CONTINUITY OF NASA EARTH OBSERVATIONS FROM SPACE: A VALUE FRAMEWORK

Briefing to NASA's Earth Science Division

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Background

- ESD faces difficult choices among competing priorities, including new responsibilities for investing in the continuation of existing measurements and developing new measurement capability to address new research priorities
  - A problem compounded by highly-constrained budgets and increased responsibility—to date without commensurate budget increases—starting after the JPSS-1 era for vertical profiles of stratospheric and upper tropospheric ozone (OMPS-L), solar irradiance (TSIS), Earth radiation budget measurements (CERES), and altimetry follow-ons beyond Jason-3.

- In 2013, at the request of the ESD, an ad hoc committee of the Academies was convened with the task of providing a framework to assist in the determination of when an ESD measurement or dataset should be collected for extended periods

COMMITTEE ON A FRAMEWORK FOR ANALYZING THE NEEDS FOR CONTINUITY OF NASA-SUSTAINED REMOTE SENSING OBSERVATIONS OF THE EARTH FROM SPACE

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Assumptions for Study

- ESD is currently in a capped budget environment
  - Increasing demands for implementation of new measurements
  - Growing demand for continuing important measurements from current mission suite
    - Executive and Congressional Branch priorities
    - ESD Program Plans
    - Survey from NRC Decadal Survey
    - International Collaboration opportunities
- Response in charge is constrained to Climate Change focus
  - Most demanding requirements and likely largest set of actionable options
  - Include issues of instrument performance, stability, cross calibration and the data issues associated with algorithm change in processing and reprocessing
- Recommendation focus is on the measurements required to determine geophysical variables, not on instruments or missions
  - NRC Decadal Survey will provide prioritized QESO's and associated Geophysical variables
  - ESD will provide the instrument and mission response to the set of QESO's
- Emphasis placed on quantitative decision approaches
  - Framework is recommended, but implementation data base still needs development

What’s In this Report

- In attempting to meet its Statement of Task the Committee presents a framework that
  - Focuses on science objectives, where space-based continuity measurements make substantial contributions
  - Relies on a small, but sufficient set of key continuity characteristics to effectively discriminate between competing climate change science-driven continuity measurements
  - Emphasizes quantitative evaluation methods to achieve process objectivity and transparency
  - Complements the existing NASA proposal evaluation processes for Research Announcements (NRA) and Earth Venture Announcements of Opportunity (AO)
  - Is extensible to decision-making between competing measurements for purposes other than climate change driven science and between sets of measurements focused on one science objective or single measurements capable of addressing multiple objectives

What’s Not in this Report

- In considering the full breadth of ESD interests and the inherent difficulties in evaluating measurements for purposes other than climate change, science-driven continuity, the presented framework does not
  - Prescribe a single, fully defined method for evaluation of climate change, science-driven continuity measurements
  - Work through the details of, or examples for, new Science or Applications driven measurements
  - Summarize the total value of a single measurement relative to all science objectives of interest.

Addressing the Statement of Task

Task Statement	Report Discussion
Define and describe roles for Continuity	Chapter 2, section 2.2
Establish methodologies and/or metrics that can be used to:	Chapter 3
Determine whether measurement should be collected for extended periods	Section 3.1, 3.2
Prioritize among extended measurements	Section 3.5, 3.6
Factor-in the impacts of quality, especially degradation and gaps	Section 3.4.2, Appendix B
Additional topics	Chapter 3, 4, & Appendices C - F
Examine alternatives for continuity	Section 3.2.4, 3.3, 3.4.1
Examine impacts of combining measurements	Section 3.7
Provide framework illustrations	Chapter 4, Appendices C - F

The Basic Framework Building Blocks – Quantified Earth Science Objectives (QESOs)

