Mass Change Overview

Lucia Tsaoussi, NASA HQ

Mass Change Program Scientist

December 12, 2019

NASA Implementation of the 2017 Earth Science Decadal Survey - Mass Change Designated Observable

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.

ESD's Decadal Survey web page:

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

Focus Area	Most Important (MI)	Very Important (VI)	Important
Hydrology	1a, 2c		3b, 4c
Climate	1a, 1b, 1c	1d	7d, 7e
Earth Surface and Interior	1b, 3a, 4a	5a	6b

Mass change is determined by measuring **gravitational changes** over set time periods.

"MC provides an integrated view of the entire physical Earth system that allows the relating of changes in one system component to changes in another."

Challenges addressed by the MC Study team

1. Translate science objectives to gravity observations
2. Science objectives require both measurement capability AND relevant analytical framework (e.g. models)
3. Continuity as relates to measurement and model capabilities AND lack of observational gaps

NASA- ESA Partnership Opportunity

1. Definition of requirements for future joint mission
2. Joint studies via cross-participation in MC DO and NGGM study activities

Mass Change Study Team Status

Bernie Bienstock, JPL/Caltech

Mass Change Study Coordinator

December 12, 2019

Mass Change Study Plan
Approved 10.28.18

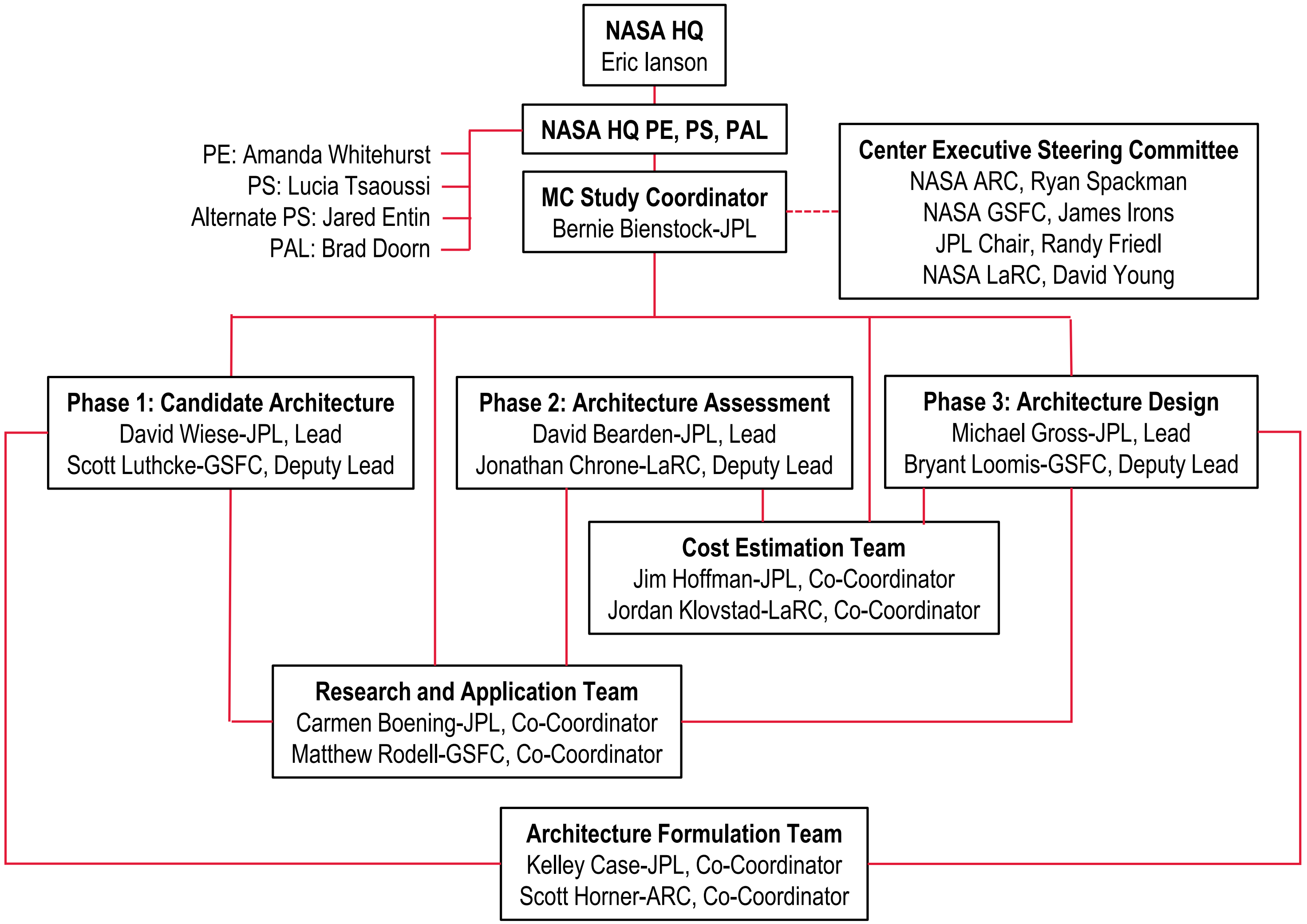
Mass Change (MC) Designated Observable Study Plan
2017 Earth Science Decadal Survey

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.

