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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Mass Change Introduction

- 2017 Decadal Survey released in January 2018
- Identified five Designated Observables, organized as 4 studies
  - Aerosols } Combined as ACCP
  - Cloud, Convection, and Precipitation } Combined as ACCP
  - Mass Change (MC)
  - Surface Biology and Geology (SBG)
  - Surface Deformation and Change (SDC)
- Mass change is determined by measuring gravitational changes over set time periods
- Link to the MC study is at

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

Mass Change Study Operational Guidelines

- Transparency
  – Multiple opportunities for public engagement via community meetings, AGU Town Hall, and on-line
- One integrated NASA Team
  – Team includes NASA HQ, as well as members from NASA Ames, NASA Goddard, NASA Langley, and JPL
- Explore international partnerships
  – Regular dialogues with ESA, Germany, and CNES

Mass Change Study Organization

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

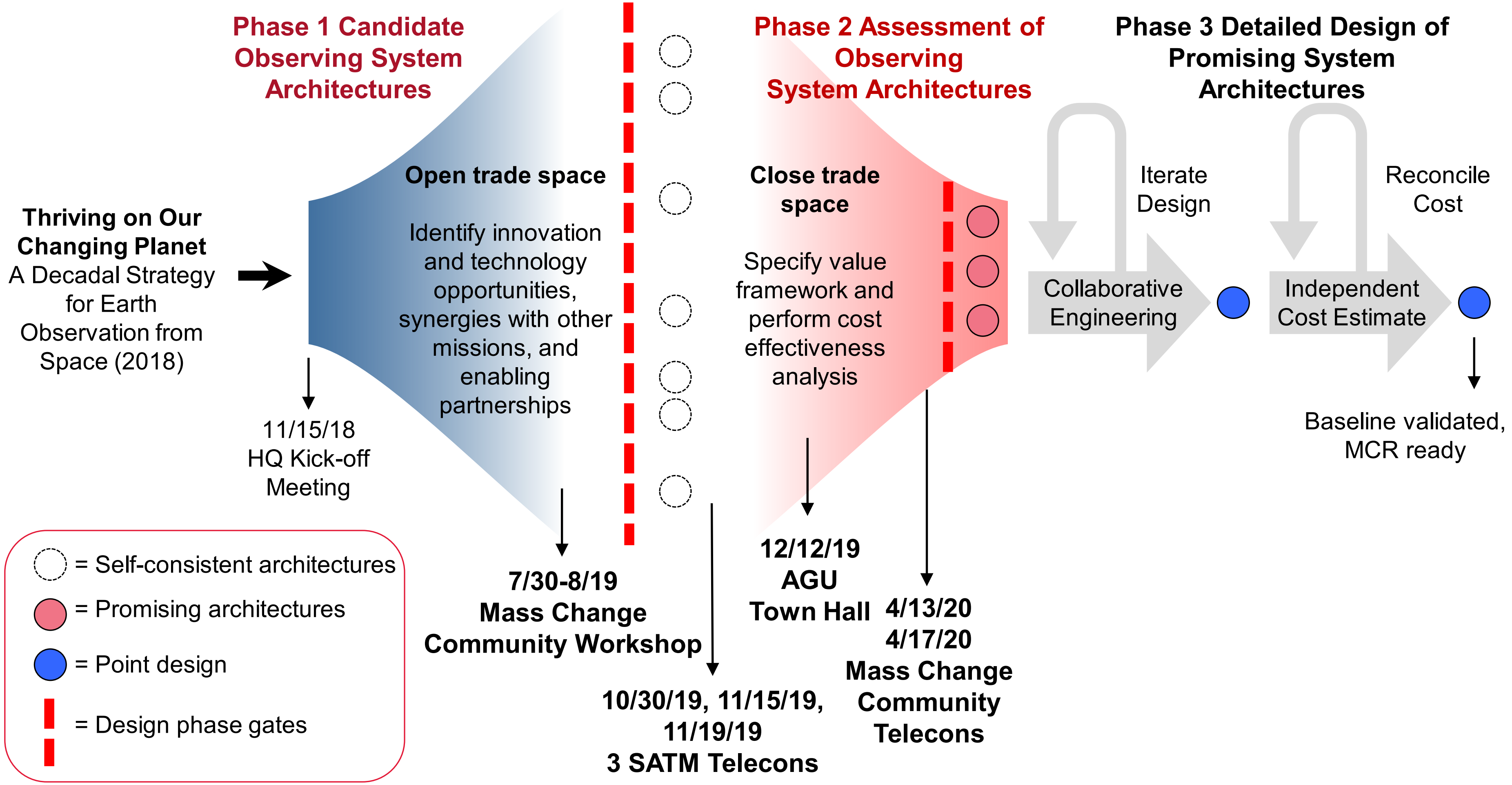
0. Study Overview

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

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

from the Mass Change Study Plan approved by NASA in October 2018

Study Phases



Architecture Options and Technology

Architecture summary

Three architectures types identified at the Phase 1 community workshop in Washington, D.C. July 30 – August 1, 2019:

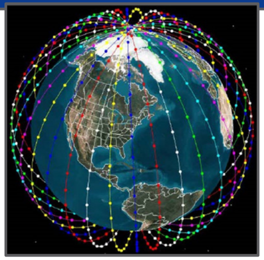
1. SST = satellite-to-satellite tracking **2. POD** = precise orbit determination **3. GG** = gravity gradiometer

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

★ These observing system architectures are at very different maturity levels → currently being assessed in Phase 2

Architecture trade space

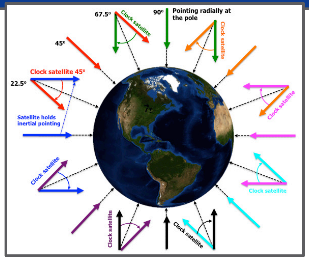
POD
Precise orbit determination



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

SST
Satellite-to-satellite tracking

GG
Gravity gradiometer



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

Single in-line pair ★ (red)

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

Single pendulum pair

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

Two in-line pairs ★ (green)

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

N-pair SmallSats

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

MARVEL concept ★ (blue)

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

★ Discussions in Germany – includes biodiversity payload

★ Favored by ESA

★ Favored by CNES

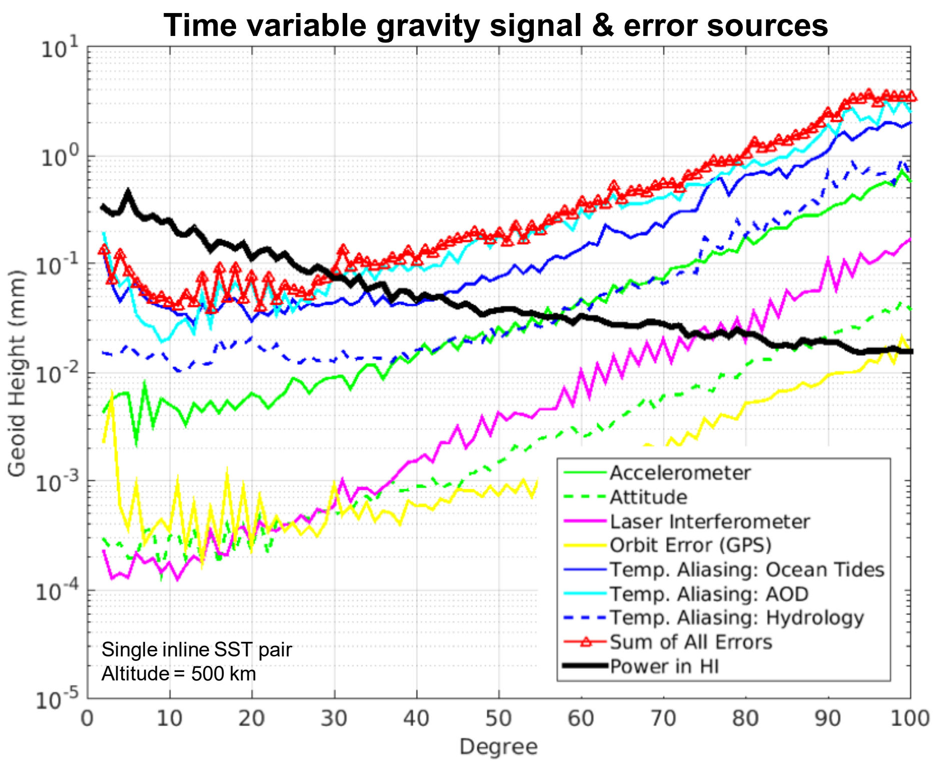
Highlighted boxes = Orbit & technology trade space

Technology summary

Key technologies identified at the Phase 1 community workshop in Washington, D.C. July 30 – August 1, 2019:

Accelerometer | **Laser ranging (LRI)** | **Gravity gradiometer** | **Drag compensation** | **Attitude control**

- **Accelerometer** errors are the dominant GRACE/GRACE-FO measurement errors; improvements not required for MC but are a top priority for possible inclusion as a technology demonstration
- Primary focus is on **accelerometer** developments and the **LRI** as the primary SST measurement for continuity and improved performance
- **Gravity gradiometer** is far reaching technology path forward for future mission advancement
- **Drag compensation** and **attitude control** technologies support further mission improvements from the LRI and accelerometer advancements – developments not currently a focus of MC team



Technology: Accelerometer

Key technologies identified at the Phase 1 community workshop in Washington, D.C. July 30 – August 1, 2019:

Accelerometer | **Laser ranging (LRI)** | **Gravity gradiometer** | **Drag compensation** | **Attitude control**

Accelerometer technologies community white paper by Conklin et al., submitted to Mass Change team Jan 2020:

- ONERA electrostatic
  - GRACE-FO pre-launch: ~2×10^{-11} m/s^2 Hz$^{1/2}$
  - Expected performance of MicroSTAR: 3×10^{-12} m/s^2 Hz$^{1/2}$; Currently TRL 4/6; ~1.5 years to get to TRL 6
- Simplified LISA Pathfinder Gravitational Reference Sensor (GRS):
  - Expected performance: 10^{-12} m/s^2 Hz$^{1/2}$ or better
  - Technology roadmap:
    - Needs 7–8 years for flight sensors and $30 M
    - Dependent on drag-free or drag-compensated for stated performance
    - Possible integration with LRI for direct measurement of test masses
- Compact optomechanical accelerometer for SmallSat/CubeSat implementation:
  - Expected performance: 10^{-7} to 10^{-10} m/s^2 Hz$^{1/2}$
  - Technology roadmap:
    - Currently at TRL 2/3; ~2–3 years and ~$500,000 to get to TRL 4/5
    - Uncertain path to flight sensors

Technology: LRI

Key technologies identified at the Phase 1 community workshop in Washington, D.C. July 30 – August 1, 2019:

Accelerometer | **Laser ranging (LRI)** | **Gravity gradiometer** | **Drag compensation** | **Attitude control**

LRI technologies community white paper by Lee, Klipstein, et al., submitted to Mass Change team Feb 2020:

- GRACE-FO LRI:
  - Successful technology demonstration; ~100x improvement over MWI; sensor system is high TRL
- LRI as primary instrument technology development path:
  - Optical bonding – pre-launch mechanical stress test caused some bonds to fail
  - Mechanical isolation – mechanical disturbances are causing phase jumps
  - Redundancy – less redundancy for LRI tech demo than required for primary instrument
  - Scale length stability – GRACE-FO LRI currently dependent on MWI to calibrate scale length
    - Data analysis options: LRI range vs. GPS range; estimate as a parameter with geopotential
    - Hardware options: High freq. cavity modulation; frequency comb; absolute frequency stabilization
- Desired LRI enhancements:
  - Noise reduction – cavity coating improvements
  - Interface between LRI and accelerometer test mass
  - High dynamic range – optical frequency comb enables pendulum orbit architecture
  - CubeSat implementation – μNPRO in development at GSFC; expected TRL 6 in 2020

Technology: Gravity gradiometer

Key technologies identified at the Phase 1 community workshop in Washington, D.C. July 30 – August 1, 2019:

Accelerometer | **Laser ranging (LRI)** | **Gravity gradiometer** | **Drag compensation** | **Attitude control**

Status of gravity gradiometer technology development:

*Gravity gradiometer white paper still in development

- AOSense lab instrument in collaboration with NASA GSFC:
  - Currently TRL 4
  - Expect to achieve measurement accuracy of <10 $E/\sqrt{Hz}$ in 2020
  - Expect to achieve measurement accuracy <1 $E/\sqrt{Hz}$ and TRL 5 early 2021
  - Ground measurement of <1 $E/\sqrt{Hz}$ corresponds to ~10^{-5} $E/\sqrt{Hz}$ in microgravity with longer interrogation time
  - Time variable gravity simulations: One or two gravity gradiometers with pseudo-radial pointing

- JPL (Nan Yu et al.):
  - Developed Transportable Quantum Gravity Gradiometer (QGG) under ESTO-IIP
  - Assessed at TRL 5 in 2015
  - Measurement accuracy of 40 $E/\sqrt{Hz}$
  - Time variable gravity simulations: LRI SST equipped with QGG

- NASA/JPL: Cold Atom Lab (CAL) atomic interferometer demo on ISS – launched May 2018 and now operating

Funded efforts relevant to MC

Selections for Category 3 funding have been made to support these technology development efforts:

- LRI improvements in optical frequency comb and optical cavities
- Compact optomechanical accelerometer
- SmallSat/CubeSat SST Constellation

Currently funded through IIP:

- Development of Gravitational Reference Sensor (GRS)

Separate efforts are underway to develop detailed technology roadmaps with work schedule and cost estimates for:

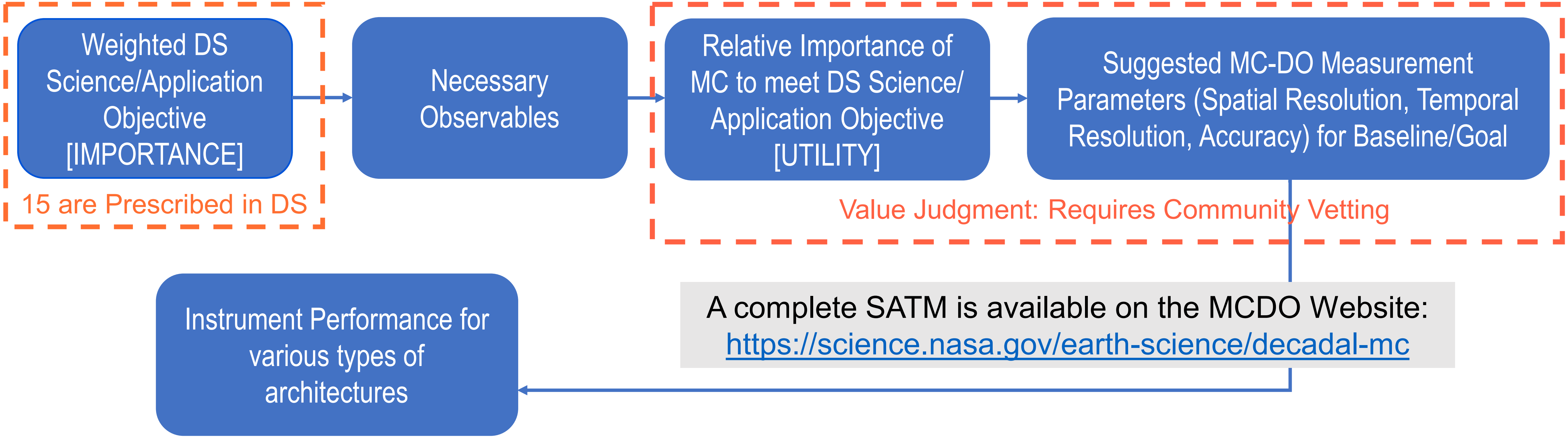
- Development of LRI as primary SST instrument
- Development of Gravitational Reference Sensor (GRS)