- The notion of a quantified Earth science objective (QESO) is the starting point for the recommended decision framework.
- A well-formulated QESO would be directly relevant to achieving an overarching science goal of the ESD and allow for an analytical assessment of how the quantified objective would help meet that science goal.
- Proposed space-based continuity measurements should be evaluated in the context of the QESO they address. The resolution, uncertainty, and repeatability of candidate measurements should all be taken into account when deciding whether a QESO is achievable.
  - An example of a QESO could be: "Determine the rate of global mean sea level rise to ±1 mm yr^{-1} $decade^{-1}$$(1\sigma)$".
- To establish a small set of QESOs, ESD could turn to the same sources that inform the development of its program plan, notably the scientific community consensus priorities expressed in decadal surveys along with guidance from the Executive and Congressional branches. The decadal survey process, which also confronts the same problem of allocating finite resources, might also benefit from expressing priorities through QESOs.

The Basic Framework Building Blocks – Measurement Characteristics and Value

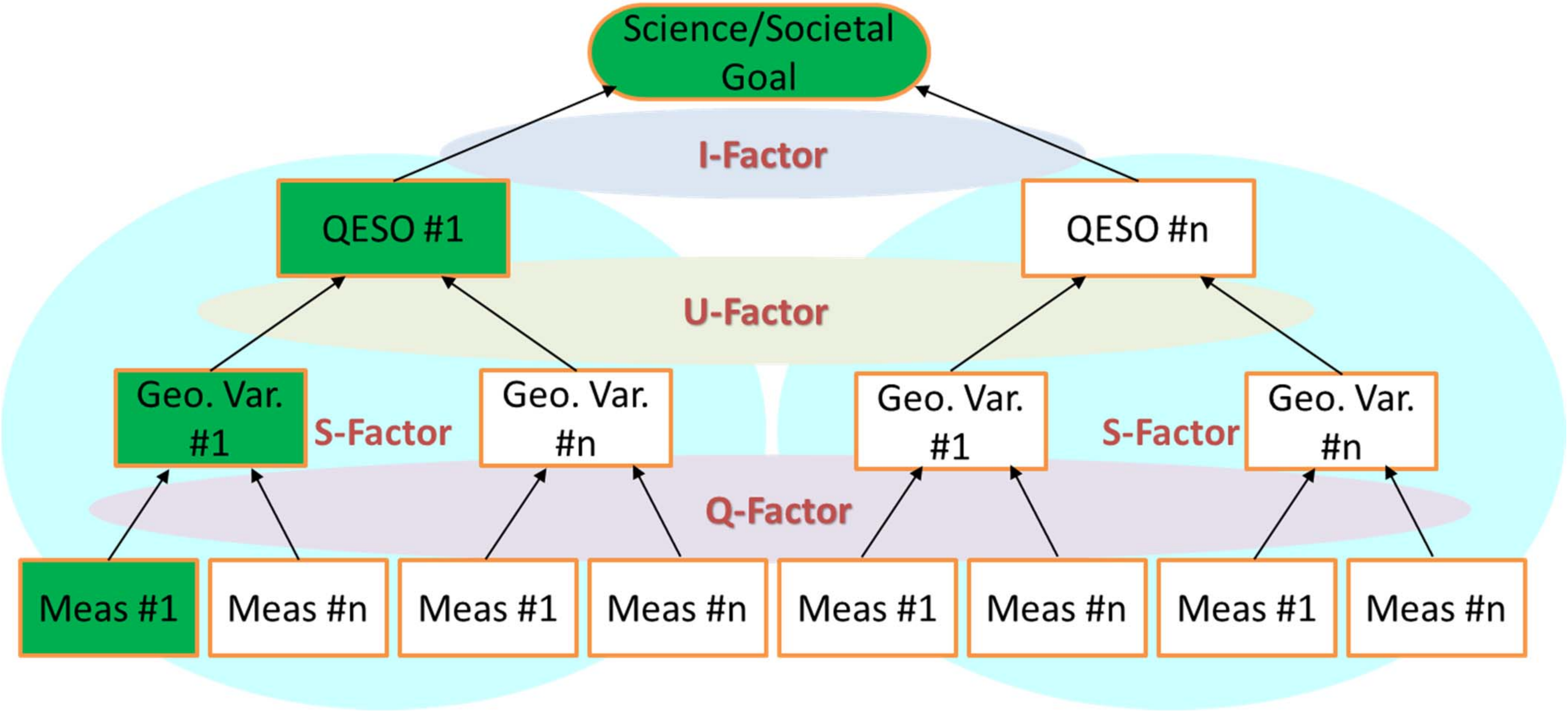
- Just as economic cost benefit analysis attempts to summarize the value of funding for a particular project or endeavor, the committee found that a value-centered framework is capable of effectively distinguishing among competing Earth measurements relevant to a QESO(s). We identify five key characteristics that define the value of a measurement proposed in pursuit of a QESO: Importance (I), Utility (U), Quality (Q), Success Probability (S), and Affordability (A)
- The committee takes Value (V) to be the product of Benefit (B) and Affordability (A); it found a useful expression of B to be an unweighted product of the factors I, U, Q, and S. Thus:

