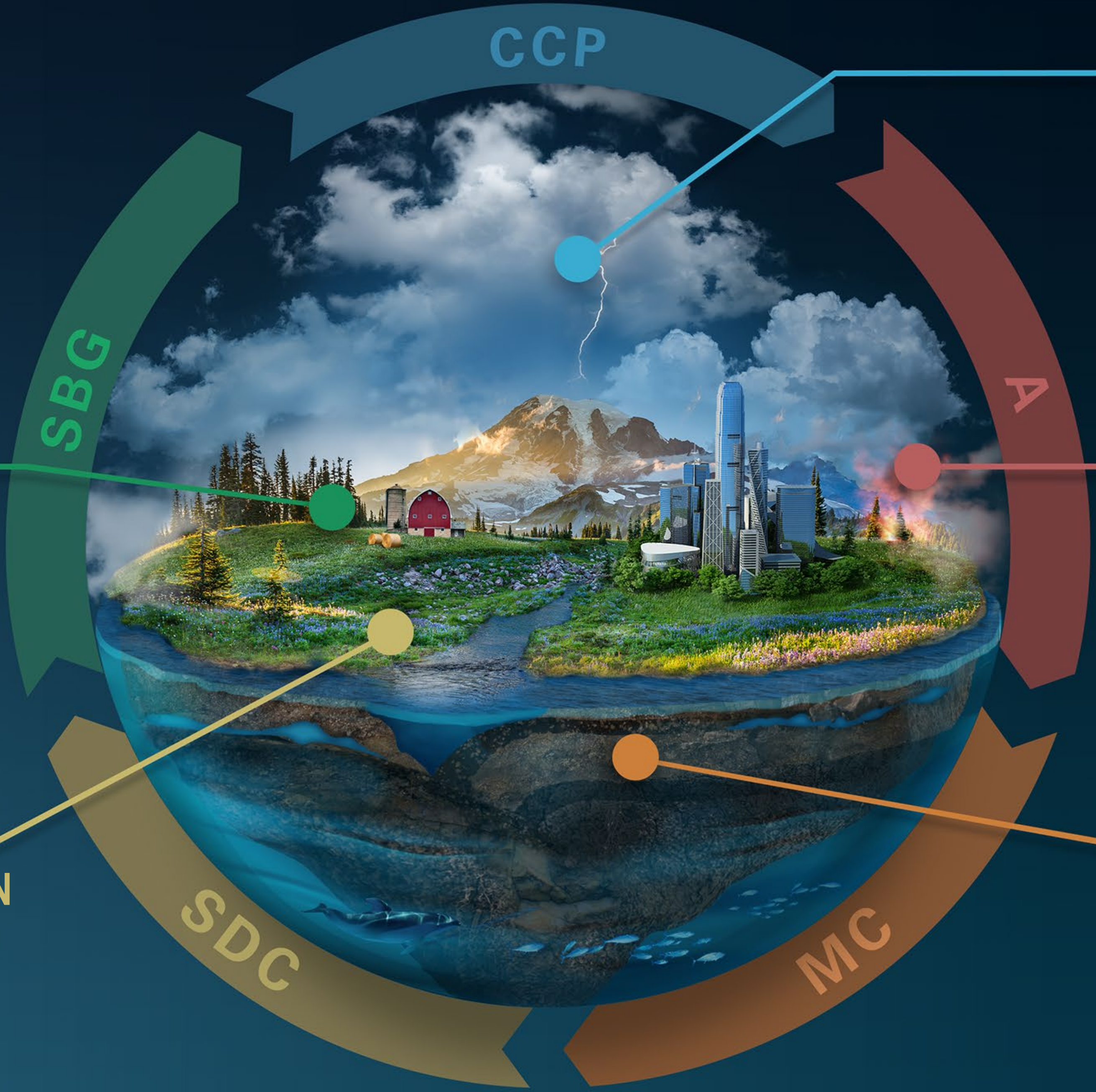
Mass Change AGU 2021 Town Hall

1. Introduction and Opening Remarks

Lucia Tsaoussi, NASA Headquarters
Bernie Bienstock, Jet Propulsion Laboratory/California Institute of Technology

EARTH SYSTEM OBSERVATORY

INTERCONNECTED CORE MISSIONS



CLOUDS, CONVECTION AND PRECIPITATION

Water and Energy in the Atmosphere

SURFACE BIOLOGY AND GEOLOGY

Earth Surface & Ecosystems

AEROSOLS

Particles in the Atmosphere

SURFACE DEFORMATION AND CHANGE

Earth Surface Dynamics

MASS CHANGE

Large-scale Mass Redistribution

Five things to know about the ESO

EARTH
SYSTEM
OBSERVATORY

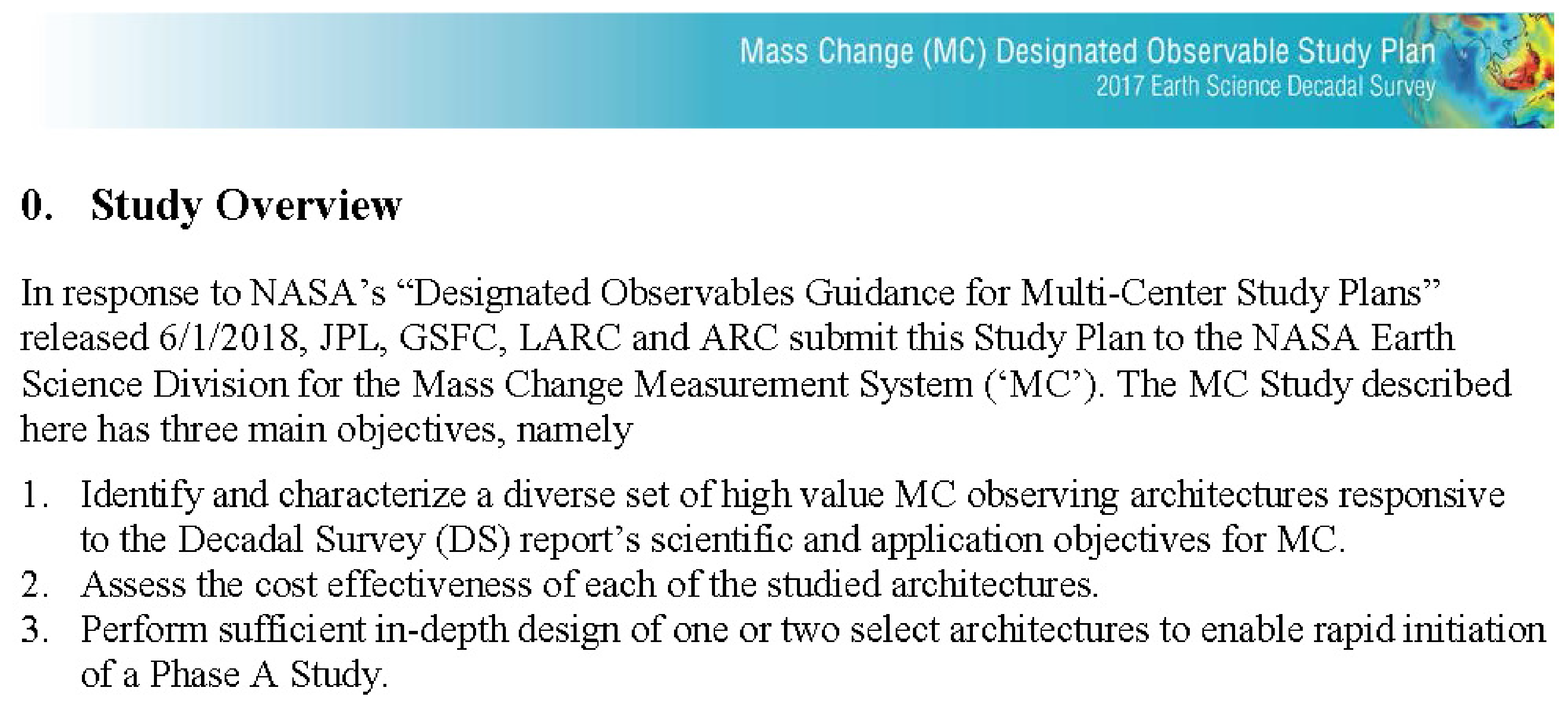
- Before the end of this decade, NASA will put into orbit the Earth System Observatory
  - A single observation system comprised of five core satellite missions and three Earth Explorer missions
- The ESO is the heart of our implementation strategy for the Decadal Survey, addressing the most pressing questions about our changing planet posed by the Earth Science community through the National Academies' Decadal process
- The ESO builds on the capabilities of NASA's 23 operating missions and the 18 in development that make up the program of record
- Competitively selected Earth Explorer missions will bring innovation and additional key observations to the ESO
  - The private sector, academic community, and international space agencies will have significant roles in ESO success
- NISAR serves as a "trailblazer" for the ESO, addressing one of the five core observables, involving substantial international partnership, advancing open source science, and strongly coupling research and applied sciences