Methodology for determining Science Value

Science and Applications Traceability Matrix Overview

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

- **Baseline** Observing System – supports full science objectives. This has been interpreted by the community to roughly mean a continuation of the current performance of the program of record
- **Goal** Observing System – supports additional science with a goal to create longevity in the mass change timeseries. May include advancements of enabling technologies



Decadal Survey Science and Application Objectives for Mass Change

A Diverse Set of Objectives Spanning Three Panels

Climate Variability and Change

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

Global Hydrological Cycles and Water Resources

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

Earth Surface and Interior

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

DS Prescribed Weights [Importance]

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

MC Utility Score

H: High
M: Medium
L: Low
VL: Very Low

→ Science Performance Targets

Decadal Survey Science and Application Objectives for Mass Change

A Diverse Set of Objectives Spanning Three Panels

Weight = Importance * Utility

Climate Variability and Change

- 1 — C-1a: Global Sea Level — H
- 1 — C-1b: Ocean Heat — H
- .67 — C-1d: Regional Sea Level — H
- 1 — C-1c: Ice Sheet Mass Change — H
- .11 — C-7d: Dynamical Ocean State — L
- .11 — C-7e: Ocean Circulation — L

Global Hydrological Cycles and Water Resources

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

Earth Surface and Interior

- 1 — S-1b: Earthquakes — H
- 1 — S-3a: Glacial Isostatic Adjustment/Local Sea Level — H
- .67 — S-4a: Landscape Changes — M
- .07 — S-5a: Earth Energy Flow — VL
- .22 — S-6b: Groundwater Flux — M

DS Prescribed Weights [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

A Diverse Set of Objectives Spanning Three Panels

Climate Variability and Change

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

DS Prescribed Weights [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

High Fidelity Numerical Simulations

Propagate satellites through a 'truth' reference world (hydrology, ice, ocean dynamics, atmosphere, ocean tides)

Generate 'truth' measurements

Add noise to measurements

Propagate orbits through a 'nominal' reference world (ocean dynamics, atmosphere, ocean tides)

Generate 'nominal' measurements

Residuals or Reduced Observations

Estimate gravity field that best fits residuals

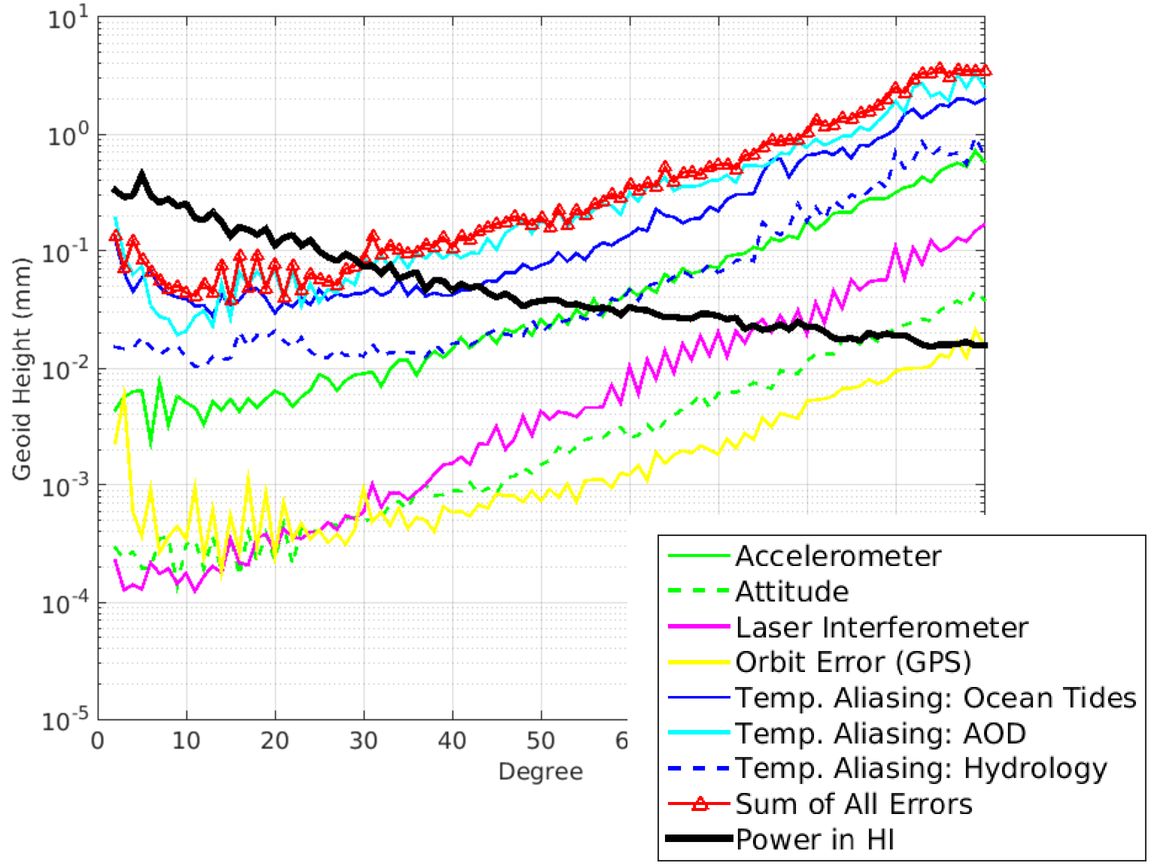
Case 1: Includes temporal aliasing errors due to inaccuracies in forward models of high frequency mass variations. 'Truth' and 'Nominal' reference worlds are different.

