Campaign-level Science Traceability for Earth Observation System Architecting

by

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B.S. Astronautical Engineering
United States Air Force Academy, 2007

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

The Earth Sciences Decadal Survey of 2007 presented a comprehensive vision for the evolution of space-based Earth Science resources. The practical development of the Decadal campaign, however, has highlighted four challenges to the original plan: the growth of expected costs and the reduction of program budget, the loss and changing status of the expected precursor missions, the opportunity afforded by international earth science efforts, and the increasing desire to operationalize key measurements of the earth. This thesis discusses how system architecting of the Decadal campaign can realistically reproduce the decision logic of the Decadal Survey, while accurately capturing the necessary constraints and value functions, and can form the basis for rational analysis of the effects of changing assumptions.

This thesis presents a technique for tracing stakeholder value to campaign architecture decisions through a system of science traceability matrices. Using a framework based upon decomposition of value-related elements, the costs and benefits of the Decadal campaign are analyzed.

This thesis refines a technique for the scheduling of space-based observation campaigns and provides insight and recommendations for the Earth Observation Program. The decision logic of the Decadal Survey is implemented through constraints and value functions, and an algorithm for scheduling is developed. Finally, this algorithm is used to examine the impacts of key changes that have occurred since the publishing of the Decadal Survey and provide recommendations for the development of the Earth Science Decadal Survey campaign.

Thesis Supervisor: Edward F. Crawley
Title: Professor of Aeronautics and Astronautics

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This thesis would not have been possible without the support and contributions of a number of people.

First and foremost I would like to thank my thesis supervisor and advisor Prof. Ed Crawley. Ed gave me the amazing opportunity to come to MIT for two years, and exposed me to so many different ideas and ways of thinking it will take me another decade just to sort them out.

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I'd also like to thank the rest of the Air Force gang, who provided all of the support and friendship I could hope for in this endeavor, particularly from my former roommates Don Petrash, Paul Tisa, and Chris Taylor.

This thesis required extensive contributions from our NASA sponsors, particularly Bob Connerton. Bob immensely clarified my understanding of almost every aspect of the problem, and worked nights and weekends to ensure I had all the information I needed.

Finally, I would like to thank my family, particularly my amazing wife Arael. Apparently I am not fun to put up with when I am really busy. Who knew?

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"The committee took as its charge the provision of a strategy for a strong, balanced national program in Earth science for the next decade that could be carried out with what are thought to be realistic resources. Difficult choices were inevitable, but the recommendations presented in this report reflect the committee's best judgment, informed by the work of the panels and discussions with the scientific community, about which programs are most important for developing and sustaining the Earth science enterprise."
—National Research Council Report, Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond

1 Introduction

1.1 Motivation

On 12 January 2006, The Secretary of the Air Force formally notified Congress that the National Polar-orbiting Operational Environmental Science System (NPOESS) program had breached Nunn-McCurdy certification by cost-overruns of greater than 25%. This allowed for three options: cancelling the program, certifying a restructured program, or certifying the program with updated cost and schedule. Faced with rapidly increasing costs, the Integrated Program Office, a joint venture between NOAA and the US Air Force, and the entity responsible for the NPOESS program, chose to restructure—saving the program, but significantly reducing its capabilities.

Ironically, the IPO was originally commissioned as a cost-saving effort to reduce redundant engineering programs. Its' purpose was simple: to design and build a polar-orbiting weather satellite network that could be used by a multitude of federal agencies, including the DoD, NOAA, NASA, USGS, and others. However, as costs rose, the NPOESS recertification required a reduction of capability, or elimination, of various instrument packages from the program. Of the 38 Environmental Data Records the mission was originally designed to capture, 21 were either demanifested or significantly degraded. The silent casualty in the process was NASA's Earth Science program, which had been counting on getting key sets of data from the mission.

In 2004 the National Research Council commissioned a Decadal Survey report for earth science to establish a first unified agenda for space-based observations. Much like the original vision of NPOESS, a long-term agenda would promote cost-sharing opportunities and eliminate redundancies while cementing the societal benefits of earth science. Not only could more be done with less, but in demonstrating its applicability to society, the community could ensure the continuing, and expanding, interest of its stakeholders. Such a plan would be a tremendous return on investment—a few months of discussion in return for decades of program support.

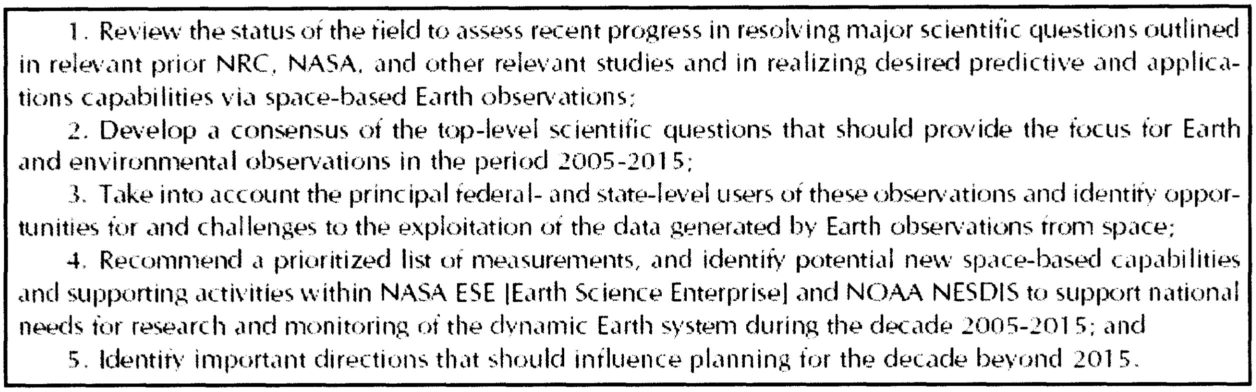
The report was released three years later, and in many ways lived up to its potential. It carefully laid out a campaign of 17 earth science space missions that, while primarily of an experimental nature, could all have strong practical applications, and carry the possibility of being continued as long-term operational programs. These missions spanned the spectrum of earth sciences, and represented the goals and objectives of many different sub-communities. The report marked a monumental consensus-building victory for the earth science community, which had never outlined a unified picture of their priorities. Perhaps most importantly, the report gave NASA and NOAA an endorsed plan for the next decade.

While the Decadal Survey marked an important step for the earth science community, its current utility is waning. A few major assumptions, such as the status of expected precursor missions (including NPOESS), the costing of the 17 proposed missions, and the budget allocated to earth science, have changed. By current estimates the "Decadal" Survey will take more than 40 years to complete.

The priorities established by the Decadal Survey are impossible to ignore, yet commissioning a new study every time assumptions change is impractical. A formal system for re-architecting the Decadal campaign is necessary, one that is practical and responsive to the changes that have occurred. The Decadal Survey is the basis for this thesis, which attempts to maintain the priorities and objectives of the Survey while re-structuring the contents of the 17 Missions according to updated constraints and assumptions.

1.2 The Decadal Survey

The Decadal Survey was commissioned with five specific tasks in its pursuance of a unified agenda for earth science (Figure 1). These tasks loosely fall into three questions: "Where are we?", "Where are we going?", and "How will we get there?"



1. Review the status of the field to assess recent progress in resolving major scientific questions outlined in relevant prior NRC, NASA, and other relevant studies and in realizing desired predictive and applications capabilities via space-based Earth observations;
2. Develop a consensus of the top-level scientific questions that should provide the focus for Earth and environmental observations in the period 2005-2015;
3. Take into account the principal federal- and state-level users of these observations and identify opportunities for and challenges to the exploitation of the data generated by Earth observations from space;
4. Recommend a prioritized list of measurements, and identify potential new space-based capabilities and supporting activities within NASA ESE [Earth Science Enterprise] and NOAA NESDIS to support national needs for research and monitoring of the dynamic Earth system during the decade 2005-2015; and
5. Identify important directions that should influence planning for the decade beyond 2015.

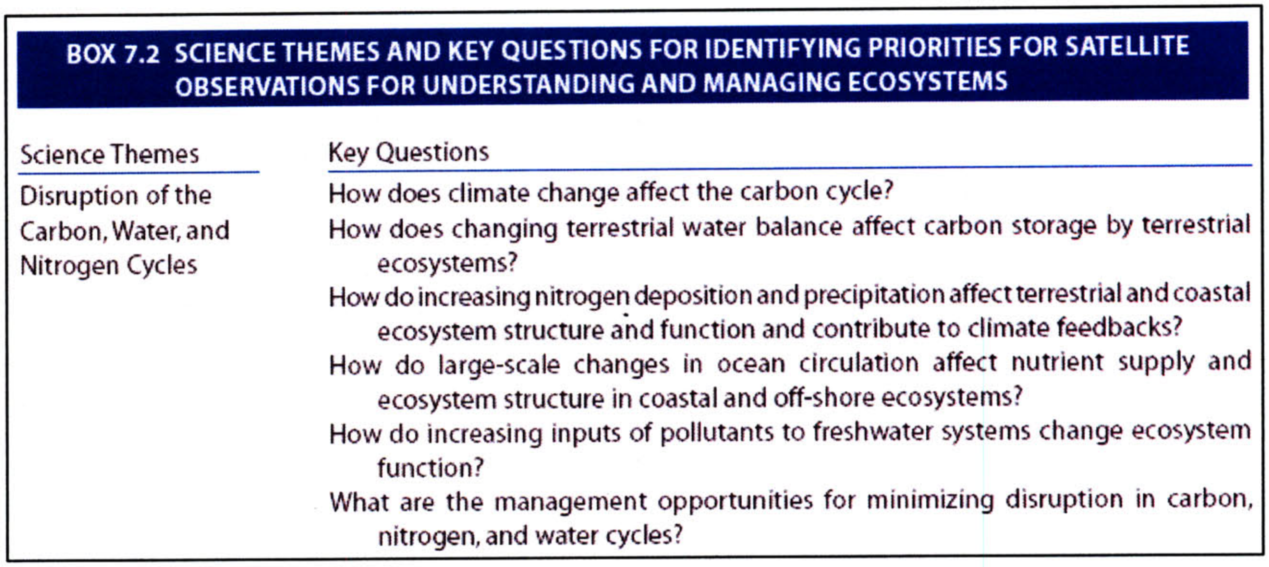
Figure 1. Decadal Survey Tasks (National Research Council, 2007)

First, the Decadal Committee wanted to understand where the earth science community stood. To this end, dozens of leading scientists and engineers were invited to participate. Divining the status of communities was a relatively straightforward matter, since current resources and applications are easily enumerable. Simply inviting a few participants from key federal agencies would have been sufficient to accurately capture the current status of earth science from space.

Second, the Decadal Committee wanted to understand where the earth science community should be going. This was, perhaps, the most controversial aspect of the survey, as synthesizing a vision required uniting disparate perspectives. Seven thematic panels were commissioned to represent different, but not homogeneous, interests:

- Earth science applications and societal benefits
- Human Health and security
- Land-use, ecosystems, and bio-diversity
- Solid Earth Hazards, natural resources, and dynamics
- Climate variability and change
- Weather Science and Applications
- Water resources and the global hydrological cycle

The six science panels were individually given the tasks of coming up with a set of recommended space missions. While the Decadal Committee had send out a request for proposals to the larger scientific community and had a list of specifically proposed missions, first each panel had to agree upon its priorities. Although each panel conducted this exercise independently, the general process involved identifying science themes and the key questions relevant to those themes (Figure 2).



BOX 7.2 SCIENCE THEMES AND KEY QUESTIONS FOR IDENTIFYING PRIORITIES FOR SATELLITE OBSERVATIONS FOR UNDERSTANDING AND MANAGING ECOSYSTEMS

Science Themes	Key Questions
Disruption of the Carbon, Water, and Nitrogen Cycles	How does climate change affect the carbon cycle? How does changing terrestrial water balance affect carbon storage by terrestrial ecosystems? How do increasing nitrogen deposition and precipitation affect terrestrial and coastal ecosystem structure and function and contribute to climate feedbacks? How do large-scale changes in ocean circulation affect nutrient supply and ecosystem structure in coastal and off-shore ecosystems? How do increasing inputs of pollutants to freshwater systems change ecosystem function? What are the management opportunities for minimizing disruption in carbon, nitrogen, and water cycles?

Figure 2. Decadal Survey Process (National Research Council, 2007)

Finally, at this point in the Decadal process, the questions "Where are we going?" and "How will we get there?" began to merge. Each key question identified by a panel was linked with an answer—a set of measurements that could possibly answer that question, and a set of instruments that could capture those measurements. Questions with similar answers were combined together to form specific objectives, objectives that could subsequently be prioritized. Each panel then reviewed the submitted mission proposals for those that satisfied their objectives, and came up with their own proposed campaign. The Decadal Committee then took the proposed campaigns of every panel and combined them. Different mission proposals were tied together, others were left out. Compromises were reached that reduced the 35 proposed panel missions into one campaign of 17 missions.

The process of reaching this answer included the work of over a hundred people over the course of three years. Although of monumental utility to the earth science community, tracing the decisions that led to the final campaign is an impossible process. Too many tradeoffs and compromises occurred before making it into the final report. This complicates and confuses the campaign architect now trying to implement this agenda—he has little idea what all the decisions were, and even less idea what assumptions actually influenced those particular decisions.

1.3 General Objective

The general objective of this thesis is as follows:

- Capture the Decadal Survey decisions processes and logic for automated and optimizable architecture development under changing assumptions.

1.4 Framework for Analysis

The process of system architecting requires a holistic consideration of "the system". While some systems, particularly simple ones, can assume isolation during the architecting process, to do so with complex, large-scale projects is to invite disaster. Developing a comprehensive framework to describe the technical, social, economic, and political environments and limitations that encompass a project is a necessary architecting step. Tim Sutherland of the MIT Space Architecture group described a framework for analyzing the Earth Observation program (Figure 3). In this framework tacit relationships are defined in context to the production of value, and different levels of abstraction are used to describe intermediate steps. For this thesis value is defined as benefit produced at some cost.

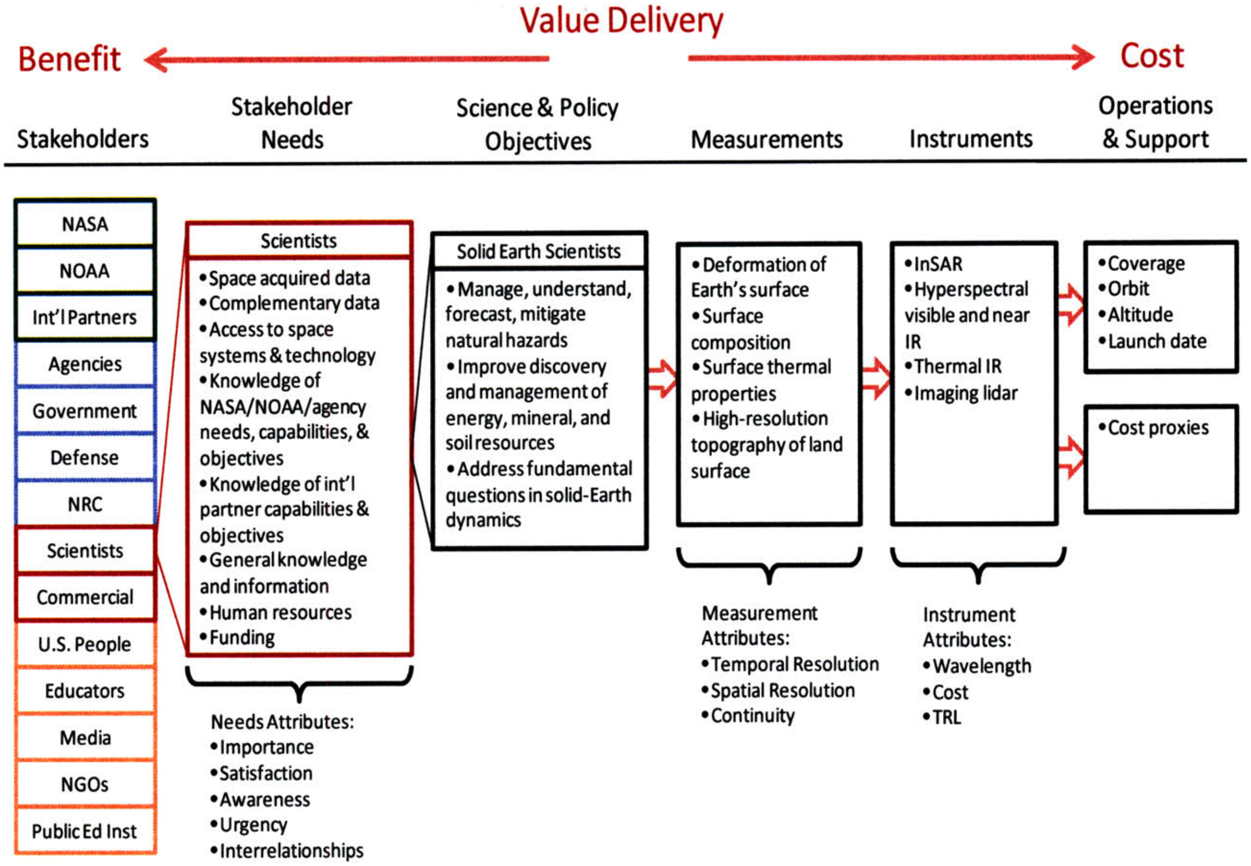


Figure 3. Framework for analysis of stakeholders and system architecture for the Earth Observations Program (Sutherland, 2009)

At its core this framework depicts value delivery on a spectrum. On the left side of the figure benefit is realized, while on the right costs are incurred. The farthest left column, Stakeholders, represent the distinct stakeholder and beneficiary groupings that Sutherland identified as central to the Earth Observation Program. While the highest level of abstraction, each of these Stakeholders has a tacit list of needs. These needs are more directly expressed by Stakeholders through Objectives. For the case of Earth Scientists in Figure 3 these Objectives are satisfied via the data produced through measurements. Measurements generated through the physical operations of instruments, and instruments are supported by the bevy operational requirements of a space program. Using this framework, the complexity of the Earth Observation system can be decomposed and understood on a component level.

Justin Colson, also of the MIT Space Architecture group, wrote his Master's thesis about the application of this framework to rescheduling the Decadal Survey missions. He demonstrated a modeling technique for satellite network scheduling that considered flexibility on in the rightmost column of this framework, varying only launch date. This thesis builds his work and expands the architecting process to the intermediate columns of this framework.

1.5 Justification for Rearchitecting the Decadal Survey Campaign

Although the changes to NPOESS have affected the preservation of data records in an unforeseen manner, the motivation for rearchitecting the Decadal campaign is multifaceted. Four factors reflect the change of assumptions since the Decadal Survey: cost growth and budget limitations, the increasing need for operational programs, the status of expected precursors missions, and the contributions of international agencies.

The Decadal campaign relies primarily on NASA for implementation (fourteen and a half of the seventeen). Recently, the Congressional Budget Office published a report highlighting projected budget growth (Figure 4).

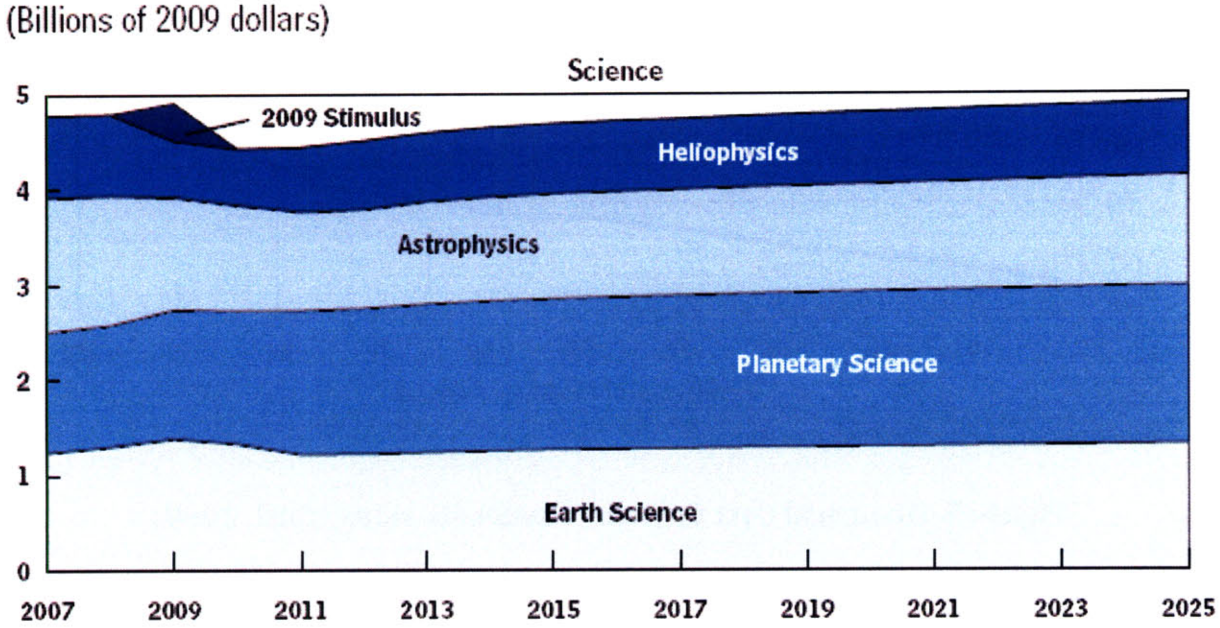
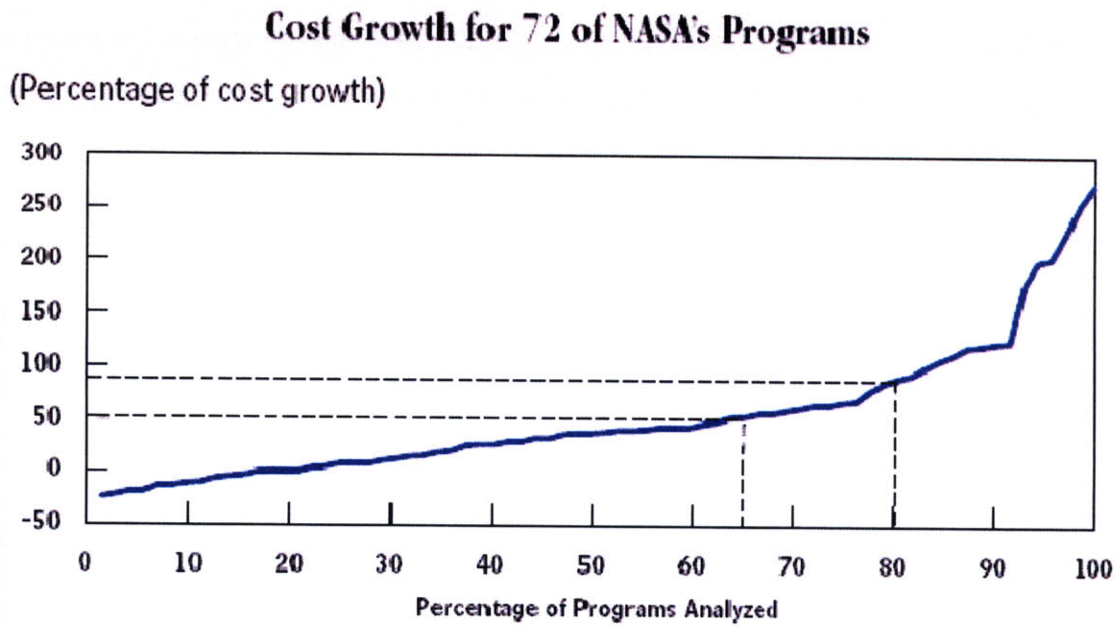


Figure 4. NASA Earth Science Budget Forecast (CBO, 2009)

Only about a quarter of the earth science budget, or about $300M/year, is projected to be directed towards the Decadal Survey campaign (NASA, 2008). One of the key assumptions of the Decadal Survey was that the budget would return to FY00 levels—approximately $750M/year. Assuming a best case linear translation of time and cost, this extends the "decadal" campaign by more than a factor of two. Although the current administration appears to favor the Decadal program, as signified by the $400M boost from the stimulus act specifically for Decadal Survey mission development, this has yet to impact long-term budgetary decisions (Public Law 111 - 5 - American Recovery and Reinvestment Act of 2009, 2009).

The budget issue is further compounded by the propensity for NASA missions to grow significantly in cost. A recent report by the Government Accountability Office highlighted this trend (Figure 5).



Source: Congressional Budget Office.

Figure 5. Historical Cost Growth of NASA Missions (GAO, 2009)

The issue is further complicated by the accounting used in cost estimation—these trends are only reflective of cost after the baseline has been established—and do not reflect the cost growth in pre phase-A development. The Decadal Survey estimated a campaign cost of totaling around $7.5B; NASA's initial cost estimate increased that number by 49% (Volz, 2008).

Further prompting an analysis of the Decadal Survey is the increased need to integrate the Decadal Survey program into a long term earth observation campaign. The success of the current earth observation program has exposed the scientific need for multi-decadal records. Additionally, earth science is starting to be recognized as an essential component of national security, and is attracting interest from the DoD and CIA (CNA, 2007). While the Decadal Survey missions tend to be experimental, there is a rising urgency to establish an operational earth science program.

Additionally, the status of planned US missions is constantly changing. The loss of the Orbiting Carbon Observatory (OCO) due to launch failure in 2009 puts into serious question the second tier ranking for the Decadal mission ASCENDS, which will also measure atmospheric carbon. The Decadal Survey expected certain missions to fly and, as changes are made to different programs, there must be a way to incorporate these decisions into future planning.

Finally, one area the Decadal Survey directed campaign planners towards was the inclusion of international efforts. The same observation needs that the Decadal planners foresaw are shared by other agencies world-wide. As international earth science missions are proposed and scheduled, it is extremely desirable that campaign planning include these missions. Leveraging international efforts reduces the technology development and budgetary risk factors to both NASA and NOAA.

1.6 Background of Relevant Literature

1.6.1 Science Traceability

While the concept of managing different levels of requirements has long been a central tent of systems engineering, only recently has a formalized system been mandated for NASA science missions. The Science Traceability Matrix (STM), as proposed by Weiss, Smythe, and Lu, in *Science Traceability*, offers a simple and logical method for conveying how specific mission requirements flow down from high level goals (Figure 6).

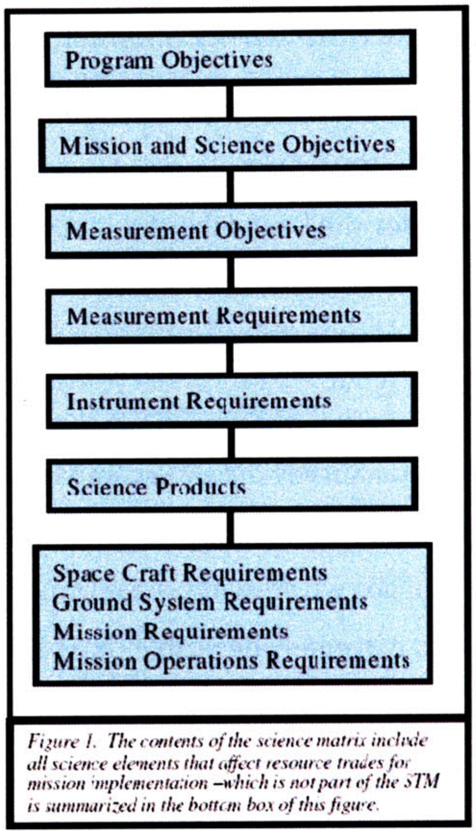
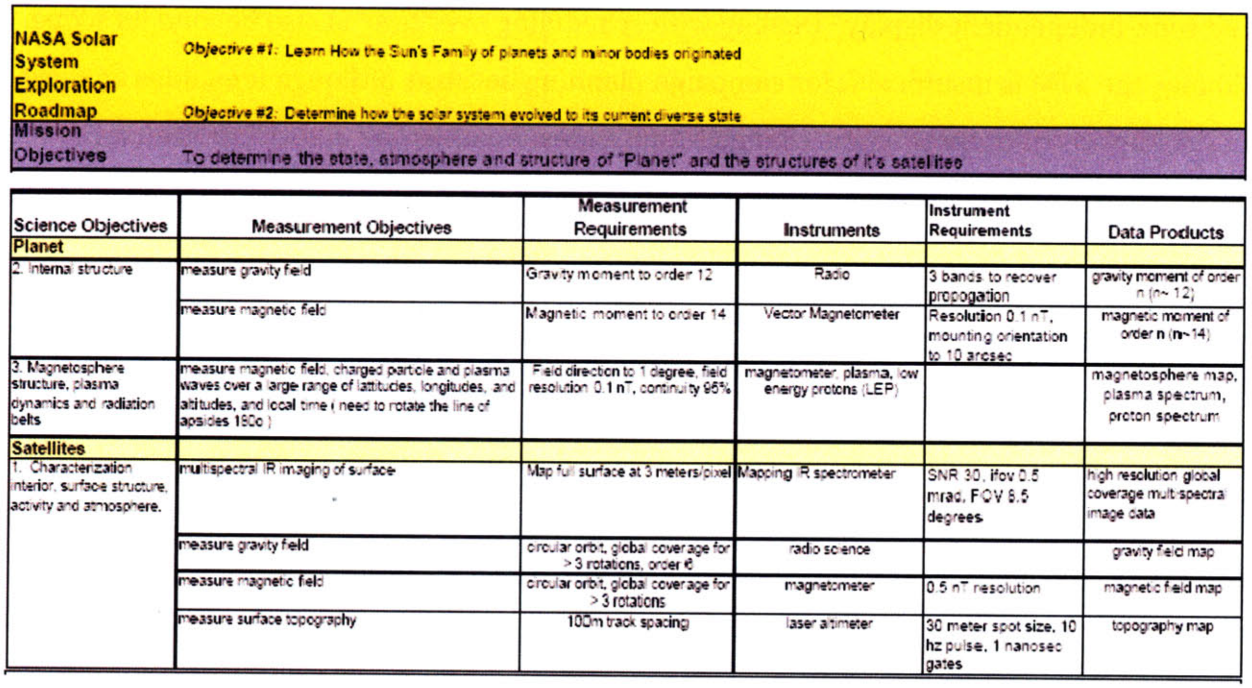


Figure 6. STM flow-down (Weiss, Smythe, & Lu, 2005)

Starting with high-level objectives, such as those enumerated in National Academy of Science decadal surveys or NASA strategic roadmaps, the explicit linkages between different levels of requirements can be enumerated. As seen in Figure 7, each successive layer of the STM provides increasingly detailed requirements.



