

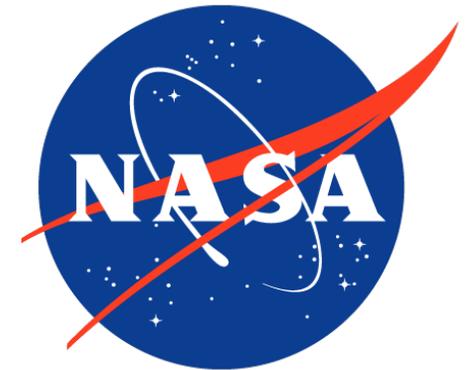


# Mass Change Overview

Lucia Tsaoussi, NASA HQ

Mass Change Program Scientist

December 12, 2019



# Mass Change Targeted Observable (TO-9 in 2017 ES Decadal Survey)

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- Mass Change is determined by measuring **gravitational changes** over set time periods
- *“MC provides an integrated view of the entire physical Earth system that allows the relating of changes in one system component to changes in another. By providing **continuity of the GRACE measurement record**, it addresses MI and VI objectives for 3 panels and contributes to several integrating themes.”* p.134 of DS

Focus Area	Most Important (MI)	Very Important (VI)	Important
Hydrology	1a, 2c		3b, 4c
Climate	1a, 1b, 1c	1d	7d, 7e
Earth Surface and Interior	1b, 3a, 4a	5a	6b

# Mass Change Targeted Observable (TO-9 in 2017 ES Decadal Survey)

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- *“Box 3.7 Using satellite gravity to understand Mass Change” p.108 in DS.*
- This section provides an overview of the GRACE enabled accomplishments and the insight provided by monthly maps and contributions to
  - Process understanding
  - Quantifying changes in ice sheets/ mountain glaciers & water losses in lakes and aquifers
  - Begin to monitor decadal trends associated with climate change
- **Challenges addressed by the MC Study team**
  1. Translate science objectives to gravity observations
  2. Science objectives require both measurement capability AND relevant analytical framework (e.g. models)
  3. Continuity as relates to measurement and model capabilities AND lack of observational gaps



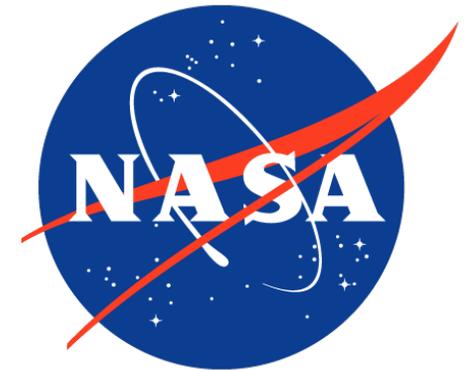
Image Credits Clockwise from Top Left: (c) jukree, (c) johnnorth, (c) EcoPicture, (c) SeanPavonePhoto (c) Scrofula, (c) releon8211, (c) Scrofula, (c) Pancaketom all @ fotosearch.com

# Mass Change Study Team Status

Bernie Bienstock, JPL/Caltech

Mass Change Study Coordinator

December 12, 2019





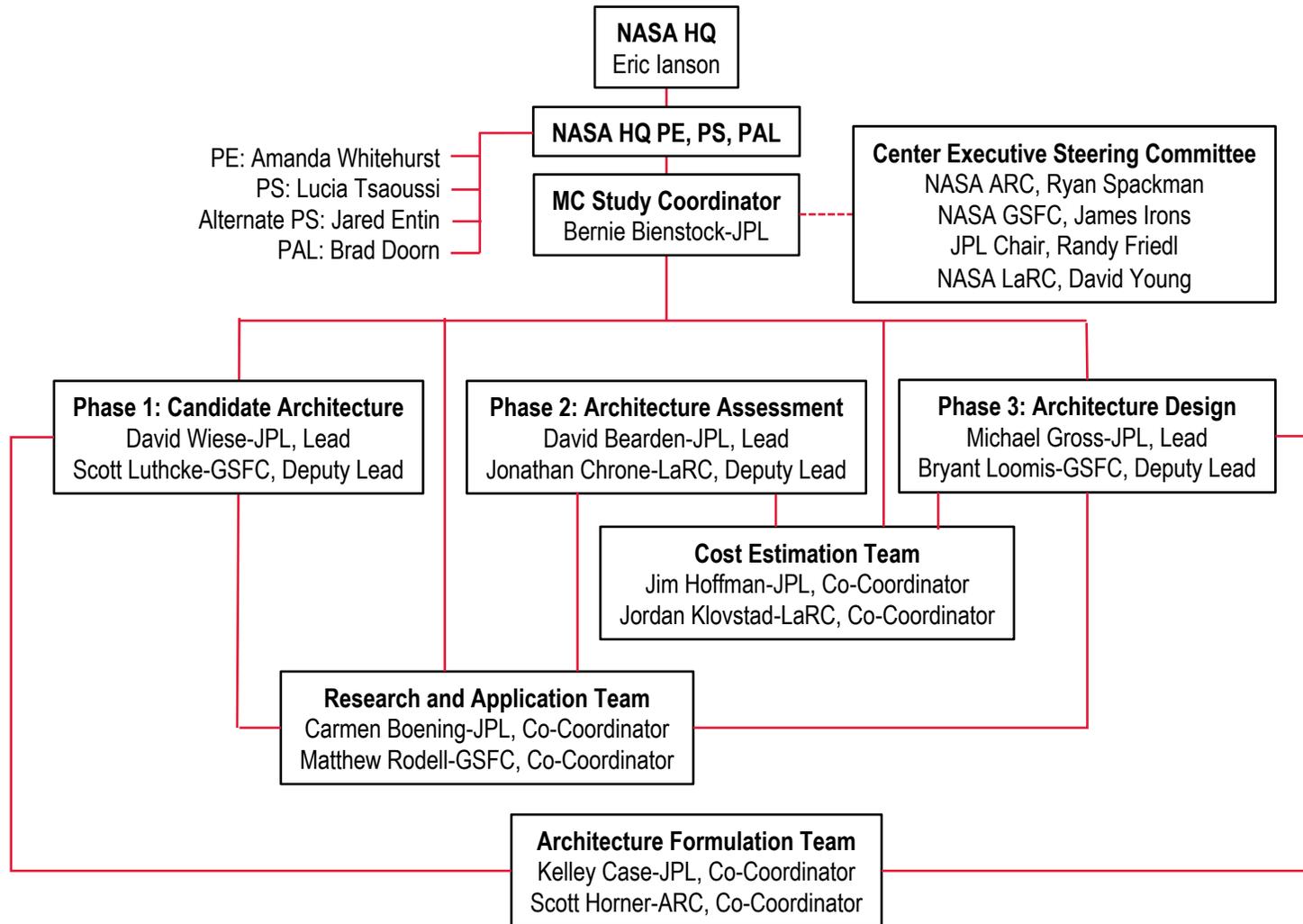
## 0. Study Overview

In response to NASA's "Designated Observables Guidance for Multi-Center Study Plans" released 6/1/2018, JPL, GSFC, LARC and ARC submit this Study Plan to the NASA Earth Science Division for the Mass Change Measurement System ("MC"). The MC Study described here has three main objectives, namely

1. Identify and characterize a diverse set of high value MC observing architectures responsive to the Decadal Survey (DS) report's scientific and application objectives for MC.
2. Assess the cost effectiveness of each of the studied architectures.
3. Perform sufficient in-depth design of one or two select architectures to enable rapid initiation of a Phase A Study.

# Mass Change Phase Org Chart

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## Mass Change Working Groups

### SATM

- David Wiese, Lead
- Carmen Boening
- Bryant Loomis
- Scott Luthcke
- Matt Rodell
- Jeanne Sauber
- Frank Webb
- Victor Zlotnicki

### Phase 2 Working Group

- Kelley Case, Lead
- Dave Bearden
- Jon Chrono
- Scott Horner
- Bryant Loomis
- Scott Luthcke
- Frank Webb
- David Wiese

### Applications

- Matt Rodell, Lead
- JT Reager
- Margaret Srinivasan

### Science & Community Engagement

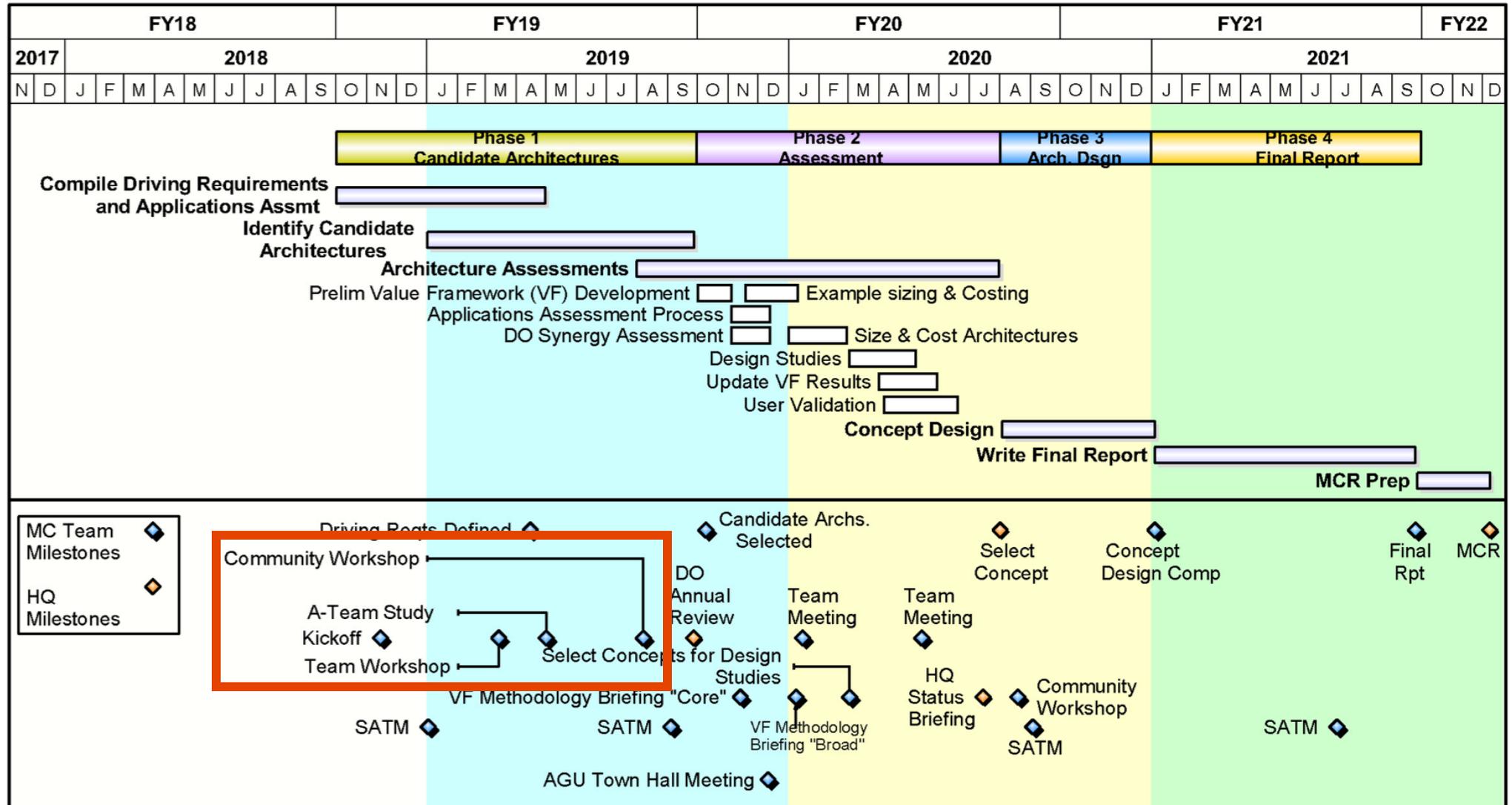
- Carmen Boening, Lead
- Rosemary Baize
- Bernie Bienstock
- Bryant Loomis
- David Wiese
- Victor Zlotnicki

### Communications

- Victor Zlotnicki, Lead
- Bernie Bienstock
- Donna Wu

# Phase 1 Accomplishments

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# A-Team Study

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- Conducted at JPL on 5/1-2/2019
- Attended by 17 members of the Mass Change team from participating centers and NASA HQ
- Meeting accomplishments
  - Explored the mass change architecture trade space as defined in the 2017 Earth Science Decadal Survey
  - Defined Mass Change architecture classifications
    - Satellite-satellite tracking (SST)
    - Precision orbit determination (POD)
    - Gravity gradiometer (GG)
  - Conducted deep dives on various Mass Change architecture options

# Community Workshop

AGU 2019

- Conducted in Washington, DC on 7/30 thru 8/1/2019
- Attended by 80 people from international space agencies, US and domestic industry, academia, NASA, and JPL
- Accomplishments
  - Thorough science review
  - Community vetting and tune-up of the Mass Change SATM
  - Discussion of applicable technologies and architectures
  - Workshop summary report available on the Mass Change website, <https://science.nasa.gov/earth-science/decadal-mc>

