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Results from the NASA Mass Change Designated Observable Study

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[1]Caltech/Jet Propulsion Laboratory
[2]NASA Langley Research Center
[3]NASA Ames Research Center
[4]NASA Goddard Space Flight Center
[5]NASA Headquarters

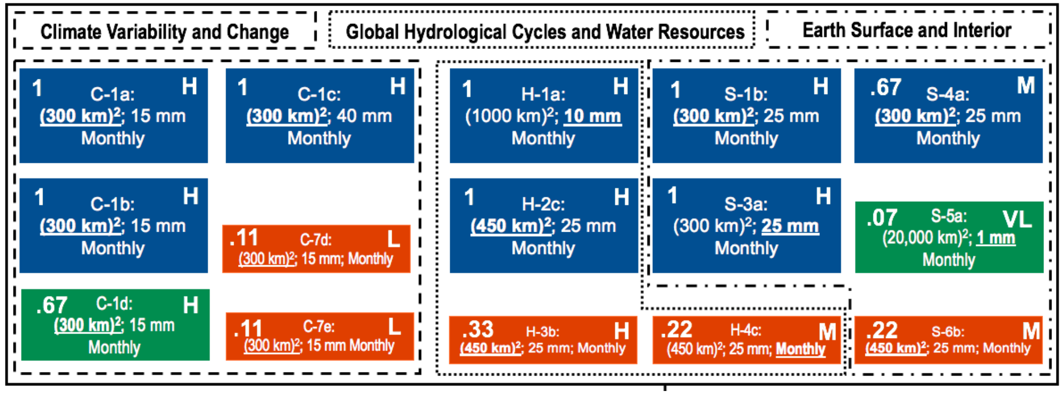
GRACE-FO Science Team Meeting | October 2021

Mass Change Designated Observable Study identifies high-value observing systems for implementation within the next decade

Decadal Survey

Traceability to Decadal Survey

Science and Applications Traceability Matrix (SATM) Baseline Measurement Parameters



Climate Variability and Change

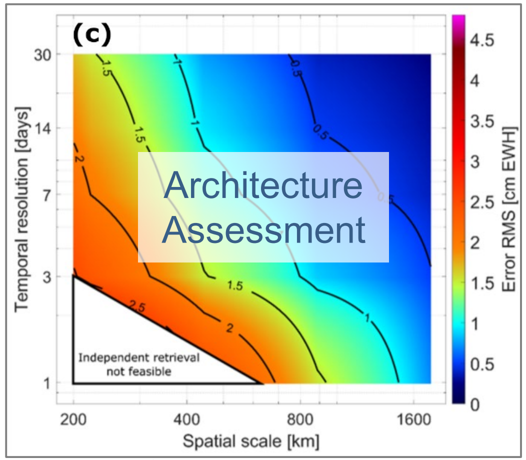
- 1 C-1a: (300 km)²; 15 mm Monthly H
- 1 C-1c: (300 km)²; 40 mm Monthly H
- 1 C-1b: (300 km)²; 15 mm Monthly H
- .11 C-7d: (300 km)²; 15 mm; Monthly L
- .67 C-1d: (300 km)²; 15 mm Monthly H
- .11 C-7e: (300 km)²; 15 mm Monthly L

Global Hydrological Cycles and Water Resources

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

Earth Surface and Interior

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



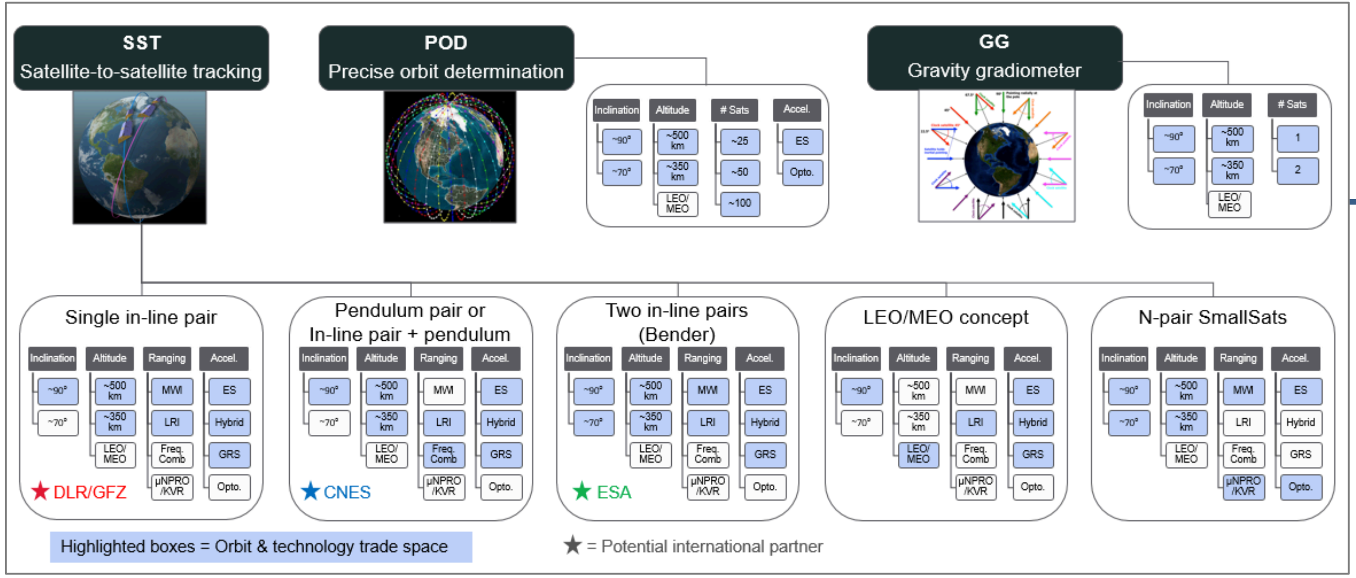
Architecture Assessment

Science Value

Value Framework Process
- Cost
- Schedule
- Risk
- Partnerships

Identification of High-Value MC Observing Systems

Architecture and Technology Tradespace



CNES	Centre National d'Études Spatiales
DLR	Deutsches Zentrum für Luft-und Raumfahrt
ES	electrostatic
ESA	European Space Agency
EWH	equivalent water height
GFZ	German Research Centre for Geosciences
GRS	Gravitational Reference Sensor
LEO	low Earth orbit
LRI	laser ranging interferometer
MEO	medium Earth orbit
MWI	Microwave Interferometer
RMS	root mean square

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1. Science and Applications Traceability Matrix

Three Focus Areas and their Research and Applications Objectives

HYDROLOGY

H-1. How is the water cycle changing?

H-2. How do anthropogenic changes in climate, land use, water use, and water storage, interact and modify the water and energy cycles locally, regionally, and globally and what are the short- and long-term consequences?

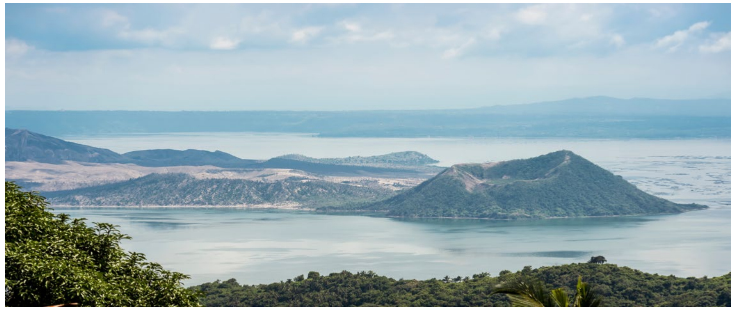
H-3. How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?

H-4. How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard-chains, and how do we improve preparedness and mitigation of water-related extreme events?

CLIMATE

C-1. How much will sea level rise globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?

C-7. How are decadal scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer-term environmental change?



SOLID EARTH

S-1. How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?

S-3. How will local sea level change along coastlines around the world in the next decade to century?

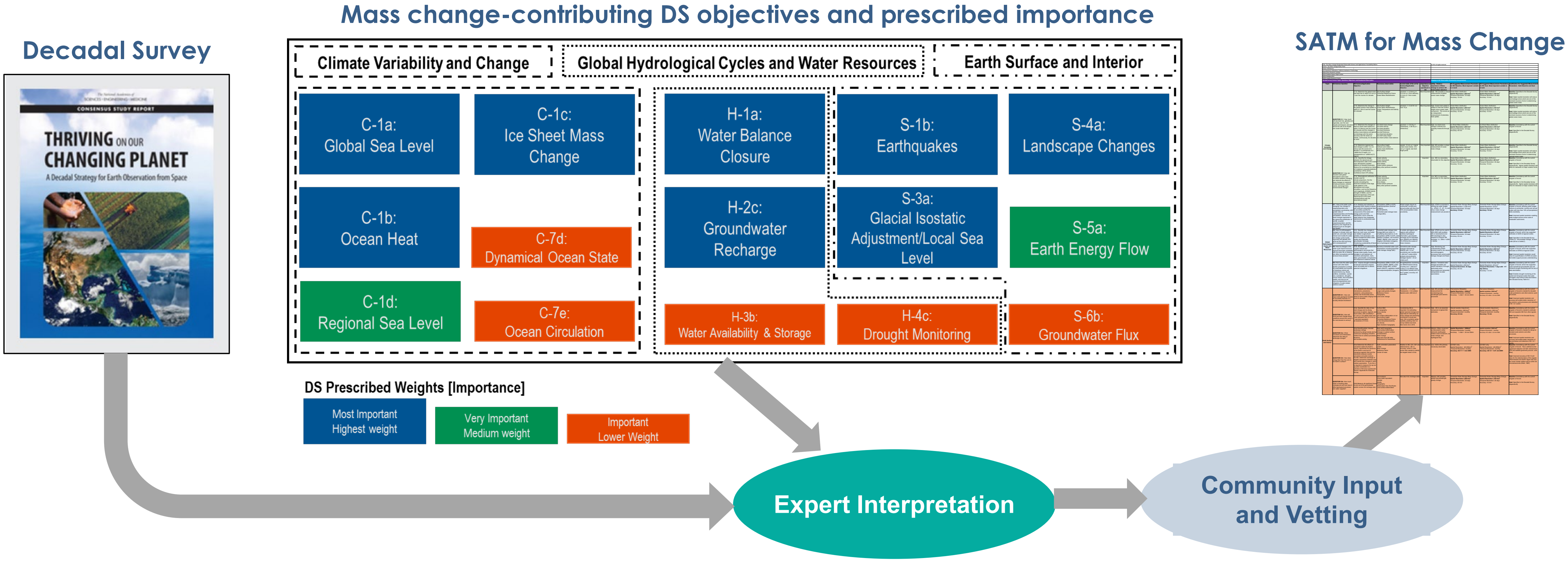
S-4. What processes and interactions determine the rates of landscape change?

S-5. How does energy flow from the core to the Earth’s surface?

S-6. How much water is traveling deep underground and how does it affect geological processes and water supplies?

Mass Change SATM Development

The development of the Mass Change (MC) Science and Applications Traceability Matrix (SATM) was driven by the 2017 Decadal Survey (DS) with significant input from the community: https://science.nasa.gov/earth-science/decadal-mc



Decadal Survey

Mass change-contributing DS objectives and prescribed importance

Climate Variability and Change
- 🟦 C-1a: Global Sea Level
- 🟦 C-1c: Ice Sheet Mass Change
- 🟦 C-1b: Ocean Heat
- 🟧 C-7d: Dynamical Ocean State
- 🟩 C-1d: Regional Sea Level
- 🟧 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-4a: Landscape Changes
- 🟦 S-3a: Glacial Isostatic Adjustment/Local Sea Level
- 🟩 S-5a: Earth Energy Flow
- 🟧 S-6b: Groundwater Flux

DS Prescribed Weights [Importance]
- 🟦 Most Important Highest weight
- 🟩 Very Important Medium weight
- 🟧 Important Lower Weight

SATM for Mass Change

Expert Interpretation

Community Input and Vetting

Decadal Survey—Interpretation for the MC SATM

- The Decadal Survey was clear in the importance of mass change measurements and continuity of the data record:

  Mass Change: Ensures continuity of measurements of groundwater and water storage mass change, land ice contributions to sea-level rise, ocean mass change, ocean heat content (when combined with altimetry), glacial isostatic adjustment, and earthquake mass movement. Also important for operational applications, including drought assessment and forecasting, hazard response, and planning water use for agriculture and consumption. Addresses various "Most Important" objectives of the Climate, Hydrology, and Solid Earth panels and key components of the Water and Energy Cycle integrating theme.
- The Decadal Survey quoted a broad range of MC observation desires, from continuity-preserving (e.g., resolution of continental-scale river basins) to aspirational (e.g., resolution of headwater catchments), captured as "Baseline" and "Goal" characteristics
- Quantifying the Decadal Survey's and community's desires and priorities with respect to mass change observational characteristics, and translating those into performance targets for the SATM, required much discussion among experts and the community (MC Community Workshop, multiple telecons, American Geophysical Union (AGU) town hall, availability of draft SATM, etc.)

SATM Development Process and Timeline

Science/ Application Objective with Defined Importance

15 are Prescribed in DS

Necessary Observables

How essential is MC to achieving DS Science/Application Objective? (Utility)

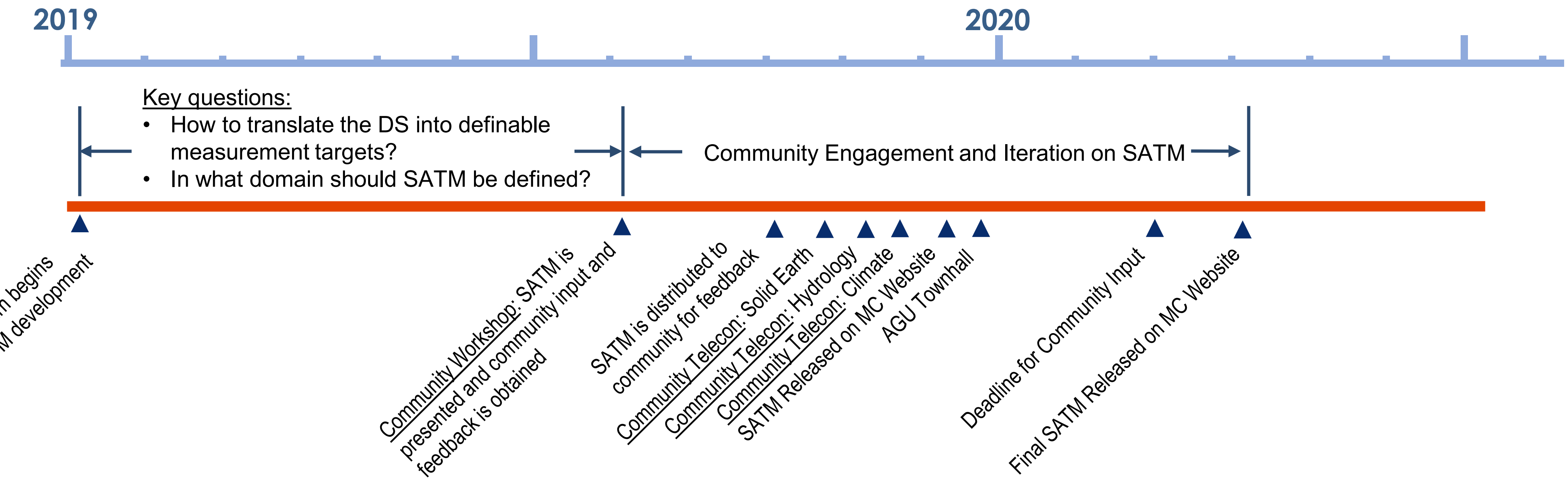
MC-Designated Observable (DO) Measurement Parameters (Spatial Resolution, Temporal Resolution, Accuracy) needed for Baseline/Goal

Expert Interpretation: Required Community Vetting

CONSENSUS STUDY REPORT

THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space



Key questions:

- How to translate the DS into definable measurement targets?
- In what domain should SATM be defined?