Agenda

EARTH SYSTEM OBSERVATORY

No	Start (PST)	Duration	Topic	Presenter
1	4:15 PM	0:05	Introduction and Opening Remarks	Lucia Tsaoussi, NASA HQ Bernie Bienstock, JPL/Caltech
2	4:20 PM	0:05	Science and Applications Traceability Matrix (SATM)	Matt Rodell, NASA GSFC
3	4:25 PM	0:05	Architectures and Technology	Bryant Loomis, NASA GSFC
4	4:30 PM	0:05	Science Value Methodology	David Wiese, JPL/Caltech
5	4:35 PM	0:05	Value Framework Process	Jon Chrone, NASA LaRC
6	4:40 PM	0:05	MC Study Summary	Bernie Bienstock, JPL/Caltech
7	4:45 PM	0:10	Mass Change Pre-Phase A Status	Charley Dunn, JPL/Caltech
8	4:55 PM	0:05	MC Applications and Community Assessment Report (CAR)	Matt Rodell, NASA GSFC
9	5:00 PM	0:15	Feedback and Community Discussion	Scott Horner NASA Ames
10	5:15 PM		Adjourn	

Mass Change Study Plan Approved October 28, 2018



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.

Phase 1 and Phase 2 Activities

Item	Review and Engagement	Complete
Science and Applications Traceability Matrix (SATM)	• MC Community Meeting • Fall 2019 SATM focused reviews • American Geophysical Union (AGU) 2019 Town Hall • April 2020 Community Telecons • European Geosciences Union (EGU) 2020	➲
Architecture classes	• AGU 2019 Town Hall • April 2020 Community Telecons • EGU 2020 • 2020 GRACE/GRACE-FO Science Team Meeting • AGU 2020 Town Hall	➲
Science value	• AGU 2019 Town Hall • April 2020 Community Telecons • EGU 2020 • 2020 GRACE/GRACE-FO Science Team Meeting • AGU 2020 Town Hall	➲
Cost estimates	• Internal Team Review	➲
Schedule estimate including continuity with the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO)	• Internal Team Review	➲
Technology readiness, risks, and maturation plans	• Internal Team Review	➲
Preliminary identification of international partnership concepts and areas of interest	• European Space Agency (ESA) – 10 meetings from Feb 2020–June 2021, including 3 tech forums *Delivery of Mass-change And Geosciences International Constellation (MAGIC) Mission Requirements Document (MRD)* • Centre National d'Études Spatiales (CNES) – 13 meetings from Feb 2020–May 2021 *Delivery of CNES Mass And Reference Variations for Earth Lookout (MARVEL) report* • Deutsches Zentrum für Luft-und Raumfahrt (DLR) / German Research Centre for Geosciences (GFZ) – 8 meetings from March 2020–March 2021 *Delivery of DLR/GFZ GRACE-I (International Cooperation for Animal Research Using Space [ICARUS]) report*	➲
Synthesis of findings for an architecture recommendation for Pre-Phase A Study	• Internal Team Review	➲

High-Level Architectures Identified

The MC study team analyses included:

- NASA Headquarters (HQ) guidance and constraints
- Decadal Survey (DS) recommendations
- Community input
- Technology readiness
- High-level cost estimates
- International partner interest, capabilities, and readiness

The highest-value architectures were identified to

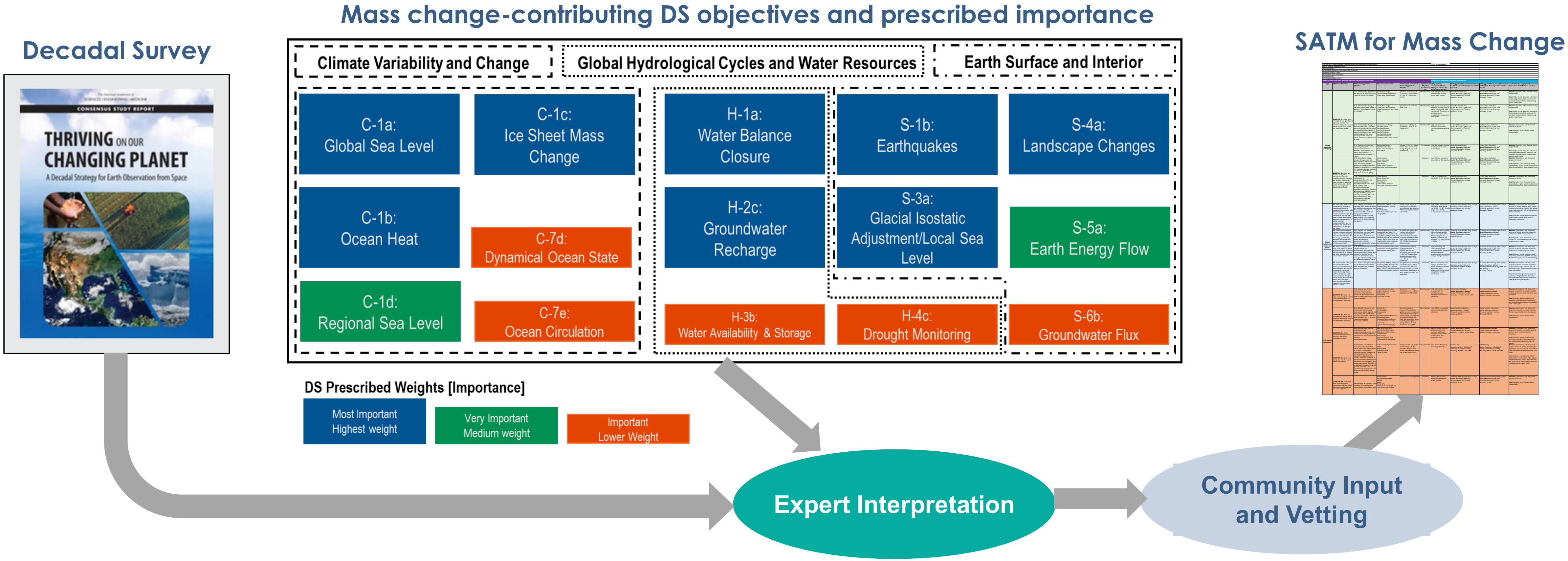
- Provide acceptable levels of DS recommended science, as judged by the community
- Include technology elements that can be matured within the DS timeframe