## Agenda

### Day 1

MC Workshop Introductions

Agency Presentations (ESA, CNES, HGF)

SATM Briefings and Breakout Sessions

### Day 2

Architecture Options

Enabling Technologies

Applications and Community Assessment Report

Applications, Technology, and Architecture Breakout Sessions

### Day 3

SATM Summary

Mass Change Future Plans

# Phase 2 Plan

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Date		Event/Milestone
Start	Stop	
12/2/19	12/15/19	Conduct sizing and costing of concepts, beginning with SST
<b>12/18/19</b>	<b>12/18/19</b>	<b>Methodology overview and examples briefing to MC Team</b>
12/19/19	1/23/20	Finalize set of architectures (SST, POD, GG)
1/24/20	3/17/20	Conduct sizing and costing studies of all concepts
2/11/20	2/12/20	MC Team Meeting at NASA Ames
<b>3/18/20</b>	<b>3/18/20</b>	<b>Preliminary AoA Presentation to MC Team</b>
3/19/20	4/15/20	Revise results based on MC Team feedback
<b>4/16/20</b>	<b>4/16/20</b>	<b>Draft AoA Presentation to MC Team</b>
4/17/20	5/12/20	Develop final AoA briefing
5/5/20	5/6/20	<b>MC Phase 2 Community Meeting</b>
<b>5/13/20</b>	<b>5/13/20</b>	<b>Final MC Team Briefing on AoA</b>
5/14/20	6/17/20	Finalize documentation
<b>6/18/20</b>	<b>6/18/20</b>	<b>Deliver final AoA documentation</b>

Legend		
<b>Boldface = Milestones</b>		
AoA = analysis of alternatives		
SST = satellite-to-satellite tracking		
POD = precise orbit determination		
GG = gravity gradiometer		



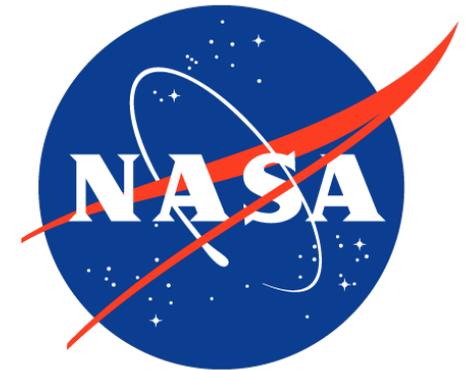
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# Architecture and Technology Options to satisfy the Science and Applications Traceability Matrix for the Mass Change Designated Observable

David N. Wiese<sup>1</sup> on behalf of the MC-DO Study Team

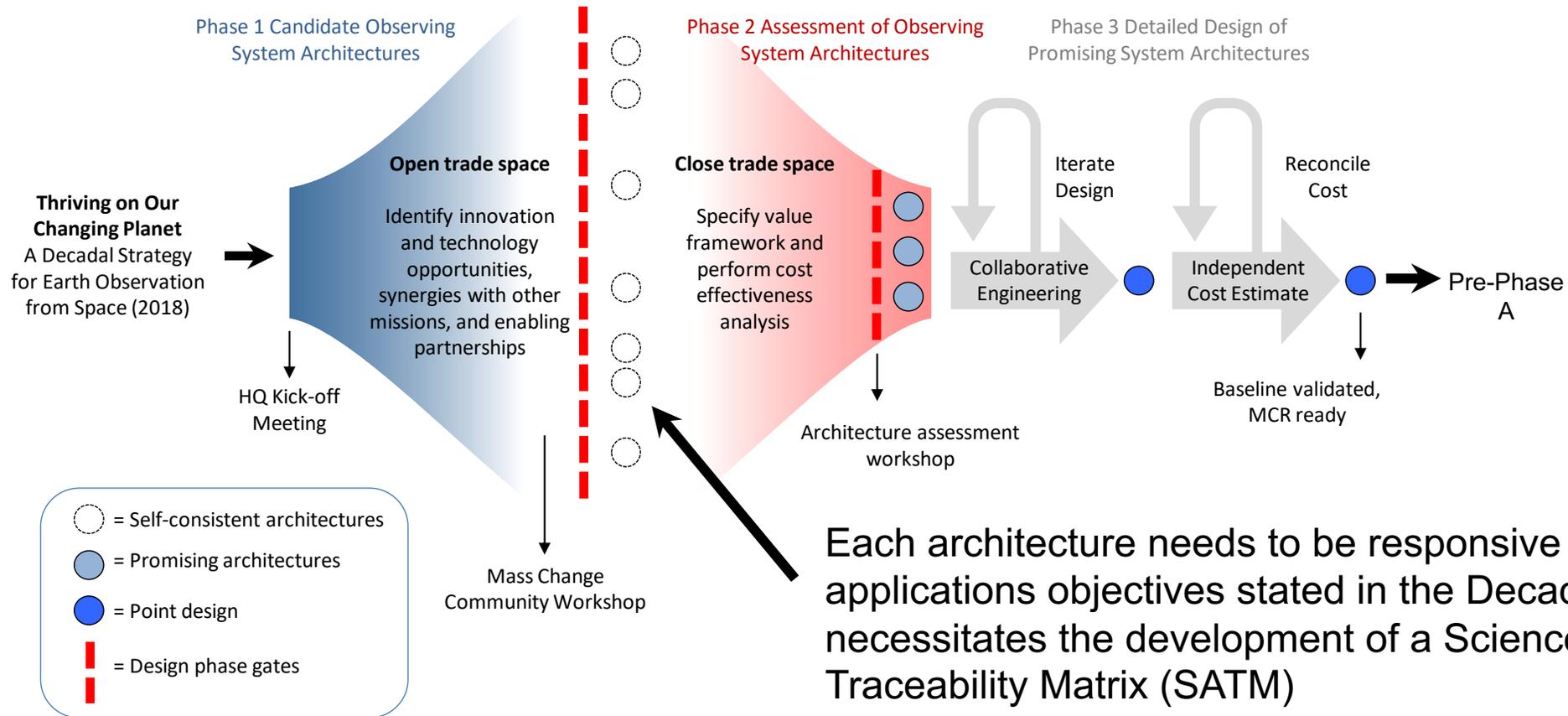
December 12, 2019

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology



# Study Phases

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Each architecture needs to be responsive to the science and applications objectives stated in the Decadal Survey. This necessitates the development of a Science and Applications Traceability Matrix (SATM)

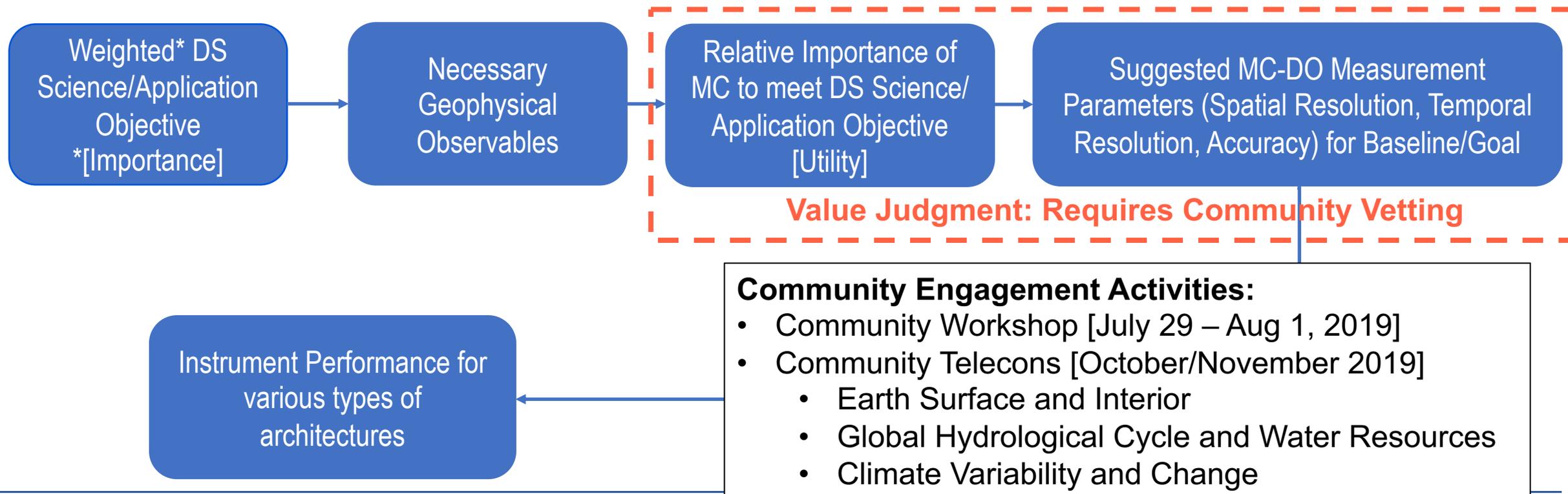
MC-DO SATM Working Group: Carmen Boening, Bryant Loomis, Scott Luthcke, Matt Rodell, Jeanne Sauber, Frank Webb, David Wiese, Victor Zlotnicki

# SATM Overview for Mass Change DO

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## Creating Traceability from DS Science/Applications Objectives to Observing System Architectures

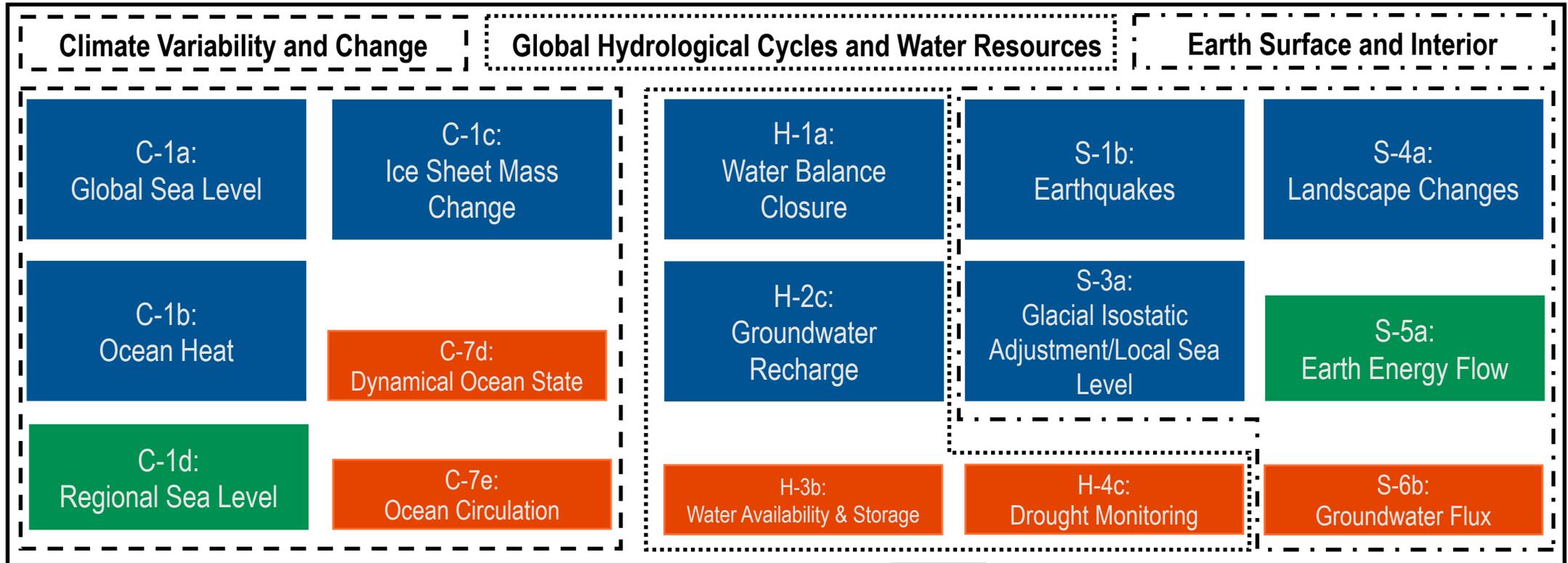
- **Baseline** Observing System – supports full science objectives
- **Goal** Observing System – supports additional science with a goal to create longevity in the mass change time series. May include advancements of enabling technologies



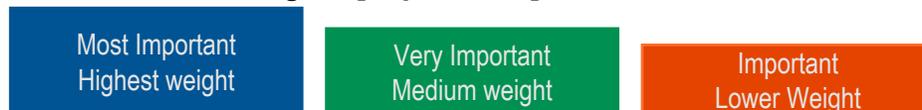
# Decadal Survey Science and Application Objectives for Mass Change

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## A Diverse Set of Objectives Spanning Three Panels



