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Mass Change as a core element of NASA's Earth System Observatory: Update and progress on pre-formulation activities

David Wiese[1], Charley Dunn[1], Michael Gross[1], Frank Webb[1], Neil Dahya[1], Andre Girerd[1], Srinivas Bettadpur[2], Bernard Bienstock[1], Brent Ware[1], Carmen Boening[1], Jonathan Chrone[3], Bryant Loomis[4], Scott Luthcke[4], Matthew Rodell[4], Jeanne Sauber[4], Nicole Herrmann[5], Lucia Tsaoussi[5]

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GRACE-FO Science Team Meeting
Potsdam, Germany

[1] Jet Propulsion Laboratory, California Institute of Technology
[2] Center for Space Research, University of Texas at Austin
[3] NASA Langley Research Center
[4] NASA Goddard Space Flight Center
[5] NASA Headquarters

Building a Mass Change Climate Data Record

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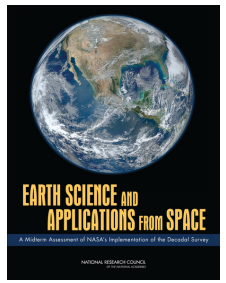
2022: TWS becomes Essential Climate Variable; GCOS implementation plan: "Urgent actions are needed to ensure continuity of gravimetry missions"

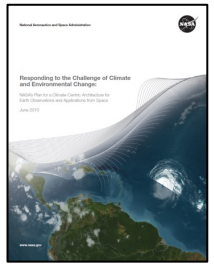
2000 — 2010 — 2020

1997: Gravity Recovery and Climate Experiment (GRACE) selected under the NASA Earth System Science Pathfinder Program.

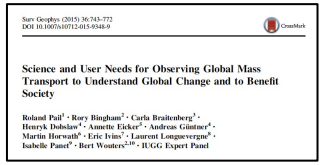
2002: Launch of GRACE



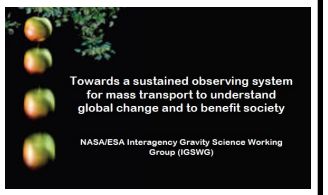
2007: Decadal Survey recommends a higher capability GRACE-II as a Tier-3 mission to continue observations from GRACE



2010: NASA Climate-Centric Architecture report recommends GRACE Follow-On as a gap-filler to continue observations between GRACE and GRACE-II



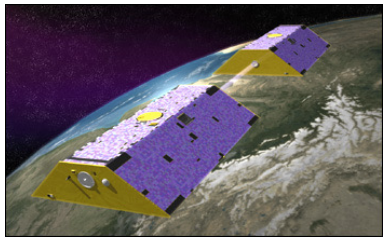
2015: IUGG Report on science and user needs for mass change to improve upon POR



2016: NASA/ESA IGSWG Report provides roadmap for 2-pair implementation to satisfy needs in IUGG report

2017: Decadal Survey recommends Mass Change as a Designated Observable to continue observations from GRACE-FO

Continuity has been called for in three community reports: DS-2007, CCA-2010, DS-2017



2017: GRACE End of Life

2018: Launch of GRACE-FO

2002-2017, 2018 – present: GRACE and GRACE-FO Establish a Mass Change Climate Data Record

