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 Overview

Lucia Tsaoussi, NASA HQ
Mass Change Program Scientist

December 12, 2019

NASA Implementation of the 2017 Earth Science Decadal Survey - Mass Change Designated Observable

AGU 2019

A “new” program element for cost-capped medium- and large-size missions/observing systems to address observables essential to the overall program.

- Addresses five of the highest-priority Earth observation needs, suggested to be implemented among three large missions and two medium missions. Elements of this program are considered foundational elements of the decade’s observations.

ESD’s Decadal Survey web page:

https://science.nasa.gov/earth-science/decadal-surveys

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 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. "

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

NASA- ESA Partnership Opportunity

1. Definition of requirements for future joint mission
2. Joint studies via cross-participation in MC DO and NGGM study activities

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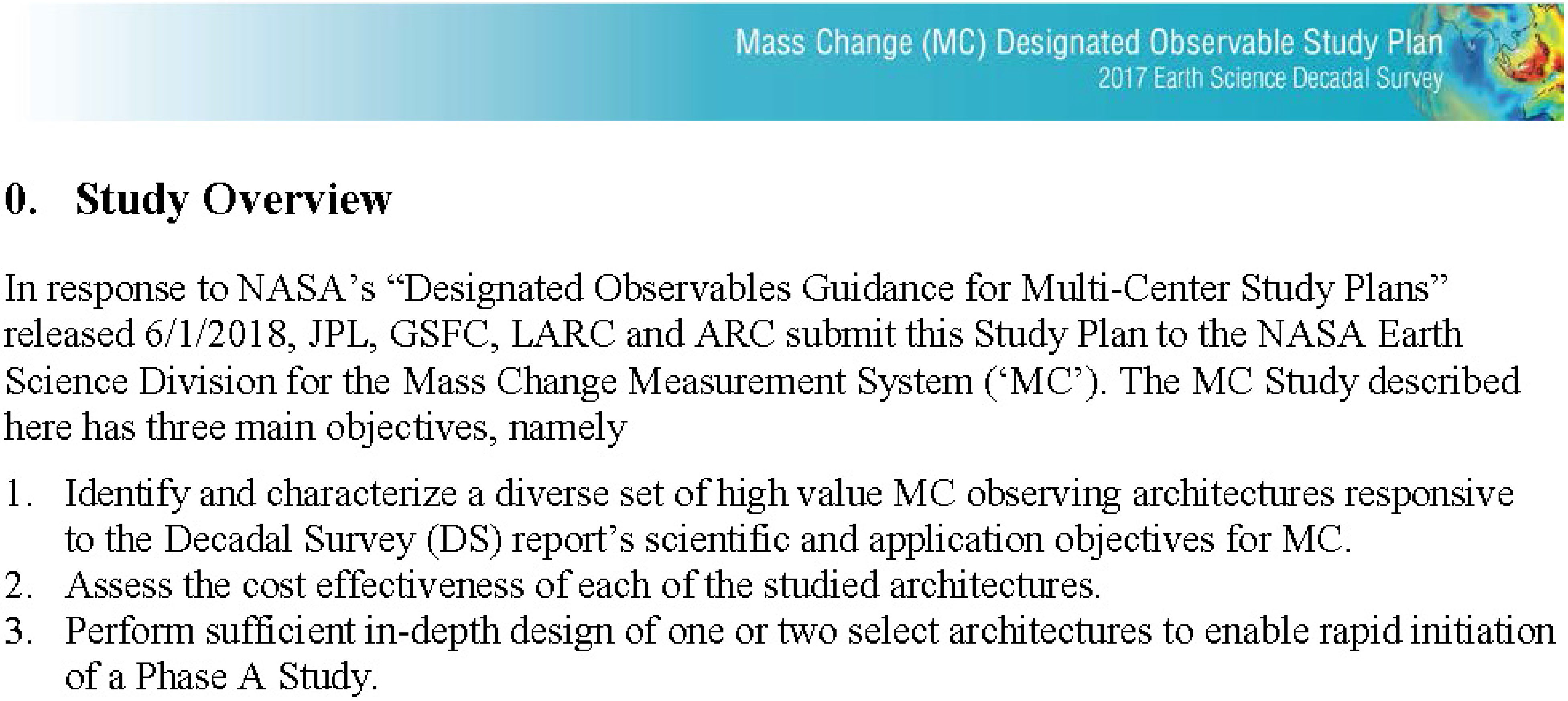
Mass Change Study Team Status

Bernie Bienstock, JPL/Caltech

Mass Change Study Coordinator

December 12, 2019

Mass Change Study Plan
Approved 10.28.18



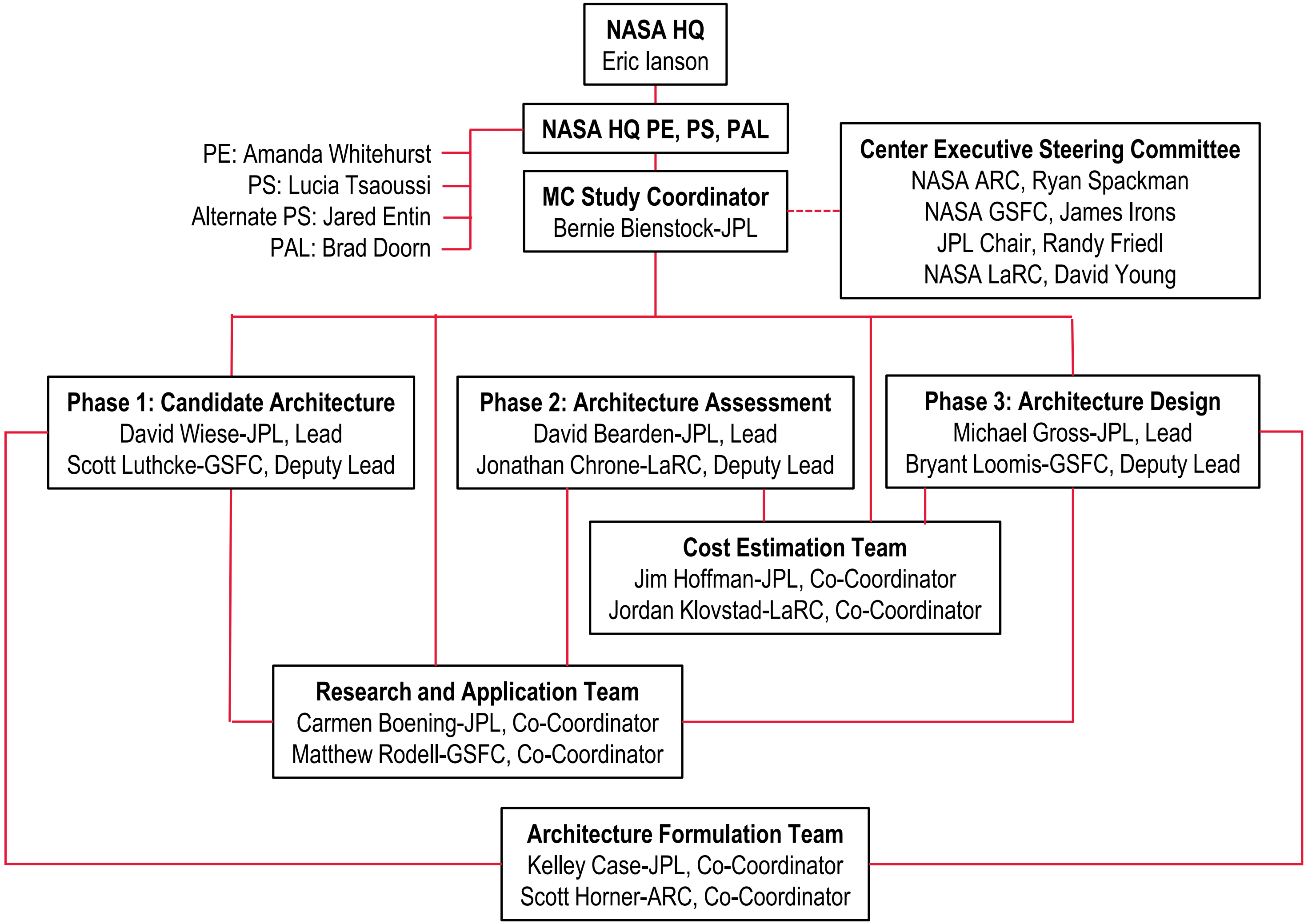
Mass Change (MC) Designated Observable Study Plan
2017 Earth Science Decadal Survey

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



NASA HQ
Eric Ianson

NASA HQ PE, PS, PAL

PE: Amanda Whitehurst
PS: Lucia Tsaoussi
Alternate PS: Jared Entin
PAL: Brad Doorn

MC Study Coordinator
Bernie Bienstock-JPL

Center Executive Steering Committee
NASA ARC, Ryan Spackman
NASA GSFC, James Irons
JPL Chair, Randy Friedl
NASA LaRC, David Young

Phase 1: Candidate Architecture
David Wiese-JPL, Lead
Scott Luthcke-GSFC, Deputy Lead

Phase 2: Architecture Assessment
David Bearden-JPL, Lead
Jonathan Chrone-LaRC, Deputy Lead

Phase 3: Architecture Design
Michael Gross-JPL, Lead
Bryant Loomis-GSFC, Deputy Lead

Cost Estimation Team
Jim Hoffman-JPL, Co-Coordinator
Jordan Klovstad-LaRC, Co-Coordinator

Research and Application Team
Carmen Boening-JPL, Co-Coordinator
Matthew Rodell-GSFC, Co-Coordinator

Architecture Formulation Team
Kelley Case-JPL, Co-Coordinator
Scott Horner-ARC, Co-Coordinator

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 Chrone
- Scott Horner
- Bryant Loomis
- Scott Luthcke
- Frank Webb
- David Wiese

Applications

- Matt Rodell, Lead
- JT Reager
- Margaret Srinavasan

Science & Community Engagement

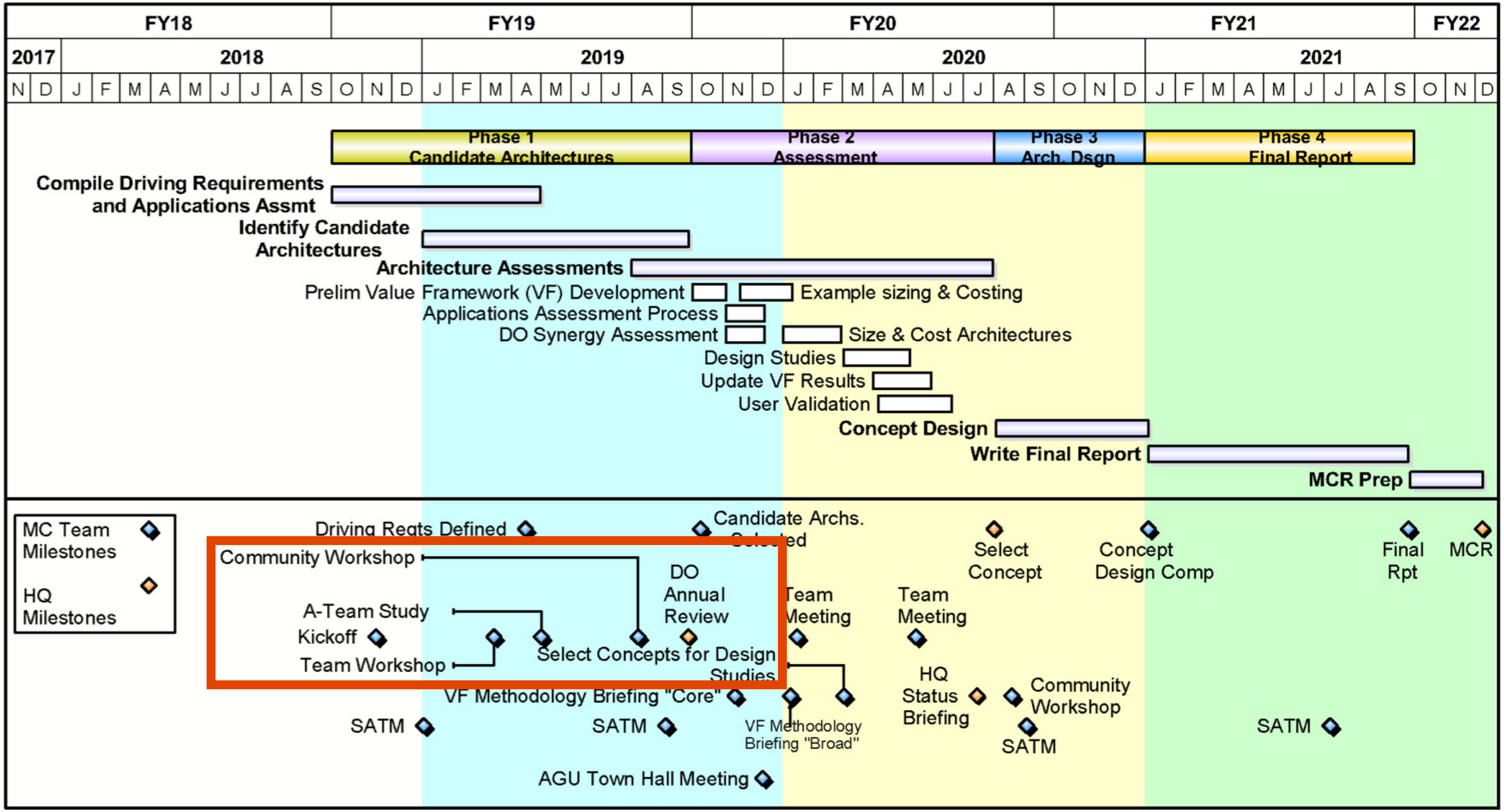
- Carmen Boening, Lead
- Rosemary Baize
- Bernie Bienstock
- Bryant Loomis
- David Wiese
- Victor Zlotnicki