### DS Prescribed Weights [Importance]



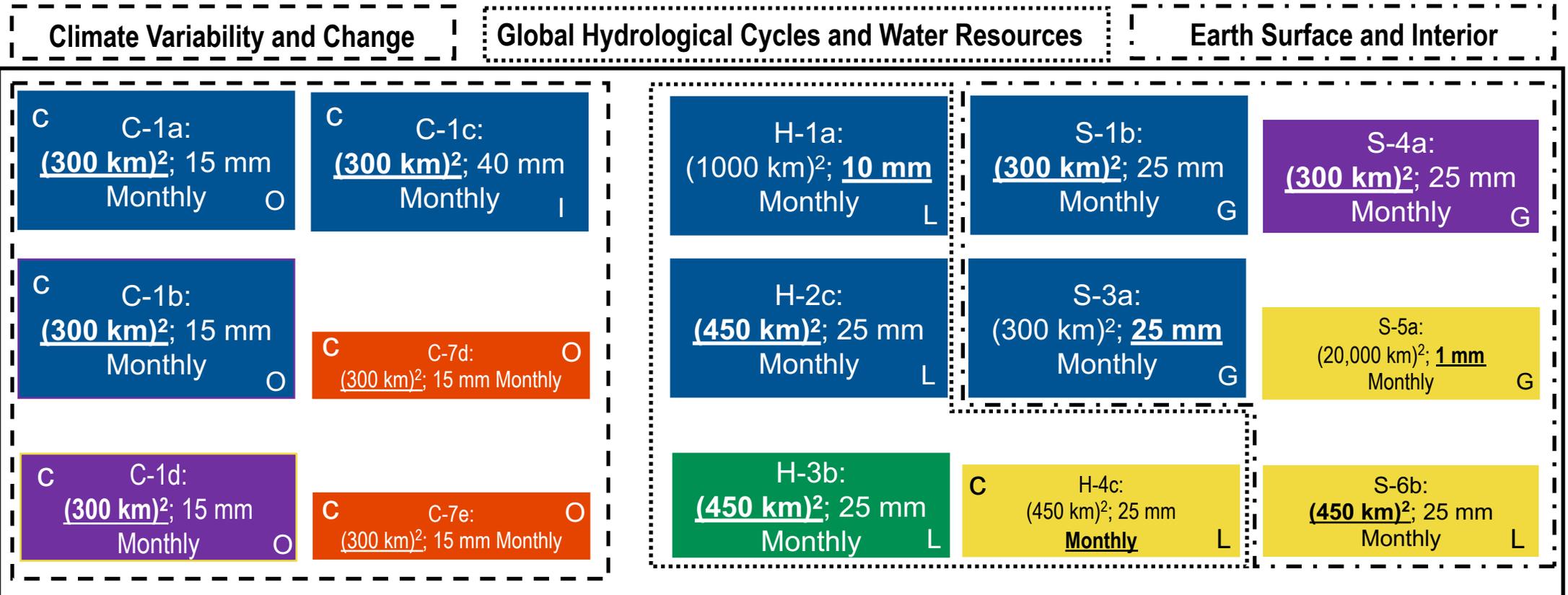
Science Performance Targets



# Suggested Measurement Parameters for Baseline

AGU 2019

Weighting Combines DS Importance with MC Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height



C: Continuity explicitly recommended in Decadal Survey

Highest Weight
Medium – High Weight
Medium Weight
Medium-Low Weight
Low Weight

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

↓  
**Science Performance Targets**



# Suggested Measurement Parameters for Goal

AGU 2019

Weighting Combines DS Weights with MC Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height

Climate Variability and Change

Global Hydrological Cycles and Water Resources

Earth Surface and Interior

C C-1a:  
(100 km)<sup>2</sup>; 15 mm  
Monthly

C C-1c:  
(100 km)<sup>2</sup>; 10 mm

H-1a:  
(3 km)<sup>2</sup>; 10 mm

S-1b:  
(200 km)<sup>2</sup>; 12 mm

S-4a:  
(200 km)<sup>2</sup>; 12 mm  
Monthly G

C C-1b:  
(100 km)<sup>2</sup>; 15 mm  
Monthly

Complete SATM is now available online for review and comment:  
<https://science.nasa.gov/earth-science/decadal-mc>  
Comments will be accepted through Jan. 31, 2020  
Please e-mail [masschange@jpl.nasa.gov](mailto:masschange@jpl.nasa.gov)

S-5a:  
(20,000 km)<sup>2</sup>; .01mm  
Monthly G

C C-1d:  
(100 km)<sup>2</sup>; 15 mm  
Monthly O

C C-7e:  
(50 km)<sup>2</sup>; 10 mm; Monthly O

(200 km)<sup>2</sup>; 25 mm  
Monthly L

C H-4c:  
(50 km)<sup>2</sup>; 1.5 mm  
Weekly L

S-6b:  
(100 km)<sup>2</sup>; 10 mm  
Monthly L

C: Continuity explicitly recommended in Decadal Survey

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

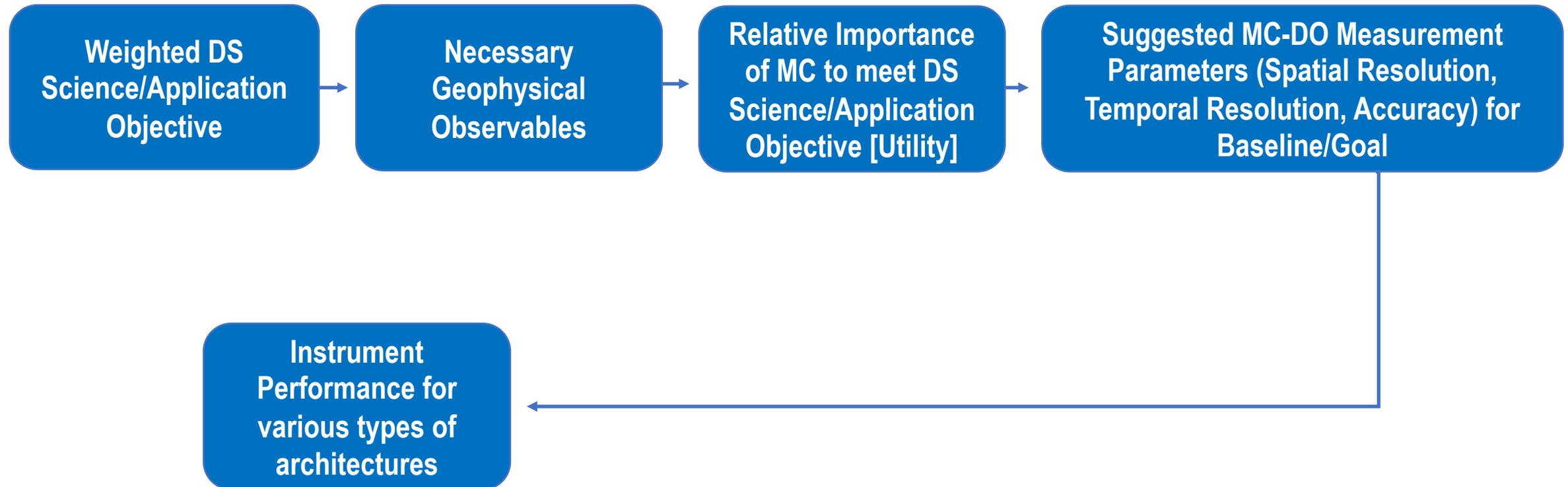
Highest Weight
Medium – High Weight
Medium Weight
Medium-Low Weight
Low Weight

Science Performance Targets



# MC Interpretation of DS Objectives

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# Summary of observing system architecture activities

AGU 2019

Activity	Summary
Literature Survey	The DO Mass Change team is surveying the published literature and conference presentations on architecture concepts, simulations, and proposals
A-Team Study	Observing system architectures for mass change can still be submitted by the community.
Community Workshop	Input will be accepted through Jan. 31, 2020 Please e-mail <a href="mailto:masschange@jpl.nasa.gov">masschange@jpl.nasa.gov</a>
Workshop Follow-up	At the conclusion of the workshop we solicited detailed observing system architecture information from the various presenters, and we continue to receive and compile this information: <u>submitted documents range from general concepts to detailed proposals</u>

Observing system architectures for mass change can still be submitted by the community.

Input will be accepted through Jan. 31, 2020  
Please e-mail [masschange@jpl.nasa.gov](mailto:masschange@jpl.nasa.gov)

# Overview of observing system architecture types

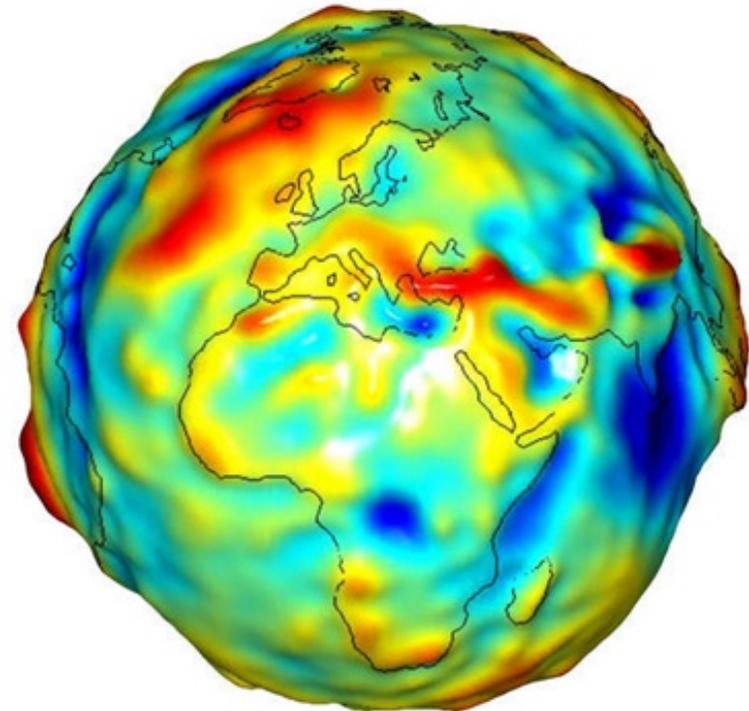
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The A-Team study and Community Workshop identified three architecture types:

- **POD**: Precise Orbit Determination (multiple satellites)
- **SST**: Satellite-to-satellite tracking (multiple satellites)
- **GG**: Gravity gradiometer (single satellite)

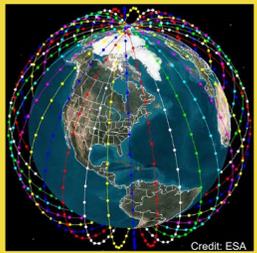
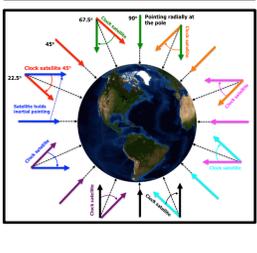
All architecture types observe the effect of gravity on the motion of objects in Low Earth Orbit:

- Satellites: **POD/SST**
- Test mass(es) within satellite(s): **GG**
- Atom clouds within satellite(s): **GG**



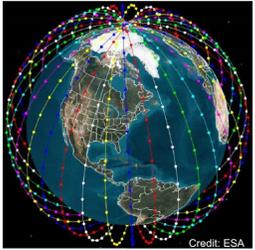
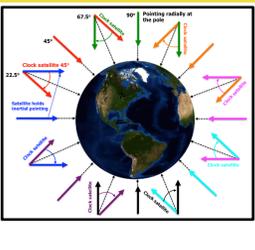
# Overview of observing system architecture types

AGU 2019

Type	Overview	Trade-space & key questions
 <p>Credit: ESA</p>	<p><b>POD</b> Precise orbit determination</p> <ul style="list-style-type: none"> <li>• Large constellation of GNSS receivers – potentially CubeSats</li> <li>• Candidate for gap filler</li> <li>• Could combine purchases of existing POD data with design/expansion of current constellations (e.g. Spire)</li> </ul>	<ul style="list-style-type: none"> <li>• Number of satellites</li> <li>• Mega-constellation performance?</li> <li>• Are accelerometers an option?</li> <li>• Performance of derived baseline? (no dedicated SST instrument)</li> </ul>
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	<p><b>GG</b> Gravity gradiometer</p> <ul style="list-style-type: none"> <li>• Atomic interferometer gravity gradiometer expected to far exceed the performance of electrostatic accelerometers of GRACE &amp; GOCE missions</li> <li>• Likely not ready for the expected MC DO timeline, but given the excellent simulated performance should be considered for more rigorous simulation studies and a key part of a technology development road map</li> </ul>	<ul style="list-style-type: none"> <li>• Gradiometer baseline size/orientation</li> <li>• Expected timeline of technology development?</li> <li>• Possible candidate for technology demonstration concurrent with a primary Mass Change observing system?</li> </ul>