NASA Solar System Exploration Roadmap	*Objective #1:* Learn How the Sun's Family of planets and minor bodies originated *Objective #2:* Determine how the solar system evolved to its current diverse state
Mission Objectives	To determine the state, atmosphere and structure of "Planet" and the structures of it's satellites

Science Objectives	Measurement Objectives	Measurement Requirements	Instruments	Instrument Requirements	Data Products
Planet					
2. Internal structure	measure gravity field	Gravity moment to order 12	Radio	3 bands to recover propogation	gravity moment of order n (n~ 12)
	measure magnetic field	Magnetic moment to order 14	Vector Magnetometer	Resolution 0.1 nT, mounting orientation to 10 arcsec	magnetic moment of order n (n~14)
3. Magnetosphere structure, plasma dynamics and radiation belts	measure magnetic field, charged particle and plasma waves over a large range of lattitudes, longitudes, and altitudes, and local time (need to rotate the line of apsides 180o)	Field direction to 1 degree, field resolution 0.1 nT, continuity 95%	magnetometer, plasma, low energy protons (LEP)		magnetosphere map, plasma spectrum, proton spectrum
Satellites					
1. Characterization interior, surface structure, activity and atmosphere.	multispectral IR imaging of surface	Map full surface at 3 meters/pixel	Mapping IR spectrometer	SNR 30, ifov 0.5 mrad, FOV 8.5 degrees	high resolution global coverage mult-spectral image data
	measure gravity field	circular orbit, global coverage for > 3 rotations, order 6	radio science		gravity field map
	measure magnetic field	circular orbit, global coverage for > 3 rotations	magnetometer	0.5 nT resolution	magnetic field map
	measure surface topography	100m track spacing	laser altimeter	30 meter spot size, 10 hz pulse, 1 nanosec gates	topography map

Figure 7. Example STM (Weiss, Smythe, & Lu, 2005)

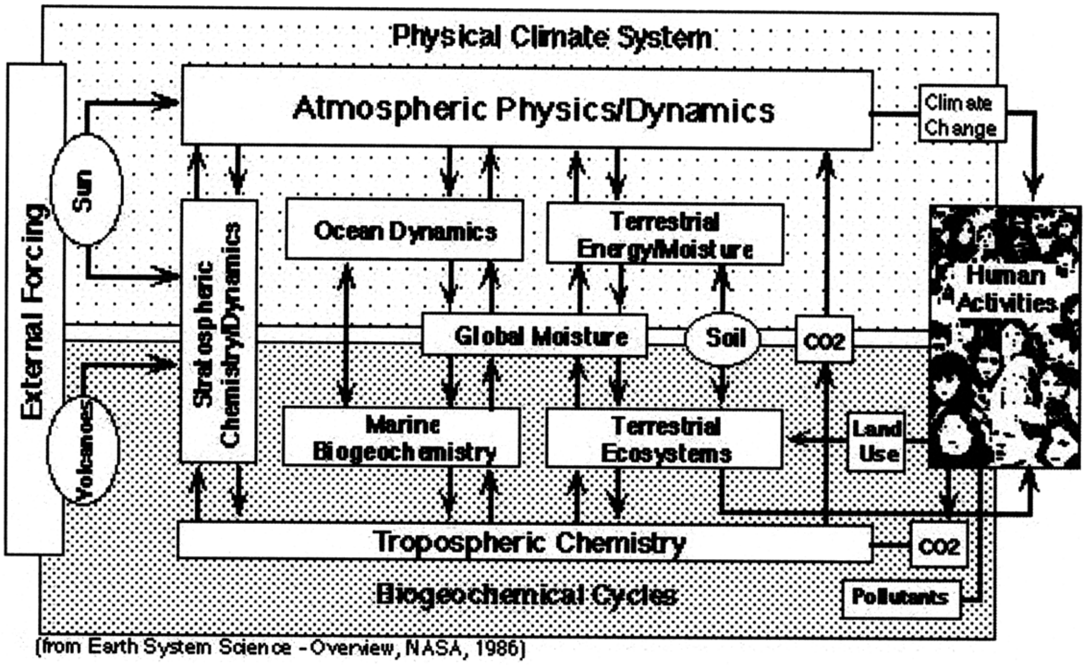
A well put-together STM, one in which requirements, and even expected publications, are clearly traceable to top-level objectives, is indicative a mature mission design. This is an invaluable tool during the formulation phase of mission design, as it essentially presents, in one table, a complete justification for the mission. As a mission moves through its design cycle, the STM again proves useful by defining a trade space; adjustments to mission capabilities can be traced to requirements, performance measures, cost evaluations, and ultimately mission feasibility.

In the earth science Decadal Survey each mission proposal was required to include a STM. However, most of these proposed missions did not reach the final campaign intact, on average being a compilation of three different proposals. The compromises panels made were not enumerated—and new STM's for each mission were not included in the final report. The Decadal Survey does not reflect the detailed traceability required of an STM.

STMs are not inherently well-suited to campaign analysis. One of the principles of the STM is simplicity—it should convey all the requisite information on just one chart; conveying the same information for a set of 17 missions is beyond the scope of the STM methodology. Additionally, although the STM is useful during the entire mission lifecycle, it is a time-independent display. Dealing with scheduling over time is also beyond its scope. Finally, the STM is insufficient for campaign planning because, although it enables analysis of the impacts of programmatic changes, it provides "no objective algorithm to quantify the relative merits of high level goals" (Weiss, Smythe, & Lu, 2005). The effects of decisions can be traced, but for most missions the importance of those decisions remains unknown.

1.6.2 Global View of Earth Science

While there are many models describing the "earth system" perhaps the most well-known is Bretherton's model (Figure 8). In this figure he presents a conceptual model for understanding global climate change as a set of interrelated modules. Processes, feedbacks, and forcings are holistically linked together in an attempt to understand the impacts of human activities within the context of natural variability. Bretherton makes the observation that the earth system is dependent both on the physical climate system and biogeochemical cycles. Hence, issues relevant to one field can be equally important to another, seemingly unrelated field. For the Decadal panels the interests of one are likely shared by several others. This is particularly true of the Human Health and Security panel, which did not recommend a dedicated mission, instead endorsing other missions it could benefit from.



(from Earth System Science - Overview, NASA, 1986)

Figure 8. Simplified Earth System Model (REMOTE SENSING)

Bretherton also recognizes the need for space-based remote sensing in understanding the earth system. Space platforms allow for both rapid, wide coverage and long-duration, repetitive observations. They are, however, most effective when multiple observations of the same phenomena can be captured.

Elachi and Van Zyl observed that a vast majority of remote sensing falls into a spectrum seen in Figure 9 (Elachi & Van Zyl, 2006). Just as the physical systems being measured express a large degrees of interrelatedness, the instrumentation necessary to observe those systems are quite similar. Subtle changes to instrument parameters can widely vary the measurements captured.

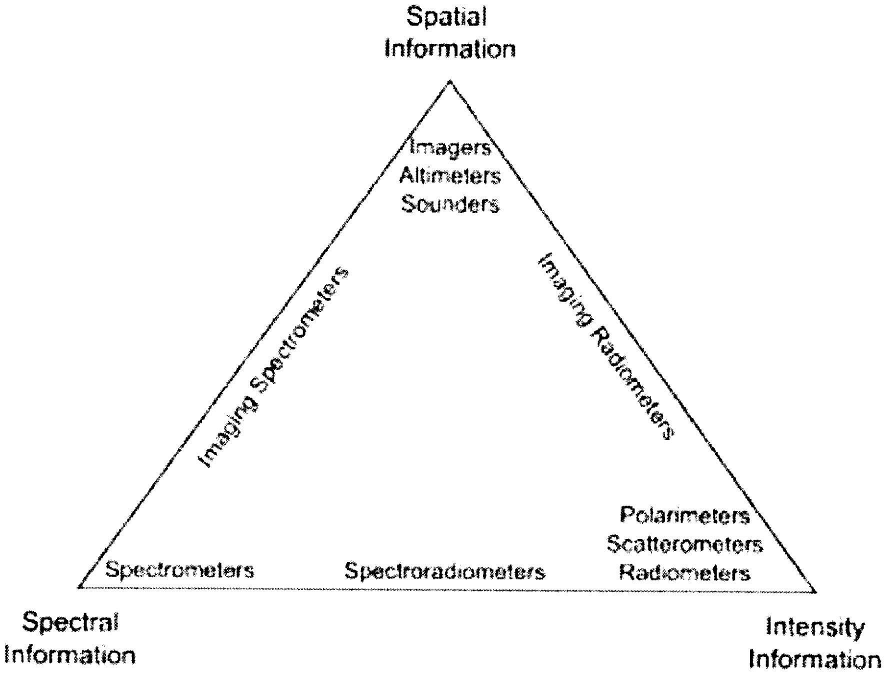


Figure 9. Remote Sensing Instruments and Information (Elachi & Van Zyl, 2006)

While this facet of remote sensing does hint at possible multi-user approaches towards instrument development, it also highlights the difficulty in quantifying small instrument differences. It takes expert knowledge of these sensors to understand how changes to mission parameter will affect them. While remote sensing remains an extremely valuable tool for understanding the earth system, it can be difficult to accurately capture the qualities of sensors for system architecting.

1.6.3 Stakeholder Value Network Analysis

The framework for analysis presented in Figure 3 indicates that benefit is realized at the stakeholder level. Hence, considering value in campaign design must include some discussion of stakeholders. Sutherland's thesis provides insight into the stakeholders of the Decadal Survey campaign through a value network analysis.

A value network presents a formal system for understanding stakeholder needs and relationships. First, individual stakeholders are identified with respect to the reference enterprise (Figure 10). With the Decadal campaign this refers to the joint NASA/NOAA efforts.

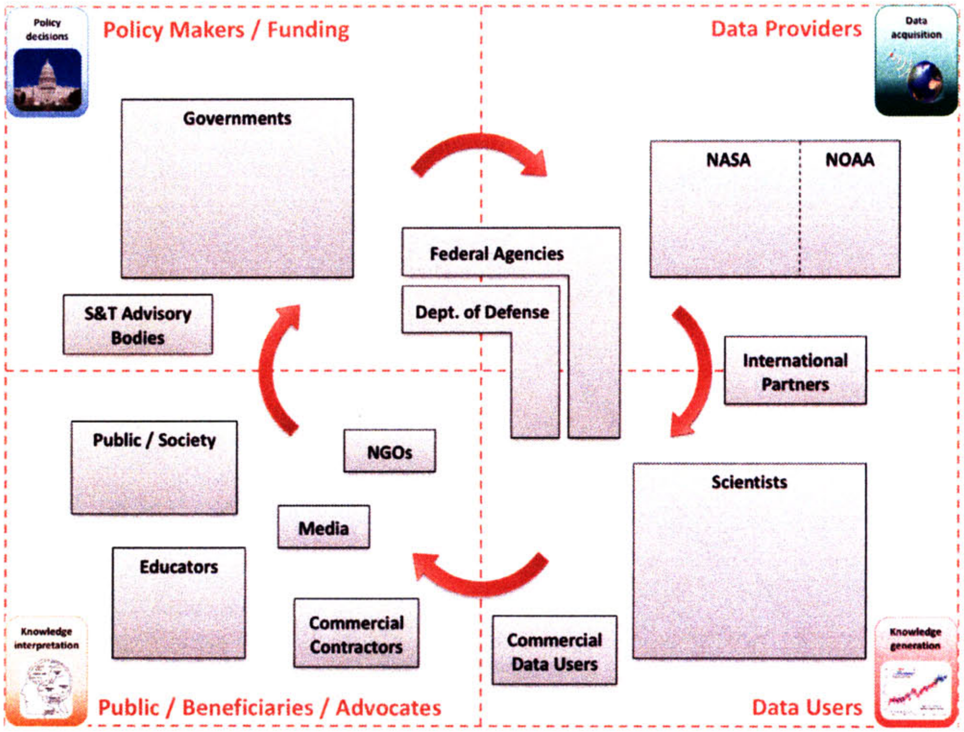
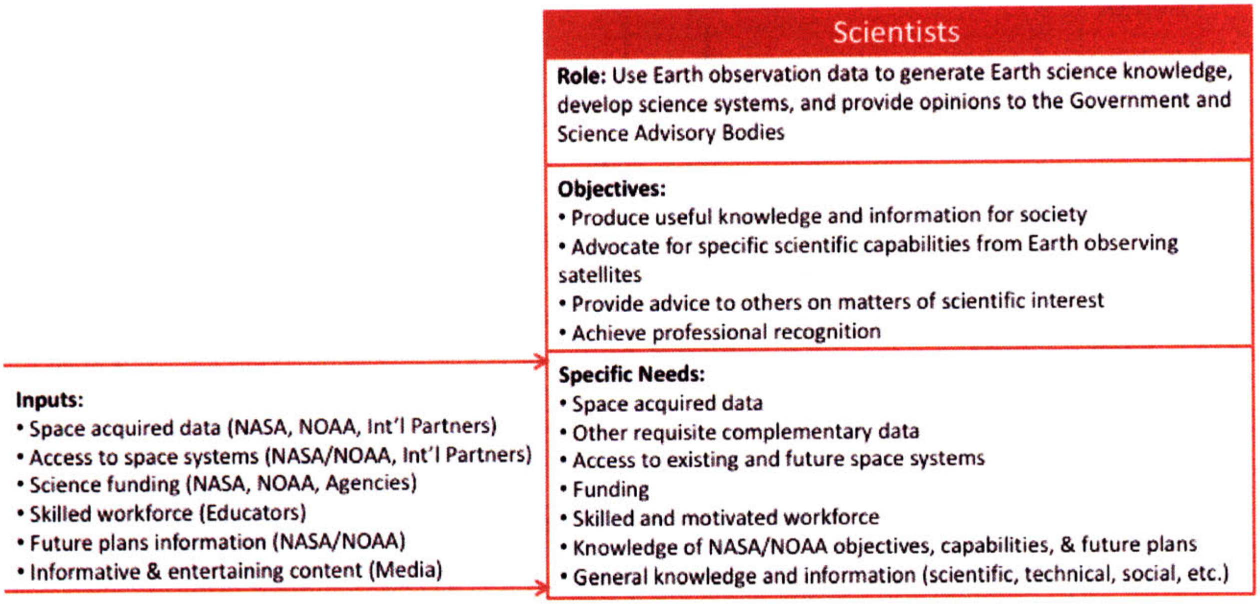


Figure 10. The Stakeholders of a NASA/NOAA Earth Observation Campaign (Sutherland, 2009)

Sutherland observed that the stakeholders of the Decadal campaign have four general roles. Stakeholders such as the federal government make policy decisions such as direction and funding levels. These decisions affect the federal agencies that perform the role of data acquisition. The acquired data then is conveyed to data users, which use it to generate knowledge. This knowledge then passes to various other beneficiaries, who interpret it. In turn these interpretations inform policy decisions.

Stakeholders are defined by not only by their roles, but also by their specific objectives and needs. Understanding these needs is essential—it is in satisfying them that benefit is generated. Figure 11 presents the characterization of Scientists in the Decadal campaign network. At a macroscopic level, the role of scientists is to generate knowledge from raw data. They have a specific set of objectives for doing this, which, in turn, reflects a set of needs from other stakeholders.



Scientists

Role: Use Earth observation data to generate Earth science knowledge, develop science systems, and provide opinions to the Government and Science Advisory Bodies

Objectives:
- Produce useful knowledge and information for society
- Advocate for specific scientific capabilities from Earth observing satellites
- Provide advice to others on matters of scientific interest
- Achieve professional recognition

Specific Needs:
- Space acquired data
- Other requisite complementary data
- Access to existing and future space systems
- Funding
- Skilled and motivated workforce
- Knowledge of NASA/NOAA objectives, capabilities, & future plans
- General knowledge and information (scientific, technical, social, etc.)

Inputs:
- Space acquired data (NASA, NOAA, Int'l Partners)
- Access to space systems (NASA/NOAA, Int'l Partners)
- Science funding (NASA, NOAA, Agencies)
- Skilled workforce (Educators)
- Future plans information (NASA/NOAA)
- Informative & entertaining content (Media)

Figure 11. Stakeholder Definition Process (Sutherland, 2009)

The value network methodology assumes that a stakeholder network is closed, and that every stakeholder need is somehow fulfilled by an output of another stakeholder. Scientists, for example, need to acquire funding from somewhere. The value network, then, is a physical mapping of the outputs of one stakeholder leading to the inputs of another (Figure 12).

These relationships can quantitatively analyzed. Sutherland uses a combination of questionnaires and supporting documentation to value each input to a stakeholder. The linkages between stakeholders can be mathematically combined to form "value chains", which trace the outputs of the reference stakeholder through the network back to its own inputs. In this way the most important relationships and inputs between the stakeholders can be calculated.

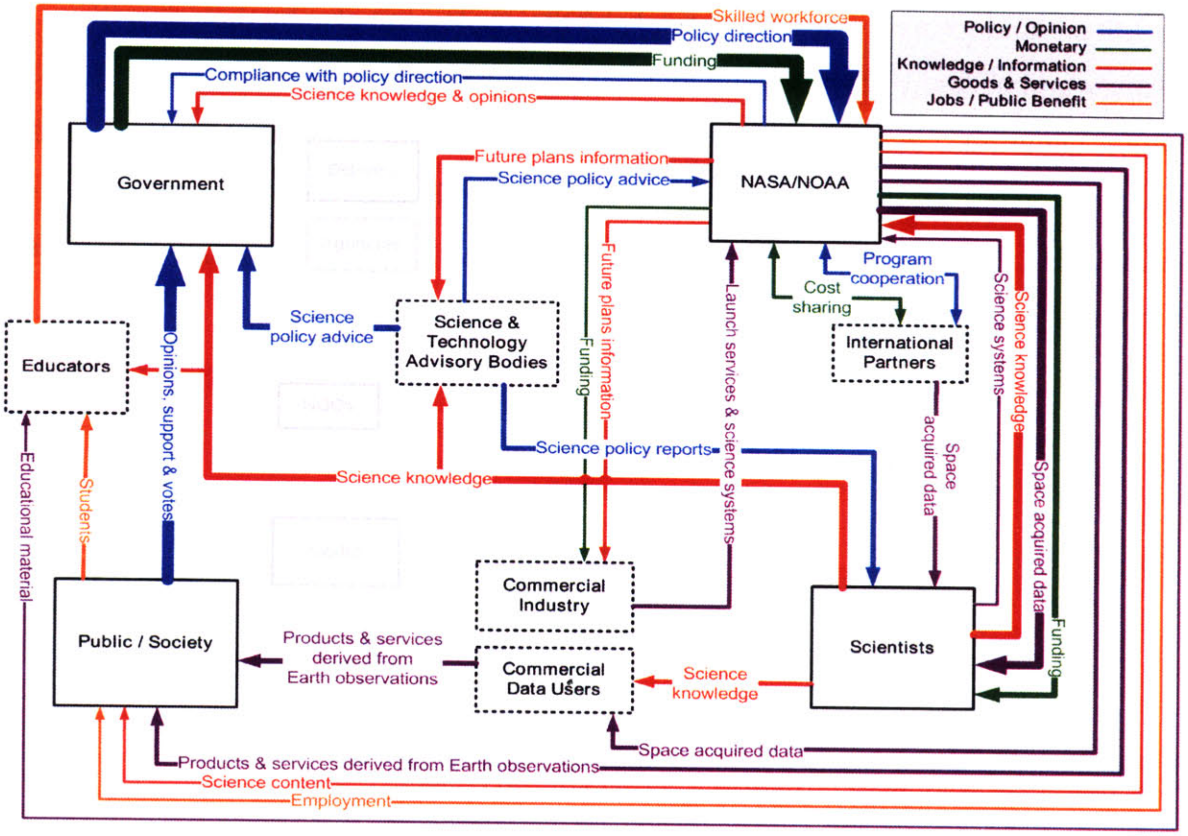


Figure 12. Simplified Decadal Campaign Stakeholder Value Network (Sutherland, 2009)

Figure 12 outlines the most important stakeholders and links for the Decadal campaign. The top three stakeholders are: the government, which provides NASA/NOAA with funding and direction; the public, which provides the driving opinion and support behind the government; and scientists, which provide knowledge to both the government and NASA/NOAA. The stakeholders represented with dotted lines are moderately important, whereas those that are grayed out are relatively unimportant. The most important inputs to the Decadal campaign are government policy direction and funding. The most important outputs are space acquired data and research funding to scientists.

1.7 Specific Objectives

The specific objectives of this thesis are as follows:

- To illustrate a method for tracing stakeholder value to campaign architecture decisions by developing a framework for campaign analysis, applying that framework to the Decadal Survey, and validating the results of the technique against the Decadal Survey.
- To refine a technique for scheduling space-based earth observation campaigns by developing constraints and value functions that an algorithm can utilize to replicate the decision logic of the Decadal Survey.
- To provide insight and recommendations for the NASA/NOAA earth observation program by examining the impacts of key changes that have occurred since the publishing of the Decadal Survey.

Central Thesis Question:

- *Can systems architecting of the Decadal campaign reproduce the decision logic of the Decadal Survey and form the basis for rational analysis of changing assumptions?*

1.8 Overview of This Document

This thesis is organized into six chapters. The remaining chapters are organized as follows:

- Chapter 2 presents an architectural framework for campaign development, the Campaign Science Traceability Matrix. It defines and decomposes the value-related attributes of a campaign such that stakeholders needs can be traced to architectural decisions.
- Chapter 3 presents the methodology required to populate the CSTM for the Decadal campaign. It presents the results of stakeholder valuation on missions, instruments, measurements, and objectives.
- Chapter 4 presents the constraints and value functions that are applied to the CSTM. It examines the different classes of constraints and their application.

It describes the development of an algorithm for campaign scheduling given the CSTM.

- Chapter 5 examines different permutations of the baseline Decadal Survey assumptions. This includes using current assumptions, variations to the annual budget, and the re-assignment of instruments to missions.
- Chapter 6 presents the insights and recommendations drawn in the other five chapters. It also summarizes areas for future work.

2 A Framework for Understanding Campaign Value

This chapter traces the development of a Campaign-level Science Traceability Matrix as a framework for understanding campaigns. A hierarchical decomposition of the value-related processes of a campaign is presented. The elements of this decomposition are then applied to a Science-Traceability like system of matrices to create the CSTM. Finally, the merits of the CSTM framework for systems architecting are discussed.

The objective of this chapter is:

Objectives of a framework for understanding campaign value:

- *To illustrate a method for tracing stakeholder value to campaign architecture decisions by developing a framework for campaign analysis*

This chapter is organized into the following sections:

- Section 2.1: Tracing value through a campaign. This section a definition of campaigns relevant to systems architecting and outlines the decomposition of the value-related processes of a campaign
- Section 2.2: A Framework for campaign analysis: the CSTM. This section presents the CSTM framework for analysis which will be applied to the Decadal campaign in Chapter 3.

2.1 Tracing Value through a Campaign

This section defines a campaign and outlines the top-level questions answered by a campaign. It presents a mapping of the value-related elements of a campaign described by Sutherland. It provides a definition of value and explains the processes undergone at every level that accrue benefit and incur costs. These elements form the basis for the CSTM.

2.1.1 Defining a Campaign

Creating a framework for analyzing the Decadal campaign requires a consistent definition of what a campaign is. A survey of current earth-observation programs reveals a lack of agreement of the common elements of a campaign. Sutherland's definition of an earth observation campaign is utilized to inform a general discussion of campaigns.

The Decadal Survey exclusively refers to "campaigns" as ground-based or airborne systematic research operations. NASA's Earth Observation handbook uses the term similarly, but adds the concept of a "validation campaign", where an instrument is pushed to a higher TRL through a progression of tests (NASA, 2006). These conceptions imply a progression over time of individual instruments, but are never applied to the entire enterprise. Both the Decadal Survey and NASA instead describe their sets of missions as "programs".

Sutherland proposed the definition of an earth observation campaign located below. At the highest level, a campaign is composed of a sequence of missions. These missions rely upon instruments to capture measurements, which in turn deliver value through objectives to stakeholders. This definition will be utilized to describe campaigns in this thesis.

Earth Observation campaign:

- *A prioritized sequence of Earth-orbiting missions containing instruments that produce measurements of the Earth, which deliver value to a diverse range of stakeholders by satisfying specific scientific and societal objectives.*

This definition was realized by first answering three descriptive questions (Table 1). At the highest level of abstraction, a complete campaign will address each question:

Campaign Question	Campaign Answer
What should be done?	Purpose
How should it be done?	Constraints
When should it be done?	Sequence

Table 1. Questions a Campaign Answers

The first question, "What", captures the purpose behind the campaign by relating the campaign objectives to the priorities, goals, and needs of relevant stakeholders. The second question, "How", captures the boundaries the campaign must fit in—including the cost, budget, TRL, data continuity and overlap, and other similar considerations that may limit the design of a campaign. This question can alternately be formulated, "How should it not be done". The final question "when", explains the sequence or schedule of the campaign. This can be as simple as the ordering of missions, or can be as detailed as forcing overlap of specific measurements.

Applying these three questions to an Earth Observation campaign reveals the two primary components described by Sutherland: the missions and the schedule (Figure 13). The missions of a campaign represent a merging of the purpose with constraints, whereas the schedule is the union of the sequence with constraints. A viable campaign will hence contain both missions and a schedule, which incorporate purpose, constraints, and schedule.

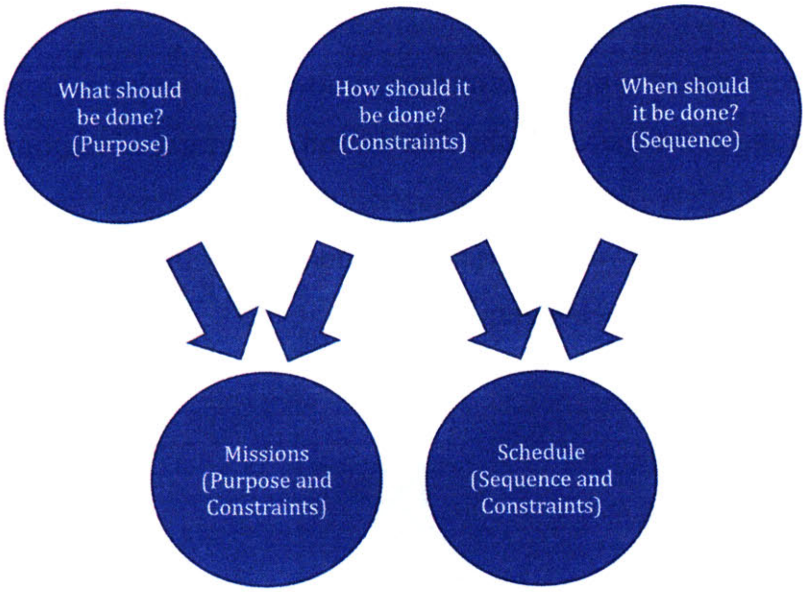


Figure 13. Attributes of a Campaign

The duality of a campaign differentiates it from a program or system. A campaign is not just a set of missions flying at once—it is the incorporation of mission elements into a schedule.

2.1.2 Defining a Campaign Metric

Every program has a desirable end-state. A campaign, due to its time-dependence, dictates an evolving desired state over time. This desired state profile is the metric against which possible campaign designs are measured. For this reason it is necessary to pick a metric capable of expressing the relevant aspects of the desired-state.

The simplest measure of a campaign is its value. The Lean Enterprise defines value as, "how various stakeholders find particular worth, utility, benefit, or reward in exchange for their respective contributions to the enterprise" (Murman, 2002). Expressed simply, value is benefit that is delivered at cost. It is a useful metric in defining campaigns because of its relation to stakeholder needs—value exists only from the perspective of the recipient. However, quantifying and comparing the value of different things can be difficult, particularly complex systems that service multiple stakeholders.

Definition of Value:

- *Value is the expression of benefit accrued at cost, evaluated from the perspective of the recipient*

Having decomposed campaigns into missions and a schedule, the source of value can be described at a more specific level. Sutherland' definition of a campaign can be expressed as a set of interrelated value elements (Figure 14). Each element has a set of attributes which dictate how value is created or modified by that element. The remainder of this section describes these elements in detail.

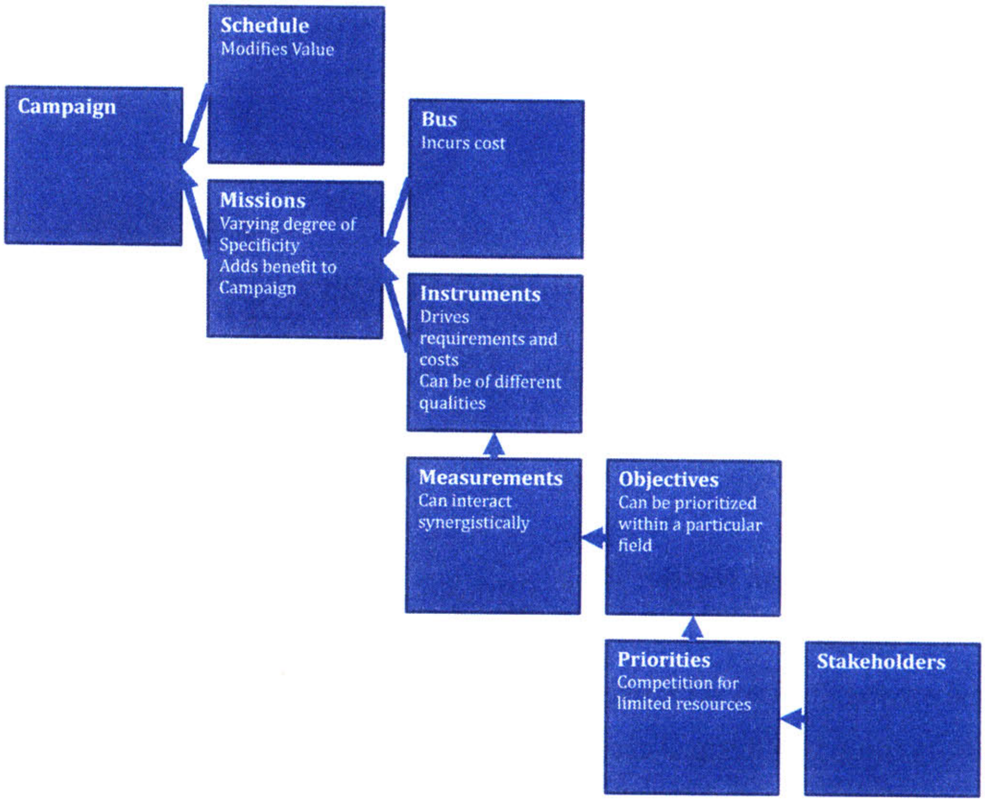


Figure 14. Value Related Elements of a Campaign

2.1.3 Schedule

The schedule of a campaign primarily serves to modify the value inherent in the missions. Changing stakeholder needs, opportunities for data continuity and overlap, synergistic measurements, and the urgency of science objectives all affect scheduling. Between these characteristics, different scientific communities will see different levels of value from identically composed, but differently scheduled campaigns.