Mass Change Timeline

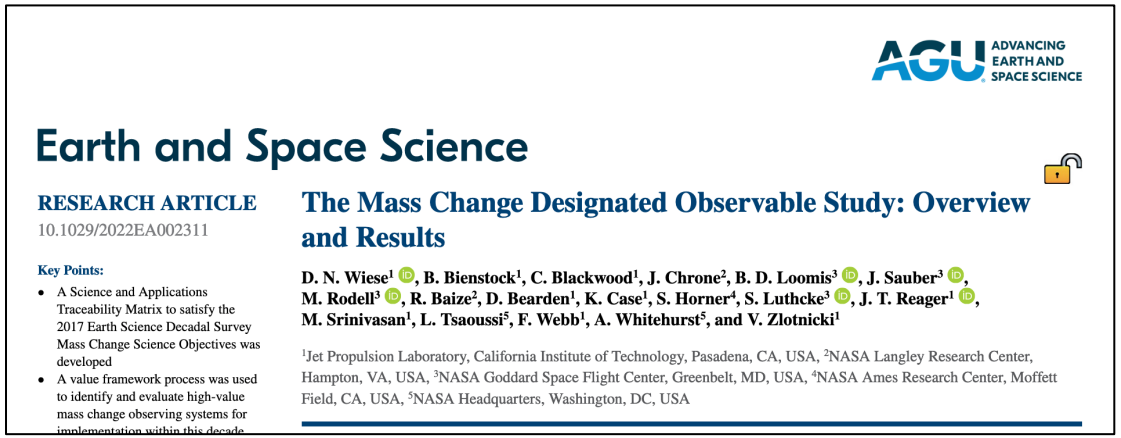
2018 — 2019 — 2020 — 2021 — 2022 — 2023

2017: Decadal Survey recommends Mass Change as a Designated Observable to continue observations from GRACE-FO

2018-2021: Mass Change Study Team studied approaches to obtaining measurements called for in DS and recommended small subset of architectures for further study

Summer 2021: Final Report Delivered to NASA HQ

Summer 2022: Open Access paper published in AGU Earth and Space Sciences



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Earth and Space Science

RESEARCH ARTICLE
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Key Points:
- A Science and Applications Traceability Matrix to satisfy the 2017 Earth Science Decadal Survey Mass Change Science Objectives was developed
- A value framework process was used to identify and evaluate high-value mass change observing systems for implementation within this decade

The Mass Change Designated Observable Study: Overview and Results

D. N. Wiese[1], B. Bienstock[1], C. Blackwood[1], J. Chrone[2], B. D. Loomis[3], J. Sauber[3], M. Rodell[3], R. Baize[2], D. Bearden[1], K. Case[1], S. Horner[4], S. Luthcke[3], J. T. Reager[1], M. Srinivasan[1], L. Tsaoussi[5], F. Webb[1], A. Whitehurst[5], and V. Zlotnicki[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [2]NASA Langley Research Center, Hampton, VA, USA, [3]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [4]NASA Ames Research Center, Moffett Field, CA, USA, [5]NASA Headquarters, Washington, DC, USA

2021-current: Mass Change Pre-Phase A activities further refine and mature the mission concept

June 2022: Mass Change successfully passed Mission Concept Review

July 2022: NASA establishes Independent Review Board to review all Earth System Observatory missions

November 2022: Expected that Mass Change will enter Phase A

MC Study Overview

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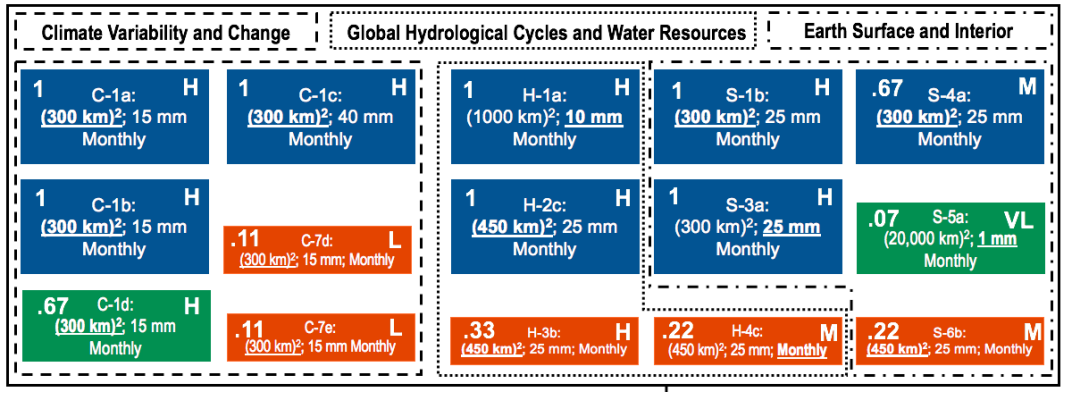
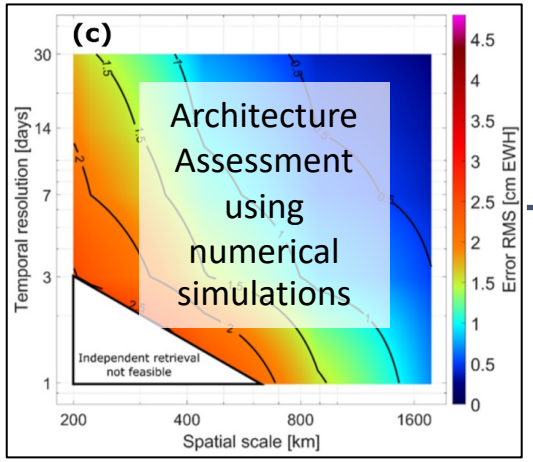
Decadal Survey