Community Engagement and Iteration on SATM

MC team begins SATM development

Community Workshop: SATM is presented and community input and feedback is obtained

SATM is distributed to community for feedback

Community Telecon: Solid Earth

Community Telecon: Hydrology

Community Telecon: Climate

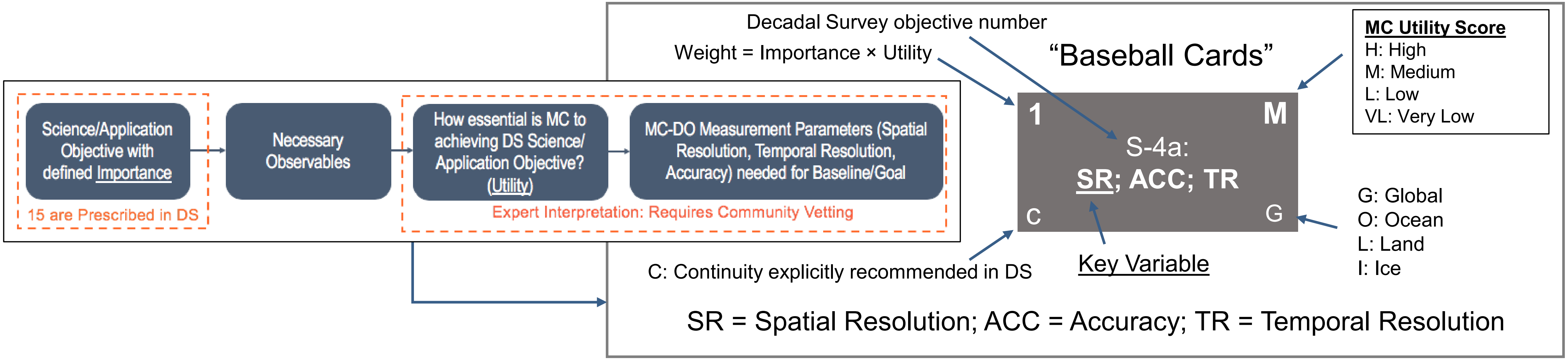
SATM Released on MC Website

AGU Townhall

Deadline for Community Input

Final SATM Released on MC Website

SATM Development Approach



Science/Application Objective with defined Importance

15 are Prescribed in DS

Necessary Observables

How essential is MC to achieving DS Science/ Application Objective? (Utility)

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

Expert Interpretation: Requires Community Vetting

Decadal Survey objective number

Weight = Importance × Utility

“Baseball Cards”

1

M

S-4a:

SR; ACC; TR

C

G

MC Utility Score
H: High
M: Medium
L: Low
VL: Very Low

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

C: Continuity explicitly recommended in DS

Key Variable

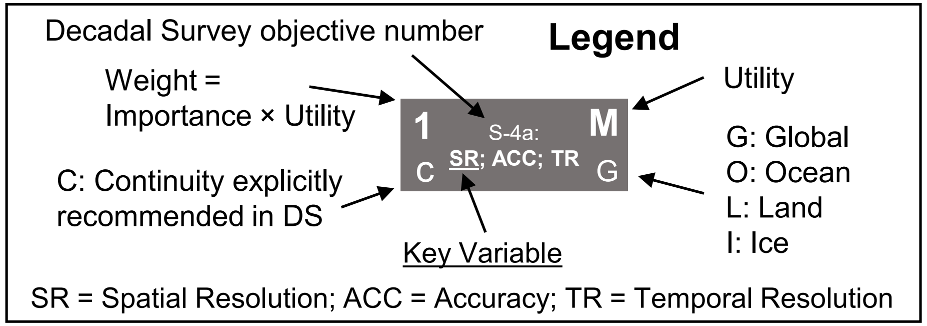
SR = Spatial Resolution; ACC = Accuracy; TR = Temporal Resolution

- A “deck” of “baseball cards” was developed for baseline science objectives and goals
- The DS has been interpreted such that the baseline science objectives were defined to roughly translate to consistency in the quality of the data products with the Program of Record (POR)
- The DS outlines many areas where improvements relative to the Program of Record would enable advancements in Earth system science. These are captured in a defined set of goals.
- Details on each science question are provided in the backup, along with cross-cutting themes with other DOs

Decadal Survey Science and Application Objectives for Mass Change

Measurement Parameters for Baseline

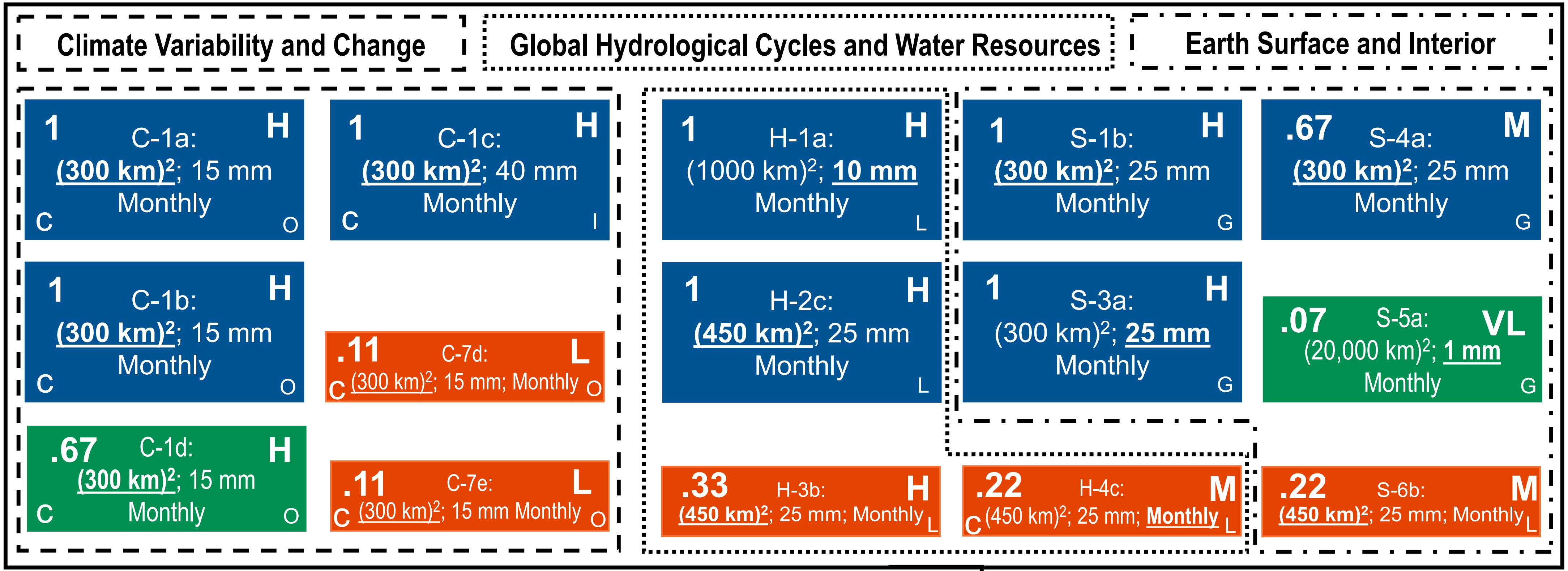
Baseline Observing System – supports full science objectives



Legend

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

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



Climate Variability and Change

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

Global Hydrological Cycles and Water Resources

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

Earth Surface and Interior

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

DS Prescribed Importance

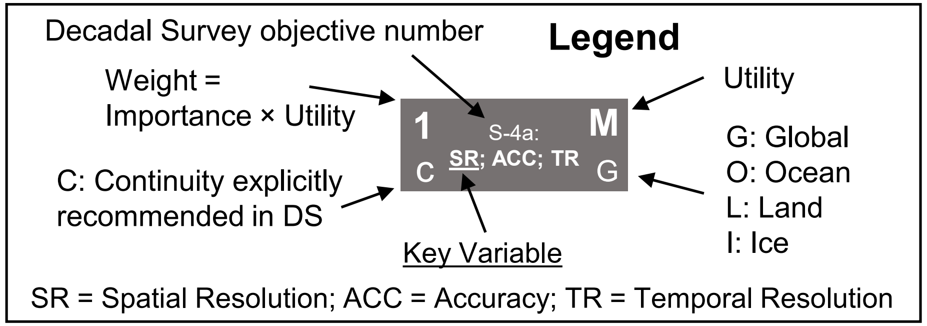
🟦	🟩	🟧
Most Important Highest weight	Very Important Medium weight	Important Lower Weight
1.0	0.67	0.33

MC Utility Score

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

→ **Science Performance Targets**

Decadal Survey Science and Application Objectives for Mass Change



Legend

Decadal Survey objective number

Weight = Importance × Utility

C: Continuity explicitly recommended in DS

Key Variable

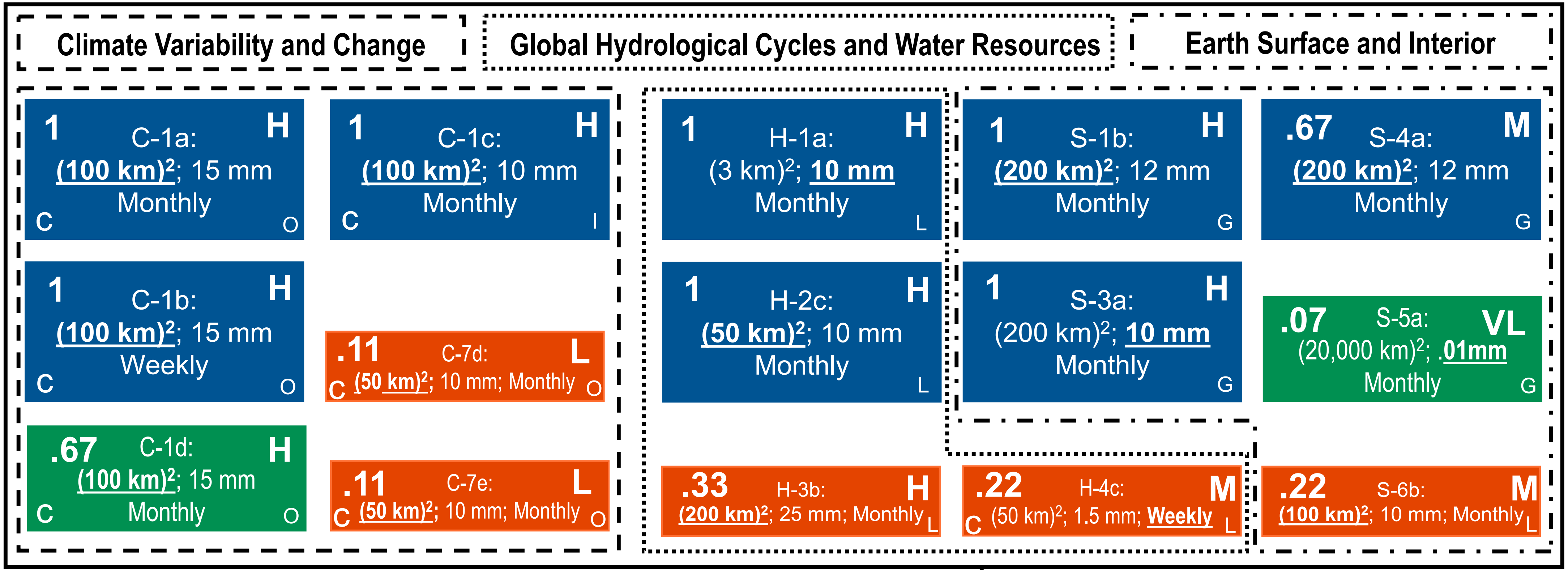
Utility

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

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

Measurement Parameters for Goal

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



Climate Variability and Change | **Global Hydrological Cycles and Water Resources** | **Earth Surface and Interior**

1 C-1a: H
(100 km)^2; 15 mm
Monthly
C O

1 C-1c: H
(100 km)^2; 10 mm
Monthly
C I

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

1 S-1b: H
(200 km)^2; 12 mm
Monthly
G

.67 S-4a: M
(200 km)^2; 12 mm
Monthly
G

1 C-1b: H
(100 km)^2; 15 mm
Weekly
C O

.11 C-7d: L
C (50 km)^2; 10 mm; Monthly O

1 H-2c: H
(50 km)^2; 10 mm
Monthly
L

1 S-3a: H
(200 km)^2; 10 mm
Monthly
G

.07 S-5a: VL
(20,000 km)^2; .01mm
Monthly
G

.67 C-1d: H
(100 km)^2; 15 mm
C Monthly O

.11 C-7e: L
C (50 km)^2; 10 mm; Monthly O

.33 H-3b: H
(200 km)^2; 25 mm; Monthly L

.22 H-4c: M
C (50 km)^2; 1.5 mm; Weekly L

.22 S-6b: M
(100 km)^2; 10 mm; Monthly L

DS Prescribed Importance

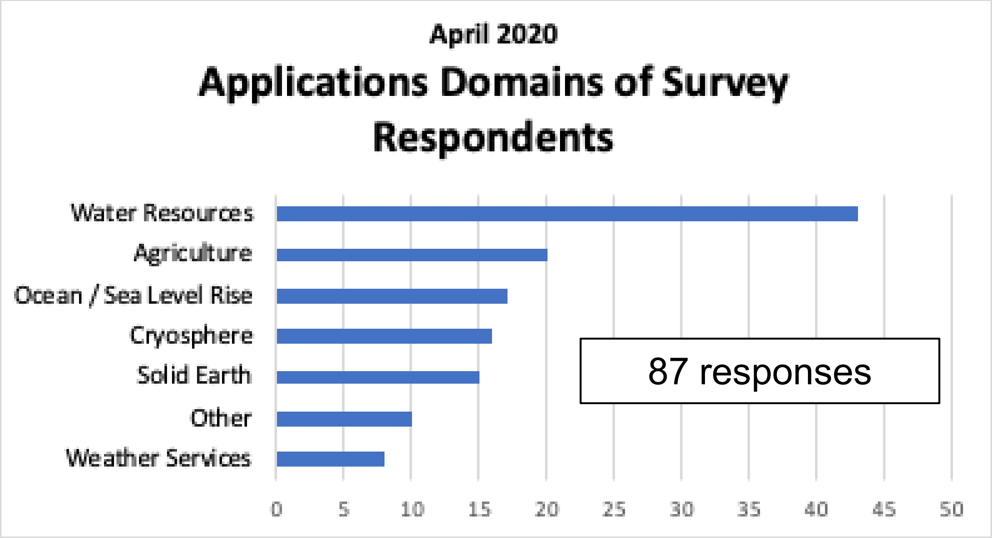
Most Important Highest weight	Very Important Medium weight	Important Lower Weight
1.0	0.67	0.33

