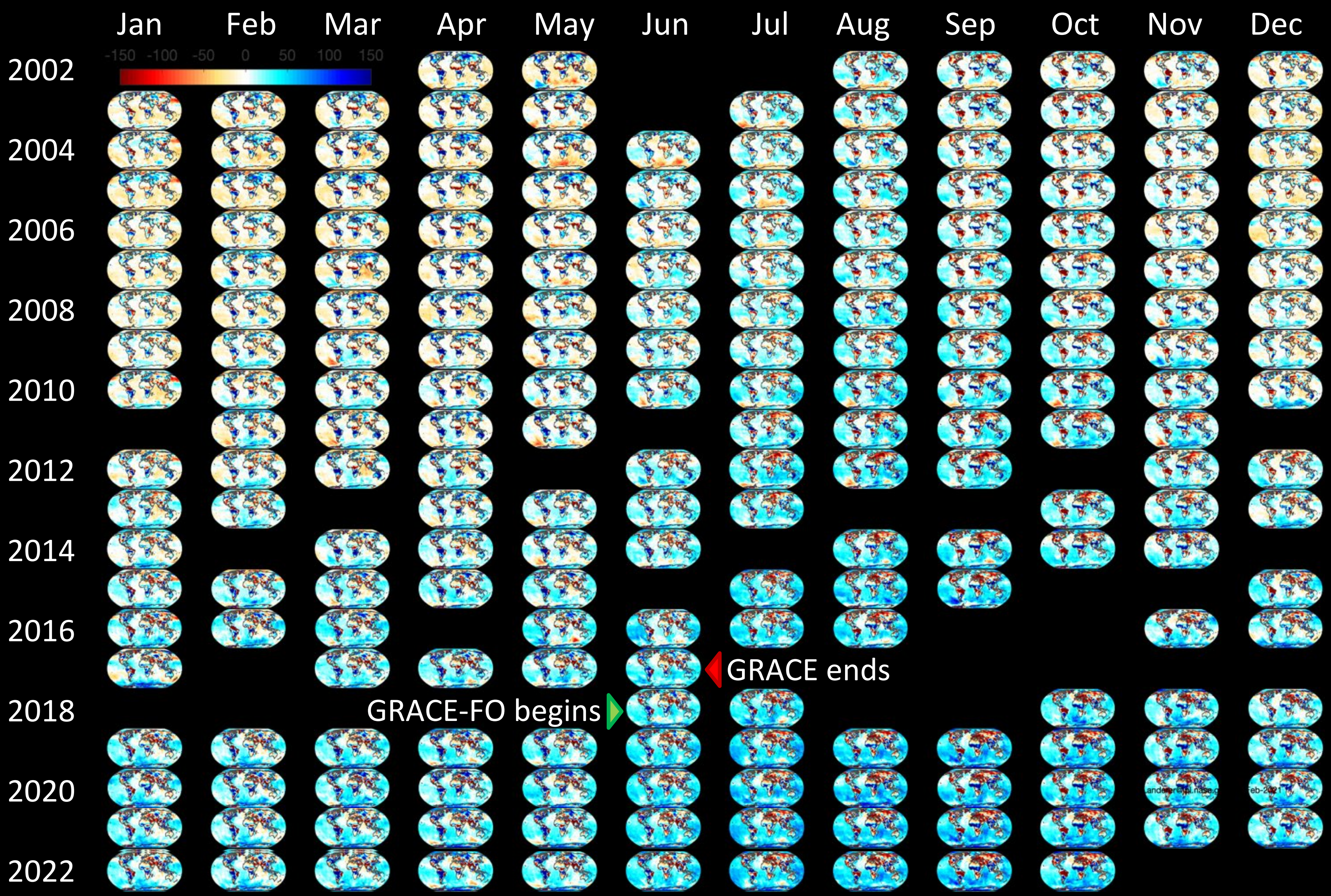
SCIENCE

David Wiese, Mass Change Scientist

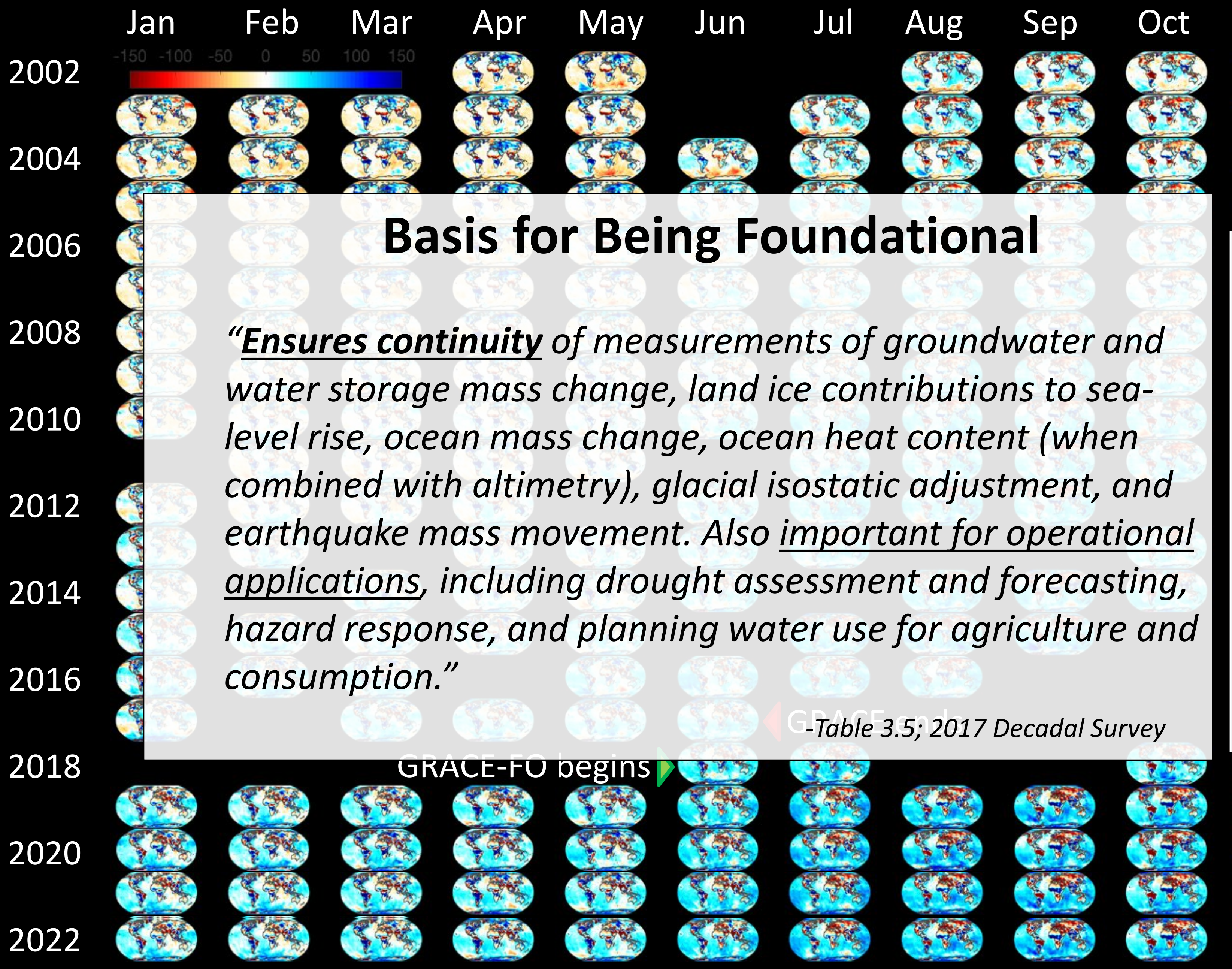
GRACE and GRACE-FO: 20 years of Amazing Discoveries