Traceability to DS

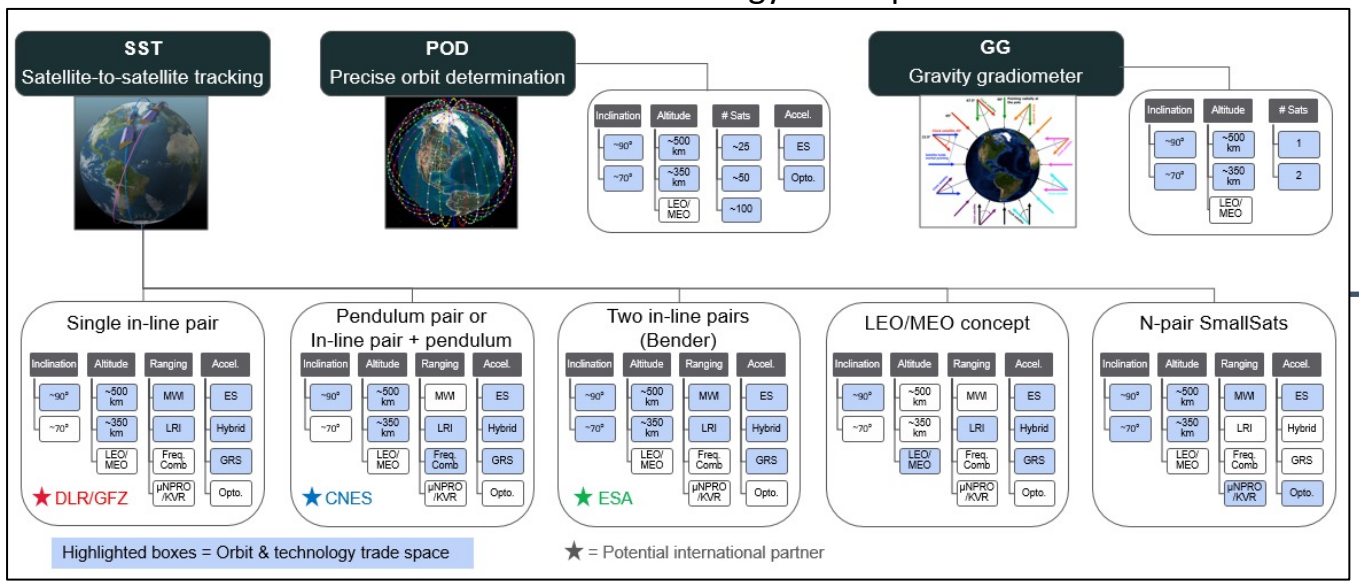
Science and Applications Traceability Matrix Baseline Measurement Parameters





