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

# The NASA Mass Change Designated Observable Study: Status Update

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

Presented by David Wiese[1], MC Deputy Study Coordinator

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[4]NASA Ames Research Center, Moffett Field, CA, United States
[5]NASA Headquarters, Washington, DC, United States

# Mass Change as a Designated Observable

- 2017-2027 Decadal Survey for Earth Science and Applications from Space released in January 2018
- Identified five Designated Observables, organized as four multi-center studies
  - Aerosols
  - Cloud, Convection, and Precipitation

    Combined as ACCP
  - **Mass Change (MC)**
  - Surface Biology and Geology (SBG)
  - Surface Deformation and Change (SDC)
- Link to the MC study is at

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

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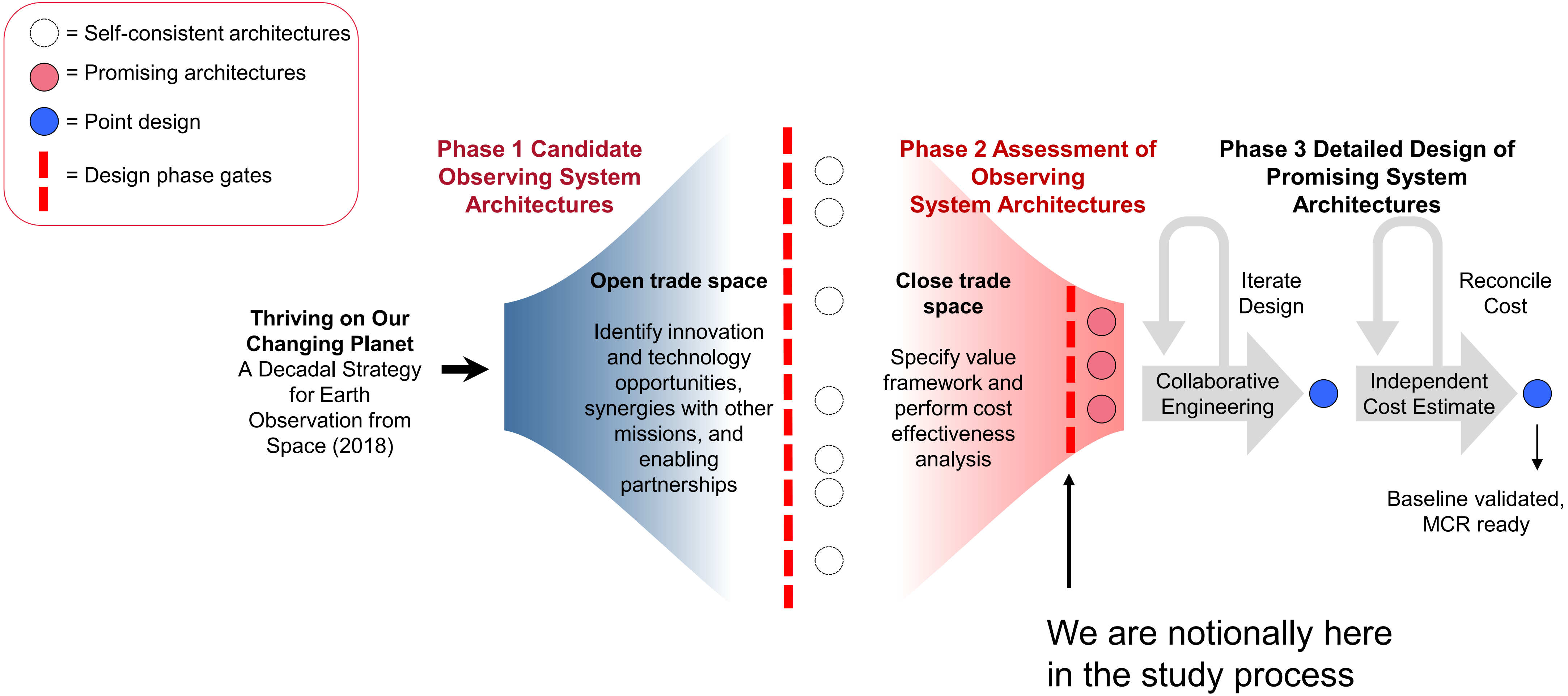
CONSENSUS STUDY REPORT

THRIVING ON OUR CHANGING PLANET

A Decadal Strategy for Earth Observation from Space

# MC Study Phases



◌ = Self-consistent architectures

🔴 = Promising architectures

🔵 = Point design

▮ = Design phase gates

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

**Phase 1 Candidate Observing System Architectures**

**Open trade space**

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

**Phase 2 Assessment of Observing System Architectures**

**Close trade space**

Specify value framework and perform cost effectiveness analysis

**Phase 3 Detailed Design of Promising System Architectures**

Iterate Design

Collaborative Engineering

Reconcile Cost

Independent Cost Estimate

Baseline validated, MCR ready

We are notionally here in the study process

# 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

- Product: Suggested Measurement Parameters for Baseline
- Product: Suggested Measurement Parameters for Goal

*Available on website*

**Decadal Survey**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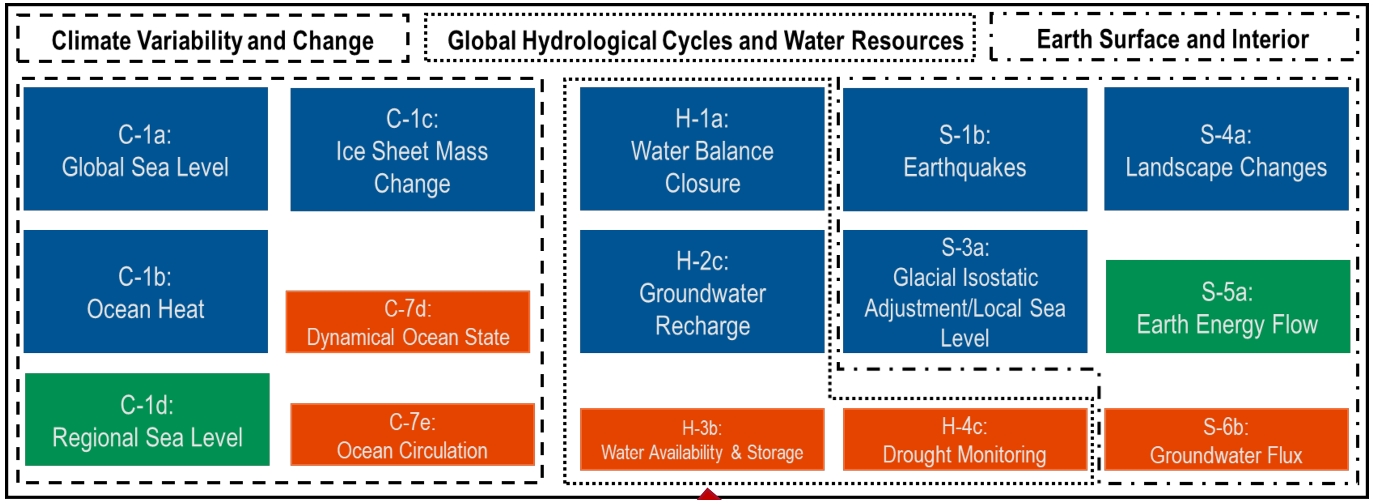
**Mass Change-contributing DS objectives and prescribed importance**


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

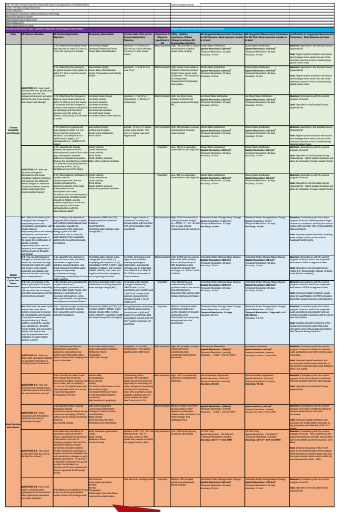
Global Hydrological Cycles and Water Resources
- H-1a: Water Balance Closure
- H-2c: Groundwater Recharge
- H-3b: Water Availability & Storage
- H-4c: Drought Monitoring

