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The NASA Mass Change Designated Observable Study: Progress and Future Plans

The Mass Change Designated Observable Study Team[1,2,3,4,5]

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[5]NASA Headquarters, Washington, DC, United States

EGU General Assembly, 30 April 2021

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

NASA Mass Change Designated Observable Study

The Committee on the Decadal Survey for Earth Science and Applications from Space (ESAS) of the National Academies of Sciences, Engineering and Medicine (NASEM) released the US Decadal Survey, “Thriving on Our Changing Planet: A Decadal Strategy for Earth Observations from Space.” in January 2018.

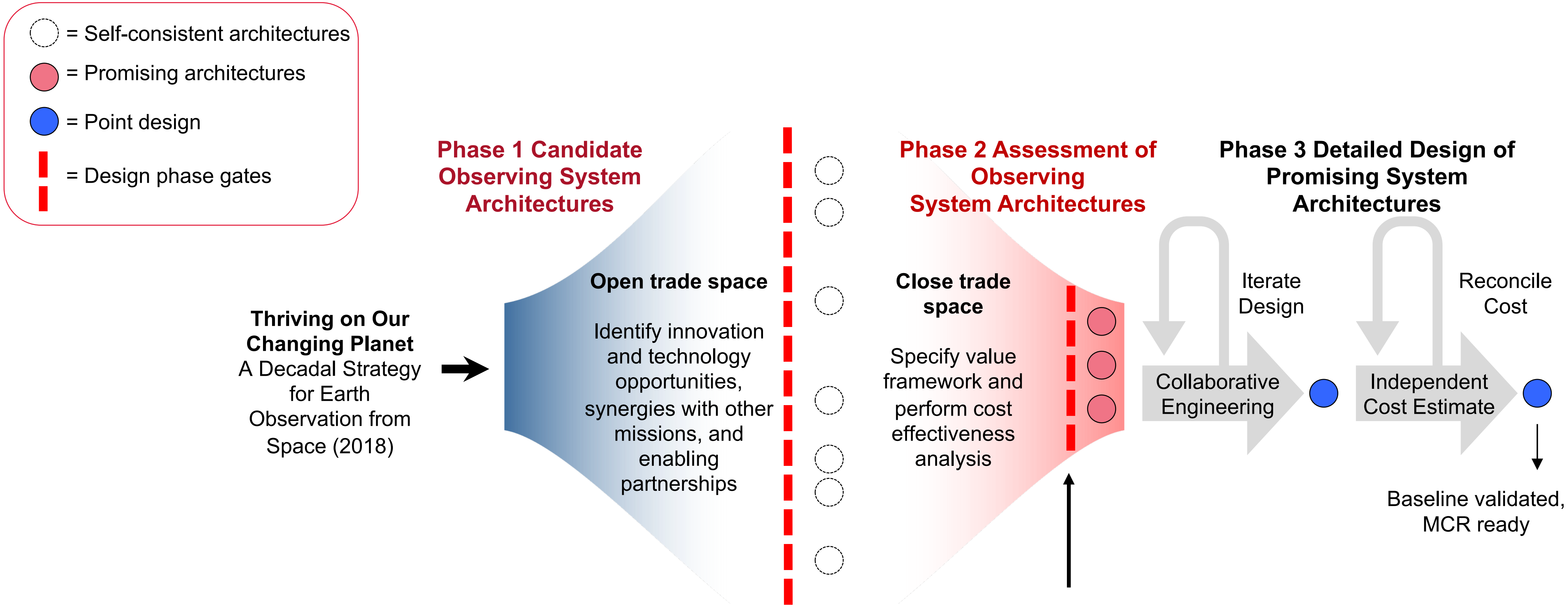
- A “new” program element for cost-capped medium- and large-size missions/observing systems to address observables essential to the overall program
- Addresses five of the highest-priority Earth observation needs, suggested to be implemented among three large missions and two medium missions. Elements of this program are considered foundational elements of the decade’s observations.
- **Mass Change** observations included among five *Designated Observables*
- Climate, Hydrology, and Solid Earth panels recommended **Mass Change Observing System**
  - NASA Initiated 4 multi-center studies in 2018 to investigate observing system architectures, considering synergies with other observations, accelerating research and applications and partnerships.

CONSENSUS STUDY REPORT

THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space

MC Study Phases



◌ = Self-consistent architectures

🔴 = Promising architectures

🔵 = Point design

▮ = Design phase gates

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

Phase 1 Candidate Observing System Architectures

Open trade space

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

Phase 2 Assessment of Observing System Architectures

Close trade space

Specify value framework and perform cost effectiveness analysis

Phase 3 Detailed Design of Promising System Architectures

Iterate Design

Collaborative Engineering

Reconcile Cost

Independent Cost Estimate

Baseline validated, MCR ready

We are notionally here in the study process

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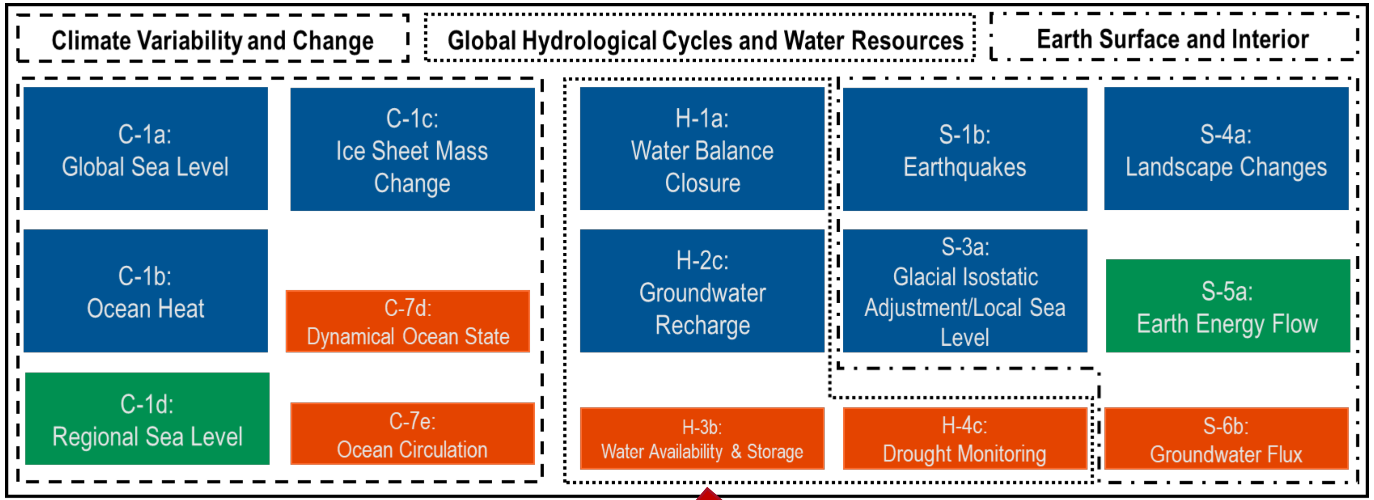
Science and Applications Traceability Matrix

Mass Change SATM Development

The development of the Mass Change Science and Applications Traceability Matrix was driven by the Decadal Survey 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

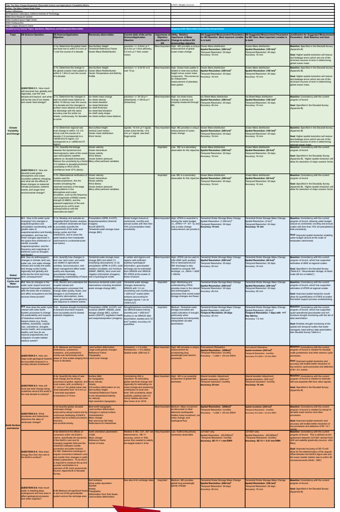
DS Prescribed Weights [Importance]

- Most Important Highest weight
- Very Important Medium weight
- Important Lower Weight

Expert Interpretation

Community Input and Vetting

SATM for Mass Change



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:

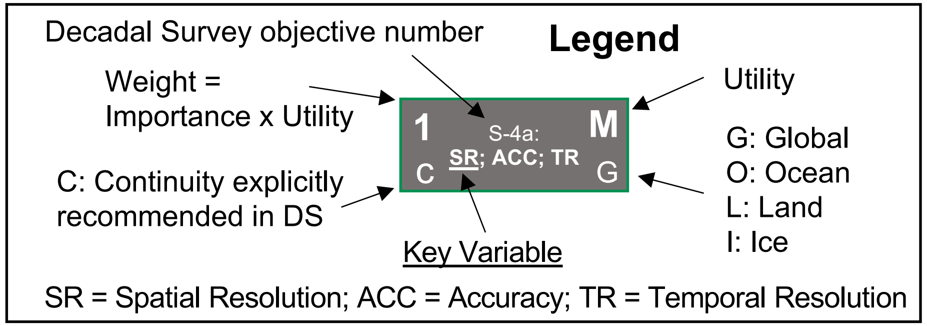
  Mass Change: Ensures continuity of measurements of groundwater and water storage mass change, land ice contributions to sea-level rise, ocean mass change, ocean heat content (when combined with altimetry), glacial isostatic adjustment, and earthquake mass movement. Also important for operational applications, 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" measurement parameters shown on next two slides
- 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, AGU town halls, availability of draft SATM, etc.)