Case 2: Measurement system errors only. 'Truth' and 'Nominal' reference worlds are the same.

Science Value versus Measurement System Performance

- Science value is calculated including temporal aliasing errors (red curve to the right). Hidden in this metric is any benefit due to improved measurement system performance that more innovative data processing, or future improvements in dealiasing models, may be able to exploit.
- This was a concern expressed by members of the community during previous community telecons
- Solution: In addition to calculating science value, we also calculate a “measurement margin” for each architecture that quantifies the performance of the measurement system only

Error from a single SST pair



Quantitatively Determining Science Value

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

Assessing value against spatial resolution

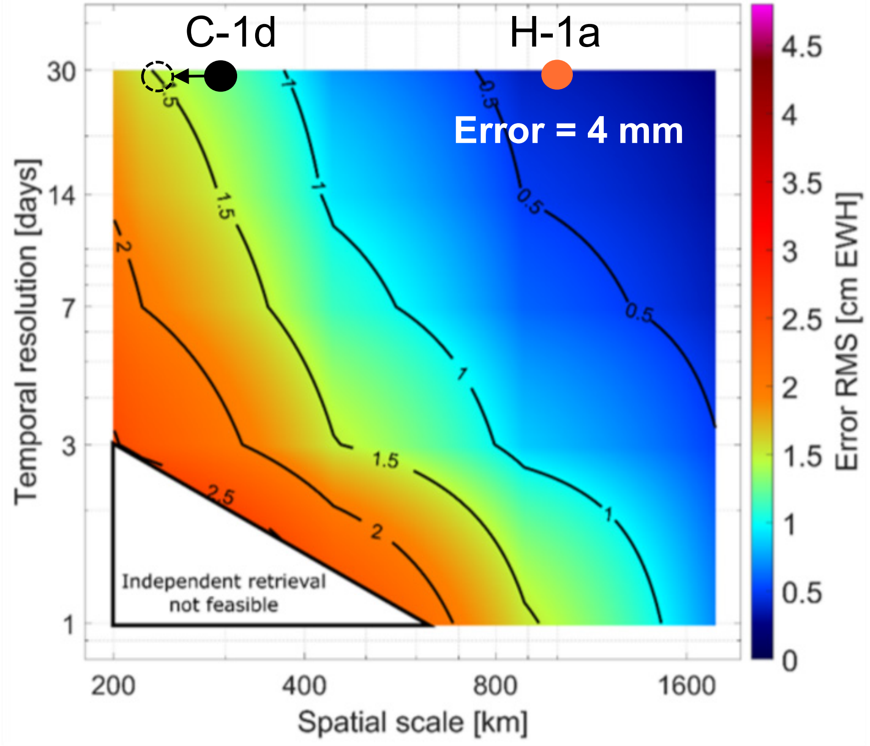
C-1d:
(300 km)^2; 15 mm
Monthly

Medium – High Weight

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

W = Importance * Utility

Architecture *a*



Hauk and Wiese, Earth and Space Science, 2020.