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**



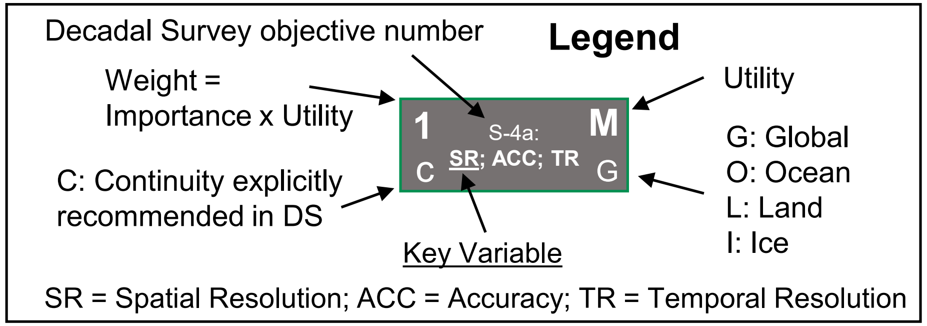
**Expert Interpretation**

**Community Input and Vetting**

# Decadal Survey Science and Application Objectives for Mass Change

## Measurement Parameters for Baseline

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



**Legend**

Decadal Survey objective number

Weight = Importance x Utility

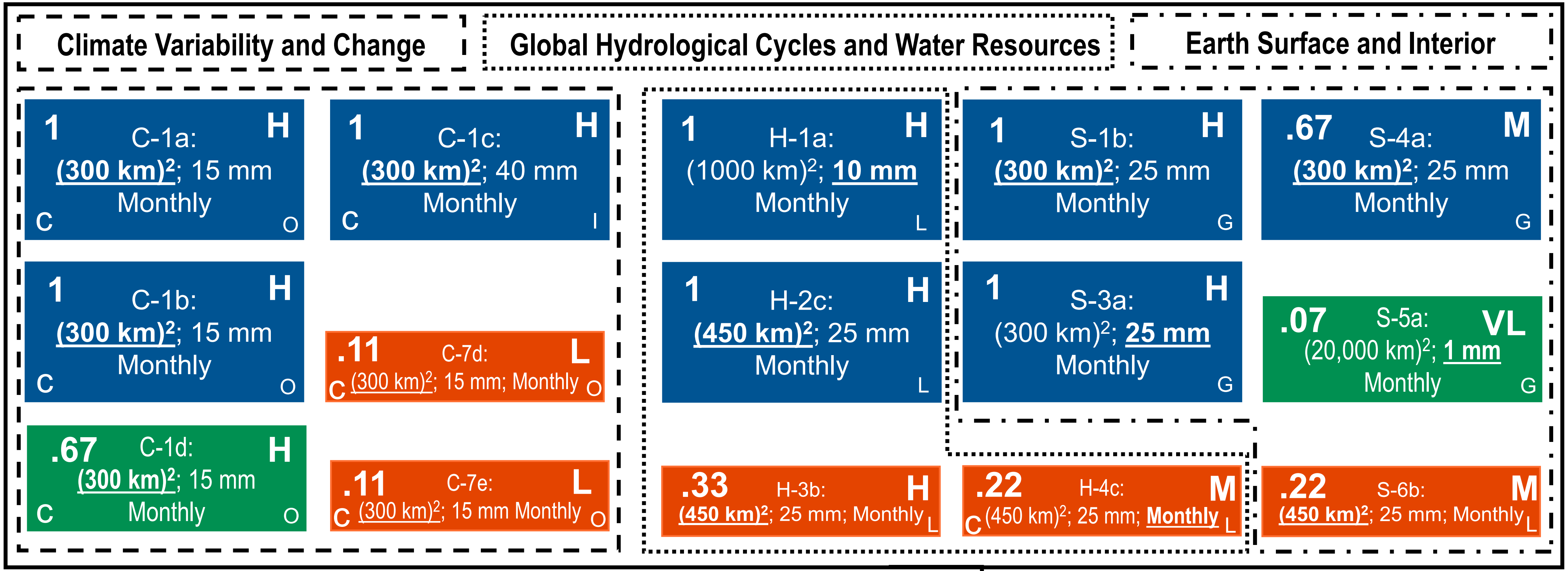
C: Continuity explicitly recommended in DS

Key Variable

Utility

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

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



### Climate Variability and Change

1 C-1a: 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

**DS Prescribed Importance**

| | | |
|---|---|---|
| Most Important<br>Highest weight | Very Important<br>Medium weight | Important<br>Lower Weight |
| 1.0 | 0.67 | 0.33 |

**MC Utility Score**

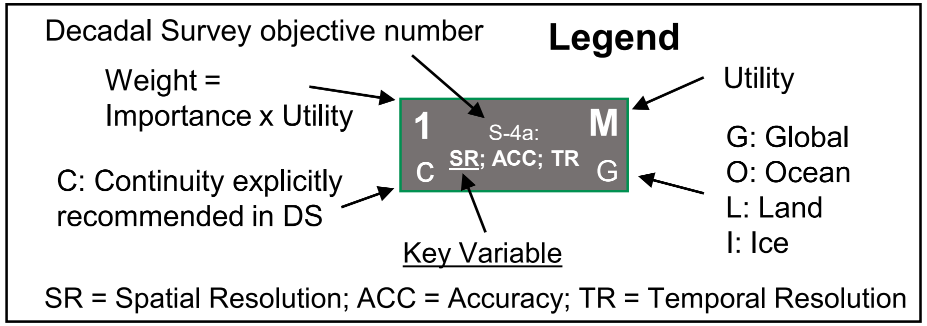
| | |
|---|---|
| H: High | 1.0 |
| M: Medium | 0.67 |
| L: Low | 0.33 |
| VL: Very Low | 0.10 |

**Science Performance Targets**

# Decadal Survey Science and Application Objectives for Mass Change

## Measurement Parameters for Goal

*Goal Observing System – supports elevated ambitions of DS while ensuring longevity in the mass change timeseries. May include advancing enabling technologies.*



**Legend**

Decadal Survey objective number

Weight = Importance x Utility

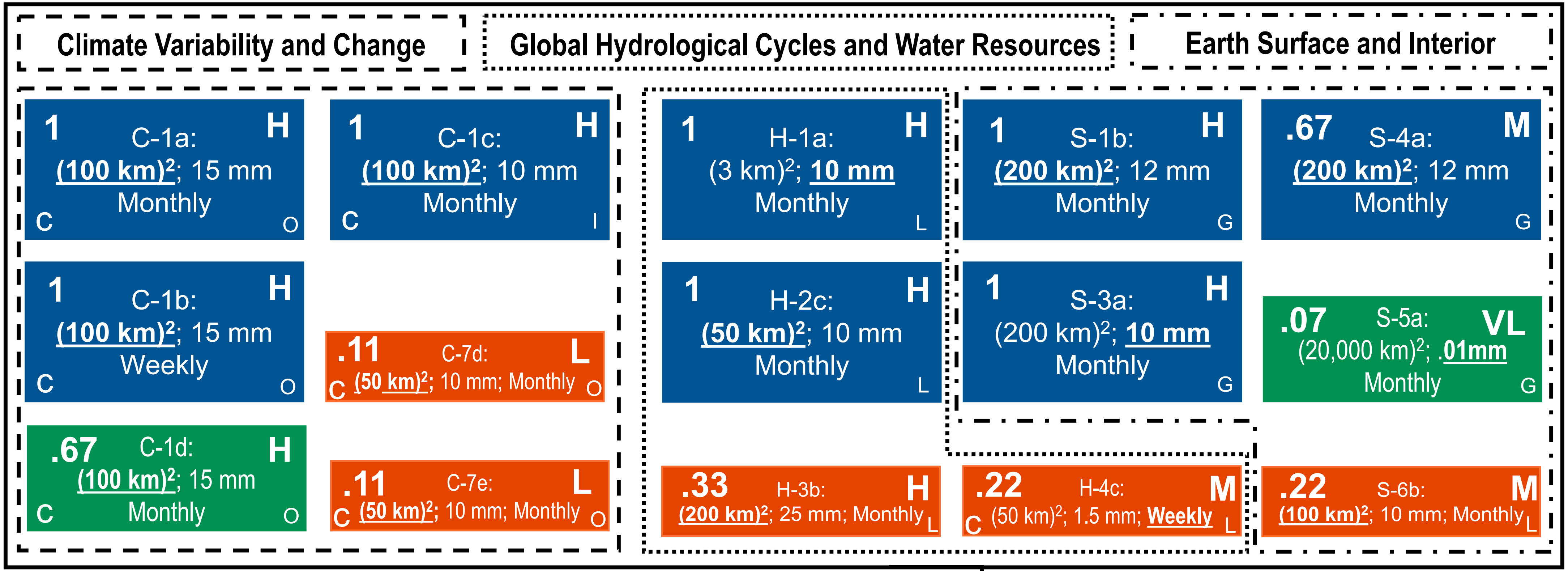
C: Continuity explicitly recommended in DS