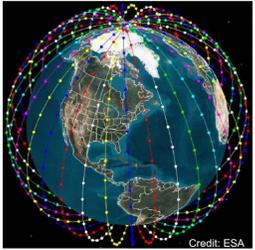
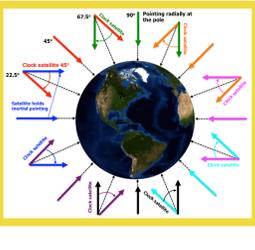
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# Observing system architecture trade space

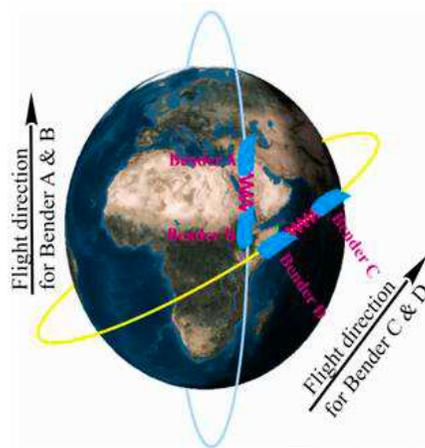
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Observing System		Spacecraft Platform		Orbit Design				Instruments				
Type	Design life	Size	# Platforms	Altitude	Inclination	Separation (SST only)	Formation (SST only)	Inertial Position	Accelerometer	Attitude determination	Ranging (SST only)	System
POD	3-5 years	Medium	1	MEO	~90°	MEO/LEO	In-line	GPS	Electrostatic	Star cameras	KBR	Attitude control
SST	5+ years	SmallSat	2	500 km	~70°	500	Pendulum		Drift mode	IMU	LRI	Thermal control
			3	400 km		200			Atomic GG		Earth IR sensors	Freq. comb
GG	5+ years	CubeSat	4	300 km	Various	100	Cartwheel		Reflecter/transponder	CCLR	Drag compensation	
			5-12			50						
			Many									

# Sample architecture: Dual SST pair with drag compensation

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Observing System		Spacecraft Platform		Orbit Design				Instruments				
Type	Design life	Size	# Platforms	Altitude	Inclination	Separation (SST only)	Formation (SST only)	Inertial Position	Accelerometer	Attitude determination	Ranging (SST only)	System
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SST	5+ years	SmallSat	2	500 km	~70°	500	Pendulum		Drift mode	IMU	LRI	Thermal control
GG			3	400 km		200			Atomic GG	Earth IR sensors	Freq. comb	Structural stability
	4	300 km	100	Reflecter/transponder	Drag compensation							
	5-12	Various	50			Cartwheel						
	Many											



Elsaka et al., 2013

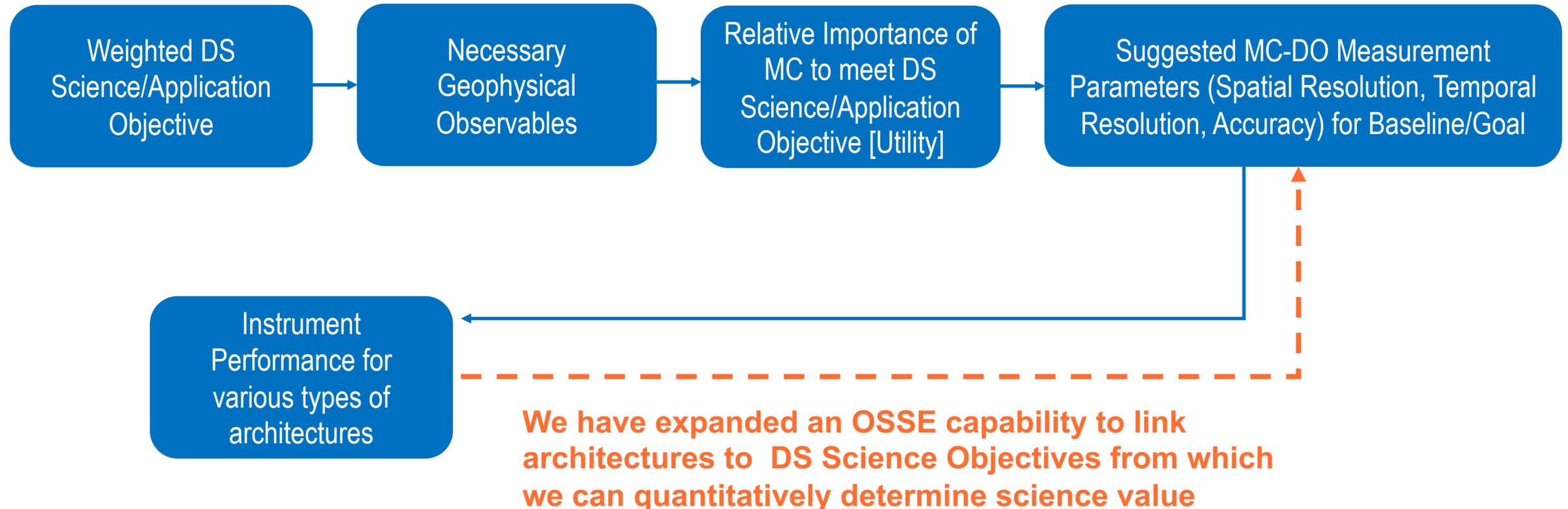
# Summary of Technology Activities

AGU 2019

Activity	Summary
Community Engagement	Solicited wide spectrum of technology talks for the Mass Change Community Workshop July 30 – Aug 1, 2019, Washington, D.C.
Community Workshop	Thirteen technology talks presented covering satellite systems, laser ranging technologies, accelerometer and inertial sensor technologies, atomic interferometer and gravity gradiometer. <b>Strong support to focus on three main technology areas: accelerometer improvements, laser ranging as primary SST measurement, gravity gradiometer as future technology.</b>
Workshop Follow-up	Assigned teams and provided guidance to produce technology summaries for the three main technology focus areas. Draft summaries have been received, with further work necessary for full completion.  Accelerometers: John Conklin, UF Laser Ranging: William Klipstein, JPL Gravity Gradiometry: Babak Saif, GSFC

# Linking Architectures to Science Performance

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# Quantitatively Determining Science Value

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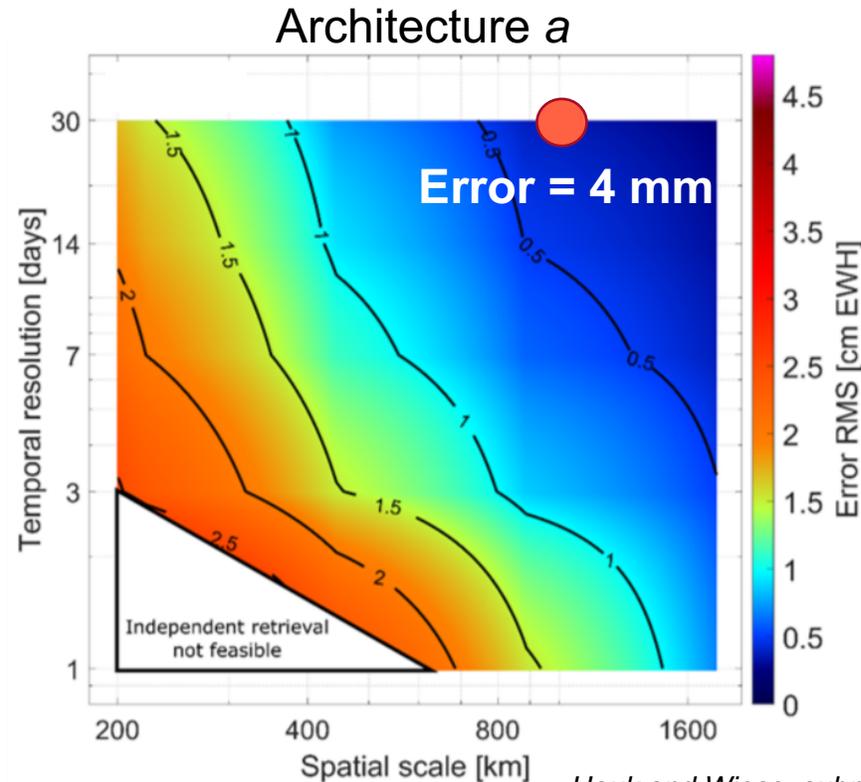
$$SV(a) = \sum_{n=1}^{15} (W_n)P_n = \sum_{n=1}^{15} \left( W_n \frac{Spatial\_Resn}{Spatial\_Res(a)} \frac{Temporal\_Resn}{Temporal\_Res(a)} \frac{Accuracy_n}{Accuracy(a)} \right)$$

Science Objective  $n$

H-1a:  
(1000 km)<sup>2</sup>; **10 mm**  
Monthly

Highest Weight

$W = \text{Importance} * \text{Utility} = 1$



Hauk and Wiese, submitted.

$$SV_n = 1 * 10/4 = 2.5$$

**Poster on Friday Morning  
G51B-0577**

Wiese and Hauk, "New methods for linking science objectives to mission architectures: A case study comparing single and dual-pair satellite gravimetry mission architectures"

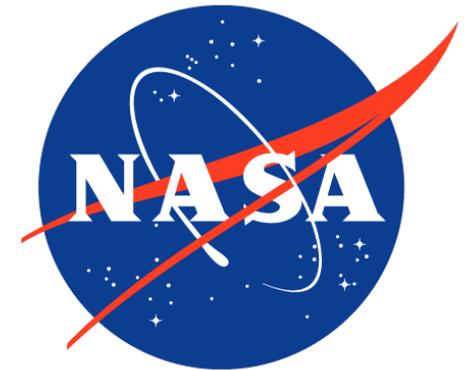


# Mass Change Designated Observable Study: Phase 2 Plan

**Jon Chrono (LaRC) – Architecture Assessment Deputy Lead**

**Dave Bearden (JPL) – Architecture Assessment Lead**

December 12, 2019



# Phase 2 Objectives

AGU 2019

- Phase 2 Objectives
  - Assess the cost effectiveness of each of the studied architectures
  - Perform sufficient in-depth design of one or two select architectures to enable rapid initiation of a Phase A study
- Phase 2 Guidelines
  - The DO study will identify architectures to support most important and very important science objectives
  - Value Framework will **assess architecture solutions** to most/very important science objectives (performance), risk, cost, schedule
  - A basis for down-selection will be necessary; justification will be needed for eliminating candidate architectures

# Phase 2 Assessment Framework

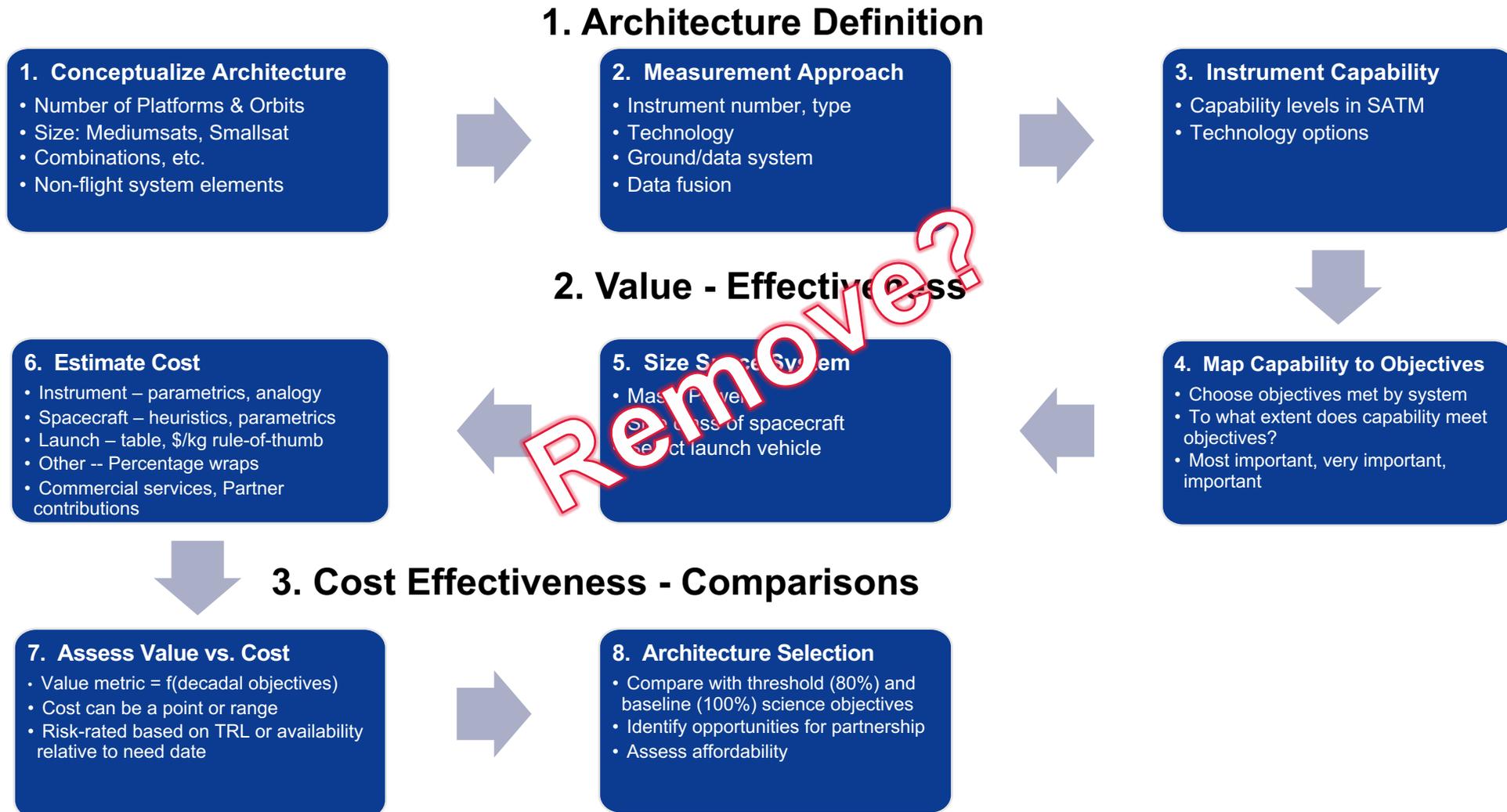
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- Measures will be defined based on the ESAS 2017 DS to assess the features relevant to decision criteria while providing the ability to discriminate between alternatives.
- Alternatives will then be evaluated through a set of analyses covering such assessment areas as capability, cost, schedule, risk, and affordability.