Decadal Survey Science and Application Objectives for Mass Change

Measurement Parameters for Baseline

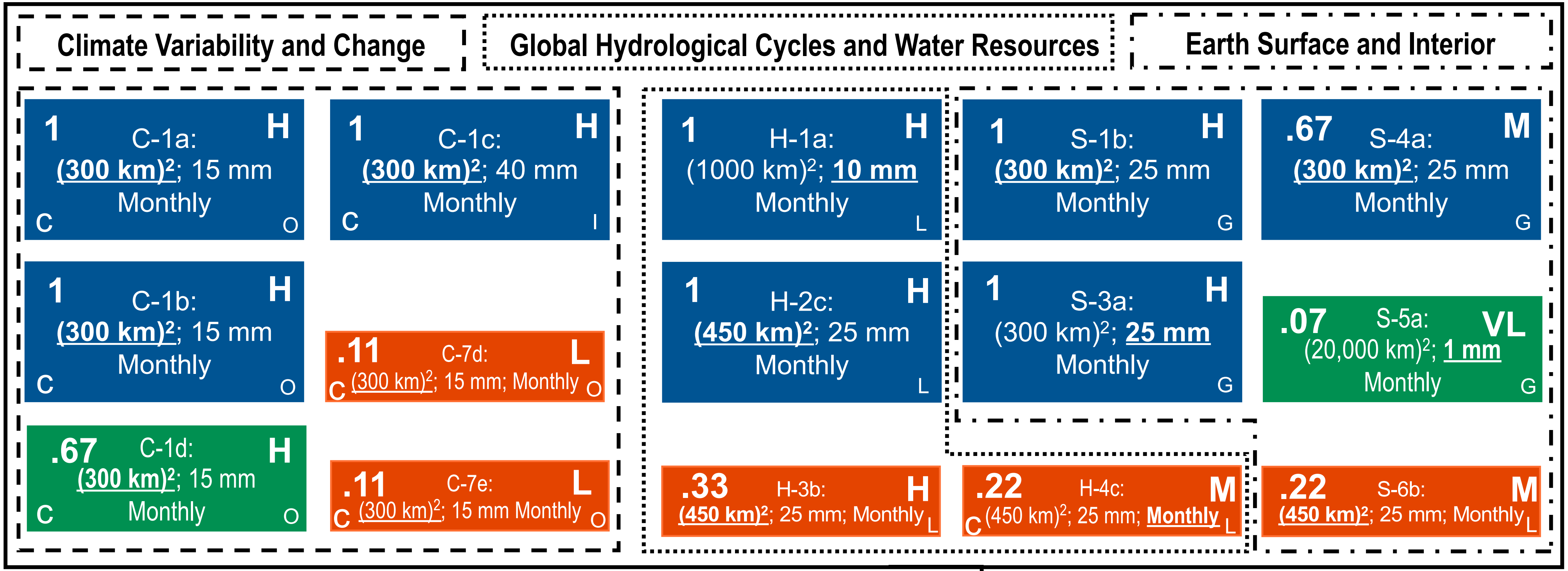
***Baseline** Observing System – supports full science objectives*



Legend

Decadal Survey objective number
Weight = Importance x 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-1b: (300 km)^2; 15 mm Monthly — H, C, O
- .67 C-1d: (300 km)^2; 15 mm Monthly — H, C, O
- 1 C-1c: (300 km)^2; 40 mm Monthly — H, C, I
- .11 C-7d: (300 km)^2; 15 mm; Monthly — L, 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
- 1 S-1b: (300 km)^2; 25 mm Monthly — H, G
- 1 S-3a: (300 km)^2; 25 mm Monthly — H, G
- .22 H-4c: (450 km)^2; 25 mm; Monthly — M, C, L

Earth Surface and Interior

- .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

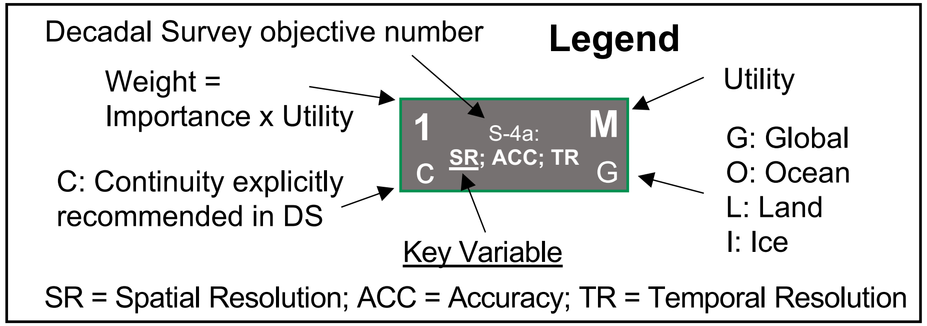
H: High	1.0
M: Medium	0.67
L: Low	0.33
VL: Very Low	0.10

→ Science Performance Targets

Decadal Survey Science and Application Objectives for Mass Change

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.*



Legend

Decadal Survey objective number

Weight = Importance x Utility

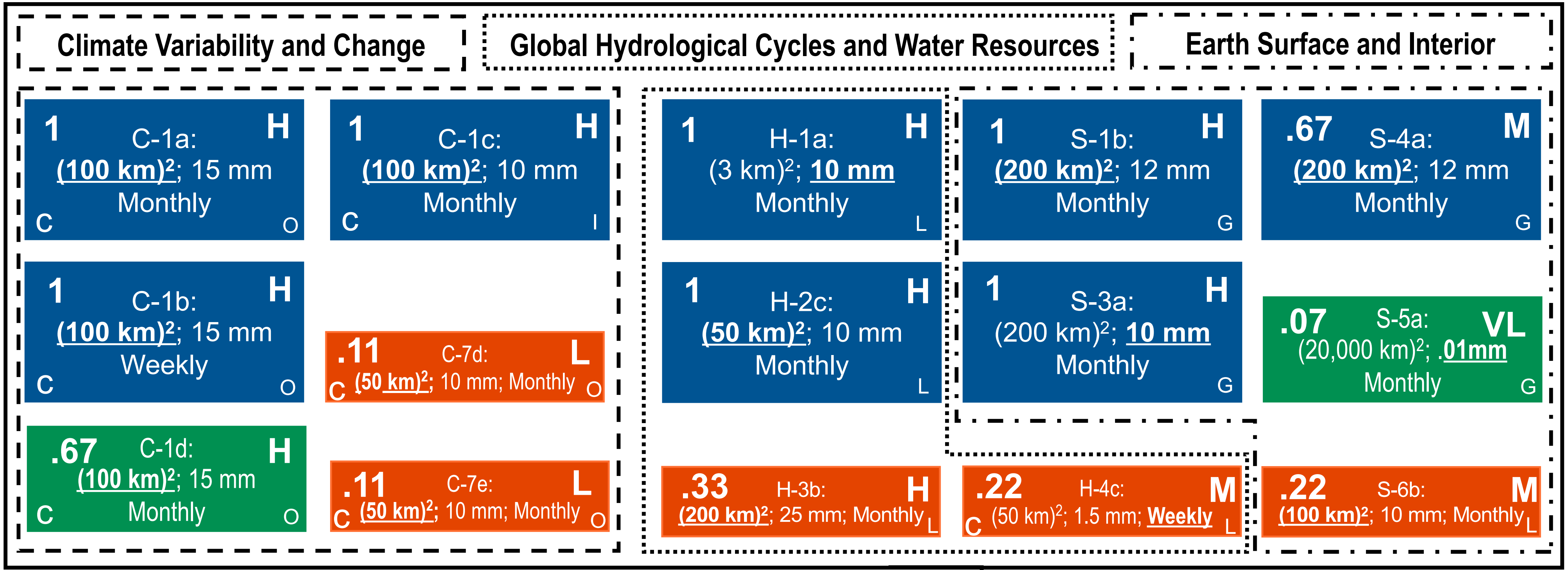
C: Continuity explicitly recommended in DS

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: (100 km)^2; 15 mm Monthly — H, C, O
- 1 C-1c: (100 km)^2; 10 mm Monthly — H, C, I
- 1 C-1b: (100 km)^2; 15 mm Weekly — H, C, O
- .11 C-7d: (50 km)^2; 10 mm; Monthly — L, C, O
- .67 C-1d: (100 km)^2; 15 mm Monthly — H, C, O
- .11 C-7e: (50 km)^2; 10 mm; Monthly — L, C, O

Global Hydrological Cycles and Water Resources

- 1 H-1a: (3 km)^2; 10 mm Monthly — H, L
- 1 H-2c: (50 km)^2; 10 mm Monthly — H, L
- .33 H-3b: (200 km)^2; 25 mm; Monthly — H, L
- .22 H-4c: (50 km)^2; 1.5 mm; Weekly — M, C, L

Earth Surface and Interior

- 1 S-1b: (200 km)^2; 12 mm Monthly — H, G
- 1 S-3a: (200 km)^2; 10 mm Monthly — H, G
- .67 S-4a: (200 km)^2; 12 mm Monthly — M, G
- .07 S-5a: (20,000 km)^2; .01mm Monthly — VL, G
- .22 S-6b: (100 km)^2; 10 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

Mass Change Applications Overview

- 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	

- Past community engagement
  - 2019: MC workshop, MC applications survey, telecons, AGU Town Hall
  - 2020: Community telecons, EGU, IGARSS, AGU Town Hall, GRACE-FO Science Team Meeting
- Ongoing MC applied sciences activities
  - Collaborating with NASA-hired contractor, RTI, to increase number of applications and broaden community
  - Working on a Community Assessment Report to be delivered summer 2021

○ MC applications survey: https://tinyurl.com/MassChangeSurvey

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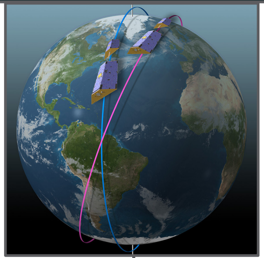
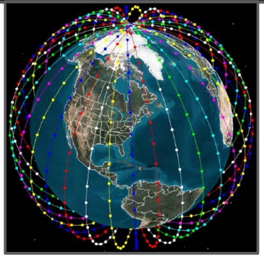
Architectures and Technology

Architectures & Technology: Trade Space

SST
Satellite-to-satellite tracking

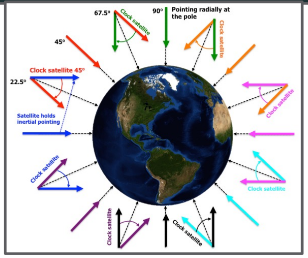


POD
Precise orbit determination



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

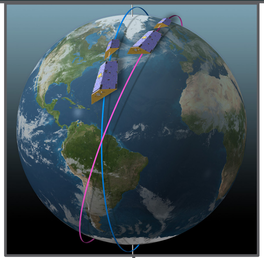
Inclination	Altitude	Ranging	Accel.
~90°	**~500 km**	**MWI**	**ES**
~70°	**~350 km**	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	**Opto.**

★ Indicates Potential Partner Interest

Highlighted boxes = Orbit & technology trade space

Architectures & Technology: Trade Space

SST
Satellite-to-satellite tracking

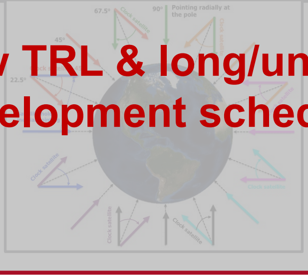


POD
Precise orbit determination

- 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.
~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°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
		µNPRO /KVR	Opto.

