The NASA Mass Change Designated Observable Study AGU 2020 Town Hall

December 11, 2020

Presented by Lucia Tsaoussi[4], Bernie Bienstock[1], Matt Rodell[2], Bryant Loomis[2], David Wiese[1], Jon Chrone[3]

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Introduction

Lucia Tsaoussi, NASA HQ

Mass Change Program Scientist

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 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 Mission**
  - NASA Initiated 4 multi-center studies in 2018 to investigate observing system architectures, considering synergies with other obs, accelerating research and applications and partnerships.

NASA DS Implementation Status

NASA continual posting of programmatic updates and Decadal Survey Implementation

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

- **Decadal Designated Observable Studies**
- Aerosol and Cloud, Convection and Precipitation (ACCP)
- Mass Change (MC)
- Surface Biology and Geology (SBG)
- Surface Deformation and Change (SDC)
- **Incubation Study Teams**
- Planetary Boundary Layer (PBL)
- Surface Topography and Vegetation (STV)

NASA community forum presentations available:

- Send us your questions about the Decadal.
- Decadal Survey Questions
- Decadal Survey Community Forums
- Presentations and Other Materials
- ESD Directive on Project Applications Program

Opening Remarks

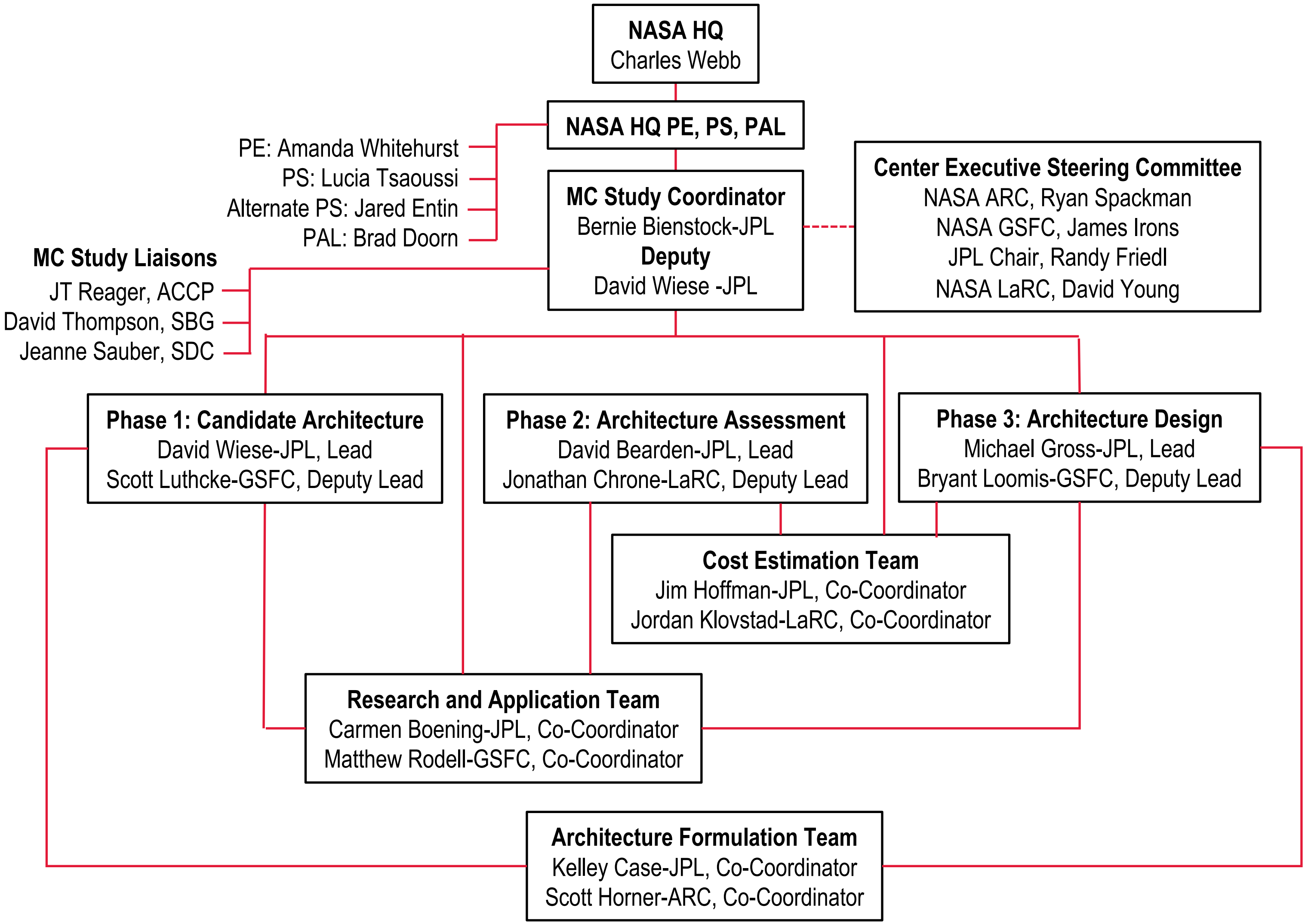
Bernie Bienstock, Caltech/JPL

Mass Change Study Coordinator

Agenda

Start	Duration	Topic	Presenter
7:00 AM	0:10	Introduction and Opening Remarks	Lucia Tsaoussi, NASA HQ Bernie Bienstock, Caltech/JPL
7:10 AM	0:05	Science and Applications Traceability Matrix	Matt Rodell, NASA GSFC
7:15 AM	0:10	Architectures and Technology	Bryant Loomis, NASA GSFC
7:25 AM	0:05	Science Value Methodology	David Wiese, Caltech/JPL
7:30 AM	0:10	Value Framework Process	Jon Chrone, NASA LaRC
7:40 AM	0:20	Feedback and Community Discussion	
8:00 AM		Adjourn	

Mass Change Org Chart



Mass Change Working Groups

Phase 2 WG
- Kelley Case, Lead
- Dave Bearden
- Jon Chrone
- Scott Horner
- Bryant Loomis
- Scott Luthcke
- Frank Webb
- David Wiese

Phase 3 WG
- Michael Gross, Lead
- Rosemary Baize
- Jon Chrone
- Scott Horner
- Bryant Loomis
- Scott Luthcke
- Frank Webb
- David Wiese
- Victor Zlotnicki