Key Variable

Utility

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

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



### Climate Variability and Change

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

### Global Hydrological Cycles and Water Resources

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

### Earth Surface and Interior

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

**Science Performance Targets**

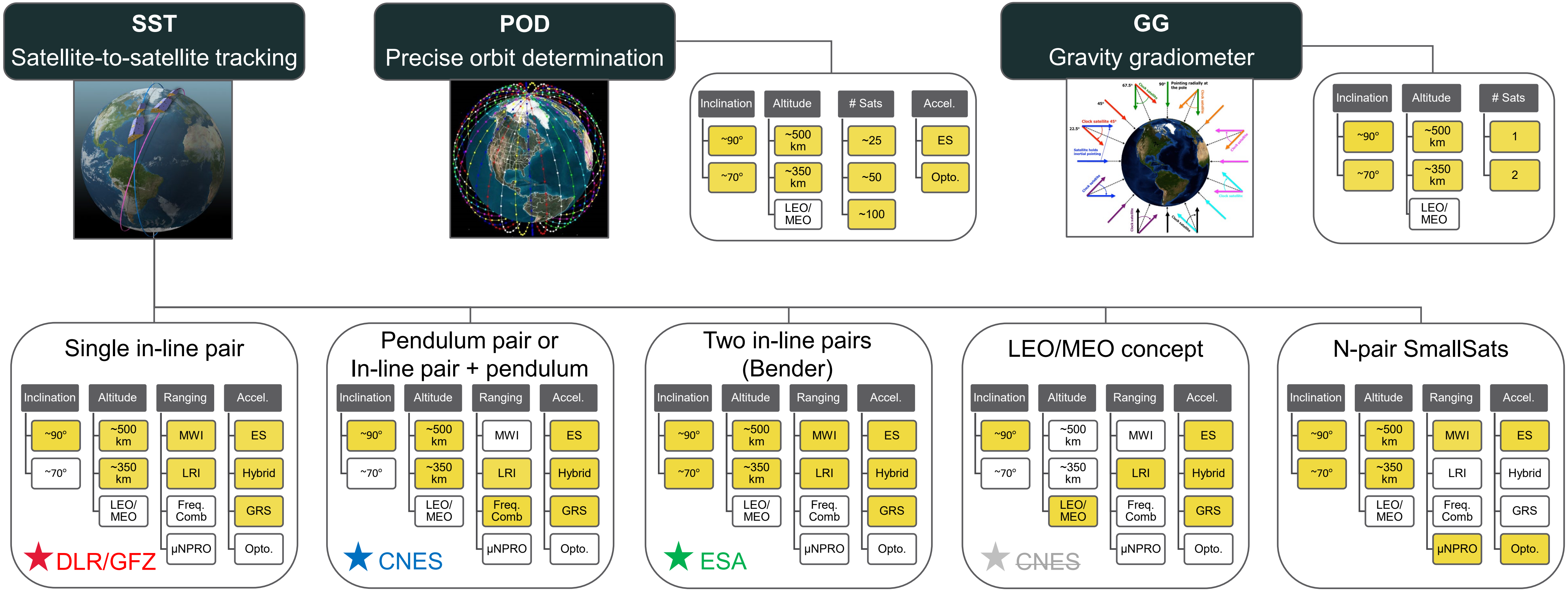
**DS Prescribed Importance**

| Most Important<br>Highest weight | Very Important<br>Medium weight | Important<br>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 |

# 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 | 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 | 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 | 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 | Opto. |

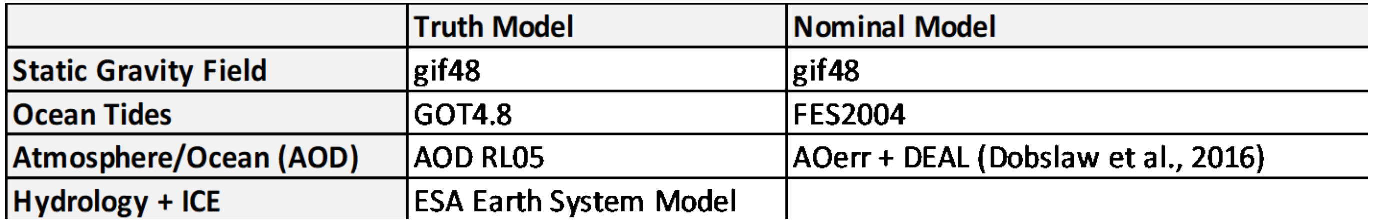
★ ~~CNES~~

### N-pair SmallSats

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

Highlighted boxes = Orbit & technology trade space

# Architecture Assessment



| | 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 | |

- Numerical simulations are run for one month, January 2006
  - With temporal aliasing errors: **Science Value**
  - Without temporal aliasing errors: **Measurement System Value**
- Instrument Noise
  - Various ranging and accelerometer technologies simulated with noise models provided by instrument developers
  - GNSS errors included
    - 1 cm white noise added to each axis – kinematic orbits
  - Attitude errors included
    - For SST architectures, GRACE-FO pre-launch estimate of errors is used
- Simulation notes
  - Max degree/order 180
  - Implements stochastic noise model for observations derived from postfit residuals (see offline poster by Ellmer et. al)
    - **Lesson Learned: This systematically improves multi-pair observing system architectures more than single-pair observing systems.**

# A Quantitative Assessment of Science Value

<u>Science Value (SV)</u>

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

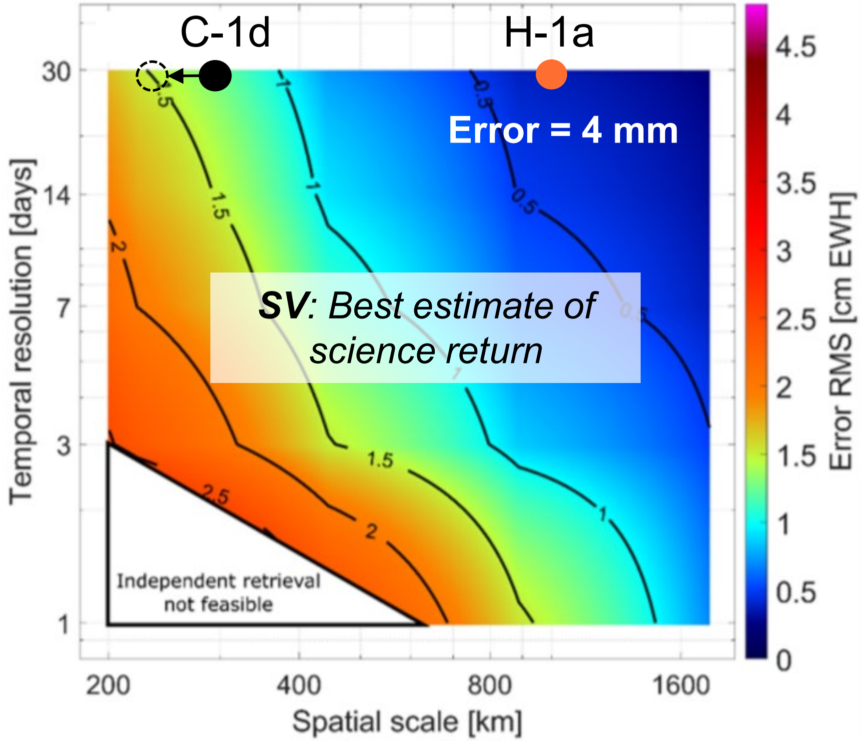
Key Variable: **Spatial Resolution**

**.67** C-1d: **H**
<u>(300 km)²</u>; 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 $\alpha$



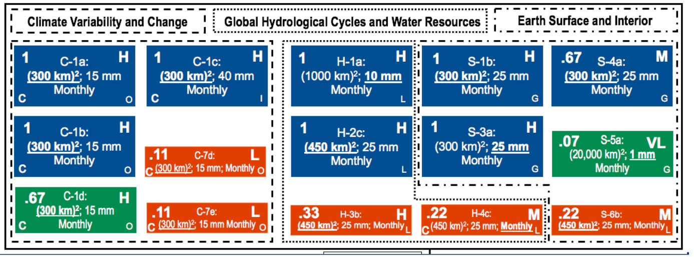
*Hauk and Wiese, Earth and Space Science, 2020.*