Highlighted boxes = Orbit & technology trade space

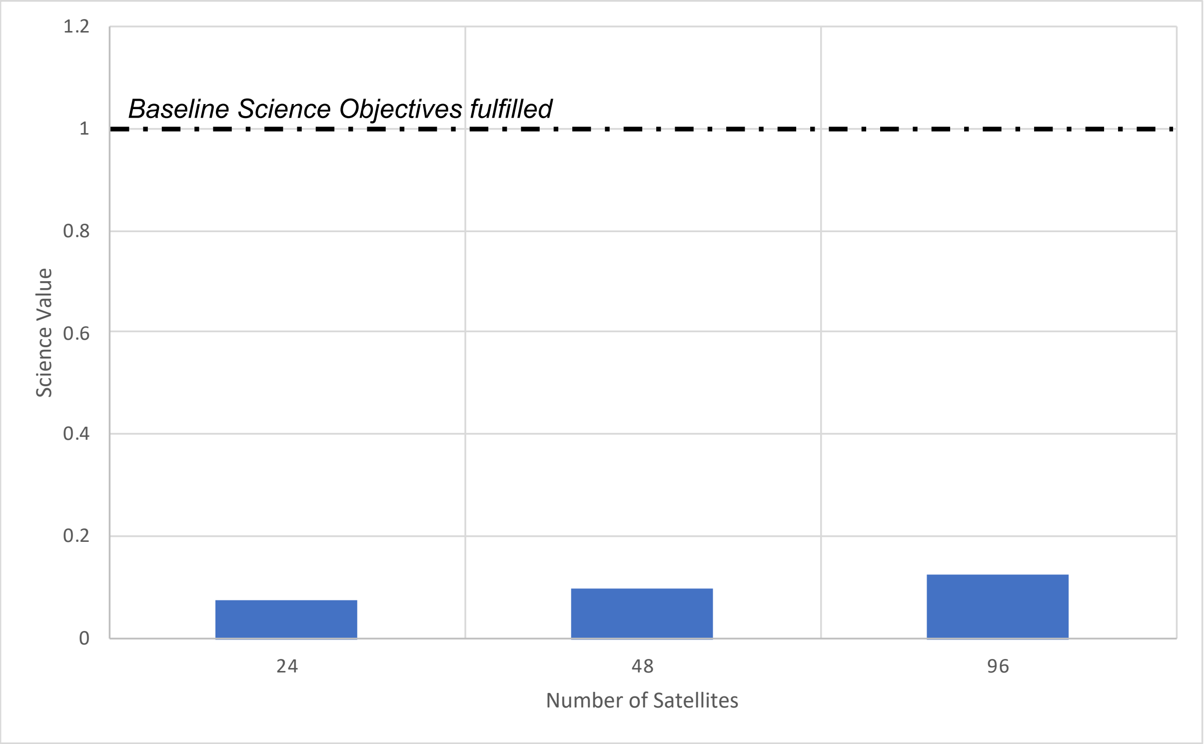
Precise Orbit Determination (POD)

Key takeaway:

POD is not a replacement for GRACE-type missions and is not capable of meeting the MC SATM needs

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

POD science value assessment



Technology Development Areas: AIGG

EGU 2021

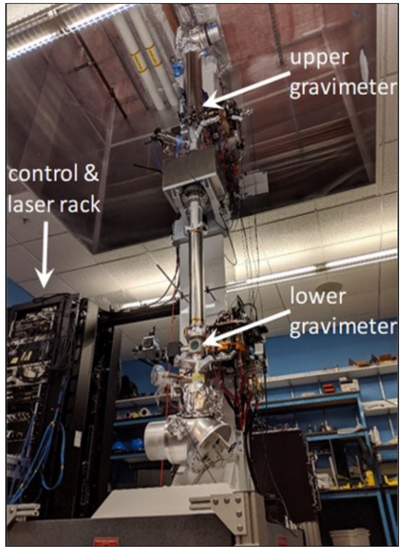
Atomic interferometer gravity gradiometer (AIGG) has high science performance but long/uncertain path to TRL 6

AOSense, Inc. lab instrument developed with NASA GSFC
- Currently TRL 4; path to TRL 6 TBD

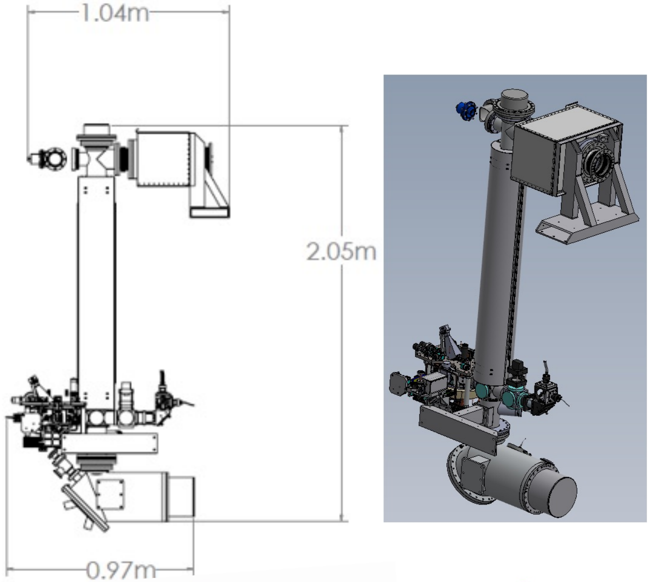
GSFC Instrument Design Lab (IDL) conducted June 1–5, 2020
- First AIGG flight instrument design
- Identified challenges
  - Laser components will likely need development to reduce power
  - Some lab components (RF and laser) lack spaceflight equivalents
  - Challenging to test instrument flight performance in a terrestrial environment

GSFC Mission Design Lab (MDL) conducted March 1–8, 2021
- Technology demonstration mission: S/C, Instrument, ConOps
  - 500 km altitude
  - 1,162 kg mission launch mass; 841 W average power
- TVG recovery performance commensurate to GRACE-FO
  - Radial (zz) gradient measurement; < 75μE sensitivity

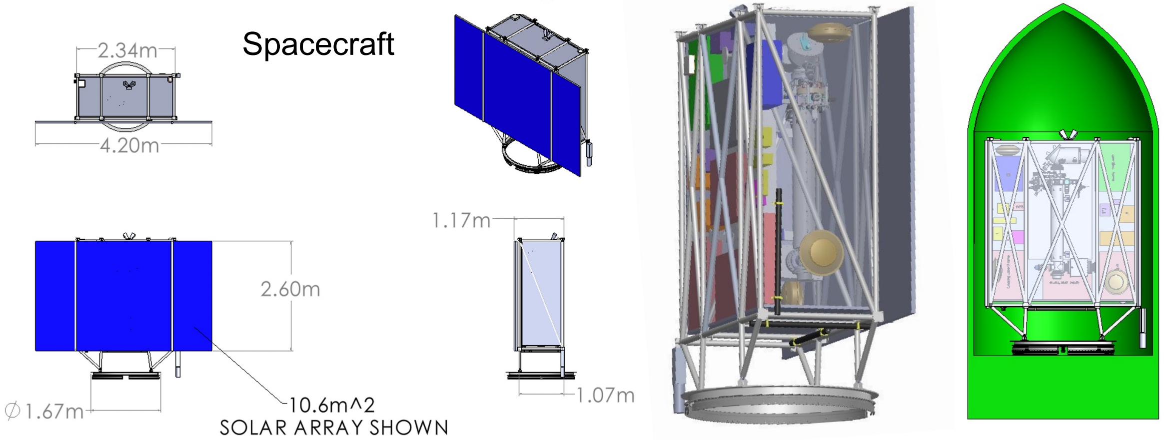
AOSense Lab Instrument



Flight Instrument



Spacecraft



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

Technology summary

- SATM baseline objectives can be met with flight-proven technology
- SATM goal objectives require advanced technologies and/or additional satellites
- Development efforts have been prioritized by MC team with input from the community:

Relevant to SST architectures

- Redundant laser ranging interferometer (LRI) as primary instrument *
- LRI enhancements *
- Advanced accelerometer *
- Miniaturization of relevant technologies *
- Drag compensation
- Attitude control
- Gravity gradiometer *

* *Focus of MC study team through community white papers and funded efforts (some details on following charts)*
Accelerometer & LRI while papers on website: https://science.nasa.gov/earth-science/decadal-mc
Gravity gradiometer white paper available on website soon

SST technologies: Accelerometers

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

SST technologies: Inter-satellite Ranging

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

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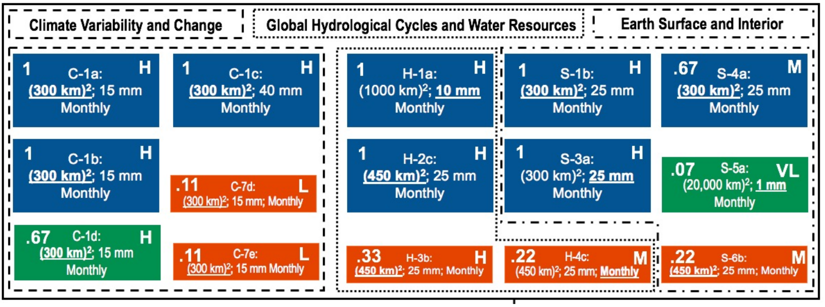
Science Value Methodology