$$\mathbf{V^* = B \times A = (I \times U \times Q \times S) \times A}$$

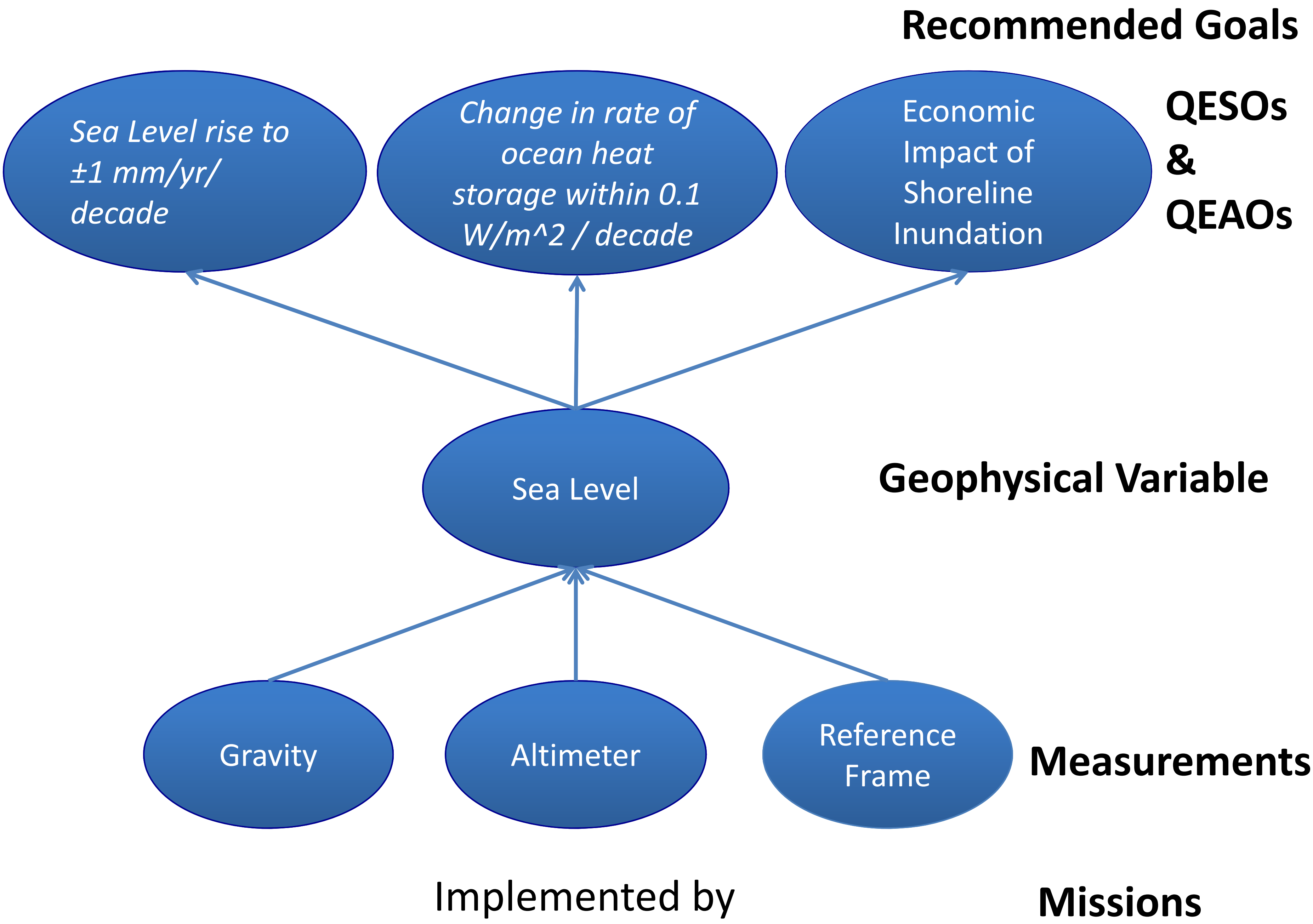
- Successful implementation of this approach requires determining the relative weights of the Benefit and Affordability terms and defining the ratings scales of the individual benefit terms in a way that maintains the relative B and A weights. A self-consistent method is to first assign ratings scales (e.g. 1 to 5) to the Importance and Affordability terms that reflect the desired relative weights for B and A, and, second, to define the Utility, Quality, and Success Probability rating scales in terms of percentages.