Mass Change Phase Org Chart



Mass Change Working Groups

SATM
- David Wiese, Lead
- Carmen Boening
- Bryant Loomis
- Scott Luthcke
- Matt Rodell
- Jeanne Sauber
- Frank Webb
- Victor Zlotnicki

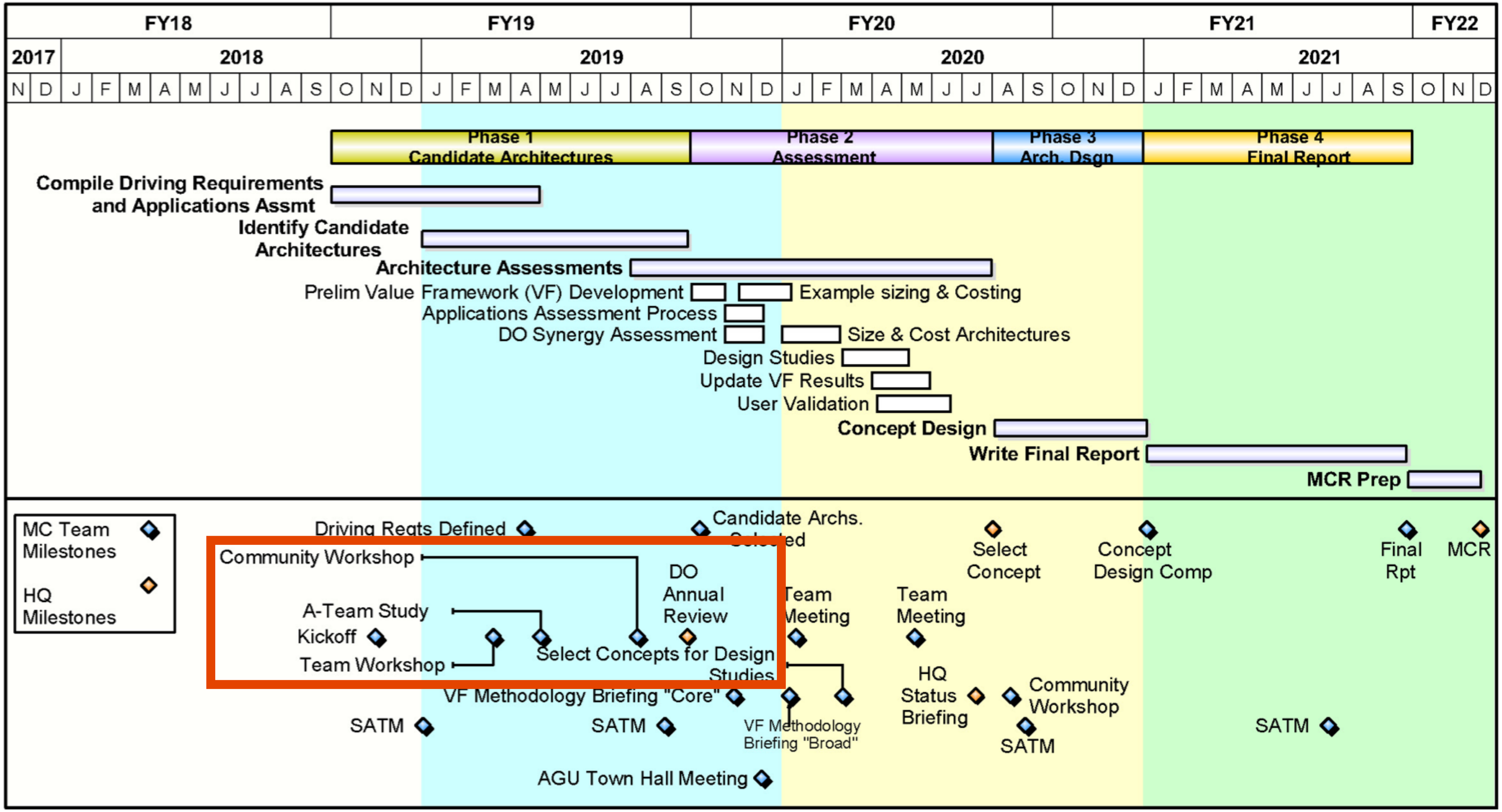
Phase 2 Working Group
- Kelley Case, Lead
- Dave Bearden
- Jon Chrone
- Scott Horner
- Bryant Loomis
- Scott Luthcke
- Frank Webb
- David Wiese

Applications
- Matt Rodell, Lead
- JT Reager
- Margaret Srinavasan

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

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

Timeline of Accomplishments



A-Team Study

- Conducted at JPL on 5/1-2/2019
- Attended by 17 members of the Mass Change team from participating centers and NASA HQ
- Meeting accomplishments
  - Explored the Mass Change architecture trade space as defined in the 2017 Earth Science Decadal Survey
  - Defined Mass Change architecture classifications
    - Satellite-satellite tracking (SST)
    - Precision orbit determination (POD)
    - Gravity gradiometer (GG)
  - Conducted deep dives on various Mass Change architecture options

Community Workshop

- Conducted in Washington, DC on 7/30 thru 8/1/2019
- Attended by 80 people from international space agencies, US and domestic industry, academia, NASA, and JPL
- Accomplishments
  - Mass Change SATM finalized with input from the community meeting and subsequent community telecons
  - Discussion of applicable technologies and architectures
  - Workshop summary report available on the Mass Change website, https://science.nasa.gov/earth-science/decadal-mc

Agenda
Day 1
MC Workshop Introductions
Agency Presentations (ESA, CNES, HGF)
SATM Briefings and Breakout Sessions
Day 2
Architecture Options
Enabling Technologies
Applications and Community Assessment Report
Appplications, Technology, and Architecture Breakout Sessions
Day 3
SATM Summary
Mass Change Future Plans

Phase 2 Plan

Date		Event/Milestone
Start	Stop	
12/2/19	12/15/19	Conduct sizing and costing of concepts, beginning with SST
12/18/19	**12/18/19**	**Methodology overview and examples briefing to MC Team**
12/19/19	1/23/20	Finalize set of architectures (SST, POD, GG)
1/24/20	3/17/20	Conduct sizing and costing studies of all concepts
2/11/20	2/12/20	MC Team Meeting at NASA Ames
3/18/20	**3/18/20**	**Preliminary AoA Presentation to MC Team**
3/19/20	4/15/20	Revise results based on MC Team feedback
4/16/20	**4/16/20**	**Draft AoA Presentation to MC Team**
4/17/20	5/12/20	Develop final AoA briefing
5/5/20	5/6/20	**MC Phase 2 Community Meeting**
5/13/20	**5/13/20**	**Final MC Team Briefing on AoA**
5/14/20	6/17/20	Finalize documentation
6/18/20	**6/18/20**	**Deliver final AoA documentation**