Communications

- Victor Zlotnicki, Lead
- Bernie Bienstock
- Donna Wu

Timeline of Accomplishments

AGU 2019



A-Team Study

- 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

- 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
  - Mass Change SATM finalized with input from the community meeting and subsequent community telecons
  - 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
Appplications, Technology, and Architecture Breakout Sessions
Day 3
SATM Summary
Mass Change Future Plans

Phase 2 Plan

Date		Event/Milestone
Start	Stop	
12/2/19	12/15/19	Conduct sizing and costing of concepts, beginning with SST
12/18/19	**12/18/19**	**Methodology overview and examples briefing to MC Team**
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
3/18/20	**3/18/20**	**Preliminary AoA Presentation to MC Team**
3/19/20	4/15/20	Revise results based on MC Team feedback
4/16/20	**4/16/20**	**Draft AoA Presentation to MC Team**
4/17/20	5/12/20	Develop final AoA briefing
5/5/20	5/6/20	**MC Phase 2 Community Meeting**
5/13/20	**5/13/20**	**Final MC Team Briefing on AoA**
5/14/20	6/17/20	Finalize documentation
6/18/20	**6/18/20**	**Deliver final AoA documentation**

Legend

Boldface = Milestones

AoA = analysis of alternatives

SST = satellite-to-satellite tracking

POD = precise orbit determination

GG = gravity gradiometer

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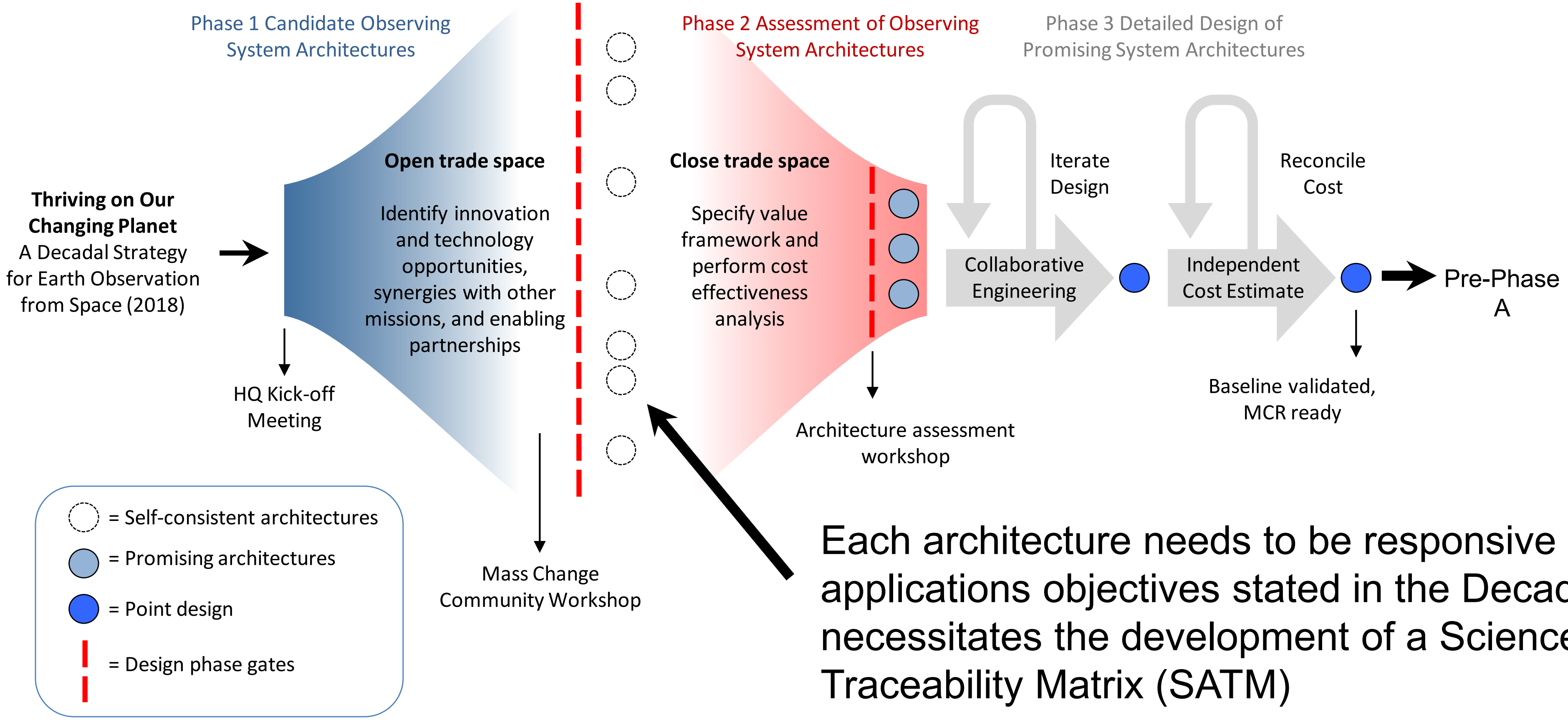
Architecture and Technology Options to satisfy the Science and Applications Traceability Matrix for the Mass Change Designated Observable

David N. Wiese[1] on behalf of the MC-DO Study Team

December 12, 2019

[1]Jet Propulsion Laboratory, California Institute of Technology

Study Phases



Phase 1 Candidate Observing System Architectures

Phase 2 Assessment of Observing System Architectures

Phase 3 Detailed Design of Promising System Architectures

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

HQ Kick-off Meeting

Open trade space

Identify innovation and technology opportunities, synergies with other missions, and enabling partnerships

Mass Change Community Workshop

Close trade space

Specify value framework and perform cost effectiveness analysis

Architecture assessment workshop

Iterate Design

Collaborative Engineering

Reconcile Cost

Independent Cost Estimate

Baseline validated, MCR ready

Pre-Phase A

◌ = Self-consistent architectures
● = Promising architectures
● = Point design
┆ = Design phase gates

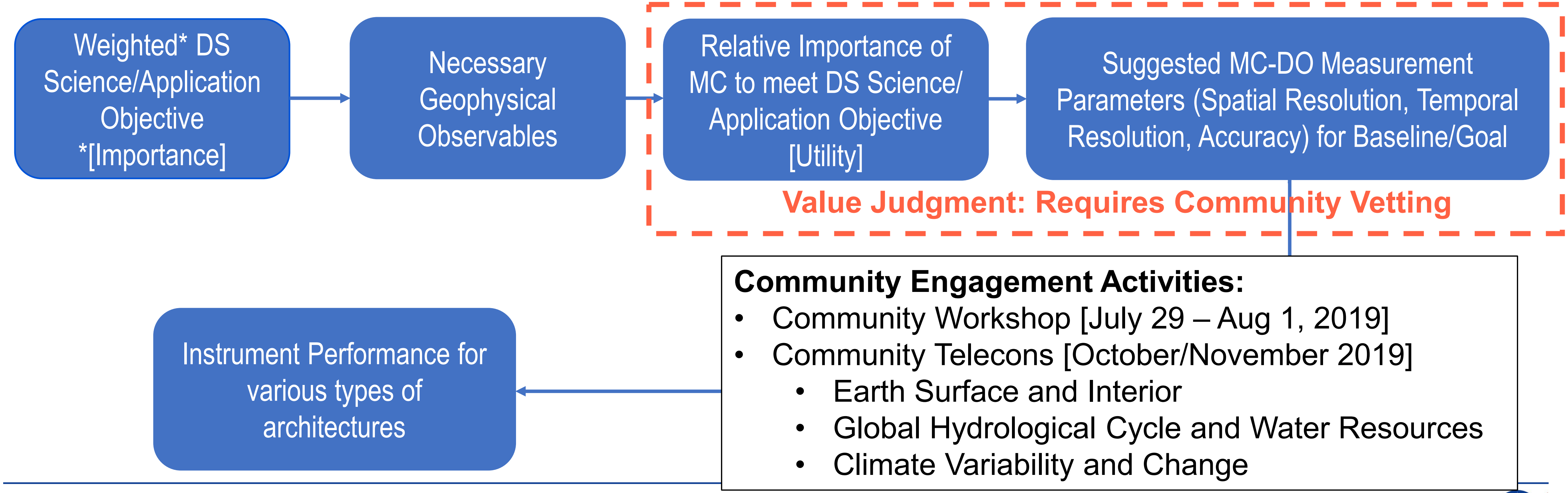
Each architecture needs to be responsive to the science and applications objectives stated in the Decadal Survey. This necessitates the development of a Science and Applications Traceability Matrix (SATM)

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

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



Weighted* DS Science/Application Objective *[Importance]

Necessary Geophysical Observables

Relative Importance of MC to meet DS Science/ Application Objective [Utility]

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Baseline/Goal

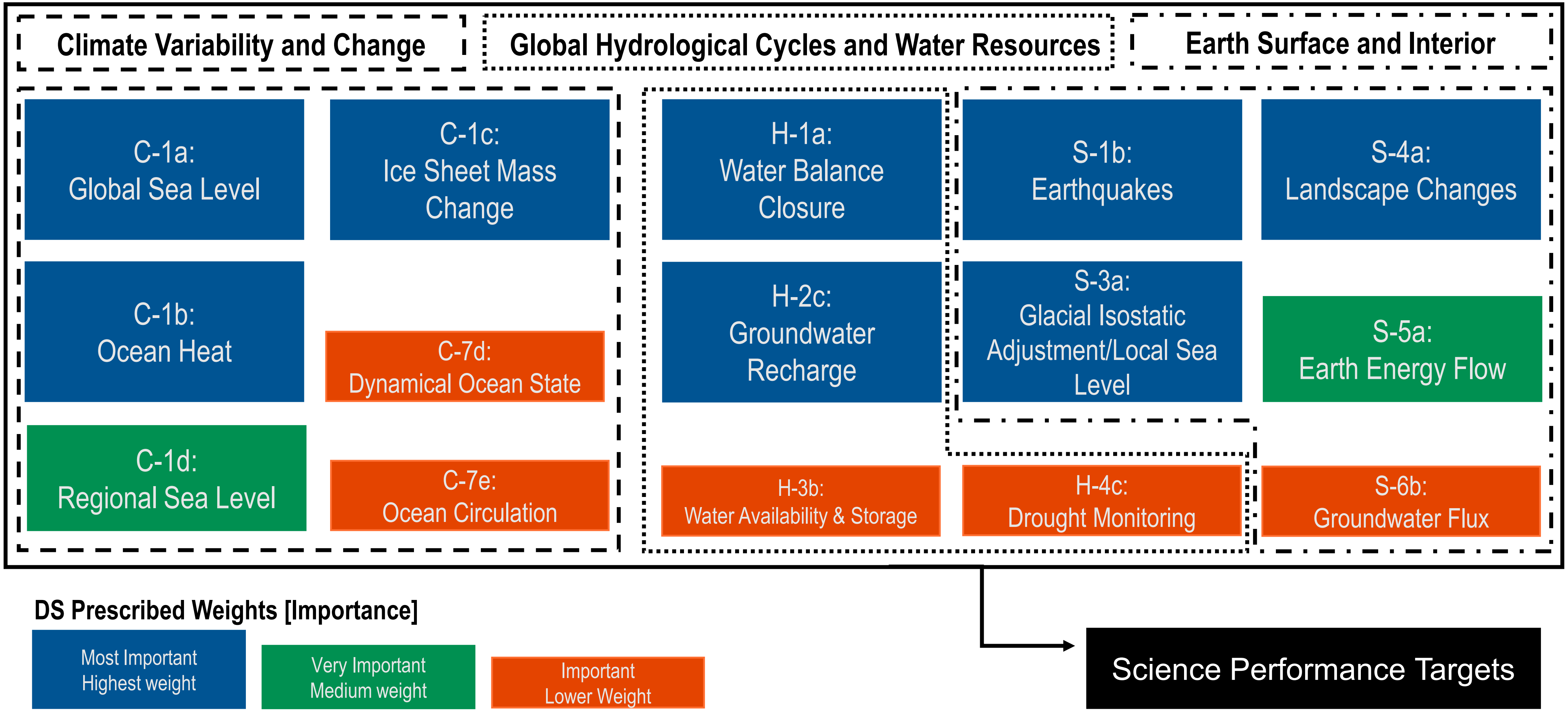
Value Judgment: Requires Community Vetting