MC Utility Score

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

Science Performance Targets

Mass Change Applications Survey

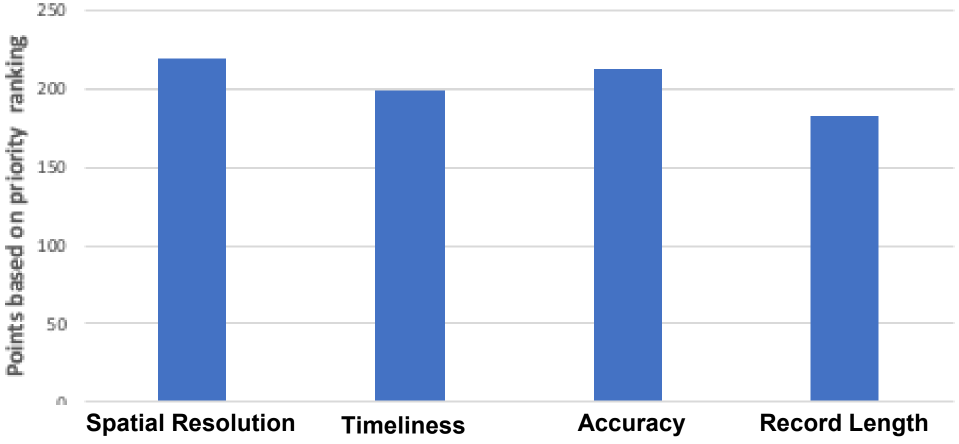


April 2020

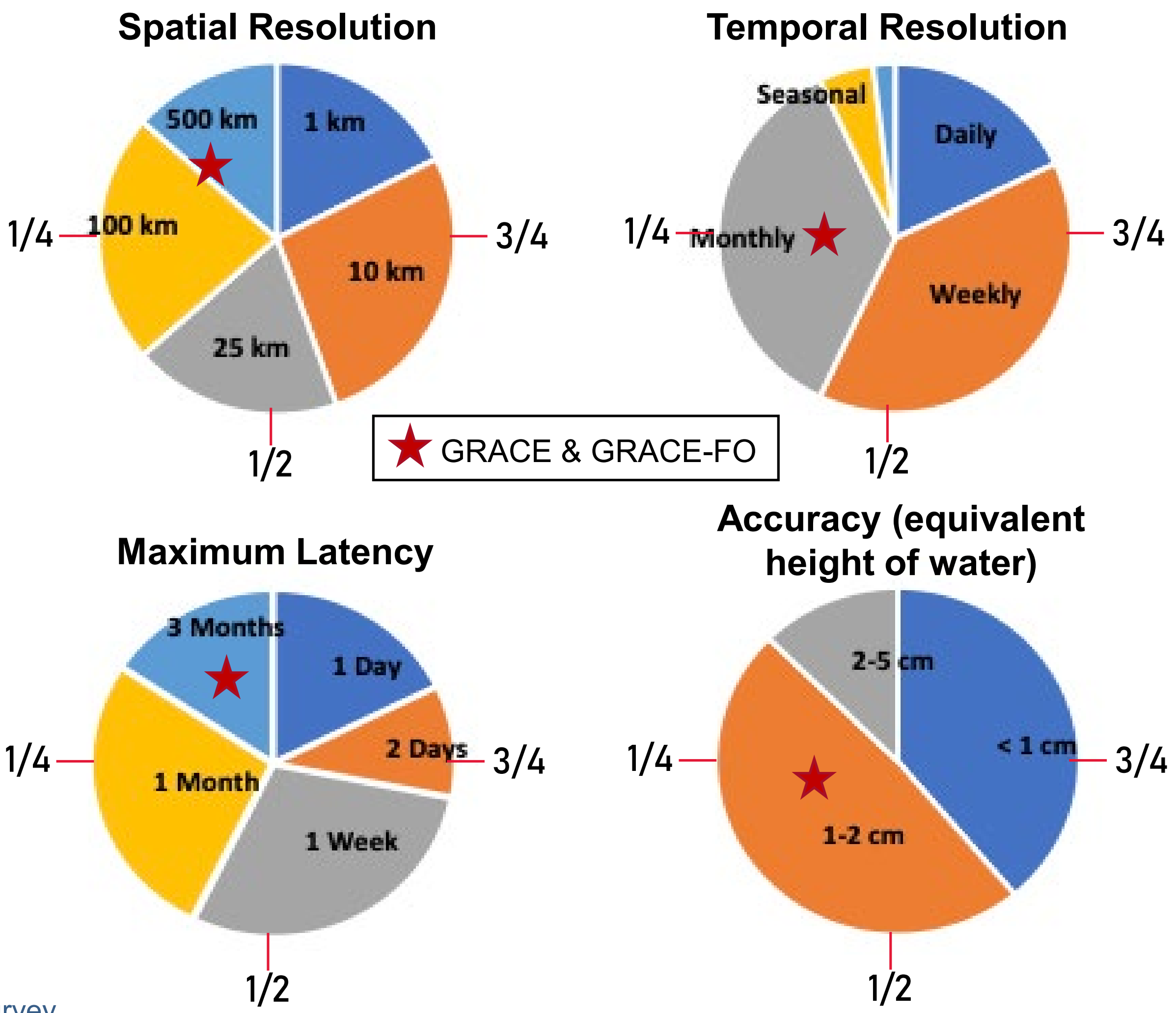
Applications Domains of Survey Respondents

87 responses

Relative Importance of Data Attributes



Fractions of Respondents Satisfied at Varying Data Attribute Thresholds



Spatial Resolution

Temporal Resolution

Maximum Latency

Accuracy (equivalent height of water)

★ GRACE & GRACE-FO

https://tinyurl.com/MassChangeSurvey

Expanding and Improving MC Applications

- Mass change observations have the potential to support numerous practical applications:

Already Contributing (with room to improve)	Areas of Future Contribution
Water resources assessments	Earthquake hazard assessment
Drought monitoring and forecasting	Weather services
Agricultural planning and yield forecasting	Forestry
Flood vulnerability	Fire risk
Local sea level rise	

- Based on the MC applications survey, focus groups, and other community interactions, common desires among current and potential mass change data users include:
  - Improved timeliness (higher frequency, reduced latency) and increased spatial resolution
    - Low latency and data assimilation products are keys to satisfying these desires
  - Confidence that there will be continuity of mass change measurements in the future
  - Improved discoverability of NASA data products
  - Products tailored to specific stakeholder/industry needs
  - Help understanding how to use/interpret NASA data products

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2. Opening of the Tradespace

Opening of the Tradespace—Architectures

MC architecture types identified and assessed for science value:

- **POD**: Precise orbit determination
  - ↳ Large constellation of Global Navigation Satellite System (GNSS) equipped satellites
- **SST**: Satellite-to-satellite tracking
  - ↳ Minimum of two satellites with precise inter-satellite ranging instrument
- **GG**: Gravity gradiometer
  - ↳ Measures gravitational impact on test masses or atom clouds within a single satellite

For **POD** and **SST**: Measurements capture gravitational impact on the motion of satellites; i.e., *the satellite is the instrument*

Given the long Program of Record (POR) of MC **SST** measurements (Gravity Recovery and Climate Experiment [GRACE] / GRACE Follow-On [FO]), an extensive amount of research and development regarding possible **SST** architectures and technologies pre-dates the MC Study.

Opening of the Tradespace—Technology

Through the MC Community Workshop, the solicitation of technology white papers, and other regular communication with the community, we sought input from experts regarding technology concepts and development efforts relevant to improving the science performance of a MC mission.

Technologies identified for improved MC performance (relevant architecture types identified) include:

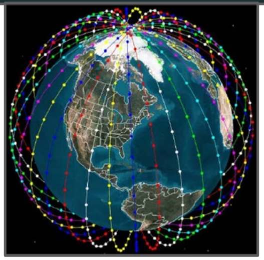
- Advanced accelerometers (SST)
- Advanced inter-satellite ranging / laser ranging interferometer (SST)
- Electric propulsion for orbit maintenance or drag compensation (SST)
- Miniaturization of relevant technologies (POD, SST)
- Atomic Interferometer Gravity Gradiometer (AIGG)

The combination of architecture and technology options defines the full tradespace (next chart)

Opening of the Tradespace—Architectures and Technology

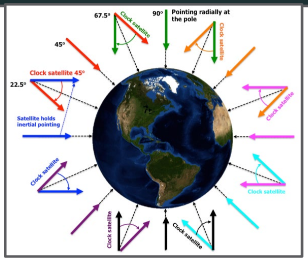
SST
Satellite-to-satellite tracking

POD
Precise orbit determination

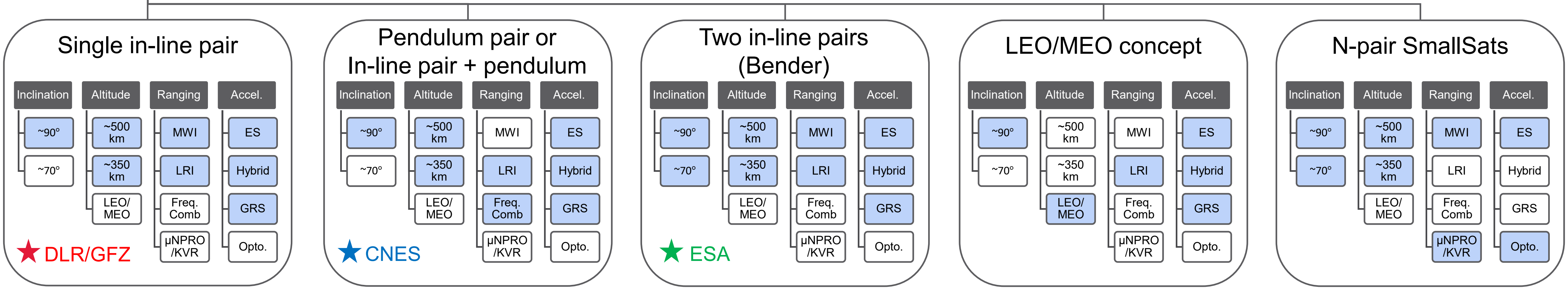


Inclination	Altitude	# Sats	Accel.
~90°	~500 km	~25	ES
~70°	~350 km	~50	Opto.
	LEO/ MEO	~100	

GG
Gravity gradiometer



Inclination	Altitude	# Sats
~90°	~500 km	1
~70°	~350 km	2
	LEO/ MEO	



Single in-line pair

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

★ DLR/GFZ

Pendulum pair or In-line pair + pendulum

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

★ CNES

Two in-line pairs (Bender)

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

★ ESA

LEO/MEO concept

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

N-pair SmallSats

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

Highlighted boxes = Orbit and technology trade space

★= Potential international partner

CNES	Centre National d'Études Spatiales
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ES	electrostatic
ESA	European Space Agency
GFZ	German Research Centre for Geosciences
GRS	Gravitational Reference Sensor
LEO	low Earth orbit
LRI	laser ranging interferometer
MEO	medium Earth orbit
MWI	Microwave Interferometer

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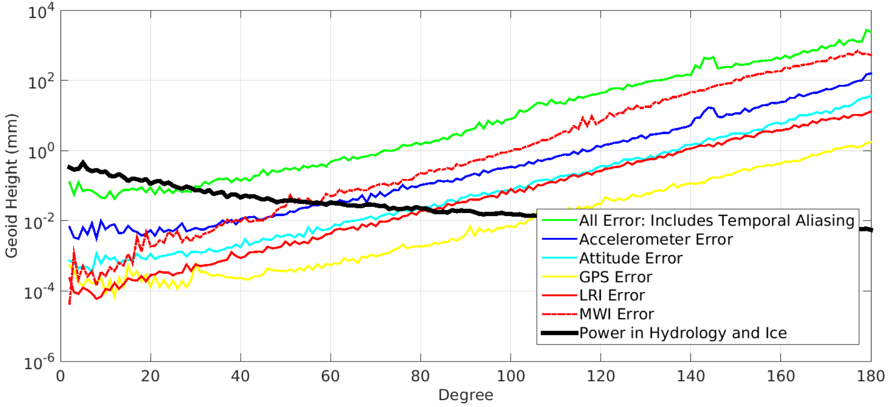
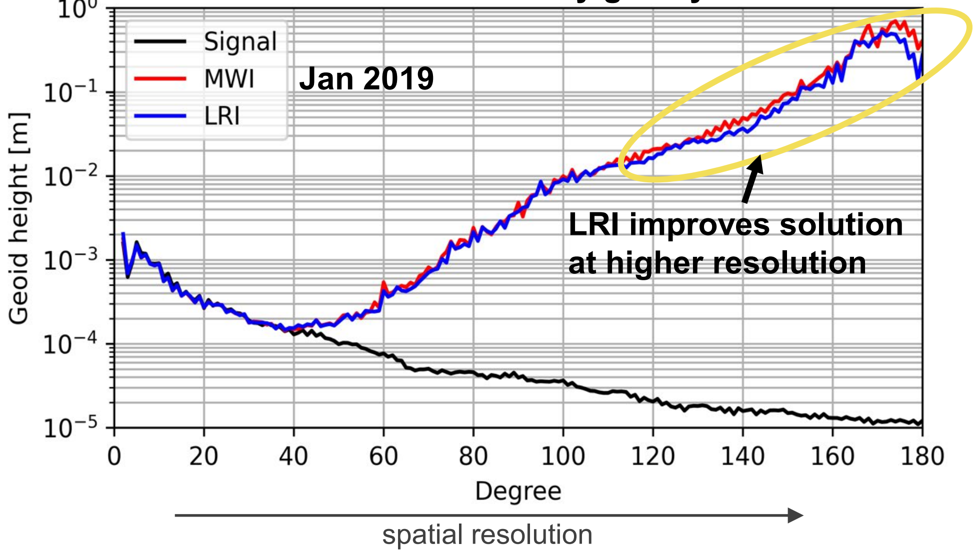
3. Technology Development Areas

Technology Development Areas—Motivation



Simulated MC monthly gravity errors



GRACE-FO MWI & LRI monthly gravity estimates

Jan 2019

LRI improves solution at higher resolution

Gravity simulation and estimation (**see figures**) motivates technology development:

- Laser ranging interferometer (LRI) performs ~100x better than the Microwave Interferometer (MWI)
  - ↳ Motivates the use of **LRI as primary ranging instrument** as this same level of precision is strongly desired by the community and is already yielding important science outcomes (along-track analysis provides larger benefit than monthly gravity estimates)
- Accelerometers are the leading Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) measurement error source
  - ↳ Motivates desire for **advanced accelerometers**
- Temporal aliasing is a major source of error that is mitigated with additional satellite platforms and certain architectures (satellite-to-satellite tracking [SST] pendulum; SST Bender; gravity gradiometry [GG])
  - ↳ Motivates the **technologies required for pendulum and GG architectures**
  - ↳ Motivates the **miniaturization of relevant technologies** for cost-effective multi-platform architectures

Additional motivation for technology development (not represented by figures):

- Lowering the altitude significantly improves signal-to-noise
  - ↳ Motivates use of **electric propulsion** required at lower altitudes

Technology Development Areas—Ranging Summary

Key takeaways:

- Current technology meets baseline objectives
- Advanced technology either improves measurement accuracy, reduces SWaP, and/or enables pendulum architecture
- Approximate budget and schedule to achieve TRL 6 has been delivered to MC study team

	Inter-satellite ranging technology	**Performance vs. GRACE-FO LRI**	**SWaP vs. LRI**	**Current TRL** (lowest component)
	GRACE-FO MWI	0.01×	1×	9
	GRACE-FO LRI	1×	1×	9
Improvements	Ball optical frequency comb[*†]	1× (increased dynamic range for pendulum)	1×	5
	LRI cavity improvements[*]	Reduces noise	N/A	N/A
	LRI/accelerometer test mass interface[*]	Improved center of mass	N/A	N/A
SmallSats	GeoOptics KVR[†]	0.01×	0.1× (SW) 0.5× (P)	6
	GSFC μNPRO[*]	0.5×	0.4× (SW) 0.6× (P)	5
	LMI transponder (ESA)	1×	1×	4
	LMI retroreflector (ESA)	1×	1×	4
	Laser chronometer (CNES)	0.01× (gimbaled instrument for pendulum)	0.5× (SW) 1.5× (P)	4

Color legend:

- Current tech (meets baseline objectives)
- U.S. tech development
- Potential international partner tech development

Footnotes:

[*] *Community white paper delivered to MC team*

[†] *Selected for Category 3 funding*

Acronyms:

KVR	K-/V-band ranging	MWI	Microwave interferometer
LMI	Laser metrology instrument	NPRO	Non-planar ring oscillator
LRI	Laser ranging interferometer	SWaP	Size, Weight, and Power

Technology Development Areas— Accelerometer Summary

Key takeaways:

- Current technology meets baseline objectives
- Advanced technology either improves measurement accuracy, reduces SWaP, and/or supports low altitude implementation
- Approximate budget and schedule to achieve TRL 6 has been delivered to MC study team

	Accelerometer technology	**Performance vs. GRACE-FO**	**SWaP vs. GRACE-FO**	**Current TRL** (lowest component)
	ONERA GRACE-FO electrostatic	1×	1×	9
Improvements	ONERA MicroSTAR electrostatic	30× with drag compensation	1×	4
	ONERA HybridSTAR ES + cold atom	60× with drag compensation	10×	3
	Simplified LISA Pathfinder Gravitational Reference Sensor (GRS)[*‡]	20× without drag compensation 200× with drag compensation	1×	2
SmallSats	ONERA CubSTAR electrostatic	1×	0.3×	3
	Compact optomechanical[*†]	0.05× – 0.4×	0.01×	2