2. Science and Applications Traceability Matrix (SATM)

Matt Rodell, NASA Goddard Space Flight Center

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]

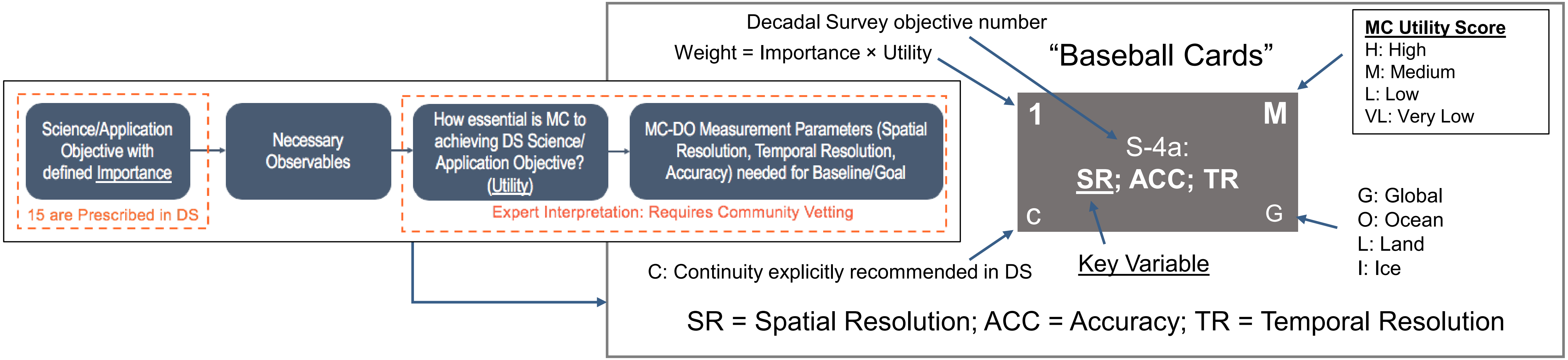
- Most Important Highest weight
- Very Important Medium weight
- Important Lower Weight

SATM for Mass Change

Expert Interpretation

Community Input and Vetting

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"

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

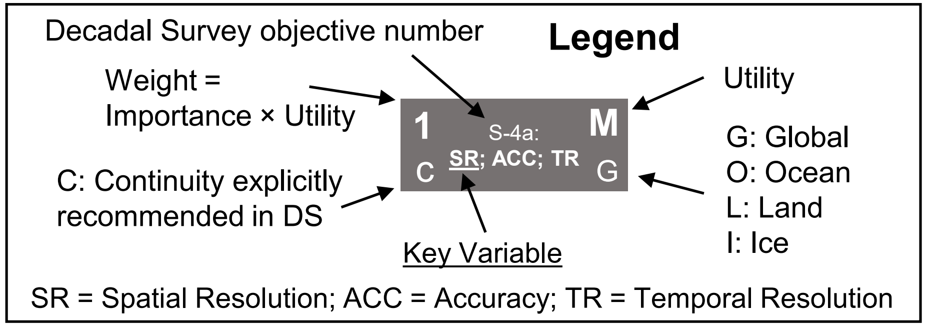
SR = Spatial Resolution; ACC = Accuracy; TR = Temporal Resolution

- A "deck" of "baseball cards" was developed for baseline science objectives and goals
- "Baseline" observing system was defined to provide data product quality that is roughly consistent with the Program of Record (POR)
- "Goal" observing system was defined to provide improvements relative to the POR that would enable advancements in Earth system science, as recommended by the DS

Decadal Survey Science and Application Objectives for Mass Change

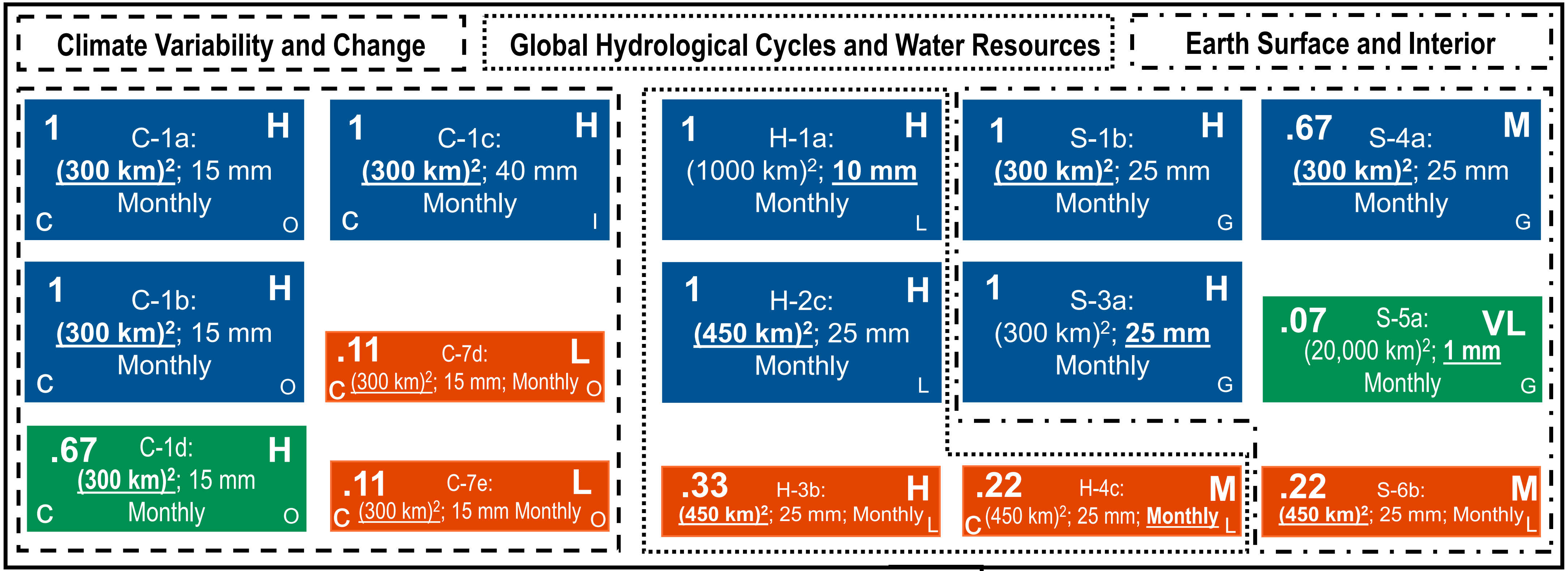
Measurement Parameters for Baseline

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: H
(300 km)^2; 15 mm
Monthly
C O

