The NASA Mass Change Designated Observable Study: Status Update

The Mass Change Designated Observable Study Team\(^1,2,3,4,5\)

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The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.
2017-2027 Decadal Survey for Earth Science and Applications from Space released in January 2018

Identified five Designated Observables, organized as four multi-center studies

- Aerosols
- Cloud, Convection, and Precipitation
- Mass Change (MC)
- Surface Biology and Geology (SBG)
- Surface Deformation and Change (SDC)

Combined as ACCP

Link to the MC study is at

https://science.nasa.gov/earth-science/decadal-mc
MC Study Phases

○ = Self-consistent architectures
□ = Promising architectures
■ = Point design
□ = Design phase gates

Phase 1 Candidate Observing System Architectures
- Open trade space
  - Identify innovation and technology opportunities, synergies with other missions, and enabling partnerships

Phase 2 Assessment of Observing System Architectures
- Close trade space
  - Specify value framework and perform cost effectiveness analysis

Phase 3 Detailed Design of Promising System Architectures
- Collaborative Engineering
- Independent Cost Estimate
- Iterate Design
- Reconcile Cost

Iterate
Reconcile
Cost

We are notionally here in the study process

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

Baseline validated, MCR ready
The development of the Mass Change Science and Applications Traceability Matrix was driven by the 2017 Decadal Survey with significant input from the community.

- Product: Suggested Measurement Parameters for Baseline
- Product: Suggested Measurement Parameters for Goal

### Decadal Survey Objectives and Prescribed Importance

<table>
<thead>
<tr>
<th>Climate Variability and Change</th>
<th>Global Hydrological Cycles and Water Resources</th>
<th>Earth Surface and Interior</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1a: Global Sea Level</td>
<td>C-1c: Ice Sheet Mass Change</td>
<td>S-1b: Earthquakes</td>
</tr>
<tr>
<td>C-1b: Ocean Heat</td>
<td>C-7d: Dynamical Ocean State</td>
<td>S-3b: Glacial Isostatic Adjustment, Local Sea Level</td>
</tr>
<tr>
<td>C-1d: Regional Sea Level</td>
<td>C-7c: Ocean Circulation</td>
<td>S-5a: Earth Energy Flow</td>
</tr>
<tr>
<td>H-1a: Water Balance Closure</td>
<td>H-2c: Groundwater Recharge</td>
<td>S-4a: Landscape Changes</td>
</tr>
<tr>
<td>H-3b: Water Availability &amp; Storage</td>
<td>H-4c: Drought Monitoring</td>
<td></td>
</tr>
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<td>H-4c: Drought Monitoring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-8b: Groundwater Flux</td>
<td></td>
<td></td>
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### Mass Change-contributing DS Objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Importance</th>
</tr>
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<tbody>
<tr>
<td>DS Prescribed Weights [Importance]</td>
<td>Most Important Highest weight</td>
</tr>
</tbody>
</table>

### Expert Interpretation and Community Input

The matrix is a tool for deciding the measurement parameters necessary to meet the objectives of the Decadal Survey. The importance of each objective is determined through expert interpretation and community input and vetting. The matrix is available on the website for further consultation.

**Example:**

- **C-1a: Global Sea Level**
  - Spatial Resolution: (450 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 15 mm

- **C-1b: Ocean Heat**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: Monthly
  - Accuracy: 10 mm

- **C-1d: Regional Sea Level**
  - Spatial Resolution: (100 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 25 mm

- **C-7d: Dynamical Ocean State**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-7c: Ocean Circulation**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 15 mm

- **C-1c: Ice Sheet Mass Change**
  - Spatial Resolution: (450 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-3a: Glacial Isostatic Adjustment, Local Sea Level**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-5a: Earth Energy Flow**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-4: Drought Monitoring**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-3b: Groundwater Flux**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-2: Water Availability & Storage**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-6: Terrestrial Water Budget Closures**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-7: Earth Energy Flow**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm

- **C-8: Groundwater Flux**
  - Spatial Resolution: (300 km)²
  - Temporal Resolution: 30 days
  - Accuracy: 10 mm
Decadal Survey Science and Application Objectives for Mass Change

Measurement Parameters for Baseline

Baseline Observing System – supports full science objectives

Decadal Survey objective number

<table>
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<tr>
<th>Utility</th>
<th>Weight = Importance x Utility</th>
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</thead>
<tbody>
<tr>
<td>H: High</td>
<td>1.0</td>
</tr>
<tr>
<td>M: Medium</td>
<td>0.67</td>
</tr>
<tr>
<td>L: Low</td>
<td>0.33</td>
</tr>
<tr>
<td>VL: Very Low</td>
<td>0.10</td>
</tr>
</tbody>
</table>