Color legend:

- Current tech (meets baseline objectives)
- U.S. tech development
- Potential vendor tech development

Footnotes:

[*] *Community white paper delivered to MC team*

[†] *Selected for Category 3 funding*

[‡] *MC study supporting development*

Acronyms:

ES	Electrostatic
SWaP	Size, Weight, and Power

Technology Development Areas—White Papers

Mass Change study technology white papers:

Laser ranging interferometer (LRI) technology roadmap

- Link: https://science.nasa.gov/science-pink/s3fs-public/atoms/files/LRI-Technology-Summary-and-Roadmap_TAGGED.pdf
- Content: LRI as primary instrument; frequency comb for pendulum implementation; other potential improvements; SmallSat/CubeSat implementation; compact optomechanical accelerometers; TRL assessments

Gravitational Reference Sensor (GRS) technology roadmap

- Link: https://science.nasa.gov/science-pink/s3fs-public/atoms/files/GRS-Technology-Summary-and-Roadmap_TAGGED.pdf
- Content: Detailed roadmap for Simplified LISA Pathfinder GRS; analysis of performance benefits; TRL assessments

Atomic Interferometer Gravity Gradiometer (AIGG) technology roadmap

- Coming Soon

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4. Value Framework

Value Framework Objectives

- Identify architectures that support the Mass Change (MC) Science and Applications objectives
  - Traceable to Decadal Survey (DS) priorities and recommendations
- Assess the cost effectiveness of each of the studied architectures
  - Impacted by multiple elements of Value
  - Capability (Science and Applications), Cost, Schedule, Risk/Complexity
- Provide a transparent and traceable mechanism for providing an observing system recommendation to NASA Earth Science Division of one or more candidate architectures
  - Justification for eliminating candidate architectures that are not recommended

Flow Diagram—Architecture Concept to Initial Value Assessment

1. Architecture Definition

1. Conceptualize Architecture
- Number of platforms and 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 Science and Applications Traceability Matrix (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 Technology Readiness Level (TRL) or availability relative to need date

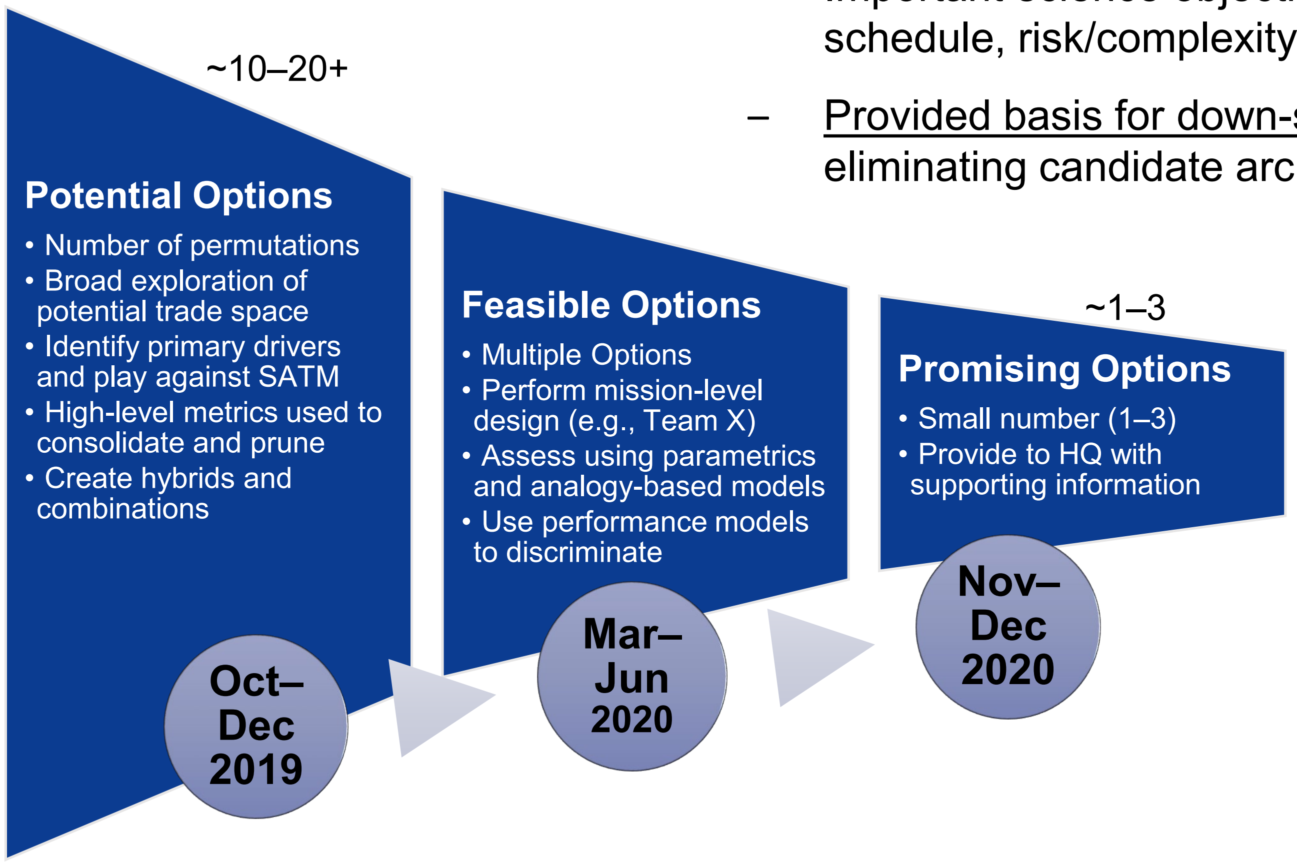
8. Architecture Selection
- Compare with baseline and goal science objectives
- Identify opportunities for partnership
- Assess affordability

Phase 2 Approach: Funnel from “Many” to “Few”

- Value Framework
  - <u>Assessed architecture solutions</u> to Most/Very Important science objectives (capability), cost, schedule, risk/complexity
  - <u>Provided basis for down-selection</u> and justification for eliminating candidate architectures

Number of Observing System Architectures

Phase 1



~10–20+

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

Mar–Jun 2020

~1–3

Promising Options

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

Nov–Dec 2020

Phase 3

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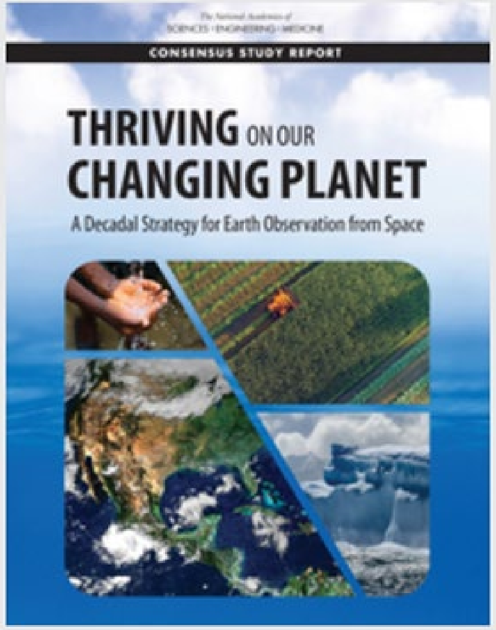
5. Science Value

Relating Observing System Capability to the DS

Decadal Survey (DS)



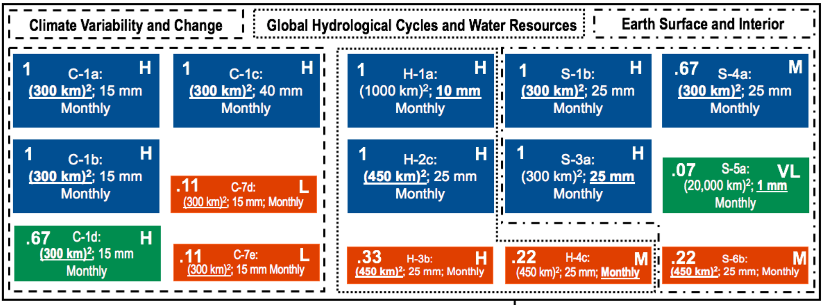
The National Academies of SCIENCES · ENGINEERING · MEDICINE

CONSENSUS STUDY REPORT

THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space

Science and Applications Traceability Matrix (SATM) Baseline Measurement Parameters



Climate Variability and Change

1 C-1a: H (300 km)²; 15 mm Monthly

1 C-1c: H (300 km)²; 40 mm Monthly

1 C-1b: H (300 km)²; 15 mm Monthly

.11 C-7d: L (300 km)²; 15 mm; Monthly

.67 C-1d: H (300 km)²; 15 mm Monthly

.11 C-7e: L (300 km)²; 15 mm Monthly

Global Hydrological Cycles and Water Resources

1 H-1a: H (1000 km)²; 10 mm Monthly

1 H-2c: H (450 km)²; 25 mm Monthly

.33 H-3b: H (450 km)²; 25 mm; Monthly

.22 H-4c: M (450 km)²; 25 mm; Monthly

Earth Surface and Interior

1 S-1b: H (300 km)²; 25 mm Monthly

1 S-3a: H (300 km)²; 25 mm Monthly

.67 S-4a: M (300 km)²; 25 mm Monthly

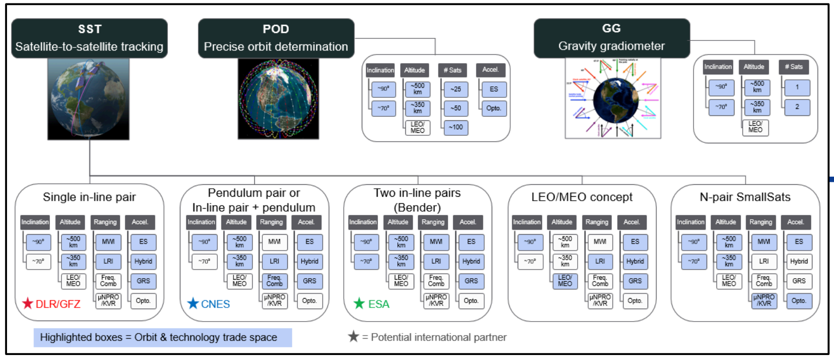
.07 S-5a: VL (20,000 km)²; 1 mm Monthly

.22 S-6b: M (450 km)²; 25 mm; Monthly

Science Value metrics directly relate the capability of an observing system architecture to achieving science and application targets relevant to Mass Change (MC) in the DS

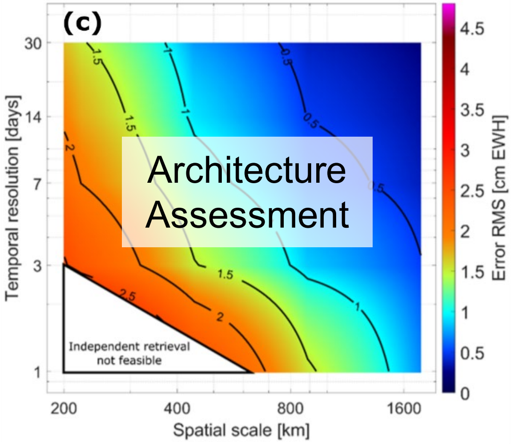
The process has been presented to the community for input and is successful in discriminating between architectures

Architecture Tree



Highlighted boxes = Orbit & technology trade space

★ = Potential international partner



Science Value

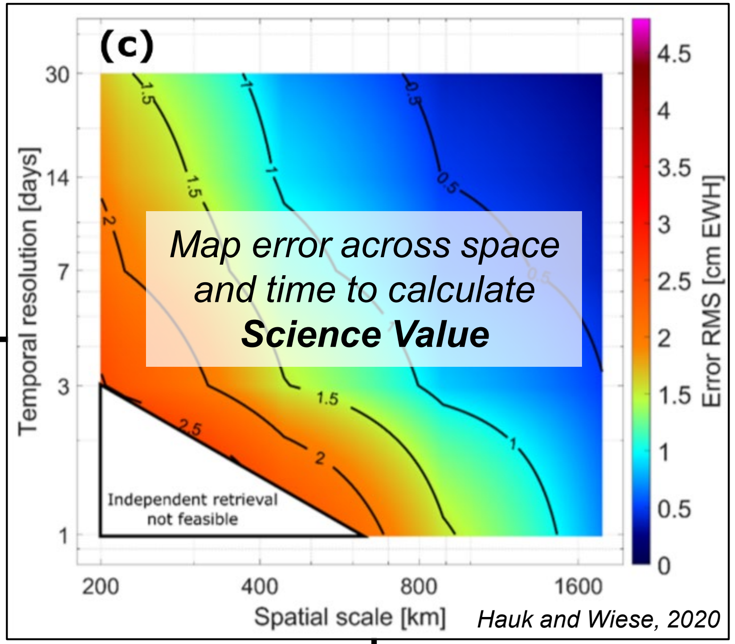
A Quantitative Framework to Assess Science Value

- Value of each architecture as it relates to the SATM is assessed using an **Observing System Simulation Experiment** (OSSE)
- OSSEs:
  - Utilize high-fidelity numerical simulations
  - Assess the integrated observing system performance
  - Have high heritage from previous missions and studies; used broadly in literature for 25+ years
  - Leverage operational software from Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) science data processing
  - Require large computing resources: ~500,000 central processing unit (CPU) hours for MC simulations; 100 TB data storage
  - Solve a large linear least-squares inversion in which analytical partial derivatives relate the observations to the parameters of interest (i.e., gravity field)

$$Ax = b$$

b = observations taken with the satellites
x = state parameters (~32,000 gravity field coefficients)
A = analytic partial derivatives

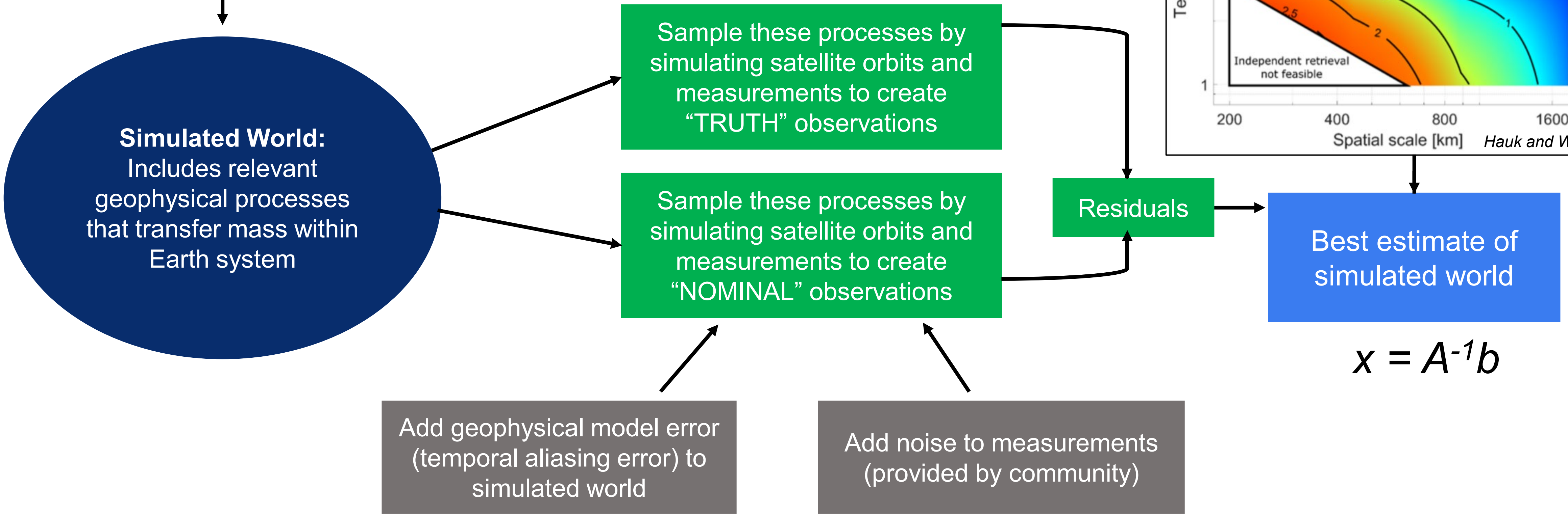
OSSE Overview: Science Value



Map error across space and time to calculate ***Science Value***

Hauk and Wiese, 2020

Compare estimate against the truth simulated world to quantify error



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

Residuals

Best estimate of simulated world

$$x = A^{-1}b$$

Add geophysical model error (temporal aliasing error) to simulated world

Add noise to measurements (provided by community)