Legend
Boldface = Milestones
AoA = analysis of alternatives
SST = satellite-to-satellite tracking
POD = precise orbit determination
GG = gravity gradiometer

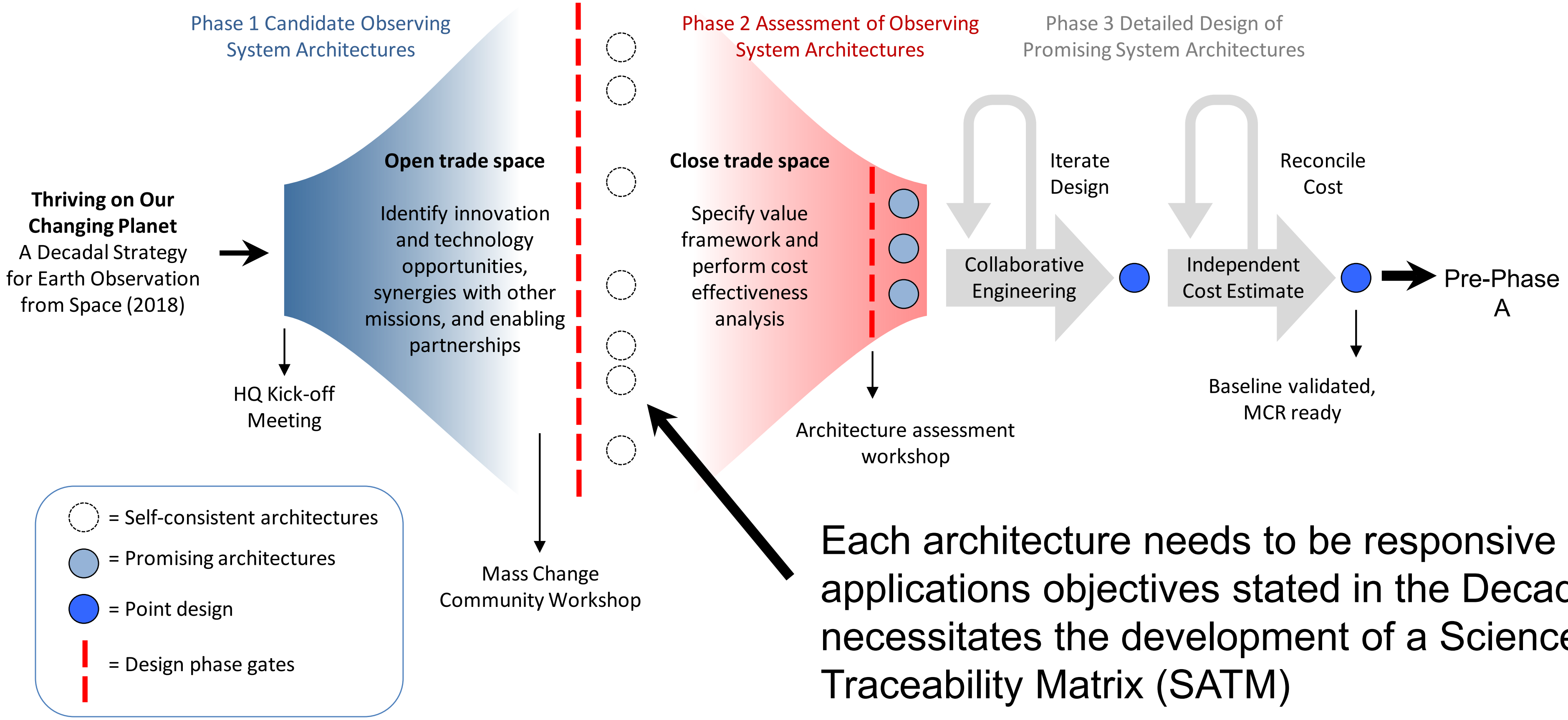
Architecture and Technology Options to satisfy the Science and Applications Traceability Matrix for the Mass Change Designated Observable