# Flow Diagram – Architecture Concept to Initial Value Assessment

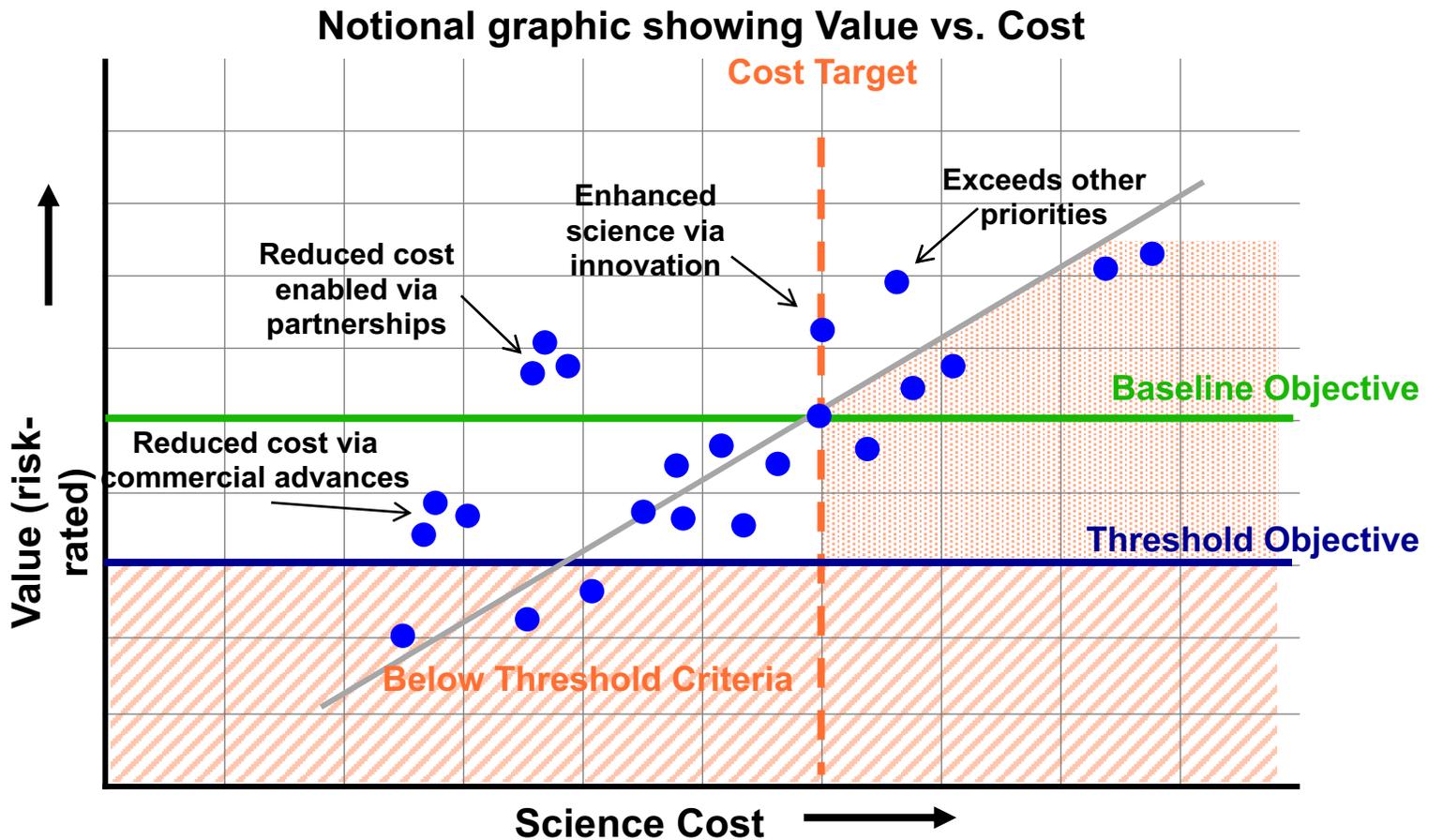
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# Cost Effectiveness Comparisons Value Framework

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- Reduced cost may be enabled through strategic partnerships and/or commercial opportunities
- Enhanced science return may be enabled through new technologies and/or innovation
- Architectures below the Threshold or significantly above cost target will not be considered
- Science value may be risk-rated based on technical or schedule risk

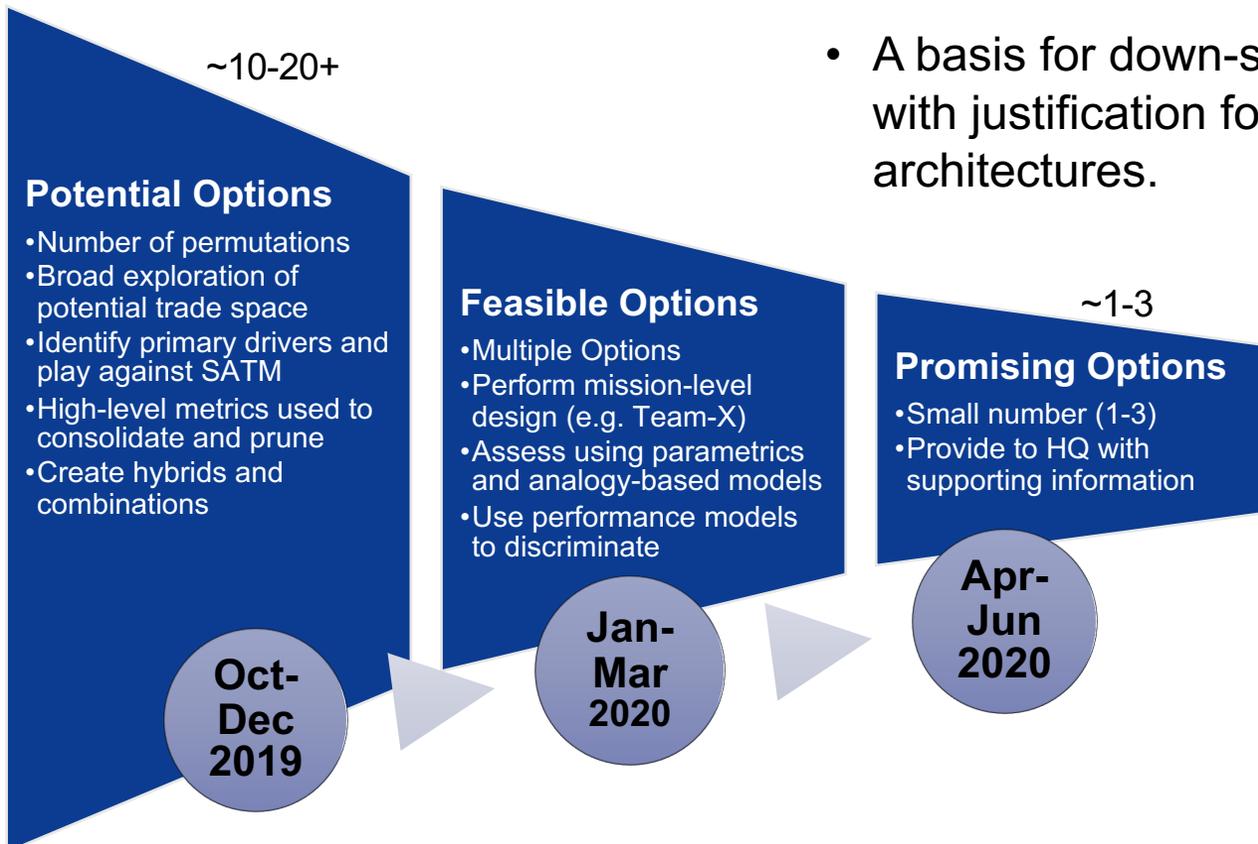


# Phase 2 Plan: Funnel from “Many” to “Few”

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## Number of Observing System Architectures

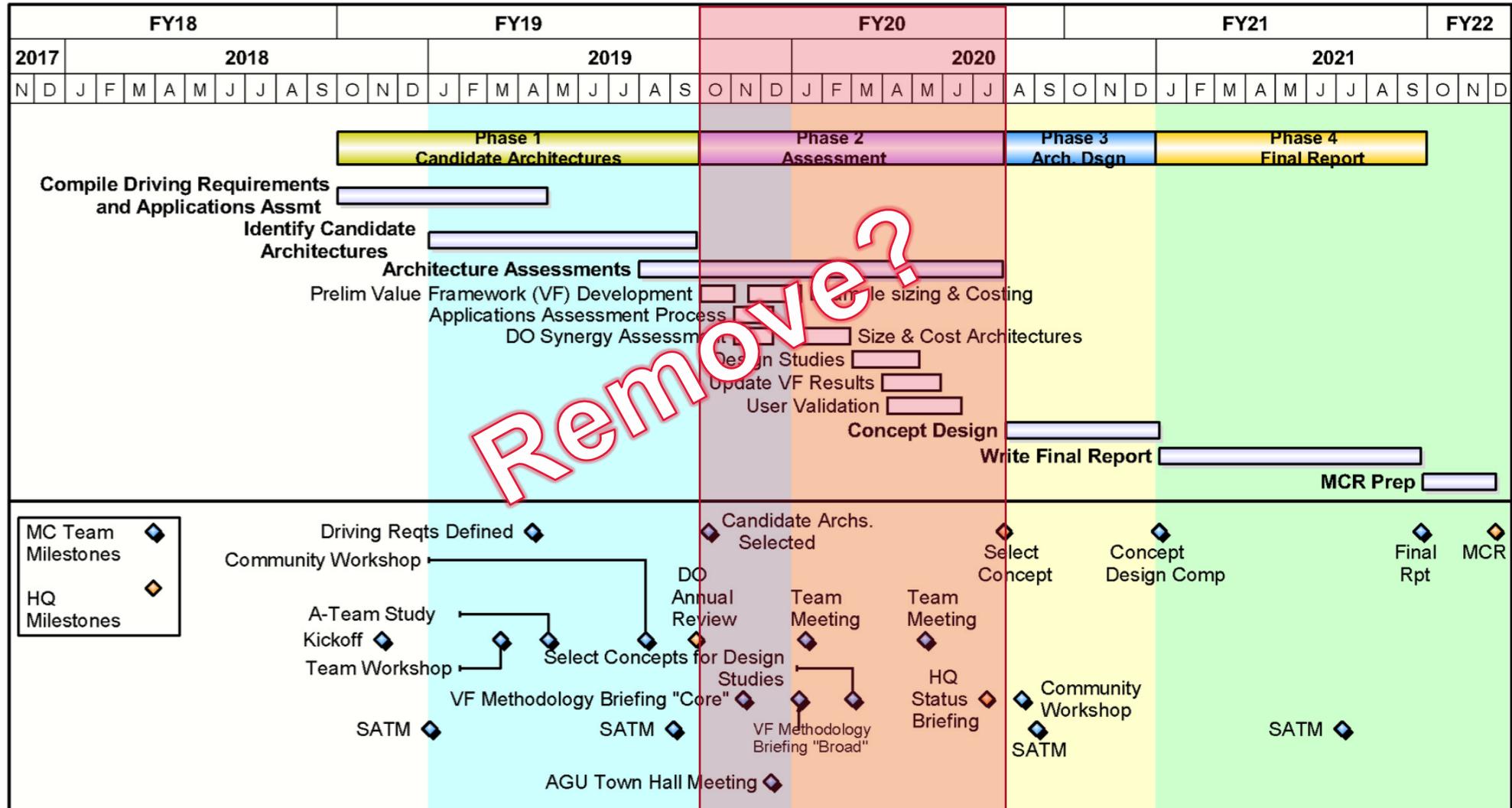
Phase 1



- Value Framework will assess architecture solutions to most/very important science objectives (performance), risk, cost, schedule.
- A basis for down-selection will be necessary with justification for eliminating candidate architectures.