Process has been widely used in the literature for mission formulation studies the previous 25+ years

A Quantitative Assessment of Science Value

Science Value (SV)

$$SV(a) = \frac{\sum_{n=1}^{15}(W_n)P_n^{OS}}{\sum_{n=1}^{15}(W_n)} = \frac{\sum_{n=1}^{15}(W_n)\frac{SR_n}{SR(a)}\frac{TR_n}{TR(a)}\frac{ACC_n}{ACC(a)}}{\sum_{n=1}^{15}(W_n)}$$

Overall SV accounts for all 15 objectives

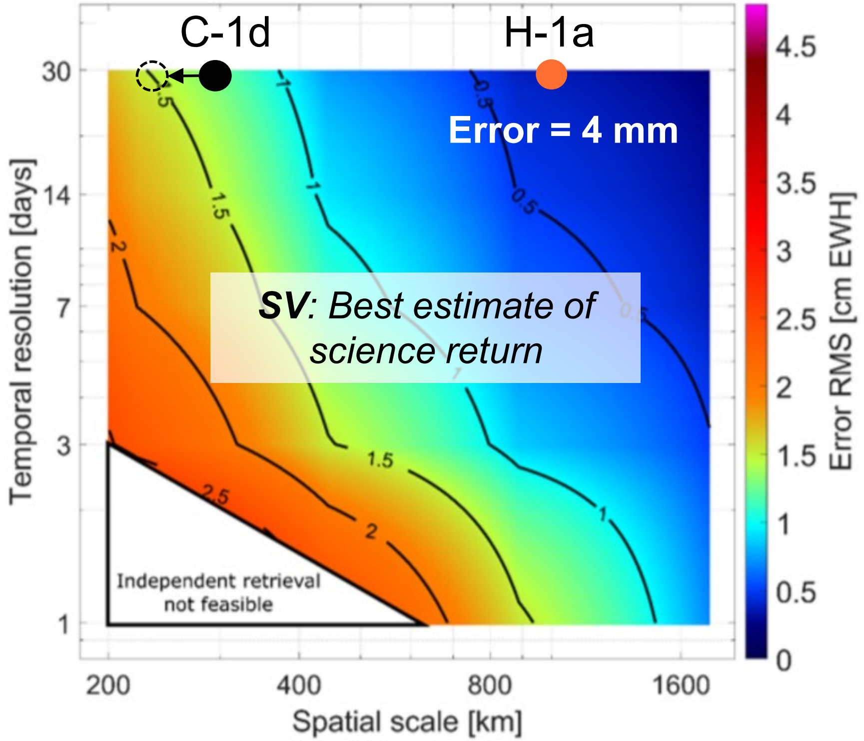
Key Variable: **Spatial Resolution**

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

$SV_{C\text{-}1d} = 0.67 * (300/225)^2 = 1.2$

W_n = *Importance$_n$ x Utility$_n$*
P_n^{OS} = *Performance of the Observing System*
SR = Spatial Resolution
TR = Temporal Resolution
ACC = Accuracy

Performance of Architecture α



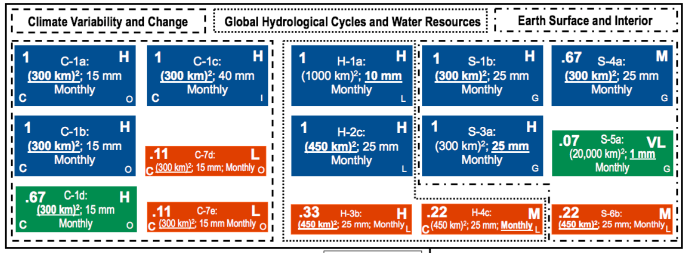
Hauk and Wiese, Earth and Space Science, 2020

Key Variable: **Accuracy**

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

$SV_{H\text{-}1a} = 1 * 10/4 = 2.5$

SATM Measurement Parameters for Baseline



Climate Variability and Change

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

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

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

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

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

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

Global Hydrological Cycles and Water Resources

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

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

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

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

Earth Surface and Interior

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

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

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

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

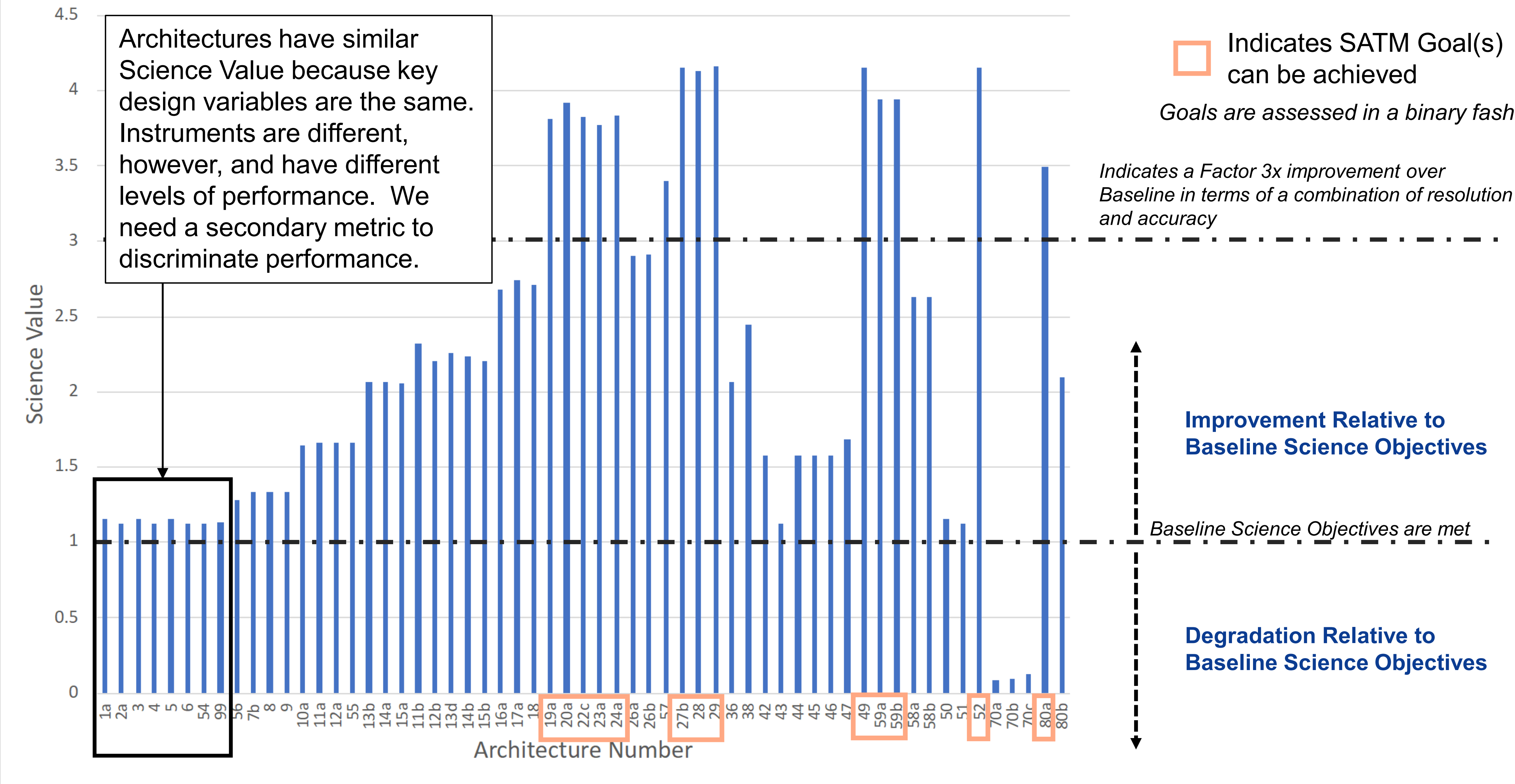
.22 S-6b: **M** (450 km)^2; 25 mm; Monthly L

Slide includes animation—best viewed in Slide Show mode

Interpretation: Science Value

- **Science Value:** Best estimate of science return given the current state of art in data processing
  - Value of 1 means the baseline science objectives are satisfied
  - Value of 2 means the baseline science objectives are exceeded by a factor of 2 (some combination of the measurement characteristics [resolution/accuracy] are improved by a factor 2)
  - Values <1 mean the architecture does not satisfy the baseline science objectives

Results: Science Value



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.

Indicates SATM Goal(s) can be achieved

Goals are assessed in a binary fashion

Indicates a Factor 3x improvement over Baseline in terms of a combination of resolution and accuracy

Improvement Relative to Baseline Science Objectives

Baseline Science Objectives are met

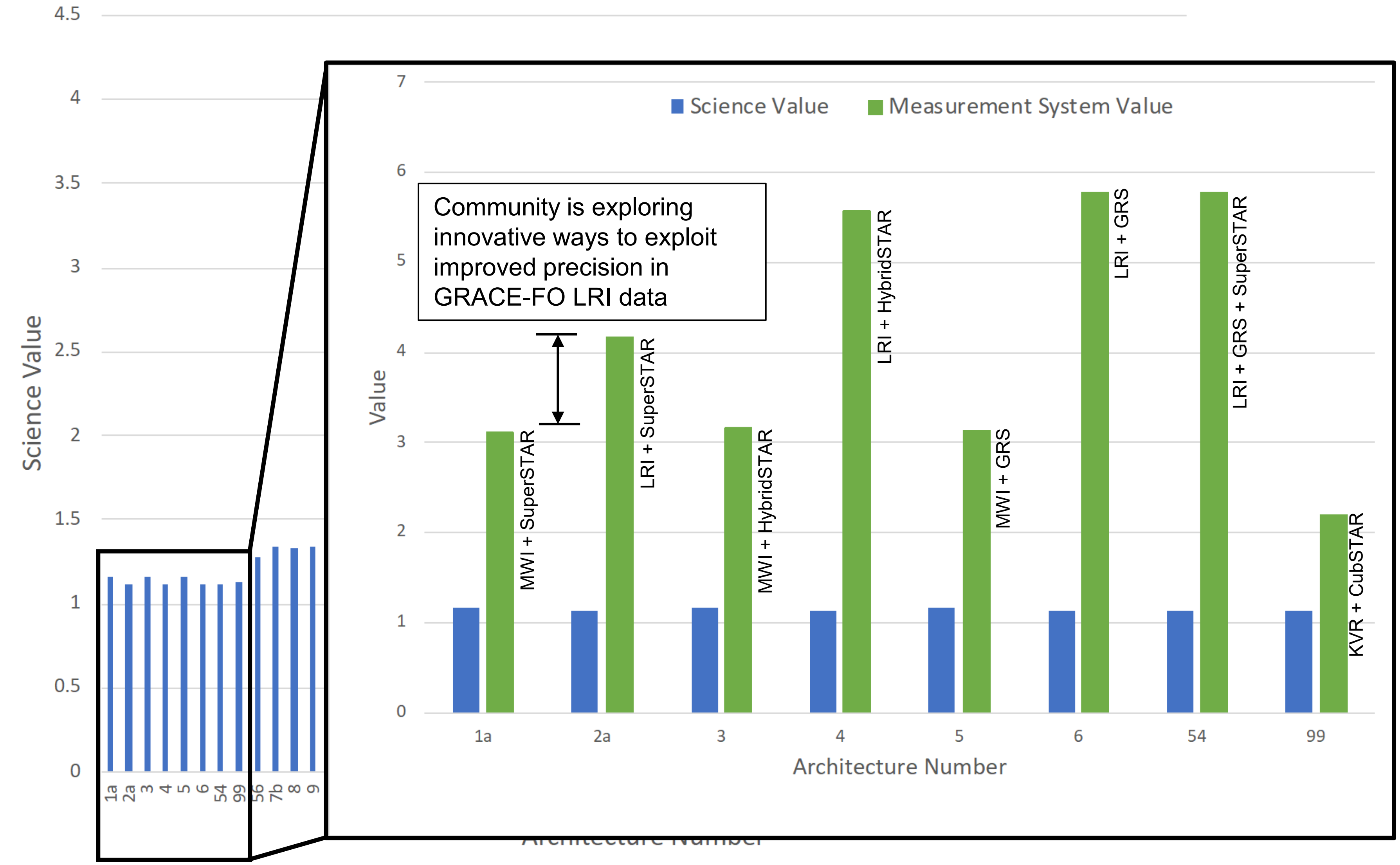
Degradation Relative to Baseline Science Objectives

Slide includes animation—best viewed in Slide Show mode

Measurement System Value: A Secondary Discriminator

- **Measurement System Value:** Best estimate of performance of the measurement system
  - The performance of the measurement system is not the limiting source of error for mass change missions
  - Due to limited spatiotemporal sampling of all architectures studied, models of high frequency mass variations (example: ocean tides) must be relied upon during the data processing, because we do not sample quickly enough to measure them directly. Errors in these models – called *temporal aliasing errors* – limit the Science Value
  - As models of high-frequency mass variations improve, and our ability to mitigate their impact on the gravity solution improves, Science Value will increase in the future, but will reach a ceiling due to the measurement system performance
  - Addition of this metric was recommended by the community
  - Measurement System Value is quantified using the same procedure as used for Science Value, except the OSSE only includes measurement system errors. Errors in models of high-frequency mass variations (i.e., temporal aliasing error) are not included in the numerical simulation
- **Measurement System Value represents the ceiling on Science Value in future data reprocessing**

Measurement System Value Results: A Secondary Discriminator



Community is exploring innovative ways to exploit improved precision in GRACE-FO LRI data

Measurement System Value becomes a discriminator among architectures with similar Science Value

GRS	Gravitational Reference Sensor
KVR	K-/V-band Ranging
LRI	Laser Ranging Interferometer
MWI	Microwave Interferometer

Slide includes animation—best viewed in Slide Show mode

Science Value: Key Takeaways

1. This methodology allows for a direct relation of the capabilities of an observing system architecture to the SATM, and hence, the Decadal Survey
2. A quantitative numerical framework (OSSE) is used to assess the Science Value – high heritage and confidence in this process
3. Science Value is the primary discriminator and represents the best estimate of the quality of the science data products given the current state-of-the art in data processing
4. Measurement System Value defines the quality of the measurement system, ultimately an upper bound on Science Value as data processing methods continue to mature, and is used as a secondary discriminator among architectures with similar Science Value

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6. Assessment Against Value Framework

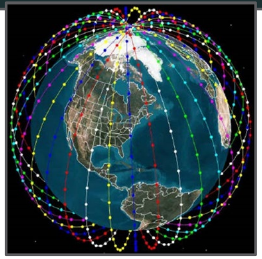
Phase 2 Assessment
Ground Rules/Assumptions

- Architecture performance based on science and applications metric
- Spacecraft/instrument sizing
  - Combination of concurrent engineering studies and engineering models
  - Implementation consistent with Class C (3-year design lifetime, 5-year consumables)
- Cost estimation
  - Contracted with The Aerospace Corporation for cost estimates
  - Combination of parametric- and analogy-based cost models process for cost risk including design uncertainty
  - Phase A–E estimates in FY18 for comparison with target
  - Launch costs assumed dedicated vehicles, estimated at $100M per orbit
- Schedule estimates
  - Phase durations developed based on mission analogies
  - Includes estimated time to achieve Technology Readiness Level (TRL) prior to Preliminary Design Review (PDR) based on current TRL status
  - Results as probabilistic S-curves
- Risks identification
  - Cost risks included in architecture cost estimates
  - Programmatic and schedule risks assessed against Program of Record (POR) and timelines with international partner opportunities
  - Performance/science risks based on component heritage, measurement techniques, and technology maturity

Architectures & Technology—Tradespace

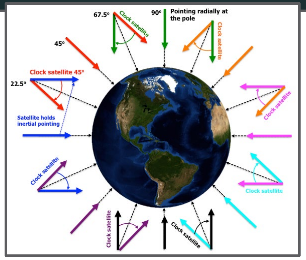
SST
Satellite-to-satellite tracking

POD
Precise orbit determination



Inclination	Altitude	# Sats	Accel.
🟦 ~90°	🟦 ~500 km	🟦 ~25	🟦 ES
🟦 ~70°	🟦 ~350 km	🟦 ~50	🟦 Opto.
	LEO/ MEO	🟦 ~100	

GG
Gravity gradiometer



Inclination	Altitude	# Sats
🟦 ~90°	🟦 ~500 km	🟦 1
🟦 ~70°	🟦 ~350 km	🟦 2
	LEO/ MEO	

Single in-line pair

Inclination	Altitude	Ranging	Accel.
🟦 ~90°	🟦 ~500 km	🟦 MWI	🟦 ES
~70°	🟦 ~350 km	🟦 LRI	🟦 Hybrid
	LEO/ MEO	Freq. Comb	🟦 GRS
		µNPRO /KVR	Opto.