Relating Observing System Capability to the DS

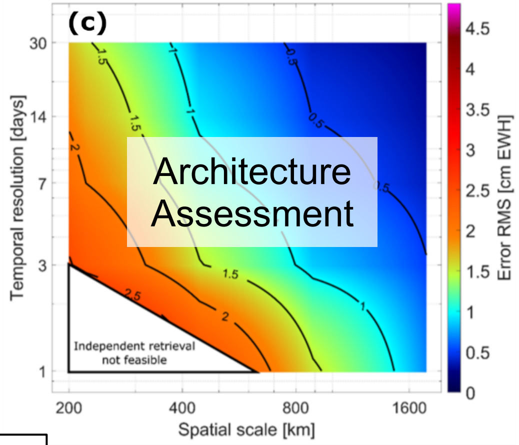
EGU 2021

Decadal Survey

Science and Applications Traceability Matrix Measurement Parameters



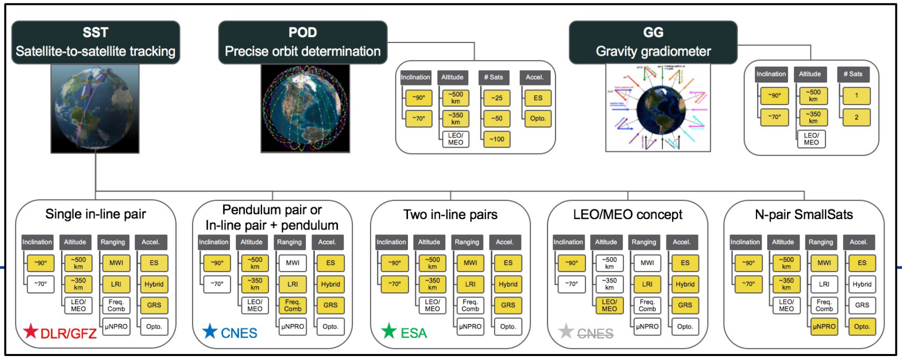
Science value metrics <u>directly relate the capability of an observing system architecture to achieving science and application targets relevant to MC in the Decadal Survey</u>



Architecture Assessment

Science Value

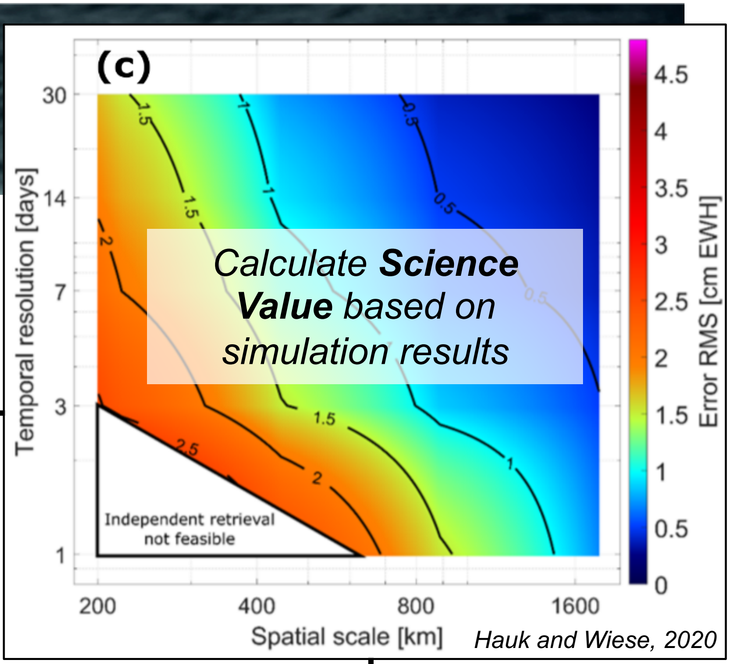
Architecture Tree



OSSE Overview: Science Value

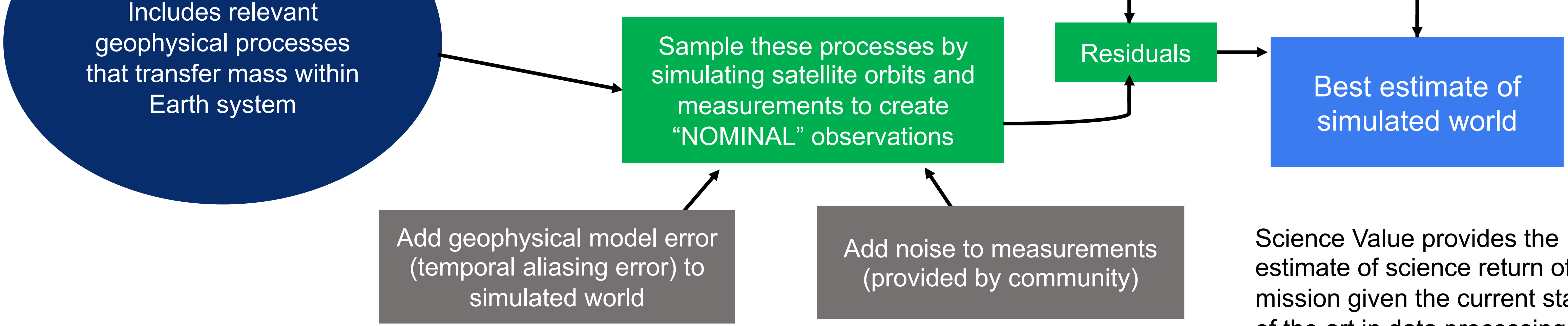
Overview of Observing System Simulation Experiment (OSSE)

Compare estimate against the truth simulated world to quantify error



*Calculate **Science Value** based on simulation results*

Hauk and Wiese, 2020



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

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

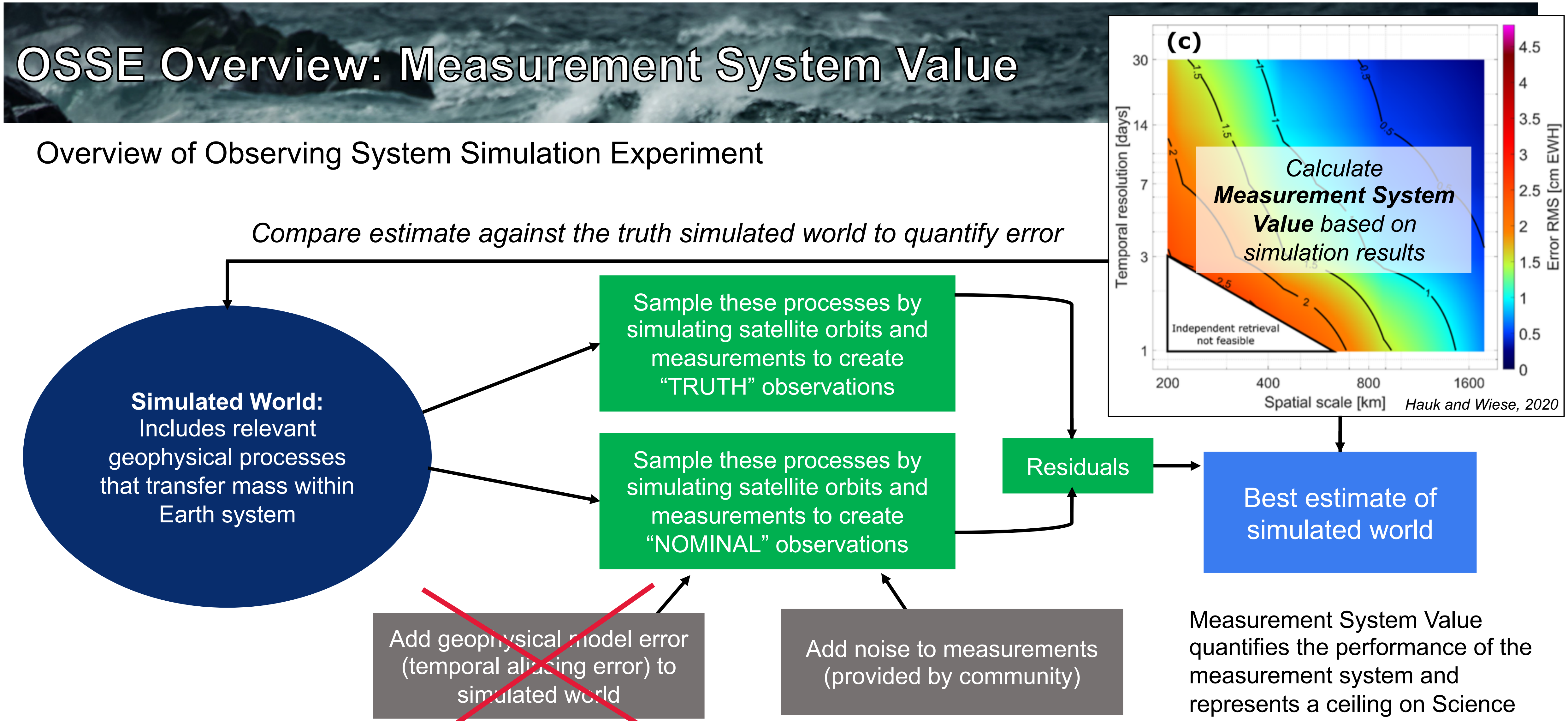
Add noise to measurements (provided by community)

	Truth Model	**Nominal Model**
Static Gravity Field	gif48	gif48
Ocean Tides	GOT4.8	FES2004
Atmosphere/Ocean (AOD)	AOD RL05	AOerr + DEAL (Dobslaw et al., 2016)
Hydrology + ICE	ESA Earth System Model	

Science Value provides the best estimate of science return of the mission given the current state of the art in data processing and geophysical model error

OSSE Overview: Measurement System Value

Overview of Observing System Simulation Experiment



Hauk and Wiese, 2020

Calculate ***Measurement System Value*** *based on simulation results*

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

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

Add noise to measurements (provided by community)

Residuals

Best estimate of simulated world

Measurement System Value quantifies the performance of the measurement system and represents a ceiling on Science Value in the future as data processing methods mature and geophysical models improve

	Truth Model	**Nominal Model**
Static Gravity Field	gif48	
Ocean Tides	GOT4.8	
Atmosphere/Ocean (AOD)	AOD RL05	
Hydrology + ICE	ESA Earth System Model	