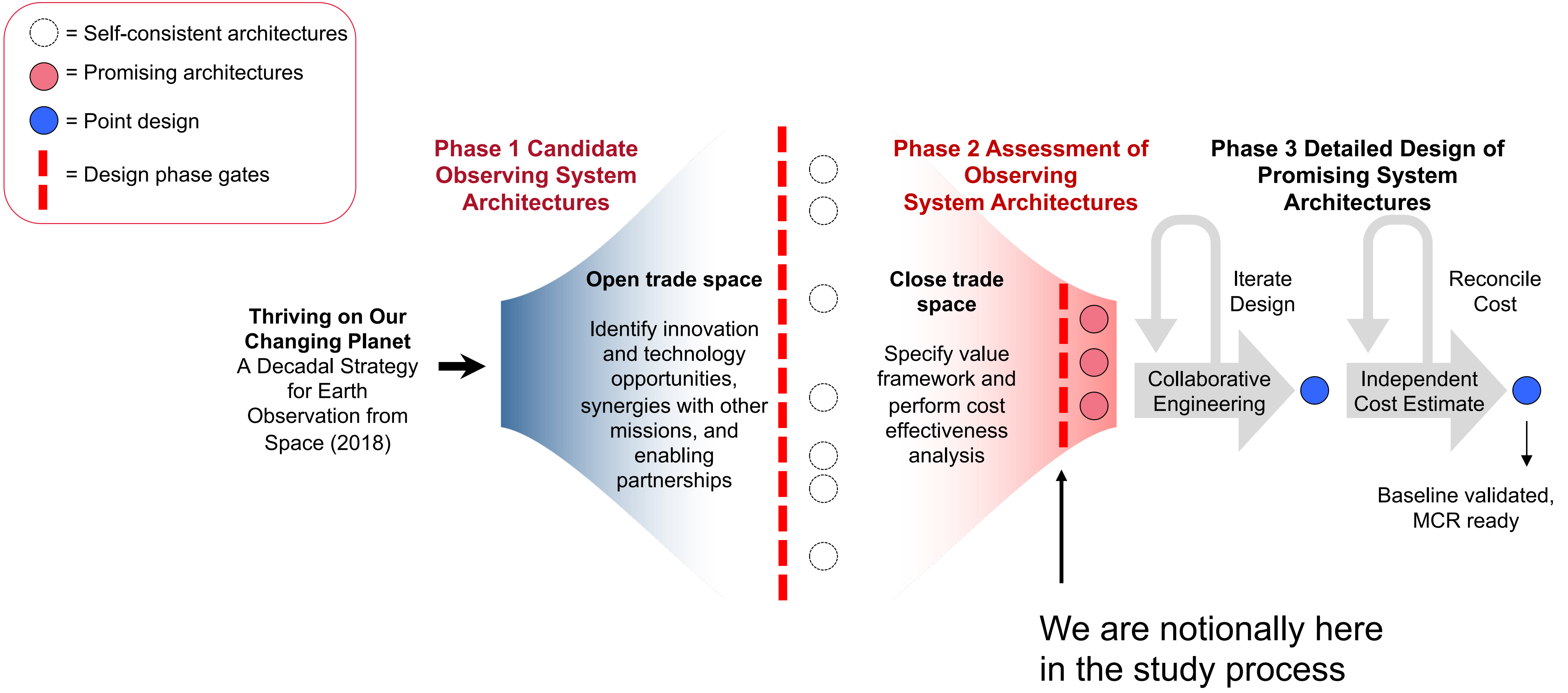
Applications
- Matt Rodell, Lead
- Rosemary Baize
- Carmen Boening
- Brad Doorn
- JT Reager
- Jeanne Sauber
- Margaret Srinavasan

Science & Community Engagement
- Carmen Boening, Lead
- Rosemary Baize
- Bernie Bienstock
- Bryant Loomis
- Matt Rodell
- David Wiese
- Victor Zlotnicki

Communications
- Victor Zlotnicki, Lead
- Bernie Bienstock
- Donna Wu

MC Study Phases

AGU 2020



Mass Change Overall Schedule

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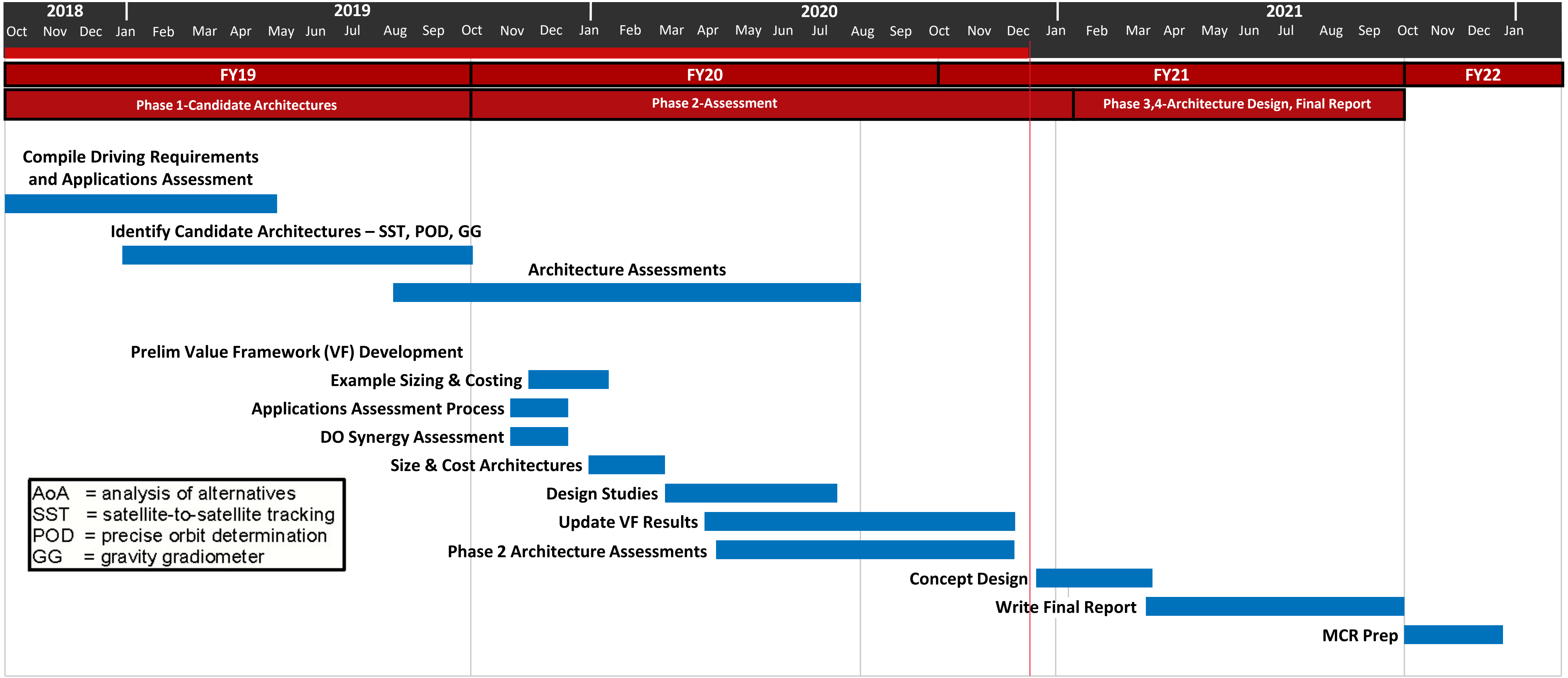