GRACE ends

GRACE-FO begins

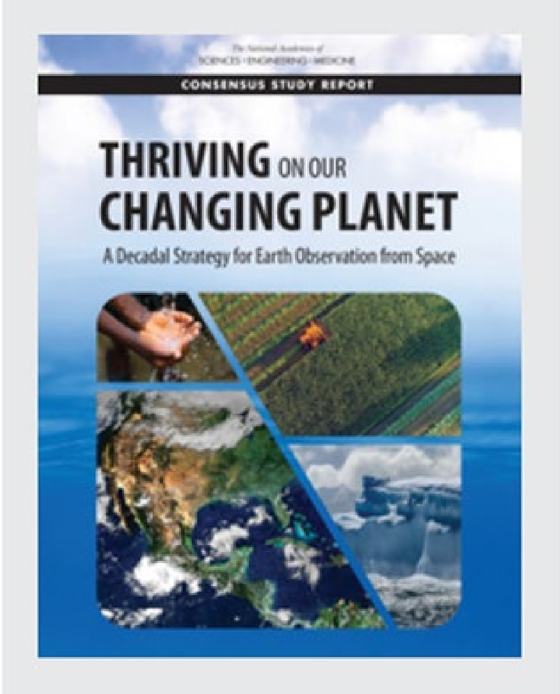
GRACE and GRACE-FO: 20 years of Amazing Discoveries



Basis for Being Foundational

*"**Ensures continuity** of measurements of groundwater and water storage mass change, land ice contributions to sea-level rise, ocean mass change, ocean heat content (when combined with altimetry), glacial isostatic adjustment, and earthquake mass movement. Also important for operational applications, including drought assessment and forecasting, hazard response, and planning water use for agriculture and consumption."*

-Table 3.5; 2017 Decadal Survey



The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space

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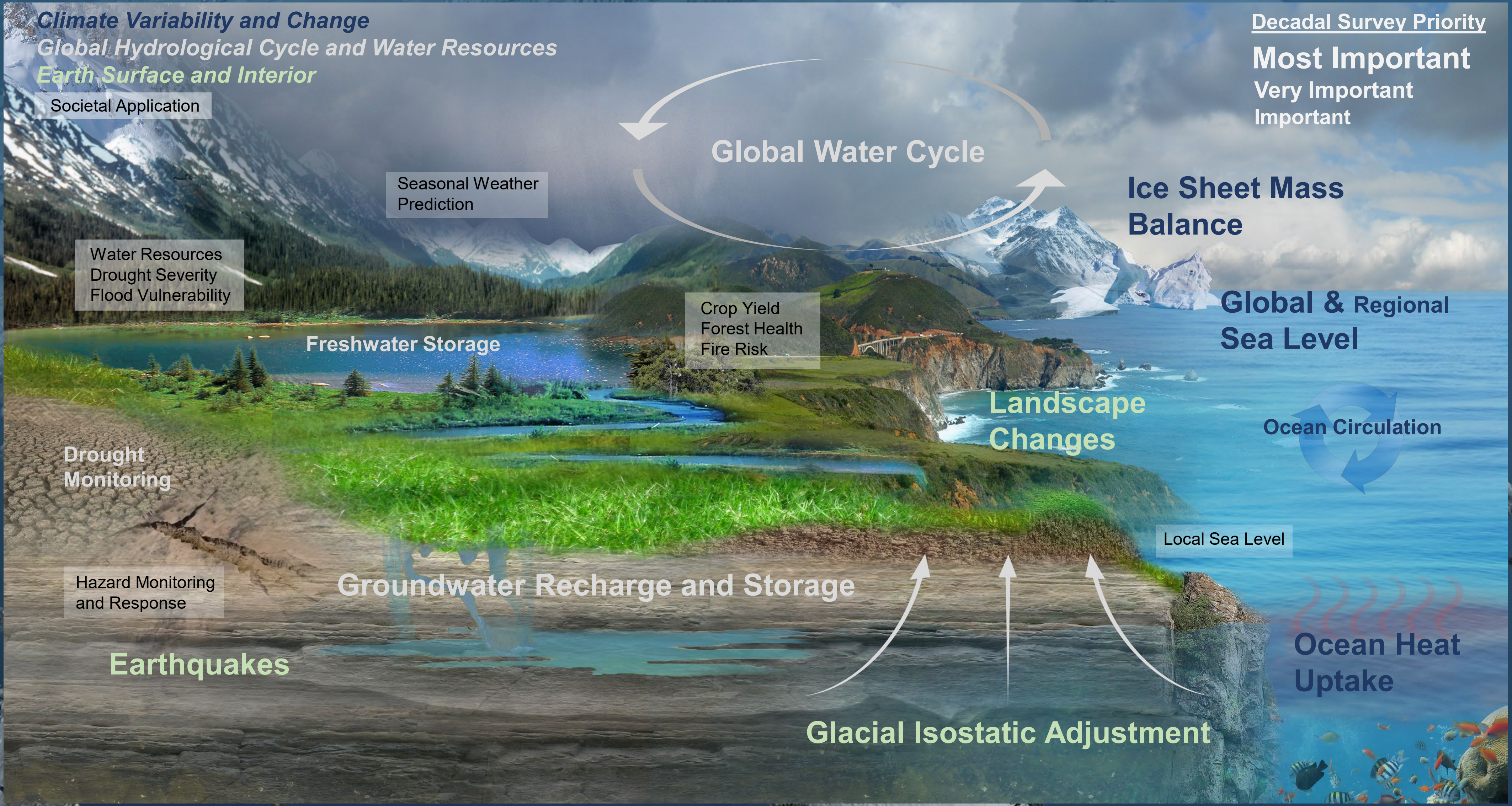
Overlap with GRACE-FO Drives FY28 MC Launch

- MCDO Study Team assessed the probability of different observing system architectures to provide overlap with GRACE-FO
  - Heritage architecture (single in-line pair with a free-drifting orbit) was found to have highest probability of providing overlap
  - GRACE-FO reliability is 50% by June 2028 (50% launch readiness date)
- GRACE-FO project continues monitoring health and potential end of life date
  - Single string on accelerometer and IPU (GNSS receiver and MWI tracking)
  - Consumables and space environment likely put end of mission in 2027-2030 timeframe
    - Current Solar Cycle 25 is above-average strength, implying relatively fast orbit decay and reduced lifetime (MCDO Study used a more benign solar cycle prediction in lifetime assessment)
    - Thruster leaks and uncertainty in future leak evolution
    - Operational decisions being made to simultaneously maximize quality of science data products considering accelerometer transplant, and to extend mission lifetime
- Desired to have a minimum 6 months of overlap with GRACE-FO
  - Vital for calibration of GRACE-FO accelerometer transplant and the resulting 10-year mass change data record (2018-2028)

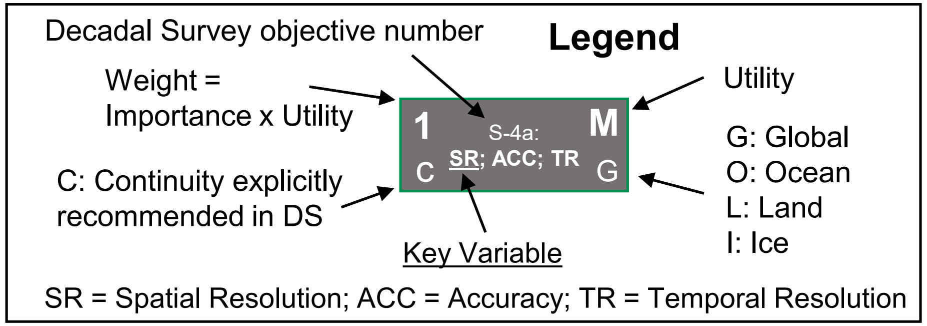
Mass Change Science and Applications at a Glance