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

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

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

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

.11 C-7e: L
(300 km)^2; 15 mm Monthly
C 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
(450 km)^2; 25 mm; Monthly
C L

Earth Surface and Interior

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

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

1 S-3a: H
(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

DS Prescribed Importance

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

MC Utility Score

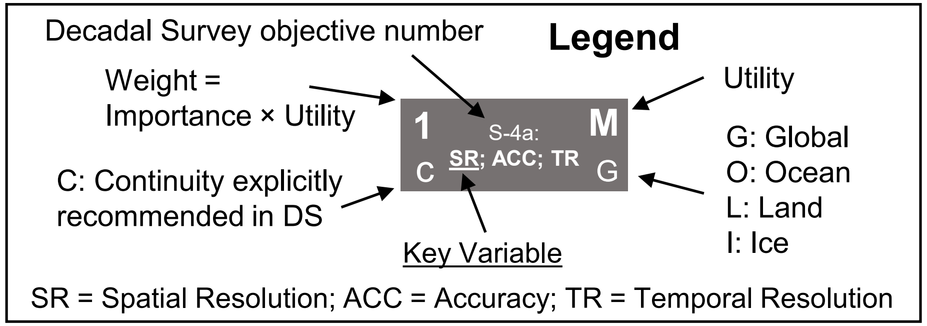
H: High	1.0
M: Medium	0.67
L: Low	0.33
VL: Very Low	0.10

→ 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 × Utility

C: Continuity explicitly recommended in DS

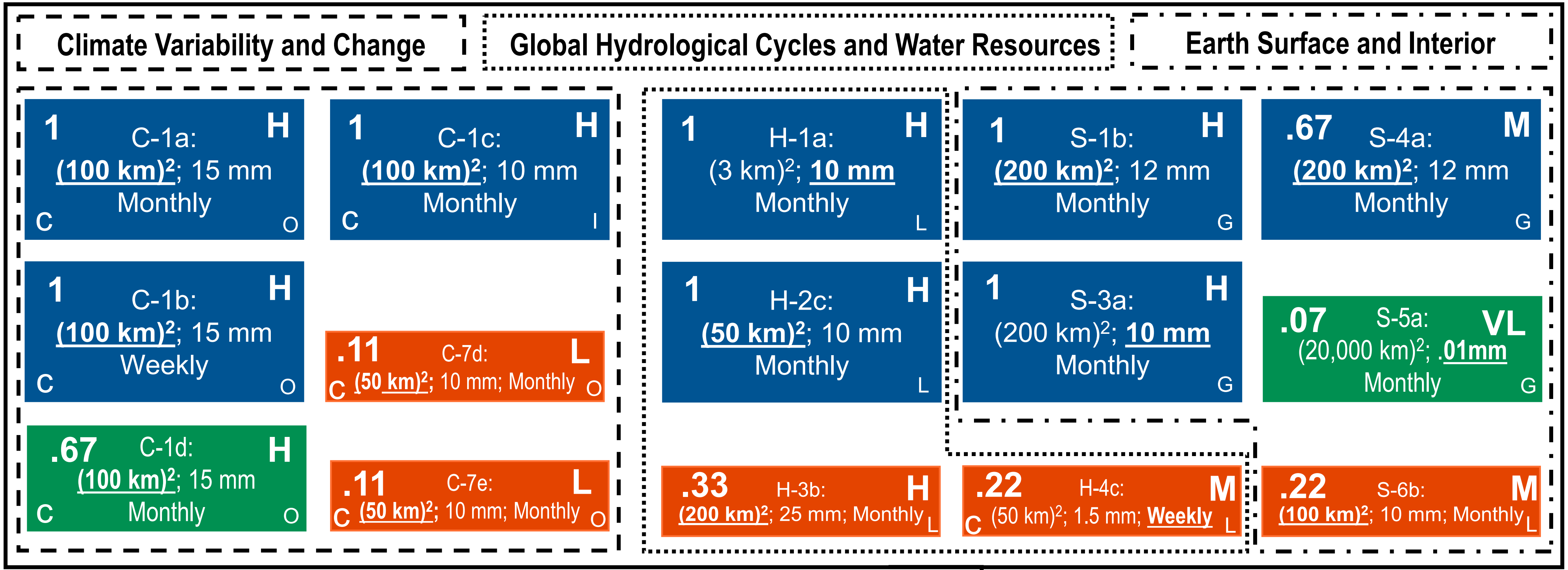
Key Variable

Utility

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

1 S-4a: M
SR; ACC; TR
C G

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



Climate Variability and Change

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

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

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

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

Global Hydrological Cycles and Water Resources

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

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

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

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

Earth Surface and Interior

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

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

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

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

.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 SATM Closing Thoughts

- Mass change is essential to Most Important objectives in three Decadal Survey areas (Climate, Hydrology, and Solid Earth) with varying spatial and temporal resolution and accuracy requirements
- Continuity of mass change measurements was emphasized by the Decadal Survey → baseline measurement characteristics
- Goal measurement characteristics describe the aspirations of the Decadal Survey which are beyond what is possible in many cases
- Spatial resolution, temporal resolution, and accuracy all three exist in one tradespace that can be used to accommodate characteristics desired for different objectives

MASS CHANGE

3. Architectures and Technology

Bryant Loomis, NASA Goddard Space Flight Center

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** & **SST**: Measurements capture gravity impact on satellite motion; *satellites are the instrument*

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

Opening of the Tradespace—Technology

Technology development efforts seek to reduce instrument errors and/or facilitate advanced architectures:

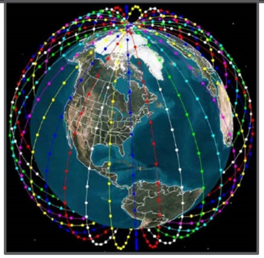
Technology*	Motivation
Laser ranging interferometer (LRI) as primary instrument	• LRI performs ~100x better than the Microwave Interferometer (MWI) • Successful tech demo on GRACE-FO; primary achievable with standard engineering • Same level of precision is strongly desired by the community and is already yielding important science outcomes (larger benefit to along-track analysis than Level 2)
Advanced accelerometers	• Leading measurement error source on GRACE-FO
SST technologies for pendulum	• Pendulum architecture adds directionality & reduces north-south stripes
GG technologies	• Capable of mitigating aliasing errors (i.e., north-south stripes) • Implementable with a single-platform
Miniaturization of SST technologies	• Cost-effective implementation of a multi-pair constellation for reducing temporal aliasing errors
Electric propulsion	• Needed for drag compensation which facilitates: ○ Altitude reduction – Increase sensitivity to gravity signal ○ Orbit maintenance – Avoid orbit resonance & maintain ground track