Key Variable: **Accuracy**

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

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

SATM Measurement Parameters for Baseline



**Climate Variability and Change**

**1** C-1a: **H** <u>**(300 km)²**</u>; 15 mm Monthly C O
**1** C-1c: **H** <u>**(300 km)²**</u>; 40 mm Monthly C I
**1** C-1b: **H** <u>**(300 km)²**</u>; 15 mm Monthly C O
**.11** C-7d: **L** C <u>(300 km)²</u>; 15 mm; Monthly O
**.67** C-1d: **H** <u>(300 km)²</u>; 15 mm Monthly C O
**.11** C-7e: **L** C <u>(300 km)²</u>; 15 mm Monthly O

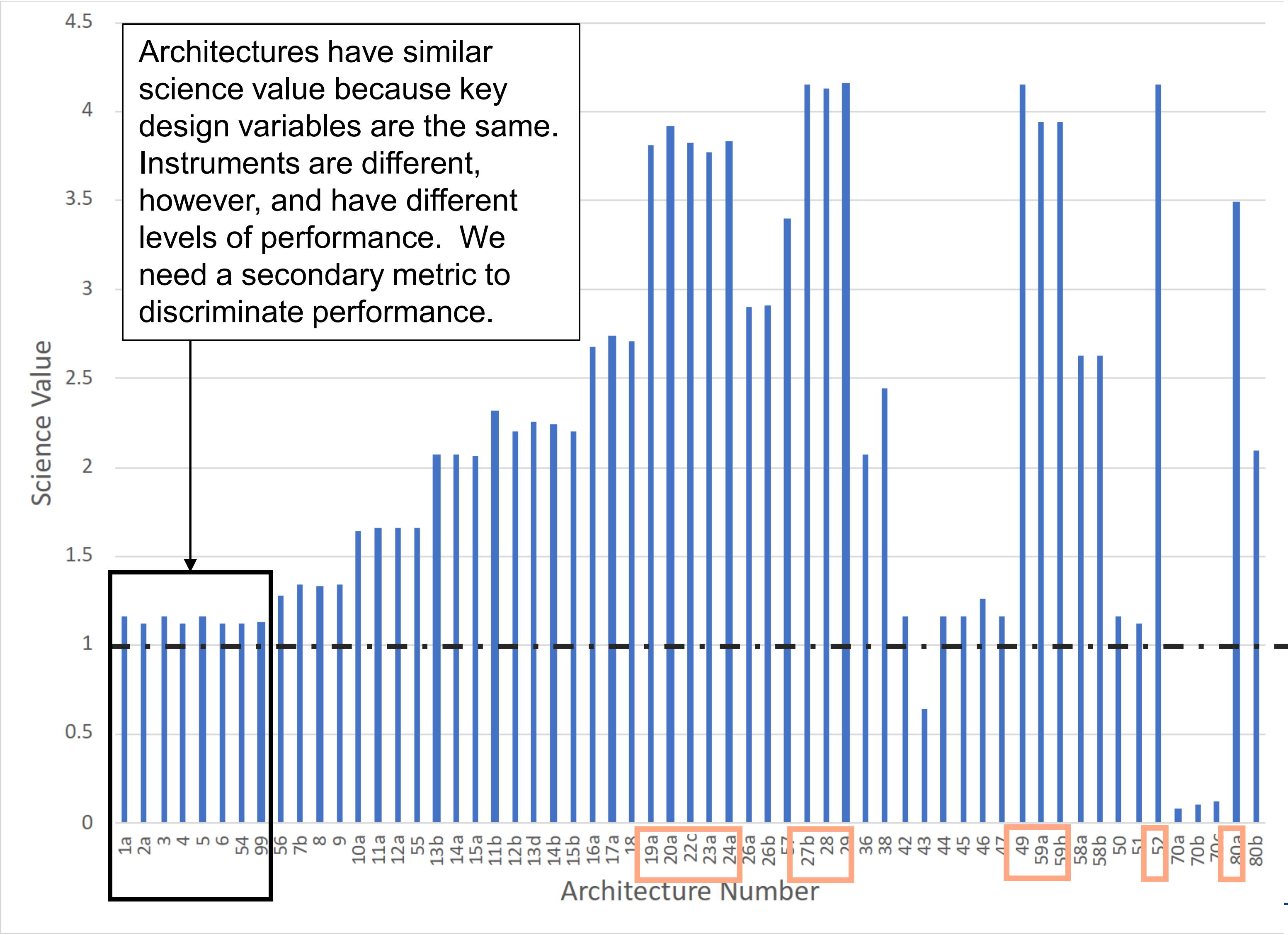
**Global Hydrological Cycles and Water Resources**

**1** H-1a: **H** (1000 km)²; <u>**10 mm**</u> Monthly L
**1** H-2c: **H** <u>**(450 km)²**</u>; 25 mm Monthly L
**.33** H-3b: **H** <u>**(450 km)²**</u>; 25 mm; Monthly L
**.22** H-4c: **M** C (450 km)²; 25 mm; <u>**Monthly**</u> L

**Earth Surface and Interior**

**1** S-1b: **H** <u>**(300 km)²**</u>; 25 mm Monthly G
**.67** S-4a: **M** <u>**(300 km)²**</u>; 25 mm Monthly G
**1** S-3a: **H** (300 km)²; <u>**25 mm**</u> Monthly G
**.07** S-5a: **VL** (20,000 km)²; <u>1 mm</u> Monthly G
**.22** S-6b: **M** <u>**(450 km)²**</u>; 25 mm; Monthly L

# Results: Science Value



Architectures have similar science value because key design variables are the same. Instruments are different, however, and have different levels of performance. We need a secondary metric to discriminate performance.

Indicates SATM Goal(s) can be achieved

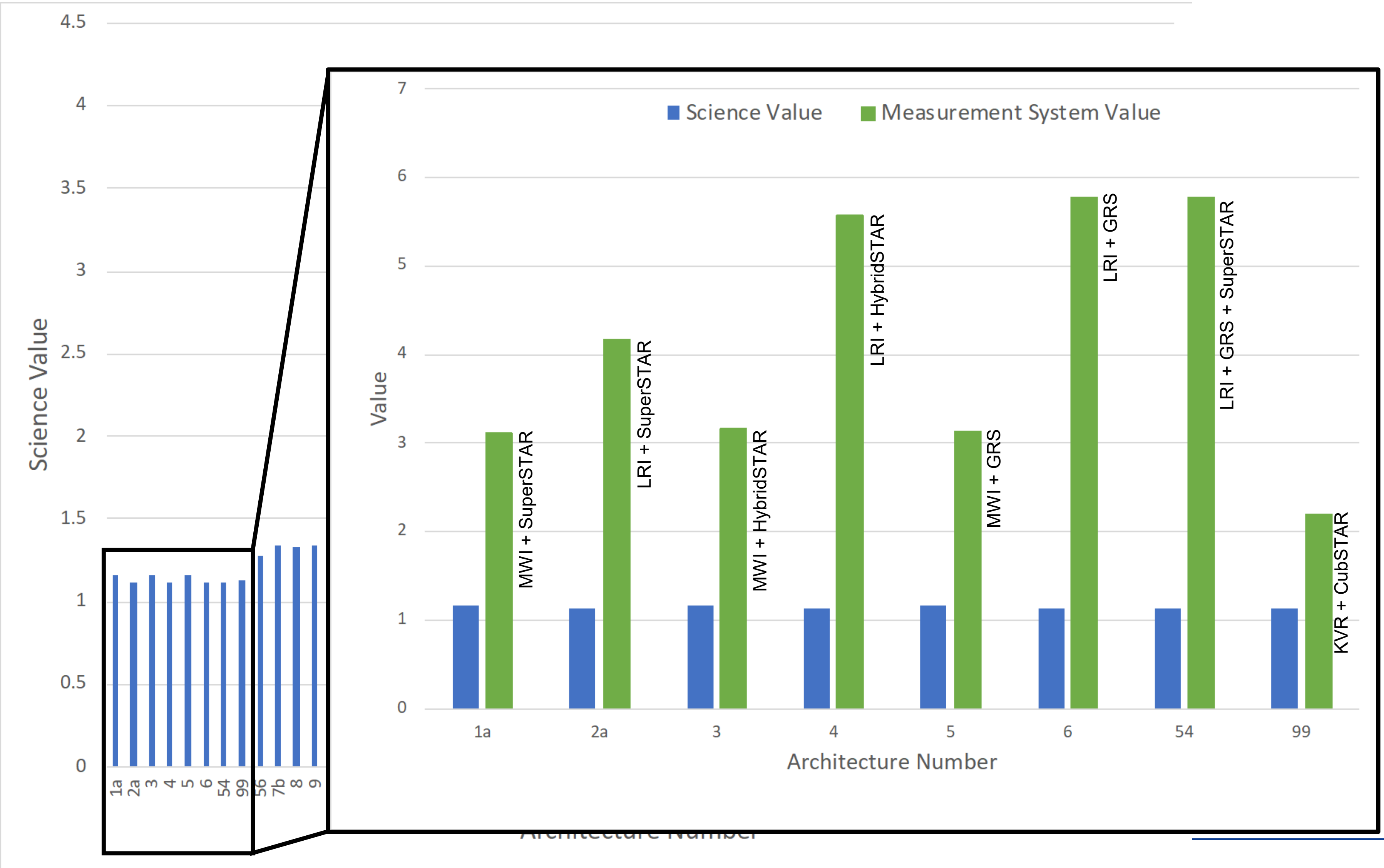
*Goals are assessed in a binary fashion*