Decadal Survey Science and Application Objectives for Mass Change

Measurement Parameters for Baseline

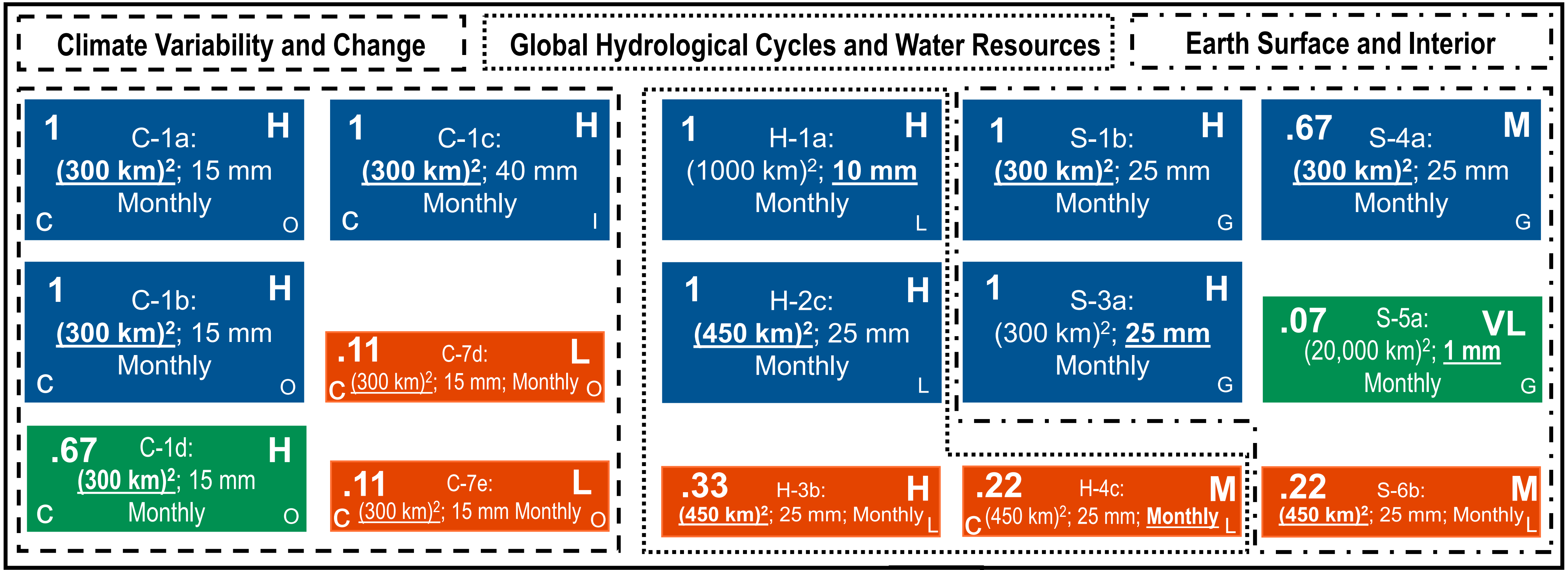
***Baseline** Observing System – supports full science objectives*



Legend

- Decadal Survey objective number
- Weight = Importance x Utility
- C: Continuity explicitly recommended in DS
- Key Variable
- Utility
- G: Global
- O: Ocean
- L: Land
- I: Ice

SR = Spatial Resolution; ACC = Accuracy; TR = Temporal Resolution



Climate Variability and Change

- **1** C-1a: **H** — (300 km)^2; 15 mm Monthly — C — O
- **1** C-1b: **H** — (300 km)^2; 15 mm Monthly — C — O
- **.67** C-1d: **H** — (300 km)^2; 15 mm Monthly — C — O
- **1** C-1c: **H** — (300 km)^2; 40 mm Monthly — C — I
- **.11** C-7d: **L** — C (300 km)^2; 15 mm; Monthly O
- **.11** C-7e: **L** — C (300 km)^2; 15 mm Monthly O

Global Hydrological Cycles and Water Resources

- **1** H-1a: **H** — (1000 km)^2; 10 mm Monthly — L
- **1** H-2c: **H** — (450 km)^2; 25 mm Monthly — L
- **.33** H-3b: **H** — (450 km)^2; 25 mm; Monthly L
- **.22** H-4c: **M** — C (450 km)^2; 25 mm; Monthly L

Earth Surface and Interior

- **1** S-1b: **H** — (300 km)^2; 25 mm Monthly — G
- **1** S-3a: **H** — (300 km)^2; 25 mm Monthly — G
- **.67** S-4a: **M** — (300 km)^2; 25 mm Monthly — G
- **.07** S-5a: **VL** — (20,000 km)^2; 1 mm Monthly — G
- **.22** S-6b: **M** — (450 km)^2; 25 mm; Monthly L

DS Prescribed Importance

Most Important Highest weight	Very Important Medium weight	Important Lower Weight
1.0	0.67	0.33