Assessing value against accuracy

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

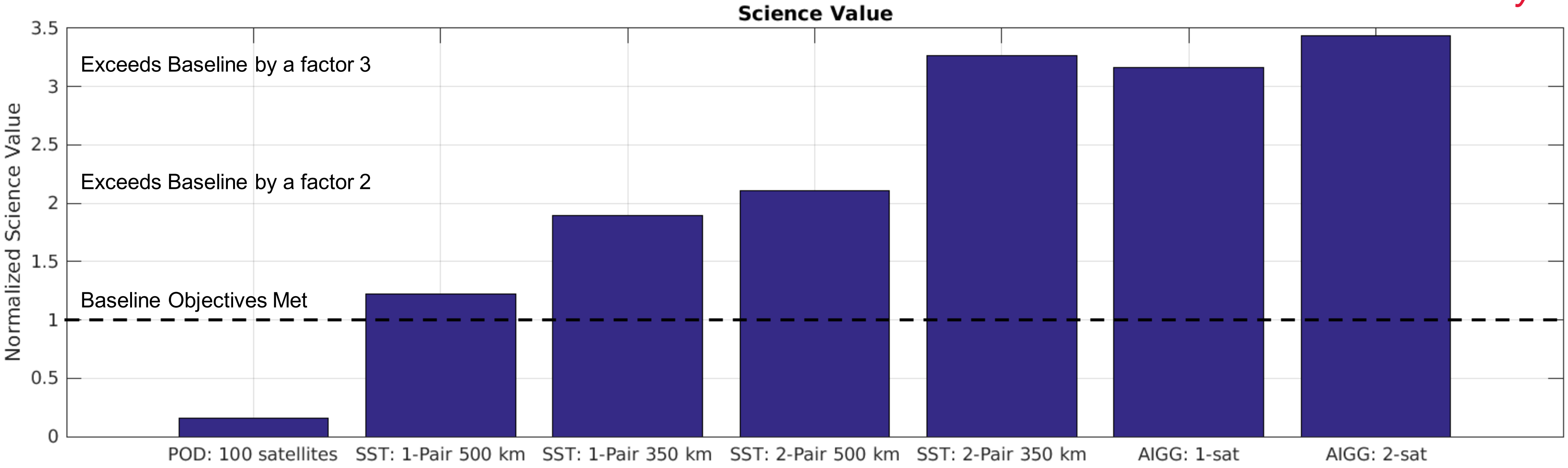
Highest Weight

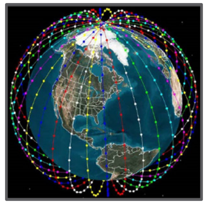
$SV_{H\text{-}1a}$ = 1 * 10/4 = 2.5

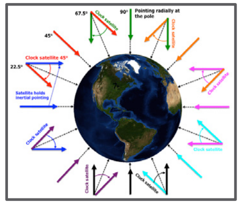
Science Value: Preliminary Results

Architectures are assessed directly against targets in the SATM to provide a quantitative science value to each architecture