Elements of a complex, long-duration campaign must align with both the physical processes they will be studying, and with the complex socio-political environment they will be implemented in. Complex engineering programs, particularly space missions, frequently experience severe cost overruns (GAO, 2009). As costs increase, so does the likelihood a program will be either descoped or cancelled. For a campaign, this entails the cancellation of later missions. This was seen, for example, in the truncation of the Apollo program, where the original campaign of 20 missions was cut down to 17, as political and popular support for repeated lunar expeditions waned. Stakeholder needs change over time—there is an incentive on flying missions earlier in the campaign sequence.

Scheduling also affects the overlap and continuity of measurements. It is often desirable and sometimes necessary to have similar instruments overlap in time to calibrate one against the other. Similarly, it is sometimes desired to have a continuous data record of a particular measurement for use in physical systems modeling. Additionally, different data products can be produced when additional measurements are added. Synergistic effects between measurements increase the utility of both measurements separately, or can lead to the emergence of entirely new measurements.

Finally, a schedule is affected by the urgency associated with each stakeholder need. Not every mission must be accomplished immediately. For the Decadal Survey, this is particularly manifested in a comparison between Climate and Solid Earth Dynamics missions: the timescales involved predispose stakeholders to prioritize understanding the anthropogenic changes to climate. Hence, the future worth of each mission is dependent on the science objectives of that mission.

2.1.4 Missions

While scheduling can greatly modify the transfer of value to stakeholders, value is primarily produced by the missions in a campaign. This section describes different classes of purpose attributable to missions which affect their expected benefit. Additionally, it discusses the decomposition of missions into instruments and buses as value-related elements.

The campaign principle of purpose discussed in the previous section manifests itself into three classes within missions: operational, research, and discovery. These classifications examine the expected value of a particular experiment.

Operational missions are best described as components of long-duration programs. They are dedicated to studying a very specific set of physical phenomena, and do so in a well understood manner. These missions often have many heritage systems taken from their precursors, and sometime are exact replicas. The costs incurred by the mission and the benefits accrued are all very well understood during the early planning phases. The progression of value from mission to stakeholder is clear: information from the mission translates into useful applications. Operational missions are usually commissioned based upon the proven utility of their precursors: demonstrate enough benefit to stakeholders, and continuing to do so will be incentivized or even mandated. A good example of an operational mission is the latest LandSat. The LandSat program is in its 37th year of continuous operation: the geospatial information it provides to a multitude of federal agencies, scientists, and commercial users has ensured its longevity.

Research missions are best described as experiments that could become operational. These missions are dedicated towards understanding physical phenomena so that a useful application can be derived. Whereas the focus of an operational mission is very specific, research missions are geared towards a more general understanding. The costs and benefits of a research mission are less well understood, but there exists a strong possibility for unintended benefit. A number of measurements are identified a priori as potentially valuable, and a research mission is designed to isolate and capture them. Research missions are vital because they drive the discovery of useful applications. A good example of a research mission was OCO, which was designed to measure carbon in the atmosphere. Earth Scientists are currently unable to close the carbon loop—large amounts of the carbon being sent into the atmosphere are disappearing somewhere. There are theories, but OCO sought to come up with a definitive answer that would enable more effective policing of international and commercial emissions agreements.

Discovery missions are best described as explorations into the unknown. These missions are dedicated to gaining knowledge without any foreknowledge of where to look; they are almost completely unconnected from specific objectives and rely upon theory for direction. The costs of these missions are less well known, and there is almost no expected benefit. These missions, however, have the greatest potential for unintended benefit, and serve the role of identifying areas for future research. Earth science does not lend itself to exploration missions: any undiscovered frontier on the planet can likely be explored more cheaply on the ground by people.

These classes of mission purpose outline a fundamental spectrum best referred to as "mission specificity" (Figure 15). This spectrum reflects a number of qualities which describe the value-related processes of missions. The scope of a mission can be general or specific, the costs can known or unknown, the benefits can be intended or unintended, and the goals can be application or discovery based. Every mission falls somewhere on this spectrum.

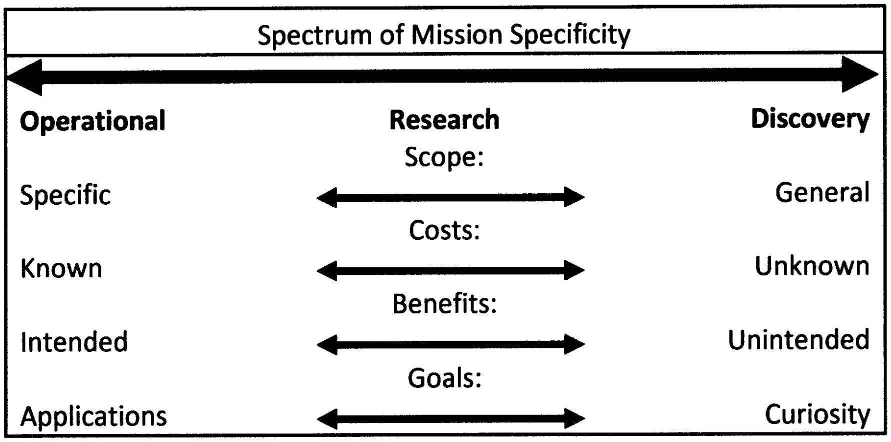


Figure 15. Spectrum of Mission Specificity

The Decadal Survey actively sought to strike a balance of research missions that leaned towards both sides of the spectrum. While more operational missions convey explicit benefit to stakeholders, discovery-focused missions allow the discovery of new applications, and are essential to a long-term strategy.

The issue of intended versus unintended benefit is perhaps the most difficult problem in tracing value. Without resorting to probabilistic modeling, one solution is assume that every mission in the Decadal Campaign was far enough to the left on the spectrum of specificity that the benefits are already understood and can be quantified and compared. This thesis assumes a uniform level of specificity so that the issue of unintended benefit can be ignored.

The specific value-related processes of a mission can be decomposed into two elements: an instrument and a bus. As explained in Sutherland's campaign definition, the instrument captures measurements which satisfy objectives, thus providing benefit to stakeholders. However, as value is a function of both cost and benefit, it is necessary to consider the costs associated with buses. For a space mission, the bus is a function of the instrument, "the payload is the single most significant driver of spacecraft design" (Larson & Wertz, 1999). A particular mission can have one or many instruments. In general, there exists a correlation between the number of instruments on-board a satellite and the cost of the mission, as the mass and power of the instruments tend to drive bus costs parametrically.

The decomposition of missions into busses and instruments is not unique to space missions—every science experiment will require some sort of support process that will incur costs. A campaign can be composed of different bus types—space, air, and ground resources can be incorporated into the same framework. For this thesis only space missions are considered.

2.1.5 Instruments

While the cost of a mission is primarily accrued by the bus, benefit is primarily delivered by the instrument. As Sutherland explained in his campaign definition, instruments create benefit by capturing measurements. Measurements are the actual data recorded by instruments and transmitted back to earth, and then interpreted by scientists.

Benefit is realized through the data, and the value of an instrument is a translation of the value of its measurements.

Different instruments capture measurements in different ways. There are substantial quantitative and qualitative differences between individual instruments. A small Field of View (FOV) sensor can have a high resolution, and a low resolution sensor can have a large FOV, but it is difficult (and prohibitively expensive) to make a large FOV hi-res sensor. The effectiveness of a particular instrument in taking a particular measurement in reality is a function of many variables. The field of view, coverage gaps, resolution, and many other factors dictate how useful an instrument will be. For the purposes of this model, these attributes were condensed into two attributes: the Quality of Data Produced, and the Quantity of Data Produced (Table 2).

Utility of Data produced		Quality of Data				
		no data produced	low quality data	moderate quality data	high quality data	highest possible quality data
Quantity of Data	no data produced	0	0	0	0	0
	a small amount of data	0	1	1	1	1
	a moderate amount of data	0	1	2	2	2
	a large amount of data	0	1	2	3	4

Table 2. Utility of Data Produced

This simplified evaluation metric can be easily applied to instruments to understand their effectiveness in capturing specific measurements. This allows for differentiation amongst instruments that capture the same measurements.

2.1.6 Measurements

The measurements captured by each instrument convey benefit. While scientists value measurements from their experiments, benefit at this level is not differentiable: one can assume every scientist finds his own type of data more valuable than anyone else's. There is no architectural significance at that level; instead, measurements must be considered by the data products that can be derived from them. Data-products are defined as the result of adding measurements to practical applications utilized by large segments of society. A good example of a data-product is weather forecasting: the measurement of ocean vectors winds at altitude has no practical significance to much of the population, but the data-product of hurricane landfall predictions does.

At the time of mission launch it is impossible to predict the totality of data-products a particular mission will produce. Instead, an ideal reference is the mission and program objectives. These objectives spell out the expected data-products as they relate to individual measurements and requirements.

2.1.7 Objectives

Every campaign can be expressed as a series of objectives. These objectives state the intended value: the practical applications and uses that a majority of society will benefit from because of this campaign. These objectives, proposed by scientists to the larger stakeholder community, indicate the measurements scientists believe they can transform into value.

Objectives have several key attributes. One objective may require several measurements, and one measurement could satisfy multiple objectives. An objective may have a primary measurement, which is essential to obtaining that objective, and it may have several supporting measurements (which synergize with the primary). Scientists, who propose objectives, can prioritize objectives within their field, but have a hard time comparing their objectives to those in other fields. As such, the value of scientific field is dependent on the priorities set by society.

The satisfaction of objectives is not wholly dependent on measurements. Data containing the measurements must be processed and analyzed to produce the data products stakeholders need. This is, however, an independent process of the campaign architecture. It is assumed that every objective will require some form of data processing; hence this property of objectives is architecturally independent.

2.1.8 Priorities

At its heart, every campaign is driven by a macroscopic set of priorities set by the larger stakeholder community. This stakeholder prioritization of scientific fields is necessary to remove the assumed biases of scientific communities. These priorities are often in competition for limited resources, and the resultant campaign architectures often reflect that.

The Decadal Survey identified that such a consideration was necessary, particularly in avoiding the tendency of research to ignore applications:

> *Extracting societal benefit from space-based measurements requires, as an equally important second step, the development of a strong linkage between the measurements and the decision makers who will use them. This linkage must be created and sustained throughout the life cycle of the space mission. In implementing future missions, scientists engaged in research intended to make both scientific and societal contributions must operate differently than they did when the advancement of science was the primary or only goal of research.* (National Research Council, 2007)

The linkages between measurements and stakeholders must be a consideration of any campaign design, and the prioritization of different communities of science is the first step in establishing these linkages. Frequently these prioritizations are made evident in high-level policy documents. Weiss' paper on Science Traceability identifies program objectives, NASA roadmaps, and Academy of Science surveys, as key sources of this information (Weiss, Smythe, & Lu, 2005).

2.1.9 Overview of Value Decomposition

The decomposition of a science campaign outlines how value traces through the system. First, stakeholder set priorities. These priorities are then more formally codified as science objectives. The objectives require a specific set of measurements to produce valuable data products. Measurements are captured by instruments, which, along with the bus elements, define the missions. The combination of a set of missions with a schedule defines a campaign. Both benefits and costs accrued in this framework can be traced to their sources, as every element in the decomposition is considered architecturally significant.

2.2 A Framework for Campaign Analysis: the CSTM

The value decomposition presented in the previous section outlines the key elements of a campaign and enables value traceability. This section introduces a methodology for keeping track of these elements and the relationships between them a large number of missions over time, the Campaign Science Traceability Matrix.

The value-decomposition framework of the previous is advantageous because it allows the traceability of value in a campaign. It does not, however, express specific relationships. The Science Traceability Matrix described by Weiss is contrastingly advantageous because it succinctly relates different elements and requirements of a mission. It, however, is only designed to describe a single mission. A new framework was developed to incorporate the advantages of both frameworks at a campaign level: the Campaign-level Science Traceability Matrix (Figure 16).

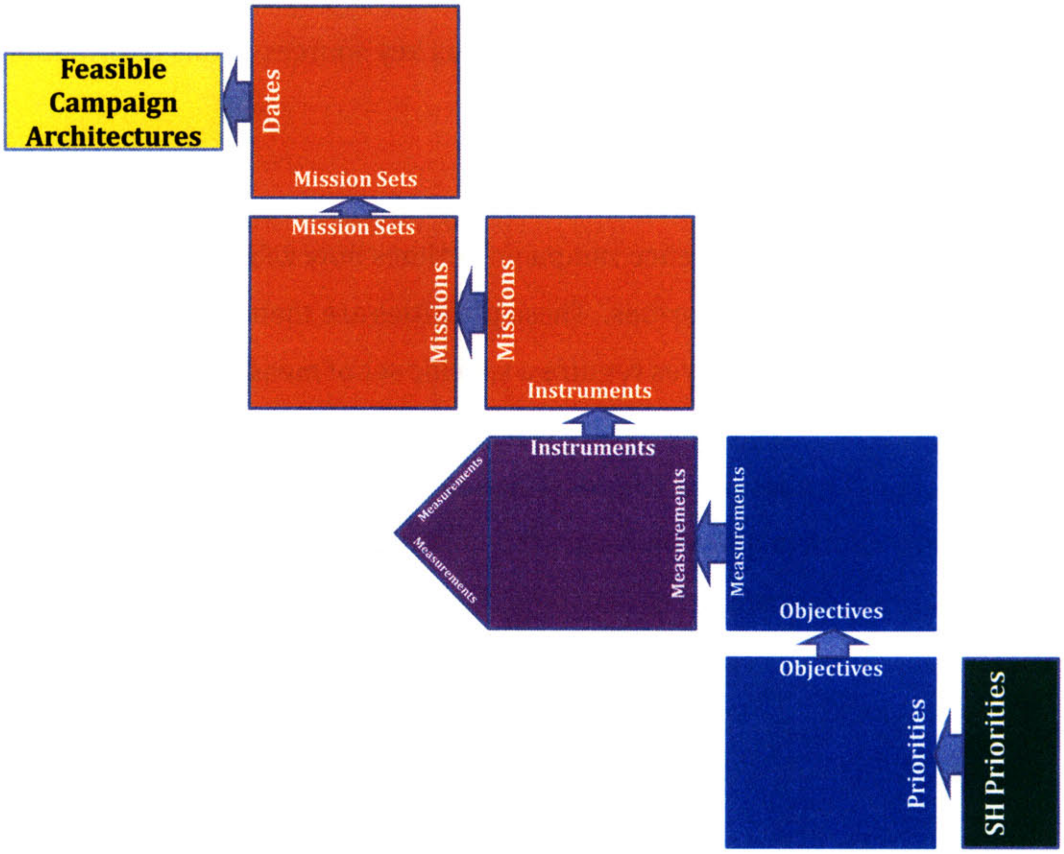


Figure 16. The Campaign-Level Science Traceability Matrix (CSTM)

The CSTM expresses different levels of campaign decomposition as a series of matrices. Each matrix expresses to the qualitative relationships between multiple instances of each campaign element. Hence, relationships such as "one objective requiring many measurements" can be expressed by populating a matrix—measurements on one axis and objectives on the other. While these are expressed as matrices, matrix math does not necessarily apply, and relationships can be described as unique functions. This allows for the architecting of a campaign on multiple levels:

- The assignment of dates to a particular mission set (scheduling)
- The assignment of missions to a particular mission set (determining the mission content)
- The assignment of instruments to missions (mission design)

Similarly, the impacts of architectural decisions can be traced on multiple levels:

- The benefit accrued by capturing measurements
- The benefit accrued by satisfying objectives
- The benefit accrued by contributing to priorities

This framework allows the architect to take into consideration many different levels of information, and judge the actual benefits associated with his decisions. It provides the basis for campaign cost-benefit analysis not only in assembling his missions, but also in determining which missions to fly and when to fly them.

The CSTM can also be expressed more generally in terms of the flow knowledge through the system (Figure 17). Societal concerns and stakeholder needs form the foundation of value discussions. Then this information must interpreted by policy-minded scientists, such as the Decadal Panel, to provide concrete priorities and objectives. Third, scientific knowledge must be applied to the specific implementation of these objectives, particularly in the design of instruments. Informed by that discussion, engineering knowledge is then required to determine the proper manifesting of instruments to missions, and the scheduling of those missions. Finally, the cumulative knowledge implicit in the campaign analysis informs the system architect the optimal manner in which to plan his campaign.

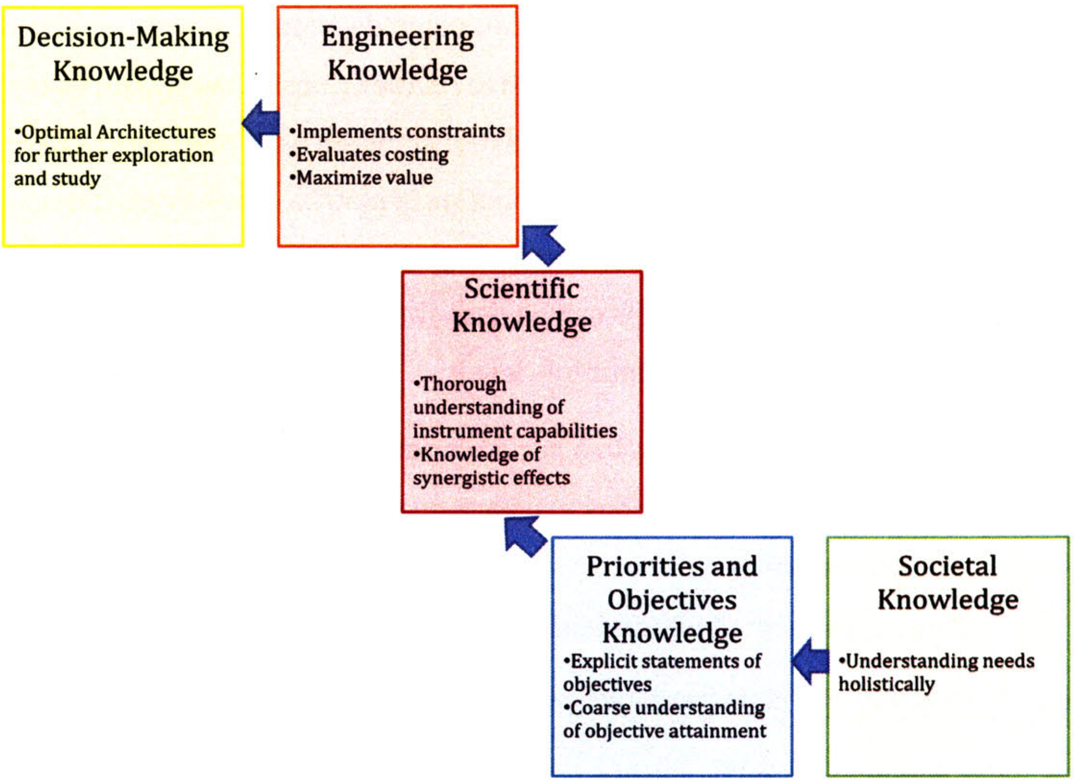


Figure 17. Generalized CSTM

The CSTM is tool for envisioning the traceability of value in a campaign. By decomposing a campaign into progressively smaller pieces, the architecturally significant components can be isolated. By representing the relationships between hierarchical components as mappings, the impacts of architectural decisions can be traced to every other component. The key advantage this method delivers is flexibility: changes can be made on any level, and the effects can be easily traced.

3 Applying the CSTM Framework to the Decadal Survey Campaign

The CSTM framework described in the previous chapter is a tool that enables traceability of campaign design decisions to stakeholder impacts. It is useful in logically enumerating the relationships between different elements of a campaign. The impacts of system architecting, both on the campaign schedule and individual mission level, can be analyzed as they affect the delivery of value to stakeholders through priorities and objectives.

This chapter describes in detail the application of the CSTM to the Decadal campaign. The objectives of this chapter are:

Objectives of applying the CSTM to the Decadal Survey

- *To apply the framework for analysis to the Decadal campaign by enumerating the relationships between campaign elements using stakeholder modeling, the Decadal Survey, and NASA surveys*
- *To validate the methods and model introduced in this thesis by comparing results using the Decadal Survey as "truth"*
- *To examine the architectural impacts of value on campaign design by tracing science value using the CSTM*

This chapter outlines the specific methodology used to populate the CSTM for the Decadal Survey. While the Decadal Survey included a brief discussion of ground and air campaigns and introduced the concept of Venture-class small satellites to further complete its science objectives, this chapter only focuses on the incorporation of the 17 named missions to the CSTM. This chapter is organized into the following sections:

- Section 3.1: Populating the CSTM. This section presents the methodology used to populate the different elements of the CSTM.
- Section 3.2: Comparison to the Decadal Survey. This section compares the completed model to the Decadal Survey.
- Section 3.3: Examination of Science Traceability. This section examines the scientific decisions made by the Decadal Survey with respect to stakeholders.
- Section 3.4: Summary of the CSTM.

3.1 Populating the CSTM

The Decadal Survey proposed a complete campaign: starting with priorities one could trace the logical connections through the CSTM and out to the notional launch tiers of specific missions (Figure 16). The specific nature of these relationships, however, was not uniformly presented in a clear and recoverable manner, and they largely lacked qualitative assertions. Using a combined approach of the Decadal Survey, Sutherland's stakeholder analysis, and a survey of NASA scientists and engineers, the CSTM matrices were populated.

3.1.1 Representing the Six Decadal Science Panels as Priorities

The first step undertaken in applying the CSTM to the Decadal Survey was quantifying stakeholder priorities (represented in the green lower-right box of Figure 16). One of the outputs of Sutherland's stakeholder analysis of the Earth Observation Program was a relative comparison of the value different Decadal Survey science panels with regards to the stakeholder network (Figure 18).

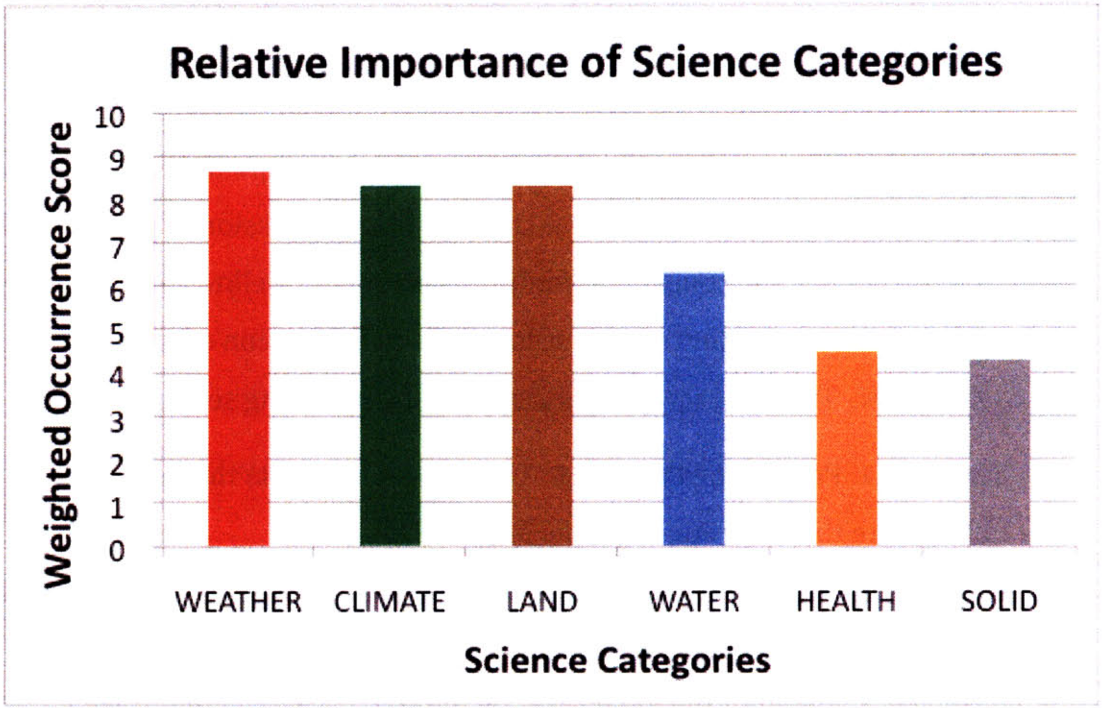


Figure 18. Sutherland's Stakeholder Analysis of Panel Weighing (Sutherland, 2009)

These six panels are sufficiently representative of stakeholder priorities for use in the CSTM. According to Sutherland, the most valuable science community to the Earth Observation enterprise's stakeholders is represented by the weather panel: weather data-products are utilized extensively by millions of people on a daily basis. The Climate-change and Land-use panels are tied as the second most valuable, reflecting the large segment of shareholders that utilize geo-spatial information, as well as the looming societal issue of anthropogenic climate change. The Water panel, although ranked fourth, is of median importance, reflective of the growing awareness of water as a limited resource. The lowest scoring panels, Human Health and Security and Solid Earth, are explained by Sutherland as non-traditional priorities for NASA and NOAA. Using Sutherland's valuations, a relative weighting of each panel can be accomplished (Equation 1).

$$w_{p\ Normal_j} = \frac{w_{p\ Occurance_j}}{\sum_{i=1}^{6} w_{p\ Occurance_i}}$$

Equation 1. Normalized Panel Weighting

The weighted occurrence score of each panel can be normalized to the relevant fraction of the total benefit in the system (Table 3):

Science Panel	Weighted Occurrence Score	Normalized Fraction of total Benefit
Weather	8.65	0.214
Climate change	8.33	0.206
Land-use	8.33	0.206
Water	6.31	0.156
Human health	4.49	0.111
Solid Earth	4.31	0.107
Total	**40.42**	**1.000**

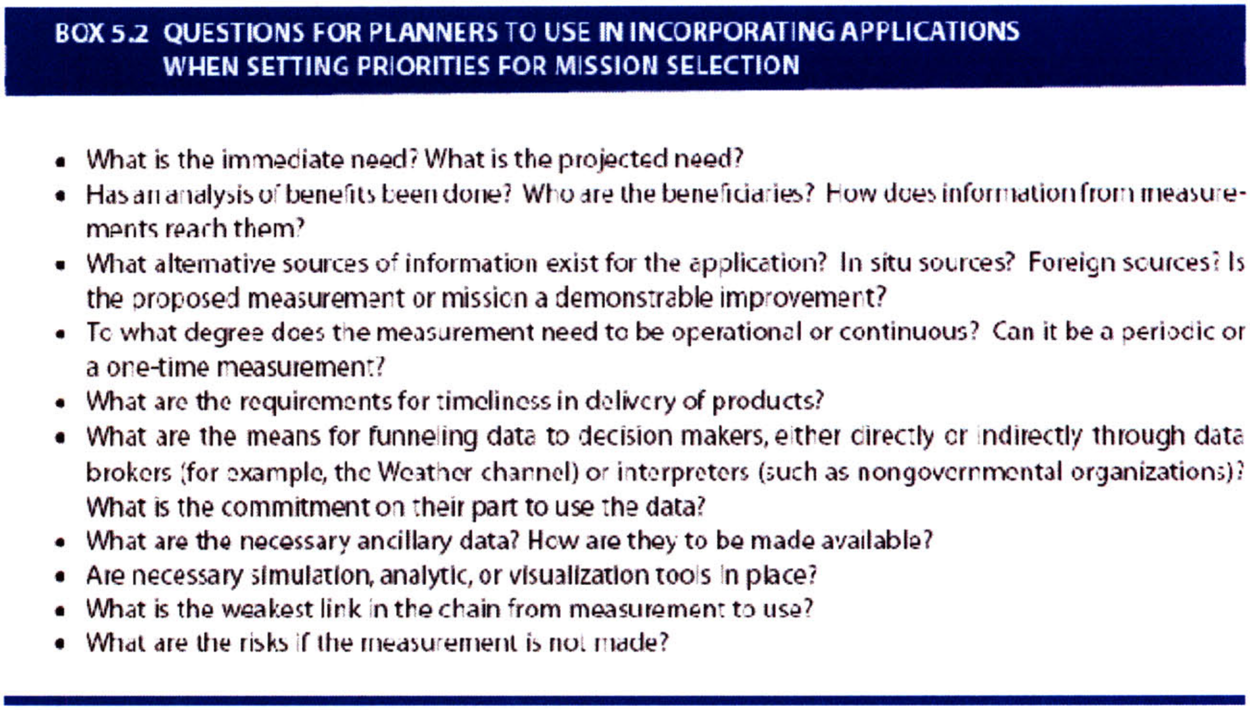
Table 3. Normalized Panel Weights

The normalized fraction of total benefit is a weighing that can be found for every panel with regards to the totality of benefit in the system. It is assumed that the 17 missions of the Decadal Survey campaign will produce 100% of the possible benefit. Synergistic effects are ignored in this initial computation, as Decadal Survey panelists were instructed to select missions based on the assumption of isolation (every mission is a stand-alone). The stakeholder prioritizations of the Decadal Survey science panels can then be utilized to weight each community's objectives.

3.1.2 Utilizing the Panel Objectives from the Decadal Survey

Each of the science-themed Decadal Survey panels outlined a set of prioritized objectives for the campaign. These can be scaled and incorporated into the lower blue matrix of CSTM in Figure 16 to relate stakeholder priorities to measurements. Additionally, the normalized weighting of the panels can be applied to the panel-ranked objectives to create an absolute prioritization of the objectives.

The Decadal Survey Committee was given the set of tasks depicted in Figure 1 (Section 1.2). This included instructions to, "develop a consensus of the top-level scientific questions that should the focus for earth and environmental observations" and, "recommend a prioritized list of measurements". These tasks were given to the different panels, and the specific implementation varied significantly. However, one process almost universally followed was the creation of prioritized objectives which would answer each panel's top–level questions. The following guidance was provided to individual panels:



BOX 5.2 QUESTIONS FOR PLANNERS TO USE IN INCORPORATING APPLICATIONS WHEN SETTING PRIORITIES FOR MISSION SELECTION

- What is the immediate need? What is the projected need?
- Has an analysis of benefits been done? Who are the beneficiaries? How does information from measurements reach them?
- What alternative sources of information exist for the application? In situ sources? Foreign sources? Is the proposed measurement or mission a demonstrable improvement?
- To what degree does the measurement need to be operational or continuous? Can it be a periodic or a one-time measurement?
- What are the requirements for timeliness in delivery of products?
- What are the means for funneling data to decision makers, either directly or indirectly through data brokers (for example, the Weather channel) or interpreters (such as nongovernmental organizations)? What is the commitment on their part to use the data?
- What are the necessary ancillary data? How are they to be made available?
- Are necessary simulation, analytic, or visualization tools in place?
- What is the weakest link in the chain from measurement to use?
- What are the risks if the measurement is not made?