Community Engagement Activities:
- Community Workshop [July 29 – Aug 1, 2019]
- Community Telecons [October/November 2019]
  - Earth Surface and Interior
  - Global Hydrological Cycle and Water Resources
  - Climate Variability and Change

Instrument Performance for various types of architectures

Decadal Survey Science and Application Objectives for Mass Change

A Diverse Set of Objectives Spanning Three Panels



Climate Variability and Change

- C-1a: Global Sea Level
- C-1b: Ocean Heat
- C-1c: Ice Sheet Mass Change
- C-1d: Regional Sea Level
- C-7d: Dynamical Ocean State
- C-7e: Ocean Circulation

Global Hydrological Cycles and Water Resources

- H-1a: Water Balance Closure
- H-2c: Groundwater Recharge
- H-3b: Water Availability & Storage
- H-4c: Drought Monitoring

Earth Surface and Interior

- S-1b: Earthquakes
- S-3a: Glacial Isostatic Adjustment/Local Sea Level
- S-4a: Landscape Changes
- S-5a: Earth Energy Flow
- S-6b: Groundwater Flux

→ Science Performance Targets

DS Prescribed Weights [Importance]

Most Important
Highest weight

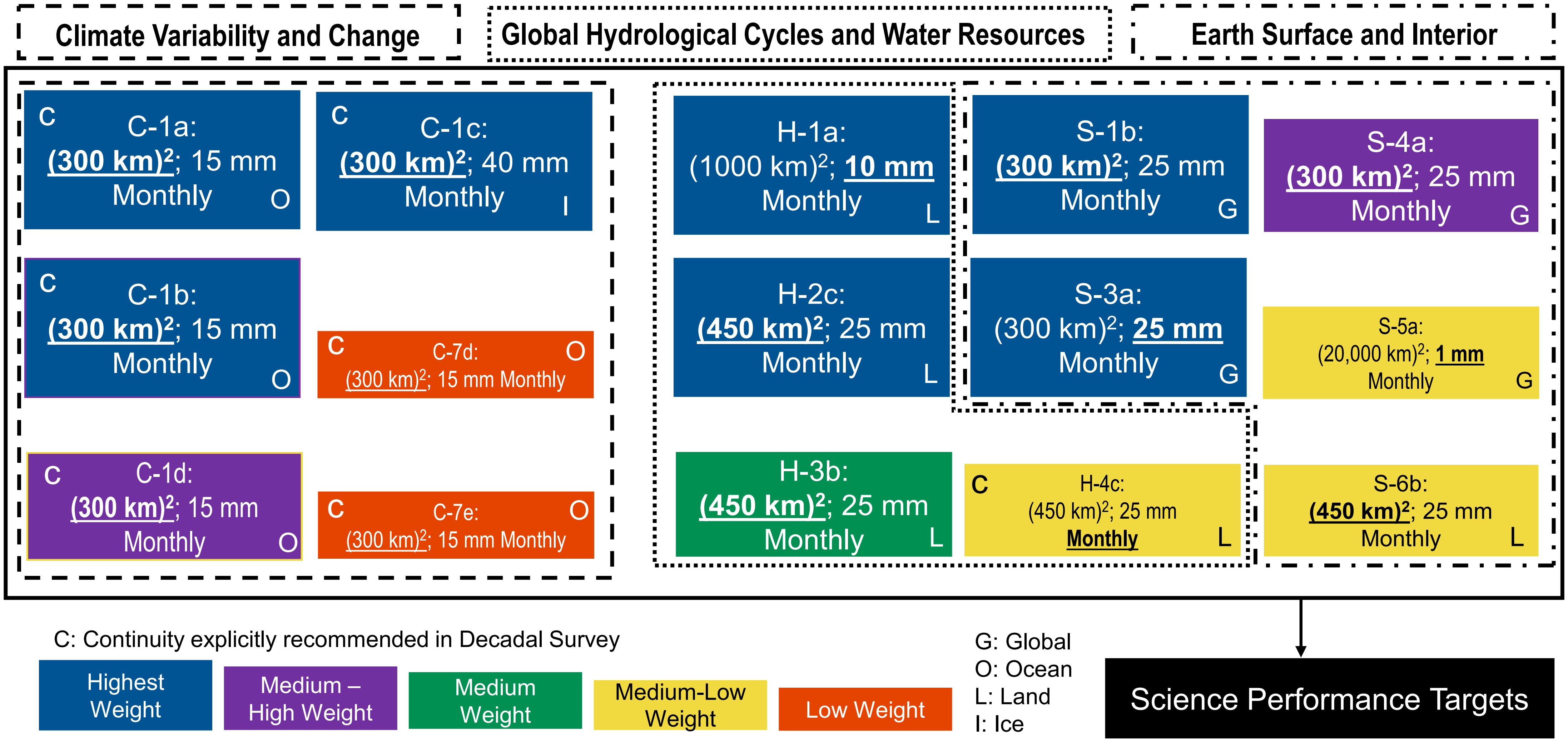
Very Important
Medium weight

Important
Lower Weight

Suggested Measurement Parameters for Baseline

AGU 2019

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



Climate Variability and Change

C C-1a: **(300 km)^2**; 15 mm Monthly O

C C-1c: **(300 km)^2**; 40 mm Monthly I

C C-1b: **(300 km)^2**; 15 mm Monthly O

C C-7d: O (300 km)^2; 15 mm Monthly

C C-1d: (300 km)^2; 15 mm Monthly O

C C-7e: O (300 km)^2; 15 mm Monthly

Global Hydrological Cycles and Water Resources

H-1a: (1000 km)^2; **10 mm** Monthly L

H-2c: **(450 km)^2**; 25 mm Monthly L

H-3b: **(450 km)^2**; 25 mm Monthly L

C H-4c: (450 km)^2; 25 mm **Monthly** L

Earth Surface and Interior

S-1b: **(300 km)^2**; 25 mm Monthly G

S-3a: (300 km)^2; **25 mm** Monthly G

S-4a: **(300 km)^2**; 25 mm Monthly G

S-5a: (20,000 km)^2; **1 mm** Monthly G

S-6b: **(450 km)^2**; 25 mm Monthly L

C: Continuity explicitly recommended in Decadal Survey

Highest Weight

Medium – High Weight

Medium Weight

Medium-Low Weight

Low Weight

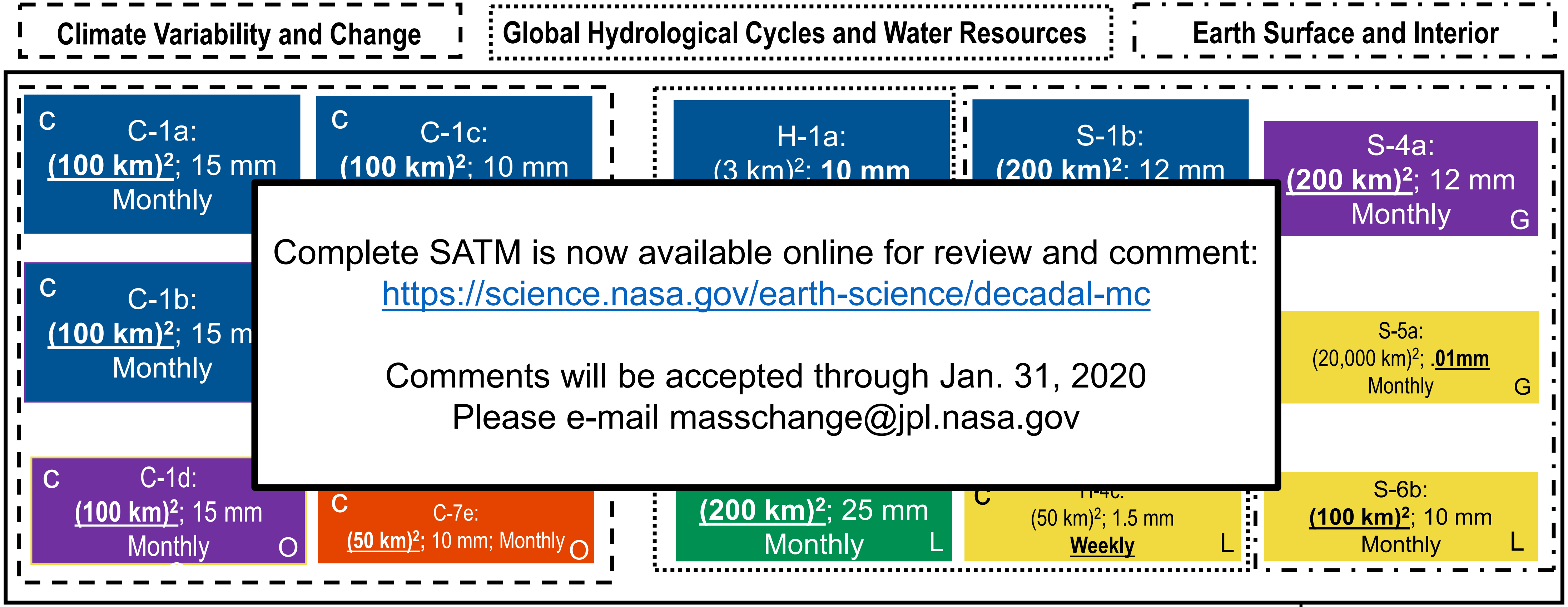
G: Global
O: Ocean
L: Land
I: Ice

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



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

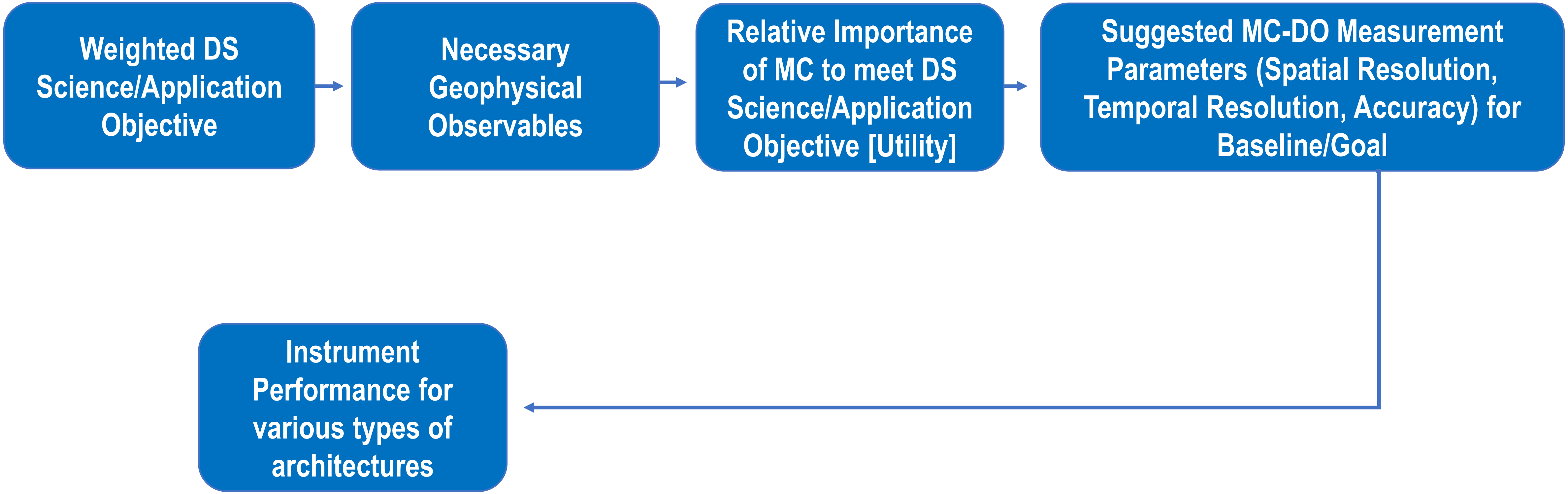
C: Continuity explicitly recommended in Decadal Survey