Nominal Model = Truth Model

A Quantitative Assessment of Science Value

Science Value (SV)

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

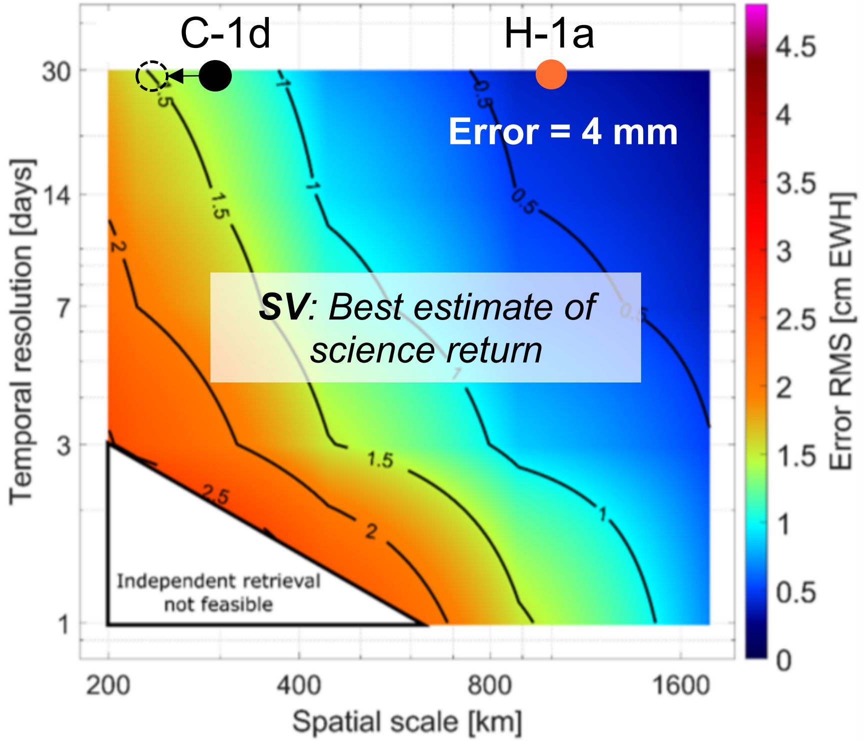
Key Variable: **Spatial Resolution**

.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



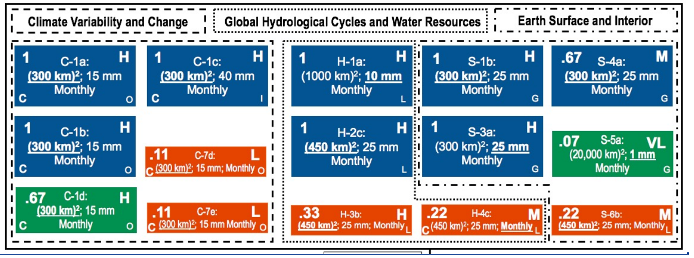
Hauk and Wiese, Earth and Space Science, 2020.

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

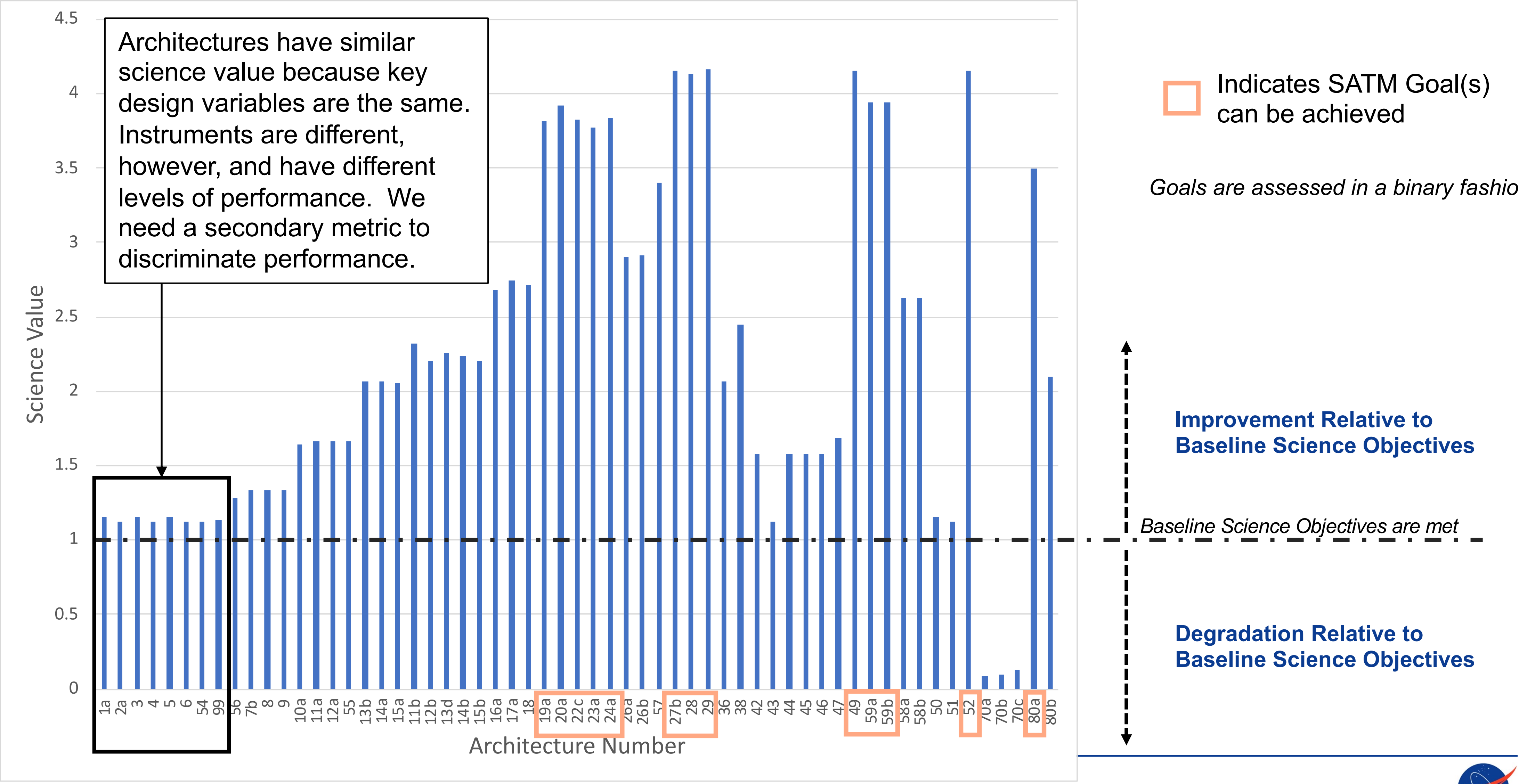


Climate Variability and Change
1 C-1a: H (300 km)^2; 15 mm Monthly C O
1 C-1b: H (300 km)^2; 15 mm Monthly C O
.67 C-1d: H (300 km)^2; 15 mm Monthly C O
1 C-1c: H (300 km)^2; 40 mm Monthly C I
.11 C-7d: L C (300 km)^2; 15 mm; Monthly O
.11 C-7e: L C (300 km)^2; 15 mm Monthly O