Figure 19. Prioritizing Objectives (National Research Council, 2007)

In answering these questions, the panels enumerated a set of specific objectives to be accomplished in the decade. These objectives, and their corresponding specific measurements, instrument types and basic requirements, and mission implementations, were summarized in tables such as seen in Figure 20. With the exception of the Human Health and Security, every panel prioritized their objectives.

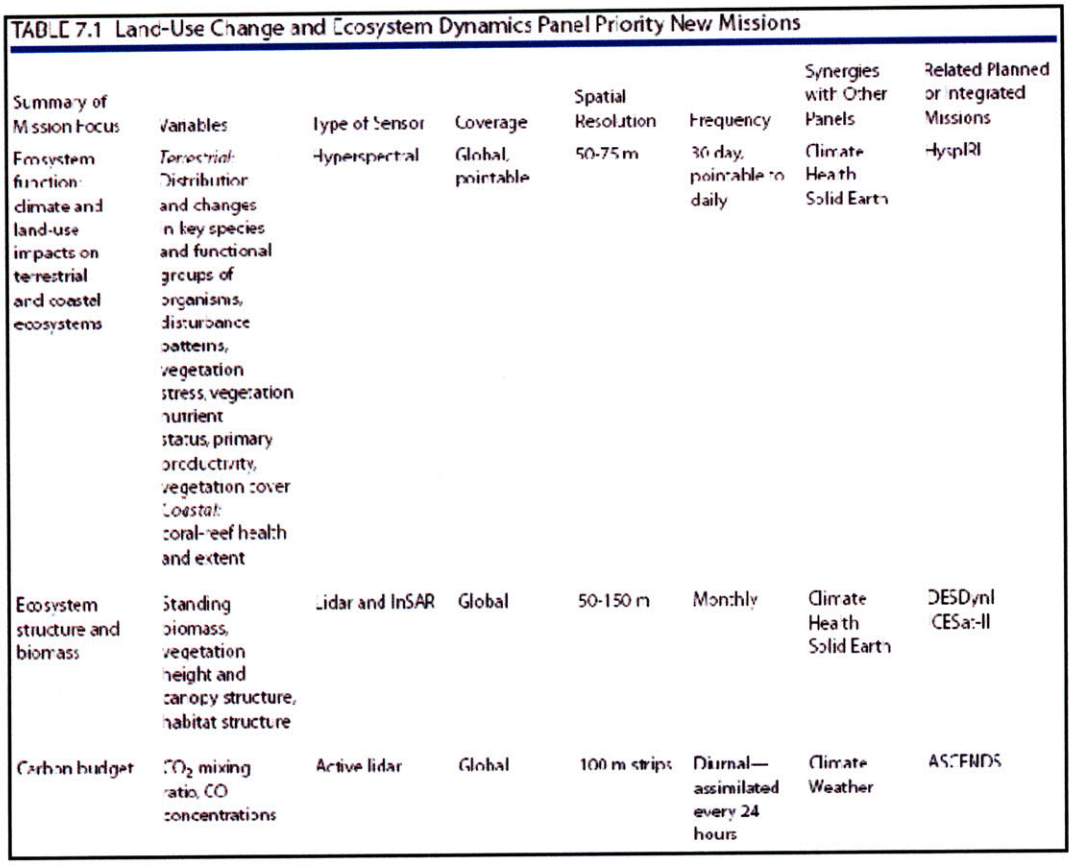


TABLE 7.1 Land-Use Change and Ecosystem Dynamics Panel Priority New Missions

Summary of Mission Focus	Variables	Type of Sensor	Coverage	Spatial Resolution	Frequency	Synergies with Other Panels	Related Planned or Integrated Missions
Ecosystem function: climate and land-use impacts on terrestrial and coastal ecosystems	*Terrestrial:* Distribution and changes in key species and functional groups of organisms, disturbance patterns, vegetation stress, vegetation nutrient status, primary productivity, vegetation cover *Coastal:* coral-reef health and extent	Hyperspectral	Global, pointable	50-75 m	30 day, pointable to daily	Climate Health Solid Earth	HyspIRI
Ecosystem structure and biomass	Standing biomass, vegetation height and canopy structure, habitat structure	Lidar and InSAR	Global	50-150 m	Monthly	Climate Health Solid Earth	DESDynI ICESat-II
Carbon budget	CO_2 mixing ratio, CO concentrations	Active lidar	Global	100 m strips	Diurnal—assimilated every 24 hours	Climate Weather	ASCENDS

Figure 20. Land-Use and Ecosystems Objectives (National Research Council, 2007)

In this format, the left hand column provides a brief descriptor, the summary of mission focus, describing the specific objective. Subsequent columns provide the specific requirements needed to achieve this objective according to the planned implementation. Objectives are presented in prioritized order.

For inclusion in the CSTM, a majority of the objectives enumerated in the Decadal Survey were left untouched. Table 4 enumerates the mapping of CSTM objectives to "Mission/Observation Type" identified in Table 2.3 of the Decadal Survey, with the Decadal represented on the vertical axis and the CSTM represented on the horizontal axis.

Health	Ozone Processes: Ultraviolet Radiation and Cancer	Heat stress and drought	Acute Toxic Pollution Releases	Air Pollution and Respiratory and Cardiovascular Diseases	Algal Blooms and Waterborne Infectious Diseases	Vector-borne and Zoonotic Disease
Ozone processes	x					
Heat stress and drought		x				
Acute toxic pollution releases			x			
Air pollution				x		
Algal blooms and waterborne infectious disease					x	
Vector-borne and zoonotic disease						x

Weather	Tropospheric winds	High-Temporal-Resolution Air Pollution	All-Weather Temperature and Humidity Profiles	Comprehensive Tropospheric Aerosol Characterization	Radio Occultation	Comprehensive Tropospheric Ozone Measurements	Aerosol-Cloud Discovery
Tropospheric winds	x						
Air pollution		x					
All-weather temperature and humidity profiles			x				
Tropospheric aerosol characterization				x			
Radio occulation					x		
Tropospheric ozone						x	
Aerosol-cloud discovery							x

Climate	Aerosol-Cloud Forcing	Ice Sheet and Sea Ice Volume	Carbon Sources and Sinks	Radiance Calibration and Time-Reference Observatory	Earth Radiation Budget (ERB) Continuity	Ice Dynamics	Ocean Circulation, Heat Storage, and Climate Forcing
Clouds, aerosols, ice, and carbon	x	x	x				
Radiance calibration				x	x		
Ice dynamics						x	
Ocean circulation, heat storage, and climate forcing							x

Ecosystems	Ecosystem Function	Ecosystem Structure and Biomass	Carbon Budget	Coastal Ecosystem Dynamics	Global Ocean Productivity
Ecosystem function	x				
Ecosystem structure and biomass		x			
Carbon budget			x		
Global ecosystem dynamics				x	
Global ocean productivity					x

Water	Soil Moisture and Freeze-Thaw State	Surface Water and Ocean Topography	Snow and Cold Land Processes	Water Vapor Transport	Sea Ice Thickness, Glacier Surface Elevation, and Glacier Velocity	Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	Inland and Coastal Water Quality
Soil moisture and freeze/thaw state	x						
Surface water and ocean topography		x					
Cold seasons			x				
Water vapor transport				x			
Sea ice thickness, glacier surface elevation, glacier velocity					x		
Groundwater storage, ice sheet mass balance, ocean mass						x	
Inland and coastal water quality							x

Solid Earth	Surface deformation	Surface composition and thermal properties	High resolution topography	Temporal variations in Earth's gravity field	Oceanic bathymetry
Surface deformation	x				
Surface composition and thermal properties		x			
High-resolution topography			x		

Table 4. Objective Identification

A small number of objectives were broken apart into more atomic pieces when no rationale was provided for the convolution of apparently disparate sub-objectives, as seen in the climate objective "Clouds, Aerosols, Ice, and Carbon". Additionally, the Decadal summary of "Mission/Observation Types" did not include two of the Solid earth objectives, which were added to the CSTM list. After correction, a total of 37 Objectives identified in Table 4 were added to the CSTM.

While the Decadal Survey panel reports provide the prioritizations amongst these objectives, they do not explicit quantify how much more important one is over another. Hence, a subjectively-tuned scaling algorithm was necessary to translate the language of the Decadal Survey into a computationally useful metric.

First, it was assumed that the median ranked objective would have the mean objective weighting (Equation 2).

$$w_{int\ b\ median} = \frac{1}{i}$$

$$i\ is\ the\ number\ of\ objectives\ for\ panel\ J$$

Equation 2. Median Objective Weight

This intermediate (unnormalized) weighting was assigned to the median objective. Hence, if a panel had five prioritized objectives, the third would be assigned an un-normalized weighting of $\frac{1}{5}$ or 0.2. The other objectives were weighed linearly with regards to the median based upon a subjective slope, set by varying the z-values for the panel:

$$w_{b\ median+2} = (w_{int\ b\ median})(1 + 2z)$$

$$w_{b\ median+1} = (w_{int\ b\ median})(1 + z)$$

$$w_{b\ median} = (w_{int\ b\ median})(1)$$

$$w_{b\ median-1} = (w_{int\ b\ median})(1 - z)$$

$$w_{b\ median-2} = (w_{int\ b\ median})(1 - 2z)$$

Equation 3. Linear Scaling around median-mean

Because some panels gave the same ranking to multiple objectives, care had to be taken such that the linearization was maintained and the sum of the objective weights equaled one. Slopes (z-values) were modified based upon descriptions given in the Decadal Survey panel chapters, although the default used was z=0.25. As the Human Health and Security panel did not prioritize objectives, every objective was weighted equally at $\frac{1}{i}$, where $i = 7$. Additionally, the Water panel had two linearizations, based upon having two distinct tiers of objectives. The weights assigned to every objective are listed in Table 5 below.

Panel	Objective	Rank within panel	Normalized Weighting	Panel weight	Absolute Objective Weight
Health	Ozone Processes: Ultraviolet Radiation and Cancer	1	0.17	0.111	0.019
	Heat stress and drought	1	0.17		0.019
	Acute Toxic Pollution Releases	1	0.17		0.019
	Air Pollution and Respiratory and Cardiovascular Diseases	1	0.17		0.019
	Algal Blooms and Waterborne Infectious Diseases	1	0.17		0.019
	Vector-borne and Zoonotic Disease	1	0.17		0.019
Ecosystems	Ecosystem Function	1	0.28	0.206	0.058
	Ecosystem Structure and Biomass	2	0.24		0.049
	Carbon Budget	3	0.20		0.041
	Coastal Ecosystem Dynamics	4	0.16		0.033
	Global Ocean Productivity	5	0.12		0.025
Solid Earth	Surface deformation	1	0.29	0.107	0.031
	Surface composition and thermal properties	2	0.24		0.025
	High resolution topography	3	0.19		0.020
	Temporal variations in Earth's gravity field	4	0.14		0.015
	Oceanic bathymetry	4	0.14		0.015
Climate	Aerosol-Cloud Forcing	1	0.18	0.206	0.037
	Ice Sheet and Sea Ice Volume	1	0.18		0.037
	Carbon Sources and Sinks	1	0.18		0.037
	Radiance Calibration and Time-Reference Observatory	2	0.14		0.029
	Earth Radiation Budget (ERB) Continuity	2	0.14		0.029
	Ice Dynamics	3	0.11		0.022
	Ocean Circulation, Heat Storage, and Climate Forcing	4	0.07		0.015
Weather	Tropospheric winds	1	0.19	0.214	0.041
	High-Temporal-Resolution Air Pollution	1	0.19		0.041
	All-Weather Temperature and Humidity Profiles	2	0.15		0.033
	Comprehensive Tropospheric Aerosol Characterization	2	0.15		0.033
	Radio Occultation	3	0.12		0.025
	Comprehensive Tropospheric Ozone Measurements	3	0.12		0.025
	Aerosol-Cloud Discovery	4	0.08		0.016
Water	Soil Moisture and Freeze-Thaw State	1	0.29	0.156	0.045
	Surface Water and Ocean Topography	2	0.24		0.037
	Snow and Cold Land Processes	3	0.19		0.030
	Water Vapor Transport	4	0.10		0.015
	Sea Ice Thickness, Glacier Surface Elevation, and Glacier Velocity	5	0.08		0.012
	Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	6	0.06		0.010
	Inland and Coastal Water Quality	7	0.05		0.007
				Total	1.000

Table 5. Objective Weighting

This methodology introduces some artifacts. Panels with a large number of objectives are penalized, as the median weighted objective is valued as the mean. This is not an inherently incorrect assumption, as it mimics human thought processes. It is possible the Climate panel intentionally convoluted their objectives to avoid this bias.

Although objectives are weighed within each panel, the normalized panel weights can be applied to each objective to produce an absolute measure of benefit for each objective (Equation 4).

$$W_{b\ absolute} = \left(w_{b,j}\right) * \left(W_{panel\ j}\right)$$

Equation 4. Absolutely Weighted Objectives

The absolute weight of the objective is equal to the product of the panel weight with the objective weight (Table 5). Objectives are assumed to be unique to panels, so that the sum of every absolutely weighted objective from a particular panel equates to the normalized panel weight. Expressed in terms of value traceability, the benefit to society of a particular science community is completely divided among its objectives. Hence satisfying each of those objectives will contribute that panel's value to the enterprise stakeholders. Additionally, since the panel weights were normalized as well, the sum of every objective across all panels will equal one. The Decadal Survey is "complete," if every objective is satisfied, 100% of the value in the system will be delivered.

These weighting can alternately be plotted by objective (Figure 21). The most beneficial objective is "Ecosystem function" (the top objective from the second-most important panel). Although the Weather panel was weighted the highest, because it proposed 7 objectives, the value of each was comparably less than the Land-use and Ecosystems panel, which only proposed 5. The least beneficial objective is "Inland and coastal water quality" (the last objective of the #4 panel). This is reflective of the water panel having two distinct linearizations, one necessarily lower than the other.

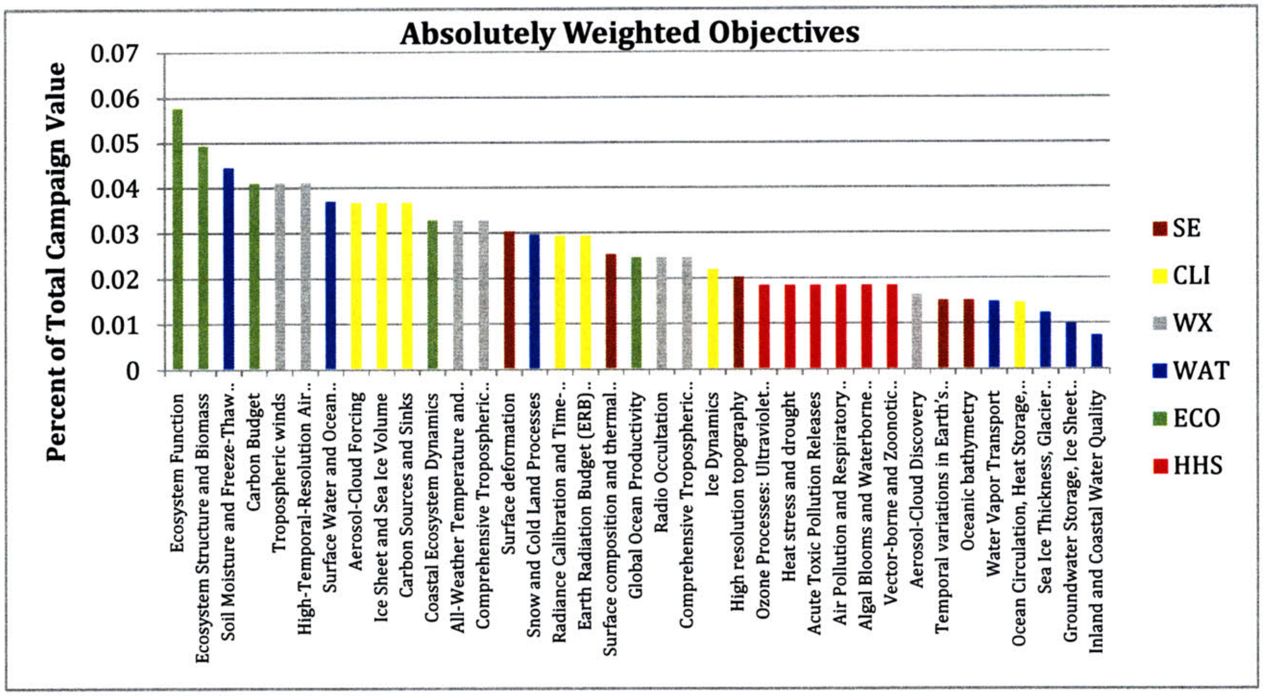


Figure 21. Absolutely Weighted Objectives

3.1.3 Derivation of Measurements

Each objective can be described in terms of the measurements required for objective satisfaction. While not always explicitly enumerated, the relevant measurements were recoverable from the Decadal Survey. A common set of measurements was derived and mapped to the CSTM objectives. This section discusses the population of the higher-right blue box of the CSTM.

While one of the stated tasks of the Decadal Survey was to "recommend a prioritized list of measurements," this was not explicitly done (Figure 1). Only two panels directly listed the measurements they required; however, every panel described the measurements relevant to their ranked objectives. The primary source of this information is the paragraph descriptions of each objective.

While the CSTM's matrix format is more expressive than the Science Traceability Matrix, it was still desirable to limit the number of measurements enumerated so that instruments of similar capability could realistically be compared against each other. To this end, a common set of measurements was created to which all the objectives in the

Decadal Survey could be mapped. It was also desirable that this set of measurements be easily traceable to other pre-existing and international missions; hence, the Committee on Earth Observation Satellites (CEOS) database categorization scheme was chosen to form the backbone of the common set of measurements, and the Decadal Survey was used to fill in the details.

In the CEOS database classification scheme, earth science is divided into five primary science areas (Table 6). Unlike the six Decadal Survey panels, these fields are less application-based and are more reflective of Bretherton's earth system (Figure 8). The CEOS database outlines 27 measurement types within these five fields. A 28th measurement type, "Surface water distribution" was added to the CEOS list from the Decadal Survey. The Surface Water and Ocean Topography mission's (SWOT) inclusion in the Decadal campaign indicated this type of measurement was important, yet it did not readily lend itself to inclusion in any other measurement type, so a new category was added.

CEOS Science Fields	Measurement Types
1) Atmosphere	1.1. Aerosol properties
	1.2. Atmospheric temperature fields
	1.3. Water vapor
	1.4. Atmospheric winds
	1.5. Cloud type, amount, and top temp.
	1.6. Cloud particle properties and profile
	1.7. Liquid water and precipitation rate
	1.8. Ozone
	1.9. Radiation budget
	1.10. Trace gases (excluding ozone)
2) Land	2.1. Albedo and reflectance
	2.2. Land topography
	2.3. Soil moisture
	2.4. Vegetation
	2.5. Surface temperature (land)
	2.6. Multi-purpose imagery (land)
	2.7 Surface water distribution*
3) Ocean	3.1. Ocean colour/biology
	3.2. Ocean topography/currents
	3.3. Ocean salinity
	3.4. Ocean surface winds
	3.5. Surface temperature (ocean)
	3.6. Ocean wave height and spectrum
	3.7. Multi-purpose imagery (ocean)
4) Snow and Ice	4.1. Ice sheet topography
	4.2. Snow cover, edge and depth
	4.3. Sea ice cover, edge and thickness
5) Gravity and Magnetic fields	5.1. Gravity, magnetic and geodynamic

Table 6. CEOS Science Fields and Measurement Types

These categorizations, however, were determined to be too generic to be architecturally distinguishing. For example, the measurement type "Aerosol Properties" can be described through numerous measurements, such as height, composition, scattering properties, size, and distribution, many of which require different instrumentation.

Specific measurements were then added to this hierarchy based upon information in the Decadal Survey. Using the "variable" information in the panel priority tables (Figure 20) and the descriptions of each objective, a list of specific measurements was derived (Table 7). This list was then screened for duplicates and sufficiently similar measurements to down-select to 81 measurements. These were then placed into the 28 measurements types categories to complete the common set of measurements.

The mapping of specific measurements to measurement categories can be found on the horizontal axis of Table 7. Additionally, this chart maps the relationships between the 81 measurements and the 37 objectives.

Panel	Objective	Total Number of Measurements	1) Atmosphere 1.1. Aerosol properties 1.1.1 aerosol height/optical depth	1.1.2 aerosol composition, physical and chemical properties	1.1.3 aerosol scattering properties	1.1.4 aerosol extinction profiles	1.1.5 aerosol size and size distribution	1.2. Atmospheric temperature fields 1.2.1 Atmospheric temperature fields	1.3. Water vapor 1.3.1 Water vapor profiles	1.3.2 Water vapor transport	1.4. Atmospheric winds 1.4.1 atmospheric wind speed	1.4.2 atmospheric wind direction	1.5. Cloud type, amount, and top temp. 1.5.1 cloud top temperature	1.5.2 Cloud type	1.5.3 Cloud amount/distribution	1.6. Cloud particle properties and profile 1.6.1 cloud height/optical thickness	1.6.2 cloud particle size distribution	1.6.3 Ice/Water transition in clouds	1.7. Liquid water and precipitation rate 1.7.1 Precipitation rate	1.7.2 droplet size	1.8 Ozone 1.8.1 stratospheric ozone	1.8.2 tropospheric ozone	1.8.3 ozone precursors	1.9. Radiation budget 1.9.1 total solar irradiance	1.9.2 spectrum of earth IR radiance	1.9.3 GPS radio occultation	1.10 Trace gases (excluding ozone) 1.10 1 short-lived reactive species	1.10 2 isotope observations (HDO, H218O, H2O)	1.10 3 tropospheric col. mr SO2, NO2, formaldehyde	1.10 4 Benzene marker trace data	1.10 5 visible atmospheric plumes	1.10 6 pollutant particle size	1.10 7 pollutant gas vertical structure	1.10 8 vertically resolved CO2 (Daytime only)	1.10 9 vertically resolved CO2 (Day/Night)	1.10 11 CO concentrations	1.10 12 O3 concentrations
Health	Ozone Processes, Ultraviolet Radiation and Cancer	9	0	1	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0
	Heat stress and drought	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Acute Toxic Pollution Releases	13	0	0	0	0	0	1	1	0	1	1	0	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	0
	Air Pollution and Respiratory and Cardiovascular Diseases	6	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0
	Algal Blooms and Waterborne Infectious Diseases	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Vector-borne and Zoonotic Disease	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ecosystems	Ecosystem Function	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ecosystem Structure and Biomass	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Carbon Budget	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
	Coastal Ecosystem Dynamics	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Global Ocean Productivity	3	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solid Earth	Surface deformation	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surface composition and thermal properties	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High resolution topography	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Temporal variations in Earth's gravity field	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Oceanic bathymetry	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Climate	Aerosol-Cloud Forcing	10	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ice Sheet and Sea Ice Volume	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Carbon Sources and Sinks	7	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Radiance Calibration and Time-Reference Observatory	5	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	Earth Radiation Budget (ERB) Continuity	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	Ice Dynamics	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ocean Circulation, Heat Storage, and Climate Forcing	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Weather	Tropospheric winds	5	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	All-Weather Temperature and Humidity Profiles	4	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Radio Occultation	3	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Aerosol-Cloud Discovery	11	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High-Temporal-Resolution Air Pollution	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0
	Comprehensive Tropospheric Aerosol Characterization	5	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Comprehensive Tropospheric Ozone Measurements	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	1	1	0	0
Water	Soil Moisture and Freeze Thaw State	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surface Water and Ocean Topography	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Snow and Cold Land Processes	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Water Vapor Transport	3	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sea Ice Thickness, Glacier Surface Elevation, and Glacier Velocity	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Inland and Coastal Water Quality	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Panel	Objective	Total Number of Measurements	2) Land	2.1. Albedo and reflectance	2.1.1 Albedo and reflectance	2.2. Land topography	2.2.1 surface deformation	2.2.2 Hi-res topography	2.3. Soil moisture	2.3.1 Freeze/thaw state	2.3.2 soil moisture	2.4. Vegetation	2.4.1 vegetation type	2.4.2 vegetation state	2.4.3 vegetation height	2.4.4 canopy density	2.5. Surface temperature (land)	2.5.1 Surface temperature (land)	2.6. Multi-purpose imagery (land)	2.6.1 land use	2.6.2 landcover status	2.6.3 disaster monitoring	2.6.4 hydrocarbon reservoir monitoring	2.6.5 surface composition	2.6.6 inland water quality	2.7 Surface water distribution	2.7.1 river and lake elevation	2.7.2 flood monitoring	2.7.3 groundwater storage
Health	Ozone Processes: Ultraviolet Radiation and Cancer	9			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Heat stress and drought	4			0		0	0		0	1		0	1	0	0		1		0	0	0	0	0	0		0	0	0
	Acute Toxic Pollution Releases	13			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Air Pollution and Respiratory and Cardiovascular Diseases	6			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Algal Blooms and Waterborne Infectious Diseases	4			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Vector-borne and Zoonotic Disease	5			0		0	0		0	1		0	1	0	0		1		0	1	0	0	0	0		0	0	0
Ecosystems	Ecosystem Function	4			0		0	0		0	0		0	1	0	0		0		0	1	1	0	0	0		0	0	0
	Ecosystem Structure and Biomass	3			0		0	0		0	0		0	1	1	1		0		0	0	0	0	0	0		0	0	0
	Carbon Budget	4			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Coastal Ecosystem Dynamics	3			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Global Ocean Productivity	3			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
Solid Earth	Surface deformation	4			0		1	1		0	0		0	0	0	0		0		0	0	1	1	0	0		0	0	0
	Surface composition and thermal properties	4			0		0	0		0	0		0	0	0	0		1		0	0	1	1	1	0		0	0	0
	High resolution topography	3			0		0	1		0	0		0	0	0	0		0		0	0	1	0	0	0		0	1	0
	Temporal variations in Earth's gravity field	4			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	1
	Oceanic bathymetry	2			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
Climate	Aerosol-Cloud Forcing	10			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Ice Sheet and Sea Ice Volume	5			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Carbon Sources and Sinks	7			0		0	0		0	0		1	0	1	1		0		0	0	0	0	0	0		0	0	0
	Radiance Calibration and Time-Reference Observatory	5			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Earth Radiation Budget (ERB) Continui	2			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Ice Dynamics	12			0		0	0		0	0		0	0	0	0		1		0	0	0	0	0	0		0	0	0
	Ocean Circulation, Heat Storage, and Climate Forcing	6			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
Weather	Tropospheric winds	5			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	All-Weather Temperature and Humidit Profiles	4			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Radio Occultation	3			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Aerosol-Cloud Discovery	11			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	High-Temporal-Resolution Air Pollution	5			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Comprehensive Tropospheric Aerosol Characterization	5			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Comprehensive Tropospheric Ozone Measurements	6			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
Water	Soil Moisture and Freeze Thaw State	2			0		0	0		1	1		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Surface Water and Ocean Topography	3			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		1	0	0
	Snow and Cold Land Processes	4			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Water Vapor Transport	3			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Sea Ice Thickness, Glacier Surface Elevation, and Glacier Velocity	4			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	0
	Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	3			0		0	0		0	0		0	0	0	0		0		0	0	0	0	0	0		0	0	1
	Inland and Coastal Water Quality	5			0		0	0		0	0		0	0	0	0		0		1	1	0	0	0	1		0	0	0

			3) Ocean														4) Snow and Ice											5) Gravity and Magnetic fields	
			3.1 Ocean colour/biology	3.2 Ocean topography/currents						3.3 Ocean salinity	3.4 Ocean surface winds		3.5 Surface temperature (ocean)	3.6 Ocean wave height and spectrum	3.7 Multi-purpose imagery (ocean)		4.1 Ice sheet topography					4.2 Snow cover, edge and depth				4.3 Sea ice cover, edge and thickness		5.1 Gravity, magnetic and geodynamic	
Panel	Objective	Total Number of Measurements	3.1.1 Ocean color	3.2.1 surface circulation	3.2.2 seafloor topography	3.2.3 coastal upswelling	3.2.4 thermal plumes	3.2.5 river plumes/sediment fluxes	3.2.6 Ocean mass distribution	3.3.1 Ocean salinity	3.4.1 Ocean surface wind speed	3.4.2 Ocean surface wind direction	3.5.1 Surface temperature (ocean)	3.6.1 Ocean wave height and spectrum	3.7.1 Visible hydrospheric pollution plumes	3.7.2 coral reef health/extent	4.1.1 Ice sheet volume	4.1.2 Glacier surface elevation	4.1.3 glacier mass balance	4.1.4 Ice sheet velocity	4.1.5 Ice Sheet topography	4.2.1 snow-water equivalence	4.2.2 snow depth	4.2.3 snow wetness	4.2.4 snow cover	4.3.1 Sea ice thickness	4.3.2 Sea ice cover	5.1.1 gravity field variations	5.1.2 magnetic field variations
Health	Ozone Processes: Ultraviolet Radiation and Cancer	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Heatstress and drought	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Acute Toxic Pollution Releases	13	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Air Pollution and Respiratory and Cardiovascular Diseases	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Algal Blooms and Waterborne Infectious Diseases	4	1	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Vector-borne and Zoonotic Disease	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ecosystems	Ecosystem Function	4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ecosystem Structure and Biomass	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Carbon Budget	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Coastal Ecosystem Dynamics	3	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Global Ocean Productivity	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solid Earth	Surface deformation	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surface composition and thermal properties	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High resolution topography	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Temporal variations in Earth's gravity field	4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
	Oceanic bathymetry	2	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Climate	Aerosol-Cloud Forcing	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ice Sheet and Sea Ice Volume	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	1	0	0	0
	Carbon Sources and Sinks	7	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Radiance Calibration and Time-Reference Observatory	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Earth Radiation Budget (ERB) Continuity	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ice Dynamics	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0
	Ocean Circulation, Heat Storage and Climate Forcing	6	0	1	1	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Weather	Tropospheric winds	5	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	All-Weather Temperature and Humidity Profiles	4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Radio Occultation	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Aerosol-Cloud Discovery	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	High-Temporal-Resolution Air Pollution	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Comprehensive Tropospheric Aerosol Characterization	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Comprehensive Tropospheric Ozone Measurements	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Water	Soil Moisture and Freeze-Thaw State	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Surface Water and Ocean Topography	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Snow and Cold Land Processes	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0
	Water Vapor Transport	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sea Ice Thickness, Glacier Surface Elevation, and Glacier Velocity	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	1	1	0	0
	Groundwater Storage, Ice Sheet Mass Balance, and Ocean Mass	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	Inland and Coastal Water Quality	5	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7. Objective to Measurement Mapping

This mapping was accomplished by reviewing the descriptions of objectives for relationships. For example, the following four measurements were derived from the descriptions of the Carbon Budget objective for the Land-use and Ecosystems panel:

Example Objective—Carbon Budget

1. "Although the OCO will yield a vastly increased volume of data for characterizing the distribution of atmospheric C02 and inferring surface sources and sinks, unavoidable physical limitations are imposed by the **passive-measurement approach, including daytime and high-Sun-only sampling"**
2. "The first step in inferring terrestrial ecosystem processes from atmospheric data is to separate photosynthesis and respiration; for this, diurnal sampling is required to **observe nighttime concentrations** resulting from respiration "
3. "It is also essential to separate physiological fluxes from biomass burning and fossil-fuel combustion, and this requires **quasisimultaneous measurement of an additional tracer, ideally CO"**
4. "A laser sounder mission, consisting of simultaneous laser remote sensing of C02 and **02 (needed to correct for atmospheric pressure, topography, and target-height effects)** would provide new active measurement capabilities to overcome the most serious of those limitations"

Figure 22. Example Text Descriptions of Objective-Measurement Mapping (National Research Council, 2007)

In this example, the text reveals two alternate primary measurements that could satisfy this objective: vertically resolved C02 measured at day, and vertically resolved C02 measured at day and at night. This objective could be satisfied using existing technology, such as the daytime sensor on OCO (had OCO not failed in launch), or it could be satisfied using the newer, less mature instrument proposed for the ASCENDS mission. For this mapping, no distinction is made between the qualities of the two methods, since both would contribute to the objective. Additionally, the text reveals that two complimentary measurements would be beneficial in satisfying this objective: CO and 02 concentrations. Although in reality these measurements are not essential, for the CSTM, measurements were mapped to objectives in binary: either they did contribute or they did not contribute to the satisfaction of an objective. There was insufficient detail in the Decadal Survey to determine qualitative differences.