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

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

Science Performance Targets

MC Interpretation of DS Objectives



Weighted DS Science/Application Objective

Necessary Geophysical Observables

Relative Importance of MC to meet DS Science/Application Objective [Utility]

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Baseline/Goal

Instrument Performance for various types of architectures

Summary of observing system architecture activities

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	JPL A-Team Study
Community Worksho	re solicited by the unity Workshop July
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: submitted documents range from general concepts to detailed proposals

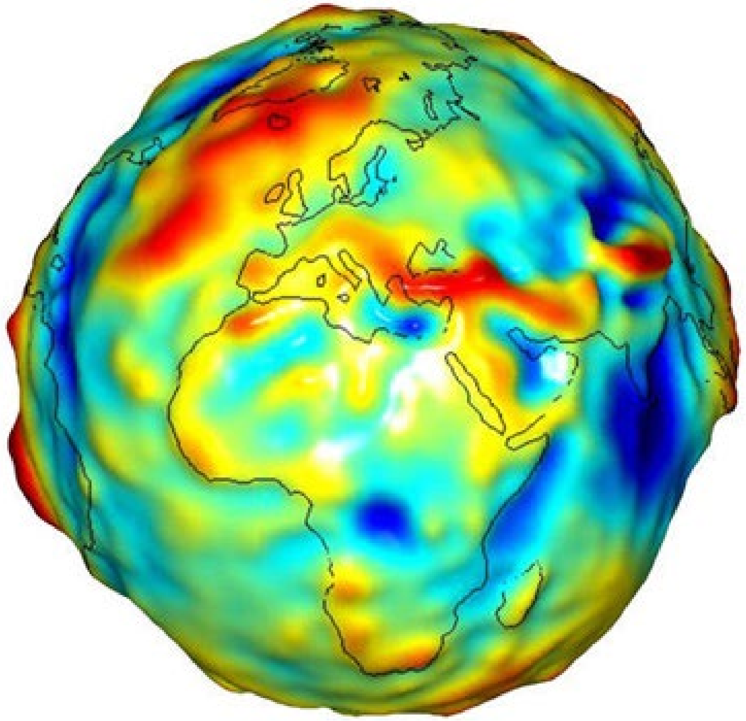
Observing system architectures for mass change can still be submitted by the community.

Input will be accepted through Jan. 31, 2020
Please e-mail masschange@jpl.nasa.gov

Overview of observing system architecture types

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)

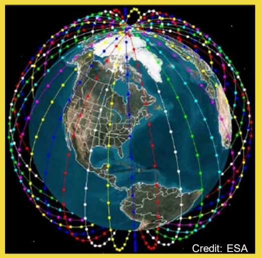


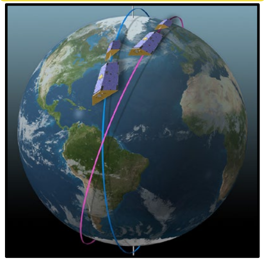
All architecture types observe the effect of gravity on the motion of objects in Low Earth Orbit:

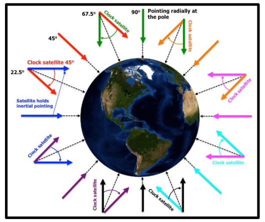
- Satellites: **POD/SST**
- Test mass(es) within satellite(s): **GG**
- Atom clouds within satellite(s): **GG**

Overview of observing system architecture types

AGU 2019

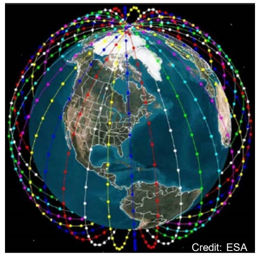






Type	Overview	Trade-space & key questions
POD Precise orbit determination	• Large constellation of GNSS receivers – potentially CubeSats • Candidate for gap filler • Could combine purchases of existing POD data with design/expansion of current constellations (e.g. Spire)	• Number of satellites • Mega-constellation performance? • Are accelerometers an option? • Performance of derived baseline? (no dedicated SST instrument)
SST Satellite-to-satellite tracking	• Same concept as GRACE/GRACE-FO missions • High heritage with GRACE/GRACE-FO reduces technical and implementation risk • Large trade space of orbits and technology has a wide range of scientific performance outcomes	• Low-low / High-low SST • Number of pairs and/or formations • Orbit planes and altitude • Ranging & accelerometer technology • Use of drag compensation
GG Gravity gradiometer	• Atomic interferometer gravity gradiometer expected to far exceed the performance of electrostatic accelerometers of GRACE & GOCE missions • 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	• Gradiometer baseline size/orientation • Expected timeline of technology development? • Possible candidate for technology demonstration concurrent with a primary Mass Change observing system?

Overview of observing system architecture types

	Type	Overview	Trade-space & key questions
	**POD** Precise orbit determination	- Large constellation of GNSS receivers – potentially CubeSats - Candidate for gap filler - Could combine purchases of existing POD data with design/expansion of current constellations (e.g. Spire)	- Number of satellites - Mega-constellation performance? - Are accelerometers an option? - Performance of derived baseline? (no dedicated SST instrument)
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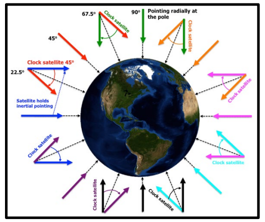
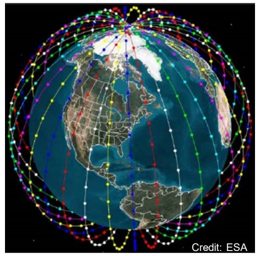
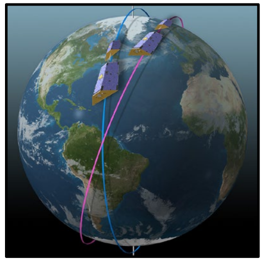
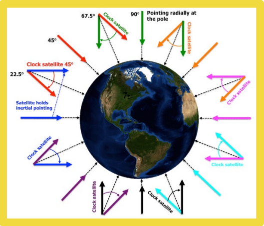
	**GG** Gravity gradiometer	- Atomic interferometer gravity gradiometer expected to far exceed the performance of electrostatic accelerometers of GRACE & GOCE missions - Likely not ready for the expected MC DO timeline, but given the excellent simulated performance should be considered for more rigorous simulation studies and a key part of a technology development road map	- Gradiometer baseline size/orientation - Expected timeline of technology development? - Possible candidate for technology demonstration concurrent with a primary Mass Change observing system?

Overview of observing system architecture types



Credit: ESA





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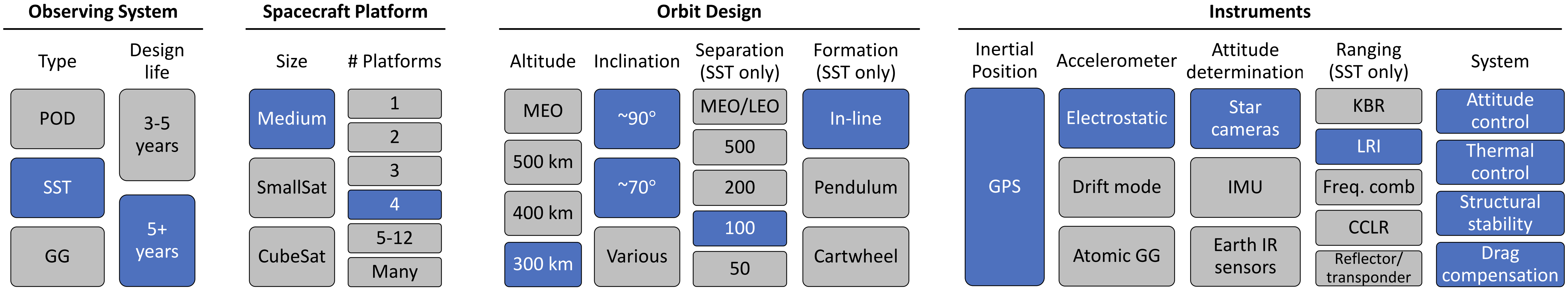
Observing system architecture trade space

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
GG		CubeSat	3	400 km	Various	200	Cartwheel		Atomic GG	Earth IR sensors	Freq. comb	Structural stability
			4	300 km		100					CCLR	Drag compensation
			5-12			50					Reflector/ transponder	
			Many									

Sample architecture:
Dual SST pair with drag compensation



Observing System		Spacecraft Platform		Orbit Design				Instruments				
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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
GG		CubeSat	3	400 km	Various	200	Cartwheel		Atomic GG	Earth IR sensors	Freq. comb	Structural stability
			4	300 km		100					CCLR	Drag compensation
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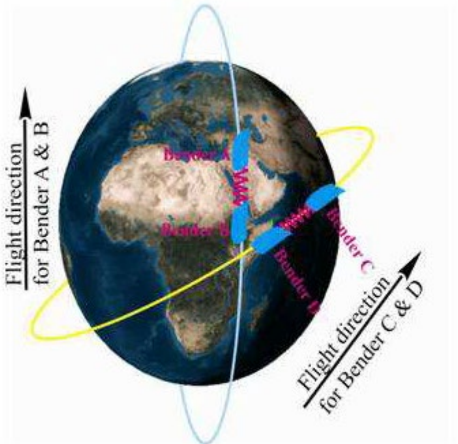
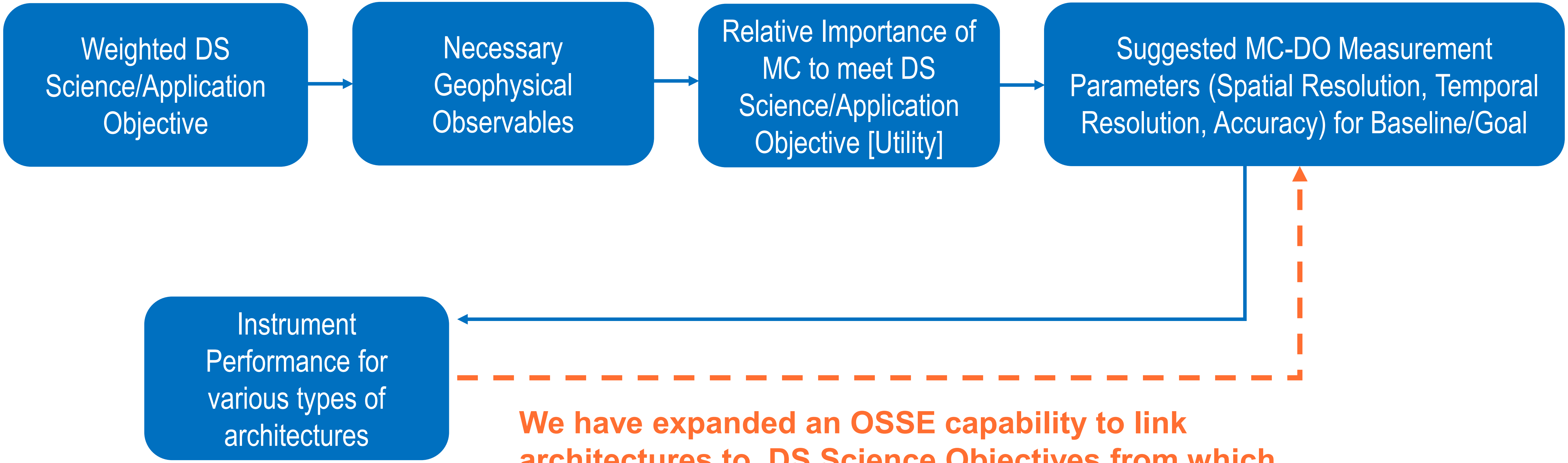


Elsaka et al., 2013

Summary of Technology Activities

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. **Strong support to focus on three main technology areas: accelerometer improvements, laser ranging as primary SST measurement, gravity gradiometer as future technology**.
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



Weighted DS Science/Application Objective

Necessary Geophysical Observables

Relative Importance of MC to meet DS Science/Application Objective [Utility]

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Baseline/Goal

Instrument Performance for various types of architectures

We have expanded an OSSE capability to link architectures to DS Science Objectives from which we can quantitatively determine science value