★ DLR/GFZ

Pendulum pair or In-line pair + pendulum

Inclination	Altitude	Ranging	Accel.
🟦 ~90°	🟦 ~500 km	MWI	🟦 ES
~70°	🟦 ~350 km	🟦 LRI	🟦 Hybrid
	LEO/ MEO	🟦 Freq. Comb	🟦 GRS
		µNPRO /KVR	Opto.

★ CNES

Two in-line pairs (Bender)

Inclination	Altitude	Ranging	Accel.
🟦 ~90°	🟦 ~500 km	🟦 MWI	🟦 ES
🟦 ~70°	🟦 ~350 km	🟦 LRI	🟦 Hybrid
	LEO/ MEO	Freq. Comb	🟦 GRS
		µNPRO /KVR	Opto.

★ ESA

LEO/MEO concept

Inclination	Altitude	Ranging	Accel.
🟦 ~90°	~500 km	MWI	🟦 ES
~70°	~350 km	🟦 LRI	🟦 Hybrid
	🟦 LEO/ MEO	Freq. Comb	🟦 GRS
		µNPRO /KVR	Opto.

N-pair SmallSats

Inclination	Altitude	Ranging	Accel.
🟦 ~90°	🟦 ~500 km	🟦 MWI	🟦 ES
🟦 ~70°	🟦 ~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		🟦 µNPRO /KVR	🟦 Opto.

🟦 Highlighted boxes = Orbit and technology trade space

★ = Potential international partner

µNPRO	micro non-planar ring oscillator
CNES	Centre National d'Études Spatiales
DLR	Deutsches Zentrum für Luft-und Raumfahrt
ES	Electro-static
ESA	European Space Agency
GFZ	German Research Centre for Geosciences
GRS	Gravitational Reference Sensor
KVR	K-/V-band ranging
LEO	low Earth orbit
LRI	Laser Ranging Interferometer
MEO	medium Earth orbit
MWI	Microwave Interferometer

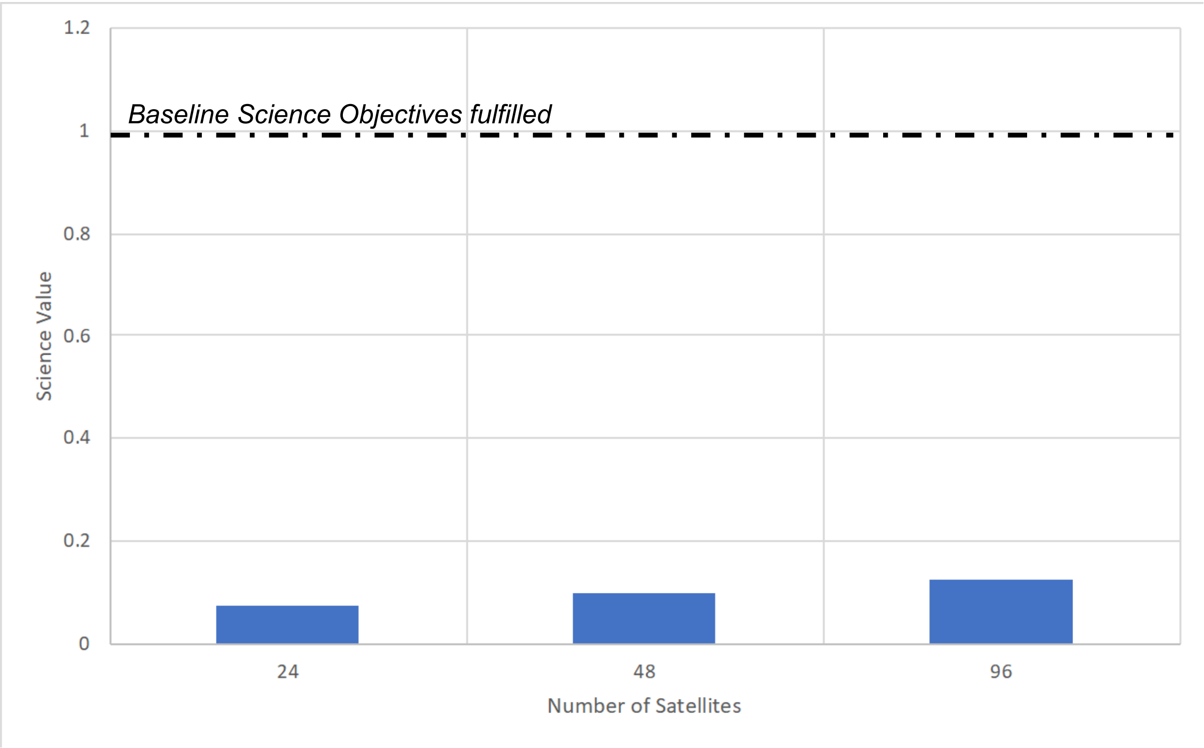
Precise Orbit Determination (POD)

Key takeaway:

- POD is not a replacement for GRACE-type missions and is not capable of meeting the Mass Change (MC) Science and Applications Traceability Matrix (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 Designated Observable (DO) team science and applications assessment validated the community assessment that POD is not a viable MC candidate architecture

POD science value assessment

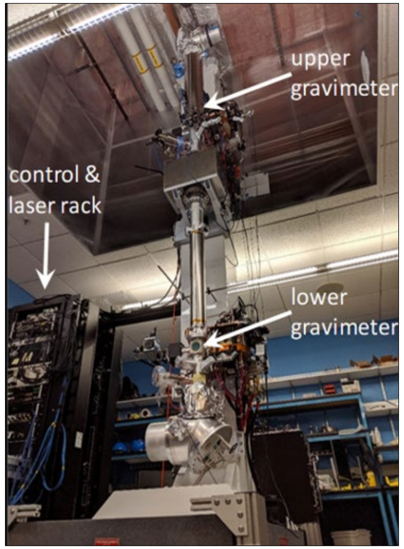


Atomic Interferometer Gravity Gradiometer

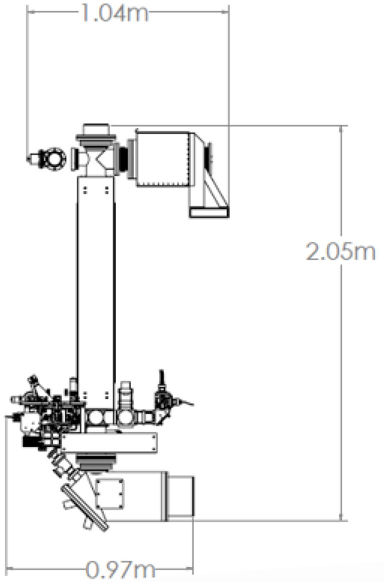
Atomic interferometer gravity gradiometer (AIGG) has high science performance but long/uncertain path to TRL 6

- AOSense, Inc. lab instrument developed with NASA GSFC
  - Currently TRL 4; path to TRL 6 TBD
- GSFC Instrument Design Lab (IDL) study conducted June 1–5, 2020
  - First AIGG flight instrument design
  - Identified challenges
    - Laser components will likely need development to reduce power
    - Some lab components (radio frequency [RF] and laser) lack spaceflight equivalents
    - Challenging to test instrument flight performance in a terrestrial environment
- GSFC Mission Design Lab (MDL) study conducted March 1–8, 2021
  - Technology demonstration mission: spacecraft, instrument, concept of operations (ConOps)
    - 500 km altitude
    - 1,162 kg mission launch mass; 841 W average power
  - Time-variable gravity (TVG) recovery performance commensurate to the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO)
    - Radial (zz) gradient measurement; < 75 μE sensitivity

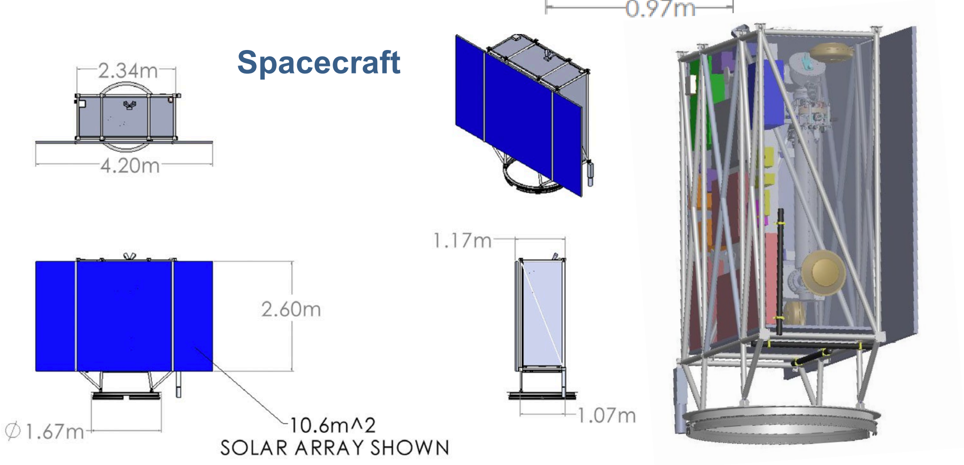
AOSense Lab Instrument



Flight Instrument

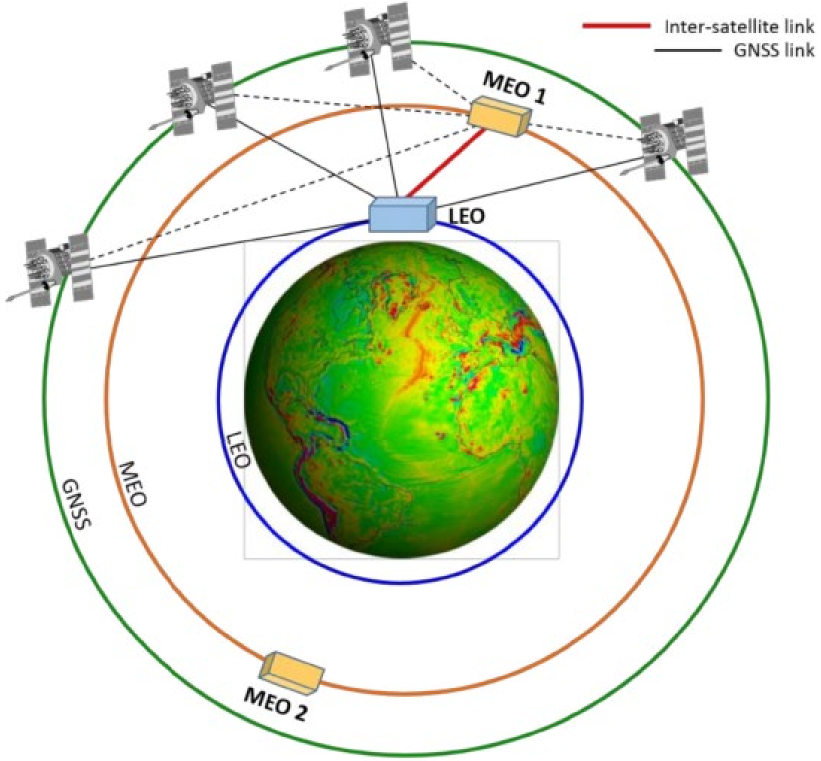


Spacecraft



LEO/MEO Ranging Concepts

- Candidate observing systems leveraging ranging between low Earth orbit (LEO) and medium Earth orbit (MEO) were included in Phase 1 and considered early in Phase 2
- A number of challenges were identified that made them impractical and unfavorable for the next MC mission
  - Laser power for the ranging systems was likely to be constrained to minimize the likelihood of impacting operation of other space assets
  - Performance estimates of observing systems leveraging LEO/MEO ranging were similar to the performance of a single in-line pair
- Candidate architectures using LEO/MEO ranging resulted in additional risks and challenges not present for single in-line pair architectures but without any significant increase in expected performance



SST SmallSats—Summary of Engineering Design Study

- JPL Team X is a “*cross-functional multidisciplinary team of engineers that utilizes concurrent engineering methodologies to complete rapid design, analysis and evaluation of mission concept designs*” – conducted May 2020 over four days

- 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)

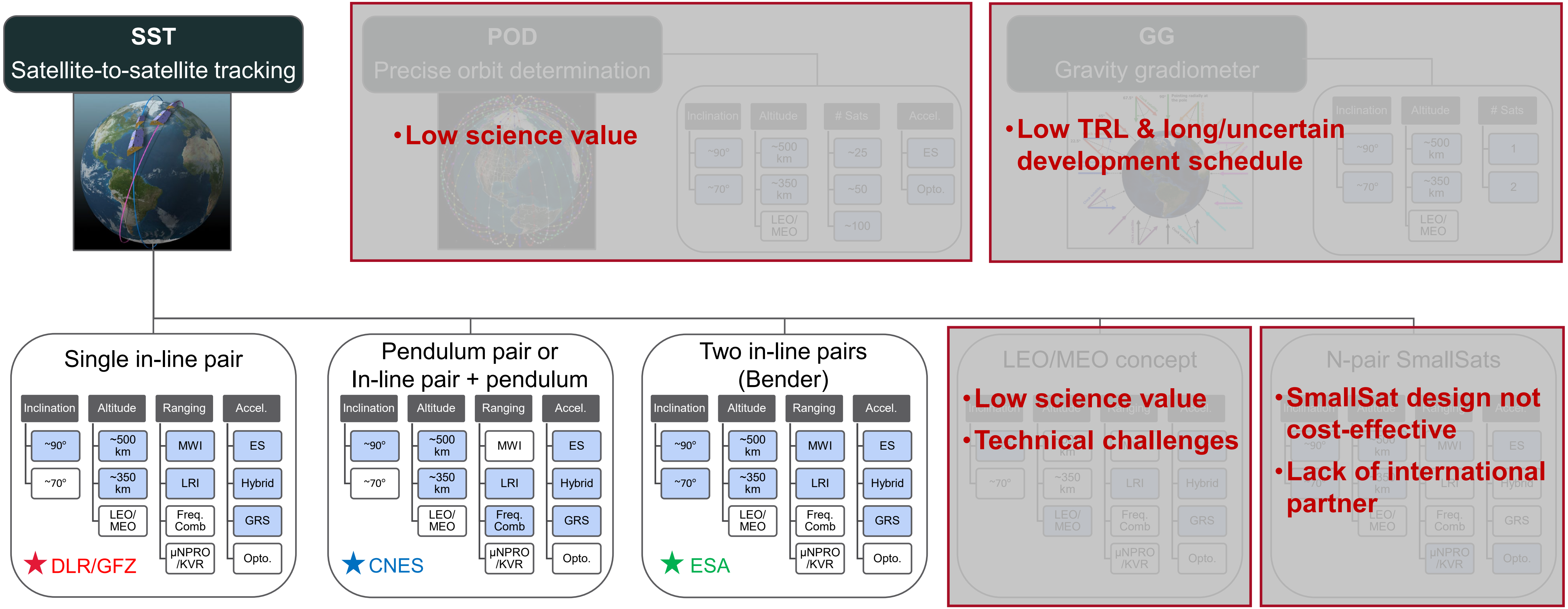
- Team X architectures:

Option 1: Dual string with heritage bus components
Redundancy: Dual string
Mass: ~430 kg
Phase A–E cost: ~$500M FY18

Option 2: Single string with SmallSat bus components
Redundancy: Single string
Mass: ~190 kg
Phase A–E cost: ~$420M FY18

- Team X major conclusions **(key takeaways)**
  - 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

Architectures & Technology—Tradespace



SST
Satellite-to-satellite tracking

POD
Precise orbit determination

- Low science value

Inclination	Altitude	# Sats	Accel.
~90°	~500 km	~25	ES
~70°	~350 km	~50	Opto.
	LEO/ MEO	~100	

GG
Gravity gradiometer

- Low TRL & long/uncertain development schedule

Inclination	Altitude	# Sats
~90°	~500 km	1
~70°	~350 km	2
	LEO/ MEO	

Single in-line pair

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

★ DLR/GFZ

Pendulum pair or In-line pair + pendulum

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

★ CNES

Two in-line pairs (Bender)

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

★ ESA

LEO/MEO concept

- Low science value
- Technical challenges

Inclination	Altitude	Ranging	Accel.
	km		
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

N-pair SmallSats

- SmallSat design not cost-effective
- Lack of international partner

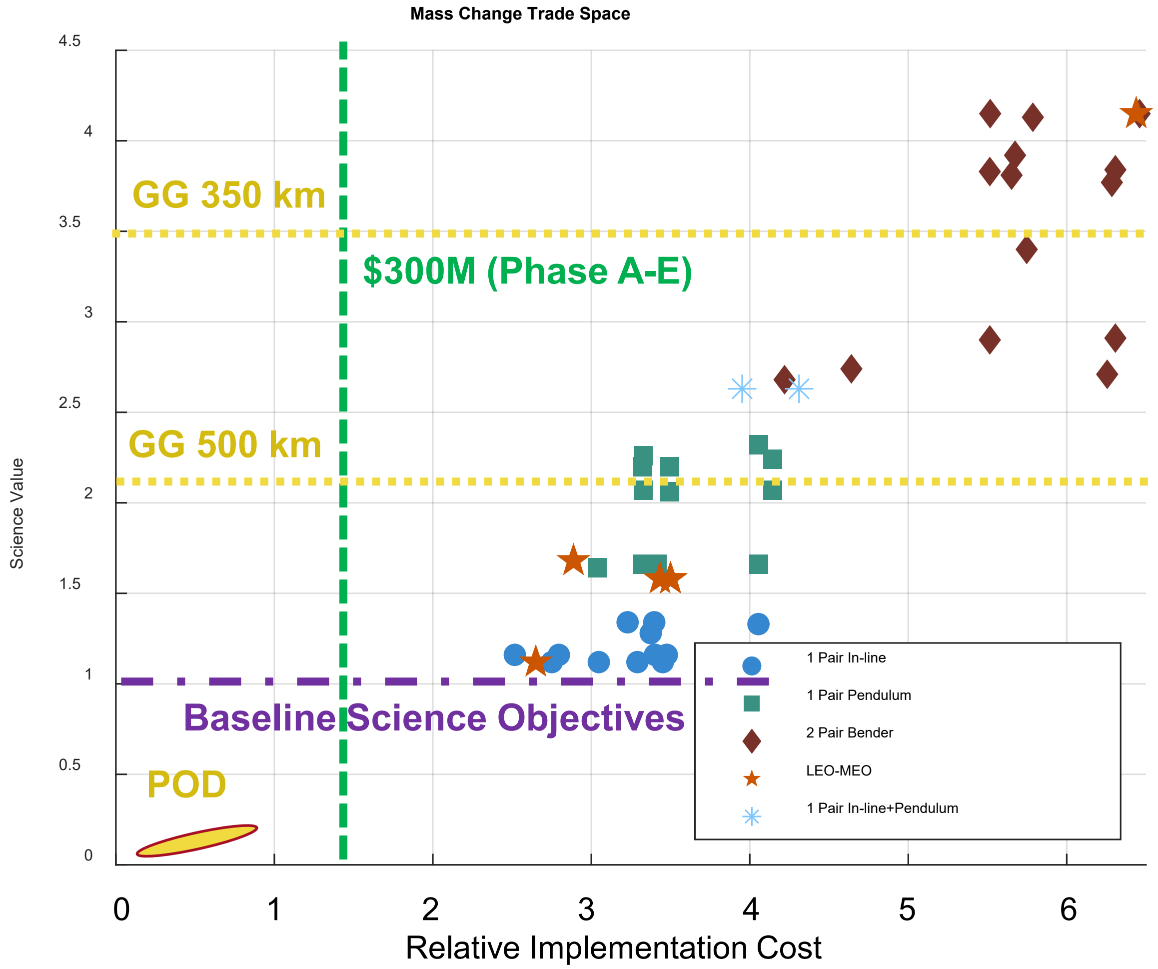
Inclination	Altitude	Ranging	Accel.
~90°	km	MWI	ES
~70°	km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

Highlighted boxes = Orbit and technology trade space

★ = Potential international partner

MC Tradespace Analysis (1/3)

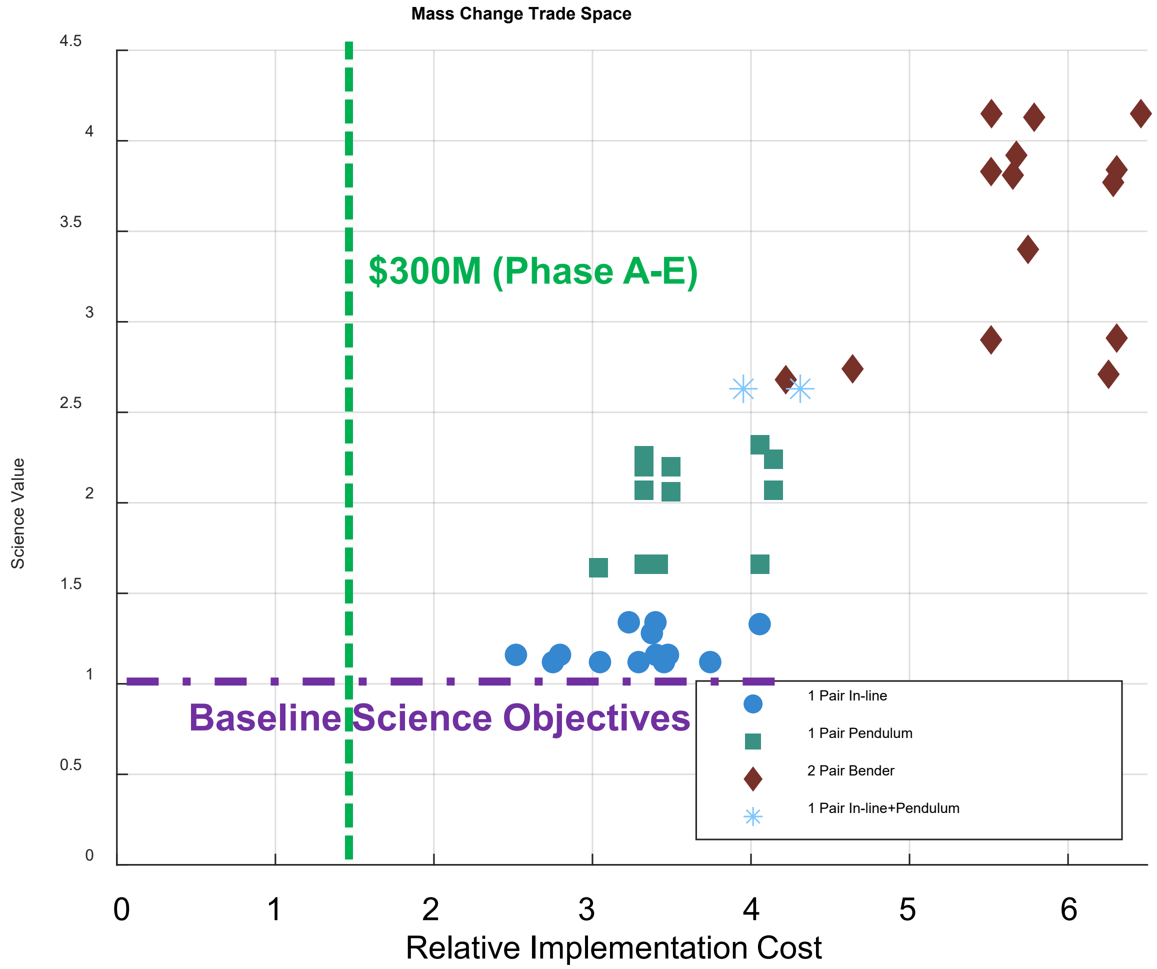
- Full tradespace from study Phase 1 is shown in figure. From this, the following architectures are pruned:
  - POD: poor performance even for large scale multi-element system implementation
  - GG: high performance ceiling but unclear maturation plans
  - LEO-to-MEO: technical challenges associated with laser power restrictions; low relative science value
- Remaining SST architectures studied during Phase 2 in various configurations (shown on next slide)
  - Single pair in-line (GRACE-like)
  - Single pair pendulum (satellites in different planes)
  - Two pair Bender (pairs with different orbit inclination)
  - Combined in-line and pendulum



*Costs shown do not include workshare with potential international partners

MC Tradespace Analysis (2/3)

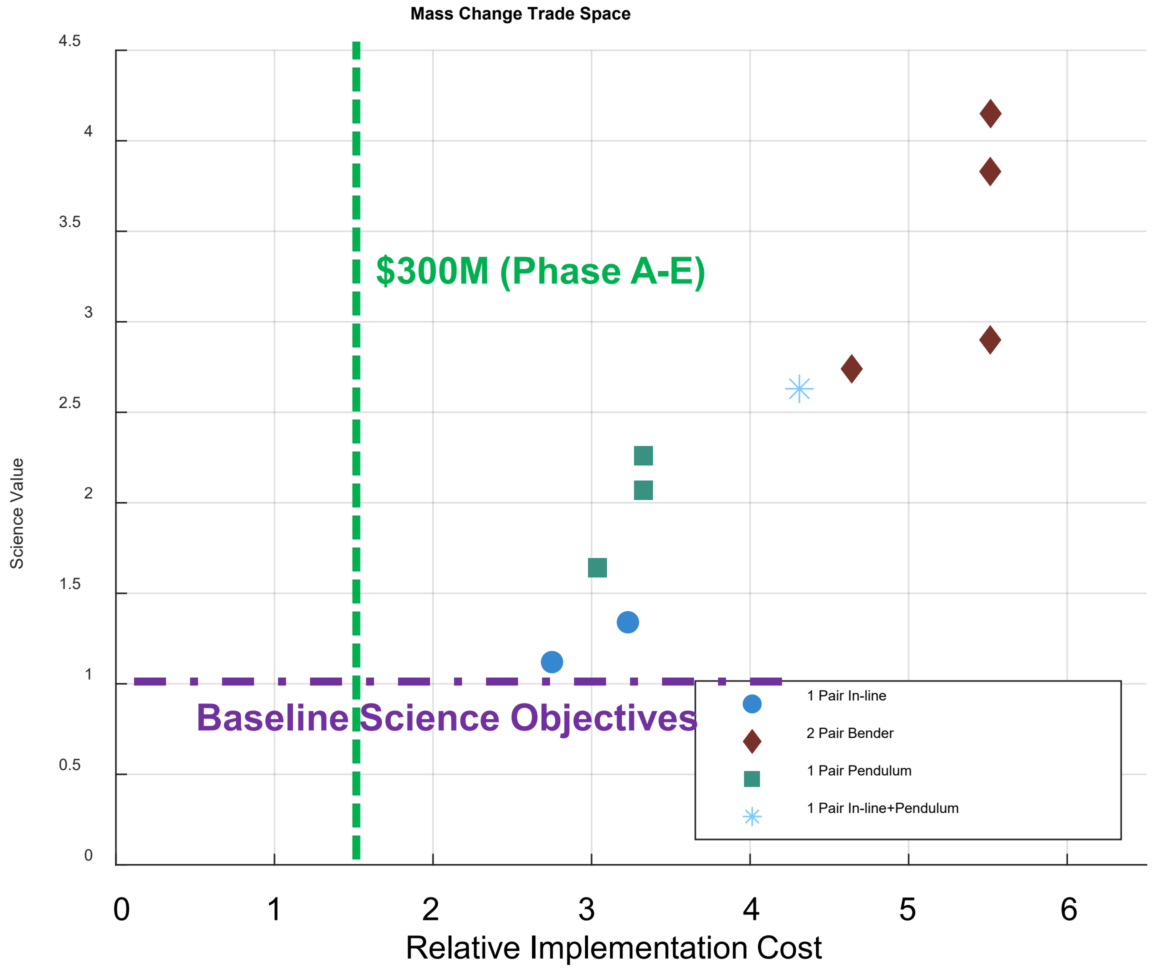
- Variation in cost and performance estimates within architecture families is driven by instrument and technology options (accelerometer, ranging system, drag compensation) and orbital parameters (altitude, inclination, pendulum opening angle)
  - Ranging system: MWI/LRI
  - Accelerometers: SuperSTAR, MicroSTAR, gravitational reference sensor (GRS), HybridSTAR, Optomechanical
  - Orbit altitude: 500 km altitude does not require drag compensation; 350 km altitude options do include drag compensation
- Architectures are pruned based on technology readiness and performance (measurement system value)
  - Accelerometers: GRS, HybridSTAR, Optomechanical unlikely to be ready for MC as primary accelerometers. Still potential technology demonstrator candidates
  - LRI preferred over MWI due to better performance (higher measurement system value) and successful technology demonstration on GRACE-FO
- Remaining SST architectures (next slide) include LRI ranging instrument and electrostatic accelerometers



*Costs shown do not include workshare with potential international partners

MC Tradespace Analysis (3/3)

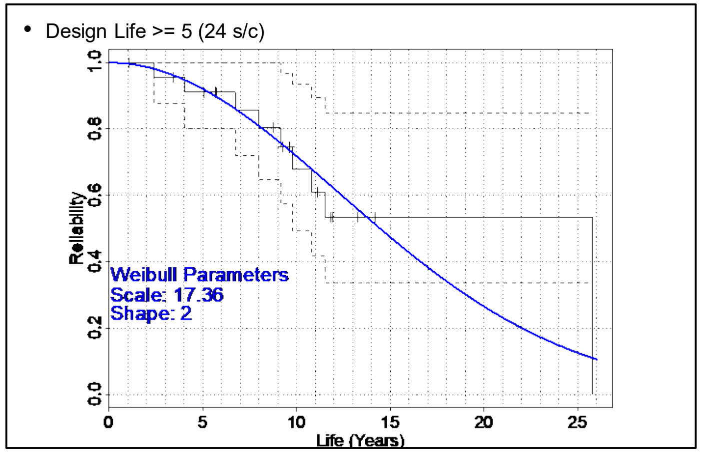
- Generally cost variation within families is driven by the included ranging and accelerometer components
- Performance is more driven by orbit configurations including altitude and inclination