Results are Preliminary

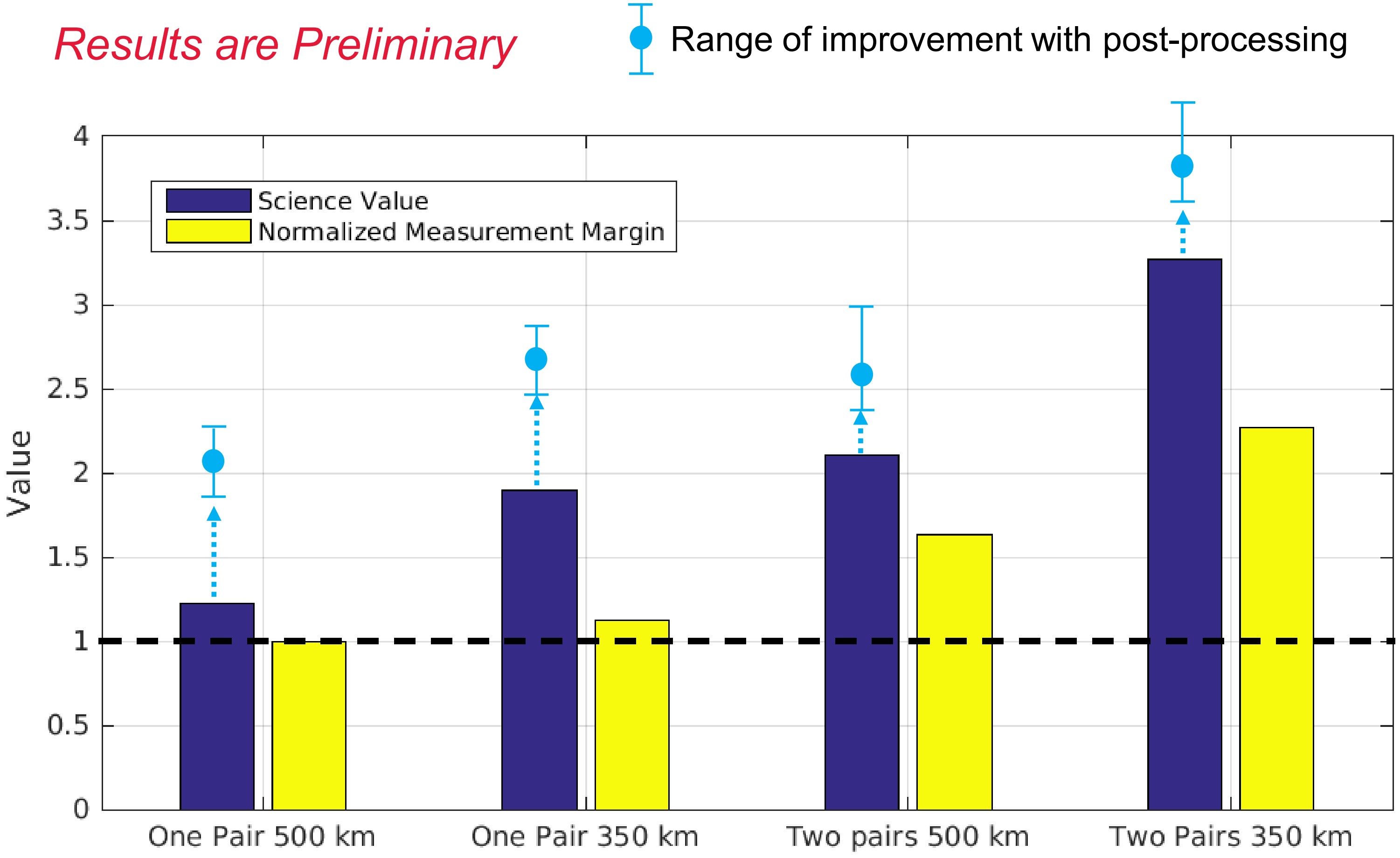






Combined Science Value Metrics

Results are Preliminary



Three metrics are assessed

- (1-2) Science Value
  - Includes temporal aliasing errors
  - Value of 1 means Baseline objectives are met on average
  - Assessed with and without post-processing applied
- (3) Normalized Measurement Margin
  - No temporal aliasing errors
  - Assesses only the capability of the measurement system
  - Normalized against program of record (POR) so a value of 1 indicates consistency with POR, and values < 1 mean degradation relative to POR

Architecture Evaluation

Architecture Evaluation

- Objectives
  - Assess the cost effectiveness of each of the studied architectures
  - Perform sufficient in-depth design of one or two select architectures to enable rapid initiation of a Phase A study
- Guidelines
  - Measures will be defined based on the ESAS 2017 DS to assess the features relevant to decision criteria while providing the ability to discriminate between alternatives
  - The DO study will identify architectures to support most important and very important science objectives
  - Value Framework will assess architecture solutions to most/very important science objectives (performance), risk, cost, schedule
  - A basis for down-selection will be necessary; justification will be needed for eliminating candidate architectures

Flow Diagram – Architecture Concept to Initial Value Assessment

Architecture Definition

1. Conceptualize Architecture
- Number of Platforms & Orbits
- Size: Medium sat, Small sat
- Combinations, etc.
- Non-flight system elements

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

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

Value Effectiveness

4. Map Capability to Objectives
- 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

Cost Effectiveness - Comparisons

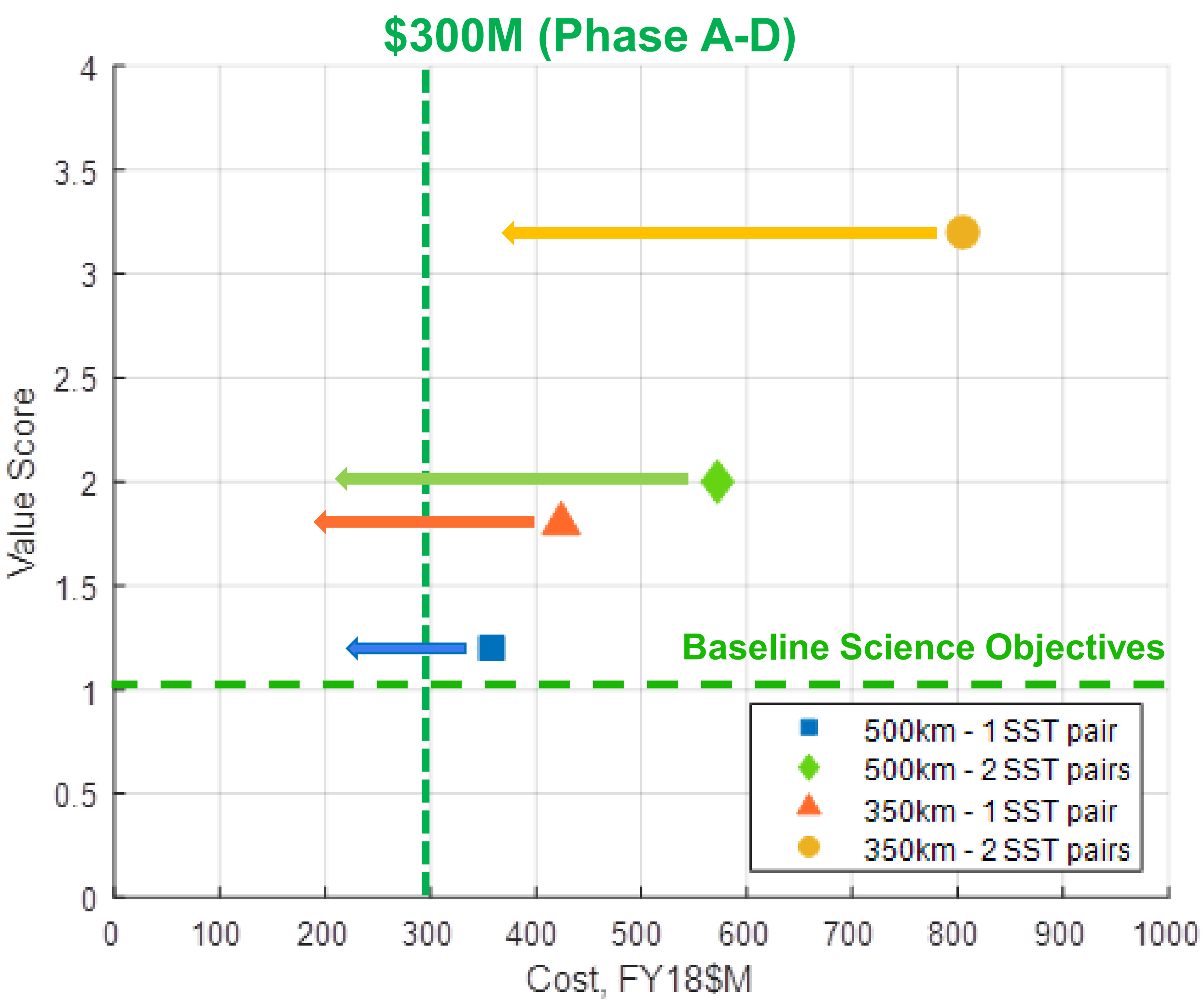
7. Assess Value vs. Cost
- Value metric = f(decadal objectives)
- Cost can be a point or range
- Risk-rated based on TRL or availability relative to need date