Mass Change Phase 2 Milestones

- HQ meetings
  - Periodic DO study and MC-specific reviews
- Community meetings
  - Multiple opportunities for community engagement during scheduled public forms
- Concurrent engineering
  - JPL's Team X, GSFC's IDL
- Architecture evaluation
  - Conducted via the Aerospace Corporation's AoA
- Engagement with potential international partners
  - Multiple meetings with ESA, CNES, and DLR/GFZ

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Science and Applications Traceability Matrix

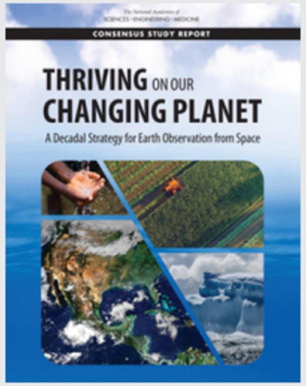
Matt Rodell, NASA GSFC

Mass Change R&A Co-Coordinator

Mass Change SATM Development

The development of the Mass Change Science and Applications Traceability Matrix was driven by the 2017 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

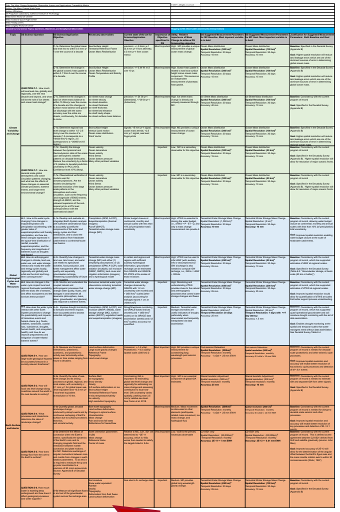
Climate Variability and Change
- C-1a: Global Sea Level
- C-1c: Ice Sheet Mass Change
- C-1b: Ocean Heat
- C-7d: Dynamical Ocean State
- C-1d: Regional Sea Level
- C-7e: Ocean Circulation

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

SATM for Mass Change



Expert Interpretation

Community Input and Vetting

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
- 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 next spring

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

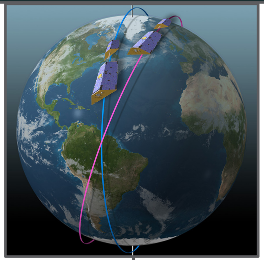
Architectures and Technology

Bryant Loomis, NASA GSFC

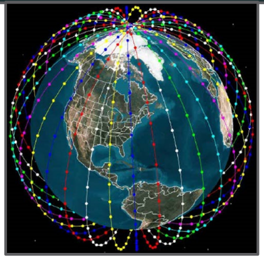
Mass Change Phase 3 Deputy Lead

Architectures & Technology: Trade Space

SST
Satellite-to-satellite tracking

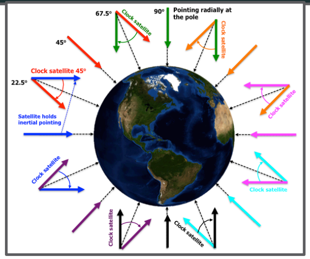


POD
Precise orbit determination



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.
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		μNPRO /KVR	Opto.

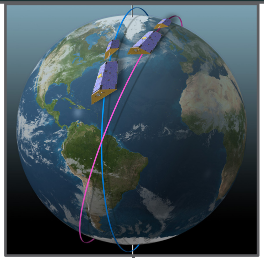
N-pair SmallSats

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 & technology trade space

Architectures & Technology: Trade Space

SST
Satellite-to-satellite tracking



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Precise orbit determination

Inclination	Altitude	# Sats	Accel.
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	LEO/ MEO	~100	

- **Low science value**

GG
Gravity gradiometer

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

- **Low TRL & long/uncertain development schedule**

Single in-line pair

Inclination	Altitude	Ranging	Accel.
~90°	~500 km	MWI	ES
~70°	~350 km	LRI	Hybrid
	LEO/ MEO	Freq. Comb	GRS
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★ DLR/GFZ

Pendulum pair or In-line pair + pendulum

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

- **Low science value**
- **Technical challenges**

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.

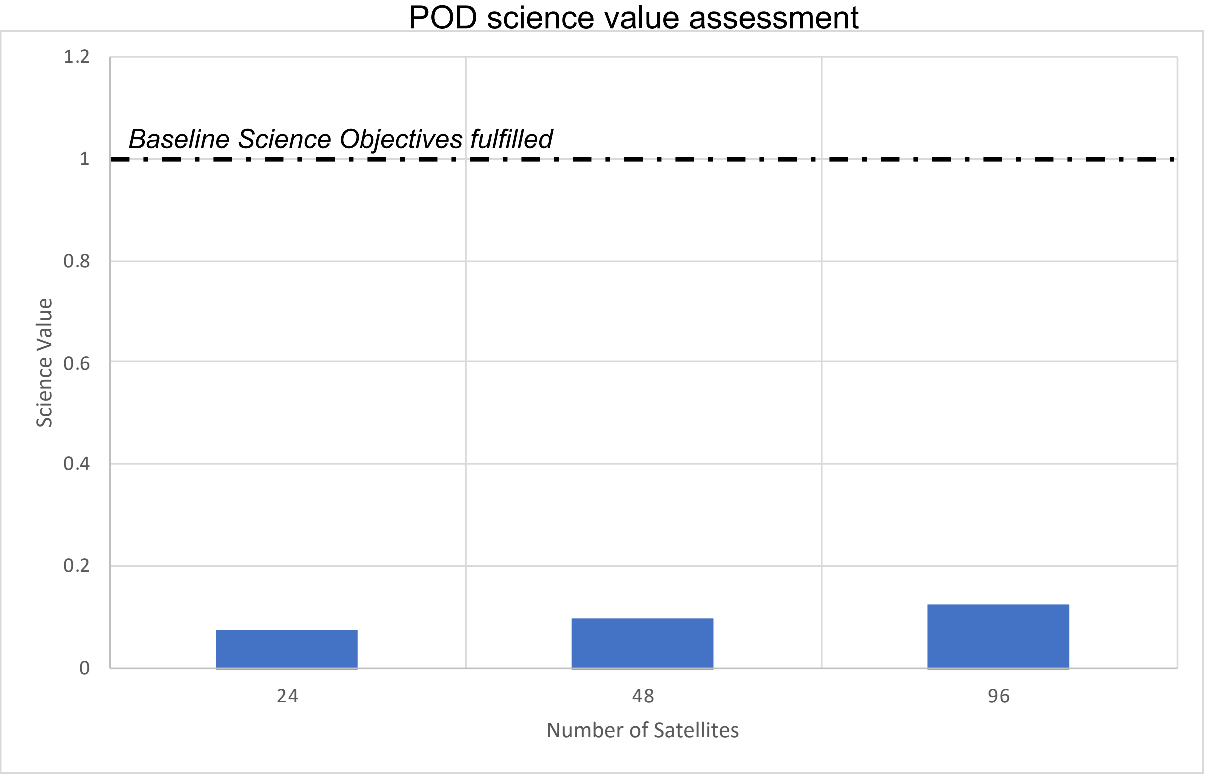
- **SmallSat design not cost-effective**
- **Lack of international partner**