*Technologies are at differing maturity levels (TRL 2–9), which was a major consideration in the Value Framework

Opening of the Tradespace—Architectures and Technology

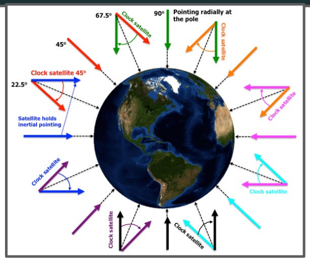
SST
Satellite-to-satellite tracking

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

Architectures and Technology—Conclusions

Key architecture takeaways

- Architectures recommended by MC study team for further study in Pre-Phase A and Phase A:
  - SST in-line pair
  - SST in-line pair plus pendulum (3 satellite configuration)
  - SST two in-line pair (Bender)
- Architectures not recommended:
  - POD: Poor science performance
  - GG: High science performance but long/uncertain path to TRL 6
  - SST LEO/MEO: Limited performance benefit for significant increase in complexity
  - SST N-pair SmallSats: Significant systems engineering challenges remain

Key technology takeaways

- Recommended SST ranging instrument: LRI
- Recommended accelerometer: ONERA electrostatic (several candidates to be considered)
- Recommended for further study in Pre-Phase A and Phase A:
  - Accelerometer tech demo options: S-GRS (high performance); optomechanical (significantly reduced SWaP)
  - Electric propulsion impacts on spacecraft design (i.e., increased power requirements)

GG	Gravity gradiometer
LEO	Low Earth Orbit
LRI	Laser Ranging Interferometer
MEO	Medium Earth Orbit
MC	Mass Change
POD	Precise Orbit Determination
S-GRS	Simplified LISA Pathfinder Gravitational Reference Sensor
SST	Satellite-to-satellite tracking
SWaP	Size, Weight, Power
TRL	Technology Readiness Level

4. Science Value Methodology

David Wiese, Jet Propulsion Laboratory/California Institute of Technology

Relating Observing System Capability to the DS

Decadal Survey (DS)

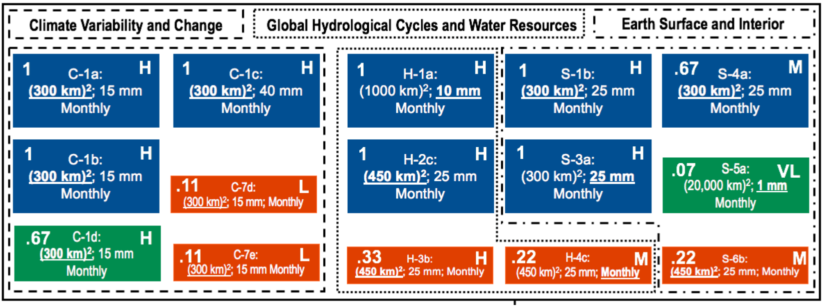
The National Academies of SCIENCES · ENGINEERING · MEDICINE

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: (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

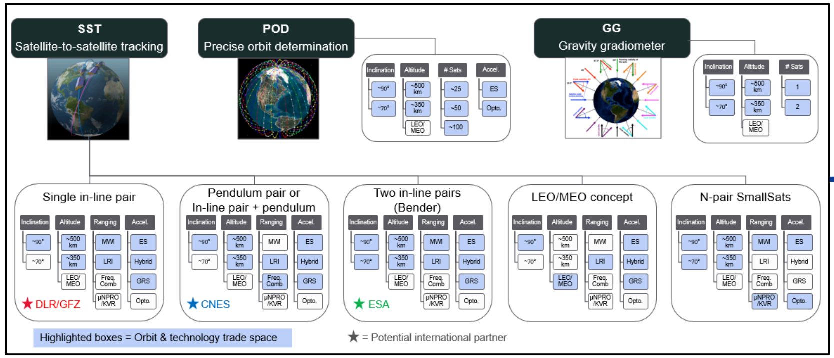
Earth Surface and Interior

- 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

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

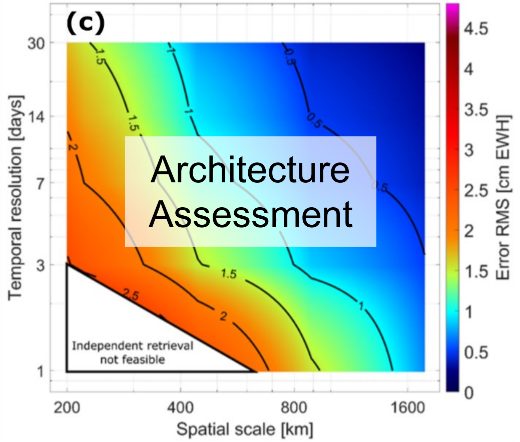
The process has been presented to the community for input and is successful in discriminating between architectures

Architecture Tree



Highlighted boxes = Orbit & technology trade space

★ = Potential international partner



Architecture Assessment

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
    - Includes temporal aliasing errors
    - Includes full suite of measurement system errors
  - 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
  - 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

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

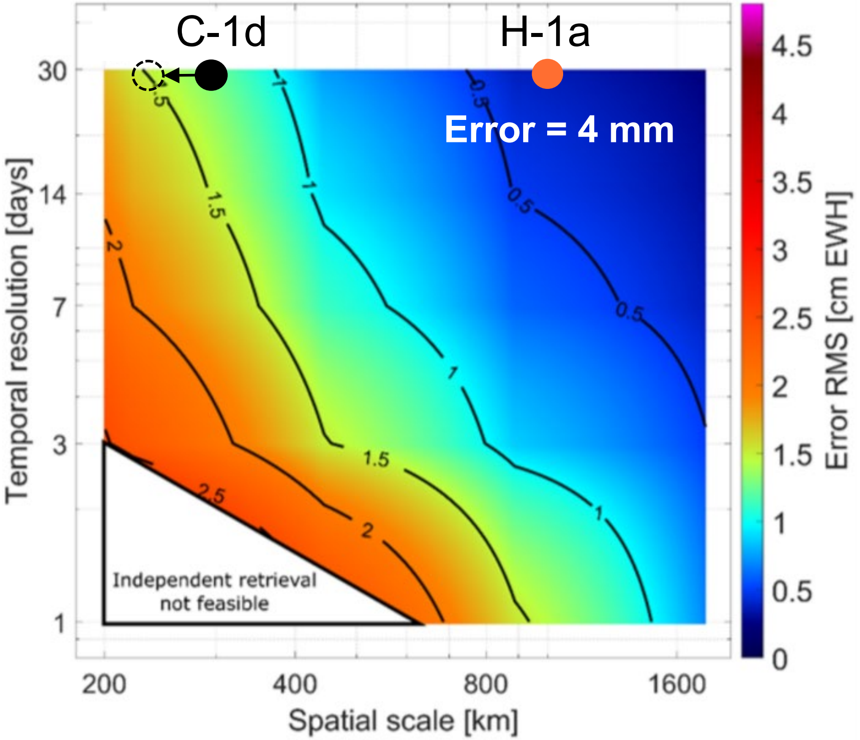
Key Variable: **Spatial Resolution**

.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



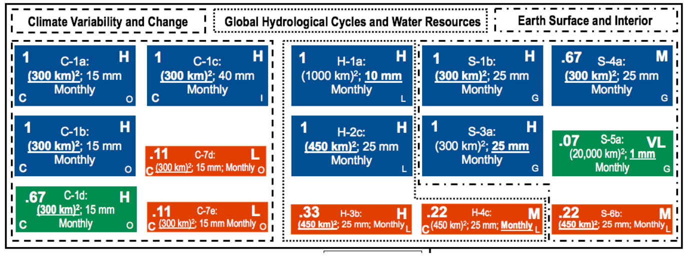
Hauk and Wiese, Earth and Space Science, 2020