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

Cost Effectiveness Comparisons Value Framework – Preliminary

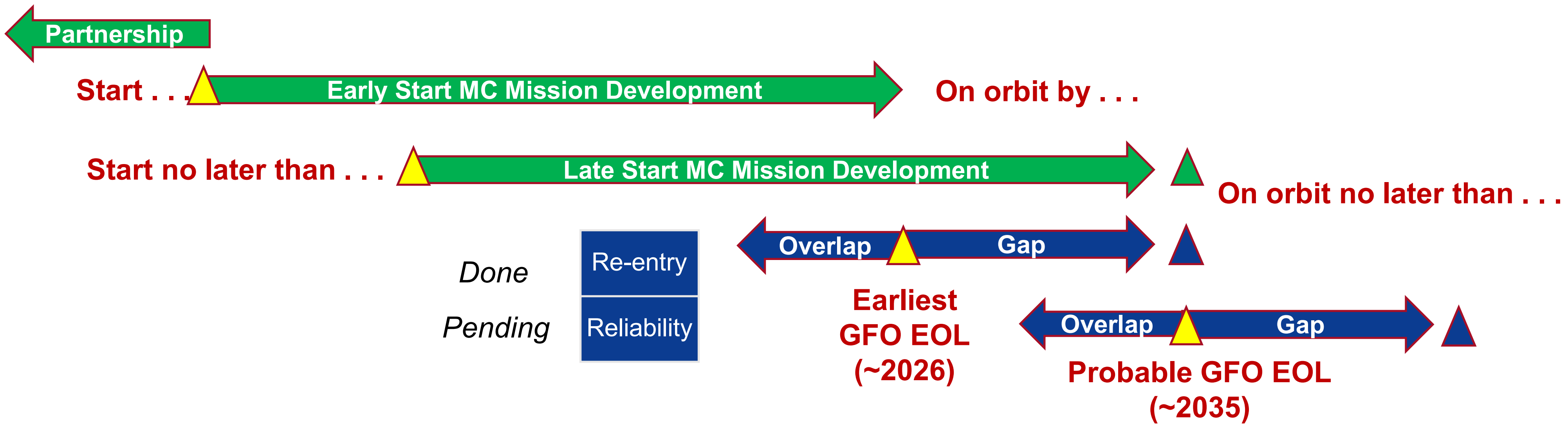
Results are Preliminary

- Preliminary results for SST based architectures at 350 and 500 km altitudes
- Value scoring does not yet account for mission duration
- Reduced cost may be enabled through strategic partnerships (indicated by notional arrow on the figure)
- Enhanced science return is enabled through new technologies and/or innovation
- Architectures below the Baseline or significantly above cost target will not be considered



Continuity with GRACE Follow-On

- Continuity is paramount
- Assess GRACE-FO (GFO) status and predicted end of life
  - Combination of orbit lifetime (re-entry date) and system reliability
- Orbit lifetime is highly dependent on solar activity and its impact on atmospheric density
  - Range of 2026 – 2035 (~95% - 50% confidence intervals) based on altitude degradation only
- Working with GFO team to understand long term system reliability based on current GFO status
- Schedule alignment with partners may affect development schedule
- Using new approaches/technology may require overlap to assess potential biases and perform calibrations



Architecture Evaluation – Path Forward Significant Events

- 5/26-29: Team X design session at JPL
  - Focus on smallest feasible SST implementation
- 6/1-9: Instrument Design Lab at GSFC
  - Focus on Gravity Gradiometer instrument concept
- June: Update Analysis of Alternatives documentation
- July: Deliver final briefing to HQ with recommended architecture candidate

NASA