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

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

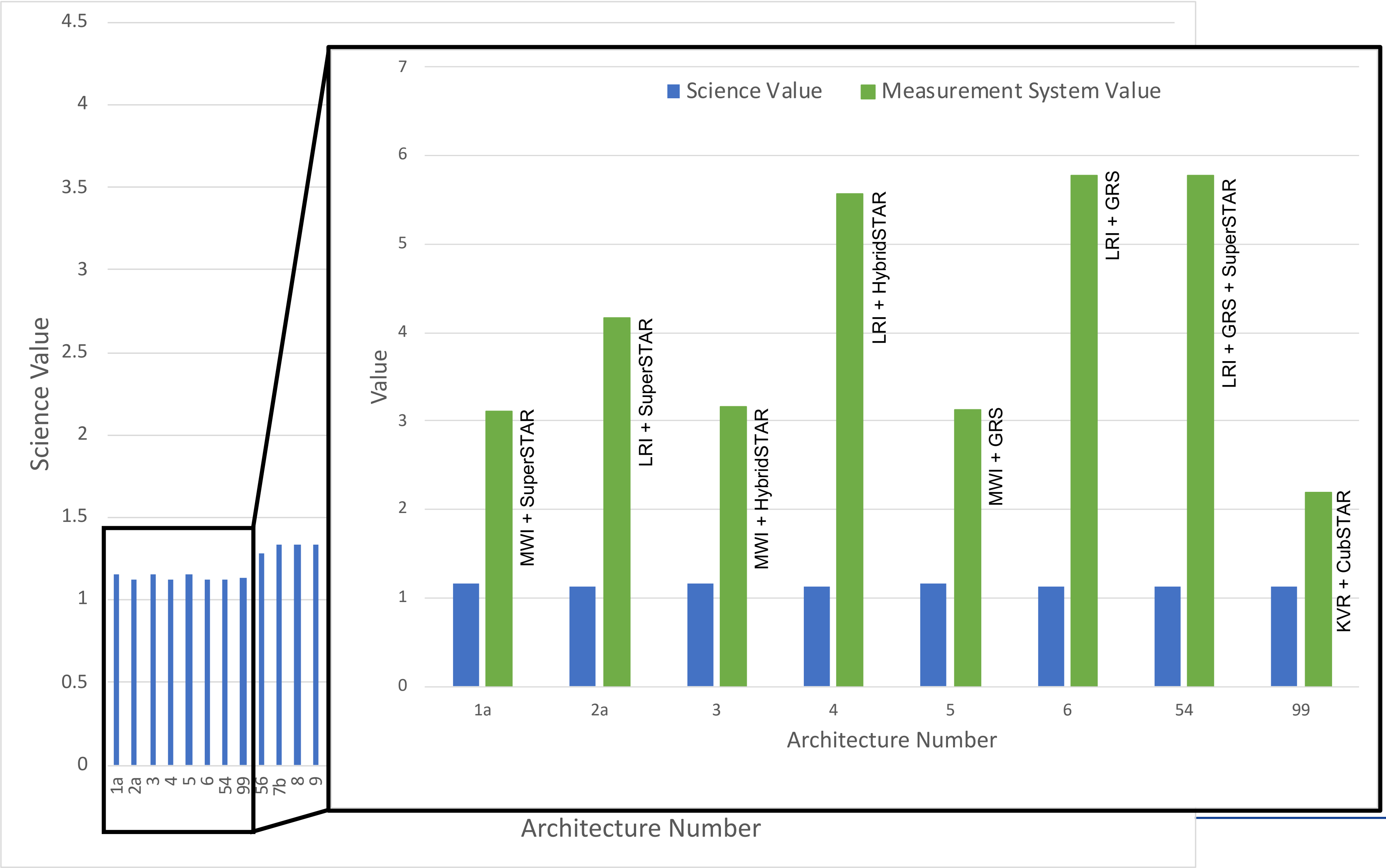
Goals are assessed in a binary fashion

Improvement Relative to Baseline Science Objectives

Baseline Science Objectives are met

Degradation Relative to Baseline Science Objectives

Measurement System Value Results: A Secondary Discriminator



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

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

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

Value Framework Process

Architecture Evaluation Objectives

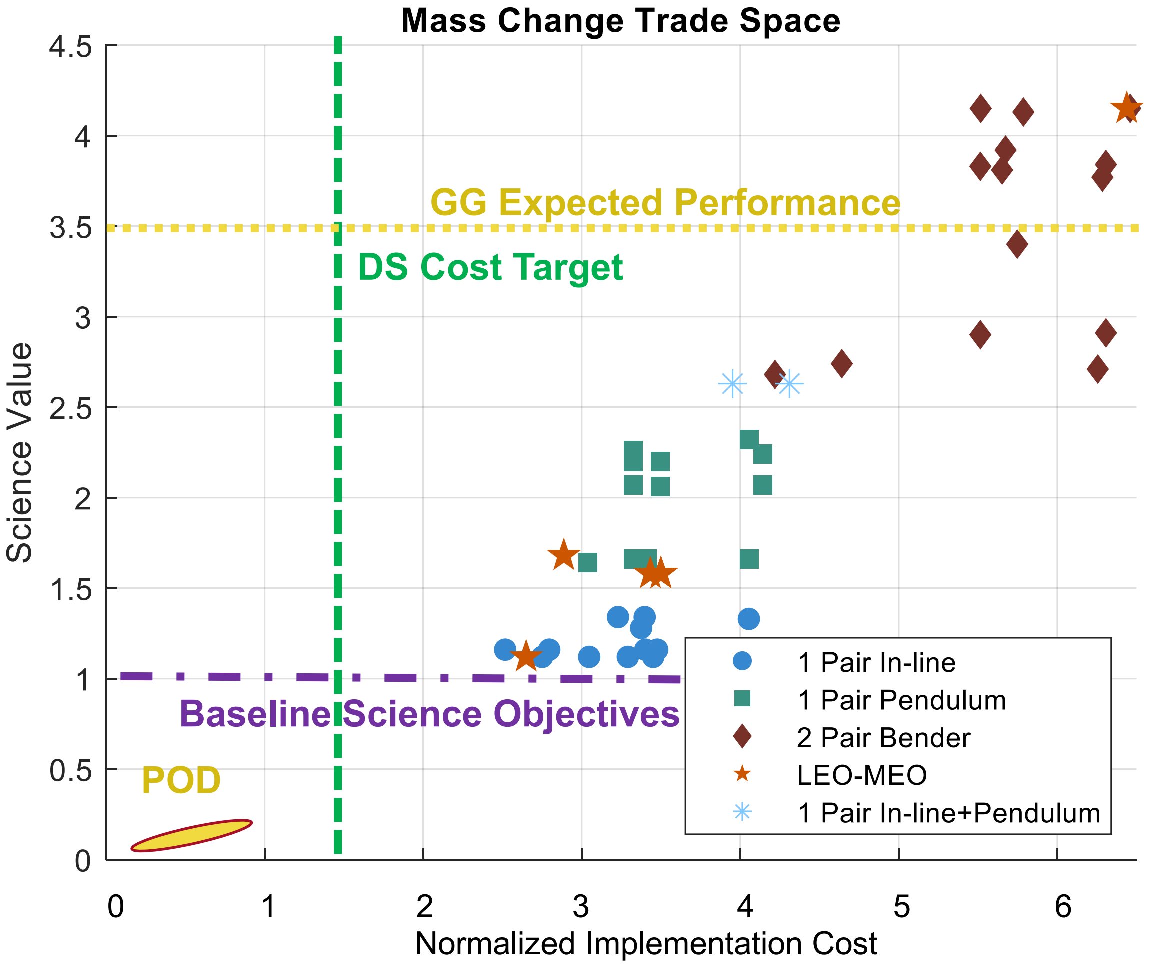
- Identify architectures that support the Mass Change Science and Applications objectives
  - Traceable to Decadal Survey
- Assess the cost effectiveness of each of the studied architectures
  - Performance (Science and Applications), Risk, Cost, Schedule
- Provide a transparent and traceable mechanism for specifying an observing system recommendation to NASA Earth Science Division of one or more candidate architectures
  - Justification for eliminating candidate architectures that are not recommended

Assessment Ground Rules/Assumptions

- Architecture Performance based on science and applications metric
- Spacecraft/Instrument sizing
  - Combination of concurrent engineering studies and engineering models
  - Implementation with minimum 3 year design lifetime and 5 years of consumables
- Cost estimation
  - Leveraging Aerospace Corporation for independent cost estimates
  - Combination of parametric and analogy based cost models process for cost risk including design uncertainty
- Schedule estimates
  - Phase durations developed based on mission analogies
  - Includes estimated time to mature technologies
- Risks considerations
  - Performance/Science risks based on heritage of components, measurement techniques, and technology maturity
  - Schedule risks assessed against Program of Record and timelines with international partner opportunities

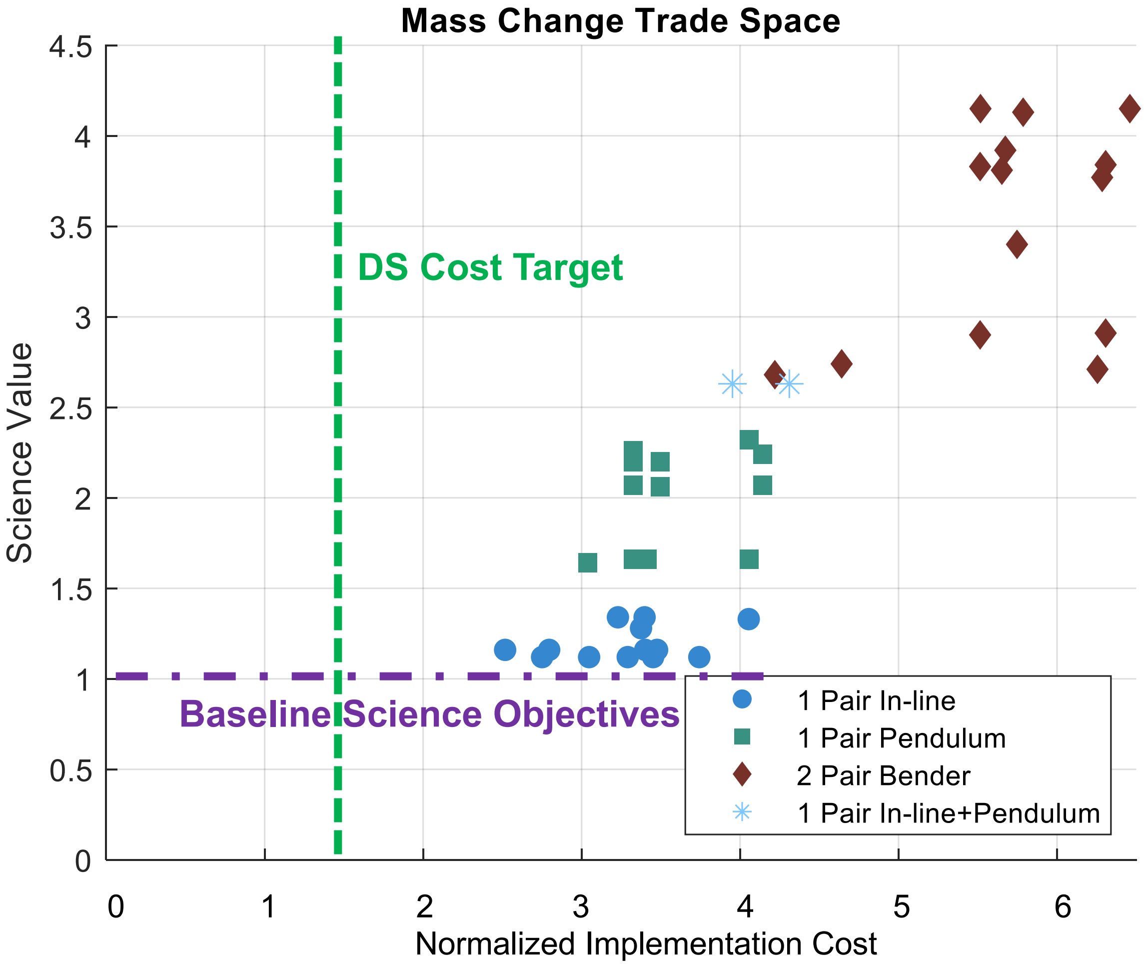
MC Tradespace Analysis (1 of 3)