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

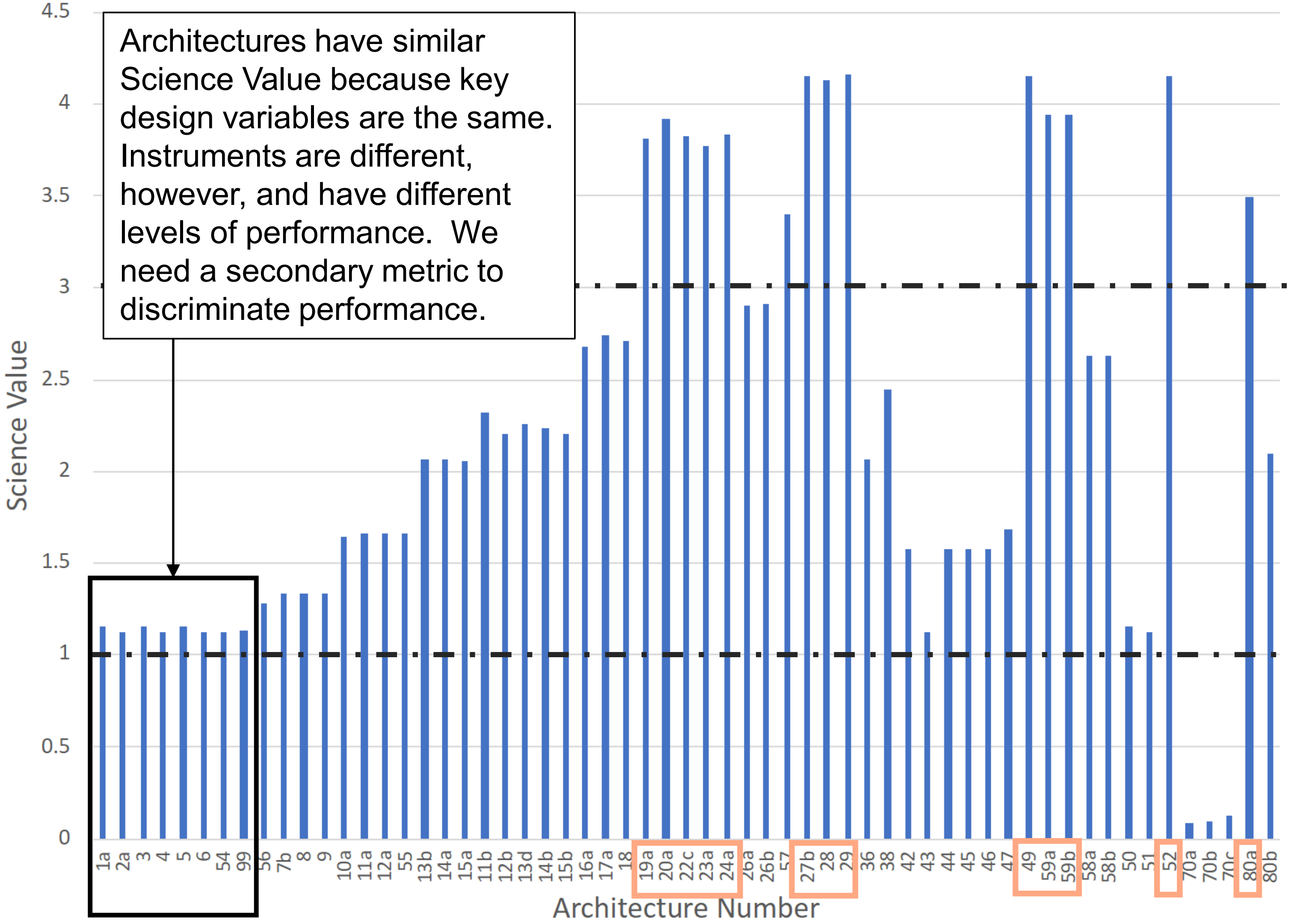
1 S-3a: H (300 km)^2; 25 mm Monthly G

.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

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

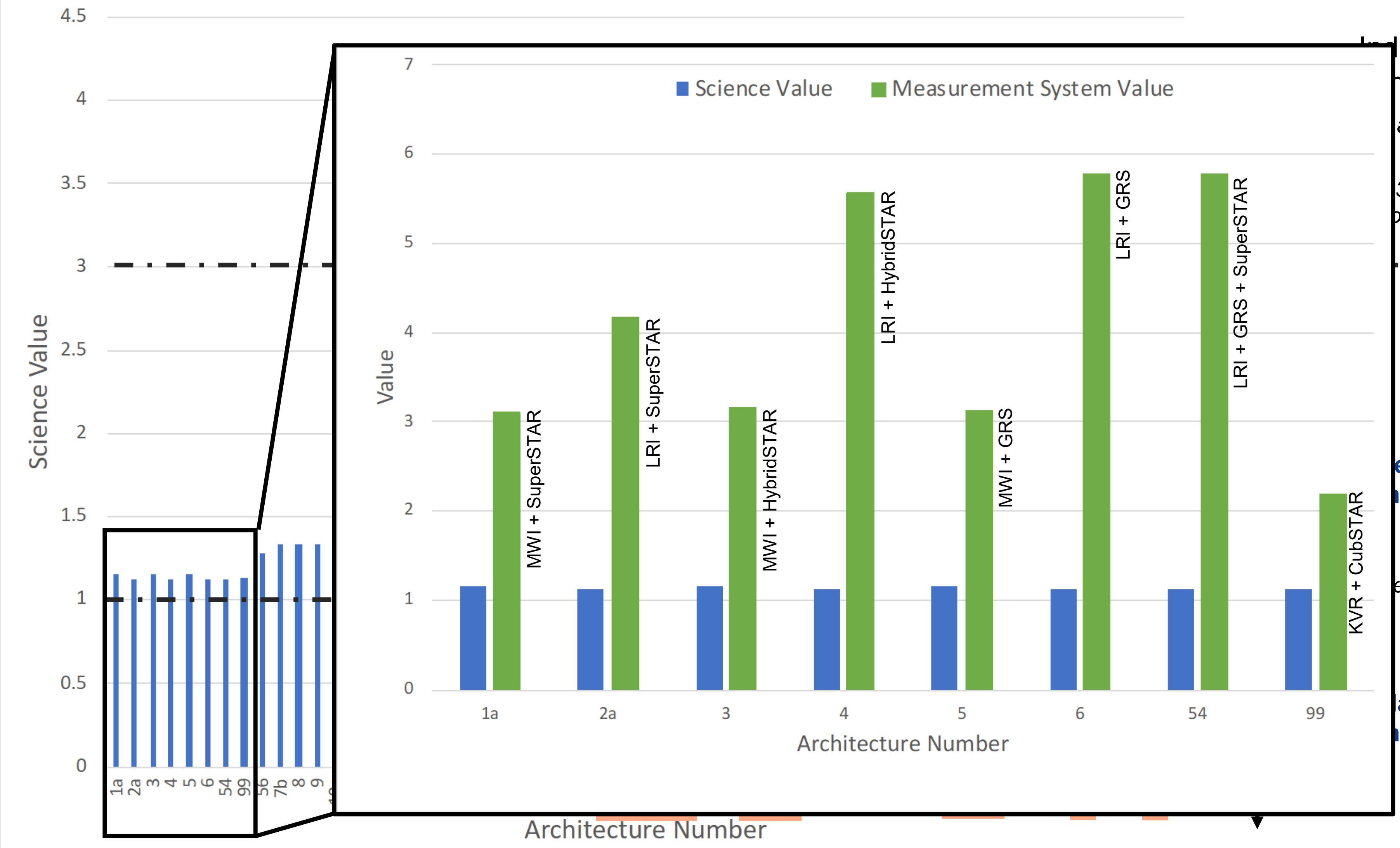
Indicates a Factor 3x improvement over Baseline in terms of a combination of resolution and accuracy