MC Utility Score

H: High	1.0
M: Medium	0.67
L: Low	0.33
VL: Very Low	0.10

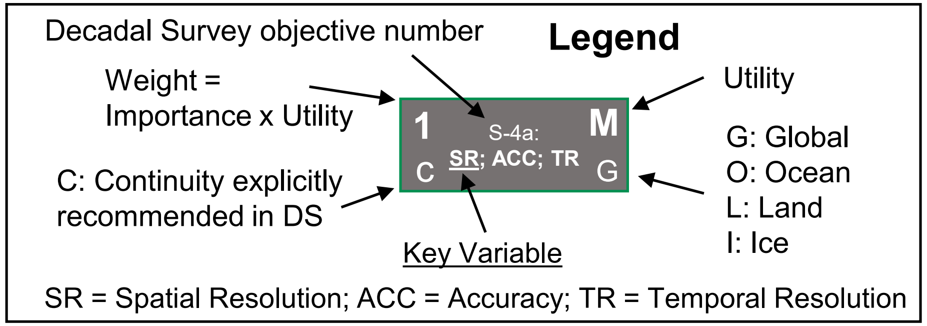
→ **Science Performance Targets**

30

Decadal Survey Science and Application Objectives for Mass Change

Measurement Parameters for Baseline

***Baseline** Observing System – supports full science objectives*



Legend

Decadal Survey objective number

Weight = Importance x Utility

C: Continuity explicitly recommended in DS

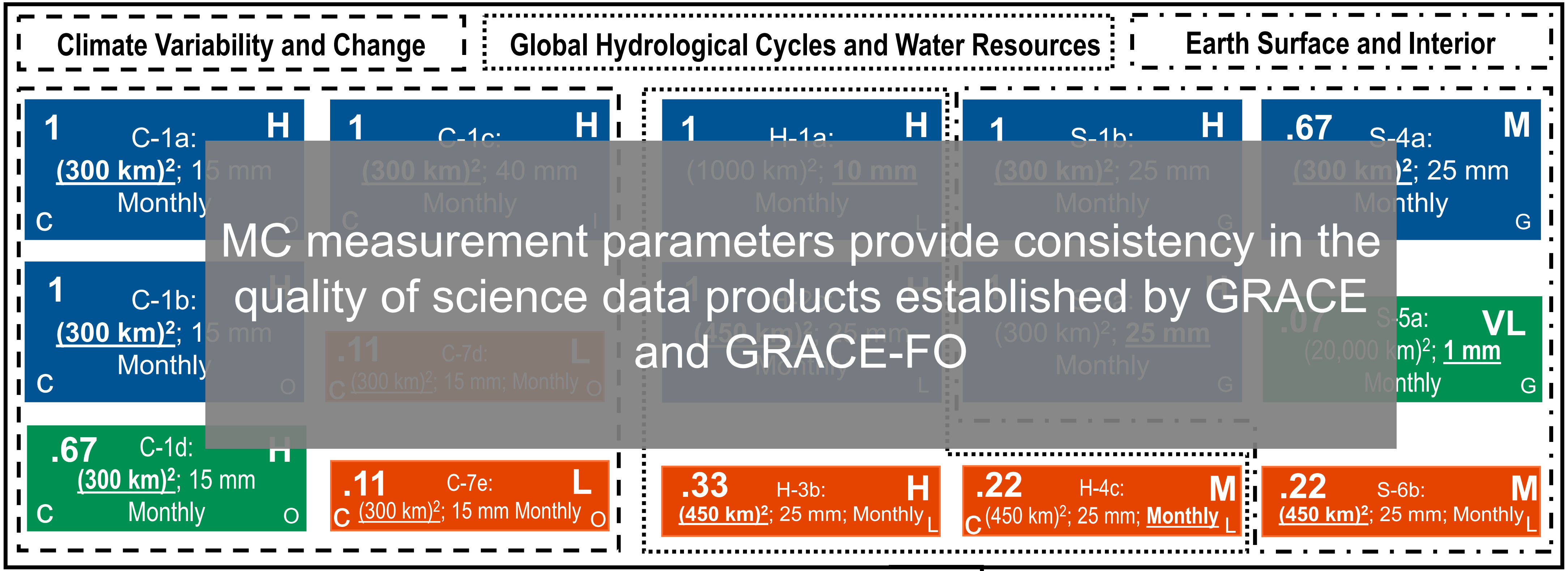
Key Variable

Utility

G: Global
O: Ocean
L: Land
I: Ice

1 S-4a: SR; ACC; TR M C G

SR = Spatial Resolution; ACC = Accuracy; TR = Temporal Resolution



Climate Variability and Change

- 1 C-1a: (300 km)^2; 15 mm Monthly C H O
- 1 C-1b: (300 km)^2; 15 mm Monthly C H O
- .67 C-1d: (300 km)^2; 15 mm Monthly C H O
- 1 C-1c: (300 km)^2; 40 mm Monthly C H I
- .11 C-7d: (300 km)^2; 15 mm; Monthly C L O
- .11 C-7e: (300 km)^2; 15 mm Monthly C L O

Global Hydrological Cycles and Water Resources

- 1 H-1a: (1000 km)^2; 10 mm Monthly H L
- 1 [illegible]: (450 km)^2; 25 mm Monthly H L
- .33 H-3b: (450 km)^2; 25 mm; Monthly H L
- .22 H-4c: (450 km)^2; 25 mm; Monthly C M L

Earth Surface and Interior

- 1 S-1b: (300 km)^2; 25 mm Monthly H G
- 1 [illegible]: (300 km)^2; 25 mm Monthly H G
- .67 S-4a: (300 km)^2; 25 mm Monthly M G
- .07 S-5a: (20,000 km)^2; 1 mm Monthly VL G
- .22 S-6b: (450 km)^2; 25 mm; Monthly M L

MC measurement parameters provide consistency in the quality of science data products established by GRACE and GRACE-FO

DS Prescribed Importance

Most Important Highest weight	Very Important Medium weight	Important Lower Weight
1.0	0.67	0.33

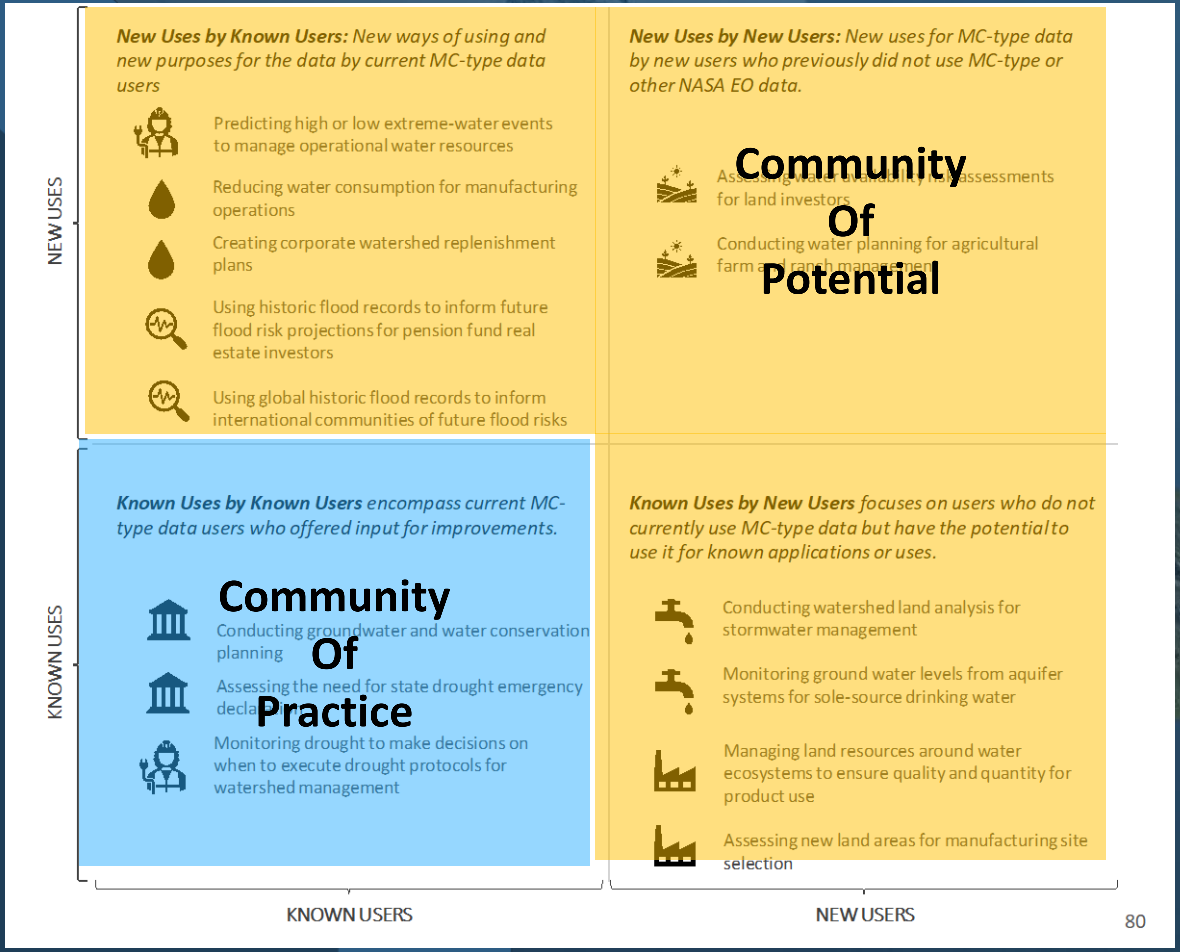
MC Utility Score

H: High	1.0
M: Medium	0.67
L: Low	0.33
VL: Very Low	0.10

Science Performance Targets

MC Applications Community Assessment

- **Goal**: Maximize the return on investment of current and future MC missions by enhancing their applications value and societal benefits
- Two communities
  - **Community of Practice**: assessed through survey and workshops
  - **Community of Potential**: Led by RTI International, through a series of discussion panels and interviews with representatives from private industry and public agencies



NEW USES

***New Uses by Known Users:** New ways of using and new purposes for the data by current MC-type data users*

- Predicting high or low extreme-water events to manage operational water resources
- Reducing water consumption for manufacturing operations
- Creating corporate watershed replenishment plans
- Using historic flood records to inform future flood risk projections for pension fund real estate investors
- Using global historic flood records to inform international communities of future flood risks

***New Uses by New Users:** New uses for MC-type data by new users who previously did not use MC-type or other NASA EO data.*

Community Of Potential

- Assessing water availability risk assessments for land investors
- Conducting water planning for agricultural farm and ranch management

KNOWN USES

***Known Uses by Known Users** encompass current MC-type data users who offered input for improvements.*

Community Of Practice

- Conducting groundwater and water conservation planning
- Assessing the need for state drought emergency declarations
- Monitoring drought to make decisions on when to execute drought protocols for watershed management