**Improvement Relative to Baseline Science Objectives**

*Baseline Science Objectives are met*

**Degradation Relative to Baseline Science Objectives**

# Measurement System Value Results: A Secondary Discriminator



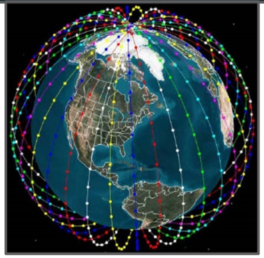
Measurement System Value is quantified using same process as Science Value except temporal aliasing errors are not included in the numerical simulation

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

# Architectures & Technology: What we have learned

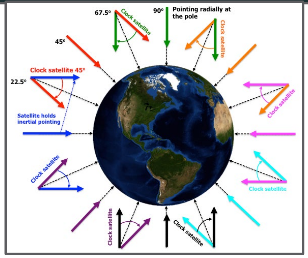
## SST
Satellite-to-satellite tracking

## 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 | 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 | 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 | 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 | Opto. |

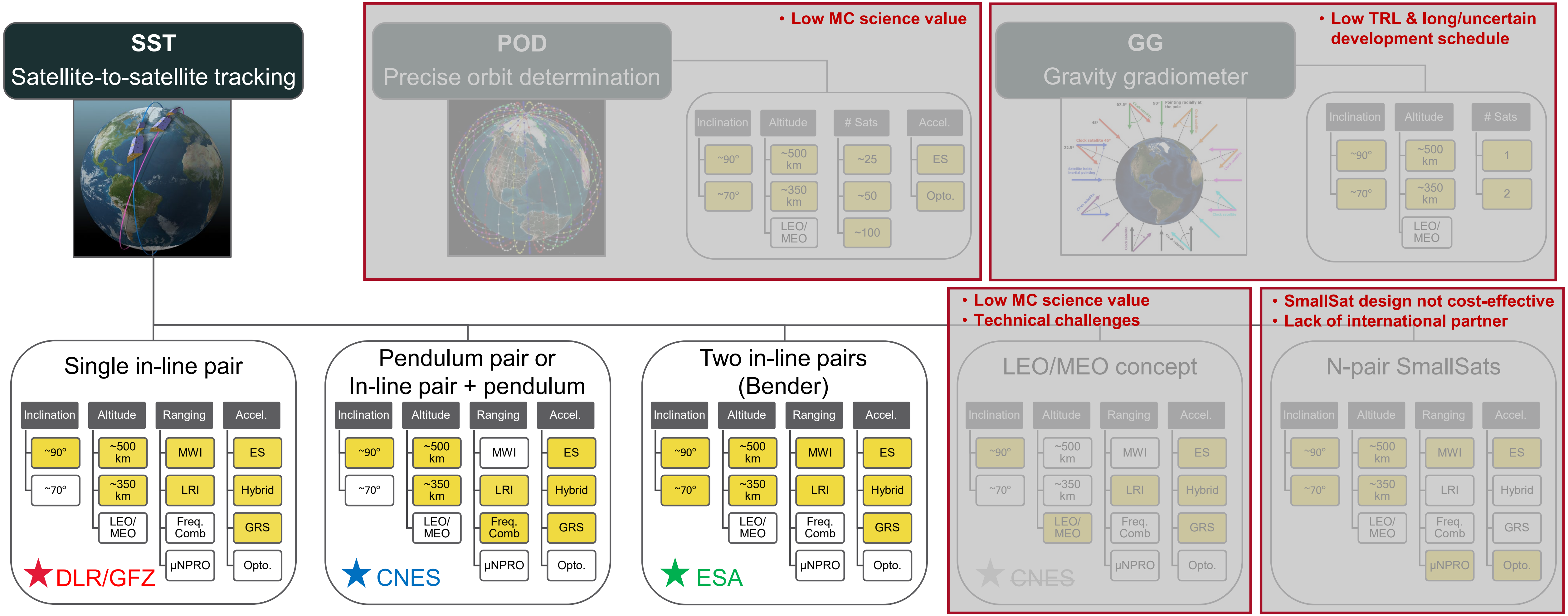
★ ~~CNES~~

### N-pair SmallSats

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

Highlighted boxes = Orbit & technology trade space

# Architectures & Technology: What we have learned



**SST**
Satellite-to-satellite tracking

**POD**
Precise orbit determination
- Low MC science value

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

**GG**
Gravity gradiometer
- Low TRL & long/uncertain development schedule

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

Single in-line pair
Inclination: 🟨 ~90° · ~70°
Altitude: 🟨 ~500 km · 🟨 ~350 km · LEO/MEO
Ranging: 🟨 MWI · 🟨 LRI · Freq. Comb · μNPRO
Accel.: 🟨 ES · 🟨 Hybrid · 🟨 GRS · Opto.
★ DLR/GFZ

Pendulum pair or In-line pair + pendulum
Inclination: 🟨 ~90° · ~70°
Altitude: 🟨 ~500 km · 🟨 ~350 km · LEO/MEO
Ranging: MWI · 🟨 LRI · 🟨 Freq. Comb · μNPRO
Accel.: 🟨 ES · 🟨 Hybrid · 🟨 GRS · Opto.
★ CNES

Two in-line pairs (Bender)
Inclination: 🟨 ~90° · 🟨 ~70°
Altitude: 🟨 ~500 km · 🟨 ~350 km · LEO/MEO
Ranging: 🟨 MWI · 🟨 LRI · Freq. Comb · μNPRO
Accel.: 🟨 ES · 🟨 Hybrid · 🟨 GRS · Opto.
★ ESA

LEO/MEO concept
- Low MC science value
- Technical challenges

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

N-pair SmallSats
- SmallSat design not cost-effective
- Lack of international partner