Quantitatively Determining Science Value

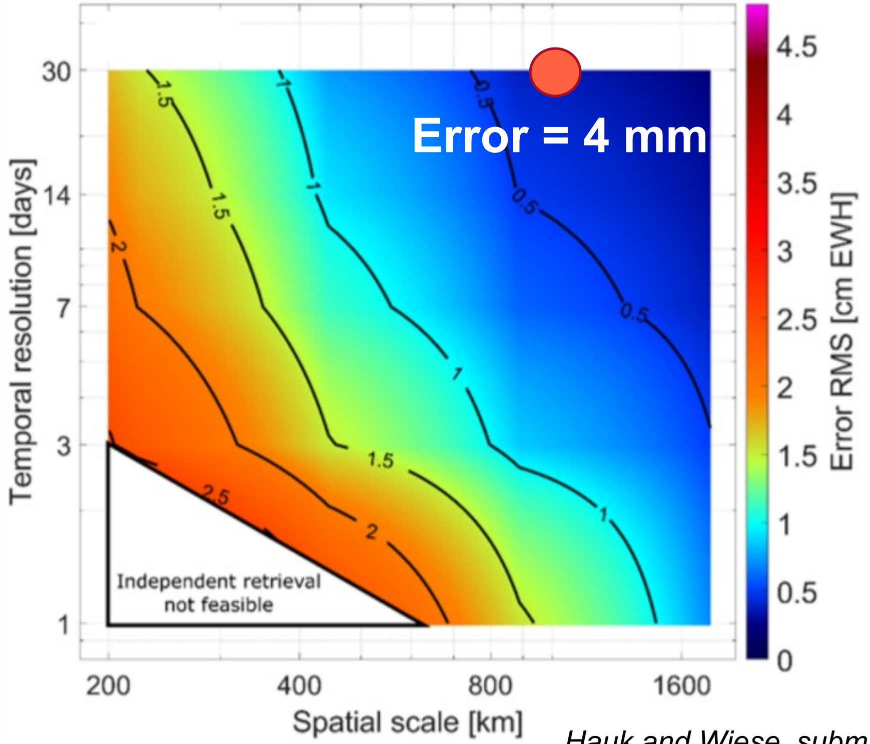
$$SV(a) = \sum_{n=1}^{15} (W_n) P_n = \sum_{n=1}^{15} \left(W_n \frac{Spatial\_Resn}{Spatial\_Res(a)} \frac{Temporal\_Resn}{Temporal\_Res(a)} \frac{Accuracy_n}{Accuracy(a)} \right)$$

Science Objective *n*

H-1a:
(1000 km)^2; **10 mm**
Monthly

Highest Weight

W = Importance * Utility = 1



Architecture *a*

Error = 4 mm

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

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Mass Change Designated Observable Study: Phase 2 Plan

Jon Chrone (LaRC) – Architecture Assessment Deputy Lead
Dave Bearden (JPL) – Architecture Assessment Lead

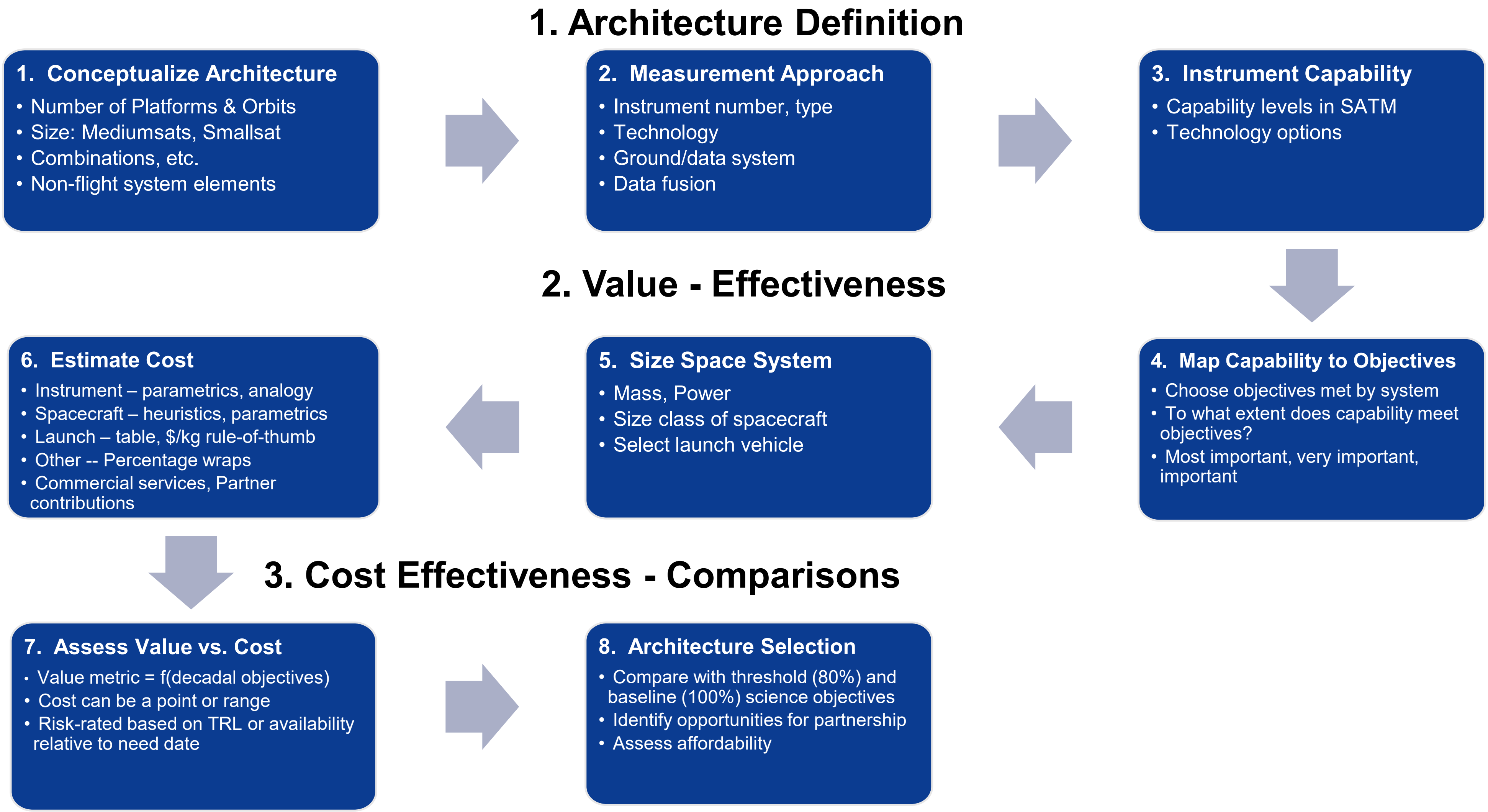
December 12, 2019

Phase 2 Objectives

- Phase 2 Objectives
  - Assess the cost and value 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

Flow Diagram – Architecture Concept to Initial Value Assessment



1. Architecture Definition

1. Conceptualize Architecture
- Number of Platforms & Orbits
- Size: Mediumsats, Smallsat
- Combinations, etc.
- Non-flight system elements

2. Measurement Approach
- Instrument number, type
- Technology
- Ground/data system
- Data fusion

3. Instrument Capability
- Capability levels in SATM
- Technology options

2. Value - Effectiveness

4. Map Capability to Objectives
- Choose objectives met by system
- To what extent does capability meet objectives?
- Most important, very important, important

5. Size Space System
- Mass, Power
- Size class of spacecraft
- Select launch vehicle

6. Estimate Cost
- Instrument – parametrics, analogy
- Spacecraft – heuristics, parametrics
- Launch – table, $/kg rule-of-thumb
- Other -- Percentage wraps
- Commercial services, Partner contributions

3. Cost Effectiveness - Comparisons

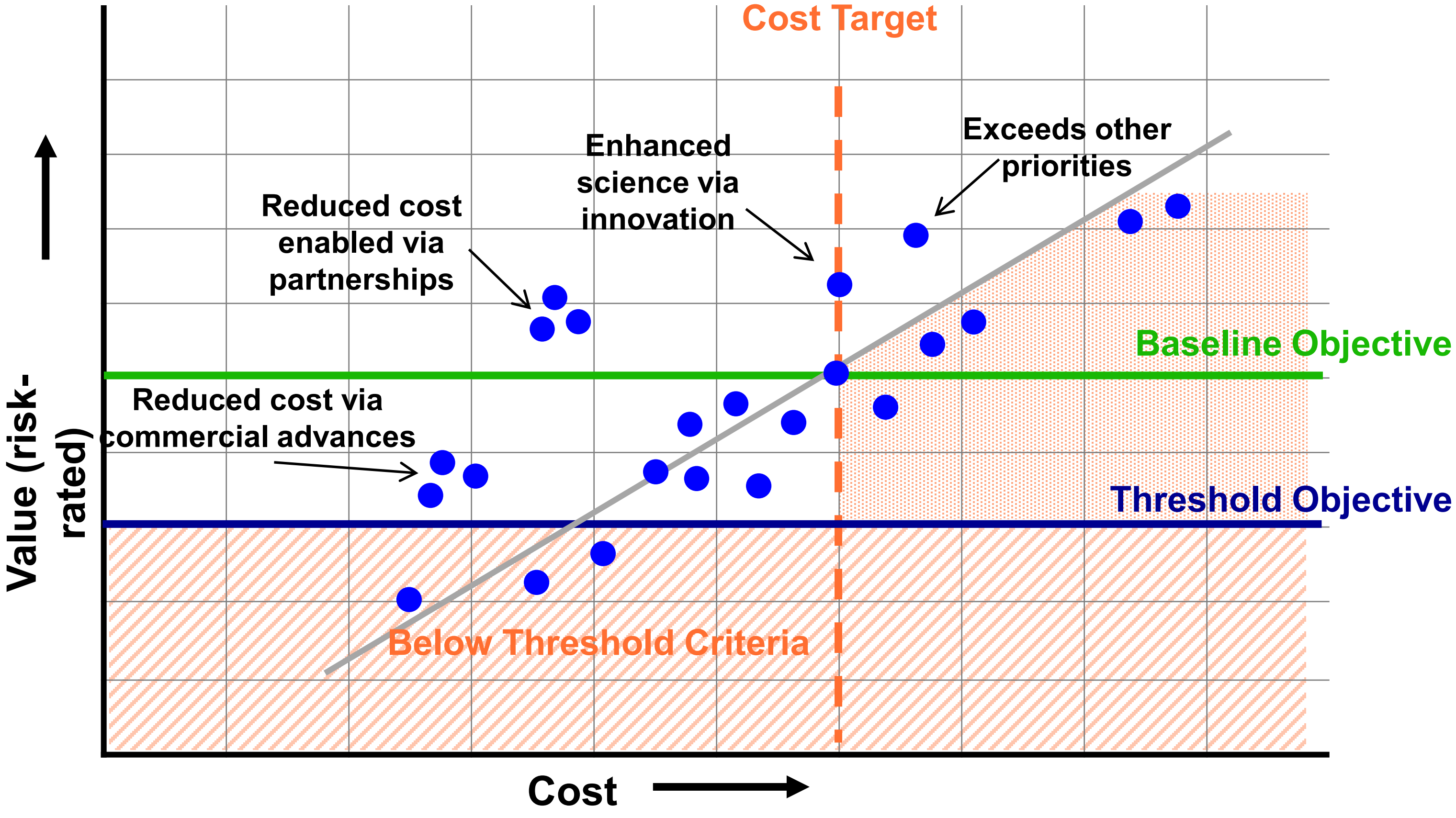
7. Assess Value vs. Cost
- Value metric = f(decadal objectives)
- Cost can be a point or range
- Risk-rated based on TRL or availability relative to need date

8. Architecture Selection
- Compare with threshold (80%) and baseline (100%) science objectives
- Identify opportunities for partnership
- Assess affordability