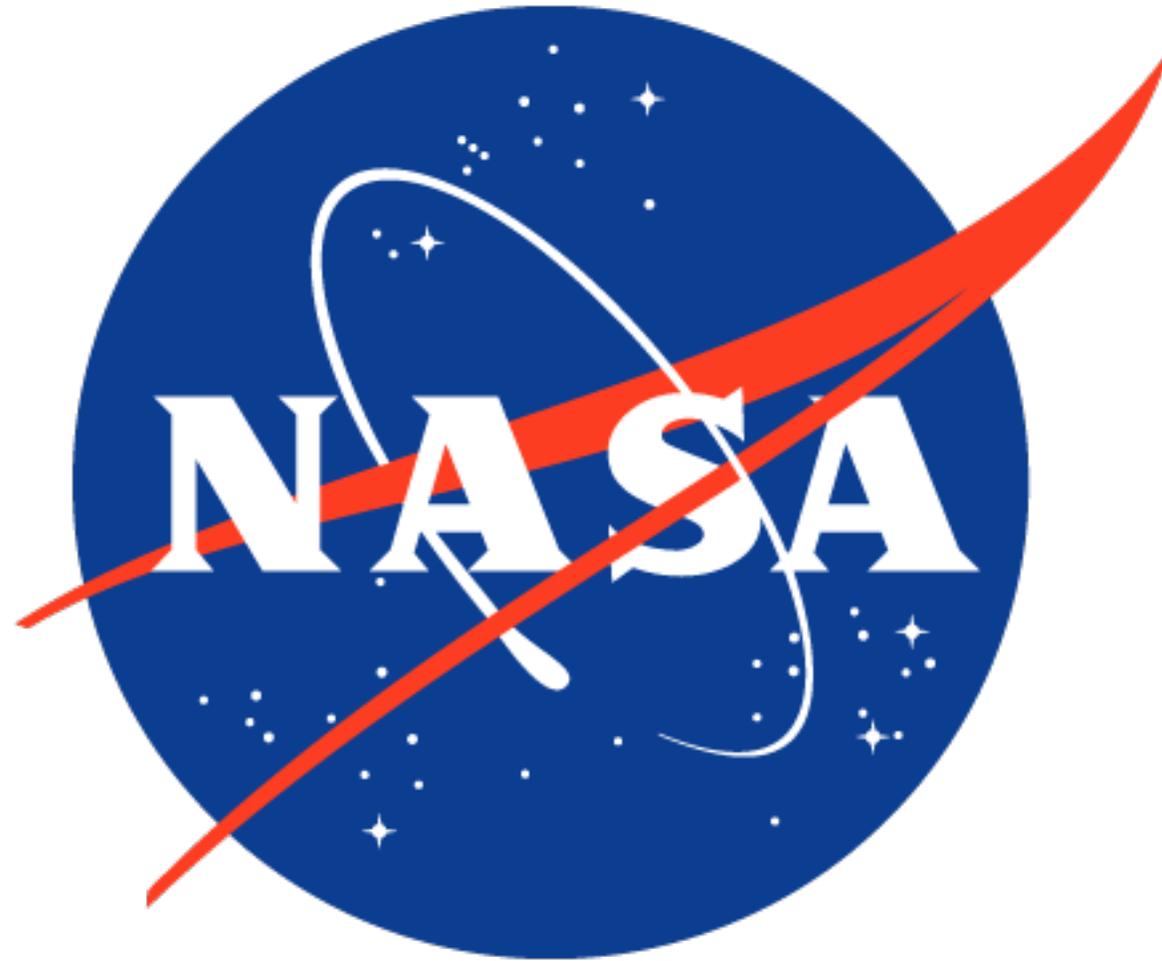
# Phase 2 Tasks and Milestones

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Remove?

# BACKUP



# Overview of technology focus areas

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## Accelerometer

Improved Gravitational  
Reference Sensors

## Laser Ranging

SST primary

Drag  
Compensation

Attitude  
Control

## Gravity Gradiometer

Atomic Interferometry,  
Superconducting

- Accelerometer errors are the dominant GRACE & GRACE-FO measurement errors
- Focus on accelerometer developments and the LRI as the primary SST measurement for continuity and improved performance
- Drag compensation and attitude control technologies support further improvements from the LRI and accelerometer advancements.
- GG is far reaching technology path forward for future mission advancement.

### Community Leads for Technology Summaries

Accelerometer:

John Conklin (UF)

Laser Ranging:

William Klipstein (JPL)

Gravity Gradiometry:

Babak Saif (GSFC)

# Architectures discussed at Community Workshop

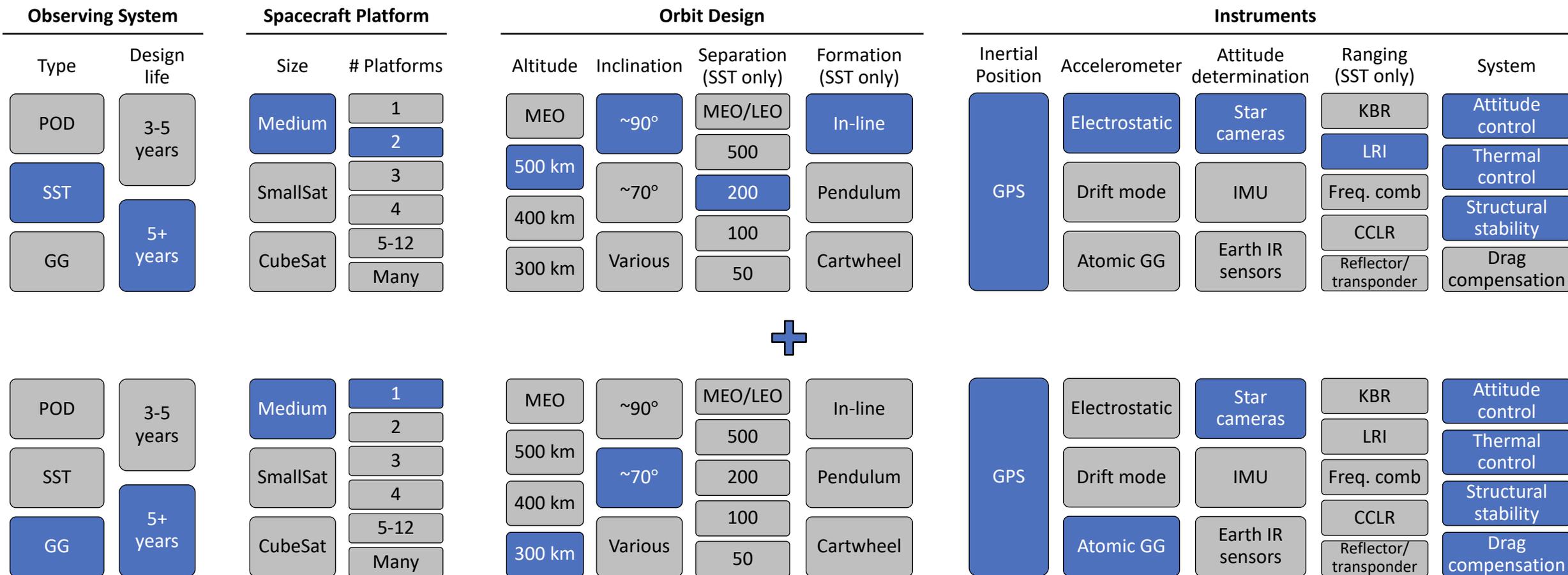
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Name/Description	Presenter(s)	Type	Summary
Single in-line pair	Various	SST	Same as GRACE-FO, but with advances in technology: ranging system, accelerometer, drag-compensation
Dual in-line pair (Bender)	ESA; TUM	SST	Two pairs of GRACE-like in-line SST: One polar pair and one moderately inclined pair (~70 degrees inclination)
MOBILE and MARVEL concepts	TUM and CNES, respectively	SST	1 LEO & 2 MEOs with SST reflector/transponder
EGO	GeoOptics Inc.	SST	SmallSat train with SST between all satellites
HDR-GRACE	Ball Aerospace & Technologies Corp.	SST	SmallSat pair in pendulum orbit with frequency comb ranging system
POD constellation	Spire Global Inc.; DLR	POD	Large constellation of GPS receivers, possible inclusion of accelerometers and/or future SST tech.
Atomic interferometer GG	GSFC/AOSense Inc.; ESA/CNES; JPL	GG	1 LEO with atomic interferometer gravity gradiometer

- ★ These observing system architectures are at very different maturity levels → to be assessed in Phase 2
- ★ This is not a comprehensive list of architectural options to be assessed in Phase 2

# Sample hybrid architecture: SST + Atomic interferometer GG

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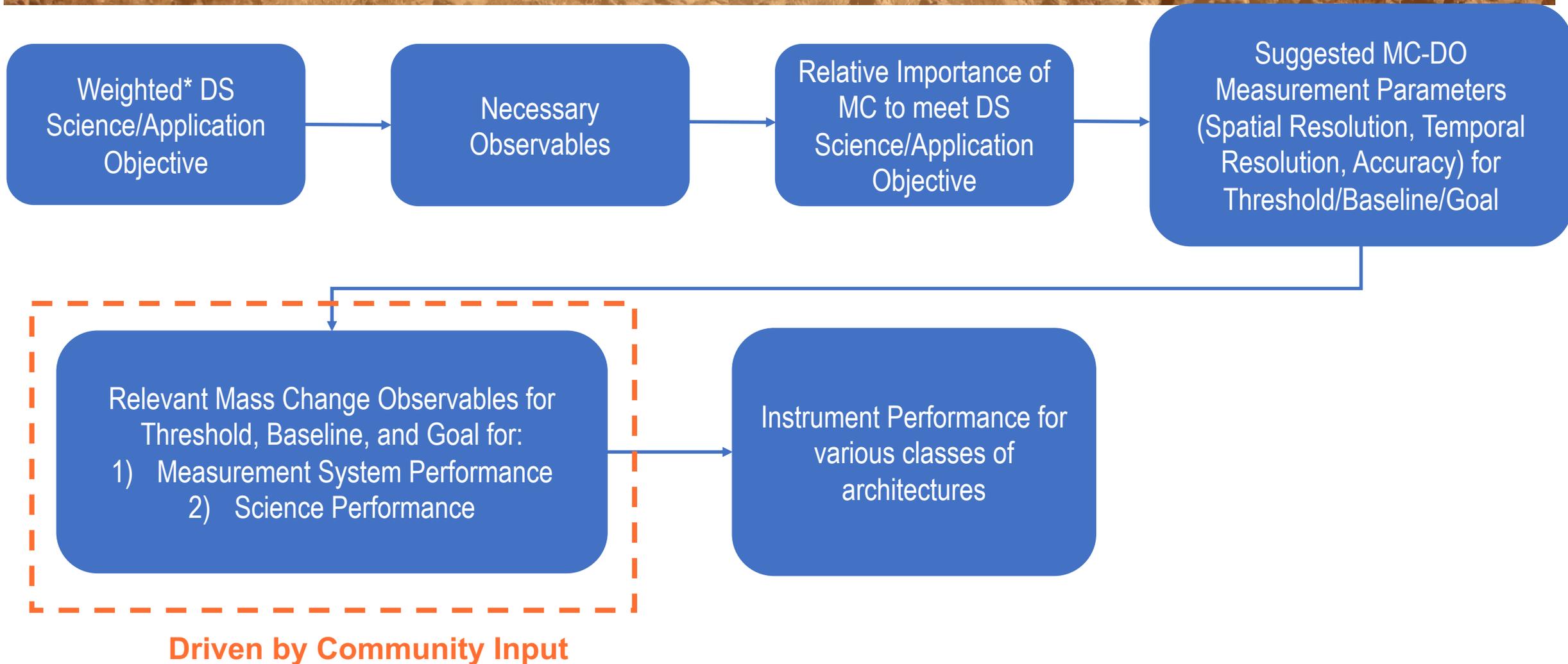


↳ Possible technology demonstration

- Community Workshop held in Washington DC July 30 - Aug 1 (~80 participants)
- Conducted breakout sessions dedicated to each panel (Climate, Hydrology, Solid Earth) with a primary focus to get and incorporate feedback into the SATM
- **Consistent themes in each breakout session did emerge**
  - Baseline Performance should be equivalent to current data record
  - Continuity (minimizing the length of any gap after the end of life of GRACE-FO to the extent possible) and a long data record are of primary importance
  - These **reaffirmed the recommendations** expressed in the Decadal Survey regarding performance and continuity for mass change
- Community telecons were held in October/November 2019 to get more feedback to further refine the SATM (~30-40 people participated in each telecon)
  - Earth Surface and Interior: October 30, 2019
  - Global Hydrological Cycle and Water Resources: November 15, 2019
  - Climate Variability and Change: November 19, 2019
- Full SATM is now publicly available for review and comment: <https://science.nasa.gov/earth-science/decadal-mc>
- **Comments will be accepted through ~Jan. 31, 2019. Please e-mail David.N.Wiese@jpl.nasa.gov**