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

Highlighted boxes = Orbit & technology trade space

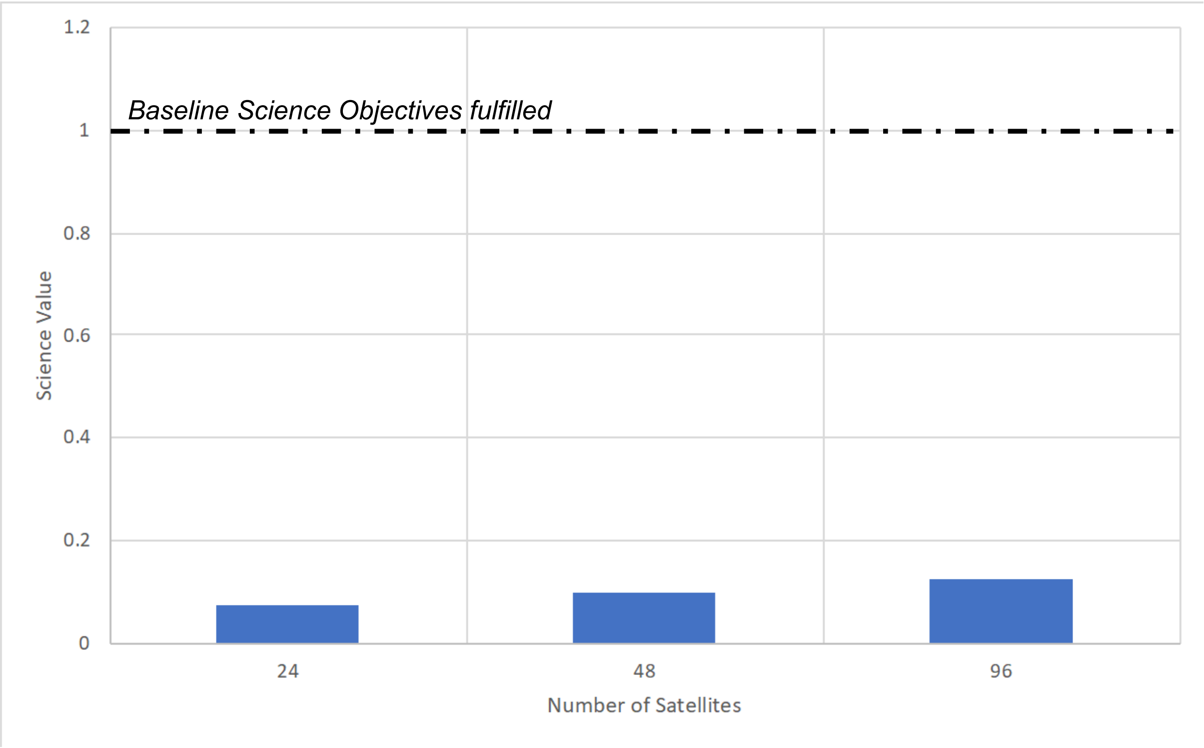
# Precise Orbit Determination (POD)

**Key point:**

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

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

POD science value assessment



# Atomic Interferometer Gravity Gradiometer (AIGG)

**Key points:**

**High science performance but long/uncertain path to TRL 6**

AOSense lab instrument in collaboration with NASA GSFC:

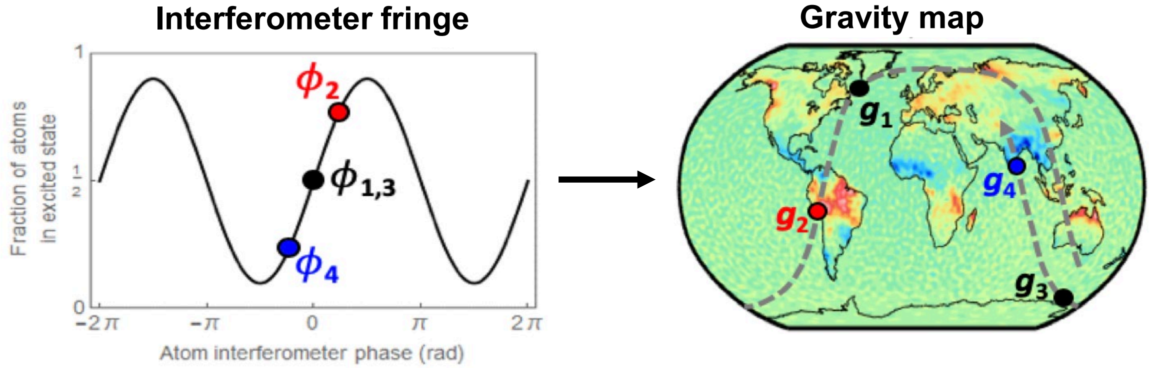
- Currently TRL 4; path to TRL 6 TBD

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

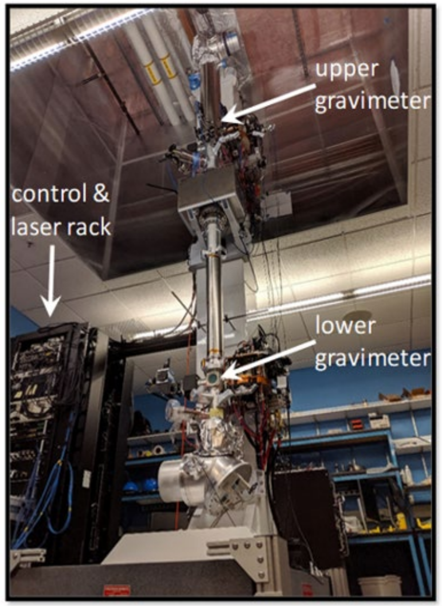
- Instrument Accommodation: 947 kg; 1049 W

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

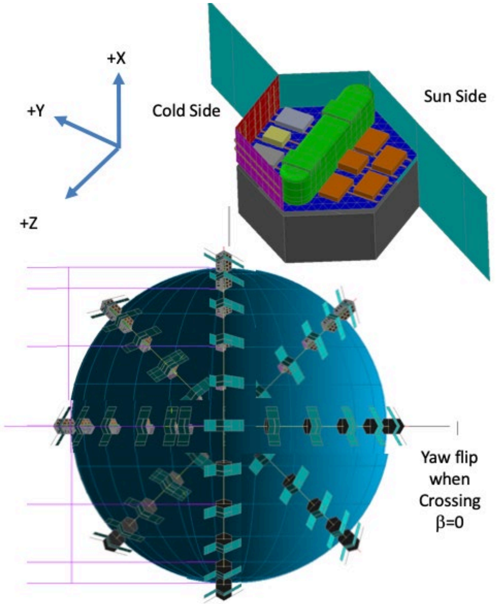


*High sensitivity interferometer fringe measurements for gravity observations*

**AIGG at AOSense**



**Flight Design**



# SST SmallSats: Summary of Team X Study

- Team X: 4-day concurrent engineering design session at JPL – conducted remotely in May 2020
- Team X study goals
  - Determine if a sub-$300M SST exists that meets baseline objectives and seeks to minimize size, weight, and power
  - Leverage smaller, less mature accelerometer (ONERA CubStar) and inter-satellite ranging technologies (GeoOptics KVR)
- Team X architectures:

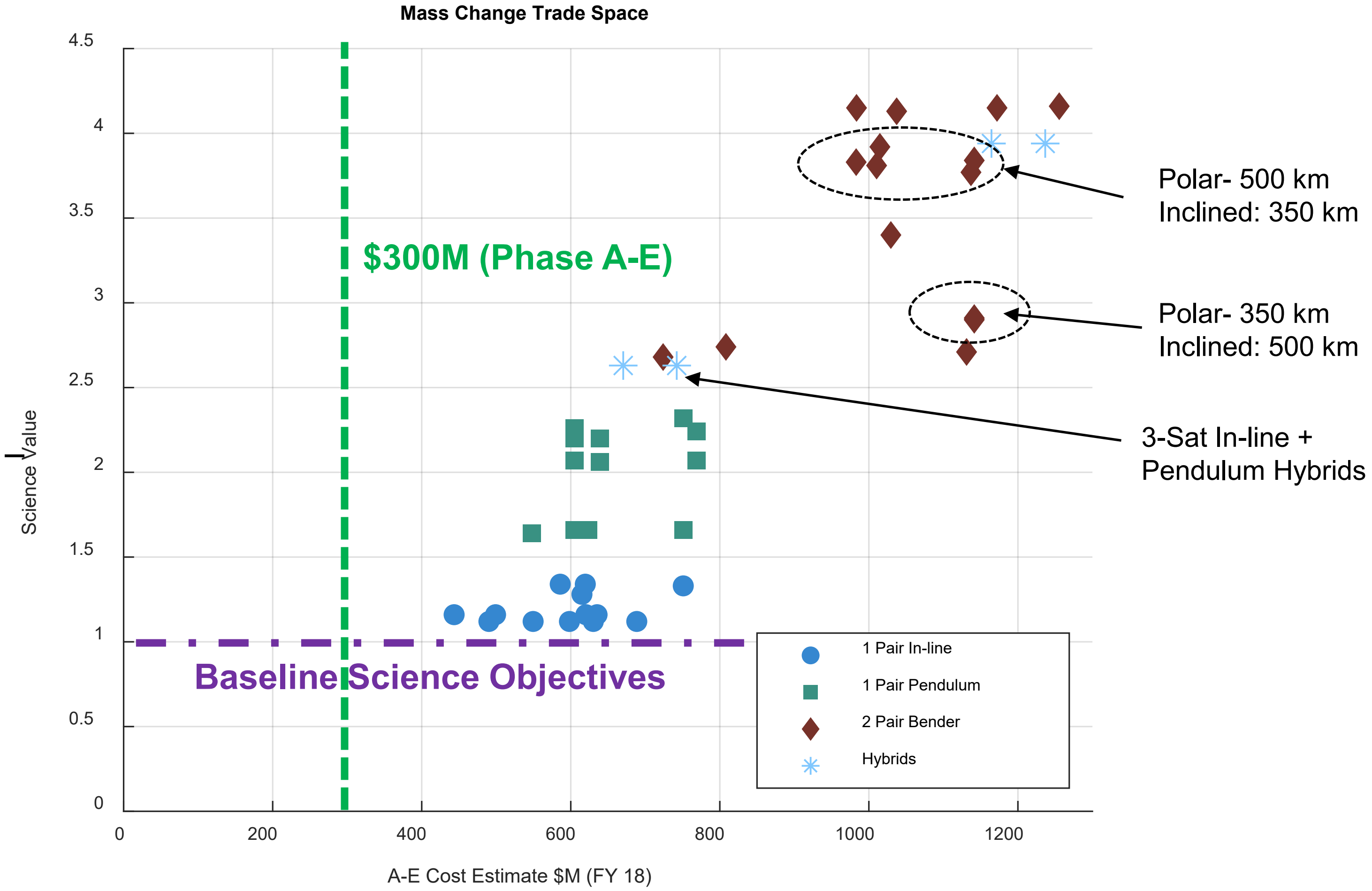
Option 1: Dual string with heritage bus components
Redundancy: Dual string
Mass: 434 kg
Phase A-E cost: $501M FY18

Option 2: Single string with SmallSat bus components
Redundancy: Single string
Mass: 194 kg
Phase A-E cost: $419M FY18

- Team X major conclusions
  - 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

# Cost Effectiveness Comparisons - Preview

- 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 ($300M FY18) for Phase A-E
  - Reduced cost to NASA may be enabled through strategic partnerships
  - Costs shown do not include workshare with potential international partners



# MC Study Path Forward

The MC Team is on track to provide the following to NASA HQ in late Fall:

- Description of high-value, affordable architectures with recommendation to HQ
  - Science and applications performance
  - Cost estimate and cost risk assessment (Phase A-E, RY$)
  - Schedule estimate and schedule risk assessment including continuity with GRACE-FO
  - Technology readiness, risks, and maturation plans
  - International partnership concepts
  - Background and supporting material (e.g., design center reports, modeling analysis)
- After decision from NASA HQ, we will enter Phase 3 of the study focused on detailed design of one or more high value architectures

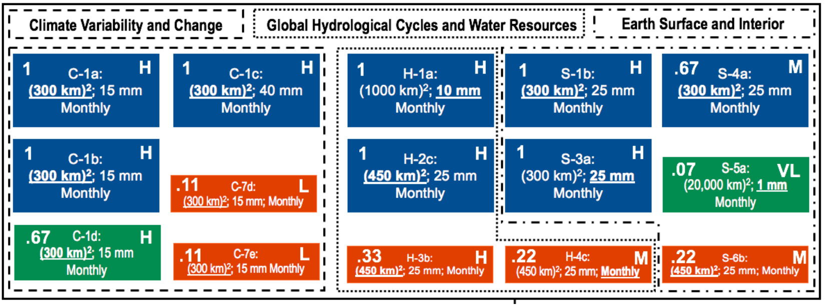
Please join us at AGU in December for a Virtual Town Hall
Friday, December 11, 2020 @ 07:00 Pacific Standard Time

# Backup

# Relating Observing System Capability to the DS

Decadal Survey

Science and Applications Traceability Matrix Measurement Parameters



**Climate Variability and Change**

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

**Global Hydrological Cycles and Water Resources**

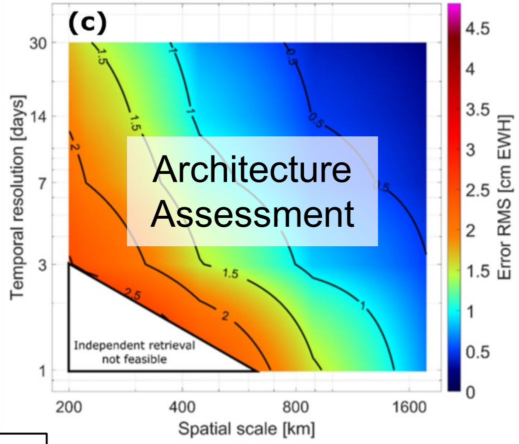
- 1 H-1a: H (1000 km)$^2$; 10 mm Monthly
- 1 H-2c: H (450 km)$^2$; 25 mm Monthly
- .33 H-3b: H (450 km)$^2$; 25 mm; Monthly
- .22 H-4c: M (450 km)$^2$; 25 mm; Monthly

**Earth Surface and Interior**

- 1 S-1b: H (300 km)$^2$; 25 mm Monthly
- .67 S-4a: M (300 km)$^2$; 25 mm Monthly
- 1 S-3a: H (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

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

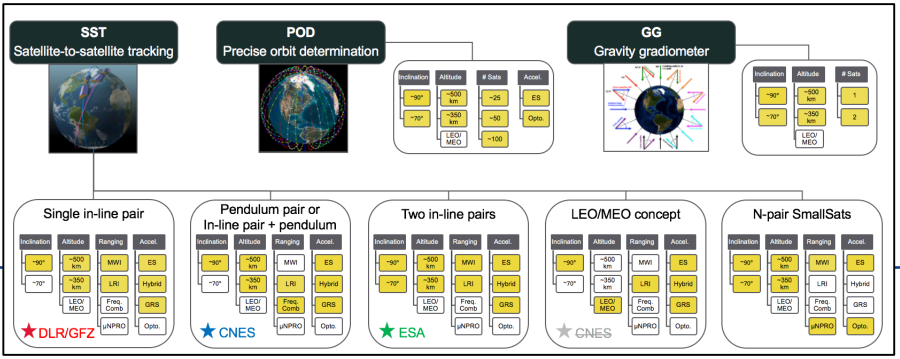
The process is successful in discriminating between architectures