Example Objective—Carbon Budget	
1.10.8 vertically resolved CO2 (Daytime only)	X
1.10.9 vertically resolved CO2 (Day/Night)	X
1.10.11 CO concentrations	X
1.10.12 02 concentrations	X

Table 8. Example Objective-Measurement Mapping

Several assumptions are implicit in the mapping from objectives to measurements in the CSTM. First, no distinction was made between essential and complimentary measurements within an objective. Second, one objective could be satisfied by multiple measurements (the lowest was two, the highest was thirteen). Finally, one measurement could contribute to the satisfaction of multiple objectives.

Having achieved a mapping of objectives to measurements, it became possible to apply the absolute weighting of objectives to the measurements. The matrix representing the mapping in Table 7 is a binary matrix with values of zero and one only, of the dimension 37x81 (objectives x measurements), and is referred to as M. This matrix is first normalized by the number of measurements per objective (Equation 5), to weight measurements equally within an objective. It is then multiplied by the absolutely weighted objectives (Equation 6). Finally, the weighted measurements mappings are summed across all objectives (Equation 7) to compile to absolutely weighted measurements.

$$m_{b\,normalized} = \frac{1}{\sum_{1}^{37} m_b}$$

Equation 5. Normalized M

$$W_{m,b} = (m_{b\,normalized}) * (W_{b\,absolute})$$

Equation 6. Weighted M

$$W_{m\ absolute} = \sum_{b=1}^{37} W_{m,b}$$

Equation 7. Absolutely Weighted Measurements

A discussion of the resultant absolutely weighted measurements can be found in Section 3.3.

Finally, although no distinction was made within an objective as to the relative importance of measurements, the relationships between measurements could be evaluated in an attempt to quantify synergistic effects. Just as multiple measurements are sometimes necessary to fulfill a particular objective, the presence or absence of one measurement fundamentally affects the utility of another. One area for future work is to quantify the synergies between measurements.

3.1.4 Instrument utility as evaluated by NASA

The value of stakeholders priorities have been traced to individual measurements. Every instrument proposed in the Decadal Survey captures the measurements necessary for objective satisfaction; however, the Decadal Survey offers no clues as to which instruments within a particular mission capture which measurement, and provides very little information as to how effective the proposed instruments are. A survey of instrument-measurement relationships was given to NASA scientists and engineers to better capture these relationships. This information was used to populate the central purple box of the CSTM (Figure 16).

The instruments contained in the 17 Decadal missions were isolated and evaluated with respect to the common set of measurements (Appendix A: NASA Worksheet Instructions). This evaluation attempted to capture the qualitative and quantitative differences amongst instruments as simplified in Table 2, and was evaluated in survey form by NASA earth scientists. Although the scoring was done with integers, NASA responses were converted to an exponential score (Table 9)

Survey Score	Scaled Scored
0	0
1	0.1
2	0.2
3	0.4
4	0.8

Table 9. Exponential Scaling for Instrument-Measurement Scores

Using the instrument-measurement scores provided by NASA, it was possible to calculate how well each instrument satisfied each objective. Although several options presented themselves for determining satisfaction, the method selected relies upon considering the original Decadal Campaign as "truth"; if every instrument is flown, 100% of the benefit is realized.

Hence, the instrument-measurement scoring is useful only for quantifying relative relationships amongst instruments. If only one instrument in the original Decadal campaign captures a particular measurement, then by default 100% of the value of that measurement is traceable to that instrument, regardless of how useful that particular instrument actually is. If multiple instruments in the original Decadal campaign do an equally excellent job of capturing a measurement, all of them must be flown to capture 100% of the benefit.

Instrument-objective satisfaction was calculated by first converting the instrument-measurement survey scores into their scaled components using Table 9. Then the scaled instrument-measurement matrix, I, is multiplied by the normalized measurement matrix (Equation 8) to express the satisfaction matrix, f.

$$f = I * m_{b\ normalized}$$

Equation 8. Satisfaction Matrix

The satisfaction matrix expresses how well each instrument satisfies every objective, and is then normalized by objective (Equation 9), such that every entry in the normalized satisfaction matrix is divided by the sum of every instrument's contribution to a particular objective.

$$F_{k,l} = \frac{f_{k,l}}{\sum_{k=1}^{number\ of\ instruments} f_l}$$

Equation 9. Normalized Satisfaction Matrix

The weighted satisfaction matrix, W_F, can then be found (Equation 10), which relates the absolutely weighted benefit of every objective to the normalized satisfaction matrix.

$$W_F = W_{b\ absolute} .* F$$

Equation 10. Weighted Satisfaction Matrix

3.1.5 Decadal Campaign Composition

The relationships from stakeholder priorities to the Decadal Survey Instruments have been mapped in a series of three matrices which compose the blue and purple lower sections of the CSTM (Figure 16). This section describes the population of the three orange sections. Although the framework is designed to handle multiple architectures, the Decadal Survey outlines only one.

Instruments in the Decadal campaign are unique to one of the proposed missions, (although a particular mission may include several instances of that instrument). The 39 instruments were taken from the mission description in the Decadal Survey; hence reassembling the relationships was trivial (Table 10). This set of 17 missions formed the basis of a single mission set, which was subsequently mapped to three tiers rather than specific dates.

The single architecture of the Decadal Survey can thus be described in one table, rather than a series of matrices. These relationships will be revisited in Chapter 4 as variables in automated campaign architecting.

Tier 1: 2010-2013	CLARREO	thermal-IR spectrometer/interferometer	Near IR-VIS-UV spectrometer/interferometer	GPS receiver	
	GPSRO	advanced GPS receiver			
	SMAP	L-band radar	L-band radiometer		
	ICESAT-II	modified GLAS (LIDAR)			
	DESDynI	L-band inSAR	IR multi-beam LIDAR		
Tier 2: 2013-2016	XOVWM	Ku band SAR scatterometer	C-band real-aperture scatterometer	passive (SRAD with K and X bands) radiometer	
	HyspIRI	thermal multispectral scanner spectrometer	optical Hyperspectral imager		
	ASCENDS	1.57 or 2.06um LIDAR	0.76 or 1.27 um LIDAR	IR radiometer	
	SWOT	Ku-band radar altimeter	Ku-band InSAR	3-band MW radiometer	
	GEO-CAPE	steerable hi-res spectrometer	NIR/VIS/UV wide-area spectrometer	IR correlation radiometer	
	ACE	cross-track scanning cloud radar	multi-band VIS/UV spectrometer	Multi-beam cross-track dual-wavelength LIDAR	Multi-angle multi-wavelength polarimeter
Tier 3: 2016-2020	LIST	LIDAR altimeter with spatial mapping			
	PATH	MW spectrometer	MW radiometer		
	GRACE-II	Sat-to-Sat ranger and accelerometer			
	SCLP	dual frequency SAR	passive MW radiometer		
	GACM	SWIR/IR spectrometer	MW spectrometer	UV/VIS spectrometer	UV/VIS differential absorption LIDAR
	3D-WINDS	non-coherent wind lidar	Coherent wind lidar		

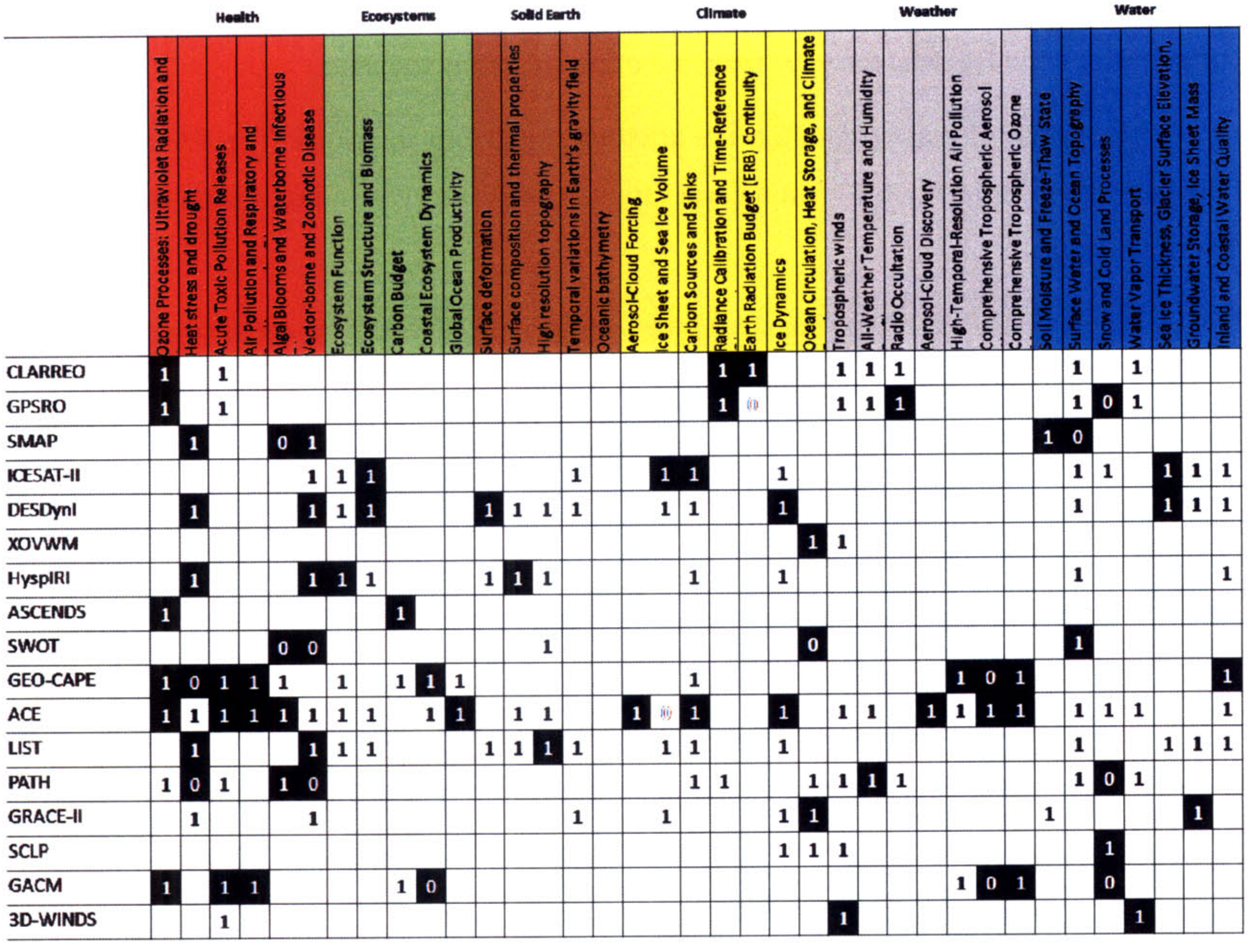
Table 10. Instrument to Mission to Mission Set to Dates Mapping

3.2 Comparison to the Decadal Survey

The relationships in the CSTM were mapped using the Decadal Survey and NASA surveys to establish truth. One mapping that the Decadal Survey directly enumerated was that between the 17 missions and the Decadal objectives. Using the CSTM, a similar summary of missions to objectives was calculated. The two mapping were compared to determine how effective the CSTM is in replicating the Decadal Survey.

An additional survey of NASA scientists was conducted in which the 17 Decadal Survey missions were evaluated by the measurements they can capture (Appendix A: NASA Worksheet Instructions), recombining the instruments in Table 10 for easy evaluation. The mission-objective satisfaction calculations were calculated using the instrument-objective equations in 3.1.4.

The mission-objective satisfaction was plotted against the Decadal Survey (Figure 23). Although the Decadal Survey did not attempt to quantify the accrual of benefit, it did indicate when a particular mission did or did not satisfy an objective, allowing the relationships to be plotted in binary. In this diagram, the CSTM objectives, sorted by panel, are listed on the x-axis and the 17 Decadal Survey missions are listed on the y-axis. The color of the intersecting square indicates the relationship explicitly enumerated in the Decadal Survey: Black squares indicate that this mission does contribute to this objective; white squares indicate that this mission is unrelated to this objective. The CSTM mission-objective satisfaction matrix can likewise be converted to binary form and plotted on this chart. The number in the intersecting square indicates the relationship traced through the CSTM: Ones indicate that this mission does contribute to this objective, zeros indicate that this mission is unrelated to this objective (white squares with no numbering are zeros).



	Health						Ecosystems					Solid Earth					Climate							Weather							Water						
	Ozone Processes: Ultraviolet Radiation and	Heat stress and drought	Acute Toxic Pollution Releases	Air Pollution and Respiratory and	Algal Blooms and Waterborne Infectious	Vector-borne and Zoonotic Disease	Ecosystem Function	Ecosystem Structure and Biomass	Carbon Budget	Coastal Ecosystem Dynamics	Global Ocean Productivity	Surface deformation	Surface composition and thermal properties	High resolution topography	Temporal variations in Earth's gravity field	Oceanic bathymetry	Aerosol-Cloud Forcing	Ice Sheet and Sea Ice Volume	Carbon Sources and Sinks	Radiance Calibration and Time-Reference	Earth Radiation Budget (ERB) Continuity	Ice Dynamics	Ocean Circulation, Heat Storage, and Climate	Tropospheric winds	All-Weather Temperature and Humidity	Radio Occultation	Aerosol-Cloud Discovery	High-Temporal-Resolution Air Pollution	Comprehensive Tropospheric Aerosol	Comprehensive Tropospheric Ozone	Soil Moisture and Freeze-Thaw State	Surface Water and Ocean Topography	Snow and Cold Land Processes	Water Vapor Transport	Sea Ice Thickness, Glacier Surface Elevation,	Groundwater Storage, Ice Sheet Mass	Inland and Coastal Water Quality
CLARREO	■ 1		1																	■ 1	■ 1			1	1	1						1		1			
GPSRO	■ 1		1																	■ 1	(i)			1	1	■ 1						1	■ 0	1			
SMAP		■ 1			■ 0	■ 1																									■ 1	■ 0					
ICESAT-II						1	1	■ 1							1			■ 1	■ 1			1										1	1		■ 1	1	1
DESDynI		■ 1				■ 1	1	■ 1				■ 1	1	1	1			1	1			■ 1										1			■ 1	1	1
XOVWM																							■ 1	1													
HyspIRI		■ 1				■ 1	■ 1	1				1	■ 1	1					1			1										1					1
ASCENDS	■ 1								■ 1																												
SWOT					■ 0	■ 0								1									■ 0									■ 1					
GEO-CAPE	■ 1	■ 0	■ 1	■ 1	1		1		1	■ 1	1								1									■ 1	■ 0	■ 1							■ 1
ACE	■ 1	1	■ 1	■ 1	■ 1	1	1	1		1	■ 1		1	1			■ 1	(i)	■ 1			■ 1		1	1		■ 1	1	■ 1	■ 1		1	1	1			1
LIST		■ 1				■ 1	1	1				1	1	■ 1	1			1	1			1										1			1	1	1
PATH	1	■ 0	1		■ 1	■ 0													1	1			1	1	■ 1	1						1	■ 0	1			
GRACE-II		1				1									1			1				1	■ 1								1					■ 1	
SCLP																						1	1	1									■ 1				
GACM	■ 1		■ 1	■ 1					1	■ 0																		1	■ 0	■ 1			■ 0				
3D-WINDS			1																					■ 1										■ 1			

Figure 23. Binary Mission-Objective Satisfaction: CSTM versus Decadal Survey

In total, the Decadal Survey outlines 72 instances of mission-objective satisfaction, whereas the CSTM indicates 148, indicating that the CSTM is effective in locating unforeseen synergies. Every "1" located in a white square indicates benefit that the Decadal Survey did not anticipate. Every "0" located on a black square indicates that the CSTM may not accurately capture all the necessary relationships.

Six of the fourteen relationship shortcomings occur with respect to the Human Health and Security panel's objectives. This is understandable given that, "most of the missions were deemed to contribute at least slightly to human health issues" (National Research Council, 2007, p45); the exact mission contributions to Human Health were not expressly mapped to begin with. Similarly, four of the fourteen shortcomings are attribuatble to the Water panel, particularly the "Snow and Cold Land processes". Since there is a dedicated Snow and Cold Land Processs (SCLP) mission, it is unclear what contributions the Decadal Survey expected other missions to make.

The remaining shortcomings are attributable to four missions. The NASA Goddard Earth Sciences Exploration Division Chief Engineer was interviewed to reason through the discrepancies:

- SMAP: studying surface water, while a logical extension of studying soil moisture as SMAP intends, is unlikely.
- SWOT: SWOT is intended to study rivers and lakes, and is tuned to making distinction between water and land; hence studying ocean circulation is not feasible.
- GEOCAPE: the lack of characterization of tropospheric aerosols potentially indicates an issue with the mapping
- GACM: it is unclear how the Decadal Survey intended to use GACM, an atmospheric composition mission, to study coastal ecosystems. However, the lack of tropospheric aerosol characterization potentially indicates an issue with the mapping.

An analysis of the individual CSTM elements revealed that the GACM and GEOCAPE instrument-measurement characterizations were insufficient to capture this objective. This was identified as an area for future work.

The CSTM is sufficiently capable of reproducing the Decadal Survey relationships. Although a few discrepancies were noted between the Decadal and CSTM mappings, the CSTM identified a significant number unintended benefits.

3.3 Examination of Science Traceability

The mapping of the CSTM was compared against the Decadal Survey to establish validity of the model. The intermediate matrices can be used to inform campaign design. The value of science fields, instrument types, and missions can be analyzed. The traceability of science value enables a cost-benefit analysis.

First, the measurement weighting process described by Equation 7 in 3.1.3 was utilized to weight each of the 81 measurements (Appendix C: Measurement Weights). The top eleven benefit producing measurements are displayed in Figure 24. The measurements depicted in the chart reflect three of the five CEOS science areas and 8 measurement categories.

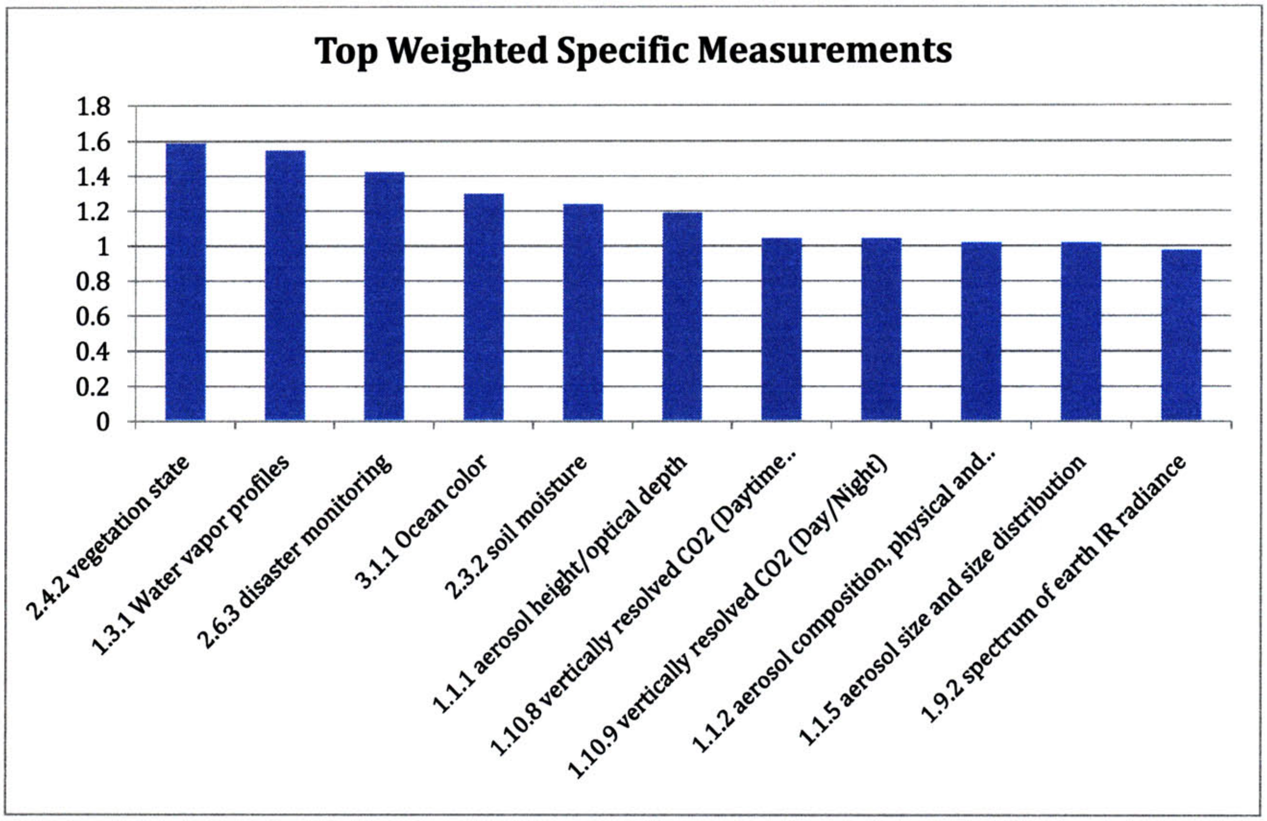


Figure 24. Top Eleven Weighted Measurements

Decomposing the first measurement reveals why it is the most valuable. The "Vegetation State" measurement contributes to the satisfaction of four objectives:

1. Ecosystem Function (#1 objective)
2. Ecosystem Structure and Biomass (#2 objective)
3. Heat Stress and Drought (#24T objective)
4. Vector-borne and Zoontic Disease (#24T objective)

The value of this measurement is logically traceable to the value of these objectives: Measuring vegetative state contributes to satisfying ecosystem function and ecosystem structure objectives.

The weighting of specific measurements can be summed to find the weightings of the 28 measurement categories (Figure 25). In this view the prevalence of certain types of measurements is much clearer. Aerosol properties are the dominant category: they are required by nine of the 37 objectives. This plot also reveals the CEOS categories that are not relevant to the Decadal Survey: Albedo and reflectance, Ocean Salinity, and Ocean Wave height and spectrum.

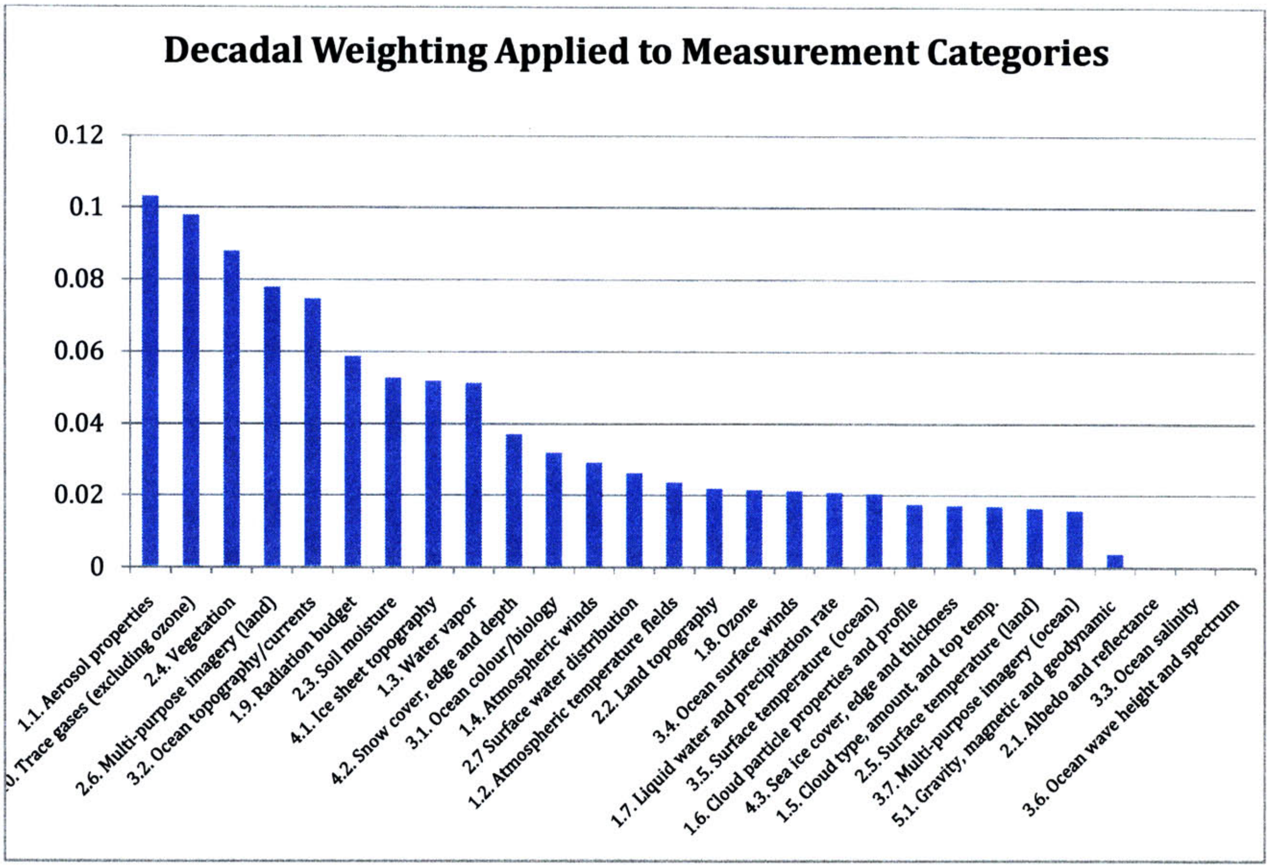


Figure 25. Weighted Measurement Categories

Finally, the weighted measurements can be reassembled into their respective science fields (Figure 26). This plot reveals an almost linear relationship amongst the science areas: atmospheric science is extremely important, whereas gravity and magnetic field has almost no value.

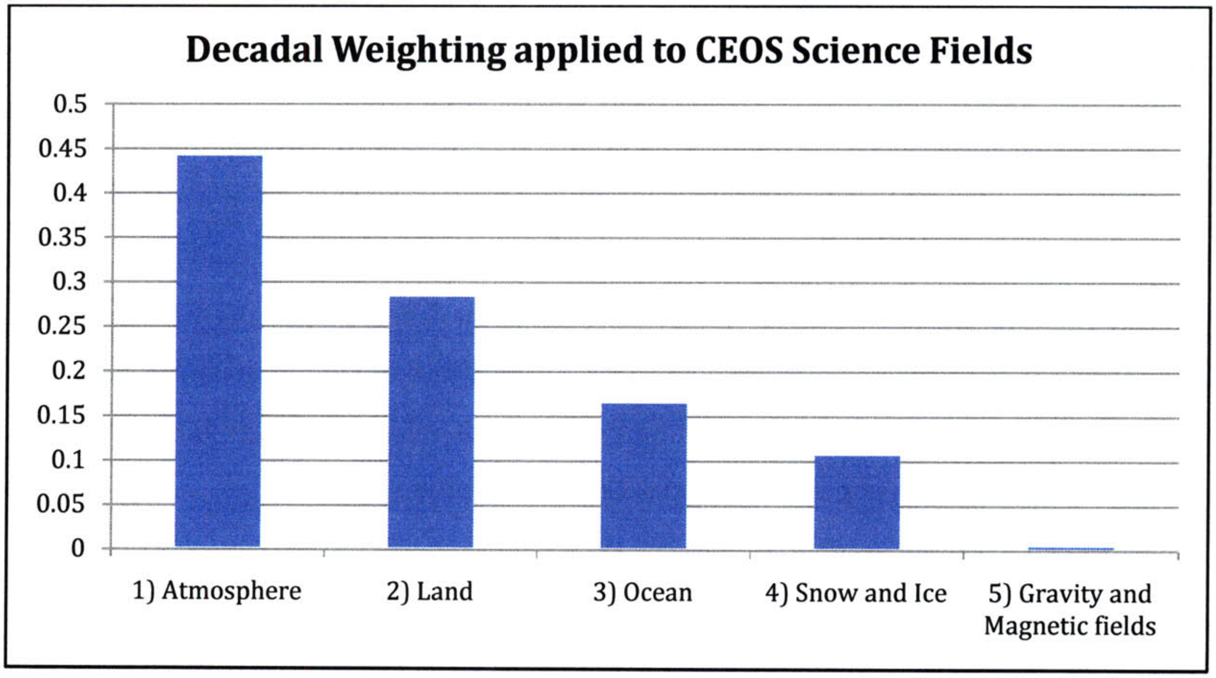


Figure 26. Weighted Science Fields

The reason for this vast discrepancy lies in the urgency of stakeholder needs. Applications for human beings tend to strongly focus on immediate concerns: this plot can almost be redrawn as "urgency" versus "benefit". This pattern is a well-know effect of earth science, as indicated in this NASA plot from 1989:

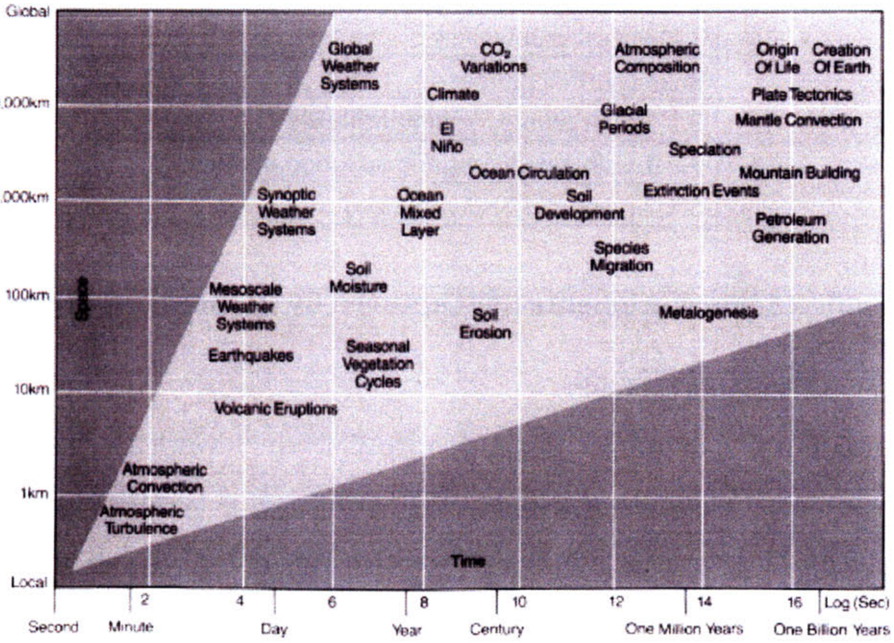


Figure 27. Earth Science Timescale (NASA, 1989)

A badly polluted day affects a person much sooner than subtle shifts in the geo-magnetic field. The air people breathe, the spread of diseases, the hole in the ozone layer, and the weather forecast are all highly dependent on atmospheric science and are all short-term, daily responses. Land concerns, such as forest growth, tend to on more of a seasonal cycle. Ocean applications of science, such as the conditions of fisheries, tend to have annual or decadal cycles. Snow and Ice considerations are annual, decadal, and centurial, particularly the advance and decline of glaciers. Gravity and magnetic issues only apply on millennial basis. This value-based traceability to science fields strongly indicates the relationship between response times and stakeholder value.