***** *These factors are not statistically independent (e.g., changes in A can affect S). Additional cross-cutting factors impact both benefit and affordability; methods to treat them appropriately within the framework are discussed in the report. (Examples of cross-cutting factors include the ability to leverage other measurement opportunities in pursuit of the science objective, and the resilience of a geophysical variable record to unexpected degradation (or gaps) in the measurement quality.)*

Relating Measurement Characteristics to Value



An Example of the Process



Recommended Goals

Sea Level rise to ±1 mm/yr/ decade

Change in rate of ocean heat storage within 0.1 W/m^2 / decade

Economic Impact of Shoreline Inundation

QESOs & QEAOs

Sea Level

Geophysical Variable

Gravity

Altimeter

Reference Frame

Measurements

Implemented by

Missions

Evaluation Factor	Value Range	Description
Importance (I)	1 – 5	Importance indicates the documented community priorities for science goals and QESOs. It represents the maximum potential benefit of a given measurement.
Utility (U)	0 – 1	Utility includes consideration of all of the key geophysical variables, and their relative contributions for addressing a QESO. It represents the percentage of a QESO that would be achieved by obtaining the targeted geophysical variable record.
Quality (Q)	0 – 1	Quality includes consideration of its uncertainty, repeatability, time and space sampling, and data algorithm characteristics relative to that required for achieving a QESO. It represents the percentage of the required geophysical variable record that would be obtained by the proposed measurement.
Success Probability (S)	0 – 1	Success Probability includes consideration of the heritage and maturity of the proposed instrument and its associated data algorithms, the likelihood of leveraging similar or complementary measurements, and the likelihood of data gaps that would adversely affect the quality of the measurement. It represents the probability that the proposed measurement would be successfully achieved.
Affordability (A)	1 – 5	Affordability of a proposed continuity measurement includes consideration of the total cost of developing, producing, and maintaining the sought-after data record.

A Note about Measurement Gap Risk

Early in its discussions, the committee included "Gap Risk" as an independent characteristic in the Value framework. It rapidly became clear, however, that Gap Risk affects many of the other characteristics in the Value framework, and thus should be addressed as part of those factors.