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



Atomic Interferometer Gravity Gradiometer (AIGG)

<u>Key takeaways:</u>
High science performance but long/uncertain path to TRL 6

AOSense lab instrument in collaboration with NASA GSFC:

- Currently TRL 4; path to TRL 6 TBD

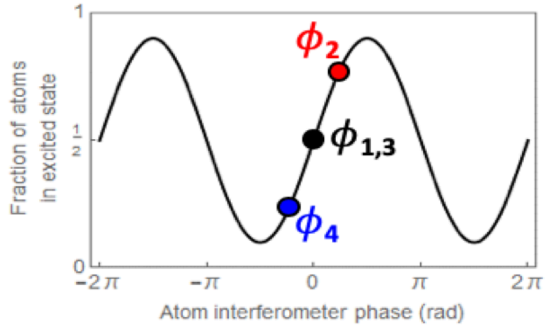
GSFC Instrument Design Lab (IDL) conducted June 1st – 5th

- 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

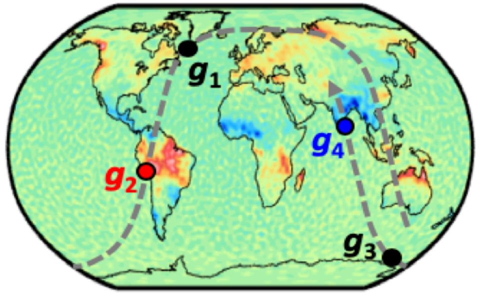
- Instrument Accommodation: 947 kg; 1049 W

- Continue engineering design refinement (follow-up MDL study at GSFC in early CY21)

Interferometer fringe

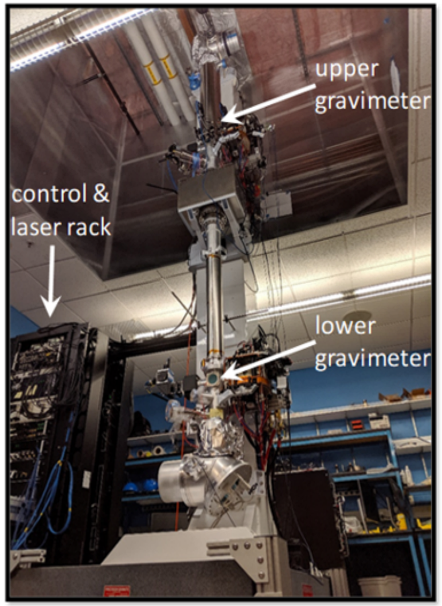


Gravity map

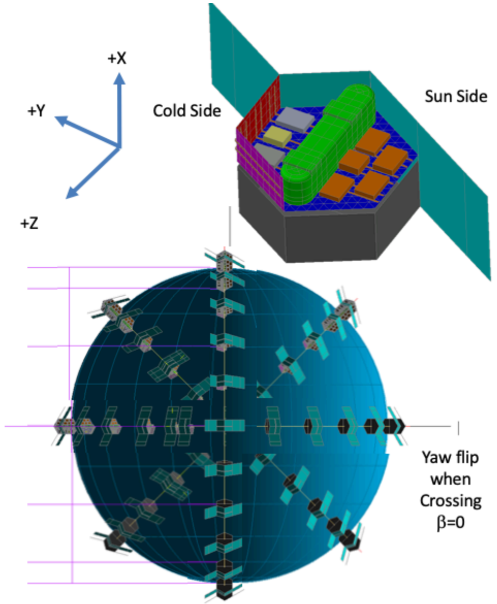


High sensitivity interferometer fringe measurements for gravity observations

AIGG at AOSense



Flight Design



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	Option 2: Single string with SmallSat bus components
Redundancy: Dual string	Redundancy: Single string
Mass: ~430 kg	Mass: ~190 kg
Phase A-E cost: ~$500M FY18	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
Improvements	ONERA HybridSTAR ES + cold atom	60× with drag compensation	10×	3
Improvements	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
SmallSats	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

SmallSats Improvements

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
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
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

Science Value Methodology

David Wiese, JPL/Caltech

Mass Change Deputy Study Coordinator

Relating Observing System Capability to the DS

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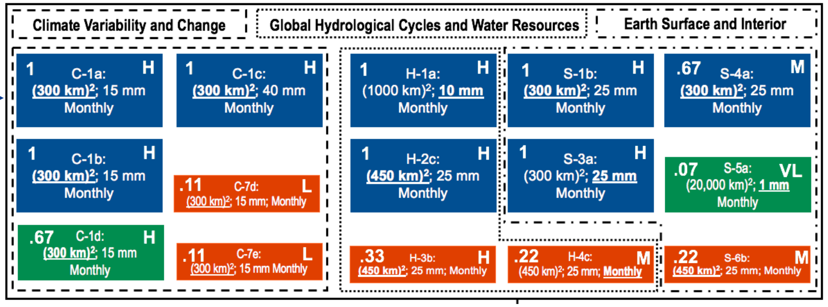
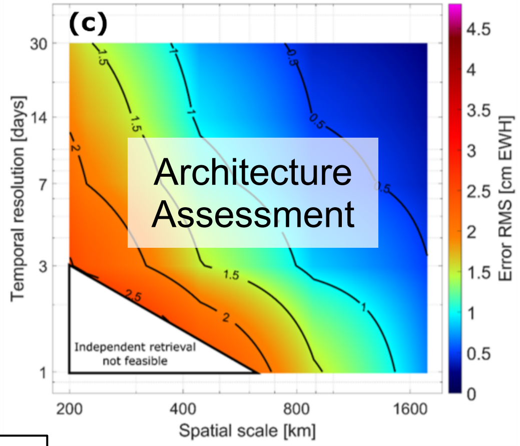
Decadal Survey