Cost Effectiveness Comparisons Value Framework

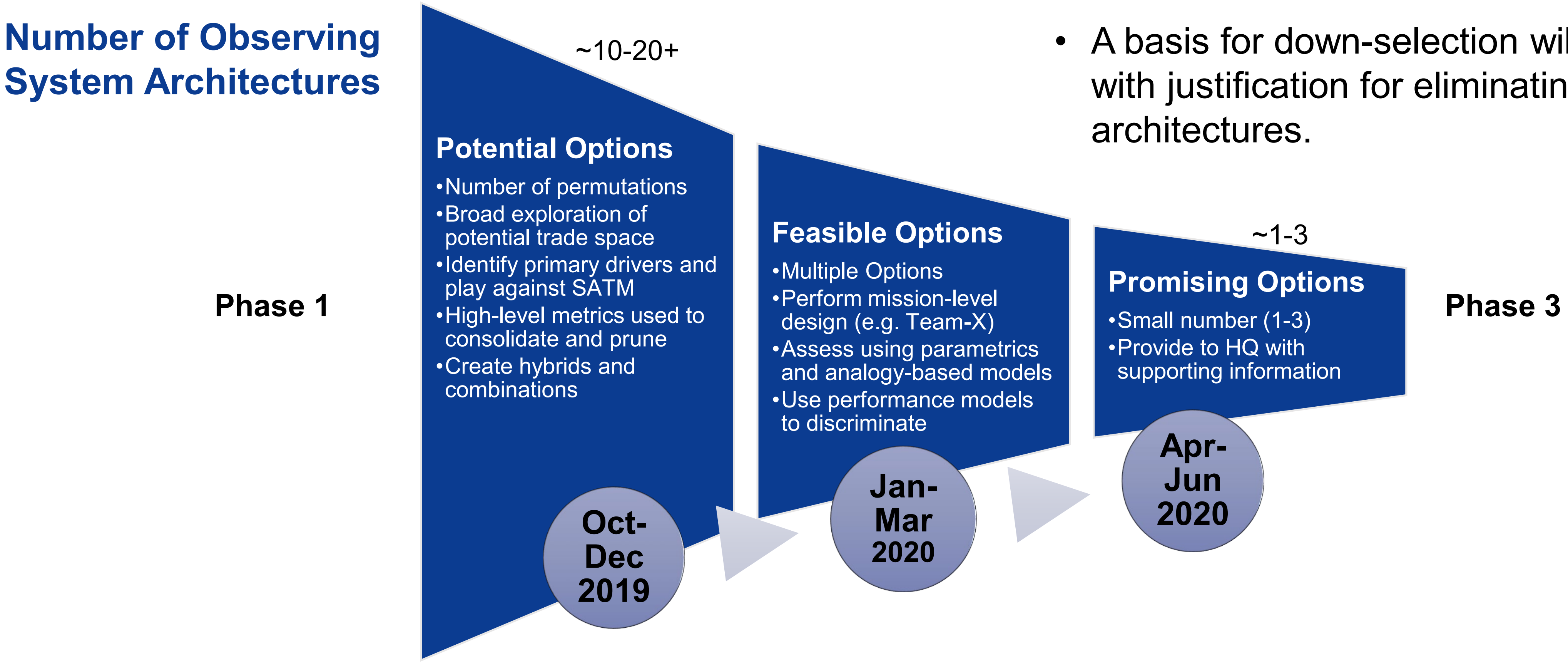
- Reduced cost may be enabled through strategic partnerships and/or commercial opportunities
- Enhanced science return may be enabled through new technologies and/or innovation
- Architectures below the Threshold or significantly above cost target will not be considered
- Science value may be risk-rated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

Notional graphic showing Value vs. Cost



Phase 2 Plan: Funnel from "Many" to "Few"

- 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.



Number of Observing System Architectures

~10-20+

Phase 1

Potential Options
- Number of permutations
- Broad exploration of potential trade space
- Identify primary drivers and play against SATM
- High-level metrics used to consolidate and prune
- Create hybrids and combinations

Oct-Dec 2019

Feasible Options
- Multiple Options
- Perform mission-level design (e.g. Team-X)
- Assess using parametrics and analogy-based models
- Use performance models to discriminate

Jan-Mar 2020

~1-3

Promising Options
- Small number (1-3)
- Provide to HQ with supporting information

Apr-Jun 2020

Phase 3

Phase 2 Tasks and Milestones

Date		Event/Milestone
Start	Stop	
12/2/19	12/15/19	Conduct sizing and costing of concepts, beginning with SST
12/18/19	**12/18/19**	**Methodology overview and examples briefing to MC Team**
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
3/18/20	**3/18/20**	**Preliminary AoA Presentation to MC Team**
3/19/20	4/15/20	Revise results based on MC Team feedback
4/16/20	**4/16/20**	**Draft AoA Presentation to MC Team**
4/17/20	5/12/20	Develop final AoA briefing
5/5/20	5/6/20	**MC Phase 2 Community Meeting**
5/13/20	**5/13/20**	**Final MC Team Briefing on AoA**
5/14/20	6/17/20	Finalize documentation
6/18/20	**6/18/20**	**Deliver final AoA documentation**

Legend

Boldface = Milestones

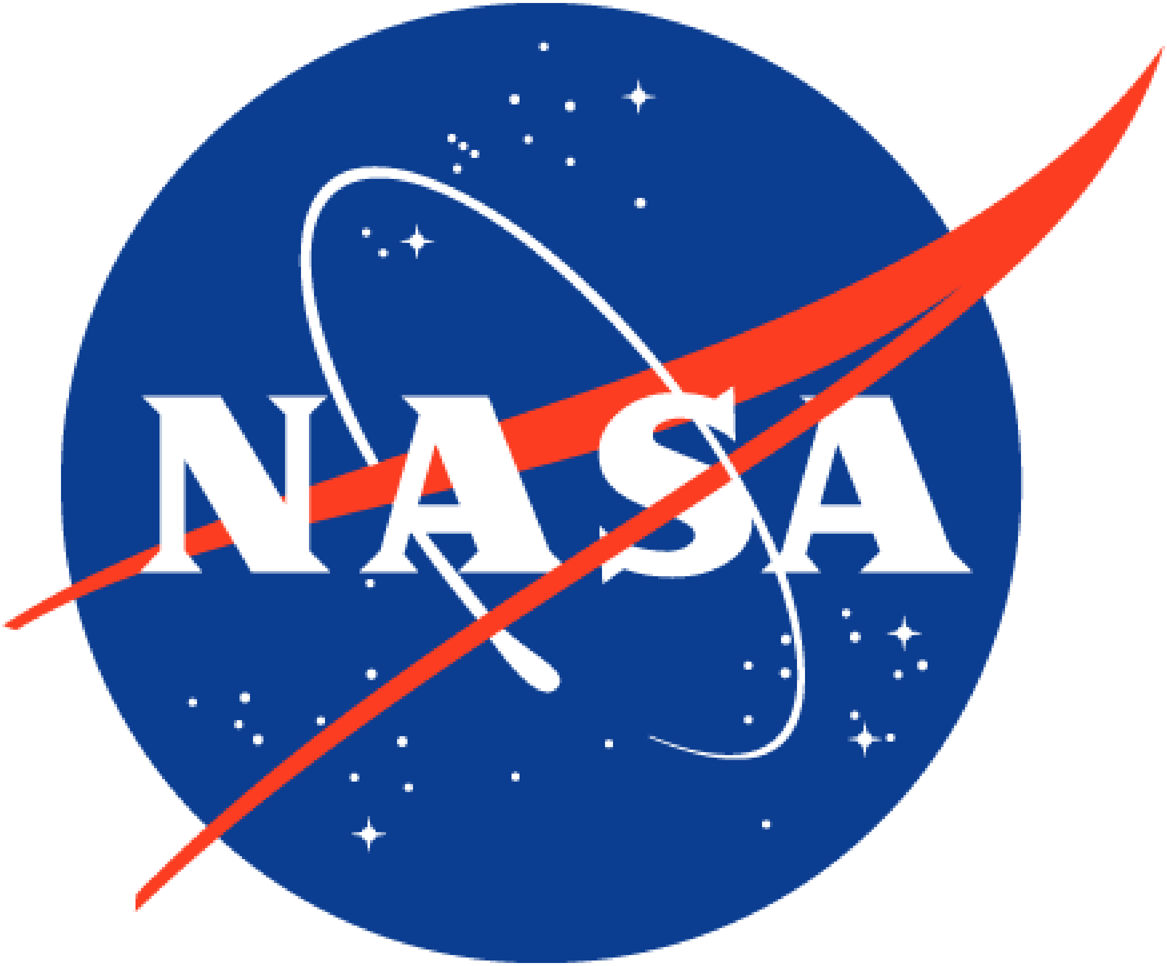
AoA = analysis of alternatives

SST = satellite-to-satellite tracking

POD = precise orbit determination

GG = gravity gradiometer

BACKUP



Overview of technology focus areas

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.

<u>Community Leads for Technology Summaries</u>

Accelerometer:	John Conklin (UF)
Laser Ranging:	William Klipstein (JPL)
Gravity Gradiometry:	Babak Saif (GSFC)

Architectures discussed at Community Workshop

AGU 2019

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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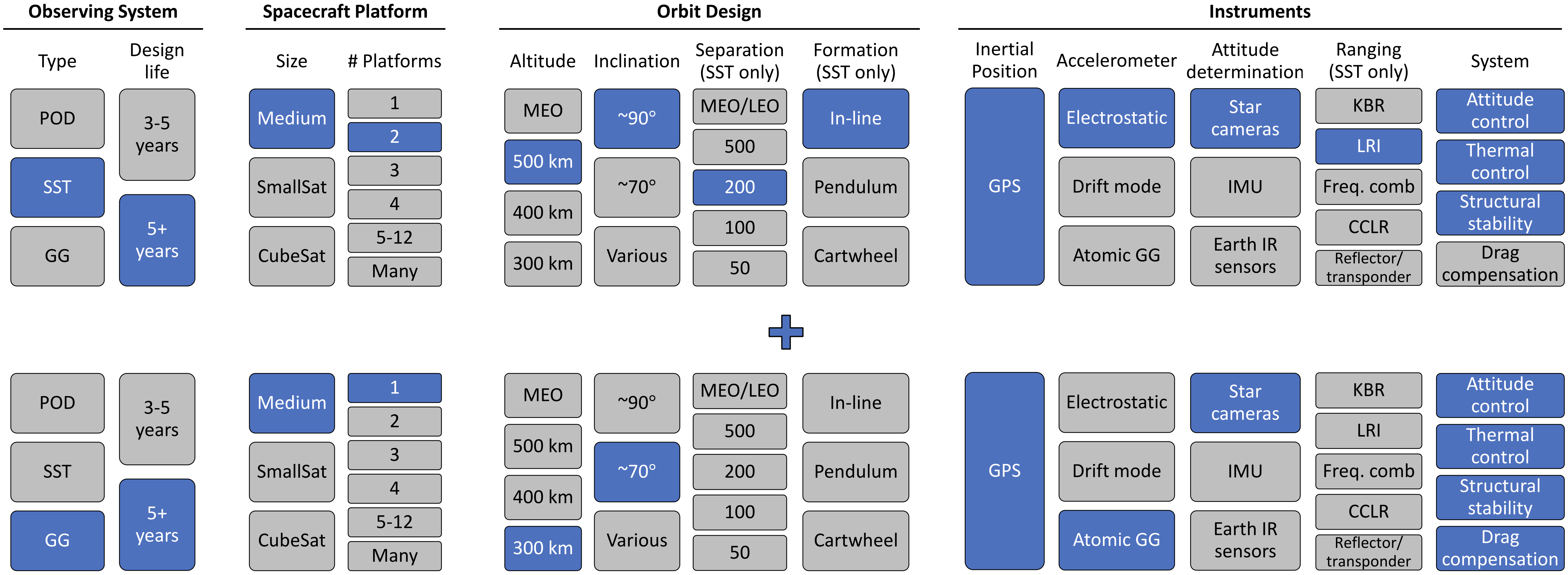

Observing System		Spacecraft Platform		Orbit Design				Instruments				
Type	Design life	Size	# Platforms	Altitude	Inclination	Separation (SST only)	Formation (SST only)	Inertial Position	Accelerometer	Attitude determination	Ranging (SST only)	System
POD	3-5 years	Medium	1	MEO	~90°	MEO/LEO	In-line	GPS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

+

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			4	300 km		100					CCLR	Drag compensation
			5-12			50					Reflector/ transponder	
			Many									