Improvement Relative to Baseline Science Objectives

Baseline Science Objectives are met

Degradation Relative to Baseline Science Objectives

Results: Science Value



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5. Value Framework Process

Jon Chrone, NASA Langley Research Center

Value Framework Objectives

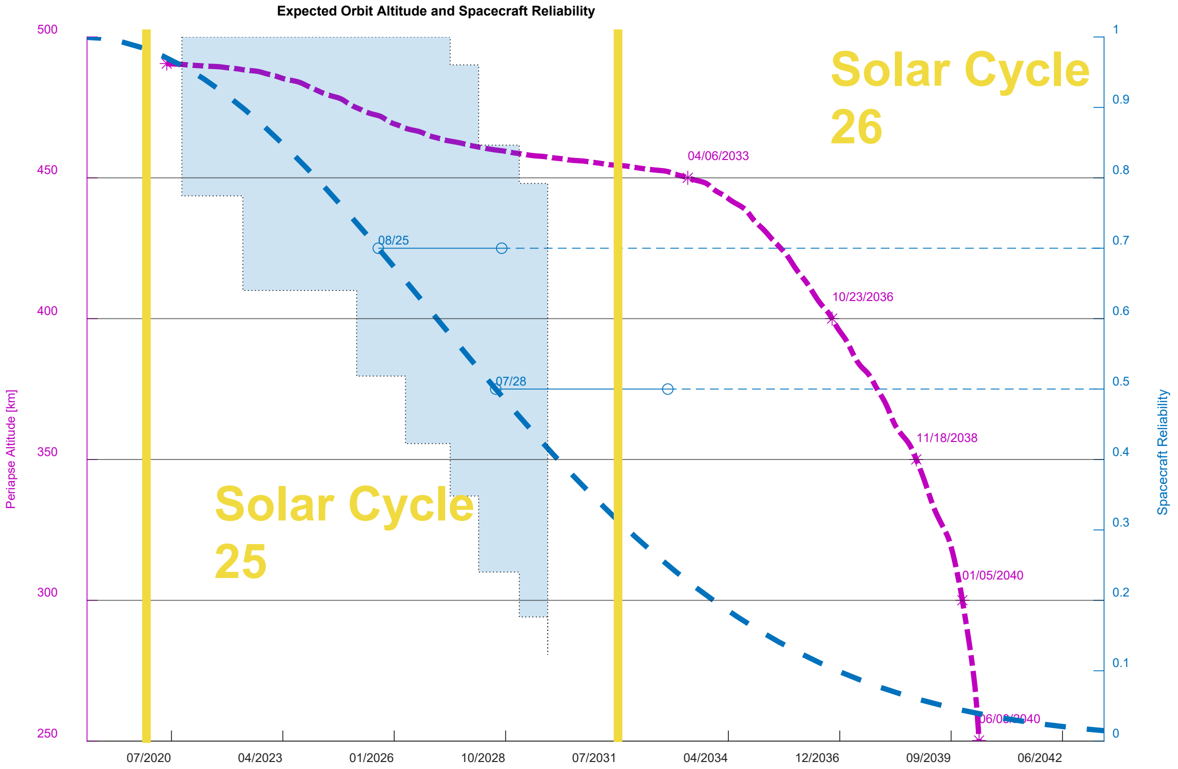
- Identify architectures that support the Mass Change (MC) Science and Applications objectives
  - Traceable to Decadal Survey (DS) priorities and recommendations
- Assess the cost effectiveness of each of the studied architectures
  - Impacted by multiple elements of Value
  - Capability (Science and 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