Science and Applications Traceability Matrix Measurement Parameters

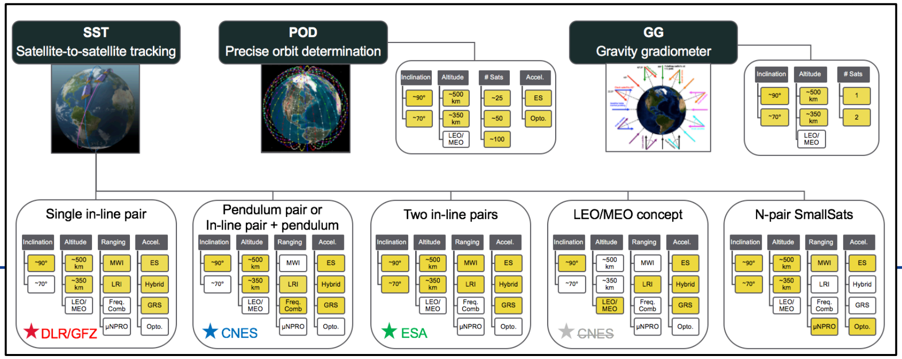


Science value metrics <u>directly relate the capability of an observing system architecture to achieving science and application targets relevant to MC in the Decadal Survey</u>



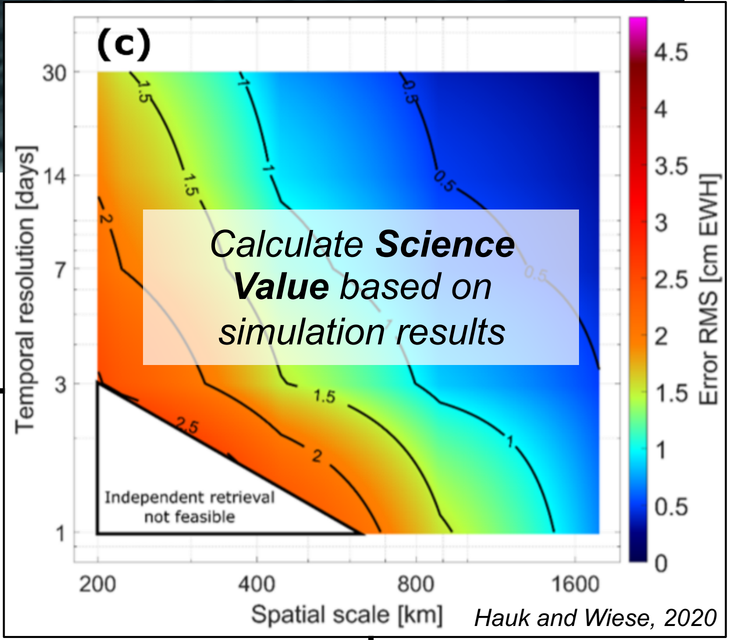
Science Value

Architecture Tree



OSSE Overview: Science Value

Overview of Observing System Simulation Experiment



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

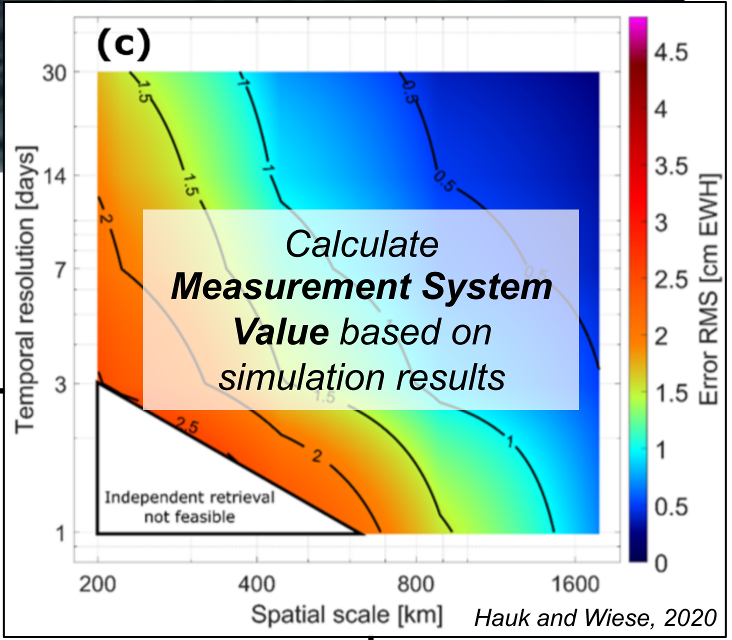
Science Value provides the best estimate of science return of the mission given the current state of the art in data processing and geophysical model error

	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	

OSSE Overview: Measurement System Value

Overview of Observing System Simulation Experiment

Compare estimate against the truth simulated world to quantify error



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)

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

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Science Value (SV)