David N. Wiese[1] on behalf of the MC-DO Study Team

December 12, 2019

[1]Jet Propulsion Laboratory, California Institute of Technology

Study Phases



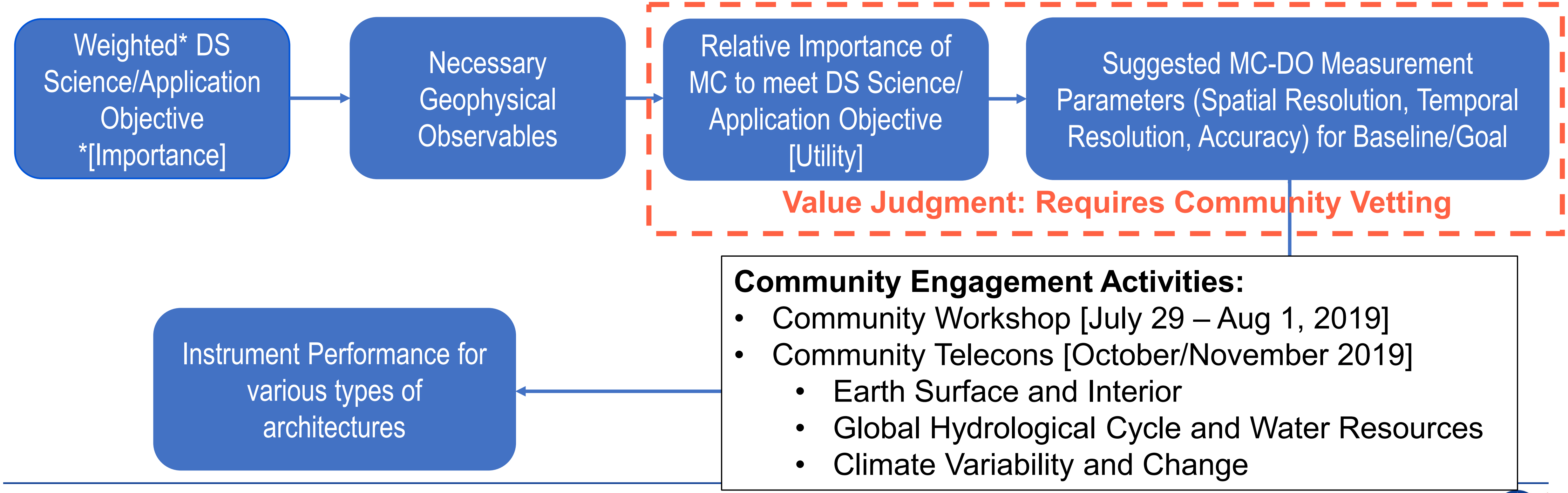
Each architecture needs to be responsive to the science and applications objectives stated in the Decadal Survey. This necessitates the development of a Science and Applications Traceability Matrix (SATM)

MC-DO SATM Working Group: Carmen Boening, Bryant Loomis, Scott Luthcke, Matt Rodell, Jeanne Sauber, Frank Webb, David Wiese, Victor Zlotnicki

SATM Overview for Mass Change DO

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

- **Baseline** Observing System – supports full science objectives
- **Goal** Observing System – supports additional science with a goal to create longevity in the mass change time series. 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
- 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

→ Science Performance Targets

DS Prescribed Weights [Importance]

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

Suggested Measurement Parameters for Baseline

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Weighting Combines DS Importance with MC Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height

Climate Variability and Change

- C — C-1a: **(300 km)^2**; 15 mm Monthly — O
- C — C-1c: **(300 km)^2**; 40 mm Monthly — I
- C — C-1b: **(300 km)^2**; 15 mm Monthly — O
- C — C-7d: (300 km)^2; 15 mm Monthly — O
- C — C-1d: **(300 km)^2**; 15 mm Monthly — O
- C — C-7e: (300 km)^2; 15 mm Monthly — O

Global Hydrological Cycles and Water Resources

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

Earth Surface and Interior

- S-1b: **(300 km)^2**; 25 mm Monthly — G
- S-3a: (300 km)^2; **25 mm** Monthly — G
- S-4a: **(300 km)^2**; 25 mm Monthly — G
- S-5a: (20,000 km)^2; **1 mm** Monthly — G
- S-6b: **(450 km)^2**; 25 mm Monthly — L

C: Continuity explicitly recommended in Decadal Survey

Highest Weight | Medium – High Weight | Medium Weight | Medium-Low Weight | Low Weight

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

Science Performance Targets

Suggested Measurement Parameters for Goal

AGU 2019

Weighting Combines DS Weights with MC Utility | Most Important Parameter Is Underlined | Units: Equivalent Water Height

Climate Variability and Change

C — C-1a: **(100 km)²**; 15 mm, Monthly

C — C-1c: **(100 km)²**; 10 mm

C — C-1b: **(100 km)²**; 15 m… Monthly

C — C-1d: **(100 km)²**; 15 mm, Monthly — O

C — C-7e: **(50 km)²**; 10 mm; Monthly — O

Global Hydrological Cycles and Water Resources

H-1a: (3 km)²; **10 mm**

(200 km)²; 25 mm, Monthly — L

C — H-4c: (50 km)²; 1.5 mm, **Weekly** — L

Earth Surface and Interior

S-1b: **(200 km)²**; 12 mm

S-4a: **(200 km)²**; 12 mm, Monthly — G

S-5a: (20,000 km)²; **.01mm**, Monthly — G

S-6b: **(100 km)²**; 10 mm, Monthly — L

Complete SATM is now available online for review and comment:
https://science.nasa.gov/earth-science/decadal-mc

Comments will be accepted through Jan. 31, 2020
Please e-mail masschange@jpl.nasa.gov

C: Continuity explicitly recommended in Decadal Survey

Highest Weight | Medium – High Weight | Medium Weight | Medium-Low Weight | Low Weight

G: Global
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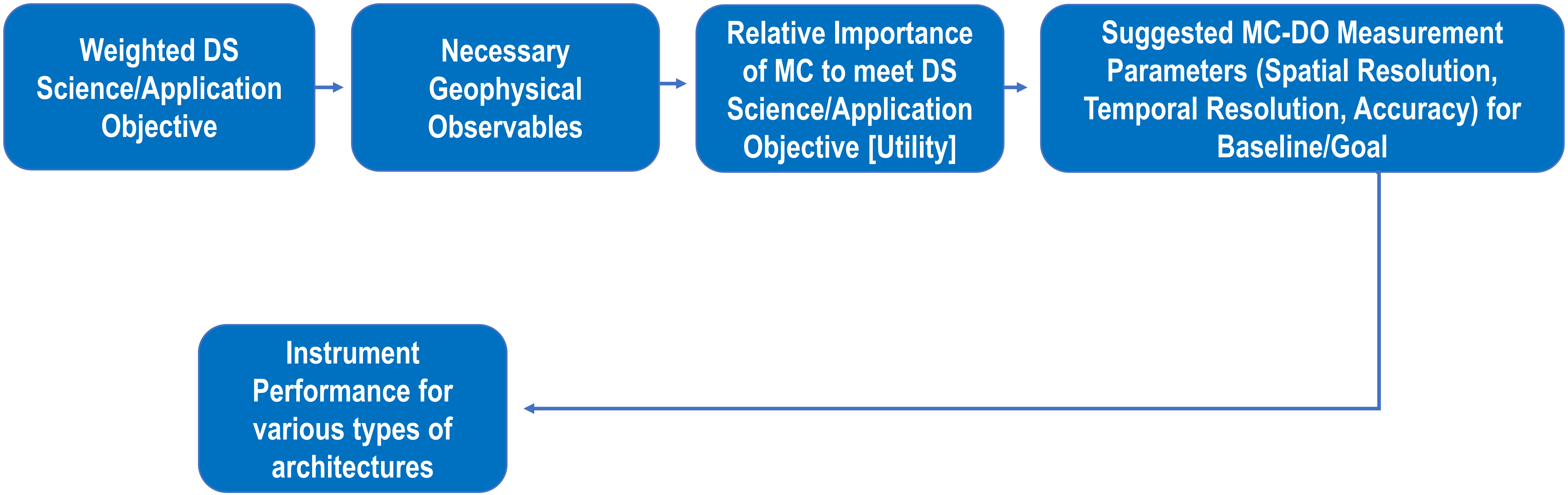
Science Performance Targets