Similarly, the traceability of science value to instruments can be used to inform campaign design. The weighting of instruments described in 3.1.4 can be used to determine both the measurements and objectives not actually captured in the Decadal campaign.

1.8.1 stratospheric ozone
1.8.2 tropospheric ozone
1.8.3 ozone precursors
2.7.3 groundwater storage
3.2.1 surface circulation
3.2.2 seafloor topography
3.2.3 coastal upwelling
3.2.4 thermal plumes
3.2.5 river plumes/sediment fluxes
3.7.1 visible hydrospheric pollution plumes
5.1.2 magnetic field variations

Table 11. Measurements not Captured by Decadal Instruments

Many of the measurements seen in Table 11 are attributable to either GEOCAPE or GACM, which were ascertained to have insufficient mappings. However, tracing these measurements back to objectives reveals that no Decadal mission actually fulfills the "Ocean Bathymetry" objective, which depends only on ocean surface circulation and seafloor topography for satisfaction. In the Decadal Survey this objective is associated with the SWOT mission.

Because of this disconnect between the value of objectives and the ability of Decadal missions to capture this value, the Decadal campaign will not accrue 100% of the value in the system. Since no Decadal mission individually can capture the relevant measurements (assuming no synergies), campaign architecting with the Decadal set of instruments will only accrue up to 96.9% of the available benefit. This effect is seen extensively in Chapters 4 and 5, which discuss the accrual of benefit over time.

The Decadal CSTM also enables a cost-benefit analysis. The mission-objective satisfaction calculations used to produce Figure 23 can also express the value of each mission. In Figure 28, the benefit of each mission, expressed as a fraction of the total benefit in the campaign, is plotted against the cost of each mission, as listed in the Decadal Survey. It is desirable to fly missions that contribute high amounts of benefit but are relatively inexpensive: hence the utopia point on this plot is the upper-left corner. This analysis suggests that the best value missions lie along the line roughly drawn between ACE and GPSRO, including SMAP, HyspIRI, ICESat-II, CLARREO, LIST, PATH, GEO-CAPE, and DESDynI. This also suggests that, given budgetary constraints, mission like GRACE-II, GACM, XOVWM, ASCENDS, SCLP, 3D-Winds, and SWOT should be removed from the campaign.

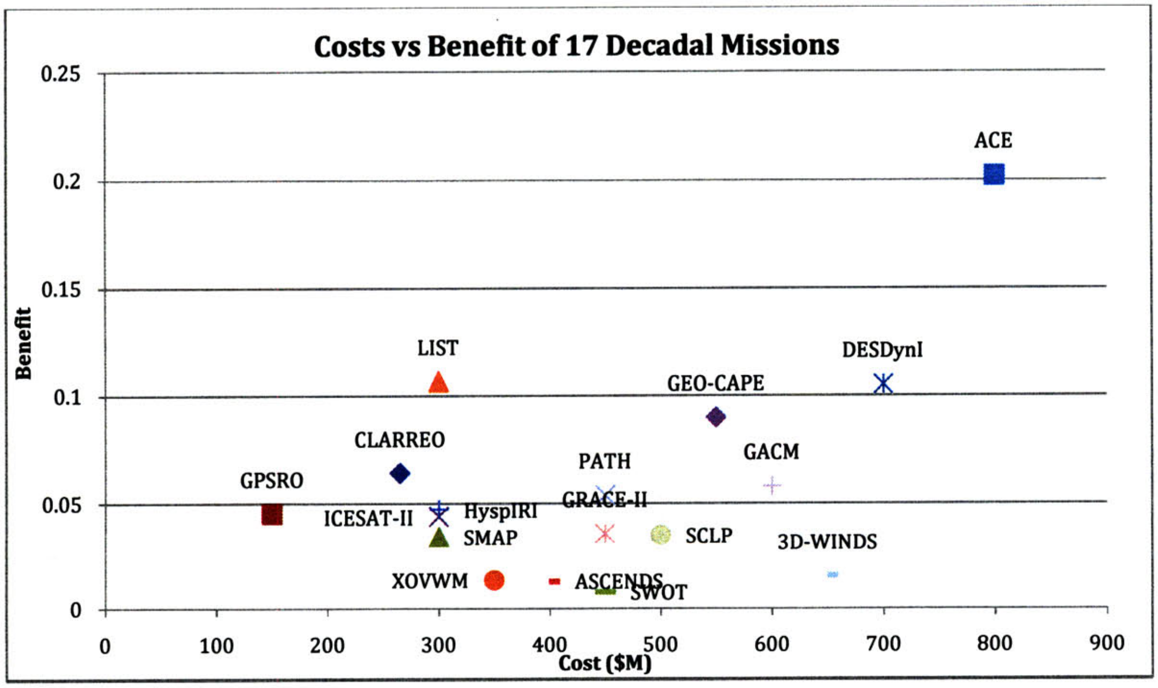


Figure 28. Cost-Benefit Plot for the Decadal Missions

Another useful visualization of the mission-objective satisfaction matrix is to present the individual panel's contribution to the value of each mission (Figure 29). While essentially conveying the same information as Figure 28, this plot displays the traceability of value to different panels. ACE is by far the most beneficial mission: it satisfies all six panels to at least some degree (the only mission to do so), and makes significant contributions to the Weather, Climate, and Land-Use and Ecosystems panels. This makes sense with regards to the Decadal Survey plan: ACE is the most expensive mission and has several instruments on-board, the most prevalent being dedicated to Aerosols and Aerosol-Cloud interactions. This also fits with the measurement valuations in Figure 26, which indicated the prevalence of atmospheric science in conveying value. Conversely, the least valuable mission, SWOT, only satisfies the Solid Earth and Water panels, and not particularly effectively.

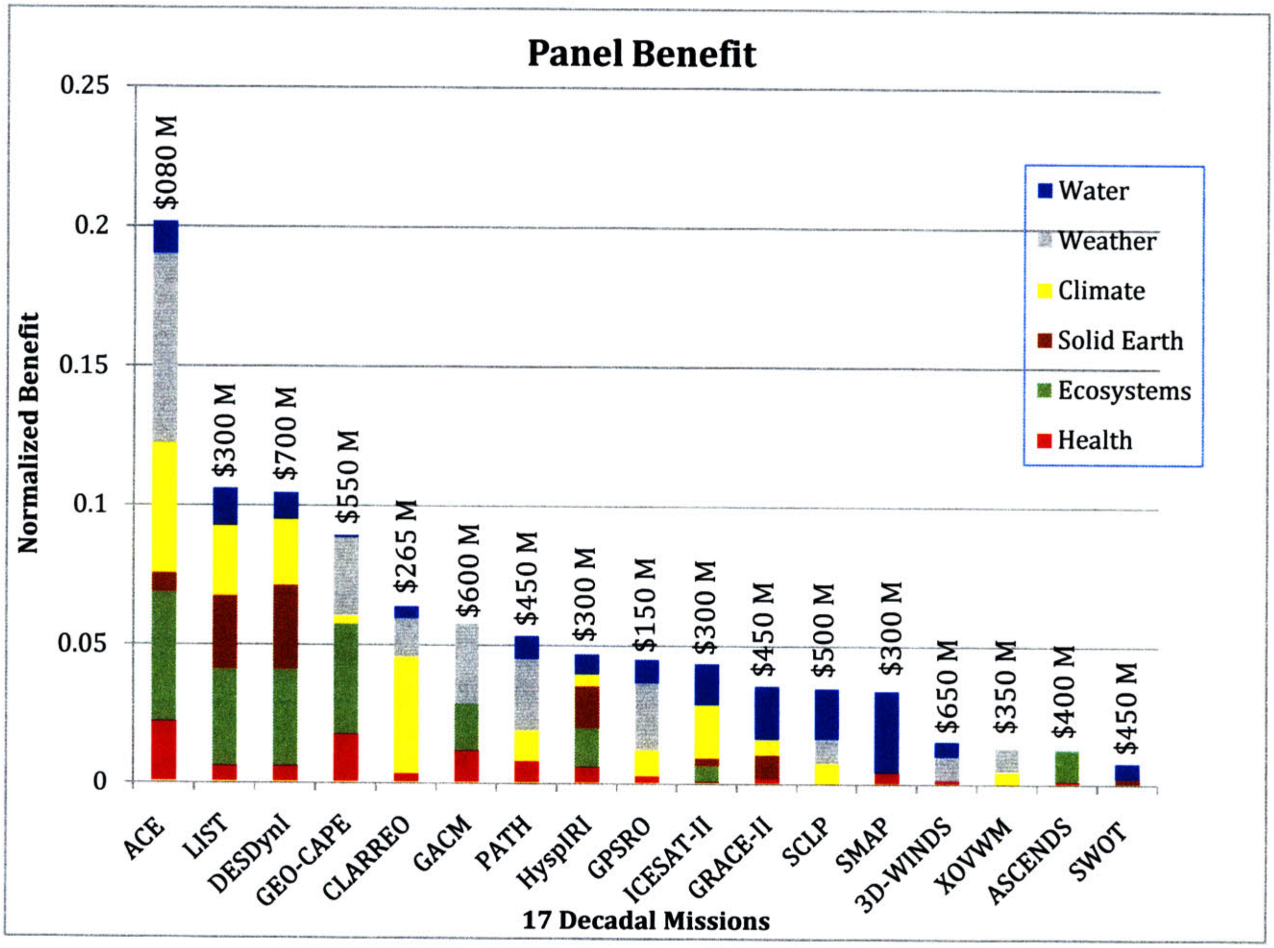


Figure 29. Benefit accrued by Panels in 17 Original Decadal Missions

It is also interesting to note the number of mission for which a panel accrues benefit (Table 12). One would expect the Human Health and Security panel to gain from the most number of missions: it did not recommend a dedicated mission because it sought to benefit from the other panels' data. However, it only accrues benefit in 12 of the 17 missions, whereas the Water panel gains from 14.

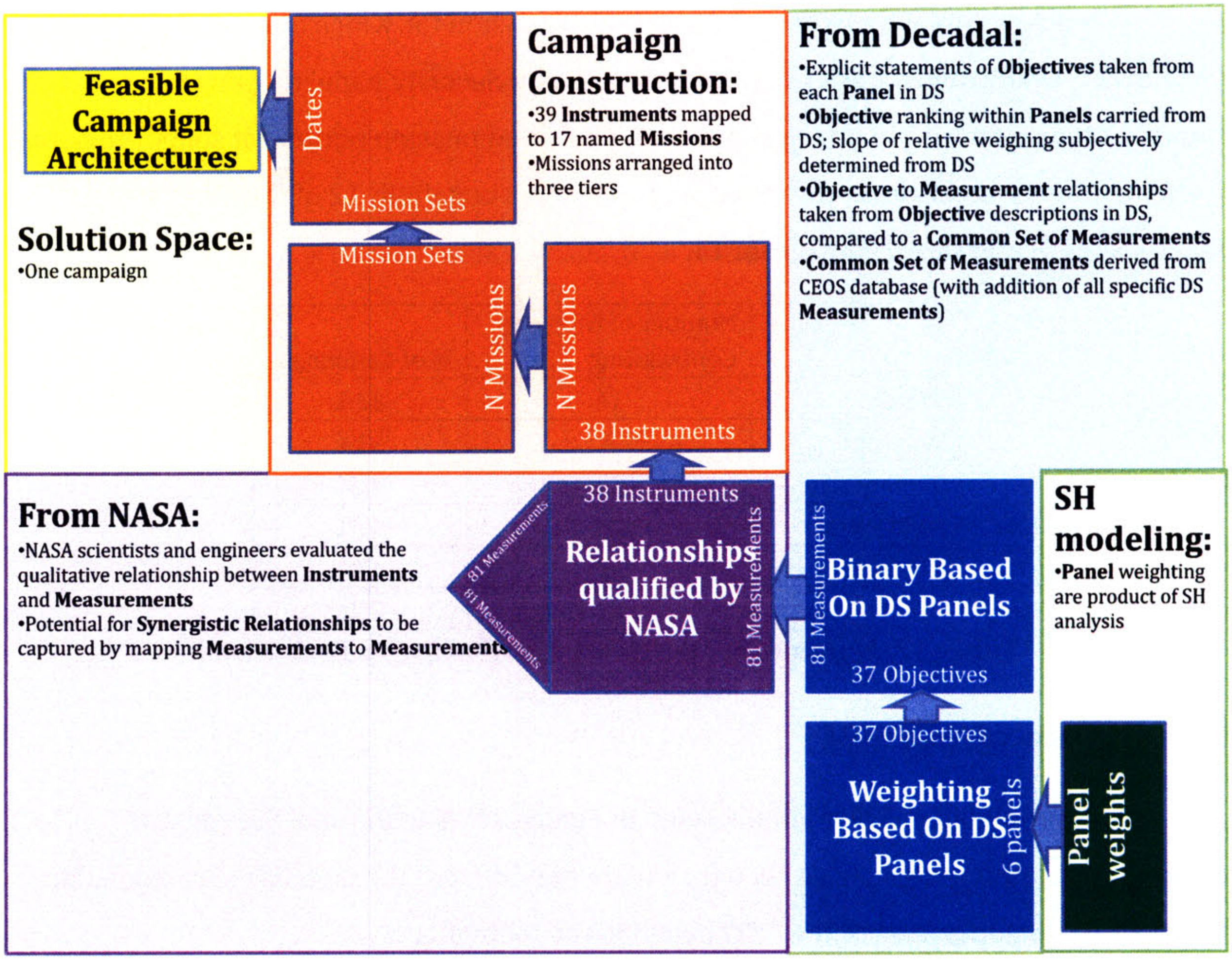
	Number of Missions Contributing	% of Campaign
Water	14	82%
Weather	9	53%
Climate	12	71%
Solid Earth	7	41%
Land-use	8	47%
Human Health	12	71%

Table 12. Number of Missions Contributing to Each Panel

3.4 Review of the CSTM

The populated CSTM is summarized in Figure 30. The Decadal Survey was decomposed to campaign elements which were then related through CSTM relationship matrices. The population of the CSTM yielded the following:

- Sutherland's stakeholder priorities were used to weight prioritized panel objectives.
- A common set of measurements was derived to qualitatively relate objective satisfaction to the instruments and missions in the Decadal Survey.
- The CSTM mapping of missions to objectives was compared to the Decadal survey mapping.
- The traceability of science value to measurements was analyzed to reveal the science field value to stakeholders.
- Value was traced to instruments and missions, enabling a cost-benefit analysis of the Decadal Survey Missions.



Campaign Construction:

- **39 Instruments** mapped to 17 named **Missions**
- Missions arranged into three tiers

Solution Space:

- One campaign

From Decadal:

- Explicit statements of **Objectives** taken from each **Panel** in DS
- **Objective** ranking within **Panels** carried from DS; slope of relative weighing subjectively determined from DS
- **Objective** to **Measurement** relationships taken from **Objective** descriptions in DS, compared to a **Common Set of Measurements**
- **Common Set of Measurements** derived from CEOS database (with addition of all specific DS **Measurements**)

From NASA:

- NASA scientists and engineers evaluated the qualitative relationship between **Instruments** and **Measurements**
- Potential for **Synergistic Relationships** to be captured by mapping **Measurements** to **Measurements**

SH modeling:

- **Panel** weighting are product of SH analysis

Figure 30. Decadal Survey CSTM

The CSTM reveals a great deal of information about the benefits associated with each Decadal mission. At this point only a static view of the campaign value has been presented. An analysis of constraints and value functions, as they apply to time-dependent campaign design, will be presented in Chapter 4.

4 Campaign Design Using the CSTM

The campaign design methodology described in this chapter enables an automated exploration of a large design space and the rapid rearchitecting of a campaign given changing assumptions, as described in Chapter 5. Although the instruments included in the Decadal Survey were the result of a rigorous selection process, the assignment of instruments to missions and the assignment of missions to dates were conducted as round-table discussions amongst panelists, rather than being approached as an optimizable problem. This chapter reviews the guidance provided by the Decadal Survey with regards to campaign design. It examines the constraints that limit these assignment processes. It provides a set of metrics for evaluating alternate campaign conceptions. Finally, it presents an algorithm for the assignment of missions to dates. Chapter 5 will discuss the application of these constraints, value-functions, and algorithm to campaign design outside of the Decadal Survey assumptions. The objectives of this chapter are:

Objectives of Campaign Design Using the CSTM

- *To replicate the decision logic of the Decadal Survey by implementing constraint and value functions using algorithm experimentation*
- *To validate the methods and model introduced in this thesis by comparing results using the Decadal Survey as "truth"*

Many of the constraints and value functions discussed in this chapter were originally proposed in Colson's Master's thesis (Colson, 2008). This chapter presents a refinement of many of these ideas, in addition to their application to the CSTM. This chapter is organized into the following sections:

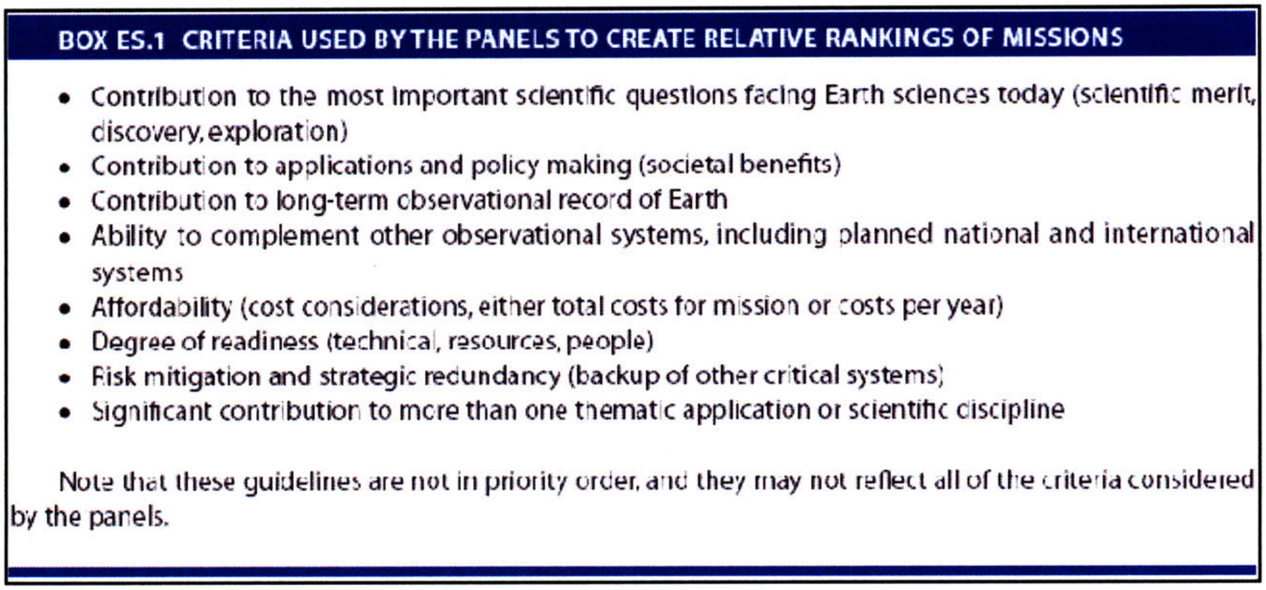
- Section 4.1: Campaign Constraints. This section discusses the classes of constraints that apply to campaign design.
- Section 4.2: Campaign Value Functions. This section describes the rationale and calculation of campaign value-functions.
- Section 4.3: Scheduling Algorithms. This section discusses the development of an algorithm for the automated campaign scheduling.
- Section 4.4: Summary

4.1 Campaign Constraints

Rearchitecting of the Decadal campaign requires manipulating the relationships between the higher order campaign elements—those represented in the orange "campaign construction" block of the CSTM (Figure 30 in Section 3.4). These relationships are limited by different classes of constraints applied on different levels. This section describes the Decadal Survey guidance regarding design constraints. Then, Colson's constraints are modified to apply to the CSTM. Finally, other classes of constraints are considered. This section concludes with a discussion of feasibility and a summary of the application of these constraints.

4.1.1 Constraint Guidance from the Decadal Survey

The Decadal Survey outlines the decision processes utilized by the panels to prioritize mission concepts (Figure 31). Although each panel underwent a unique process to arrive at their final set of proposed mission concepts, these guidelines can inform the application of constraints.



BOX ES.1 CRITERIA USED BY THE PANELS TO CREATE RELATIVE RANKINGS OF MISSIONS

- Contribution to the most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration)
- Contribution to applications and policy making (societal benefits)
- Contribution to long-term observational record of Earth
- Ability to complement other observational systems, including planned national and international systems
- Affordability (cost considerations, either total costs for mission or costs per year)
- Degree of readiness (technical, resources, people)
- Risk mitigation and strategic redundancy (backup of other critical systems)
- Significant contribution to more than one thematic application or scientific discipline

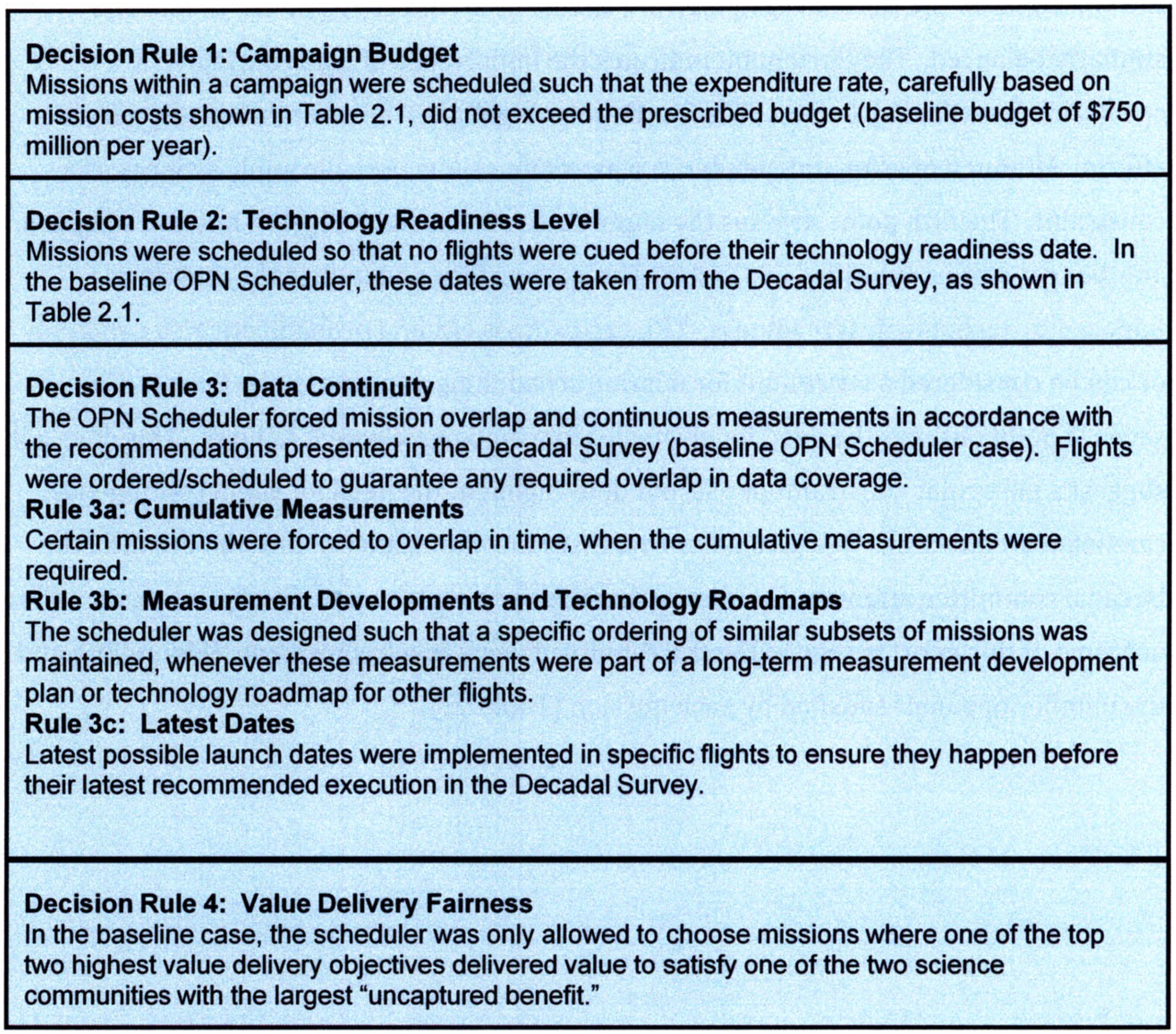
Note that these guidelines are not in priority order, and they may not reflect all of the criteria considered by the panels.

Figure 31. Mission Prioritization Guidance (National Research Council, 2007)

Each of these eight criterion reflect possible constraints. The first two points highlight the balancing act between discovery and application bias of research missions that the Decadal Survey underwent. Missions must address societal applications or research potential future applications by answering important science questions. Although the CSTM assumes a uniform level of mission specificity (as described in 2.1.4) if the objectives of the Decadal campaign are also to be architected, objectives must be similarly balanced. The third point indicates the importance of data continuity, a constraint identified by Colson. The fourth point highlights the desirability of synergistic effects. Although mission independence was assumed, it is possible apply synergy as a constraint. The fifth point stresses the importance of cost and budget in mission selection, another constraint identified by Colson. The sixth criterion identifies the limitations imposed by technological readiness. TRL can express either a probabilistic risk valuation or can be considered a strict limit for mission scheduling, as proposed by Colson. The seventh point outlines the need for strategies for campaign element failures. This does not suggest a particular constraint per se, but does highlight the need for rapid contingency campaign architecting. The final point expresses the importance of mission breadth; the Decadal committee attempted to ensure that missions represented diverse interests. The outcome of this effort is seen in the traceability of value to measurements (Figure 26), and the number of panels satisfied by each mission (Table 12).

4.1.2 Colson's Constraints Applied to the Decadal Survey CSTM

Colson adopted four of the eight criteria outlined by the Decadal Survey for mission prioritization (Figure 32). The following sections outline how they are applied to the CSTM. Although the specific implementations do differ, the concepts are reflective of the Decadal decision logic.



Decision Rule 1: Campaign Budget
Missions within a campaign were scheduled such that the expenditure rate, carefully based on mission costs shown in Table 2.1, did not exceed the prescribed budget (baseline budget of $750 million per year).

Decision Rule 2: Technology Readiness Level
Missions were scheduled so that no flights were cued before their technology readiness date. In the baseline OPN Scheduler, these dates were taken from the Decadal Survey, as shown in Table 2.1.

Decision Rule 3: Data Continuity
The OPN Scheduler forced mission overlap and continuous measurements in accordance with the recommendations presented in the Decadal Survey (baseline OPN Scheduler case). Flights were ordered/scheduled to guarantee any required overlap in data coverage.

Rule 3a: Cumulative Measurements
Certain missions were forced to overlap in time, when the cumulative measurements were required.

Rule 3b: Measurement Developments and Technology Roadmaps
The scheduler was designed such that a specific ordering of similar subsets of missions was maintained, whenever these measurements were part of a long-term measurement development plan or technology roadmap for other flights.

Rule 3c: Latest Dates
Latest possible launch dates were implemented in specific flights to ensure they happen before their latest recommended execution in the Decadal Survey.

Decision Rule 4: Value Delivery Fairness
In the baseline case, the scheduler was only allowed to choose missions where one of the top two highest value delivery objectives delivered value to satisfy one of the two science communities with the largest "uncaptured benefit."

Figure 32. Colson's Four Constraints (Colson, 2008)

4.1.2.1 Mission Costs and Annual Budget

The first constraint Colson imposed on campaign design is an annual spending limit which a campaign expenditure rate cannot exceed. This limitation constrained the frequency of mission launch. No translation was necessary to apply this to the CSTM; however, Colson's rationale will be explained.

NASA's budget for earth science and the Decadal Survey campaign is limited in size and scope. While funding may sporadically appear over the course of a year, the general trend reflects a relatively stable program budget (Figure 4). It is assumed that the budget will remain at a constant level for the duration of a campaign and that the annual funding profile will average out linearly.

It is also assumed that every mission will accrue costs over time according to a predictable distribution (Larson & Wertz, 1999 p 804). A standard distribution, for example, can represent the spending profile of a mission over time: during early studies little money is actually spent; as the design matures staffing increases and hardware is purchased; as the assembly begins the design staff moves on to other projects, and begins to decline; after launch, only a small operations cost remains.

The cumulative spending profile of multiple missions over time represents campaign spending (Figure 33). Because a campaign is limited to a linear annual budget (or spending limit), the most efficient scheduling will overlap mission spending distributions such that the combined mission spending is closest to this limit. Although each mission individually has a normal spending distribution, the campaign can be expressed as a sequence of step functions, with only one mission being developed at a time (Figure 34).