***Known Uses by New Users** focuses on users who do not currently use MC-type data but have the potential to use it for known applications or uses.*

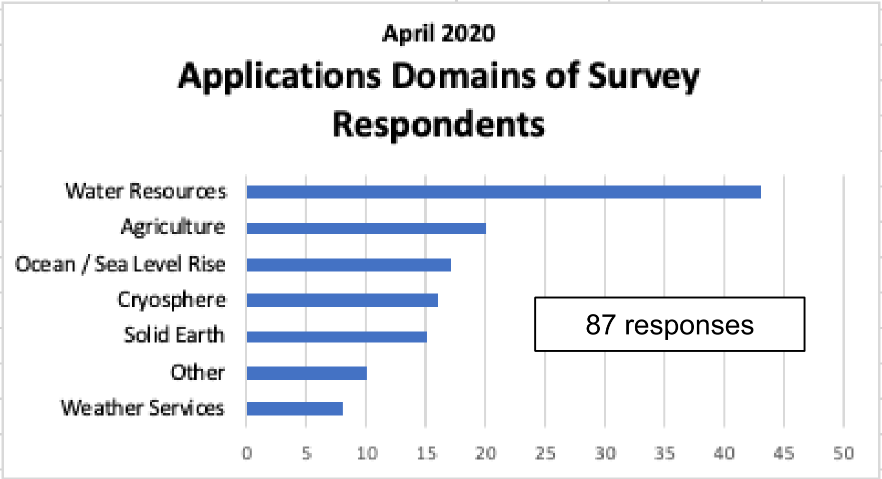
- Conducting watershed land analysis for stormwater management
- Monitoring ground water levels from aquifer systems for sole-source drinking water
- Managing land resources around water ecosystems to ensure quality and quantity for product use
- Assessing new land areas for manufacturing site selection

KNOWN USERS

NEW USERS

80

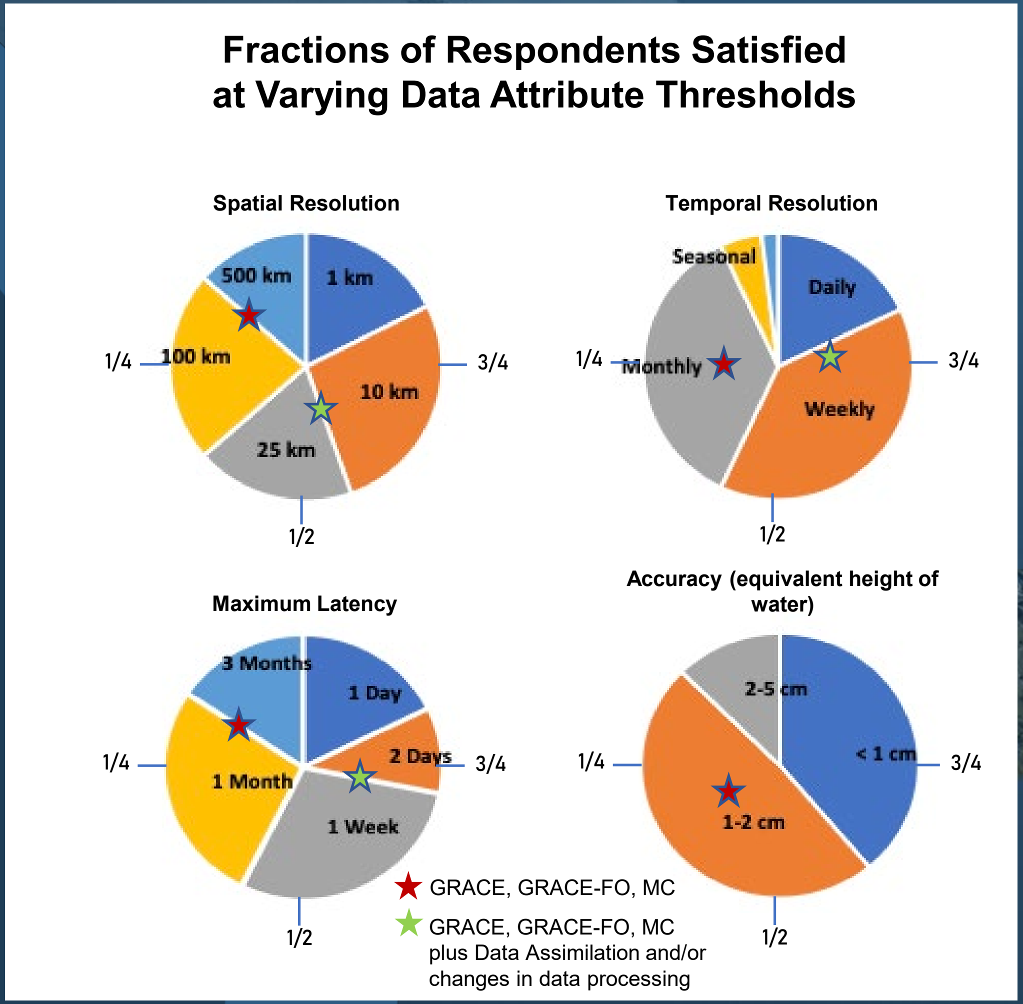
MC Community of Practice


April 2020

Applications Domains of Survey Respondents

Table 1. Select questions from MC Applications Survey

Desired Spatial Resolution	*GRACE terrestrial water storage data have a resolution no better than 3° x 3° latitude/longitude (~100,000 km^2), with some assimilated products at 0.125° resolution. Are those spatial resolutions adequate? If no, what spatial resolution would you require/prefer for your application?*
Desired Temporal Resolution	*GRACE terrestrial water storage data are typically provided as monthly means, with some assimilated products updated weekly. Are those temporal resolutions adequate? If no, what temporal resolution would you require/prefer for your application?*
Desired maximum Latency	*GRACE terrestrial water storage products were released with roughly 2-to-4-month latency, while some assimilated products had 2-to-8-day latency. Are those timely enough for your application? If no, what latency would be sufficient?*
Desired Accuracy	*GRACE terrestrial water storage data have an uncertainty of roughly 1.5 cm equivalent height of water over a 100,000 km^2 area. What accuracy or precision is required to be useful for your application?*