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

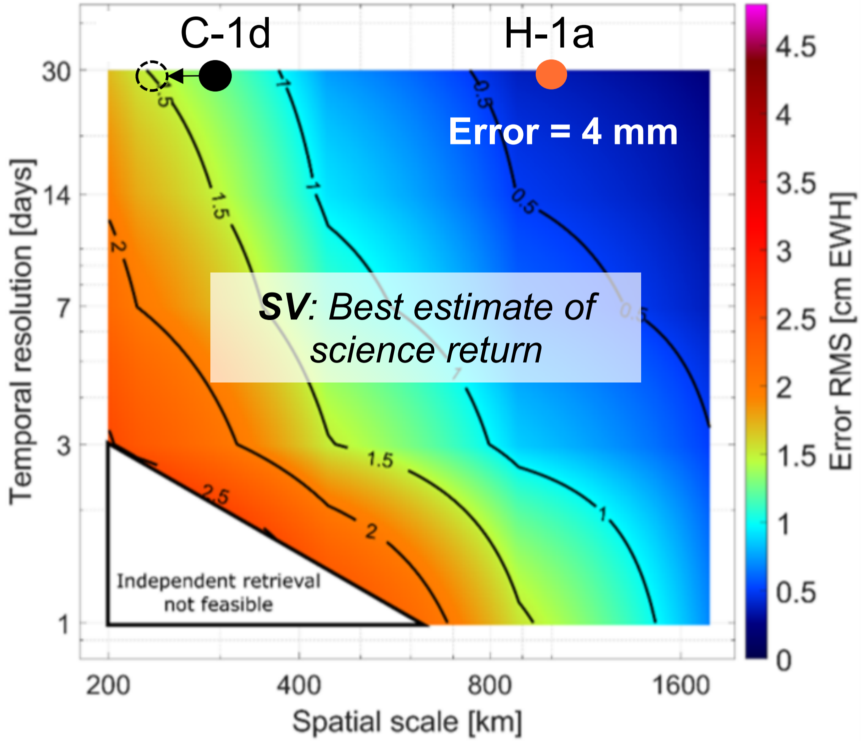
Key Variable: **Spatial Resolution**

.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



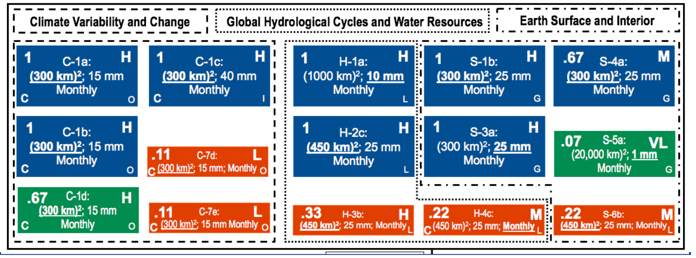
Hauk and Wiese, Earth and Space Science, 2020.

Key Variable: **Accuracy**

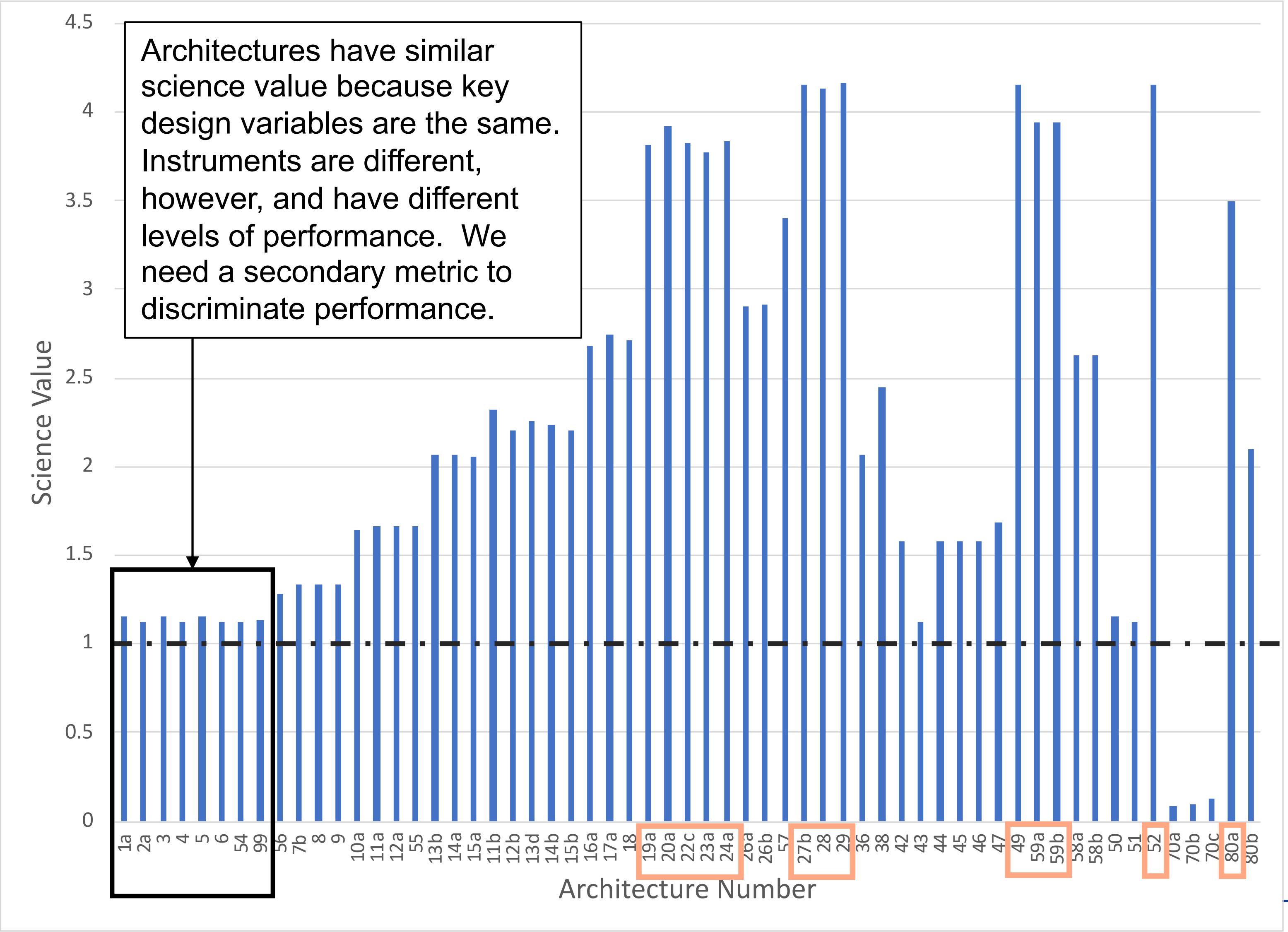
1 H-1a: **H**
(1000 km)²; **10 mm**
Monthly
L