MC Interpretation of DS Objectives



Summary of observing system architecture activities

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Activity	Summary
Literature Survey	The DO Mass Change team is surveying the published literature and conference presentations on architecture concepts, simulations, and proposals
A-Team Study	JPL A-Team Study
Community Worksho	re solicited by the unity Workshop July
Workshop Follow-up	At the conclusion of the workshop we solicited detailed observing system architecture information from the various presenters, and we continue to receive and compile this information: <u>submitted documents range from general concepts to detailed proposals</u>

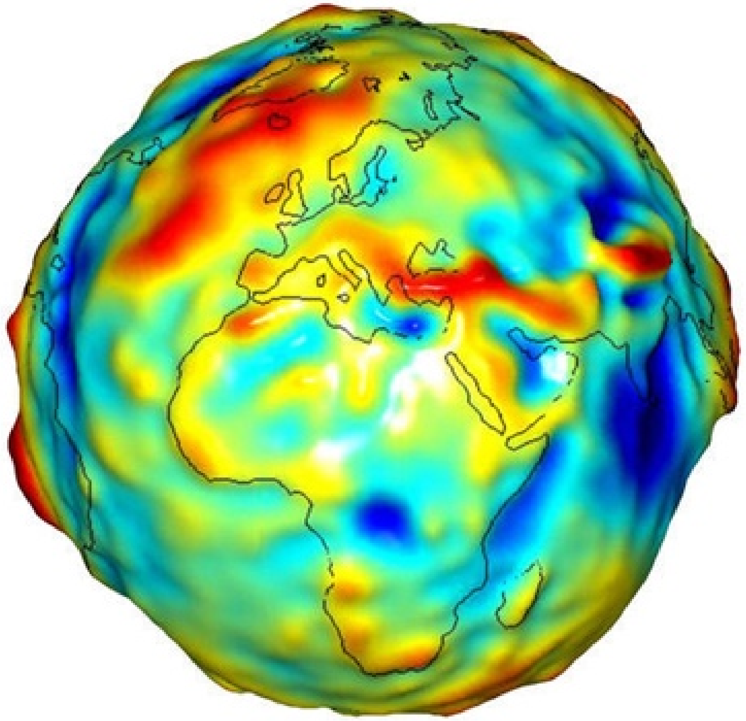
Observing system architectures for mass change can still be submitted by the community.

Input will be accepted through Jan. 31, 2020
Please e-mail masschange@jpl.nasa.gov

Overview of observing system architecture types

The A-Team study and Community Workshop identified three architecture types:

- **POD**: Precise Orbit Determination (multiple satellites)
- **SST**: Satellite-to-satellite tracking (multiple satellites)
- **GG**: Gravity gradiometer (single satellite)



All architecture types observe the effect of gravity on the motion of objects in Low Earth Orbit:

- Satellites: **POD/SST**
- Test mass(es) within satellite(s): **GG**
- Atom clouds within satellite(s): **GG**

Overview of observing system architecture types

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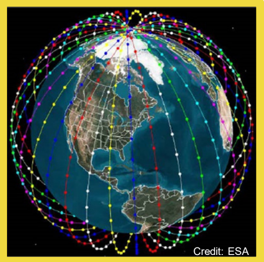
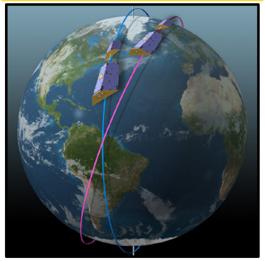
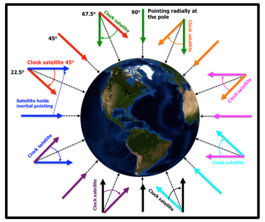
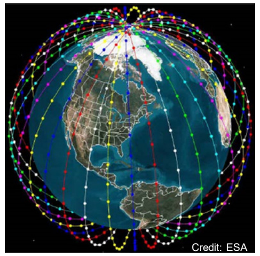


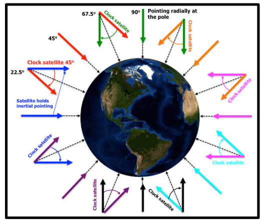




Type	Overview	Trade-space & key questions
POD Precise orbit determination	• Large constellation of GNSS receivers – potentially CubeSats • Candidate for gap filler • Could combine purchases of existing POD data with design/expansion of current constellations (e.g. Spire)	• Number of satellites • Mega-constellation performance? • Are accelerometers an option? • Performance of derived baseline? (no dedicated SST instrument)
SST Satellite-to-satellite tracking	• Same concept as GRACE/GRACE-FO missions • High heritage with GRACE/GRACE-FO reduces technical and implementation risk • Large trade space of orbits and technology has a wide range of scientific performance outcomes	• Low-low / High-low SST • Number of pairs and/or formations • Orbit planes and altitude • Ranging & accelerometer technology • Use of drag compensation
GG Gravity gradiometer	• Atomic interferometer gravity gradiometer expected to far exceed the performance of electrostatic accelerometers of GRACE & GOCE missions • Likely not ready for the expected MC DO timeline, but given the excellent simulated performance should be considered for more rigorous simulation studies and a key part of a technology development road map	• Gradiometer baseline size/orientation • Expected timeline of technology development? • Possible candidate for technology demonstration concurrent with a primary Mass Change observing system?