Fractions of Respondents Satisfied at Varying Data Attribute Thresholds

Data Assimilation Frameworks can satisfy needs of majority of users

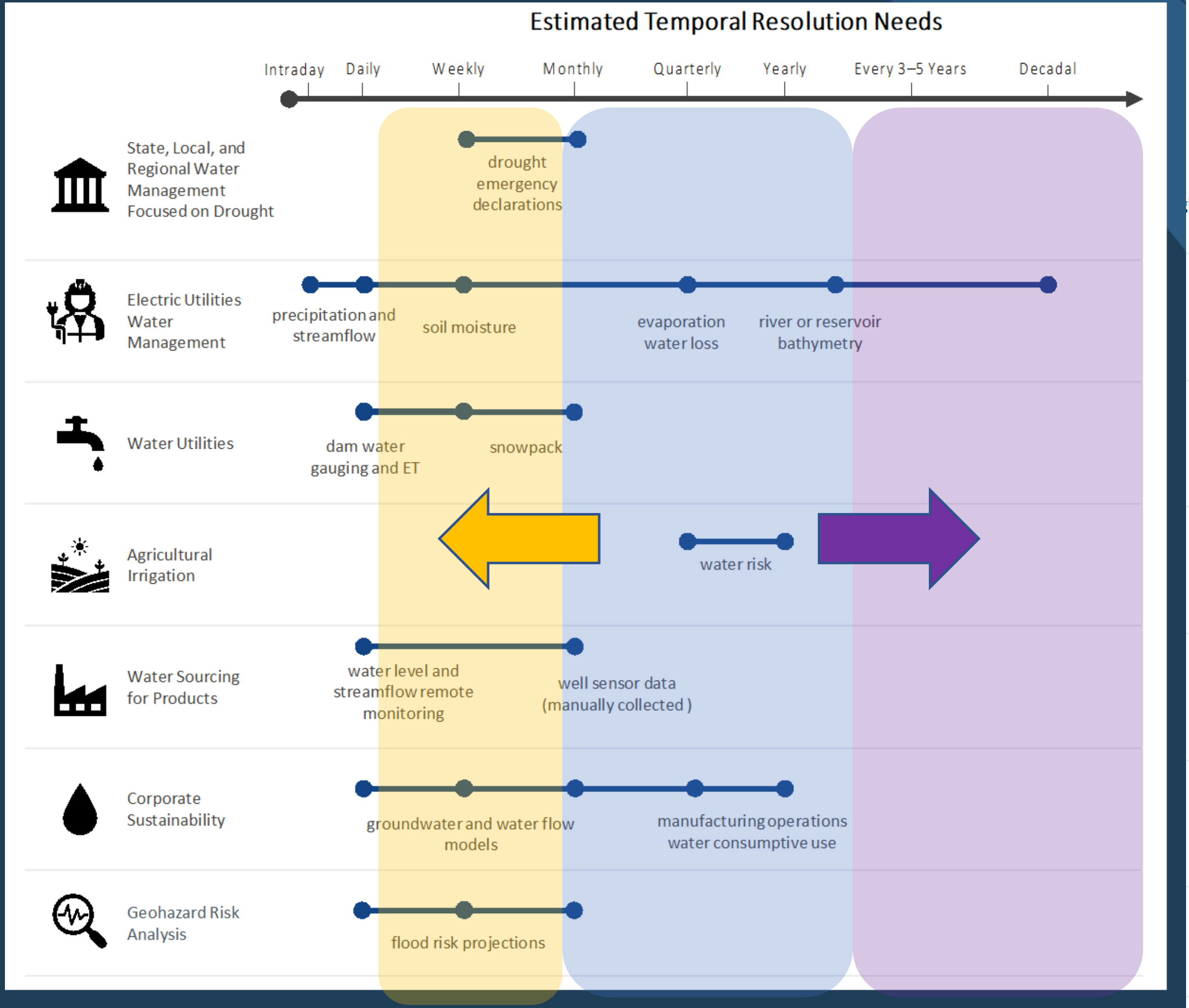
MASS CHANGE

MC Community of Potential

Capturing and aggregating anecdotal interview results

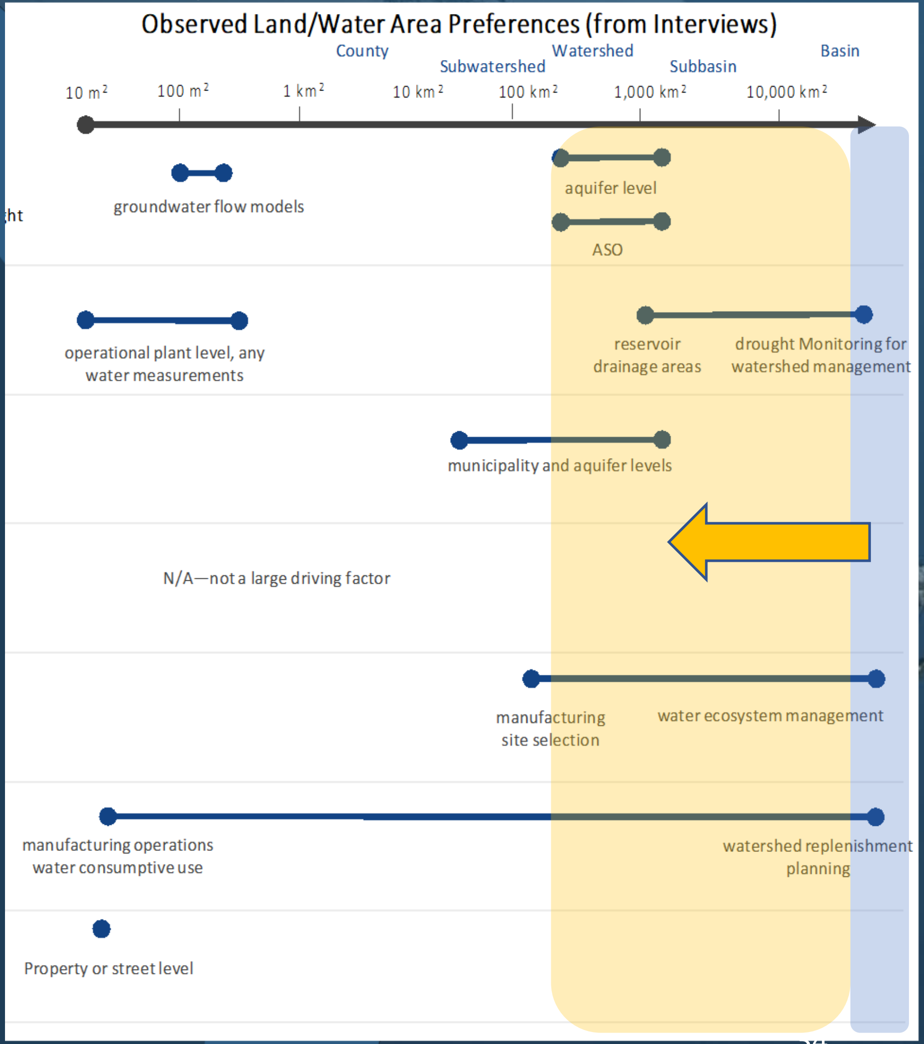
EARTH SYSTEM OBSERVATORY

Temporal Resolution Needs



Science Data System　　1 pair: raw data　　Continuity of the record

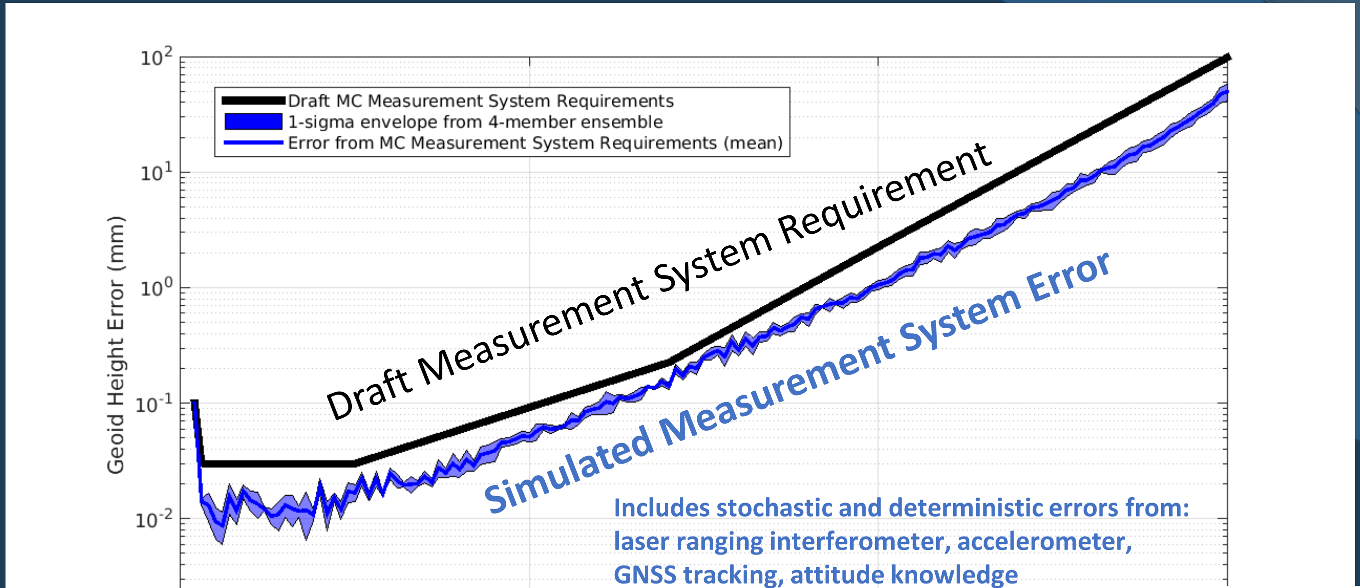
Spatial Resolution Needs



Science Data System　　1 pair: raw data

MC Measurement System Requirements

- Compliance with the Decadal Survey is ensured by placing an overarching requirement on the MC measurement system performance