Science Value

Architecture and Technology Tradespace



Value Framework Process

- Cost
- Schedule
- Risk
- Partnerships

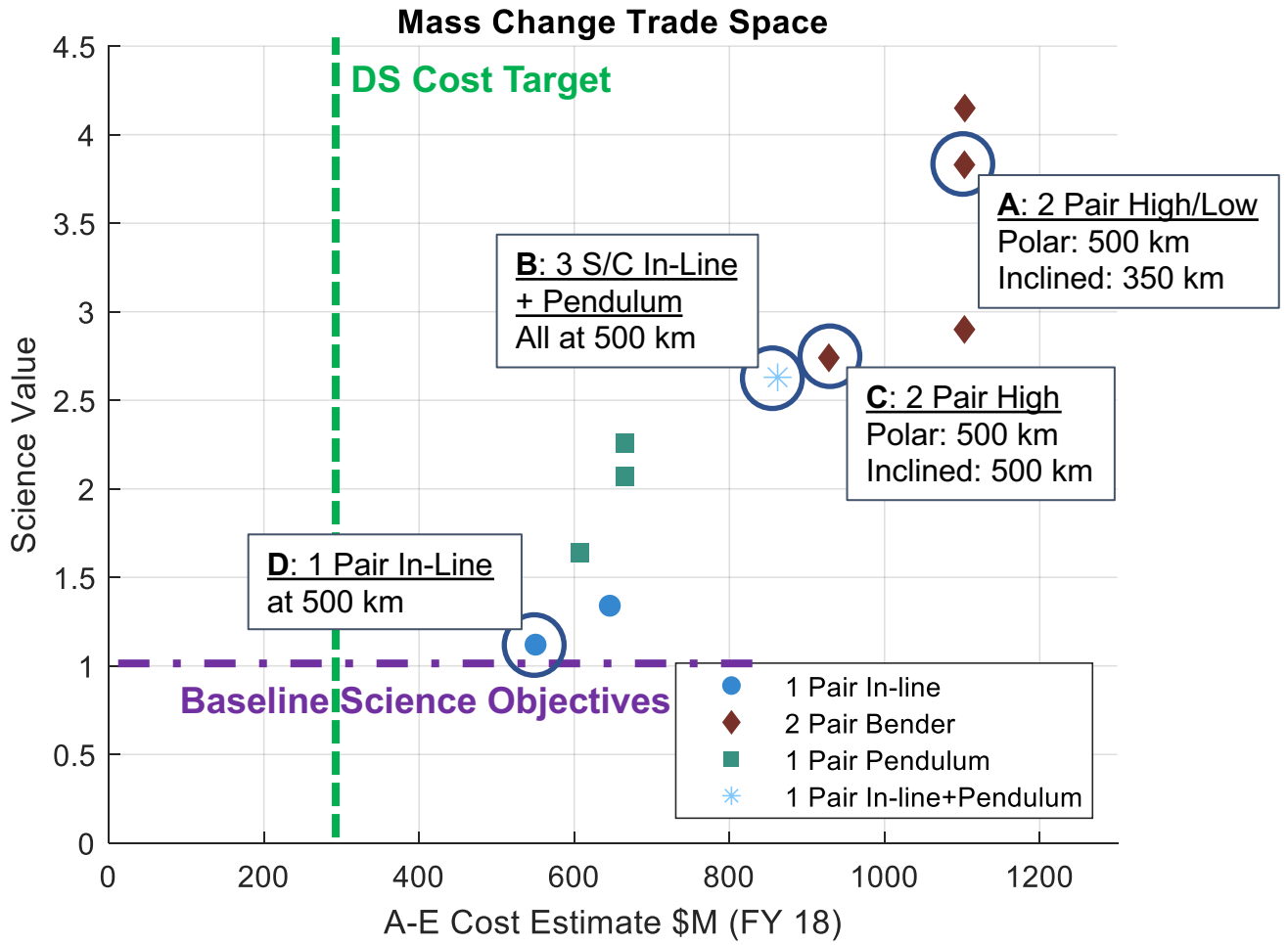
Identification of High Value MC Observing Systems

MCDO Study Recommendations

- For over a decade, the community has **stressed the importance of continuity** in mass change measurements as the basis for being a foundational measurement

	Estimated 50th Percentile LRD	Expected GRACE-FO Reliability at LRD
Single In-Line (no drag comp.)	June 2028	50%*
Pendulum (no drag comp.)	July 2029	40%
Bender (w/ drag comp.)	March 2030	35%