- *First*, the occurrence of a gap can increase the uncertainty and decrease the repeatability and therefore affects the *Quality* characteristic for that record. The primary effect on *Quality* arises from discontinuities in a long-term geophysical variable record without sufficient absolute calibration uncertainty of the measurement. Another *Quality* impact can occur if there are time-space gaps that do not capture abrupt changes (e.g., volcanic eruption) or sufficiently average over internal natural variability (such as ENSO).
- *Second*, the statistical likelihood of a data gap depends on instrument and spacecraft reliability design (e.g., 3 yr., 5 yr., 7 yr.), launch schedules, as well as existing instruments and their age in orbit. All of these factors in the observing system design will affect the *Success Probability* of achieving a geophysical variable record of desired *Quality*.
- *Third,* the strategy to avoid gaps will involve instrument and spacecraft reliability and launch schedules. These factors will then drive cost and the associated *Affordability* factor.

For these reasons, a careful gap risk analysis is required as part of the Value analysis, but gap risk must be considered in 3 of the characteristics (Quality, Success, and Affordability) and cannot be treated as a single factor.

Guidelines for Continuity Measurement Framework Input-I

1. **Identify the QESO(s) the measurement under consideration addresses**
2. **Describe the *Importance* of the QESO to a high priority, societally-relevant science goal**
    - Description should be short, referenced, but understandable to a broader audience.
    - Provide a perspective on how the QESO fits within the broader scientific issues of understanding global change.
    - Provide a perspective on how the QESO benefits society, beyond the science.
3. **Explain the *Utility* of the measured geophysical variable(s) to achieving the QESO**
    - Explanation of the geophysical variables to be provided by the mission / measurement(s).
    - Description of the utility of these variables in terms of the <u>*relative fraction**</u> they contribute to answering the QESO.
    - A list of auxiliary data required to deliver the proposed measurement(s), but not part of the proposed mission, delineated by program and instrument.

* The committee notes that its evaluation methods for the Importance and Utility characteristics are subjective; however, it recommends (see chapter 3) that the sum of the utility of all observations needed by the QESO be equal to 1.0. This allows the framework to account for some observations being more important than others, while avoiding a “check the box” process that just counts the number of observation sources without consideration of relative importance. It also normalizes the utility of all QESOs to the same numerical scale, thereby allowing an “apples-to-apples” comparison. The report also shows a path toward future more rigorous and objective analysis of Utility using a Bayesian framework.

Guidelines for Continuity Measurement Framework Input – II

4. **Detail the *Quality* of the measurement relative to that needed for the QESO**
   - Assess the quality of the proposed measurement against the requirements of the QESO.
   - Includes, *inter alia*, calibration uncertainty, repeatability, time and space sampling, algorithms, reprocessing of the complete data stream, availability of all data products.
   - Assess the ability to satisfy QESO both with and without proposed observation(s).
5. **Discuss the *Success Probability* of achieving the measurement**
   - Provide an assessment of the heritage and maturity of proposed instruments and data algorithms
   - Assess the likelihood of leveraging similar or complementary non-NASA measurements
   - Provide a quantitative analysis of the risk of a gap in the measurement, and the effect of that gap on quality of the long-term record and the ability to remain useful in meeting the QESO.
6. **Provide an estimate of the Affordability of the measurement**
   - Estimate the total cost of the proposed observation(s)
   - Include the expected years of record on orbit at reasonable levels (e.g. 85%) of reliability
   - Include additional costs to mitigate unacceptable risks of measurement gaps

Measurement Evaluation – Ice Sheet Mass Balance Example

QESO	**Relevant Geophysical Variables**	**Example Instrument Data Types**
Ice Sheet Mass Balance Change *(Determine changes in ice sheet mass balance within 15 Gt/yr per decade or 1.5 Gt/yr^2)*	• Ice Sheet Mass • Ice Sheet Elevation • Ice Sheet Velocity • Ice Sheet Base Topography • Ocean Temperature Profile near Ice Sheet Edge	• Surface Interferometry • Radar and laser altimetry, supplemented by SAR, Broadband radiances • Gravity Change Measurements • Spectrally-resolved solar irradiances VIS/IR radiances, VIS/IR imager radiances