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

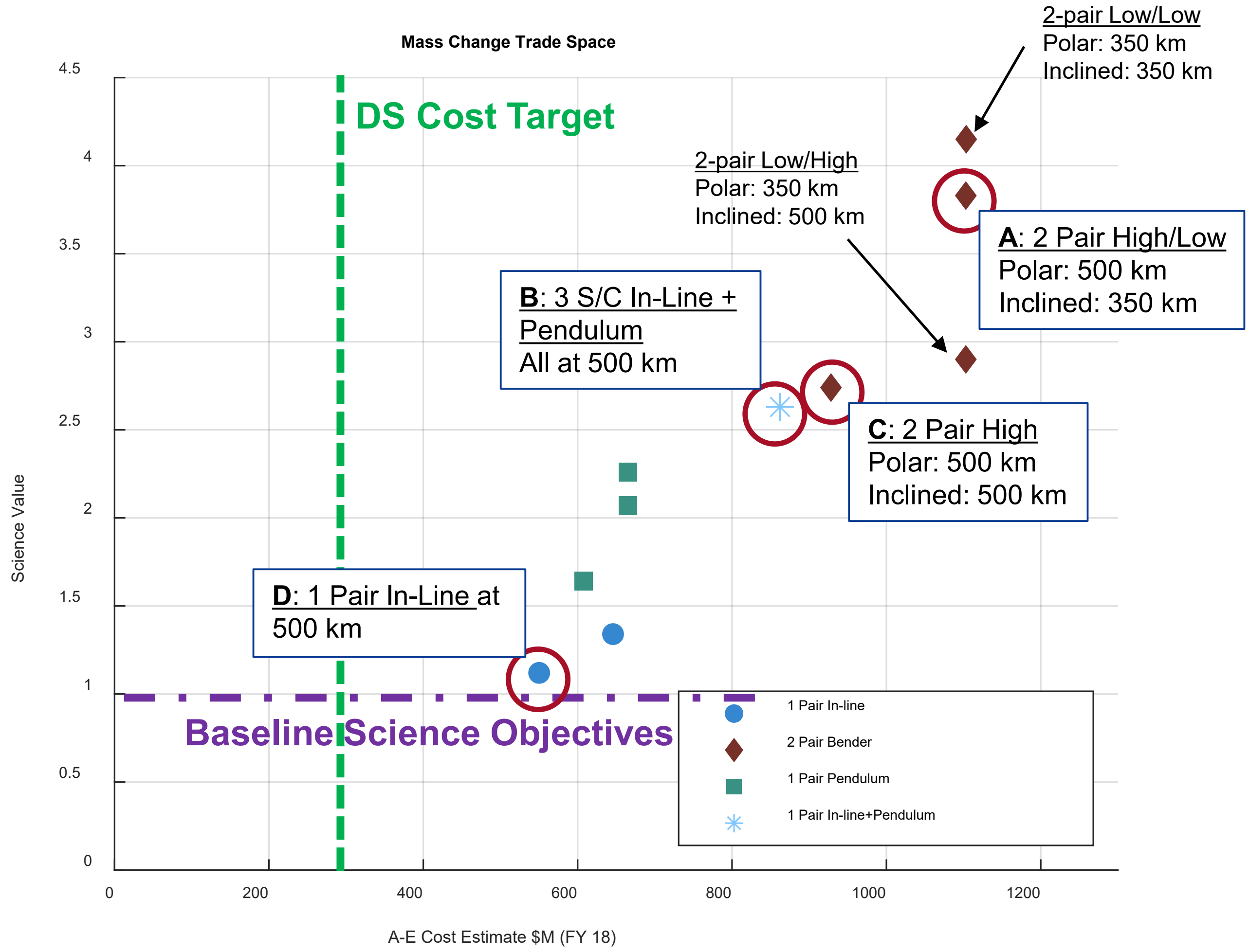
GRACE-FO Orbit Lifetime and Expected Reliability

- 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



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 A, B, C can be staggered; Architecture D can be launched first with remaining elements launched later
- Architecture A (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
- Architectures (A, B, C, D) are compatible with international interests



6. MC Study Summary

Bernie Bienstock, Jet Propulsion Laboratory/California Institute of Technology

Conclusions

- Much study effort focused on developing and vetting the MC SATM
- The MC observing system tradespace, including architectures and technologies, is well understood, with the most promising candidates identified for further study and refinement in MC Pre-Phase A
- Evolvable observing system includes a baseline configuration that accelerates science return, increases likelihood of continuity with GRACE-FO, and provides programmatic flexibility to enable improved science return via enhancements benefiting from international participation and contributions
- Pre-Phase A activity is focused on developing workshare options with international partners and refining cost/schedule estimates to establish expected cost to NASA for the baseline and enhancements

7. Mass Change Pre-Phase A Status

Charley Dunn, Jet Propulsion Laboratory/California Institute of Technology

Mass Change Pre-Phase A

- NASA Authorized the start of Pre-Phase A in May, 2021:
  - Overarching trade study of three architecture options based on a staggered two-pair constellation architecture
  - Target first launch in ‘27 or ‘28 with cost constraints
  - Work with ESA and other international partners

- Pre-Phase A activities:
  - Determine work-share and architecture scenario with potential international partners
  - Develop coherent plan: requirements, design concept, schedule & budget

Mass Change Pre-Phase A Status

- Partner discussions with ESA, DLR, CNES, ASI and other potential partners
- Architecture and work-share converging:
  - Early pair of satellites (P1) launched to ensure continuity of the science record:
    - 2027- 2028 launch
    - Orbit similar to GRACE-FO (~500 km near polar)
  - A later pair of satellites (P2) launched later (~2029-2031) with more advanced technology for science advancement & sustainment
    - Lower orbit (300-400 km) at ~70° inclination
  - P1 may carry demonstration technology to reduce the risk of P2

MASS CHANGE

8. MC Applications and the Community Assessment Report (CAR)

Matt Rodell, NASA Goddard Space Flight Center

Mass Change Contributes to Practical Applications

WATER RESOURCES

Provide unique information on changes in the availability of water resources, including groundwater, in regions where in situ measurements are lacking or inaccessible.

Constrain estimates of precipitation, evapotranspiration, and runoff, which are needed by water managers, via water budget closure.

DROUGHT

Quantify soil dryness in the shallow and deep subsurface.

Provide maps of drought with high spatial and temporal resolution after integration with other observations within a numerical model via data assimilation.

FLOOD

Assess flood vulnerability and enhance predictability by comparing current and historical terrestrial water storage levels.

AGRICULTURE

Inform crop yield forecasts with soil moisture data.

Improve estimation of seasonal snowpack, leading to better predictions of surface water availability for agricultural irrigation.

Track irrigation water demand and predict future availability in regions where aquifers are the primary water resource for agriculture.

SEA LEVEL

Monitor and predict local and regional sea level changes.

Together with satellite altimetry, measure ocean heat content to constrain Earth's energy imbalance and improve predictability of future sea level rise.

OTHER POTENTIAL

Support earthquake hazard assessment and forecasting.

Constrain land surface boundary conditions in short-term and seasonal weather prediction systems.

Provide long-term changes in moisture availability for forest health assessments.

Assess fire risk based on drought/wetness maps.

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 finding, using, and interpreting NASA data products

MC Community Assessment Report (CAR)

Goal: Maximize the return on investment of current and future MC missions by enhancing their applications value and societal benefits

Approach: Identify potential MC user communities who have information needs which resemble the types of data that can be derived from MC observations

CAR Development

- Assessment of the current community of practice for Mass Change, including existing GRACE and GRACE-FO data users, through workshops and a survey of 87 users
- Assessment of the community of potential, led by RTI International, through a series of discussion panels and interviews with representatives from private industry and public agencies
- RTI International delivered a report in May that provided the basis for the CAR
- The Mass Change Applications Team (MCAT) has provided guidance throughout the CAR development and is executing the final version of the CAR report

MC Community Assessment Report (CAR)

Key Outcomes

- Majorities of current and potential users would prefer products with 25 km or better horizontal resolution and weekly or better temporal resolution and latency, with accuracy similar to that of the program of record
- User confidence that the data record will be uninterrupted going forward is crucial
- Building awareness of NASA Earth Observational data and making it easier to find and access are the first steps to attracting new users
- Most users require higher-level products, where mass change observations are integrated with land, ocean, and/or ground water models that integrate other Earth observations

Availability

- The final draft of the MC CAR will be delivered to NASA's Applied Sciences Program in December and is expected to be posted on their website (https://appliedsciences.nasa.gov/) and the MC website (https://science.nasa.gov/earth-science/decadal-mc) around the start of the new year

MASS CHANGE

9. Feedback and Community Discussion

Scott Horner, NASA Ames Research Center