Overview of observing system architecture types





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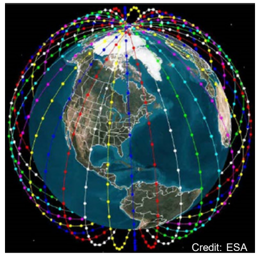

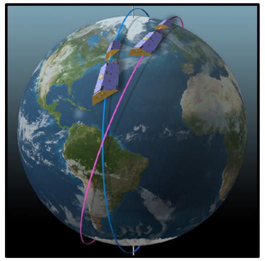

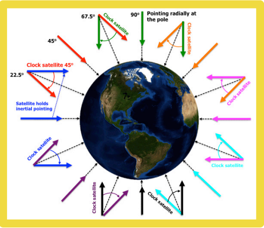

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Observing system architecture trade space

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Category	Parameter	Options
Observing System	Type	POD; SST; GG
Observing System	Design life	3-5 years; 5+ years
Spacecraft Platform	Size	Medium; SmallSat; CubeSat
Spacecraft Platform	# Platforms	1; 2; 3; 4; 5-12; Many
Orbit Design	Altitude	MEO; 500 km; 400 km; 300 km
Orbit Design	Inclination	~90°; ~70°; Various
Orbit Design	Separation (SST only)	MEO/LEO; 500; 200; 100; 50
Orbit Design	Formation (SST only)	In-line; Pendulum; Cartwheel
Instruments	Inertial Position	GPS
Instruments	Accelerometer	Electrostatic; Drift mode; Atomic GG
Instruments	Attitude determination	Star cameras; IMU; Earth IR sensors
Instruments	Ranging (SST only)	KBR; LRI; Freq. comb; CCLR; Reflector/ transponder
Instruments	System	Attitude control; Thermal control; Structural stability; Drag compensation

Sample architecture:
Dual SST pair with drag compensation

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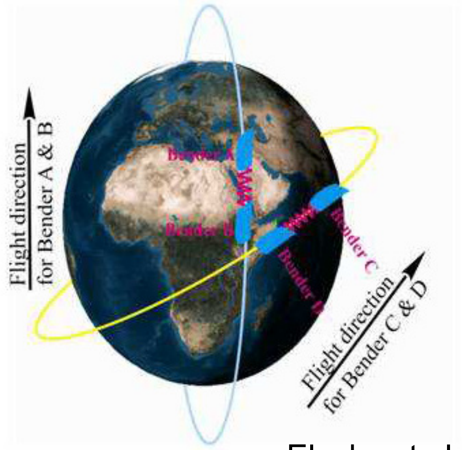
Observing System		Spacecraft Platform		Orbit Design				Instruments				
Type	Design life	Size	# Platforms	Altitude	Inclination	Separation (SST only)	Formation (SST only)	Inertial Position	Accelerometer	Attitude determination	Ranging (SST only)	System
POD	3-5 years	**Medium**	1	MEO	**~90°**	MEO/LEO	**In-line**	**GPS**	**Electrostatic**	**Star cameras**	KBR	**Attitude control**
SST	**5+ years**	SmallSat	2	500 km	**~70°**	500	Pendulum		Drift mode	IMU	**LRI**	**Thermal control**
GG		CubeSat	3	400 km	Various	200	Cartwheel		Atomic GG	Earth IR sensors	Freq. comb	**Structural stability**
			4	**300 km**		**100**					CCLR	**Drag compensation**
			5-12			50					Reflector/ transponder	
			Many									



Elsaka et al., 2013

Summary of Technology Activities

Activity	Summary
Community Engagement	Solicited wide spectrum of technology talks for the Mass Change Community Workshop July 30 – Aug 1, 2019, Washington, D.C.
Community Workshop	Thirteen technology talks presented covering satellite systems, laser ranging technologies, accelerometer and inertial sensor technologies, atomic interferometer and gravity gradiometer. **Strong support to focus on three main technology areas: accelerometer improvements, laser ranging as primary SST measurement, gravity gradiometer as future technology**.
Workshop Follow-up	Assigned teams and provided guidance to produce technology summaries for the three main technology focus areas. Draft summaries have been received, with further work necessary for full completion. Accelerometers: John Conklin, UF Laser Ranging: William Klipstein, JPL Gravity Gradiometry: Babak Saif, GSFC