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

SATM Measurement Parameters for Baseline



Results: Science Value



Indicates SATM Goal(s) can be achieved

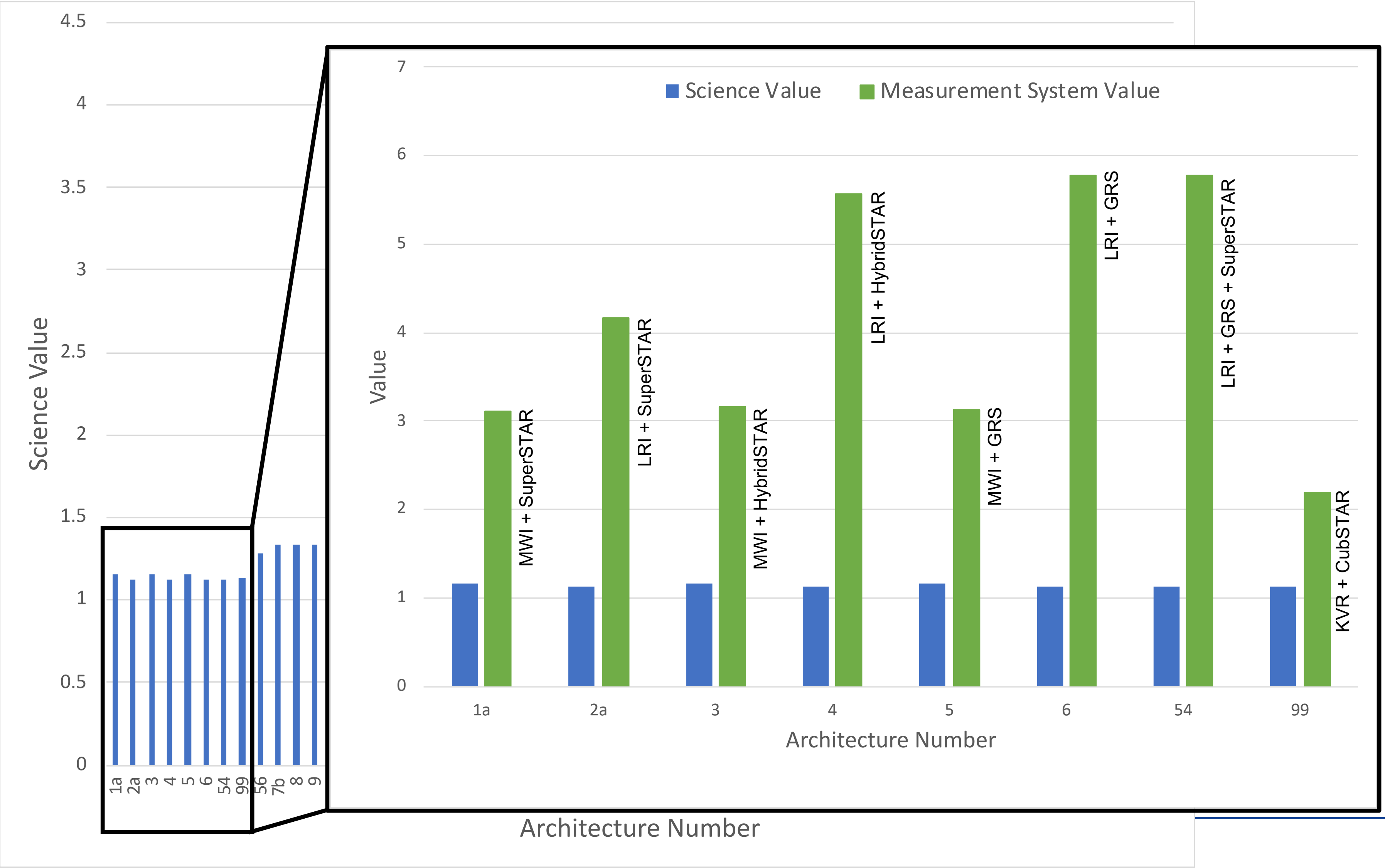
Goals are assessed in a binary fashion

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

Jon Chrone, NASA LaRC

Mass Change Phase 2 Deputy Lead

Architecture Evaluation Objectives

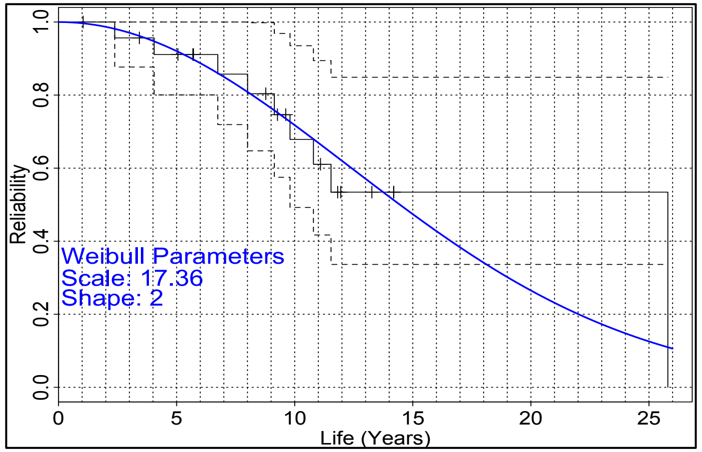
- Identify architectures that support the Mass Change Science and Applications objectives
  - Traceable to Decadal Survey
- Assess the cost effectiveness of each of the studied architectures
  - Performance (Science and Applications), Risk, Cost, Schedule
- Provide a transparent and traceable mechanism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