- 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



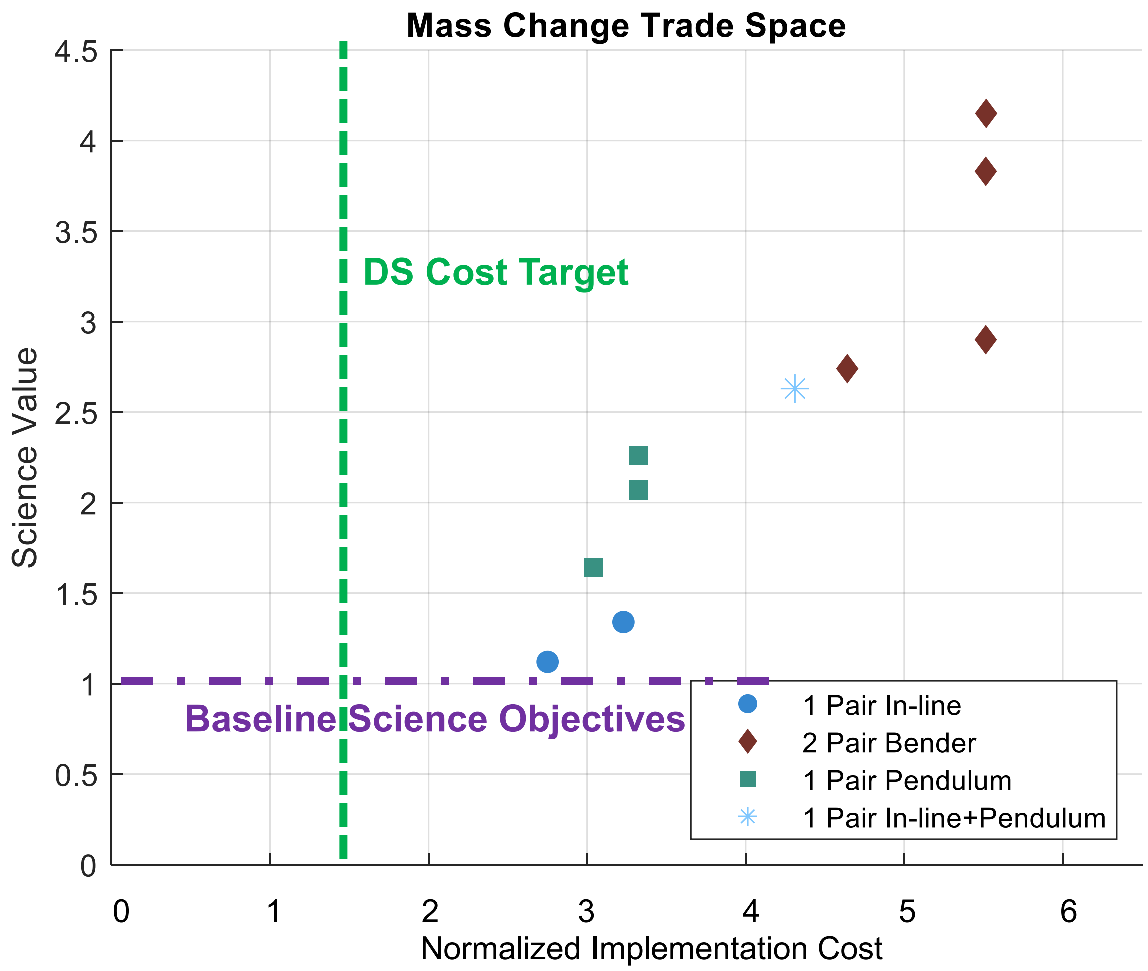
MC Tradespace Analysis (2 of 3)

- 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, 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 as 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



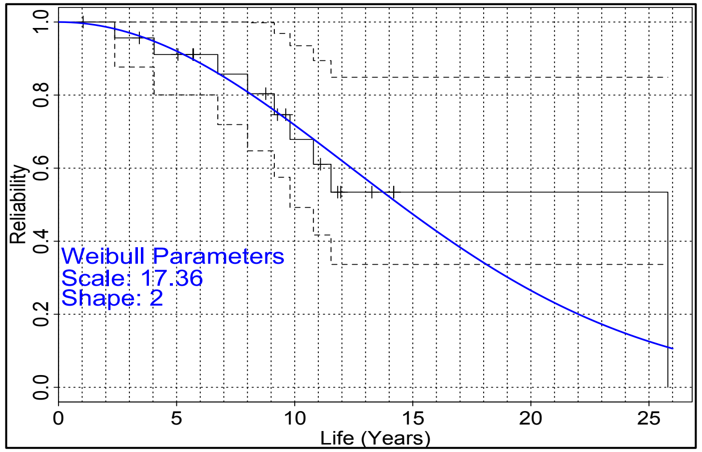
MC Tradespace Analysis (3 of 3)

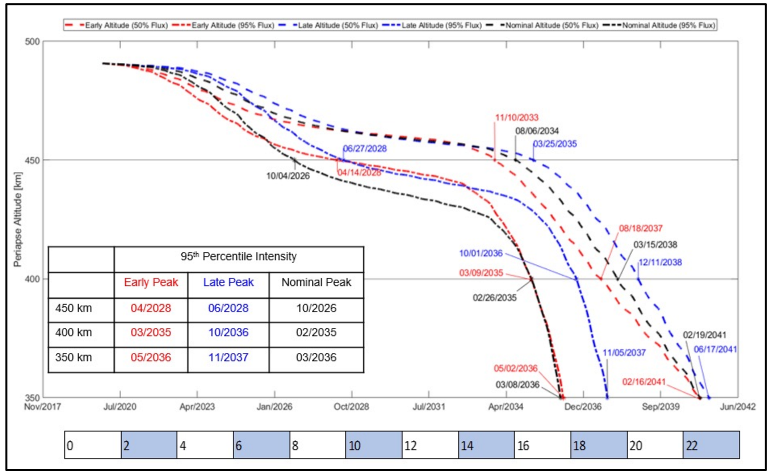
- Generally cost variation within families is driven by inclusion of drag compensation or not
- Performance is driven by orbit configurations (altitude and inclination)



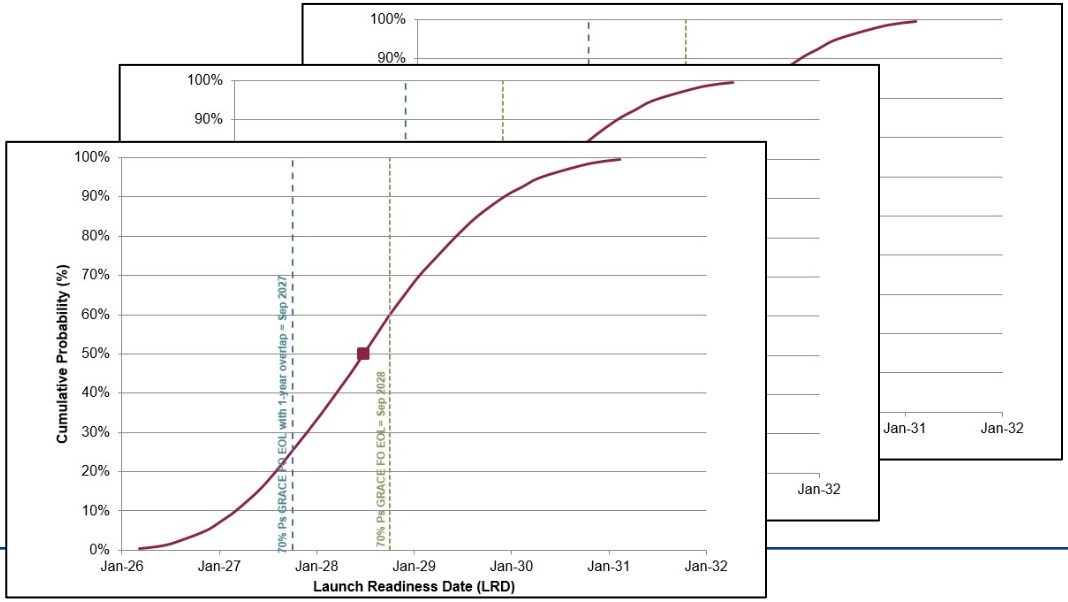
Continuity with GRACE Follow On

- 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



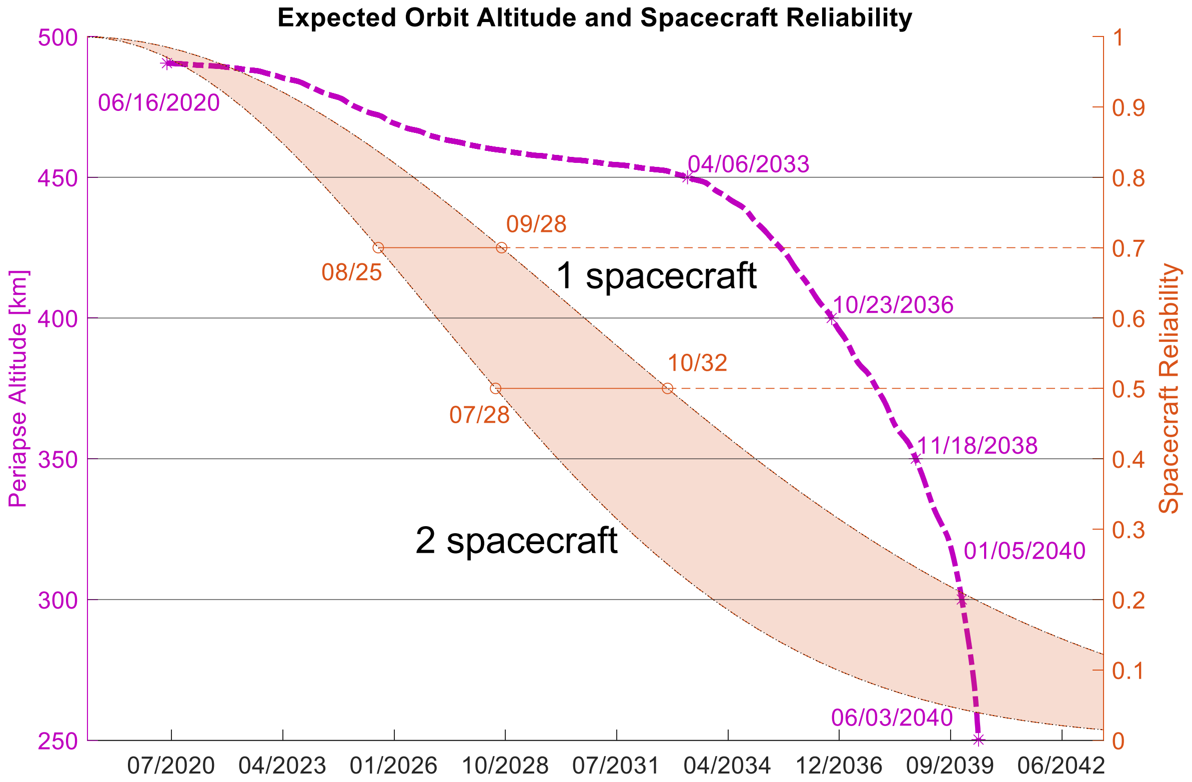


	95th Percentile Intensity		
	Early Peak	Late Peak	Nominal Peak
450 km	04/2028	06/2028	10/2026
400 km	03/2035	10/2036	02/2035
350 km	05/2036	11/2037	03/2036