Linking Architectures to Science Performance

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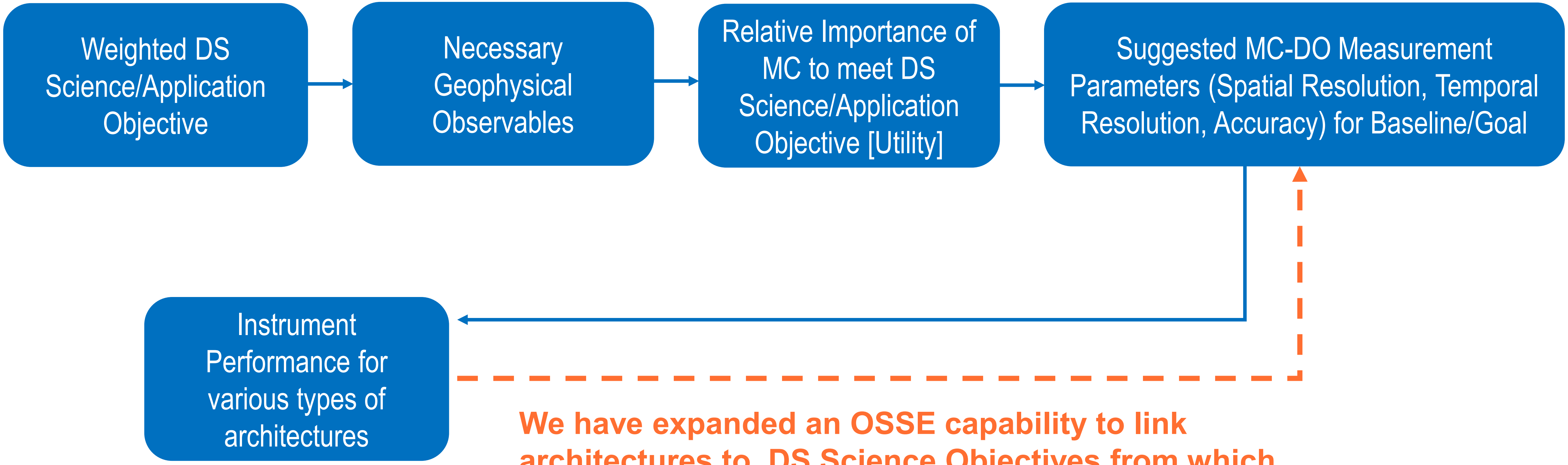


We have expanded an OSSE capability to link architectures to DS Science Objectives from which we can quantitatively determine science value

Quantitatively Determining Science Value

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

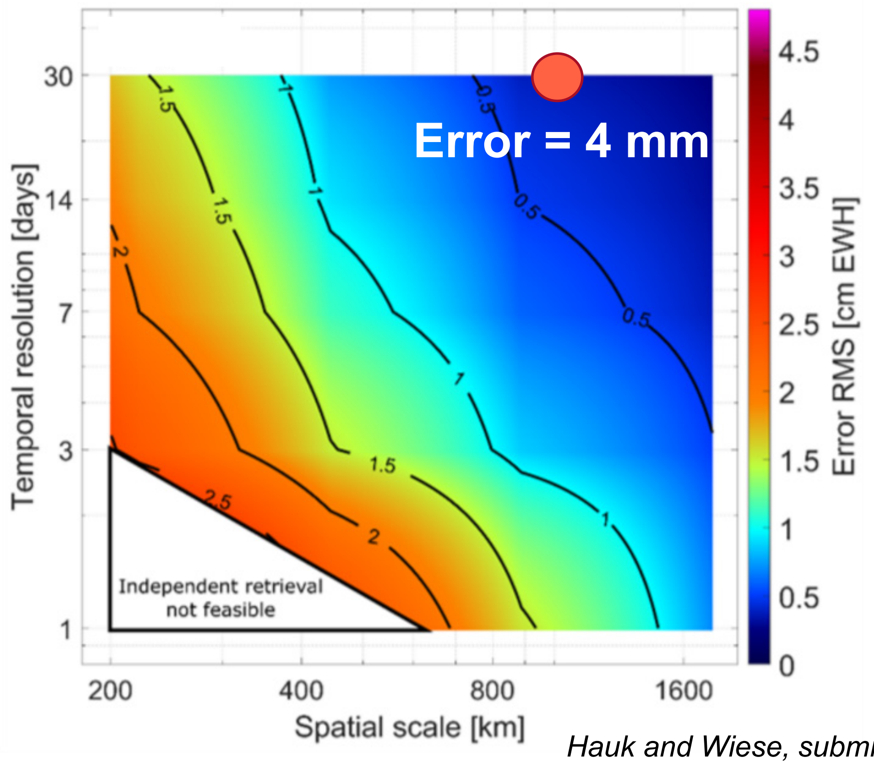
Science Objective *n*

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

Highest Weight

W = Importance * Utility = 1

Architecture *a*



Hauk and Wiese, submitted.

SV_n = 1 * 10/4 = 2.5

Poster on Friday Morning
G51B-0577
Wiese and Hauk, “New methods for linking science objectives to mission architectures: A case study comparing single and dual-pair satellite gravimetry mission architectures

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

Mass Change Designated Observable Study: Phase 2 Plan

Jon Chrone (LaRC) – Architecture Assessment Deputy Lead

Dave Bearden (JPL) – Architecture Assessment Lead

December 12, 2019

Phase 2 Objectives

- Phase 2 Objectives
  - Assess the cost and value 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

- Phase 2 Guidelines
  - 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

1. Architecture Definition

1. Conceptualize Architecture
- Number of Platforms & Orbits
- Size: Mediumsats, Smallsat
- Combinations, etc.
- Non-flight system elements

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

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

2. Value - Effectiveness

4. Map Capability to Objectives
- Choose objectives met by system
- To what extent does capability meet objectives?
- Most important, very important, important

5. Size Space System
- Mass, Power
- Size class of spacecraft
- Select launch vehicle

6. Estimate Cost
- Instrument – parametrics, analogy
- Spacecraft – heuristics, parametrics
- Launch – table, $/kg rule-of-thumb
- Other -- Percentage wraps
- Commercial services, Partner contributions