C: Continuity explicitly recommended in DS

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

Legend

Key Variable

Baseline Observation System – supports full science objectives

Climate Variability and Change

1 C-1a: (300 km)²; 15 mm Monthly

1 C-1b: (300 km)²; 15 mm Monthly

1 C-1c: (300 km)²; 40 mm Monthly

1 C-1d: (300 km)²; 15 mm Monthly

C-7d: (300 km)²; 15 mm Monthly

H-1a: (1000 km)²; 10 mm Monthly

H-2c: (450 km)²; 25 mm Monthly

H-3b: (450 km)²; 25 mm Monthly

H-4c: (450 km)²; 25 mm Monthly

S-1b: (300 km)²; 25 mm Monthly

S-3a: (300 km)²; 25 mm Monthly

S-4a: (300 km)²; 25 mm Monthly

S-5a: (20,000 km)²; 1 mm Monthly

S-6b: (450 km)²; 25 mm Monthly

S-7d: (300 km)²; 15 mm Monthly

MC Utility Score

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

Legend

Baseline Observation System – supports full science objectives

Global Hydrological Cycles and Water Resources

Earth Surface and Interior

1 H-1a: (1000 km)²; 10 mm Monthly

1 S-1b: (300 km)²; 25 mm Monthly

1 S-3a: (300 km)²; 25 mm Monthly

1 S-4a: (300 km)²; 25 mm Monthly

1 S-5a: (20,000 km)²; 1 mm Monthly

1 S-6b: (450 km)²; 25 mm Monthly

1 H-3b: (450 km)²; 25 mm Monthly

1 H-4c: (450 km)²; 25 mm Monthly

Utility

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

Decadal Survey Science Performance Targets
Decadal Survey Science and Application Objectives for Mass Change

Measurements Parameters for Goal

**Goal:** Observing System – supports elevated ambitions of DS while ensuring longevity in the mass change timeseries. May include advancing enabling technologies.

**Decadal Survey Science and Application Objectives for Mass Change**

**Climate Variability and Change**

- C-1a: (100 km)$^2$; 15 mm Monthly
- C-1b: (100 km)$^2$; 15 mm Weekly
- C-1c: (100 km)$^2$; 10 mm Monthly
- C-1d: (100 km)$^2$; 15 mm Monthly

**Global Hydrological Cycles and Water Resources**

- H-1a: (3 km)$^2$; 10 mm Monthly
- H-1c: (100 km)$^2$; 10 mm Monthly
- H-2c: (50 km)$^2$; 10 mm Monthly
- H-3b: (200 km)$^2$; 25 mm Monthly

**Earth Surface and Interior**

- S-1b: (200 km)$^2$; 12 mm Monthly
- S-3a: (200 km)$^2$; 10 mm Monthly
- S-4a: (200 km)$^2$; 12 mm Monthly
- S-5a: (20,000 km)$^2$; 0.01 mm Monthly

**Legend**

- **SR:** Spatial Resolution
- **ACC:** Accuracy
- **TR:** Temporal Resolution

**Utility Score**

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

**MC Utility Score**

- C: Continuity explicitly recommended in DS

**Science Performance Targets**
Architectures & Technology: Trade space

SST
Satellite-to-satellite tracking

POD
Precise orbit determination

GG
Gravity gradiometer

Single in-line pair

Pendulum pair or In-line pair + pendulum

Two in-line pairs (Bender)

LEO/MEO concept

N-pair SmallSats

Highlighted boxes = Orbit & technology trade space
Numerical simulations are run for one month, January 2006
- With temporal aliasing errors: **Science Value**
- Without temporal aliasing errors: **Measurement System Value**

Instrument Noise
- Various ranging and accelerometer technologies simulated with noise models provided by instrument developers
- GNSS errors included
  - 1 cm white noise added to each axis – kinematic orbits
- Attitude errors included
  - For SST architectures, GRACE-FO pre-launch estimate of errors is used

Simulation notes
- Max degree/order 180
- Implements stochastic noise model for observations derived from postfit residuals (see offline poster by Ellmer et al.)
  - **Lesson Learned:** This systematically improves multi-pair observing system architectures more than single-pair observing systems.
A Quantitative Assessment of Science Value

Science Value (SV)\[ SV(a) = \frac{\sum_{n=1}^{15} (W_n) P_{nOS}}{\sum_{n=1}^{15} (W_n)} = \frac{\sum_{n=1}^{15} (W_n)^{SR_n} TR_n}{\sum_{n=1}^{15} (W_n)^{TR(a)}} \frac{ACC_n}{ACC(a)} \]

Key Variable: Spatial Resolution

\[ SV_{C-1d} = 0.67 \times (300/225)^2 = 1.2 \]

Key Variable: Accuracy

\[ SV_{H-1a} = 1 \times 10/4 = 2.5 \]


\[ W_n = \text{Importance}_n \times \text{Utility}_n \]
\[ P_{nOS} = \text{Performance of the Observing System} \]
\[ SR = \text{Spatial Resolution} \]
\[ TR = \text{Temporal Resolution} \]
\[ ACC = \text{Accuracy} \]
Architectures have similar science value because key design variables are the same. Instruments are different, however, and have different levels of performance. We need a secondary metric to discriminate performance.
Measurement System Value Results: A Secondary Discriminator

Measuring System Value is quantified using the same process as Science Value except temporal aliasing errors are not included in the numerical simulation.