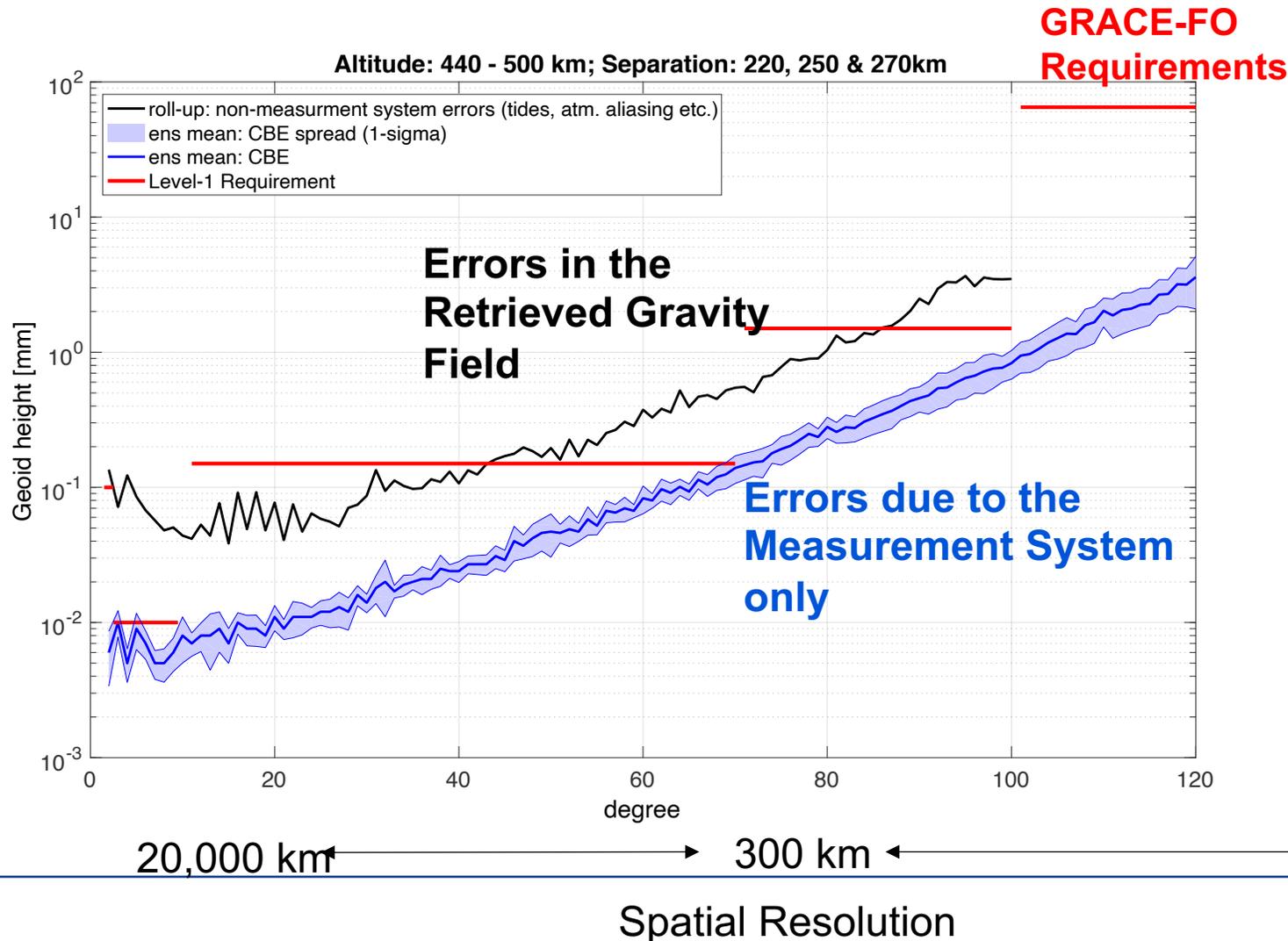
# Mass Change Observables

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# Gravity Field Errors vs Measurement System Errors

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In the current state of the art (GRACE-FO), the gravity fields are not limited by the onboard measurement system: rather they are limited by our inability to model high frequency mass variations with periods < 1 month (ocean tides, atmospheric and oceanic mass variations).

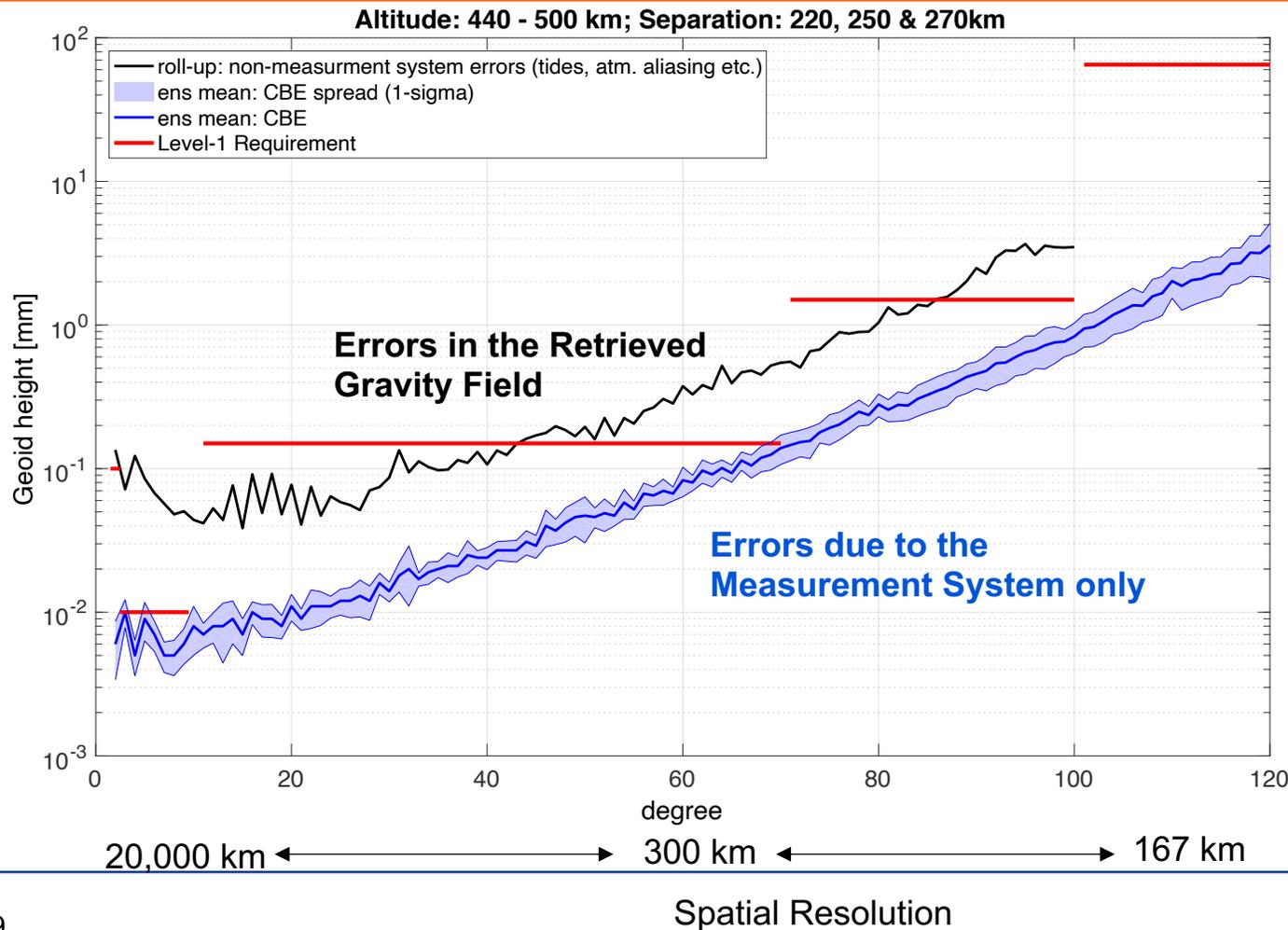
Future data reprocessing has the potential to improve the gravity fields down to the limit of the measurement system.

# GRACE-FO Gravity Errors vs Measurement only errors

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For GRACE-FO, requirements were placed solely on the measurement system. For MC-DO, we define two sets of targets:

- 1) On the measurement system
- 2) On the retrieved gravity fields



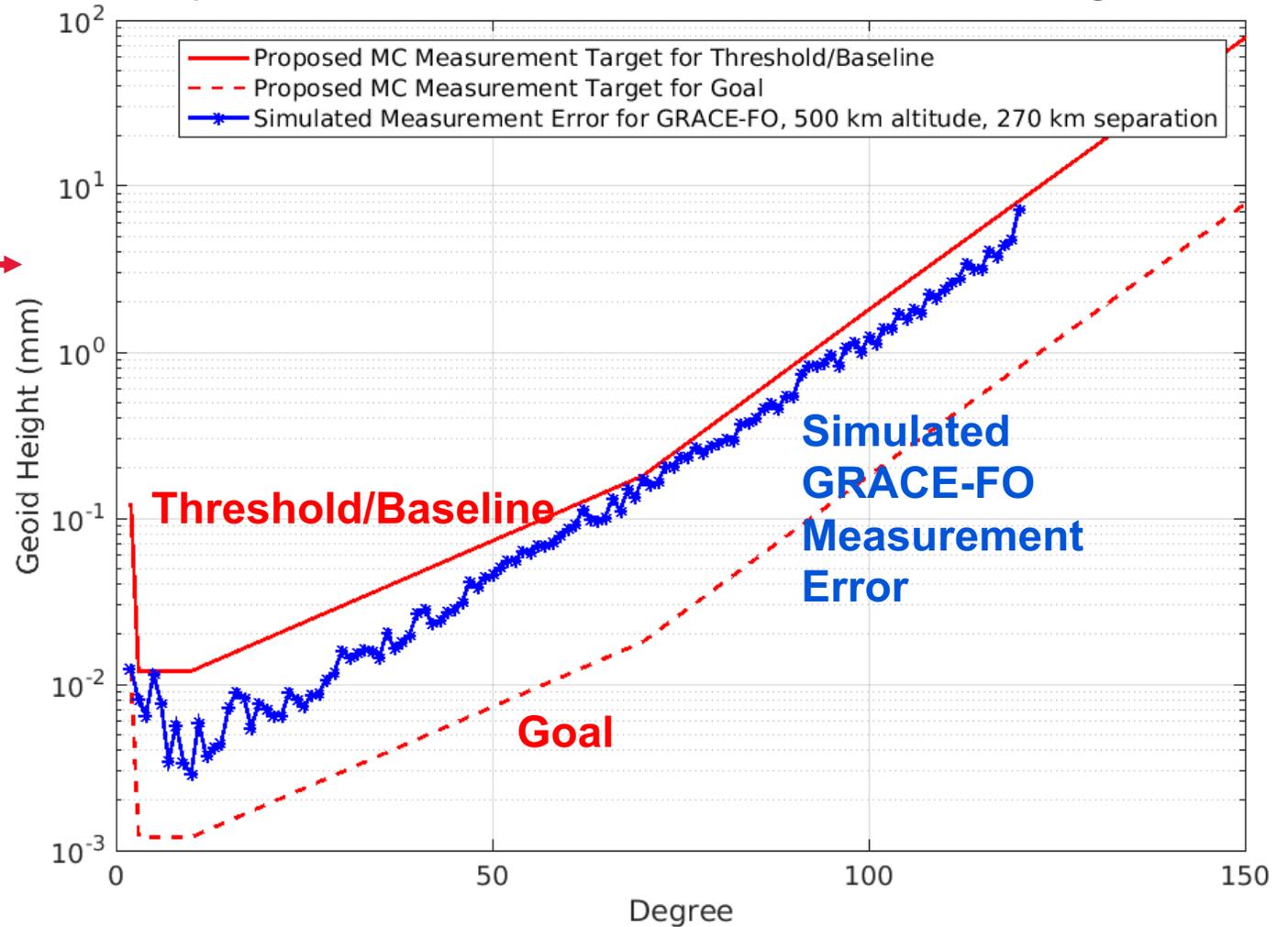
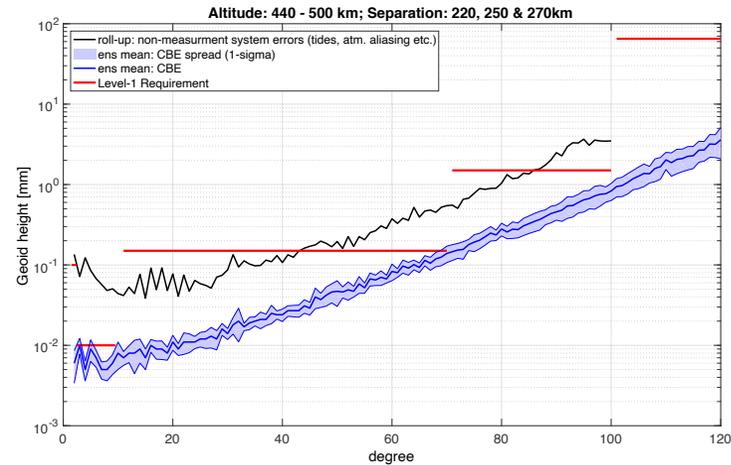
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# Measurement System Performance Targets