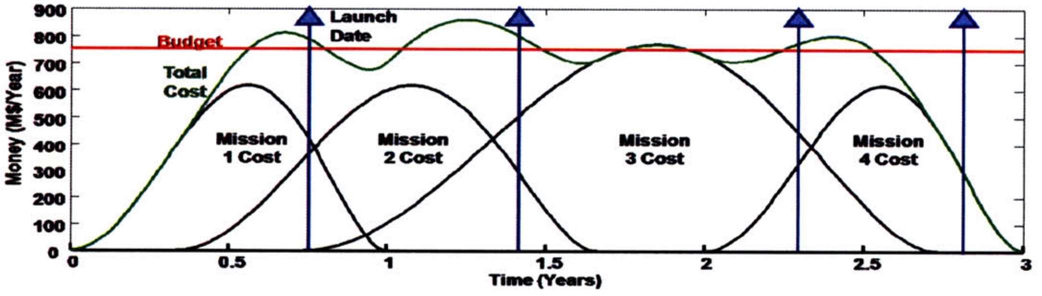


Figure 33. Campaign Spending with Standard Distributions (Colson, 2008)

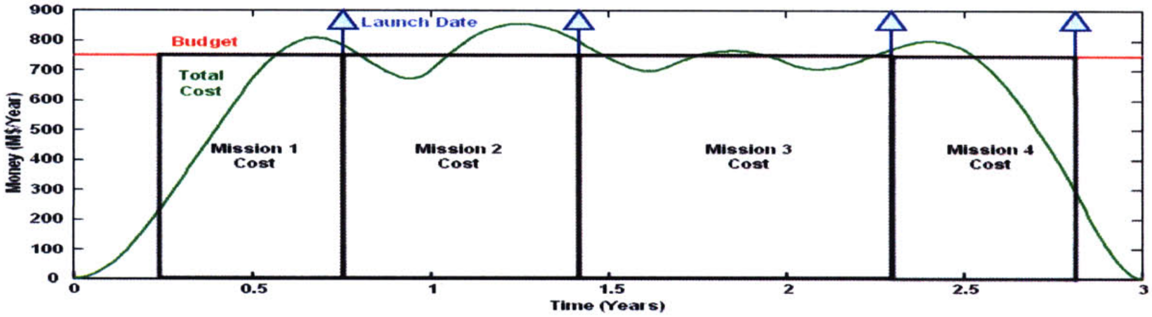


Figure 34. Campaign Spending with Step Distribution (Colson, 2008)

Using the assumption of annual budget linearity and the assumption of step-function mission costing enables the conversion of costs to time (Equation 11). A sequence of missions can be scheduled at a rate where time between mission launches is a function of annual budget and mission costs.

$$t = \frac{Mission\ Cost\ (\$M)}{Annual\ Budget\ \left(\frac{\$M}{year}\right)}$$

Where t is time elapsed between mission launch dates

Equation 11. Time as a Function of Budget

The budget constraint dictates that annual spending cannot exceed the annual budget. This constraint applies to the mission level of the CSTM; although cost is driven by instruments, is a primary attribute of missions.

Mission Cost and Annual Budget Constraint:

- *Annual spending cannot exceed the annual budget*

4.1.2.2 Technology Readiness Level

The second constraint Colson applied to campaign design is a Technology Readiness Level (TRL) date. Missions cannot be flown before the instrument onboard have actually been developed and tested. Colson assumed that the launch dates attributed to missions in the Decadal Survey were representative of the earliest dates a mission would be technologically ready.

This constraint is implemented on the instrument level of the CSTM rather than the mission level. Although for some missions engineering challenges delay the expected readiness date (such as SMAP which requires a rotating 6m antenna), it is assumed that this limitation is a quality of instruments. Additionally, it is assumed that the TRL date of a mission is equal to the latest TRL of the instruments onboard.

Technology Readiness Level Constraint:

- *Missions cannot be flown before the instruments on-board have all reached technological maturity*

4.1.2.3 Data Continuity

The third constraint Colson applied to campaign design is a need for data continuity. However, for the CSTM it was determined that making data continuity a constraint was unfeasible. This section describes the rationale for making data continuity a value function.

Colson include three sub-definitions of the data continuity constraint: missions with known synergies must be in-orbit during each other's lifetimes, missions that contained early versions of later tier instruments must fly before their later tier counterparts, and missions replacing current assets must be in-orbit before those assets reach end-of–life. For Colson's simulation these were easily enforceable limitations, as they only affected a small number of missions.

While the Decadal Survey expressed contributions to long-term observational records as an important factor in decision making, it did not have a systematic view for considering measurements over time. As part of NASA's emphasis on climate science, a list of 28 Essential Climate Variables has been developed by NASA Goddard, and corresponding mission-measurement profiles have been assembled (NASA, 2009). There is, however, no distinction made as to the relative importance of one measurement over another. These ECV's were translated to the common set of measurements to highlight 34 measurements desiring data continuity (Table 13).

34 Measurements needing continuity

- 1.1.1 aerosol height/optical depth
- 1.1.2 aerosol composition, physical and chemical properties
- 1.1.3 aerosol scattering properties
- 1.1.4 aerosol extinction profiles
- 1.1.5 aerosol size and size distribution
- 1.2.1 Atmospheric temperature fields
- 1.3.1 Water vapor profiles
- 1.5.1 cloud top temperature
- 1.5.2 Cloud type
- 1.5.3 Cloud amount/distribution
- 1.6.1 cloud height/optical thickness
- 1.6.2 cloud particle size distribution
- 1.7.1 Precipitation rate
- 1.8.1 stratospheric ozone
- 1.8.2 tropospheric ozone
- 1.9.2 spectrum of earth IR radiance
- 1.10.4 Benchmark tracer data (CO2, CO, HDO/H2O, NOy, N2O, CH4, halogen source molecules)
- 1.10.11 C02 concentrations
- 2.1.1 Albedo and reflectance
- 2.3.2 soil moisture
- 2.4.2 vegetation state
- 2.4.4 canopy density
- 2.6.2 landcover status
- 2.7.1 river and lake elevation
- 3.1.1 Ocean color
- 3.2.1 surface circulation
- 3.3.1 Ocean salinity
- 3.4.1 Ocean surface wind speed
- 3.4.2 Ocean surface wind direction
- 3.5.1 Surface temperature (ocean)
- 4.1.1 ice sheet volume
- 4.1.2 Glacier surface elevation
- 4.2.4 snow cover
- 4.3.1 Sea ice thickness

Table 13. Measurements Desiring Data Continuity

While continuity of measurements and instrument overlap is desirable, the CSTM does not treat it as a constraint. The Decadal Survey made note of continuity considerations, but did not require them. Instead, for the CSTM the number of breaks in continuous measurement is evaluated for each campaign architecture as a secondary value function.

Data Continuity Value-Function:

- *Assuming a notional average mission life, count the number of breaks incontinuous coverage of34 key measurements.*

4.1.2.4 Fairness

The final constraint Colson applied to campaign design is a conception of fairness. Although the objectives in the Decadal campaign represented the interests of a diverse science community, Colson believed it was necessary to constrain the scheduling of missions in a manner that distributed the accrual of benefit over time to different science panels. Colson evaluated fairness with respect to either of the two least satisfied panels.

The CSTM assumes that the Decadal Survey has already allocated all of the possible mission value in the system. Hence, fairness is a constraint that affects the ordering of missions based upon the amount of uncaptured benefit in the system. The traceability of value in the CSTM presented several opportunities for an algorithmic fairness routine. Experimentation, as will be described in 4.3.3.2, reveal an "impartial" definition of fairness, applied on the panel level, to most accurately reproduce the Decadal Survey decision logic.

The fairness constraint requires an equal weighing of all panels, although the satisfaction of those panels is still subject to the other CSTM relationship weightings. Fairness requires minimizing the deviation between the benefit accrued over time by different panels (Figure 35)

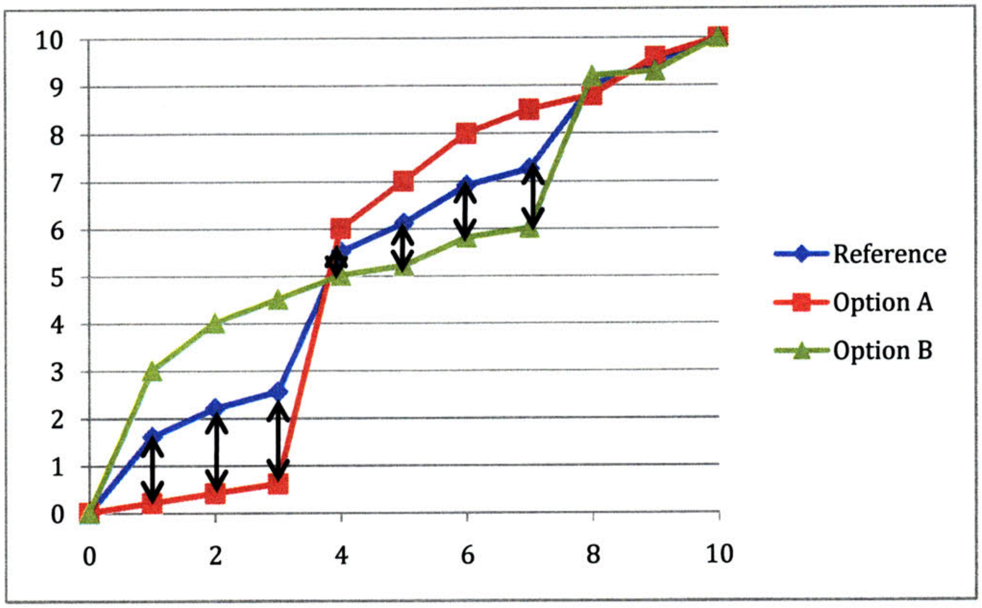


Figure 35. Fairness Implementation

In this example the deviation of the least satisfied option from some notional reference is marked in black. The application of the fairness constraint requires the next mission selected to attempt to close the gap in some way.

Fairness Constraint:

- *Minimize the deviation of the relative benefit accrued by each panel over time*

4.1.3 Other Constraints

Another constrain implemented in the CSTM is the concept of mission scope. Missions should not be assembled with an unreasonably large number of instruments. The Decadal Survey recommended a balance between mission sizes. Although they categorized by mission cost, their campaign of 17 missions included a blend of single and multiple instrument missions (Table 10). Campaign design with the CSTM should limit the assignment of instruments to missions.

Scope Constraint

- *Limit number of instruments per mission*

Additionally, because the Decadal Survey is a research campaign, the constraint that each mission can be flown only once is added. In reality, as the Decadal mission demonstrate their utility in providing applications they will be operationalized, and flying multiple copies of the same mission will be considered.

Operationalizing Constraint

- *Each mission can only be scheduled once*

4.1.4 Summary of Constraints

The Decadal Survey implicitly recommends a set of campaign design constraints. Colson codified these into four classes: cost, TRL, data continuity, and fairness. Constraints of scope and operationalizing were added based upon Decadal Survey recommendations. The implementation of these constraints in the CSTM is summarized in the following figure:

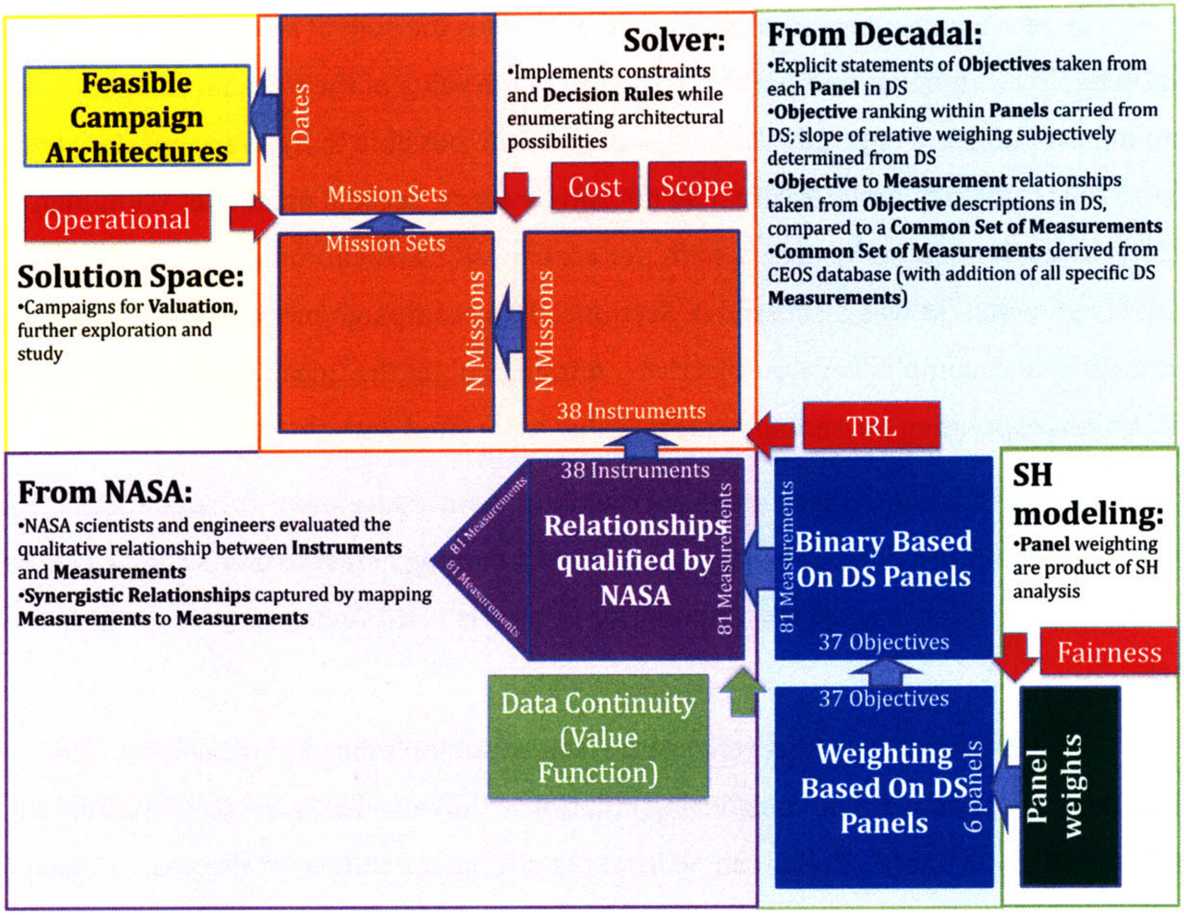


Figure 36. Constrained CSTM

Campaign design relies upon recreating the mappings in the "Solver" block of Figure 36. Constraints are applied to the CSTM to ensure architectural feasibility of campaign design. Value functions, such as data continuity, are used to compare viable campaign architectures against each other. Section 4.2 introduces the primary value functions used to evaluate CSTM campaigns.

4.2 Valuing a Campaign

While constraints are used to limit campaign design options to feasible solutions, value functions are used to compare designs. Colson assumed a single value function, time discounting, for campaign architecture differentiation. In addition to his method and the data continuity function discussed in Section 4.1.2.3, two other metrics are applicable to the CSTM: the percentage of total value accrued in the system and the synergistic benefits of scheduling.

The percentage of total value accrued expresses the sum of all objective satisfaction completed in a campaign relative to the total possible value of the Decadal campaign. If a campaign is budget or time constrained, it may not be possible to fly every mission; hence, a particular campaign architecture may not satisfy every Decadal objective. Campaign architectures dominated by high benefit per cost missions will accomplish more given these constraints. As was discussed in Section 3.3, the campaign proposed in the Decadal Survey fails to accomplish every objective—missing out on the Ocean Bathymetry objective and the corresponding percentage of total value associated with that objective.

Second, if the synergistic effects of overlapping measurements are quantified, the additional benefit provided through concurrent scheduling of instruments can be captured. This metric, like quantifying measurement synergies, is identified as an area for future work.

Colson's time discounting reflects the concept of the time value of money. The principle states that, without considering inflation, a dollar today is worth more than a dollar in a year, as today's dollar can be invested and earn a return for the year. Colson applied the principle of net present value to the accrual of benefit over time through the use of value discounting (Equation 12). The value in the future at time t is equal to the starting value modified by the discount rate.

$$Value(t) = \frac{Value(t_0)}{(1+R_d)^t}$$

Equation 12. Present Value Discounting

Every permutation in the campaign solution space will have a unique arrangement of instruments and missions. It is assumed that benefit is accrued at the time of mission launch; hence the value delivered by each instrument can be discounted by when that instrument launches. Colson assumed the following discount rates for the objectives of different panels:

Science Panel	Depreciation Rate (%)
Climate	15
Water Resources	10
Health and Human Security	10
Weather	10
Ecosystems	10
Solid Earth	5

Table 14. Panel Discount Rates (Colson, 2008)

A discount rate of 10% is a standard assumption for analysis, and was consequently assigned to the benefit of most science panels (Larson & Wertz, 1999, p 807). Climate was given a higher discount rate, reflective of the apparent urgency of understanding anthropomorphic climate change. Solid Earth objectives were given a lower rate, reflective of the priorities seen in Section 3.3.

Colson assumed that every campaign architecture will include all 17 original Decadal missions—discounted benefit was his only metric to separate mission sequences. With the CSTM, it is necessary to consider architectures where different instruments are never flown. Hence, the use of Colson's metric is applied on top of the percentage of Decadal value accrued.

Campaign architecting with the CSTM relies upon Colson's discounted value metric as applied of the percentage of total value accrued. Data continuity is calculated, but serves as a secondary consideration. Quantifying synergistic effects for use as a value-function is an area for future work.

Value Functions

- *Primary: The present value of a mission is calculated by discounting the weighted satisfaction of that mission with respect to the different panels. The discounted value of every mission in a campaign is summed and expressed as a percentage of total possible value.*
- *Secondary: The number of Data-continuity gaps is counted as a secondary metric*
- *Tertiary: Studying synergistic effects is identified as a possible metric requiring future work*

4.3 An Algorithm for Replicating the Decadal Survey Decision Logic

The previous two sections discussed the constraints and value functions applicable to campaign architecting with the CSTM. This section discusses the application of the Decadal Survey decision logic to an algorithm for campaign scheduling. First, the guidance provided by the Decadal Survey is analyzed. Then, a reference schedule is defined. Third, the development and structure of an enhanced algorithm is discussed. This section concludes with a summary.

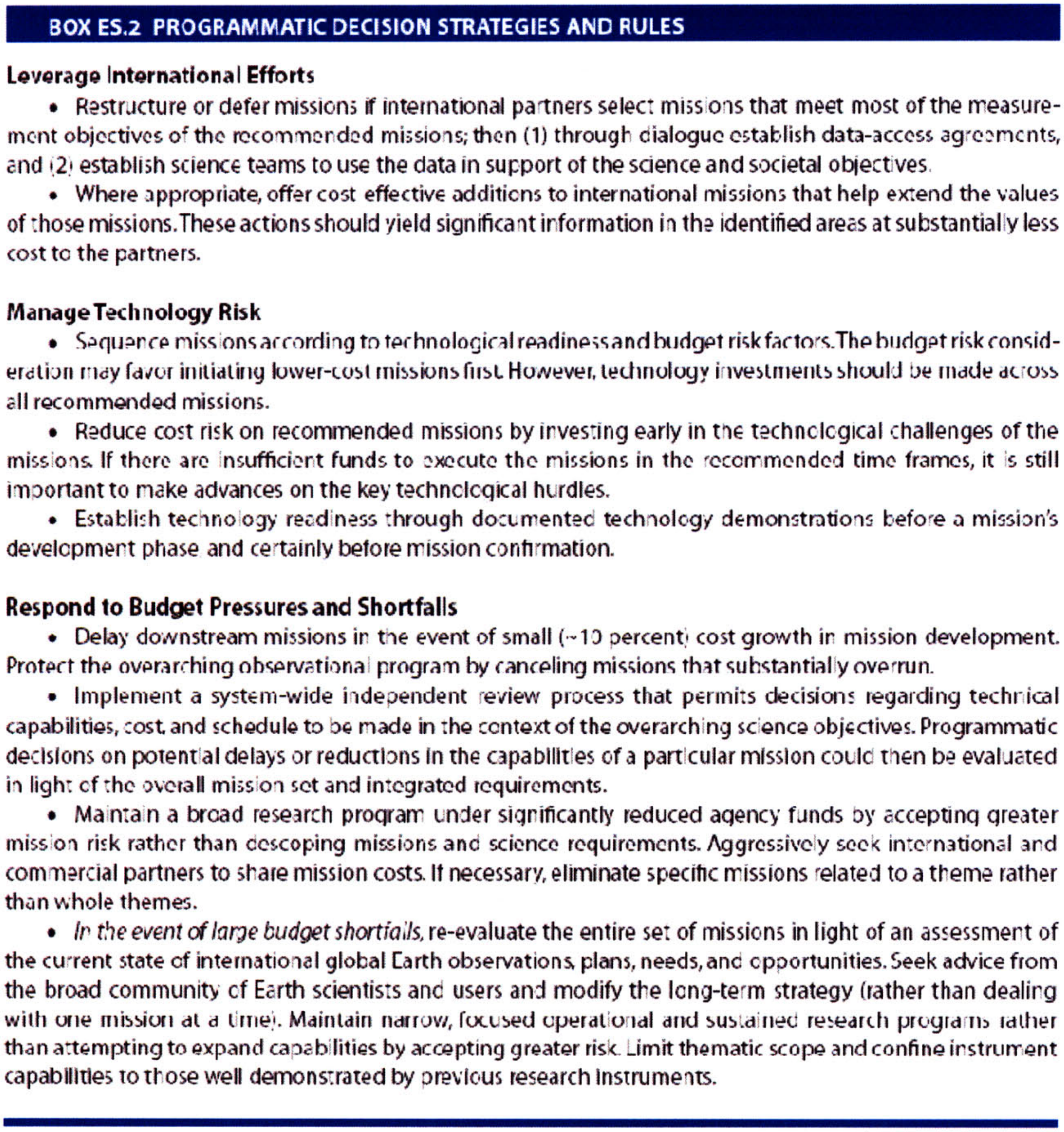
4.3.1 Algorithm Guidance from the Decadal Survey

The Decadal Survey enumerated a set of programmatic decision strategies and rules that can be used to inform campaign development (Figure 37). This list includes three primary principles: leverage international efforts, manage technology risk, and respond to budget pressures and shortfalls.

The rationale for these principles is summarized:

1. Leverage international efforts: earth science, by definition, applies to a greater community than the United States. The benefits of an earth science campaign are not exclusive, and the costs do not need to be. Taking advantage of other space program's missions will help ensure a robust campaign.
2. Manage technology risk: technological development can be a huge risk, not only in increases to the costs of a particular mission, but in the progression of an entire campaign. A campaign can avoid technology issues by enacting individual mission development campaigns.
3. Respond to budget pressures and shortfalls: cost and budget concerns affect the entire campaign, and changes need to be evaluated with respect to the whole program. Large cost overruns on one mission can put the remainder of campaign at risk. However, if a mission is at risk of being cancelled, it is best to degrade its performance parameters, and therefore cost, as much as possible to keep the mission in the campaign. Even if a particular mission is cancelled, the objectives it would have satisfied should not be ignored.

Included in this list is the specific recommendation that a campaign should "sequence missions according to technological readiness and budget-risk factors" (Figure 37). The Decadal Survey acknowledges that this principle biases a campaign schedule towards a "cheaper first" approach. However, considering the factors that put campaign at risk, the Decadal determined that this was the best solution. This recommendation is the basis for any discussion into scheduling algorithms.



BOX ES.2 PROGRAMMATIC DECISION STRATEGIES AND RULES

Leverage International Efforts

- Restructure or defer missions if international partners select missions that meet most of the measurement objectives of the recommended missions; then (1) through dialogue establish data-access agreements, and (2) establish science teams to use the data in support of the science and societal objectives.
- Where appropriate, offer cost effective additions to international missions that help extend the values of those missions. These actions should yield significant information in the identified areas at substantially less cost to the partners.

Manage Technology Risk

- Sequence missions according to technological readiness and budget risk factors. The budget risk consideration may favor initiating lower-cost missions first. However, technology investments should be made across all recommended missions.
- Reduce cost risk on recommended missions by investing early in the technological challenges of the missions. If there are insufficient funds to execute the missions in the recommended time frames, it is still important to make advances on the key technological hurdles.
- Establish technology readiness through documented technology demonstrations before a mission's development phase and certainly before mission confirmation.

Respond to Budget Pressures and Shortfalls

- Delay downstream missions in the event of small (~10 percent) cost growth in mission development. Protect the overarching observational program by canceling missions that substantially overrun.
- Implement a system-wide independent review process that permits decisions regarding technical capabilities, cost, and schedule to be made in the context of the overarching science objectives. Programmatic decisions on potential delays or reductions in the capabilities of a particular mission could then be evaluated in light of the overall mission set and integrated requirements.
- Maintain a broad research program under significantly reduced agency funds by accepting greater mission risk rather than descoping missions and science requirements. Aggressively seek international and commercial partners to share mission costs. If necessary, eliminate specific missions related to a theme rather than whole themes.
- *In the event of large budget shortfalls,* re-evaluate the entire set of missions in light of an assessment of the current state of international global Earth observations, plans, needs, and opportunities. Seek advice from the broad community of Earth scientists and users and modify the long-term strategy (rather than dealing with one mission at a time). Maintain narrow, focused operational and sustained research programs rather than attempting to expand capabilities by accepting greater risk. Limit thematic scope and confine instrument capabilities to those well demonstrated by previous research instruments.

Figure 37. Programmatic Decision Guidance (National Research Council, 2007)

4.3.2 Establishing a Reference

An algorithm for campaign scheduling needs to be validated against a reference. The Decadal Survey proposes both a reference schedule and, as discussed in the previous section, a decision rule for scheduling. This section describes the establishment of a reference using these two sources in addition to some of the constraints discussed in section 4.1. Additionally, this section introduces the plotting of benefit over time as a tool for informing campaign development.

4.3.2.1 The Reference Schedule

The Decadal Survey stops short of recommending a specific timeline for the development and launch of its 17 missions. It does, however, imply a preferred order that has been arranged in accordance with its proposed algorithm (Appendix B: Reference Sequence). This sequence is referred to as the "Reference" case and is summarized in Table 15 below:

Decadal Survey Reference Case			
Tier	**Mission**	**Readiness Date**	**DS FY06 Cost (M$)**
Tier 1 2010-2013	CLARREO	2010	265
	GPSRO	2012	150
	SMAP	2012	300
	ICESat-II	2010	300
	DESDynI	2010	700
Tier 2 2013-2016	XOVWM	2013	350
	HyspIRI	2015	300
	ASCENDS	2013	400
	SWOT	2013	450
	GEO-CAPE	2015	550
	ACE	2015	800
Tier 3 2016-2020	LIST	2017	300
	PATH	2015	450
	GRACE-II	2016	450
	SCLP	2016	500
	GACM	2017	600
	3D-Winds	2016	650

Table 15. Reference Sequence

Each mission in the Decadal Survey was assigned a readiness date based upon a combination of fairness, TRL, and data continuity considerations. As these considerations are not explained, it is assumed this date is analogous to the TRL date metric utilized by Colson. Each mission is allocated to the tier which contains its readiness date, with the exception of PATH, which is confusingly attributed a date of "about 2010-2015" (National Research Council, 2007, p 125). This architecture thus reflects the decision rule recommendation to sequence missions first by technology readiness risk by putting missions into three TRL tiers.

The first tier includes the missions CLARREO, GPSRO, SMAP, ICESat-II, and DESDynI. Reflecting the second algorithmic decision principle, to prioritize missions by budget risk, these five missions are arranged by increasing cost, with the exception of GPSRO. This exception explainable by a data continuity consideration, as GPSRO is designed to replace the COSMIC mission (which is expected to last until 2012), also measuring occultation.

The second tier includes XOVWM, HyspIRI, ASCENDS, SWOT, GEO-CAPE, and ACE. These missions are similarly prioritized by cost within this tier, with the exception of HyspIRI. The Decadal Survey provides no rationale for the later TRL date of this mission, but its lower price does bring it forward in the sequence relative to its TRL date.

The final tier includes LIST, PATH, GRACE-II, SCLP, GACM, and 3D-Winds. These missions are sequenced by cost with no exceptions.

Using the cost assumption discussed in 4.1.2.1 to infer timing (Equation 11), this sequence can be converted into a schedule (Table 16). The Decadal survey assumed that the annual budget would return to the FY00 level of funding of approximately $750M/year. Hence, the reference schedule fits almost entirely within a decade.

Decadal Survey Reference Case		
Tier	Mission	Launch Date
Tier 1 2010-2013	CLARREO	2010.353
	GPSRO	2010.553
	SMAP	2010.953
	ICESAT-II	2011.353
	DESDynI	2012.287
Tier 2 2013-2016	XOVWM	2012.753
	HyspIRI	2013.153
	ASCENDS	2013.687
	SWOT	2014.287
	GEO-CAPE	2015.02
	ACE	2016.087
Tier 3 2016-2020	LIST	2016.487
	PATH	2017.087
	GRACE-II	2017.687
	SCLP	2018.353
	GACM	2019.153
	3D-WINDS	2020.02

Table 16. Reference Case Schedule

Using the cost assumption, the missions loosely stay within the periods of their intended tiers. The first tier completes in less time than expected, the second tier takes longer than planned, and the third tier is matches its projection.

This schedule can be combined with the information regarding mission values, as derived in section 3.3, to depict the accrual of benefit over time (Figure 38). The horizontal axis express time and the vertical axis express the percentage of weighted value relative to the entire campaign. Although benefit is actually realized at the time of launch, this plot illustrates accrual at the decision point (the time when the step function costing profile begins); hence, the decade begins with the value of CLARREO already counted, even though it does not launch until the second quarter of 2010.