↳ Possible technology demonstration

Community Feedback

- 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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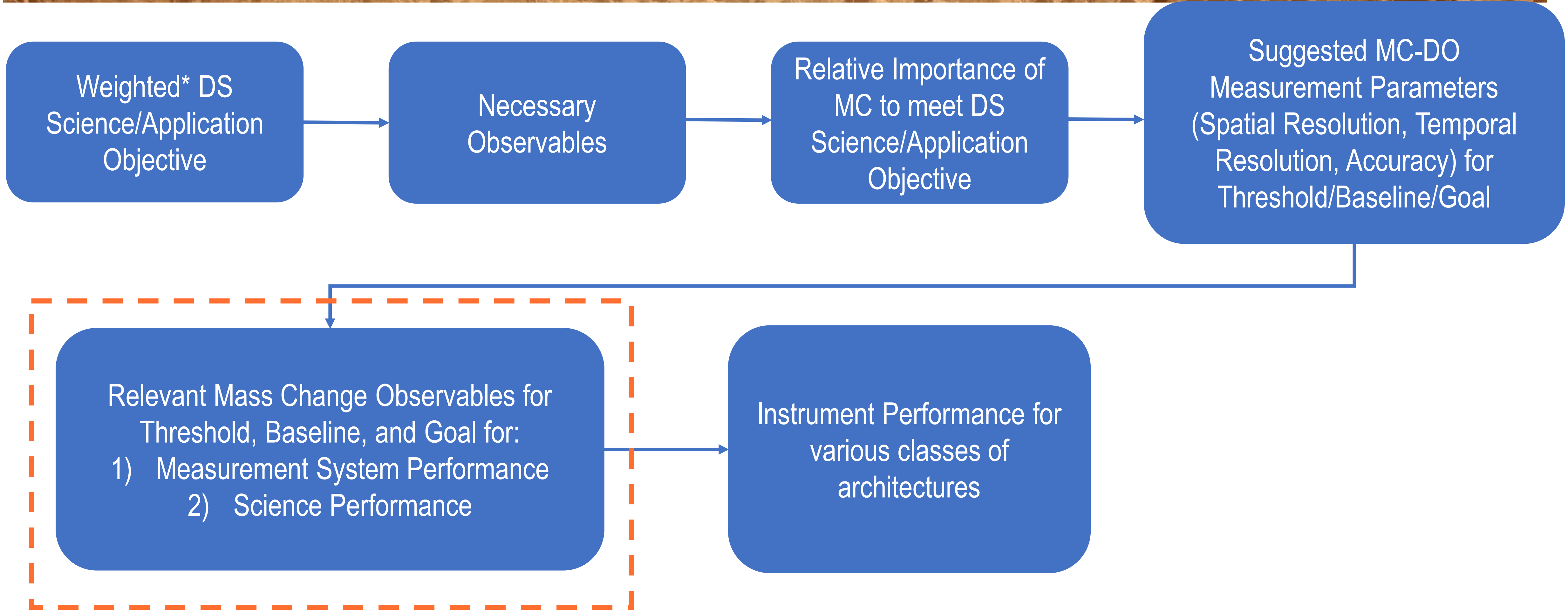


Weighted* DS Science/Application Objective

Necessary Observables

Relative Importance of MC to meet DS Science/Application Objective

Suggested MC-DO Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) for Threshold/Baseline/Goal

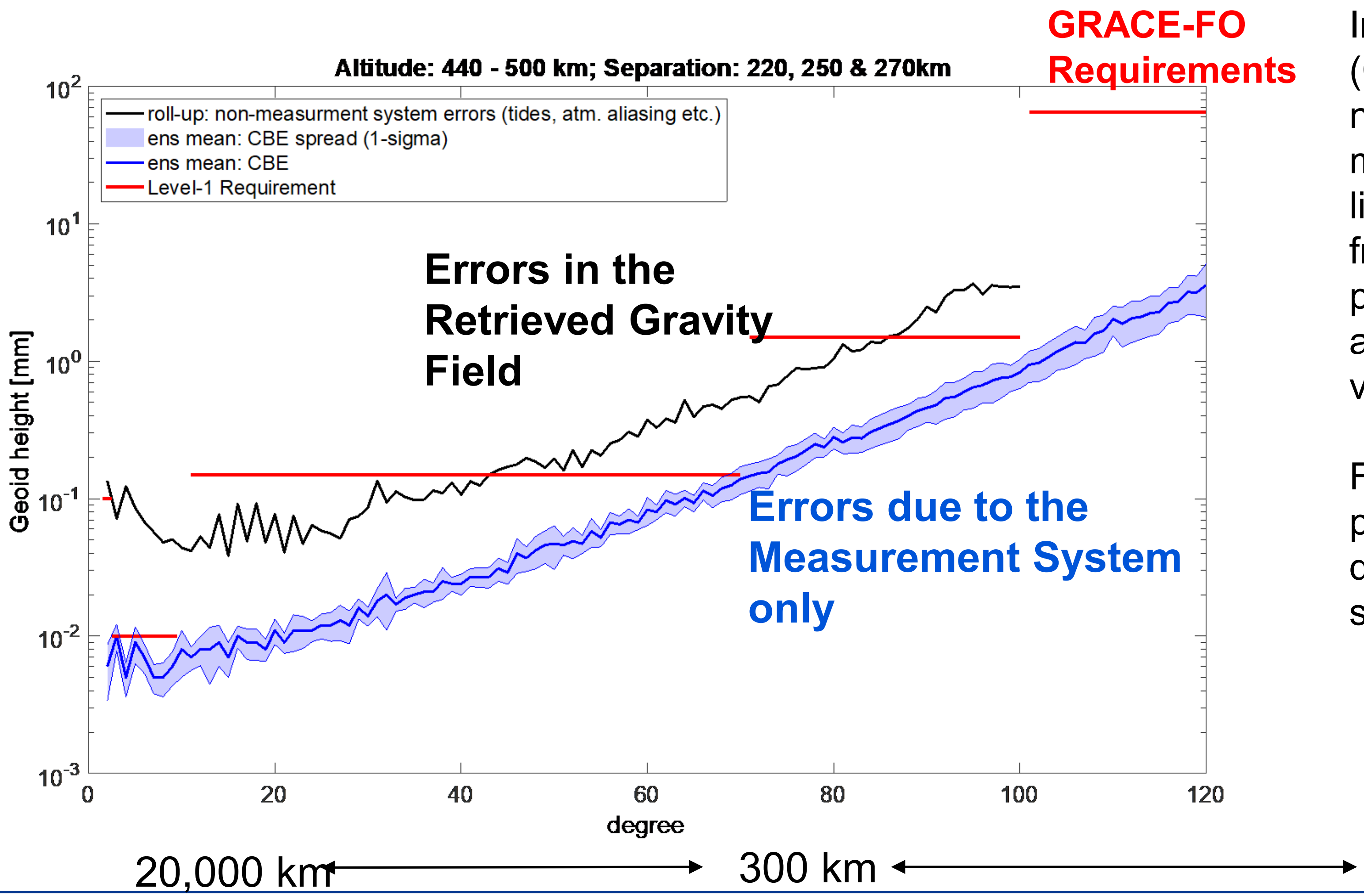
Relevant Mass Change Observables for Threshold, Baseline, and Goal for:

1) Measurement System Performance
2) Science Performance

Instrument Performance for various classes of architectures

Driven by Community Input

Gravity Field Errors vs Measurement System Errors



GRACE-FO Requirements

Errors in the Retrieved Gravity Field

Errors due to the Measurement System only

20,000 km ⟷ 300 km ⟷ 167 km

Spatial Resolution

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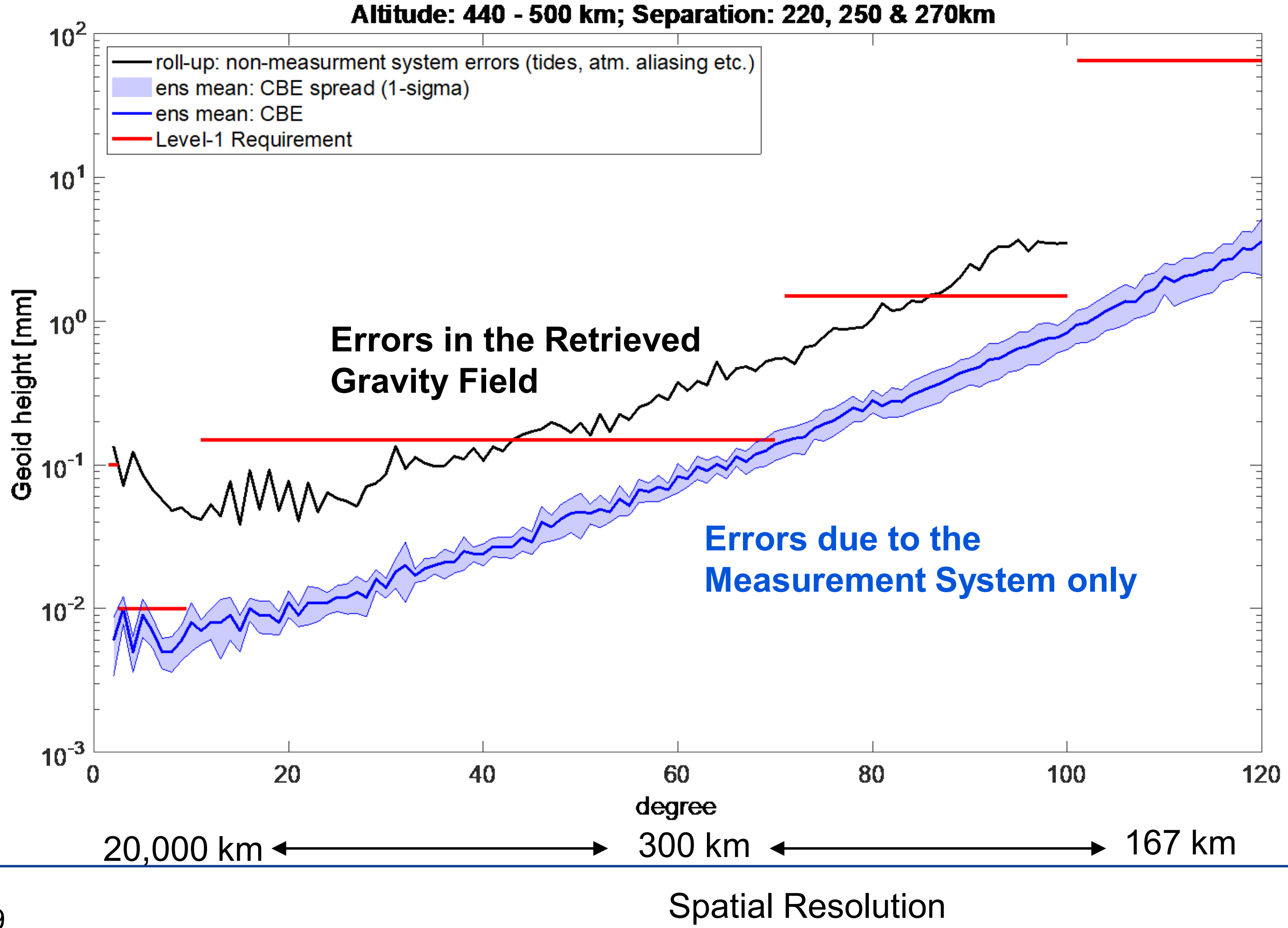
For GRACE-FO, requirements were placed solely on the measurement system. For MC-DO, we define two sets of targets:

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



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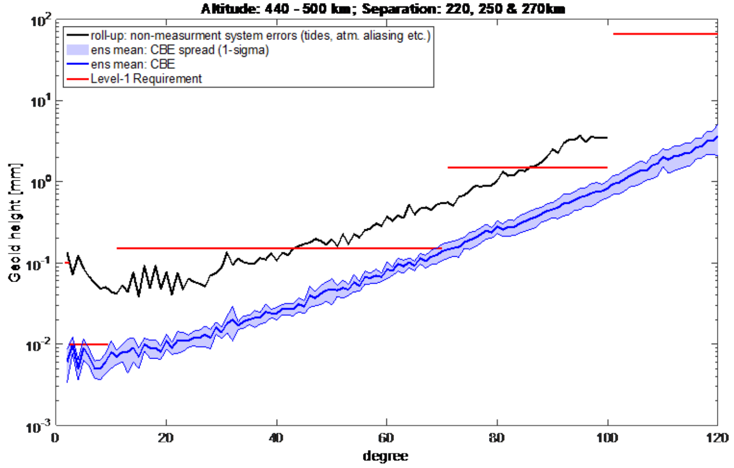
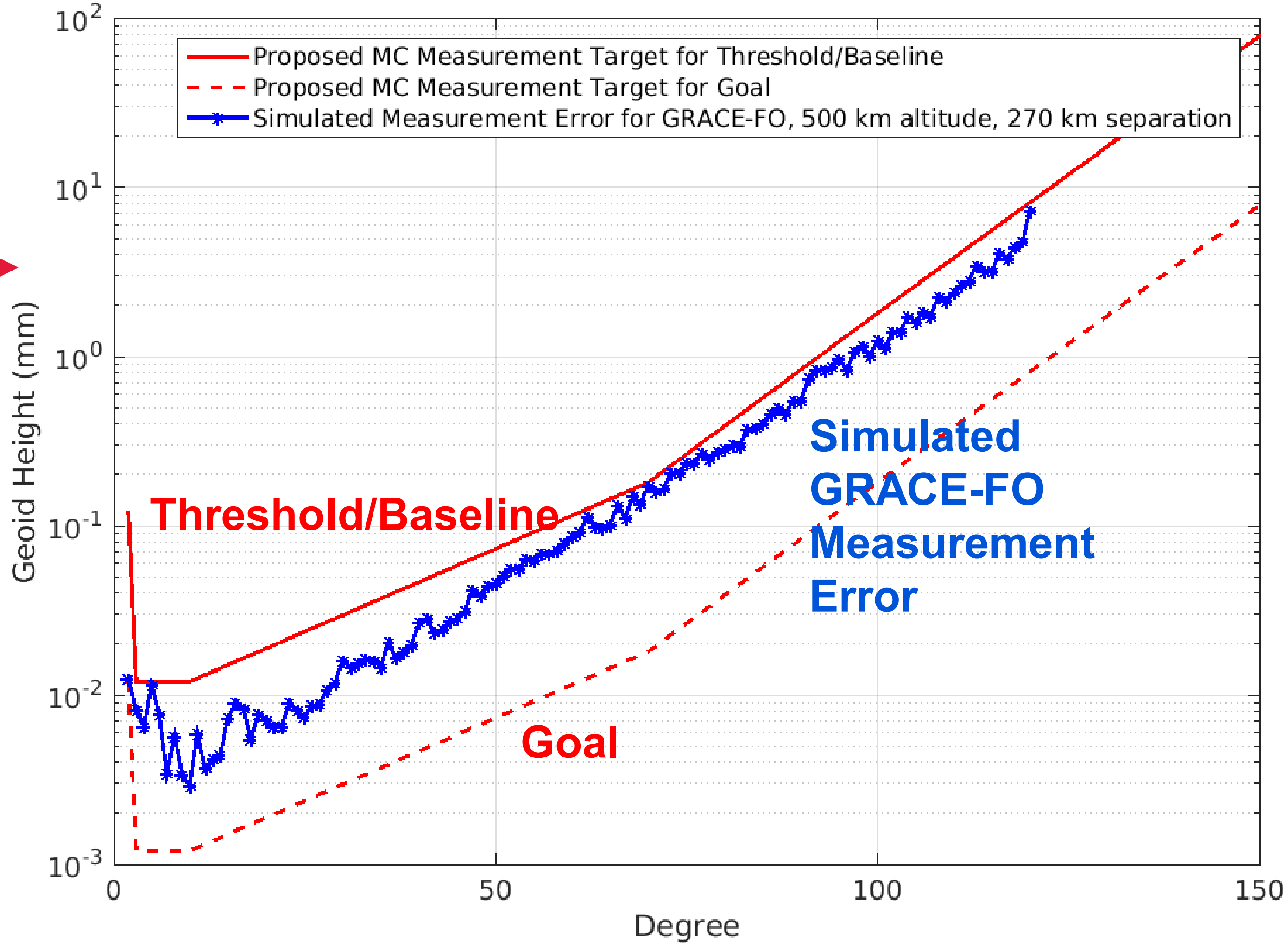
Measurement System Performance Targets


Altitude: 440 - 500 km; Separation: 220, 250 & 270km

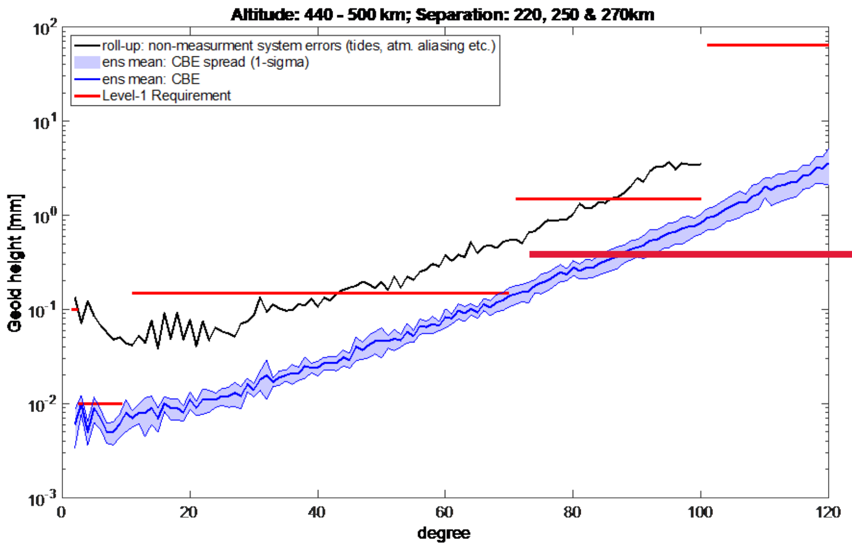

Proposed MC-DO Measurement Performance Targets

Threshold/Baseline

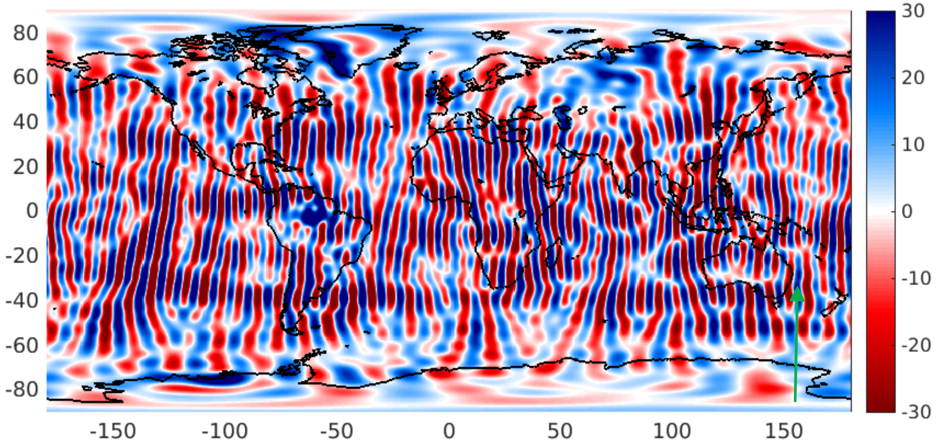
Goal

Simulated GRACE-FO Measurement Error

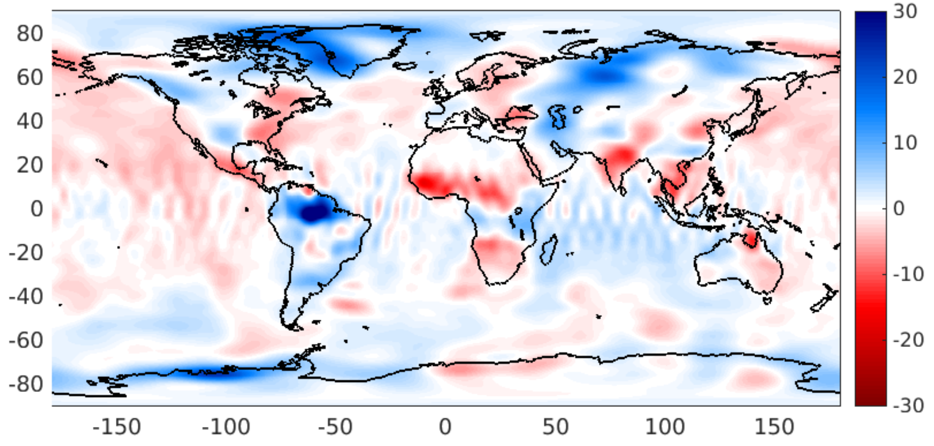
Science Performance Targets



Raw Errors



Postprocessing



Science Performance Targets are written on this field

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.

Relevant Mass Change Observables

To Do: Review Science Performance Language

- Measurement System Performance:

  Threshold and Baseline

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

  Goal

  <= 30-day average values of the geopotential coefficients to spherical harmonic degrees <=150 with equivalent room 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.

Minimizing Data Gaps after GRACE-FO

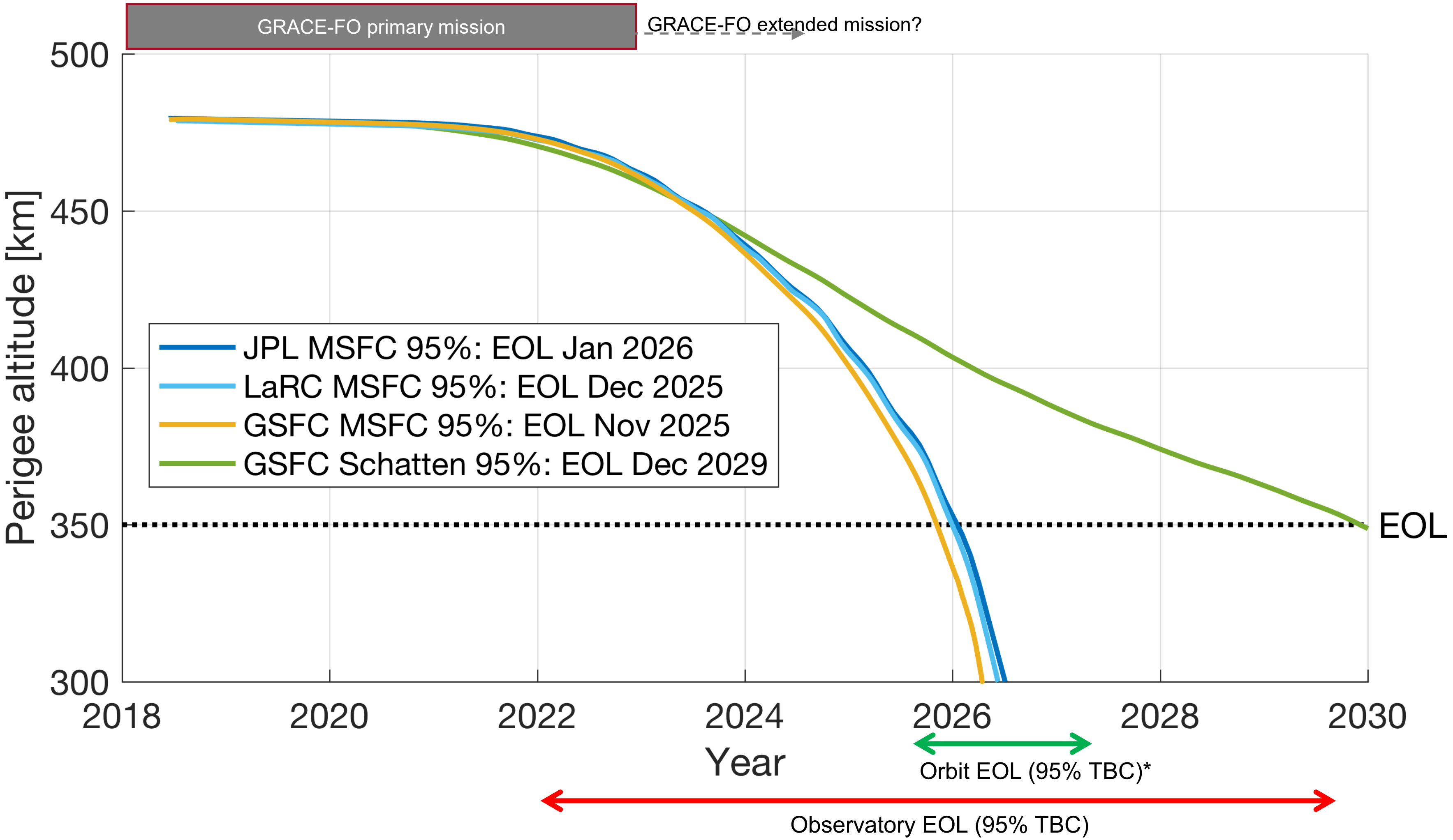
- A strong desire for a **long data record and minimizing any potential data gap** between GRACE-FO and an MC-DO was expressed at the community workshop. This exceeded all other priorities and was agreed upon by all scientific disciplines
- Fundamentally, there is no need for inter-mission calibration, 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

- 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



Orbit EOL (95% TBC)*

Observatory EOL (95% TBC)

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. Chrone – to be updated with latest GFO state vector and solar activity