3. Cost Effectiveness - Comparisons

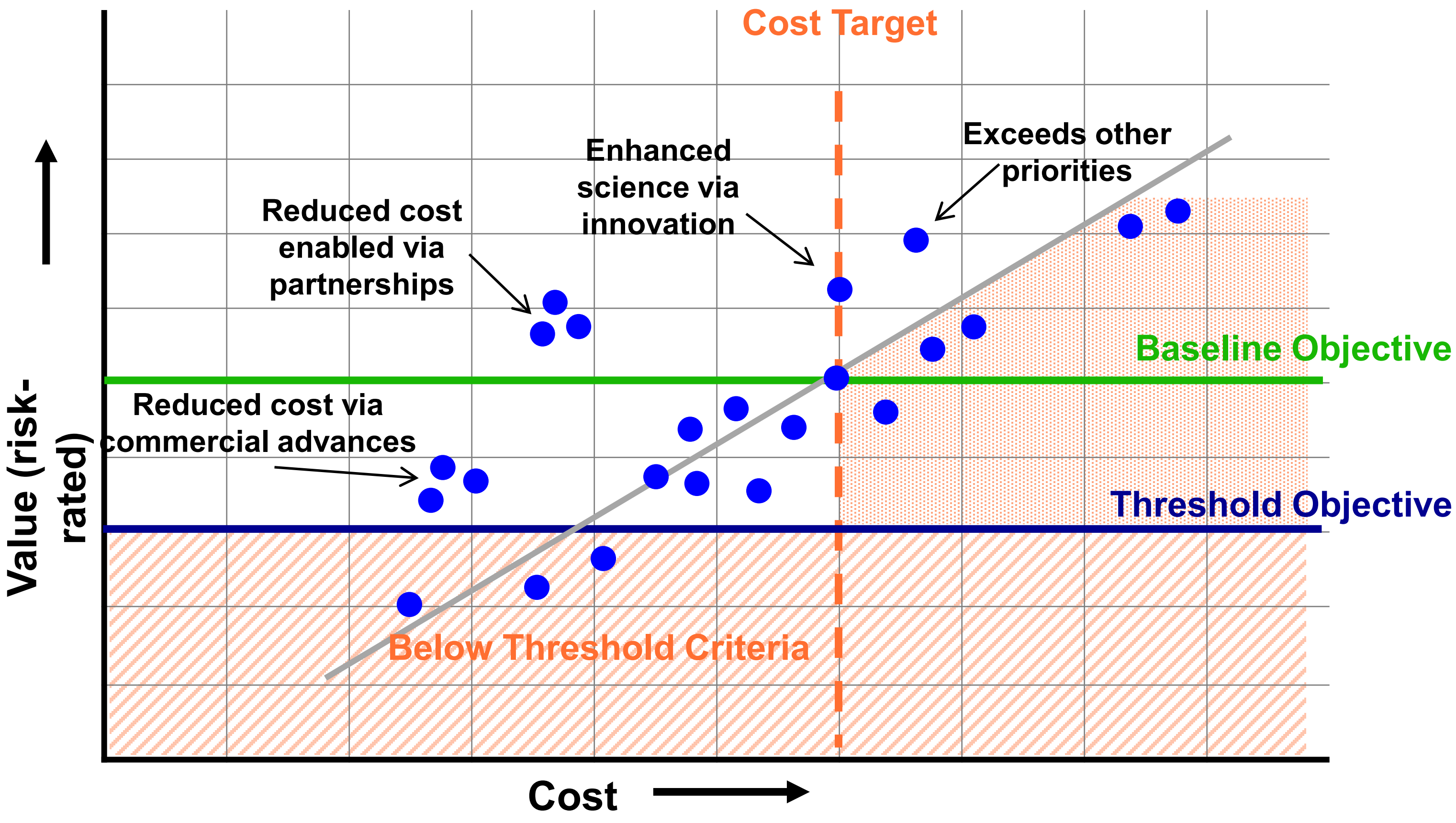
7. Assess Value vs. Cost
- Value metric = f(decadal objectives)
- Cost can be a point or range
- Risk-rated based on TRL or availability relative to need date

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

Cost Effectiveness Comparisons Value Framework

- Reduced cost may be enabled through strategic partnerships and/or commercial opportunities
- Enhanced science return may be enabled through new technologies and/or innovation
- Architectures below the Threshold or significantly above cost target will not be considered
- Science value may be risk-rated based on technical or schedule risk

Notional graphic showing Value vs. Cost



Phase 2 Plan: Funnel from "Many" to "Few"

- Value Framework will assess architecture solutions to most/very important science objectives (performance), risk, cost, schedule.
- A basis for down-selection will be necessary with justification for eliminating candidate architectures.

Number of Observing System Architectures

Phase 1

~10-20+

Potential Options

- Number of permutations
- Broad exploration of potential trade space
- Identify primary drivers and play against SATM
- High-level metrics used to consolidate and prune
- Create hybrids and combinations

Oct-Dec 2019

Feasible Options

- Multiple Options
- Perform mission-level design (e.g. Team-X)
- Assess using parametrics and analogy-based models
- Use performance models to discriminate

Jan-Mar 2020

~1-3

Promising Options

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

Apr-Jun 2020

Phase 3

Phase 2 Tasks and Milestones

Date		Event/Milestone
Start	Stop	
12/2/19	12/15/19	Conduct sizing and costing of concepts, beginning with SST
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1/24/20	3/17/20	Conduct sizing and costing studies of all concepts
2/11/20	2/12/20	MC Team Meeting at NASA Ames
3/18/20	**3/18/20**	**Preliminary AoA Presentation to MC Team**
3/19/20	4/15/20	Revise results based on MC Team feedback
4/16/20	**4/16/20**	**Draft AoA Presentation to MC Team**
4/17/20	5/12/20	Develop final AoA briefing
5/5/20	5/6/20	**MC Phase 2 Community Meeting**
5/13/20	**5/13/20**	**Final MC Team Briefing on AoA**
5/14/20	6/17/20	Finalize documentation
6/18/20	**6/18/20**	**Deliver final AoA documentation**

Legend
Boldface = Milestones
AoA = analysis of alternatives
SST = satellite-to-satellite tracking
POD = precise orbit determination
GG = gravity gradiometer