GRACE-FO Orbit Lifetime and Expected Reliability

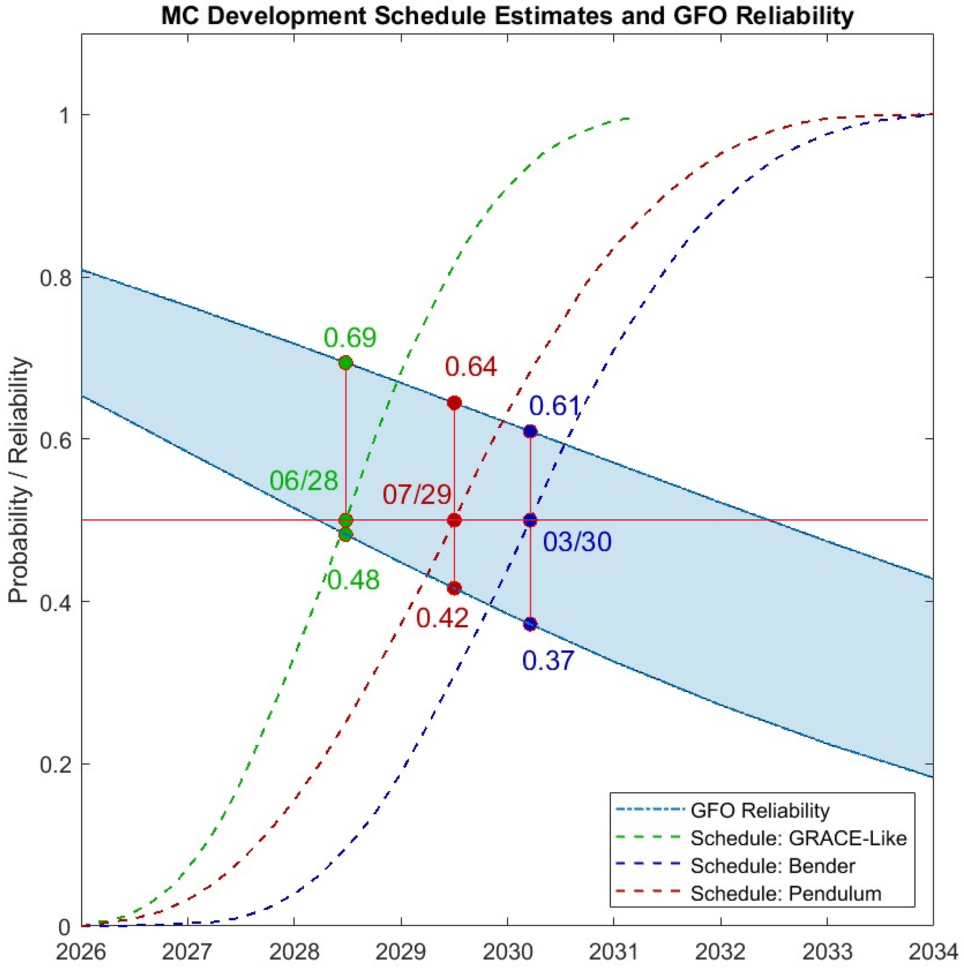
- Historical data for reliability of spacecraft with design life similar to GRACE-FO predicts 70th percentile lifetime through 2025-28 and 50th percentile lifetime into 2028-2032
- Orbit lifetime predictions indicate GRACE-FO altitude is likely to remain above 450 km into the next decade
  - Solar cycle 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
- **GRACE-FO lifetime more likely limited by system reliability rather than orbit lifetime**



Reliability and Schedule Curves

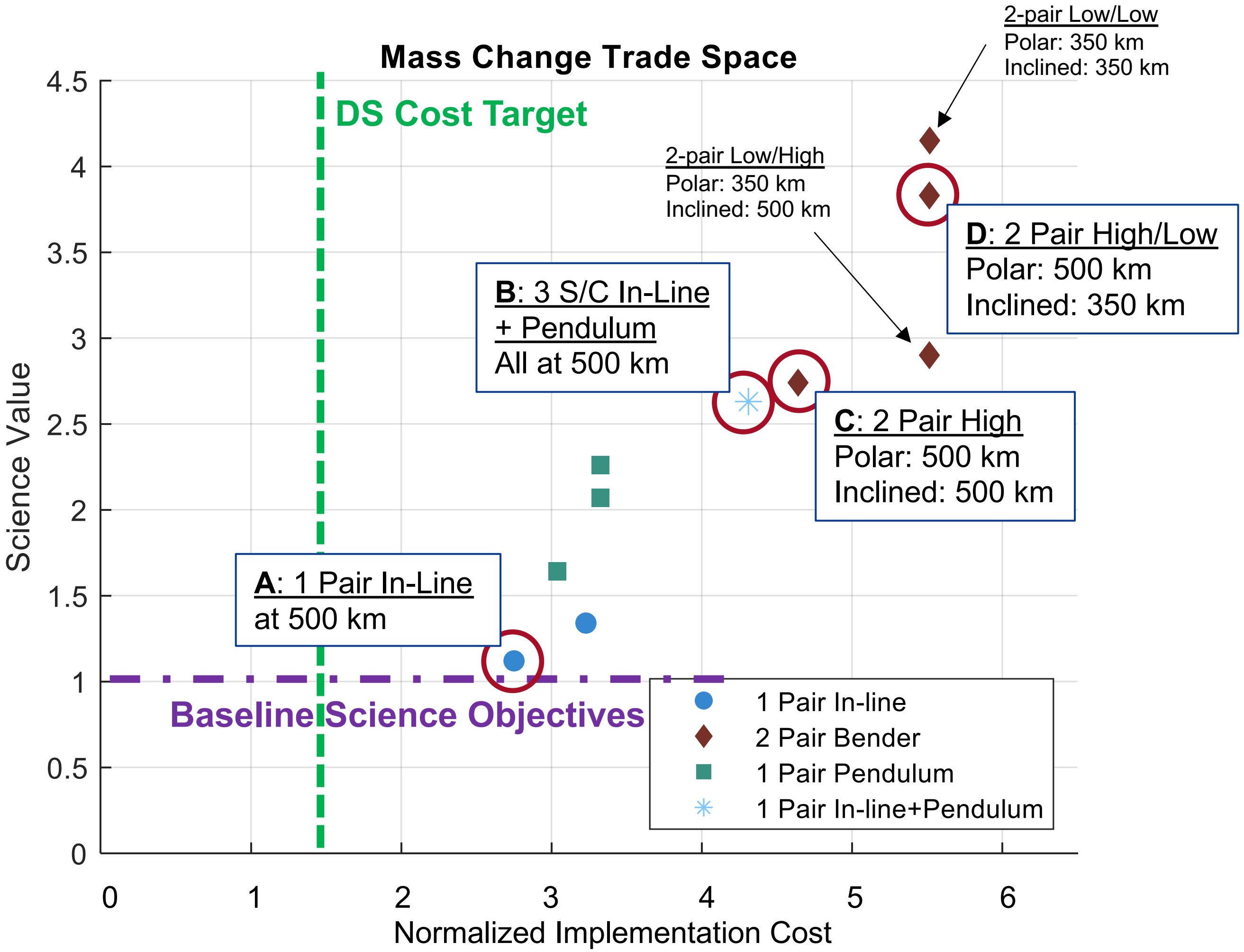
- Schedule estimates indicate that the single in-line pair is likely to have the earliest launch readiness date and more likely to enable continuity with GRACE-FO
  - Schedule estimates based on parametric modeling and should be further refined

	Estimated 50th Percentile Launch Readiness Date	Expected GRACE-FO Reliability at Launch Readiness Date
Single In-Line	Jun 2028	48 - 69%
Pendulum	Jul 2029	42 - 64%
Bender	Mar 2030	37 - 61%



Identification of architectures with highest value: improved 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; Element A can be launched first and 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



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Summary and Next Steps

Summary

- The MC Study Team has compiled a description of high-value architectures based on
  - Science value and applications performance
  - Cost estimate and cost risk assessment
  - Schedule estimate and schedule risk assessment including continuity with GRACE-FO
  - Technology readiness levels, risks, and maturation plans
  - International partnership concepts
- **Satellite-Satellite-Tracking (SST) is the recommended architecture** for implementation as the MC observing system. Promising variants include
  - Single in-line Pair
  - Two in-line Pairs (Bender)
  - Pendulum Pair and In-line + Pendulum architectures
- **Architectures have been identified that allow for highest likelihood of continuity with GRACE-FO while also enabling improved science outcomes**; implementation of the full observing system can be synchronous or staggered
  - Single in-line pair + second inclined pair at either high altitude or low altitude
  - Single in-line pair + pendulum S/C
- Gravity Gradiometry via quantum sensors is recognized as a promising technology for future implementations beyond the next decade

The Path Forward

- MC is in the process of transitioning to Pre-Phase A
  - Refines the mission concept
  - Allows for further in-depth study of identified high value architecture variants
- Awaiting guidance from NASA HQ on scope of Pre-Phase A activities
- Ongoing International Formulation Activities and Collaborations with MC Study Team
  - ESA NGGM Concept
  - DLR/GFZ GRACE-I Concept
  - CNES MARVEL Concept

MC Links and Communications

- MC Website
  - https://science.nasa.gov/earth-science/decadal-mc
- ESD website for Decadal Survey Community Forums
  - https://science.nasa.gov/earth-science/decadal-survey-community-forum
- Email address for MC questions/comments
  - masschange@jpl.nasa.gov