Measurement System Value becomes a discriminator among architectures with similar Science Value.
Architectures & Technology: What we have learned

SST
Satellite-to-satellite tracking

POD
Precise orbit determination

GG
Gravity gradiometer

Highlighted boxes = Orbit & technology trade space
Architectures & Technology: What we have learned

POD
Precise orbit determination

- Low MC science value

Inclination
- ~90°
- ~70°

Altitude
- ~500 km
- ~350 km

# Sats
- ~25
- ~50
- ~100

Accel.
- ES
- Opto.

SST
Satellite-to-satellite tracking

• Low MC science value
• Low TRL & long/uncertain development schedule
• SmallSat design not cost-effective
• Lack of international partner

Inclination
- ~90°
- ~70°

Altitude
- ~500 km
- ~350 km

LEO/MEO

# Sats
1
2

Highlighted boxes = Orbit & technology trade space
Key point:
POD is not a replacement for GRACE-type missions and is not capable of meeting the MC SATM needs

- Simulations assumed overly optimistic accelerometer performance, orbit altitude, and instrument noise specifications
- Single and multi-plane configurations with increasing number of satellites
- Observed ~25% improvement in science value as number of constellation elements doubles. Unclear if this trend continues as constellation grows to 1000s of elements, but due to low science value of 100 elements, this was not pursued.
- MC DO team science and applications assessment validated the community assessment that POD is not a viable MC candidate architecture
Key points:
High science performance but long/uncertain path to TRL 6

AOSense lab instrument in collaboration with NASA GSFC:
• Currently TRL 4; path to TRL 6 TBD

GSFC Instrument Design Lab (IDL) conducted June 1st – 5th
• First AIGG flight instrument design
• Identified challenges
  – Laser components will likely need development to reduce power
  – Some lab components (RF and laser) lack spaceflight equivalents
  – Challenging to test instrument flight performance in a terrestrial environment

• Instrument Accommodation: 947 kg; 1049 W
• Continue engineering design refinement (follow-up MDL study at GSFC in early CY21)
SST SmallSats: Summary of Team X Study

• Team X: 4-day concurrent engineering design session at JPL – conducted remotely in May 2020

• Team X study goals
  – Determine if a sub-$300M SST exists that meets baseline objectives and seeks to minimize size, weight, and power
  – Leverage smaller, less mature accelerometer (ONERA CubStar) and inter-satellite ranging technologies (GeoOptics KVR)

• Team X architectures:

<table>
<thead>
<tr>
<th>Option 1: Dual string with heritage bus components</th>
<th>Option 2: Single string with SmallSat bus components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redundancy: Dual string</td>
<td>Redundancy: Single string</td>
</tr>
<tr>
<td>Mass: 434 kg</td>
<td>Mass: 194 kg</td>
</tr>
<tr>
<td>Phase A-E cost: $501M FY18</td>
<td>Phase A-E cost: $419M FY18</td>
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</table>

• Team X major conclusions
  – The benefit of reduced technical footprint of the ranging/accelerometer technologies on the spacecraft bus is limited due to stringent center of mass, structural stability, thermal, attitude, and pointing requirements
  – The single string option reduced cost, but was unable to meet the cost target: Leveraging less mature, potentially lower reliability components in a single string configuration is not recommended and is only shown to identify the cost ‘floor’
  – A fully domestic implementation that meets the baseline objectives may not be feasible within the $300M FY18 cost target
Cost Effectiveness Comparisons - Preview

- Preliminary results for SST architectures in various configurations
  - Single pair in-line (GRACE-like)
  - Single pair pendulum (in different planes)
  - Two pair Bender (pairs with different orbit inclination)
  - Hybrids (combined in-line, pendulum)
- Within each configuration are different altitudes (350 km – 500 km), instruments, and formations
- Cost estimates for domestic only implementation are above cost target ($300M FY18) for Phase A-E
  - Reduced cost to NASA may be enabled through strategic partnerships
  - Costs shown do not include workshare with potential international partners
The MC Team is on track to provide the following to NASA HQ in late Fall:

- Description of high-value, affordable architectures with recommendation to HQ
  - Science and applications performance
  - Cost estimate and cost risk assessment (Phase A-E, RY$)
  - Schedule estimate and schedule risk assessment including continuity with GRACE-FO
  - Technology readiness, risks, and maturation plans
  - International partnership concepts
  - Background and supporting material (e.g., design center reports, modeling analysis)
- After decision from NASA HQ, we will enter Phase 3 of the study focused on detailed design of one or more high value architectures

Please join us at AGU in December for a Virtual Town Hall
Friday, December 11, 2020 @ 07:00 Pacific Standard Time
Backup
Relating Observing System Capability to the DS

Science value metrics directly relate the capability of an observing system architecture to achieving science and application targets relevant to MC in the Decadal Survey.