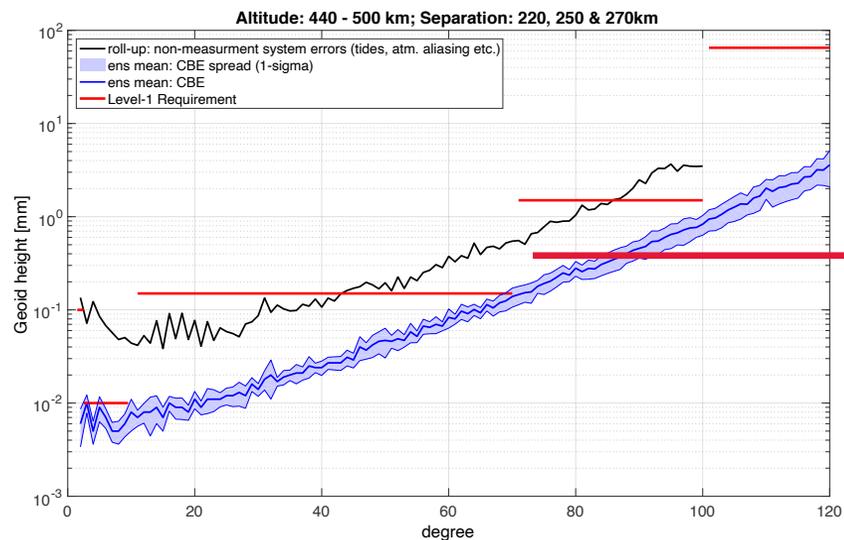
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## Proposed MC-DO Measurement Performance Targets

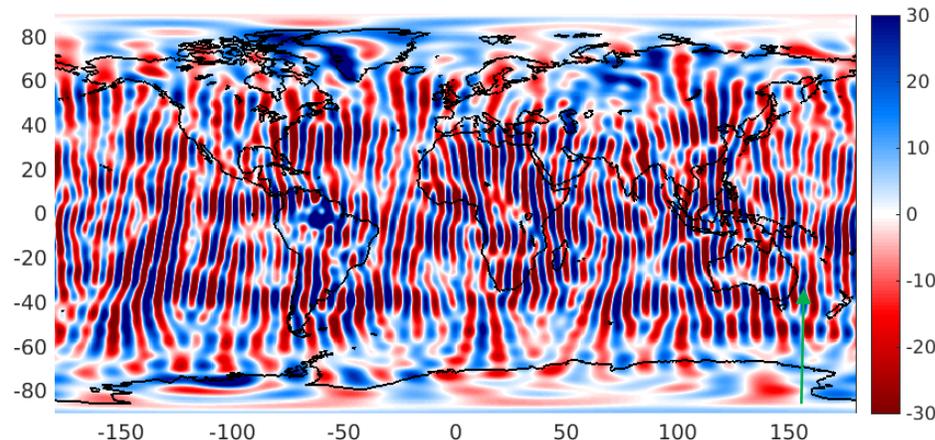


# Science Performance Targets

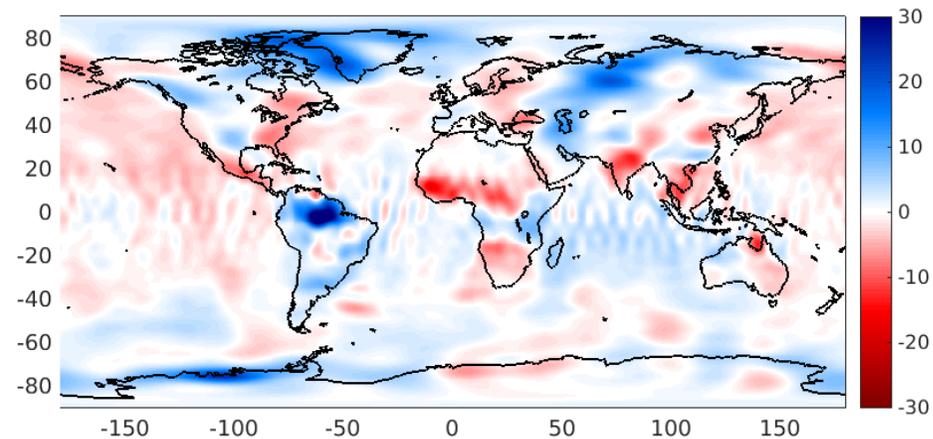
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Raw  
Errors



Postprocessing



Our definition of science performance targets allows for the inclusion of post-processing algorithms. This approach allows for a more realistic assessment of science value.

Science Performance Targets are written on this field

# Relevant Mass Change Observables

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## To Do: Review Science Performance Language

- Measurement System Performance:

### Threshold and Baseline

$\leq$  30-day average values of the geopotential coefficients to spherical harmonic degrees  $\leq 150$  with equivalent root mean square geoid height error due to the measurement system errors are below that seen in the solid blue line in Figure 1.

### Goal

$\leq$  30-day average values of the geopotential coefficients to spherical harmonic degrees  $\leq 150$  with equivalent root mean square geoid height error due to the measurement system errors are below that seen in the dashed blue line in Figure 1.

- Science Performance:

### Threshold and Baseline

When considering both measurement system and systematic errors due to temporal aliasing, the architecture, including optimized data processing and filtering choices, shall be capable of recovering global monthly mass variations (the average of modeled hydrologic, oceanic, and cryospheric mass variations) at 300 km spatial scales with an accuracy of 40 mm [TBR] equivalent water height. A baseline reference for temporal aliasing errors is prescribed by Dobslaw et al., 2016 for non-tidal atmosphere and ocean mass variability and the difference between the FES2014 and GOT4.7 ocean tide models for mass variability from ocean tides.

### Goal

When considering both measurement system and systematic errors due to temporal aliasing, the architecture, including optimized data processing and filtering choices, shall be capable of recovering global monthly mass variations (the average of modeled hydrologic, oceanic, and cryospheric mass variations) at 200 km spatial scales with an accuracy of 20 mm [TBR] equivalent water height. A baseline reference for temporal aliasing errors is prescribed by Dobslaw et al., 2016 for non-tidal atmosphere and ocean mass variability and the difference between the FES2014 and GOT4.7 ocean tide models for mass variability from ocean tides.

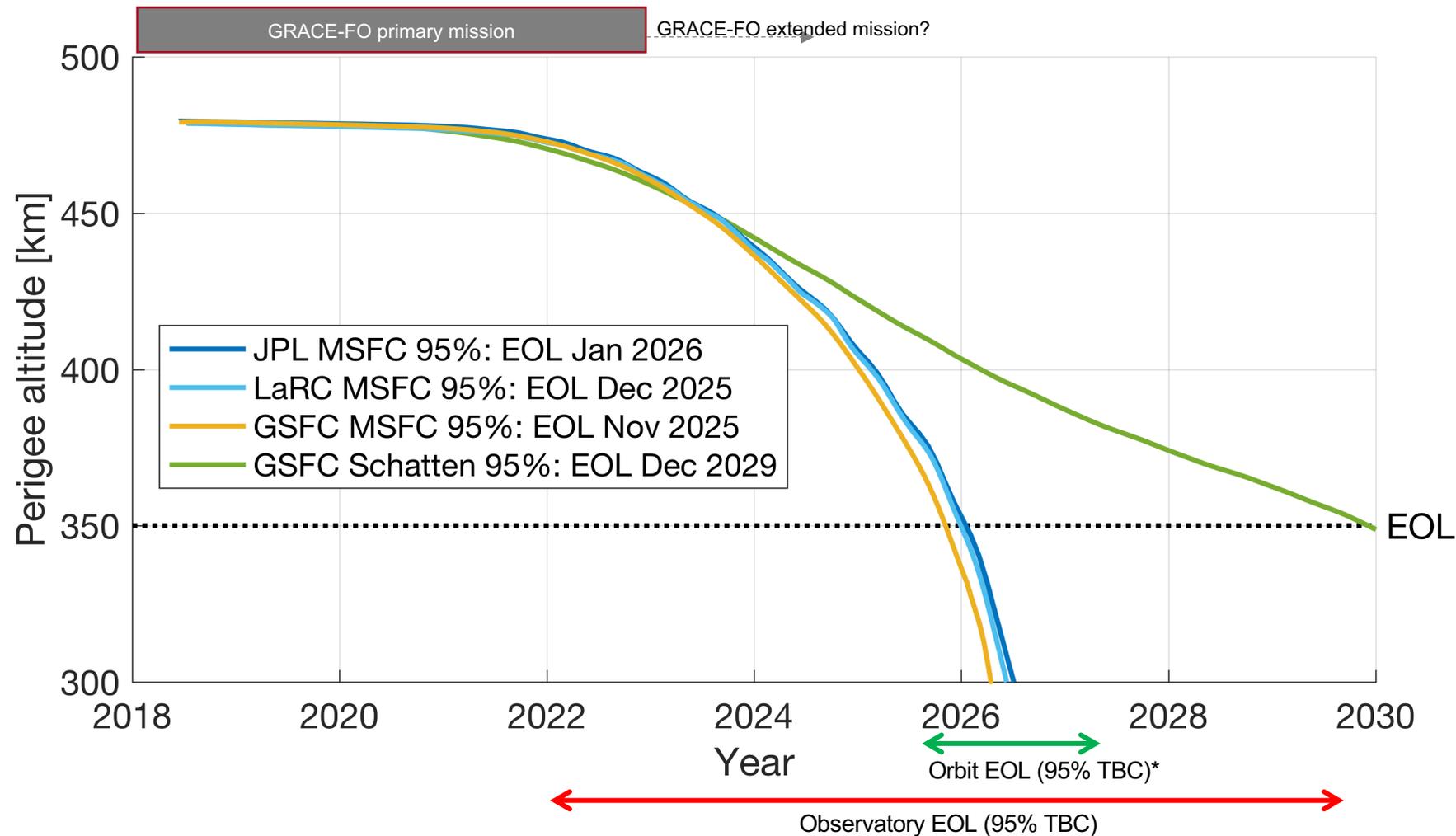
- A strong desire for a **long data record and minimizing any potential data gap** between GRACE-FO and an MC-DO was expressed at the community workshop. This exceeded all other priorities and was agreed upon by all scientific disciplines
- Fundamentally, there is no need for inter-mission calibration, because we measure the full gravitational field. There is no bias between missions → hence the success of GRACE-FO (1-year gap after GRACE)
- Having **overlap between missions is the best form of calibration/validation** for MC due to the uniqueness of the measurement
- Having overlap becomes more important for architectures that differ significantly from GRACE-FO should the structure of the error be different. A gap could affect consistency in the mass change data record for instance.
- Long\* (\*still to be defined) data gaps could affect the ability to estimate decadal trends because of interannual variability in the Earth's climate system
- The full impact of any gap on science/applications is still being assessed by the community
- **Continuity is not part of the SATM but should be a programmatic target for evaluation of options in phase 2** (because some options will have higher maturity and lower development risk/shorter schedule than others).

- Proposed continuity targets
  - Threshold Continuity Objective: the MC-DO gravity field data product should at least meet the GRACE-FO Threshold science requirements on spatial/temporal resolution and accuracy with any gap between GRACE-FO and MC-DO not to exceed 12 months.\*
  - Baseline Continuity Objective: the MC-DO gravity field data product should at least meet the GRACE-FO Baseline science requirements on spatial/temporal resolution and accuracy with at least 12 months of overlap between the GRACE-FO and MC-DO to assess potential differences between the two data sets to support calibration and validation efforts

*\*rationale: we have effectively already encountered a gap of this magnitude (perhaps more considering some degradation in the last year of GRACE operations); assessments of that impact are still underway but we are assuming that it will ultimately be “acceptable”. We identified 3 potential impacts of data gaps that should be assessed by the MC team and members of the science community for the 3 primary disciplines: 1) impact on applied science/operational products (e.g., loss of groundwater data), 2) science impact from missing an important geophysical signal during the gap, 3) science/applications impact due to uncharacterized differences in measurement system performance (random and systematic) between GRACE-FO and MC-DO.*

# GRACE-FO Orbit Decay Predictions

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Predictions are uncertain.

These curves will continue to be updated throughout the course of the study as solar activity evolves.

\*Curves courtesy JPL, B. Loomis, J. Chroné – to be updated with latest GFO state vector and solar activity