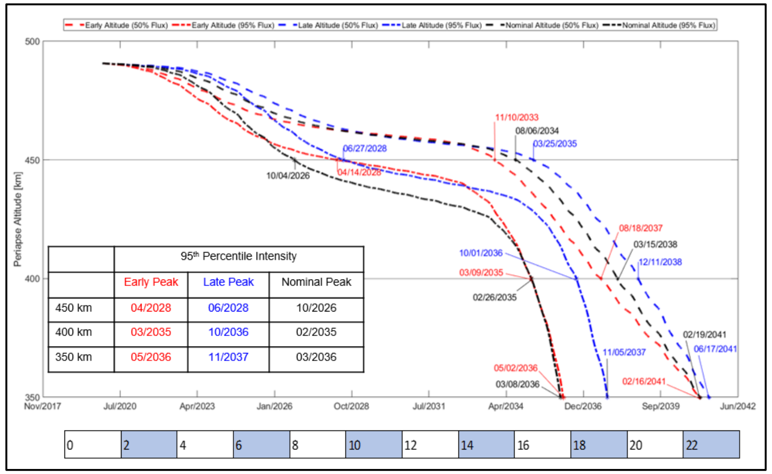


*Costs shown do not include workshare with potential international partners

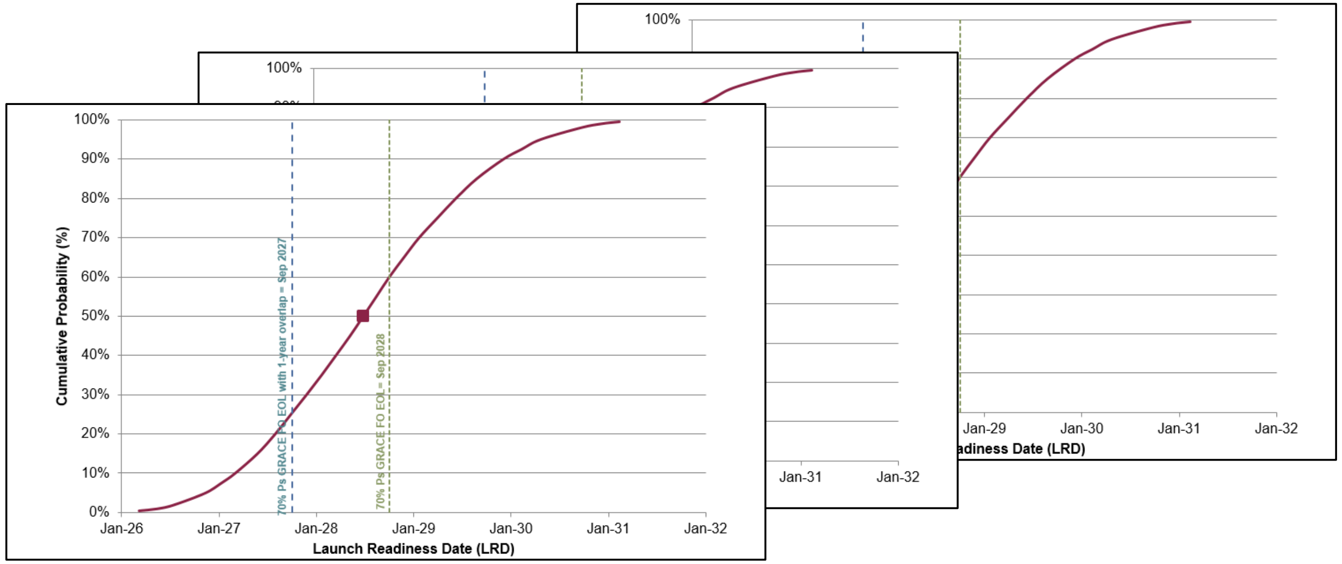
Continuity with GRACE-FO

- GRACE-FO lifetime estimated based on reliability and orbit lifetime
- Stochastic analysis provides a range of dates for GRACE-FO lifetime based on variation in solar flux predictions and historical spacecraft reliability
- Schedule estimates (“S” curves) generated for the MC candidate observing system architectures
  - Phase durations based on mission analogies
- Inputs from GRACE-FO team regarding planned spacecraft operations are combined with MC orbit lifetime analysis to define the likely MC observing system need date for continuity and compared with architecture readiness dates from MC schedule estimates


- Design Life >= 5 (24 s/c)

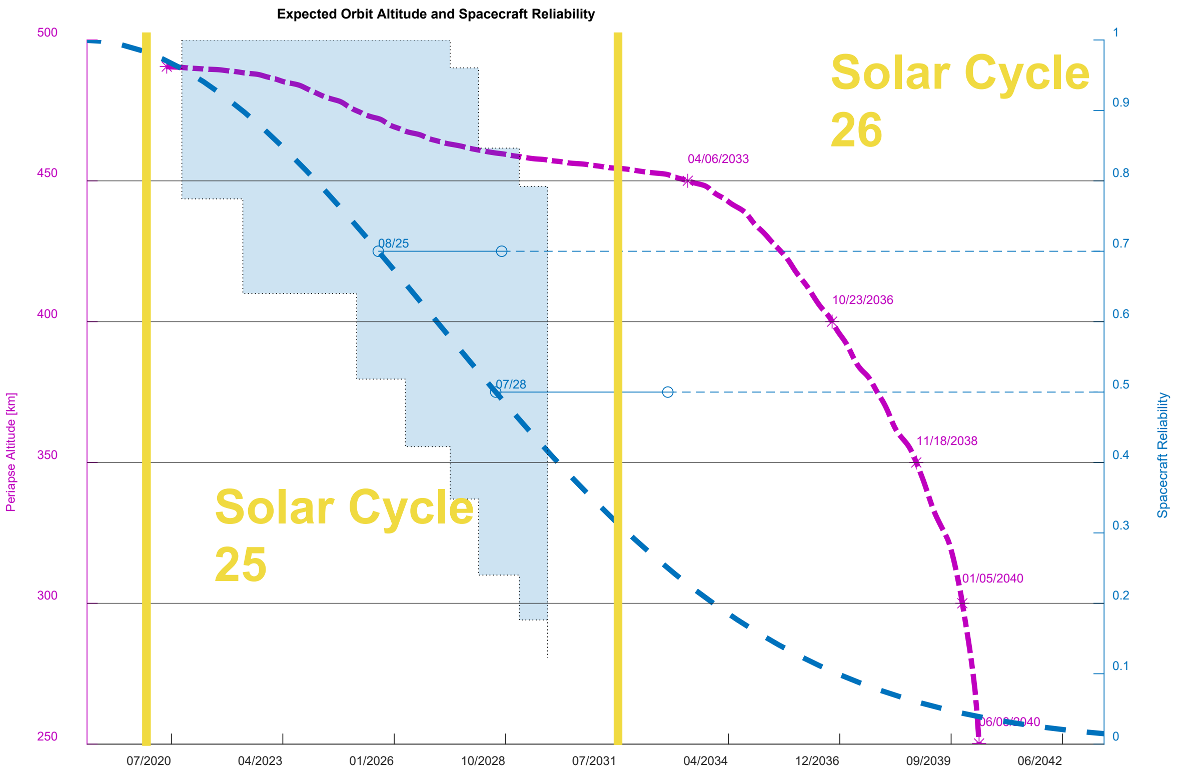


	95th Percentile Intensity		
	Early Peak	Late Peak	Nominal Peak
450 km	04/2028	06/2028	10/2026
400 km	03/2035	10/2036	02/2035
350 km	05/2036	11/2037	03/2036



GRACE-FO Orbit Lifetime and Expected Reliability

- Historical data for reliability of spacecraft with design life similar to GRACE-FO predicts 70th percentile lifetime through 2025–2028 and 50th percentile lifetime into 2028–2032
- Orbit lifetime predictions indicate GRACE-FO altitude is likely to remain above 450 km into the next decade
  - Solar cycle 25/26 forecast is currently similar in magnitude to cycle 24
  - Orbit altitude would decay faster if solar activity is stronger than expected for the current or next cycle
- Continuity between GRACE-FO and the mass change observing system is more likely driven by GRACE-FO reliability than orbit lifetime

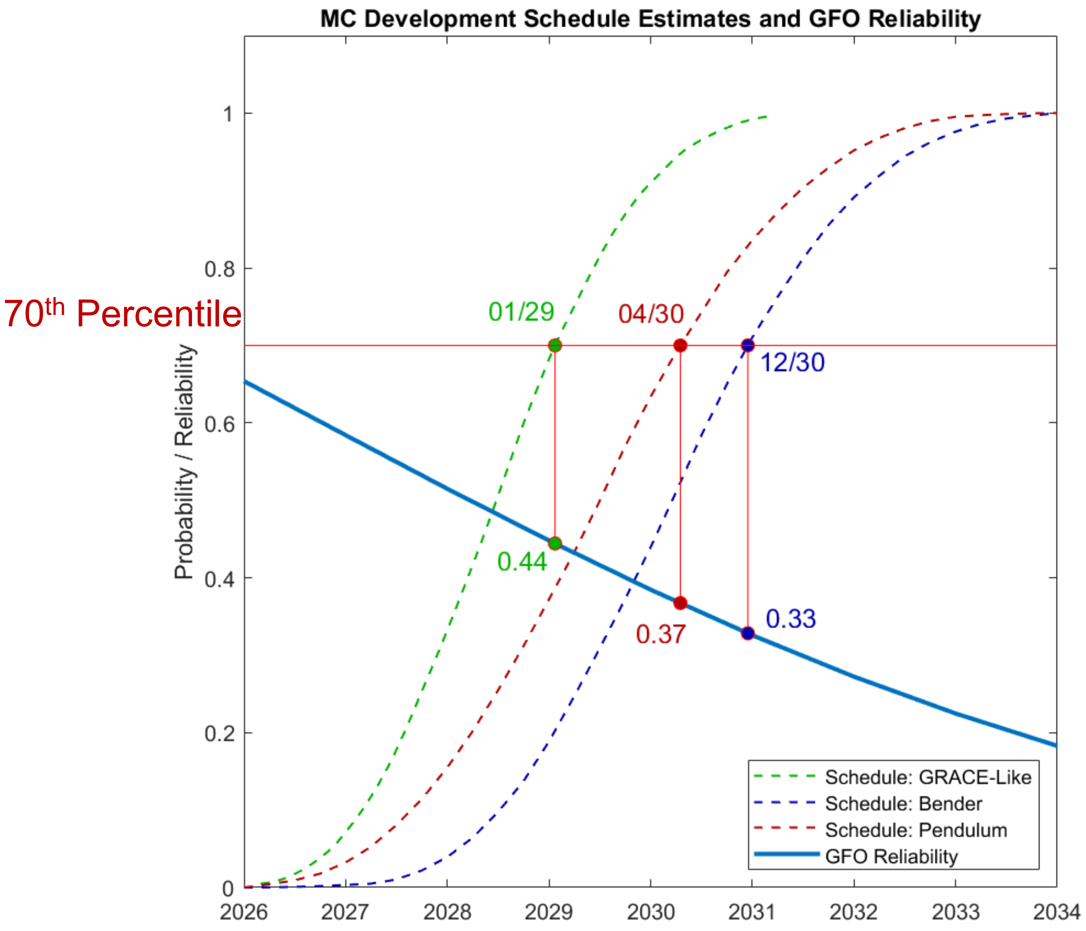


GRACE-FO Reliability and MC Schedule

- Schedule estimates indicate that the single in-line pair is likely to have the earliest launch readiness date and more likely to enable continuity with GRACE-FO
  - Schedule estimates based on parametric modeling and should be further refined

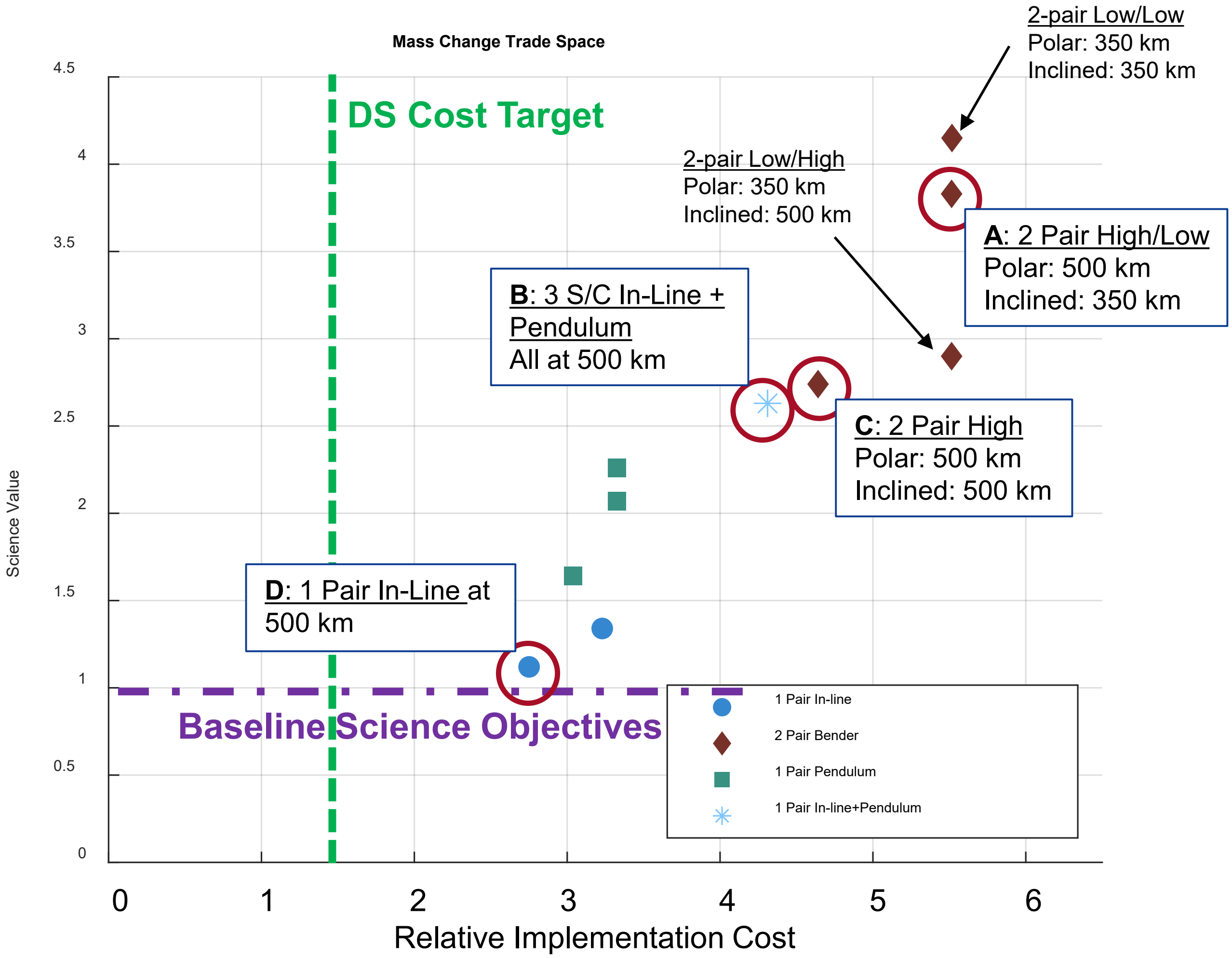
	Estimated 70th Percentile LRD	Expected GRACE-FO Reliability at LRD
Single In-Line	Jan 2029	44%
Pendulum	Apr 2030	37%
Bender	Dec 2030	33%

LRD launch readiness date



Identifying Architectures with the Highest Value—Improving Science Return while Enabling Continuity

- The Decadal Survey stressed the importance of continuity in mass change measurements
  - GRACE-FO lifetime is more likely to be limited by system reliability than orbit lifetime
  - Schedule estimates indicate that the single in-line pair is likely to have the earliest launch readiness date (LRD) and is most likely to enable continuity with GRACE-FO
- Architectures (A, B, C, D) are identified which have at least one component that include a single in-line polar pair to allow the highest likelihood of continuity with GRACE-FO
  - Implementation of B, C, D may be staggered; Architecture A can be launched first with remaining elements launched later
- Architecture D (2-pair high/low) provides only slightly degraded science value relative to highest performing architecture (2-pair low/low)
  - Placing the inclined satellite in a lower altitude provides primary increase in science value
- A, B, C, D are compatible with international interests



MC Architecture Study Status

- MC has transitioned to Pre-Phase A
  - See next talk by Charley Dunn
- Architecture Study Team has delivered final report to NASA HQ
- Two journal articles are in preparation
  - 1) Overview of study and main conclusions
  - 2) In-depth comparison of architecture options to recovery time variable gravity