The process is successful in discriminating between architectures.
Mass Change Designated Observable Study: Background

- **January 2018**: Mass Change is identified as a Designated Observable in the 2017-2027 Decadal Survey for Earth Science and Applications from Space
  - 15 Science Questions related to mass change are identified
  - Recommended cost target: $300M
- **December 2018**: Formation of Mass Change Designated Observable Study Team
  - Participations from multiple NASA Centers
  - Charter is to cast a wide net to identify possible observing systems that can be responsive to science questions identified in the Decadal Survey
  - Create a “Value Framework” to quantify science value, cost, technology readiness level, schedule (including continuity with GRACE-FO), risk, and potential international partners for possible observing systems
  - Recommend a small set of high-value affordable architectures to NASA HQ for eventual selection of an observing system for full implementation
- **July 2019**: Community Workshop focused on architectures, technology, science focus areas
- **February 2020**: Release of final Science and Applications Traceability Matrix Measurement Parameters after significant community input
- **May 2020**: Release of LRI and Gravitational Reference Sensor Technology Summaries and Roadmaps

https://science.nasa.gov/earth-science/decadal-mc
Simulated World:
Includes relevant geophysical processes that transfer mass within Earth system

- Sample these processes by simulating satellite orbits and measurements to create “TRUTH” observations
- Sample these processes by simulating satellite orbits and measurements to create “NOMINAL” observations
- Add geophysical model error (temporal aliasing error) to simulated world
- Add noise to measurements (provided by community)

Residuals

Best estimate of simulated world

Calculate Science Value based on simulation results

Comparison against the truth simulated world to quantify error

<table>
<thead>
<tr>
<th>Static Gravity Field</th>
<th>Truth Model</th>
<th>Nominal Model</th>
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<td>gif48</td>
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• POD has poor performance even for large scale multi-element system implementation
• GG has high performance ceiling but unclear maturation plans
• Preliminary results for SST architectures in various configurations
  • Single pair in-line (GRACE-like)
  • Single pair pendulum (in different planes)
  • Two pair Bender (pairs with different orbit inclination)
  • LEO to MEO ranging including combined LEO-MEO with in-line pairs
  • Hybrids (combined in-line, pendulum)
• Cost estimates for domestic only implementation are above cost target ($300M FY18) for Phase A-E
  • Derived from parametric and analogy-based cost models
  • Reduced cost to NASA may be enabled through strategic partnerships
  • Costs shown do not include workshare with potential international partners
  • LEO-MEO costs include only the LEO portion of the observing system implementation
High Fidelity Numerical Simulations

- Numerical simulations are run that include realistic measurement system errors as well as dynamic force model errors to quantify the expected performance of each architectural variant.
- Simulations mimic processing of real GRACE and GRACE-FO data.
- Analytic partial derivatives relate the simulated observations to the state parameters of interest – this allows for a quantitative metric of performance.
- Numerically intensive: ~300,000 CPU hours.
- Performance is analyzed across space and time.

Dynamic force models used in simulations:

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Error is mapped across space and time.
• Overview
  – GeoOptics proposed a constellation of MicroSats (consistent with Class-D) as potential MC architecture
  – Same ranging and accelerometer technologies as SmallSat Team X study
  – MC study team worked with Aerospace Corp. to analyze and cost
  – Proposed design is not viable due to lack of power budget closure (requires larger spacecraft)
  – Thermal requirements are also not resolved
  – Costing efforts revealed lack of savings even for non-viable design

• Details
  – Class-D lifetime is 2.5 years based on historical analogies
  – To achieve Class-C implementation (for consistent comparison) requires satellites to be replenished once
    • 2-pair implementation + 2-pair spares (4-pair/8-satellites total): $550M
    • 4-pair implementation + 4-pair spares (8-pair/16-satellites total): $960M

• Conclusions
  – Due to high costs of non-viable design, the closure of the power budget and thermal requirements not pursued
  – Conclusions of Team X study are consistent with the non-viability of the proposed GeoOptics architecture
    (i.e. single-string SmallSat implementation is the ‘floor’ design that meets science objectives)