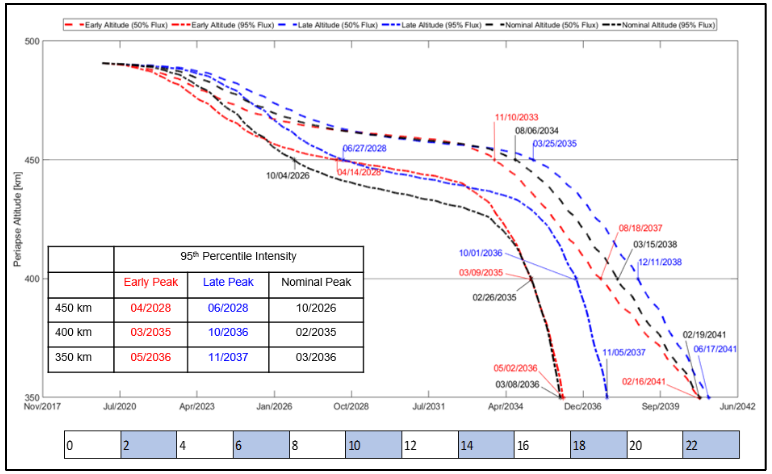
Assessment Ground Rules/Assumptions

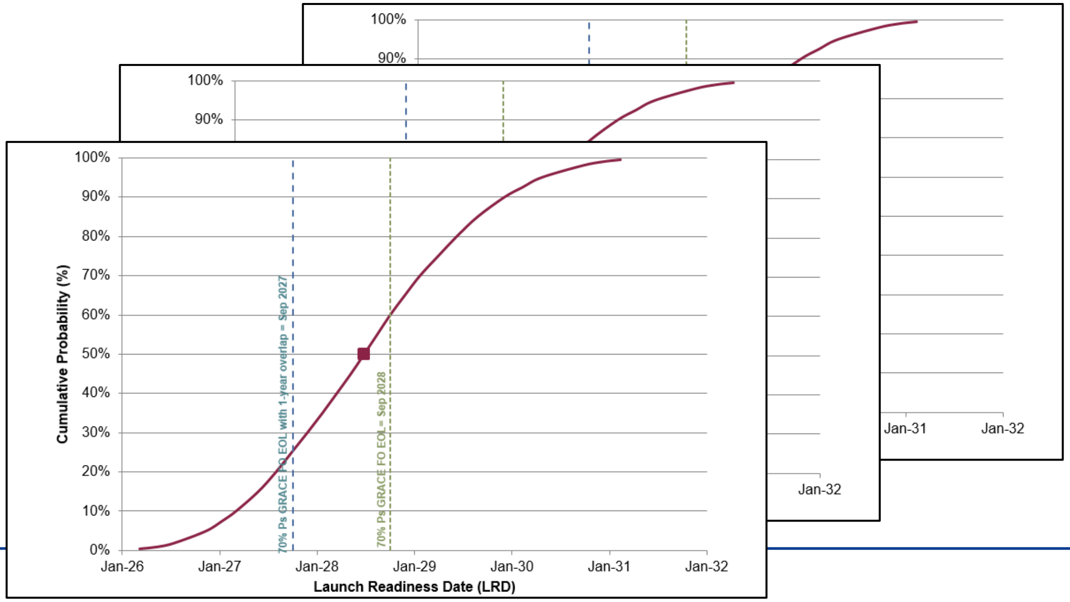
- Architecture Performance based on science and applications metric
- Spacecraft/Instrument sizing
  - Combination of concurrent engineering studies and engineering models
  - Implementation with minimum 3 year design lifetime and 5 years of consumables
- Cost estimation
  - Leveraging Aerospace Corporation 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

Continuity with GRACE Follow On (GFO)

- GFO lifetime estimated based on reliability and orbit lifetime
- Stochastic analysis provides a range of dates for GFO 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 GFO 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

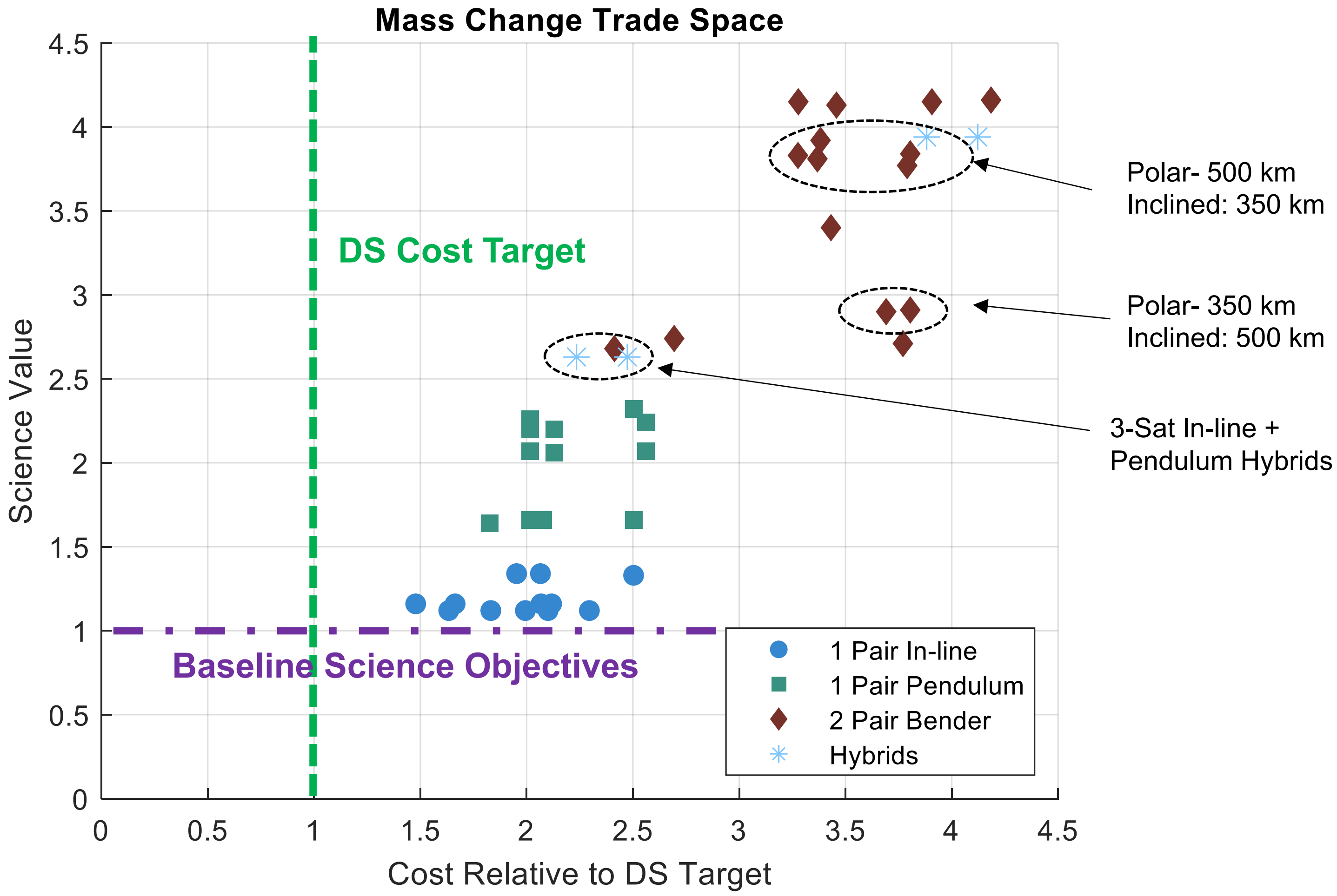






Phase 2 Tradespace

- Preliminary results for SST architectures in various configurations
    - Single pair in-line (GRACE-like)
    - Single pair pendulum (in different planes)
    - Two pair Bender (pairs with different orbit inclination)
    - Hybrids (combined in-line, pendulum)
- Within each configuration are different altitudes (350 km – 500 km), instruments, and formations
- Cost estimates for domestic only implementation are above cost target
- Remaining trade space includes options that are compatible with international interests
    - Reduced cost to NASA may be enabled through strategic partnerships
    - Costs shown do not include workshare with potential international partners



Summary

Bernie Bienstock, JPL/Caltech

Mass Change Study Coordinator

MC Study Path Forward

MC is on track to deliver the following to NASA HQ in January 2021

- Description of high-value, affordable architectures with recommendation 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
  - Background and supporting material
- After decision from NASA HQ, Mass Change will enter Phase 3 of the study focused on a detailed design of one or more high-value architectures

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

Feedback and Community Discussion