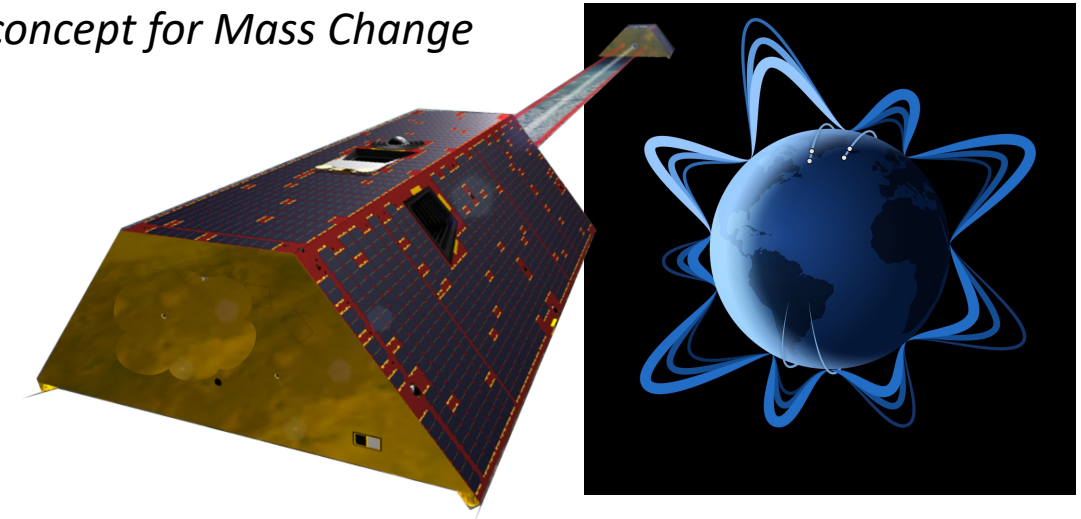
- Architectures (A, B, C, D) have at least one component that includes a single in-line polar pair to allow the highest likelihood of continuity with GRACE-FO
  - Implementation of Architectures A, B, and C may be staggered; Architecture D can be launched first and remaining elements launched later
- No architectures were identified that simultaneously satisfied Baseline Science Objectives and met the DS Cost Target
  - In the DS, a Cost and Technical Evaluation (CATE) was not done for MC; CATE was done only for missions estimated to be > $500M



In Pre-Phase A, further refinements have led to:
Architecture D: Baseline concept for MC (NASA/DLR)
Architecture B and C: Eliminated
Architecture A: Possible; combination of MC and NGGM (ESA)

Mass Change Baseline Concept

Pre-Phase A activities matured the mission concept for Mass Change



Project/Program Constraints

- Partnership between NASA & DLR
- Two identical Spacecraft separated by 100-300 km
- Launch Date: Nov, 2027
- Launch Vehicle: Space-X Falcon 9
- Spacecraft Bus: Airbus; GRACE-FO Heritage
- Redundancy*: Single String Instruments
- Baseline design life: 2 years (7 years consumables)
- Orbit: 500 km altitude, 89º Inclination

Measurement System

- Satellite to Satellite Tracking:
  - Laser Ranging Interferometer
  - Accelerometer
  - GNSS Receiver
  - Star Camera Attitude determination

*Redundant and single string configurations were studied in Pre-Phase A with DLR, but only single string was consistent with the Decadal Survey budget guidance. See next talk for redundant options considered.

Mission Science

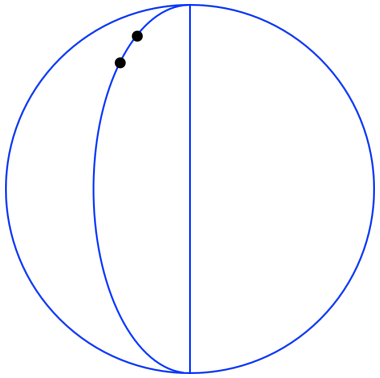
- Mass Change provides continuity of the Earth system mass change data record, which is foundational to the program as recommended in the DS
- Mass Change produces observations consistent with the GRACE and GRACE-FO science record, documented in the baseline MCDO study Science and Applications Traceability Matrix
- One of 5 Core Focus Areas addressed by 4 missions for Earth System Observatory (MC, SBG, AOS, SDC)