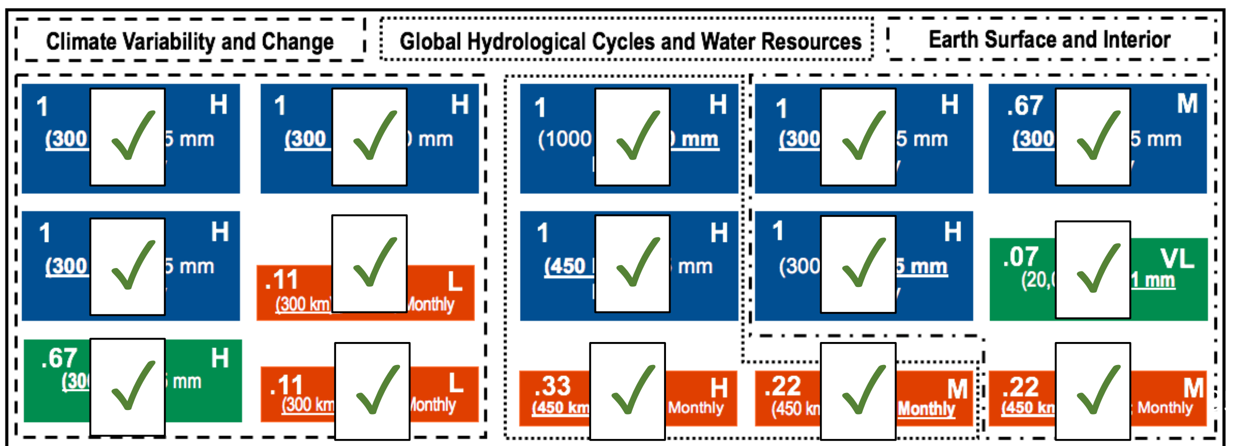
Draft Measurement System Requirement

Simulated Measurement System Error

Includes stochastic and deterministic errors from: laser ranging interferometer, accelerometer, GNSS tracking, attitude knowledge

Requirements are met across all harmonic degrees

Adding temporal aliasing error to measurement system error



Climate Variability and Change		Global Hydrological Cycles and Water Resources		Earth Surface and Interior
1 (300 ✓ 5 mm H	1 (300 ✓) mm H	1 (1000 ✓) mm H	1 (300 ✓ 5 mm H	.67 (300 ✓ 5 mm M
1 (300 ✓ 5 mm H	.11 (300 km) ✓ onthly L	1 (450 ✓ mm H	1 (300 ✓ 5 mm H	.07 (20,(✓ 1 mm VL
.67 (30 ✓ mm H	.11 (300 km ✓ onthly L	.33 (450 km ✓ Monthly H	.22 (450 kr ✓ Monthly M	.22 (450 kn ✓ Monthly M

All MC SATM Measurement Parameters are met, ensuring responsiveness to the Decadal Survey Science Objectives

National Aeronautics and
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MISSION IMPLEMENTATION

André Girerd
Mass Change Project Systems Engineer

Spacecraft Leverages Heritage

The system performance requirements for the Mass Change mission are identical to the performance requirements of GRACE-FO

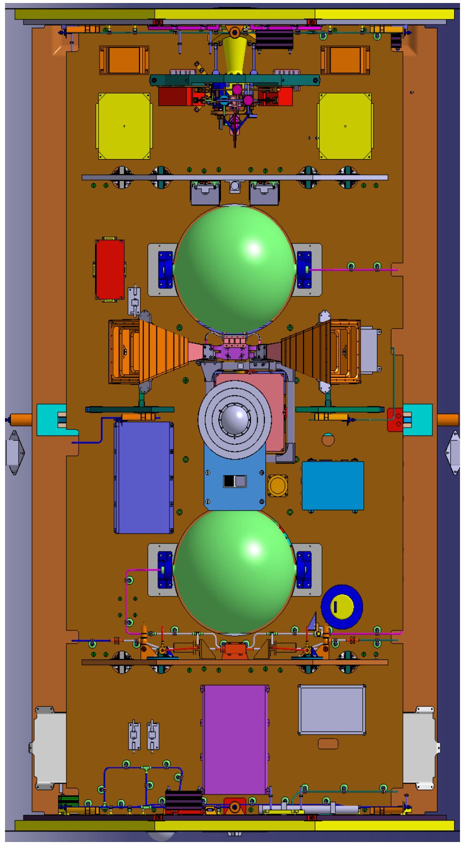
- Maintenance of true heritage of the GRACE-FO system allows for a minimization of cost and risk and a maximization of the probability of success

Changes to the Mass Change system are under consideration for the following categories

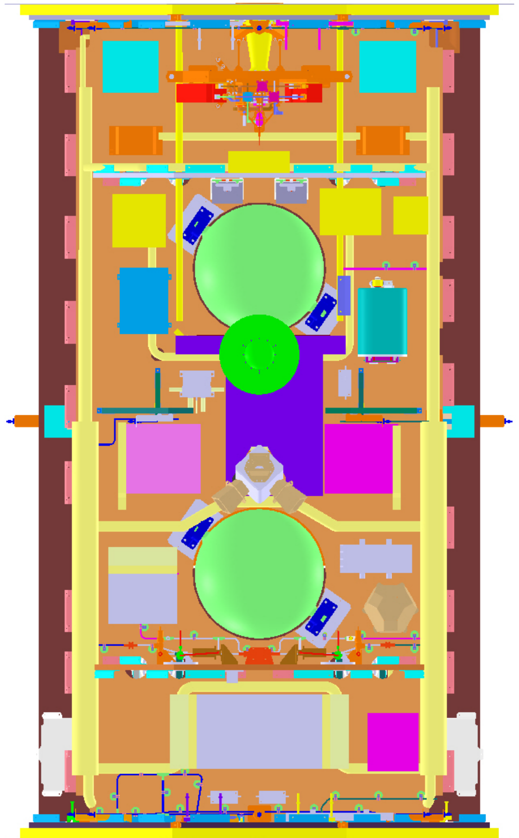
- Removal of Microwave Instrument (MWI)
- Accommodation of LRI Scale Factor Unit
- Redundancy options
- Resolution of issues discovered on the GRACE-FO mission
- Utilization of current generation of Airbus spacecraft

Heritage of Configuration

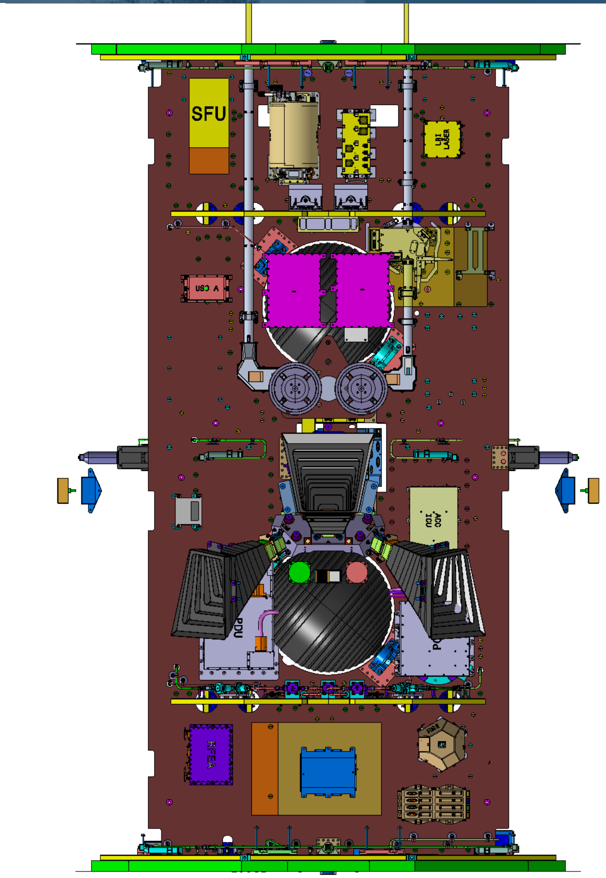
- Elimination of the Microwave Instrument for the Mass Change Mission results in GRACE like component spacing and higher radiator margins