<u>Measurements/Missions to Compare</u>

1) ICESAT-2, OIB
2) GRACE-FO
3) NISAR

Example Measurement Value Comparison

Measurement	I	U*	Q	S	B	Scoring Rationale
ICESat-2, OIB (Altimetry series)	5	1	0.6	0.8	2.4	Established performance less than 1.5 cm/yr objective. Laser longevity uncertain
GRACE-FO (Gravity series)	5	1	0.9	1.0	4.5	Established performance meets objective for most regions. Long-term instrument performance well established.
NISAR (SAR series)	5	1	0.9	0.8	3.6	Established performance from previous SAR missions for most regions of interest. Interferometric instrument performance uncertain.

*Given the complementarity of the three geophysical variables for achieving the quantified objective, each variable is given the same utility score in this example.

Recommendations and Findings-I

- There are many inherent challenges in moving from subjective to quantitative evaluations, which is why the report uses a hybrid approach that combines subjective ratings for Importance, semi-analytical ratings for Utility and Success Probability, and analytical ratings for Quality and Affordability.
- These metrics establish a transparent way to rate different measurement characteristics; as noted in previous slide, they are not statistically independent.
- Should NASA use this framework, it would be essential to develop a consistent procedure for assigning a numerical value to each factor and for combining these factors to calculate the overall Value (V).

Recommendation: NASA should establish a value-based decision approach that includes clear evaluation methods for the recommended framework characteristics and well-defined summary methods leading to value assessment.

Recommendations and Findings-II

Finding: Continuity of an Earth measurement exists when the quality of the measurement for a specific QESO is maintained over the required temporal and spatial domain set by the objective.

- Assessing the Quality characteristic of a particular measurement requires knowledge of the measurement’s combined standard uncertainty, the instrument’s calibration accuracy, the stability of that calibration over time, and the consequences of data gaps on the relevant QESO. After applying this framework to measurements collected by current missions, it became clear that the relative Value of a measurement is closely linked to its Quality.

Recommendations and Findings-III

- Evaluation of a measurement's affordability and benefit characteristics for decision-making purposes can likely be accomplished through a number of equally valid methods. Regardless of the evaluation methods that NASA and the community adopt, the application of those methods should make consistent use of well-documented and understood tools and studies, as highlighted in the following recommendations.

- **Recommendation: NASA should foster a consistent methodology to evaluate the utility of geophysical variables for achieving quantified Earth science objectives.** The committee notes that such a methodology could also be utilized by the Earth Science Decadal Survey in its priority recommendations.

- **Recommendation: NASA should extend their current mission cost tools to address continuity measurement-related costs needed for the decision-framework.**

Recommendations and Findings-IV

- The ability of ESD officials to make informed decisions requires unbiased and consistent information on benefits and affordability that is re-evaluated regularly and presented on a time frame appropriate for NASA planning. The committee advises that inputs to these evaluations be derived from sources including submitted proposals as well as face-to-face interactions with measurement advocates.

Recommendation: NASA ESD should establish a regular process for critical evaluation and modification of QESOs and QEAOs and their associated measurements. The committee suggests creating an analog to the Senior Review of current satellite operations, which uses senior researchers from a range of communities and results in consistent recommendations to the ESD Director.

Recommendations and Findings-V

- In addition to research, Earth observations and their derived information products support numerous user communities both inside and outside federal agencies. Extending this decision framework to measurements focused on societal-benefit applications is desirable but will require expertise outside of the Earth science community to formulate quantitative Earth application objectives (QEAOs) that are analogous to QESOs.

Recommendation: NASA should initiate studies to identify and assess quantified Earth application objectives (QEAOs) related to high-priority, societal-benefit areas.