Relationship to Other Missions

GRACE-FO

GRACE to GRACE-II gap filler†

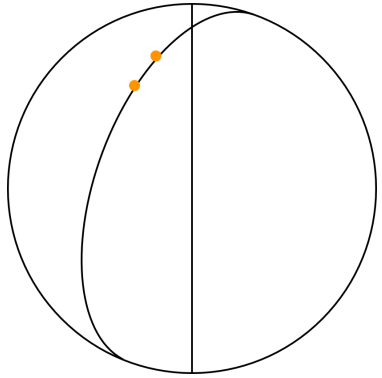
Partnership	NASA/GFZ
Launch:	May 22, 2018
LV:	Falcon-9
Orbit:	500 km; 89°
Baseline Design Lifetime:	5 years
Primary Instr.	MWI (Microwave) Redundant
Tech Demo.	LRI (Laser)
Accelerometer	ONERA Single String
Expected Lifetime	through 2027-2031



Mass Change

More capable, laser based, GRACE-II

Partnership	NASA/DLR
Launch:	Nov , 2027
LV:	Falcon-9
Orbit:	500 km; 89°
Baseline Design Lifetime:	2 years
Primary Instr.	LRI (Laser) Single String
Tech Demo.	Not baselined
Accelerometer*	GRACE-FO Spares Single String



Next Generation Gravity Mission

Lead	ESA
Launch:	2030-2032
LV:	Baseline: Vega-C
Orbit:	~400 km, ~70°
On-Orbit Lifetime:	~7 years
Primary Instr.:	Laser tracking
Accelerometer:	MicroSTAR Electrostatic
Propulsion:	Hybrid cold gas + EP with drag compensation

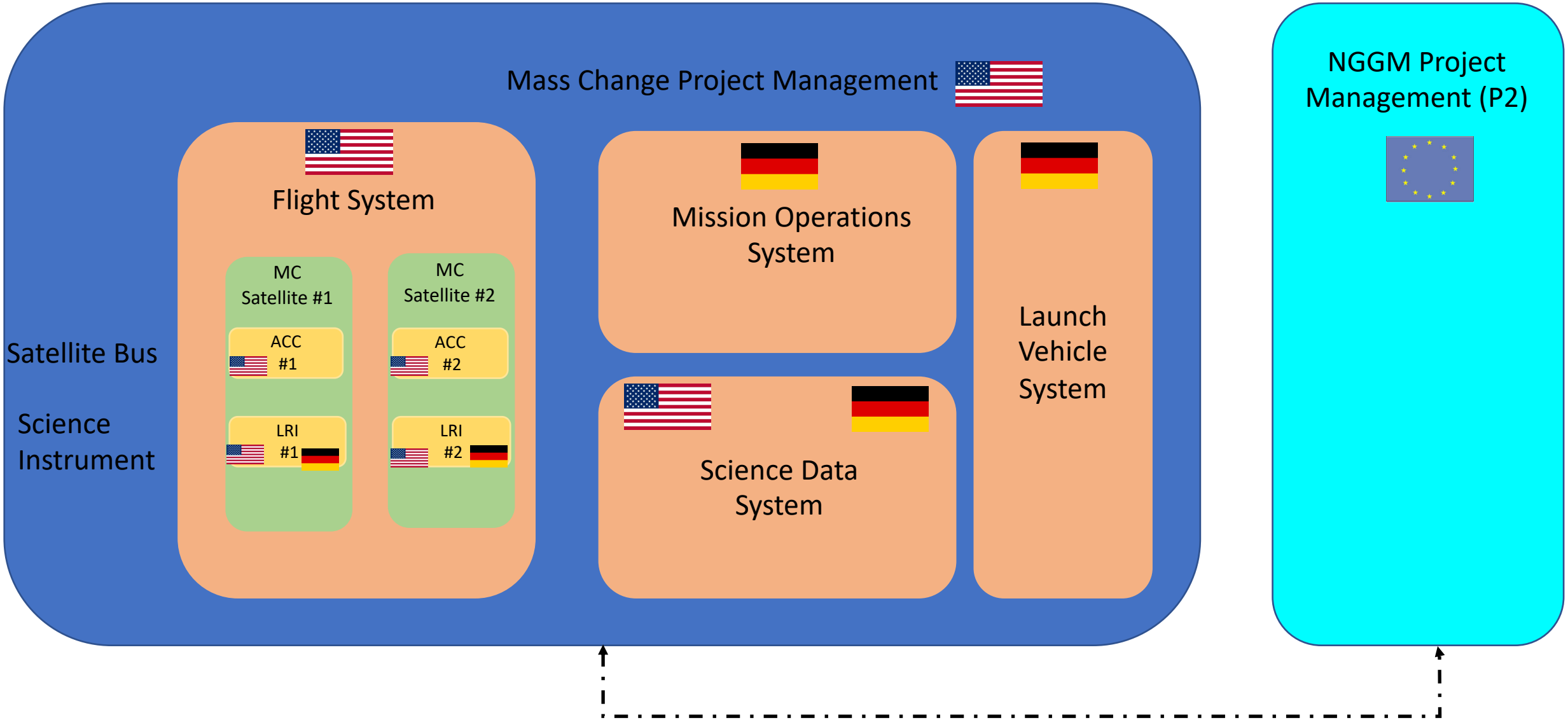
*Study contracts are being put in place through Phase A with Ball Aerospace/University of Florida/Fibertek and ONERA to better understand alternative accelerometer options