GRACE



GRACE-FO



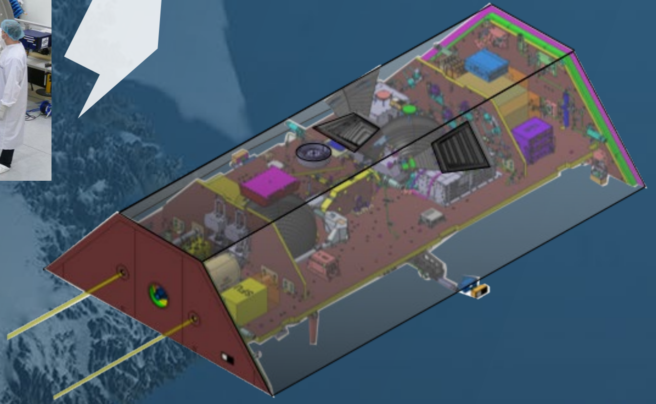
Mass Change

Heritage Spacecraft Platform

CHAMP
Launched 2000

GRACE
Launched 2002

GRACE Follow-On
Launched 2018



Mass Change
Planned 2027

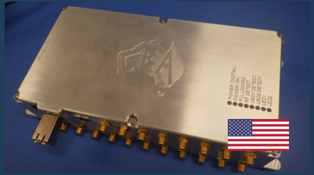
GOCE
Launched 2009

Cryosat 2
Launched 2010

SWARM
Launched 2013

Sentinel-6 (MF)
Launched 2020

Laser Ranging Interferometer is Proven

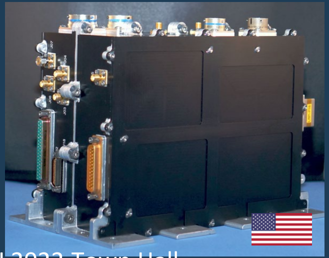


Scale Factor Unit (SFU)
Measures the change of the laser frequency over long durations by relating the USO clock to the cavity Free-Spectral Range
(TRL 6)

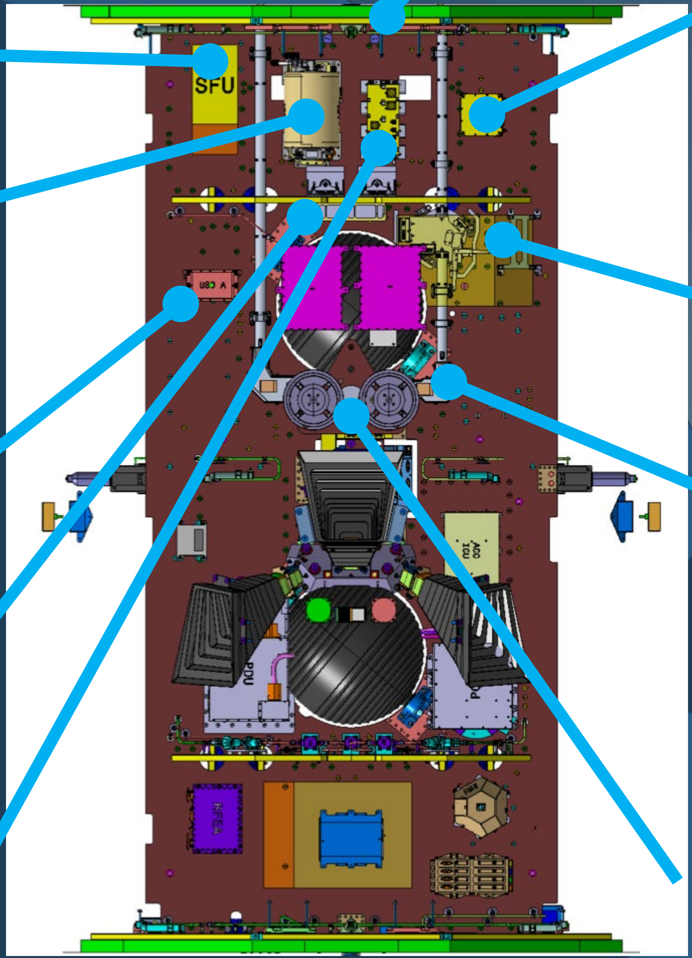
Optical Cavity (CAV):
Passive resonator used to stabilize the laser frequency on spacecraft in the Reference role
(TRL 7)

Ultra Stable Oscillator (USO):
Provides the stable 40 MHz clock to LRP, SFU, and 10 MHz to GNSS
(TRL 7)

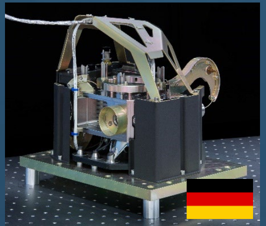
Optical Bench Electronics (OBE)
Powers the steering mirror and photoreceivers and provides signal conditioning for the science signal
(TRL 7)



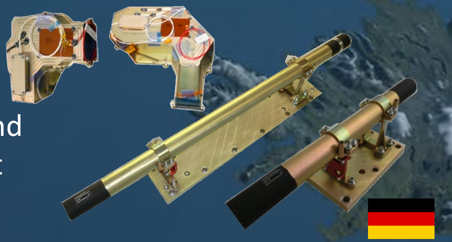
Laser Ranging Processor (LRP) :
Measures the interferometer phase and records the science signal; Laser frequency stabilization electronics; Commands the steering mirror angle for acquisition and tracking. Secondary power for OBE, LAS, CAV
(TRL 7)



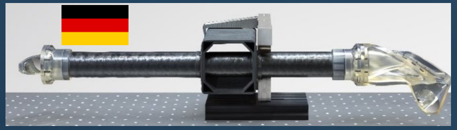
Laser (LAS): Provides 25 mW of 1064nm light; frequency stabilized to the optical cavity (reference), or to the incoming light (transponder)
(TRL 7)



Optical Bench Assembly (OBA)
Includes the quadrant photoreceiver (QPR), fine steering mirror (FSM), and main interferometer optical bench
(TRL 7)



Baffles + Light Path Closures (BAF+LPC)
Baffles and Light Path Closures ensure unobstructed field view and protect the system against ATOX
(TRL 7)



Triple Mirror Assembly (TMA)
Three mirror CFRP “virtual” corner-cube retroreflector. Routes the laser beams around the fuel tanks
(TRL 7)

MASS CHANGE

National Aeronautics and
Space Administration

EARTH SYSTEM OBSERVATORY

SUMMARY

Mike Gross, Mass Change Project Manager

EARTH SYSTEM OBSERVATORY

Summary

- International Partnership with Germany has lead to the success of GRACE and GRACE-FO, and continues to be enabling for the success of Mass Change
- The MC Project has made a tremendous amount of progress over the last year
- The end-to-end system has high heritage of both the design and the team
    - Ensures high probability of an on-schedule launch
    - Minimizes risk to loss of continuity of the gravity record
- NASA, ESA, EC (European Commission), DLR, ASI, CNES and other Agencies continue to discuss approaches to establishing a long-term international plan for sustained gravimetry observations beyond MC and NGGM

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COMMUNITY QUESTIONS/DISCUSSION

David Wiese, Mass Change Science