Implementing the Framework: Suggested Steps

1. Decide on the approach to, and cadence for, collecting input to apply the continuity framework
2. Finalize and document detailed evaluation criteria definitions and scoring approach
3. Develop appropriate tools for quantitative (or semi-quantitative) evaluation of measurement utility (OSSEs), quality (analytics for measurement uncertainty), success probability (satellite and mission lifetime probability analysis) and affordability (CATEs)
4. Begin development of approach to QEAOs, and QESOs for new exploratory measurements

Backup Slides

Quantification of the Quality Characteristic - I

- An example provided for quantifying the Quality characteristic is the use of time to detect an anthropogenic trend. This type of metric relates more clearly to societal impact based on delay in narrowing uncertainty.
- The time ***Δt*** to detect the trend ***m*** in a geophysical variable is given by (e.g. Wielicki et al. 2013, Leroy et al. 2008)

$$\Delta t = \sqrt[3]{12 s^2 \left(\sigma_{var}^2 \tau_{var} + \sigma_{cal}^2 \tau_{cal} + \sigma_{sam}^2 \tau_{sam} + \sigma_{alg}^2 \tau_{alg}\right) \Big/ m^2}$$

- where:
  - ***s*** is the confidence level required (for 95% confidence s = 2)
  - $\boldsymbol{\sigma_{var}}$ is the standard deviation of natural variability for the geophysical variable
  - $\boldsymbol{\tau_{var}}$ is the autocorrelation time for natural variability for the geophysical variable
  - $\boldsymbol{\sigma_{cal}}$, $\boldsymbol{\tau_{cal}}$ are the standard deviation and autocorrelation time of calibration uncertainty
  - $\boldsymbol{\sigma_{sam}}$, $\boldsymbol{\tau_{sam}}$ are the standard deviation and autocorrelation time of sampling uncertainty
  - $\boldsymbol{\sigma_{alg}}$, $\boldsymbol{\tau_{alg}}$ are the standard deviation and autocorrelation time of algorithm uncertainty
- *Time to detect a trend for a perfect or ideal climate observing system is limited only by natural variability and provides a reference*
- *Time for an actual observing system is longer depending on quality level*

Quantification of the Quality Characteristic - II

- Quality metric Q_2 is the difference between time to detect a trend using the proposed observing system Δt versus a perfect observing system Δt_P.

$Q_2 = 1 - (\Delta t - \Delta t_P)/30$ for $Q_2 > 0$,
$Q_2 = 0$ for $Q_2 < 0$ (delay longer than 30 years)

- 30 years is chosen as a time scale with unacceptably long delay for both science and societal uses, so that $Q_2 = 0$. For 0 year delay, $Q_2 = 1$.

Time Delay $\Delta t - \Delta t_p$ (years)	Q_2
0	1.0
5	0.83
10	0.67
15	0.50
20	0.33
25	0.16
30	0

- *Evaluate Q_2 both with and without continuity to evaluate Quality impact*

Quantification of the Quality Characteristic - III

- Examples from Appendix B of the report for the difference in Quality Q_2 (0 to 1 scale) with and without continuity:

	Total Solar Irradiance	Global Total Ozone	MSU Mid-Trop Temperature	Arctic Sea Ice Area	Global Sea Level
Q_2 with Continuity	1.00	0.97	0.99	1.00	0.98
Q_2 without Continuity	0.22	0.00	0.00	0.72	0.68

- *A wide variation of impacts in Quality occur with and without continuity.*

Quantification of the Quality Characteristic - IV

- Example from Appendix C of the report for the difference in Quality Q_2 (0 to 1 scale) in three observing system options:
  - no continuity of broadband radiation budget measurement (CERES, RBI): replace with MODIS/VIIRS across gaps in observations.
  - continuity and overlap of broadband radiation budget measurement (CERES, RBI)
  - use CLARREO mission higher absolute accuracy to inter-calibrate CERES, RBI to higher accuracy level even if gaps occur.

	Shortwave Cloud Radiative Forcing (cloud feedback)
Q_2 without CERES/RBI continuity	0
Q_2 with CERES/RBI continuity	0.23
Q_2 with CLARREO/CERES/RBI but no continuity	0.83

- *A large range of Quality exists depending on continuity of current observations as well as the capability of new instruments.*