P1 P2

- Demonstrates a ”Bender Constellation” during mutual operations
  - Reduces dominant Atmosphere/Ocean de-aliasing error

Contribution by Country

Mass Change international partnership is modelled on the the 20+ years of successfully partnering on GRACE and GRACE-FO



Architecture: Spacecraft Evolution & Accommodation

Potential Upscopes identified in Pre-Phase A (Not Currently Planned)

Add Capability

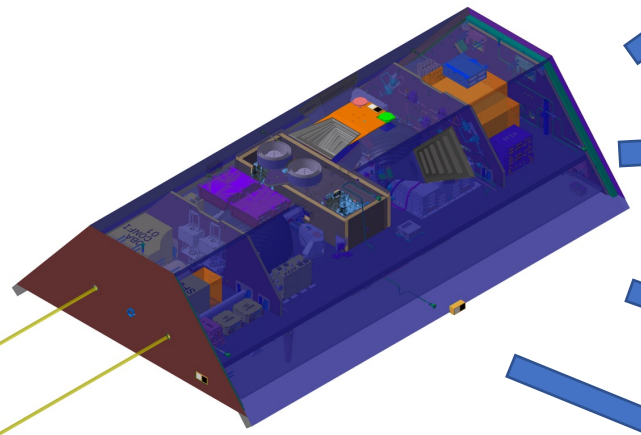
Electric Propulsion for orbit maintenance
Improves ΔV capability, extending the on-orbit mission life beyond 7 years consumables

Gyro-stellar estimator
Improves AOCS pointing

Electronic pressure regulator
Reduces thrust imbalance

Proportional thrusters
Further reduces shock

Mass Change Baseline



Candidate Secondary Payloads

Increase Scope beyond core gravity science

ICARUS (Germany)

Animal tracking payload

Quantum Gravity Gradiometer (QGG) Tech Demo (US/Germany)

Recently descoped but separate focused US/German study ongoing

Radio Occultation (Germany)

Microstar Accelerometer Tech Demo (ESA)

Redundancy Upscopes Not Currently Planned

Increases Cost, Mitigates Risk

Add Accelerometer and/or LRI redundancy

Closing Remarks

- Mass Change provides continuity of the mass change science data record
  - Continuity is the basis for being foundational to the program, per the Decadal Survey, and has been called for in multiple community reports
- Quality of science data will be consistent with the program of record
- Mass change is a mature concept based on flight proven designs with high heritage
- Mass change is based on a partnership with Germany that takes advantage of historic relationships that provides the lowest technical and cost risk
- NASA established an independent review board (IRB) to review technical concepts across all Earth System Observatory (ESO) missions for robustness and the ability to satisfy the mission's essential requirements
  - Mass Change is supporting IRB as requested
  - IRB anticipated to deliver final report to NASA this Fall
  - Results of IRB will be used to inform any architecture changes to ESO mission concepts prior to entering Phase A
- Mass Change is targeting a November 2027 launch and expects to enter Phase A by the end of this year