Architecture Assessment

Science Value

Architecture Tree



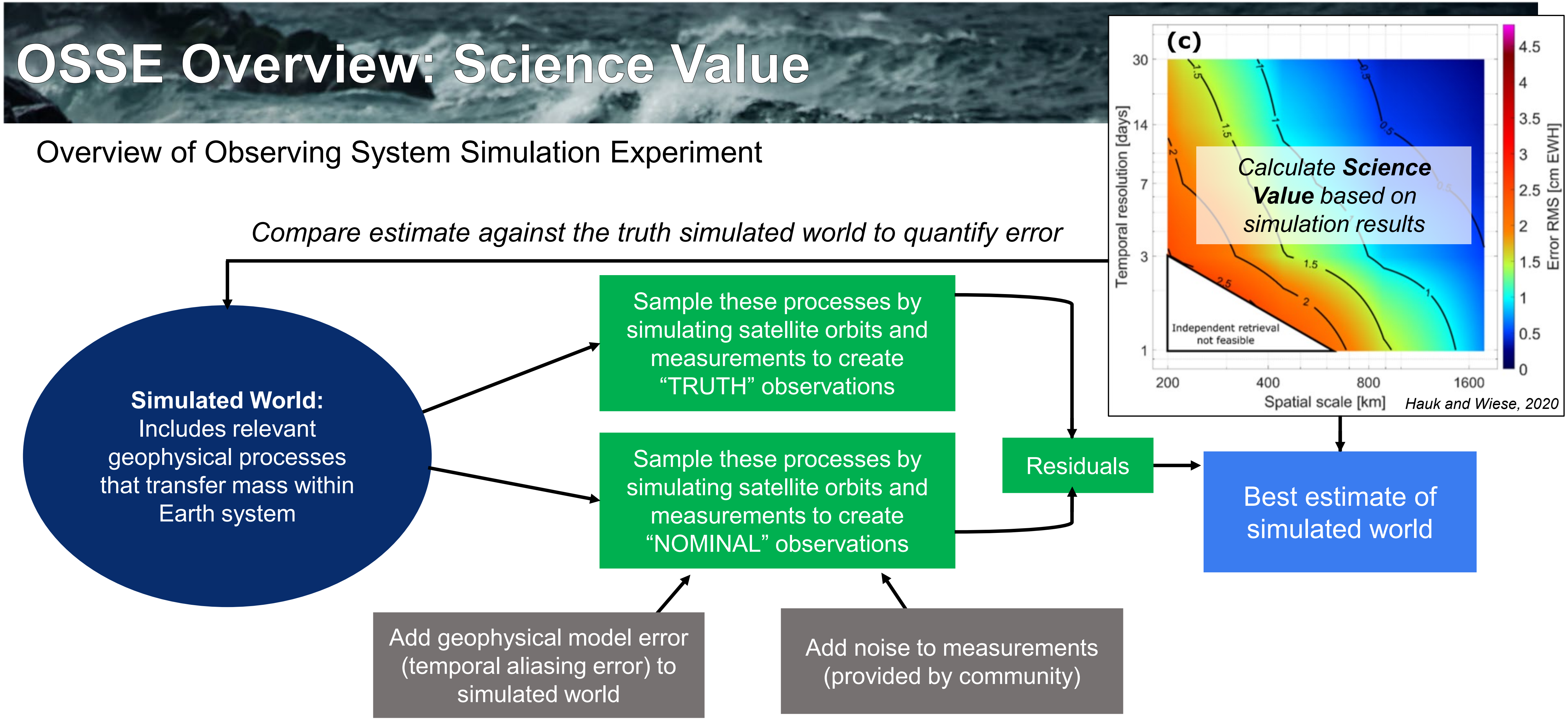
# Mass Change Designated Observable Study: Background

- **January 2018**: Mass Change is identified as a Designated Observable in the 2017-2027 Decadal Survey for Earth Science and Applications from Space
  - 15 Science Questions related to mass change are identified
  - Recommended cost target: $300M
- **December 2018**: Formation of Mass Change Designated Observable Study Team
  - Participations from multiple NASA Centers
  - Charter is to cast a wide net to identify possible observing systems that can be responsive to science questions identified in the Decadal Survey
  - Create a “Value Framework” to quantify science value, cost, technology readiness level, schedule (including continuity with GRACE-FO), risk, and potential international partners for possible observing systems
  - Recommend a small set of high-value affordable architectures to NASA HQ for eventual selection of an observing system for full implementation
- **July 2019**: Community Workshop focused on architectures, technology, science focus areas
- **February 2020**: Release of final Science and Applications Traceability Matrix Measurement Parameters after significant community input
- **May 2020**: Release of LRI and Gravitational Reference Sensor Technology Summaries and Roadmaps

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

# 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

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

*Hauk and Wiese, 2020*

| | 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 | |

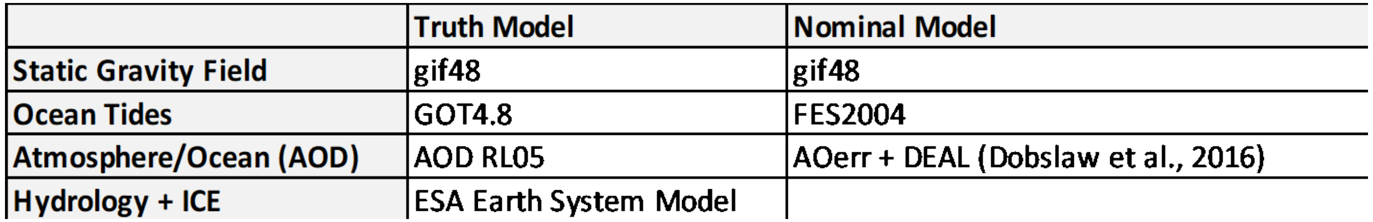
# Cost Effectiveness Comparisons - Preview

- POD has poor performance even for large scale multi-element system implementation
- GG has high performance ceiling but unclear maturation plans
- 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)
  - LEO to MEO ranging including combined LEO-MEO with in-line pairs
  - Hybrids (combined in-line, pendulum)
- Cost estimates for domestic only implementation are above cost target ($300M FY18) for Phase A-E
  - Derived from parametric and analogy-based cost models
  - Reduced cost to NASA may be enabled through strategic partnerships
  - Costs shown do not include workshare with potential international partners
  - LEO-MEO costs include only the LEO portion of the observing system implementation

# High Fidelity Numerical Simulations

- Numerical simulations are run that include realistic measurement system errors as well as dynamic force model errors to quantify the expected performance of each architectural variant
- Simulations mimic processing of real GRACE and GRACE-FO data
- Analytic partial derivatives relate the simulated observations to the state parameters of interest – this allows for a quantitative metric of performance.
- Numerically intensive: ~300,000 CPU hours
- Performance is analyzed across space and time

Dynamic force models used in simulations



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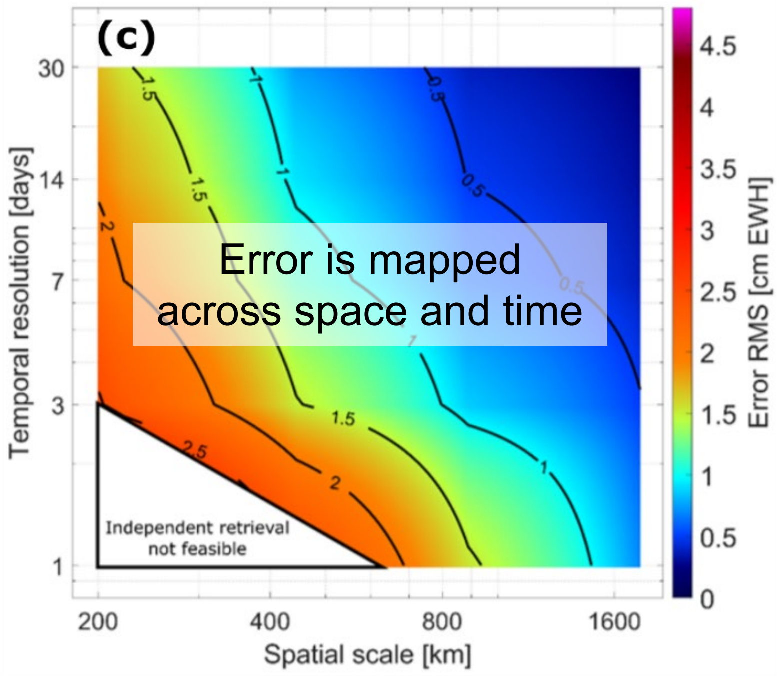

Error is mapped across space and time

# SST SmallSats: MicroSat option

- Overview
  - GeoOptics proposed a constellation of MicroSats (consistent with Class-D) as potential MC architecture
  - Same ranging and accelerometer technologies as SmallSat Team X study
  - MC study team worked with Aerospace Corp. to analyze and cost
  - **Proposed design is not viable** due to lack of power budget closure (requires larger spacecraft)
  - **Thermal requirements are also not resolved**
  - Costing efforts revealed **lack of savings even for non-viable design**
- Details
  - Class-D lifetime is 2.5 years based on historical analogies
  - To achieve Class-C implementation (for consistent comparison) requires satellites to be replenished once
    - 2-pair implementation + 2-pair spares (4-pair/8-satellites total): $550M
    - 4-pair implementation + 4-pair spares (8-pair/16-satellites total): $960M
- Conclusions
  - Due to high costs of non-viable design, the closure of the power budget and thermal requirements not pursued
  - Conclusions of Team X study are consistent with the non-viability of the proposed GeoOptics architecture (i.e. single-string SmallSat implementation is the ‘floor’ design that meets science objectives)