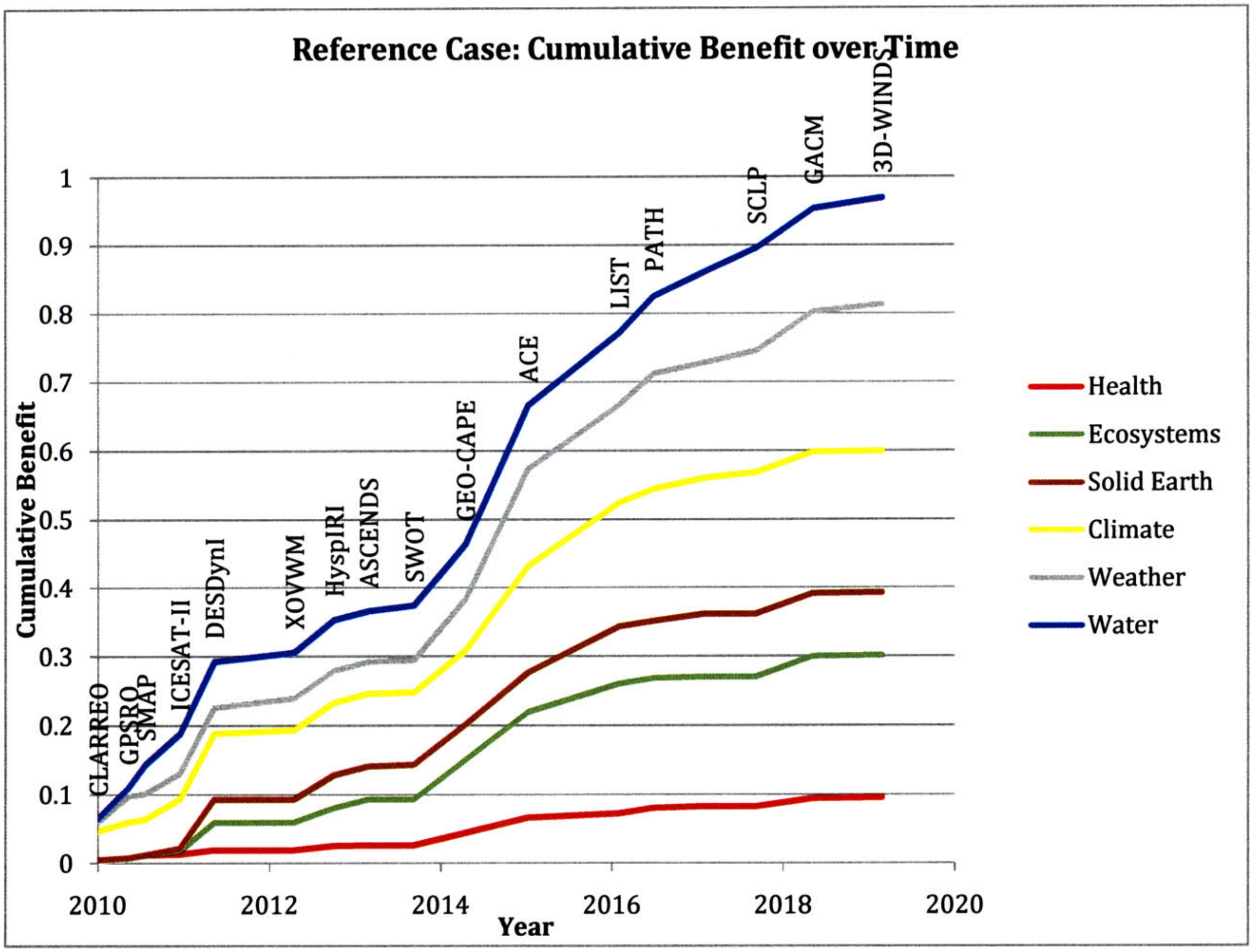


Figure 38. Cumulative Benefit over Time

The algorithm used by the Decadal Survey is reflected in the time between mission launches—the cheaper missions fly first within each tier, highlighting the tier breaks (such as that between DESDynI and XOVWM). Although this plot clarifies the weighted contributions of each panel to stakeholders, it is difficult to distinguish benefit profiles of individual panels.

Panel-level benefit trends are highlighted by plotting the relative accrual of benefit over time (Figure 39). In this plot the benefit gained by each panel is normalized—every panel starts at 0% and ends with 100% of its value for the campaign. The visualization makes clear the differences technology readiness makes in benefit accrual. The Climate and Water panels benefit the most from the first tier, whereas the Weather, Human Health and Security, and Land-use panels gain the most in the second. Additionally, the Weather panel consistently lags behind all other—it relies the most on later TRL missions. The outlier is the Solid Earth panel—because not every objective can be satisfied with these 17 missions, it never actually reaches 100% satisfaction.

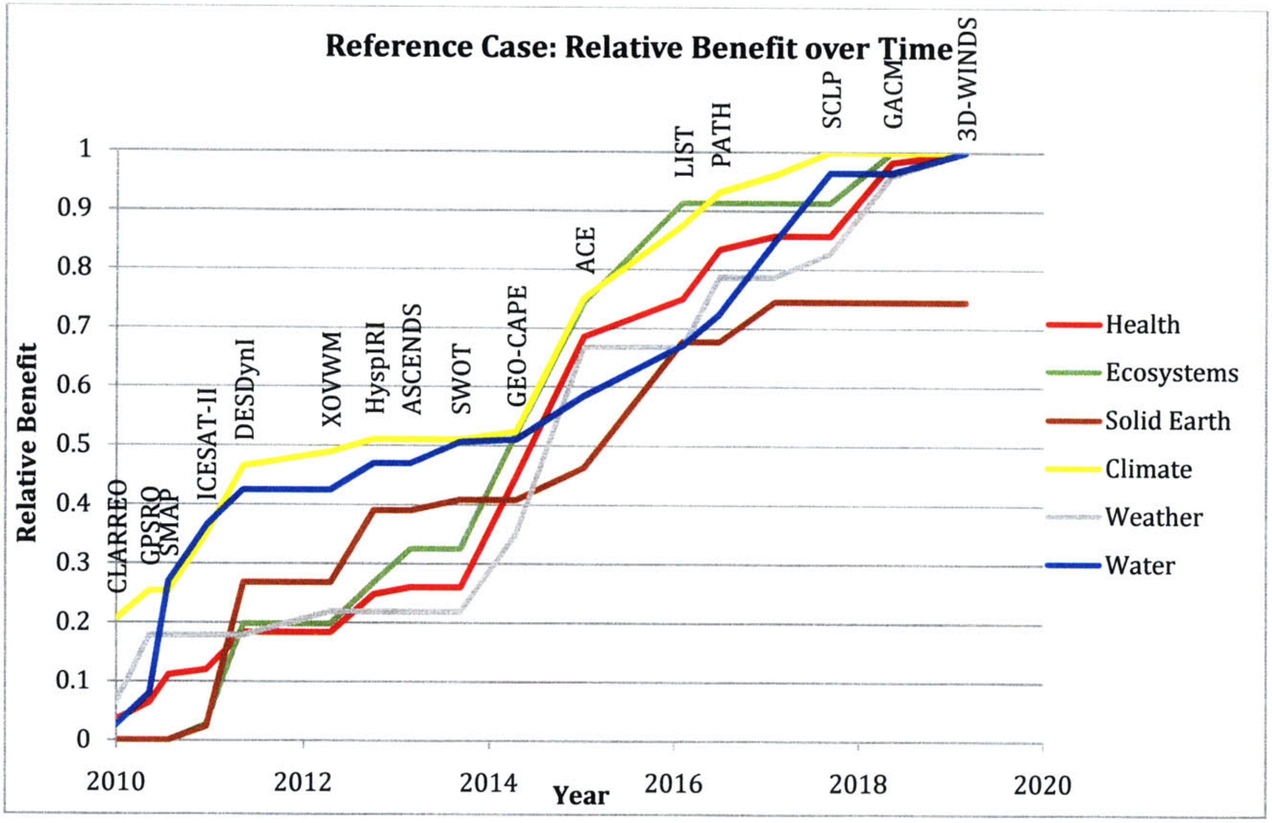
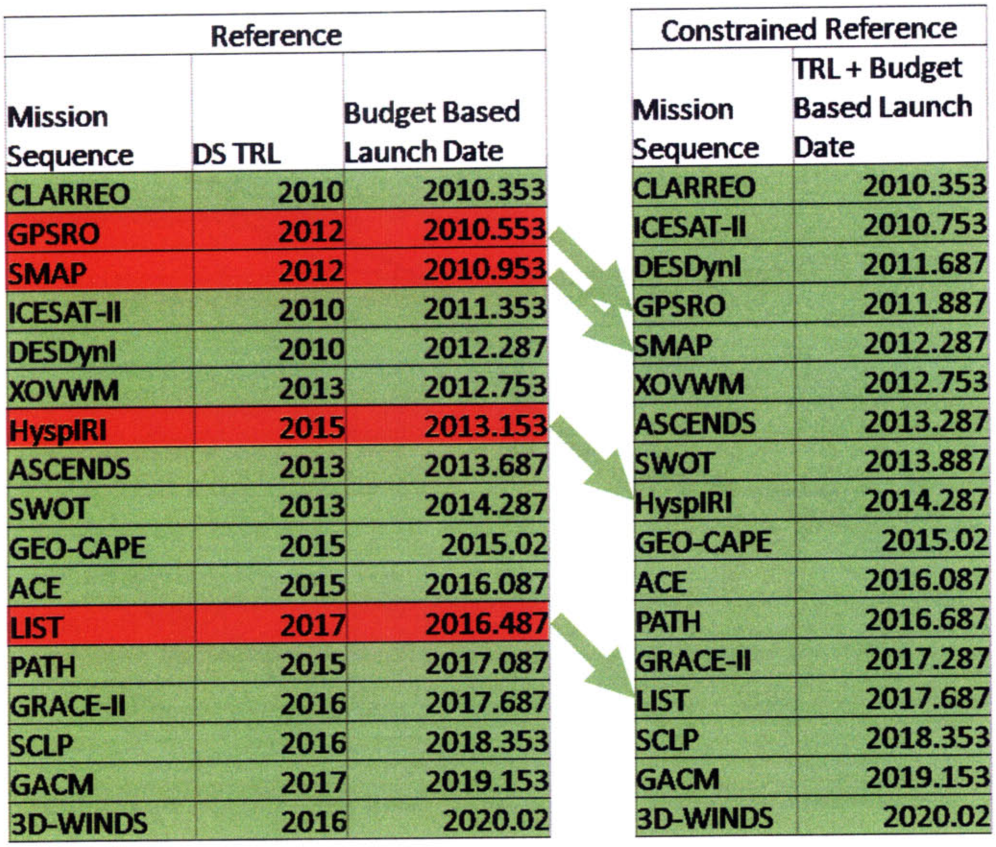


Figure 39. Relative Panel Benefit Profile for Reference Schedule

4.3.2.2 *The Constrained Reference Case*

The reference case schedule is composed using only the cost constraint and the sequence proposed by the Decadal Survey. The schedule enumerated in Table 16 noticeably violates the TRL constraint: although missions are ordered by tier, the actual readiness date is ignored. Applying the TRL constraint results in the "Constrained Reference" schedule (Figure 40). This approach forces missions with later TRL dates to launch later on within a tier; tier boundaries are still respected.



Reference		
Mission Sequence	DS TRL	Budget Based Launch Date
CLARREO	2010	2010.353
GPSRO	2012	2010.553
SMAP	2012	2010.953
ICESAT-II	2010	2011.353
DESDynI	2010	2012.287
XOVWM	2013	2012.753
HyspIRI	2015	2013.153
ASCENDS	2013	2013.687
SWOT	2013	2014.287
GEO-CAPE	2015	2015.02
ACE	2015	2016.087
LIST	2017	2016.487
PATH	2015	2017.087
GRACE-II	2016	2017.687
SCLP	2016	2018.353
GACM	2017	2019.153
3D-WINDS	2016	2020.02

Constrained Reference	
Mission Sequence	TRL + Budget Based Launch Date
CLARREO	2010.353
ICESAT-II	2010.753
DESDynI	2011.687
GPSRO	2011.887
SMAP	2012.287
XOVWM	2012.753
ASCENDS	2013.287
SWOT	2013.887
HyspIRI	2014.287
GEO-CAPE	2015.02
ACE	2016.087
PATH	2016.687
GRACE-II	2017.287
LIST	2017.687
SCLP	2018.353
GACM	2019.153
3D-WINDS	2020.02

Figure 40. Constrained Reference Derivation

However, the constrained reference case also violates the strict TRL dates by scheduling missions before they are ready. This occurs only when there are no other possibilities: hence XOVWM, the first of the second tier missions, launches in 2012 rather than waiting until its TRL date in 2013 to fly, as there are no other missions with lower TRL dates.

The constrained reference pushes four missions backwards in the campaign sequence: GPSRO, SMAP, HyspIRI, and LIST. Although these missions' relatively lower costs prioritize them within a tier, they are limited by the actual dates associated with the schedule. The accrual of benefit for this schedule can then be compared against that of the reference case (Figure 41).

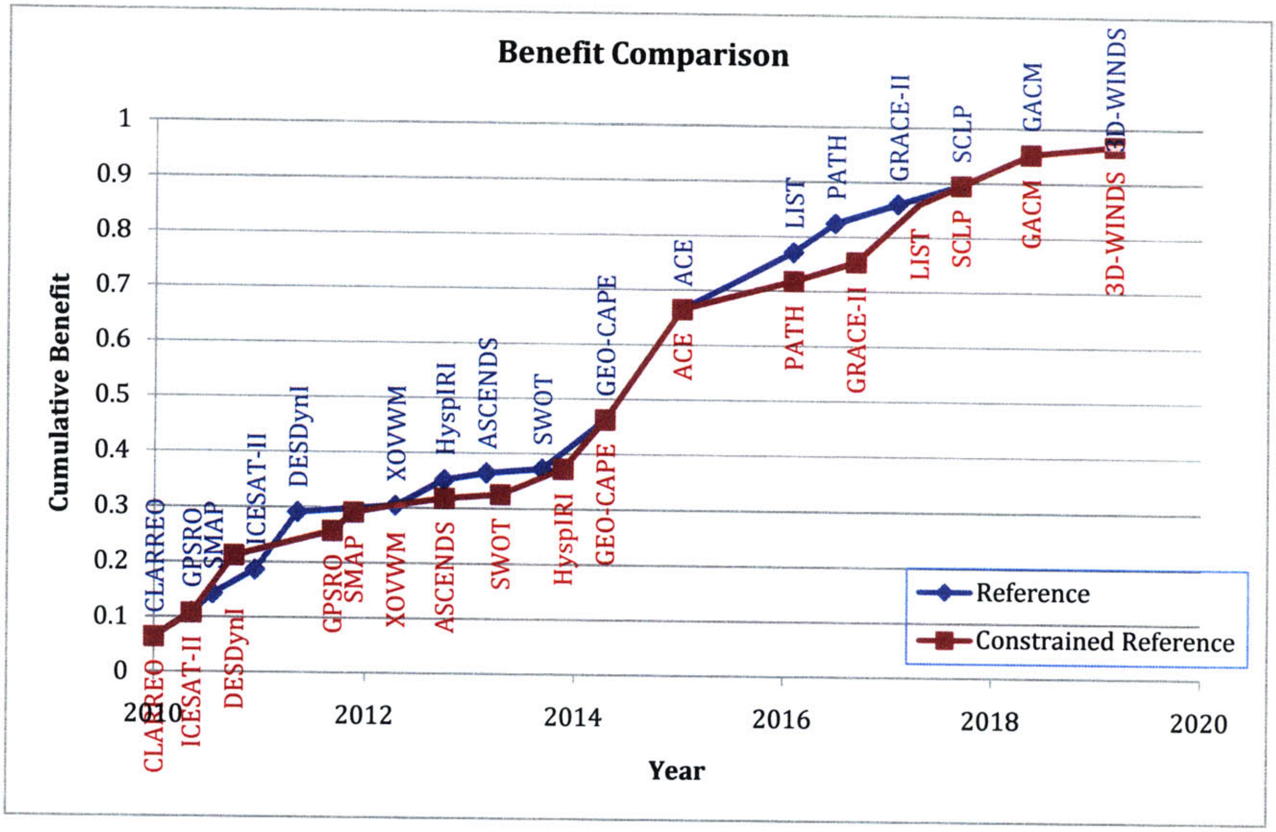


Figure 41. Benefit Profile Comparison

The additional constraint subtly changes the benefit profile. In the unconstrained case missions were much closer to being arranged by cost within a tier—with the TRL constraint implemented the pattern is still evident, but each tier tends to have two arrangements rather than one, reflecting the two TRL dates in each tier as evidenced in Table 15.

As with the reference case, the relative benefit profile of the constrained reference schedule can be plotted (Figure 42). This rescheduling does not result in significant changes to the patterns seen in the reference case, since the TRL restrictions only rearrange missions within a tier.

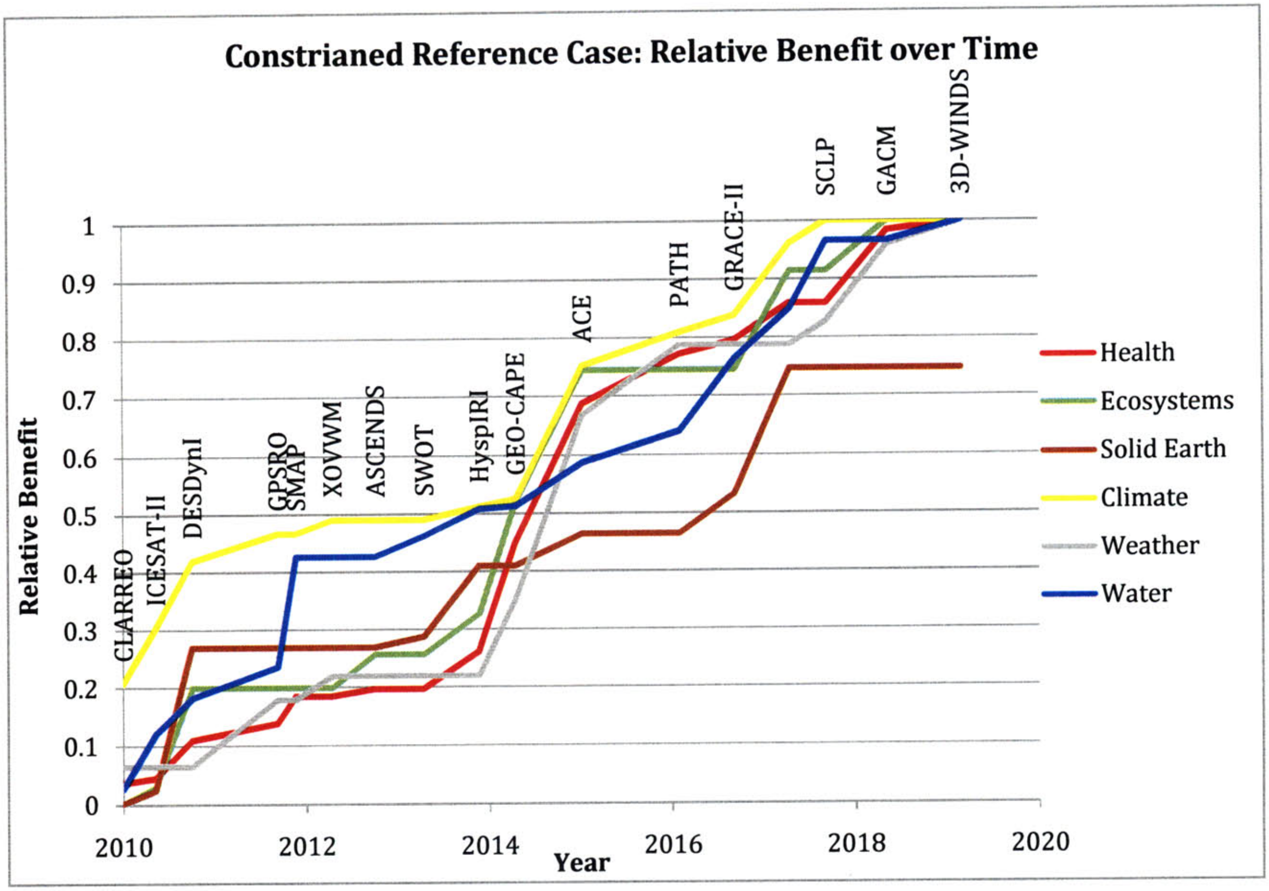


Figure 42. Relative Panel Benefit Profile for the Constrained Reference Schedule

Of the classes of constraints discussed in 4.1, the constrained reference only incorporates two: cost and TRL. The scope constraint does apply to scheduling algorithms. The data continuity value-function has limited applicability: missions are close enough together in time that no continuity issues addressed in the Decadal Survey are raised. The issue of fairness does not overtly arise: with the exception of the unsatisfied Ocean Bathymetry objective, all six panels accrue the totality of their respective benefits.

Despite its limited constraints and slight difference from the reference sequence, the constrained reference case more accurately presents the sequencing algorithm enumerated in the Decadal Survey. For this reason, algorithm development for rearchitecting the Decadal campaign, as explained in the following section, is baselined against the constrained reference.

4.3.3 Enhanced Algorithm Development

The constrained reference case presents a valid schedule because of the assumptions inherent in the Decadal Survey, primarily that the mission costs and program budget will allow the completion of the campaign within a decade. An enhanced algorithm is necessary to deal with cases when missions can be descoped or cancelled, and the budget severely limits the timing of missions. This section outlines the process used to define a desirable algorithm for campaign scheduling given uncertainty. First, the metrics used for selection and the options for analysis are defined. Then, the results of three sensitivity experiments are presented. Finally, the selected algorithm is summarized.

4.3.3.1 *Metrics for Evaluation and Algorithm Options*

The fitness of campaign scheduling algorithms was determined using three metrics: closeness to the constrained reference, normalized undiscounted benefit, and normalized discounted benefit.

1. Closeness to the constrained reference (years): Every campaign schedule will assign a particular launch date to each mission. The sum of the absolute differences in launch dates between the constrained reference schedule and the algorithmic schedule is a measure of how "close" the sequence of the enhanced algorithm schedule is to the constrained reference sequence.
2. Normalized undiscounted benefit (percent of total value): This metric represents an algorithm's propensity to pick high value missions. It is calculated by summing the undiscounted benefit accrued by each mission, and then normalizing this value by time. For resequences of the baseline Decadal missions this metric will not be useful, as every mission will be flown.
3. Normalized discounted benefit (percentage of total value): This metric reflects an algorithms ability to arrange missions in an optimal manner, minimizing discounting as discussed in 4.2.

The constraints discussed in 4.1 and the instrument benefit contributions discussed in 3.3 present several options for campaign algorithm criteria. The algorithm experiments described in the following sections explain the evaluations of the following five factors:

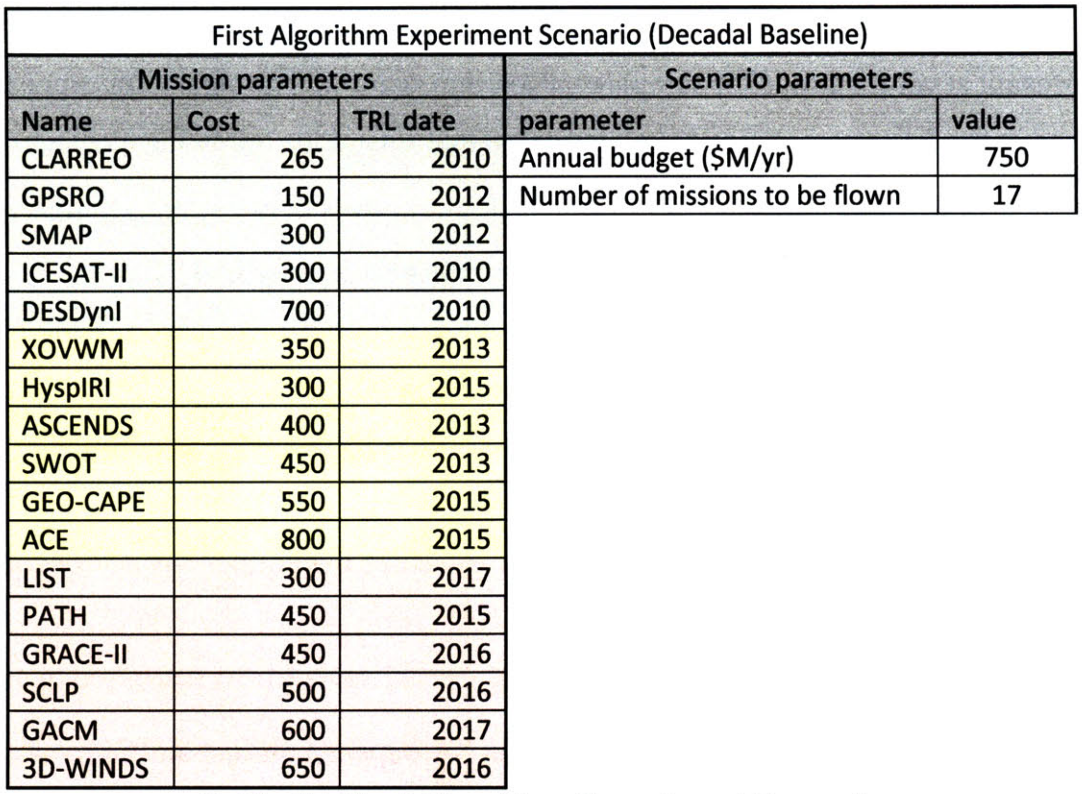
1. TRL: The TRL constraint applied as a limitation to the earliest launch date of a mission, as described for the constrained reference in 4.3.2.2.
2. Cost: Cost applied as a preference for scheduling lower-cost mission first, as described for the constrained reference in 4.3.2.2.
3. Benefit: Prefer missions with higher traceable benefits, as outlined in section 3.3.
4. Value: Prefer missions with higher traceable benefit per cost rations, as described in section 3.3.
5. Fairness: Minimize relative benefit accrual deviation as discussed in 4.1.2.4.

The algorithm proposed by the Decadal Survey depends on cost and TRL for sequencing. The algorithm proposed by Colson relies primarily on TRL and fairness for sequencing. Hence, it was assumed that the TRL constraint would be applied in every algorithm. The experiments described in the next section were conducted to evaluate combinations of these options with respect to the metrics described above.

4.3.3.2 Algorithm Sensitivity Analysis

Three experiments were conducted to evaluate the options described above. The first experiment studied variations of fairness as an algorithm parameter. The second experiment explored the fitness of algorithm options with respect to the constrained reference. The final experiment was used to tune the parameters of the algorithm in a less restrictive scenario.

First, the effectiveness of various fairness options were considered. Using the scenario parameters in Table 17, six algorithms were used to generate campaigns. This scenario replicates the Decadal Survey assumptions for cost and budget:



First Algorithm Experiment Scenario (Decadal Baseline)

Mission parameters			Scenario parameters	
Name	Cost	TRL date	parameter	value
CLARREO	265	2010	Annual budget ($M/yr)	750
GPSRO	150	2012	Number of missions to be flown	17
SMAP	300	2012		
ICESAT-II	300	2010		
DESDynl	700	2010		
XOVWM	350	2013		
HyspIRI	300	2015		
ASCENDS	400	2013		
SWOT	450	2013		
GEO-CAPE	550	2015		
ACE	800	2015		
LIST	300	2017		
PATH	450	2015		
GRACE-II	450	2016		
SCLP	500	2016		
GACM	600	2017		
3D-WINDS	650	2016		

Table 17. First Algorithm Experiment Scenario

The results of the experiment can be found in (Table 18). The general trend this experiment revealed is that the more specific the fairness criteria used, the less valuable the campaign architecture will be. The algorithms that considered objectives sacrificed significant value for the sake of fairness, and it was not clear this was necessary. The algorithm that sought to minimize the benefit deviation of either of the two least satisfied panels was selected for further simulations. While the campaign the 2-panel algorithm produced was not as valuable as the 1-panel option, it was within a reasonable range. Allowing the algorithm to pick missions that contribute to two most unsatisfied panels opens up the solutions space and enables the algorithm to deal with situations when TRL does not allow any missions for the least satisfied panel.

Minimize the Fairness Deviation of...	Campaign Discounted Value
The Sum of Every Panel	0.640013
Only the least satisfied panel	0.641255
Either of the two least satisfied panels	0.639711
Only the least satisfied objective	0.626557
Either of the two least satisfied objectives	0.628445
Any of the three least satisfied objectives	0.633817

Table 18. Fairness Experiment Results

Using the same scenario parameters, a second algorithm experiment was conducted analyzing other algorithm criteria with respect to the constrained reference. A total of 16 algorithms were assembled exploring various strengths of the options discussed in 4.3.3.1. Campaigns were assembled using these algorithms and the scenario parameters in Table 17, and were subsequently evaluated with respect to the constrained reference and depreciated value. Three algorithms were identified to be on the Pareto frontier and were selected for further study (Table 19).

Algorithm Option:	1	2	3
Depreciated Value:	64.31%	64.38%	64.92%
Constraint:	TRL	TRL	TRL
Strong Criteria:	cost	cost	value
Weak Criteria:	fairness	benefit	fairness
1	CLARREO	CLARREO	CLARREO
2	ICESAT-II	ICESAT-II	ICESAT-II
3	DESDynl	DESDynl	DESDynl
4	GPSRO	GPSRO	GPSRO
5	SMAP	SMAP	SMAP
6	XOVWM	XOVWM	XOVWM
7	ASCENDS	ASCENDS	ASCENDS
8	SWOT	SWOT	SWOT
9	HyspIRI	HyspIRI	HyspIRI
10	GEO-CAPE	GEO-CAPE	**ACE**
11	ACE	ACE	**GEO-CAPE**
12	PATH	PATH	**GRACE-II**
13	GRACE-II	GRACE-II	**PATH**
14	LIST	LIST	LIST
15	SCLP	**GACM**	**GACM**
16	GACM	**SCLP**	**3D-WINDS**
17	3D-WINDS	3D-WINDS	**SCLP**
Differences from constrained reference marked in red			

Table 19. Viable Algorithm Sequences in Baseline Scenario

The campaign sequences produced by these algorithms are not significantly different from each other: the first algorithm identically replicates the constrained reference, the second option reverses the order of one pair of missions, and the third rearranges three sets of missions.

The sensitivities of the strong and weak criteria for these three algorithms were analyzed with the final experiment. Scenario parameters were chosen that did not allow the completion of a campaign in one decade, and included already flown missions (Table 20). An updated version of this scenario is discussed in Chapter 5.

Second Algorithm Experiment Scenario				
Mission parameters			Scenario parameters	
Name	Cost	TRL date	parameter	value
CLARREO	579	2010	Annual budget ($M/yr)	300
GPSRO	***230***	***2012***	Number of missions to be flown	8
SMAP	***393***	***2012***	Other constraints:	The two NOAA missions were not eligible for scheduling The SMAP and ICESAT-II missions have fixed launch dates
ICESAT-II	***607***	***2010***		
DESDynI	1500	2010		
XOVWM	***538***	***2013***		
HyspIRI	500	2015		
ASCENDS	500	2013		
SWOT	800	2013		
GEO-CAPE	1276	2015		
ACE	1627	2015		
LIST	600	2017		
PATH	800	2015		
GRACE-II	500	2016		
SCLP	600	2016		
GACM	1030	2017		
3D-WINDS	800	2016		

Table 20. Second Algorithm Experiment Scenario

The results of the sensitivity analysis are plotted below (Figure 43). The metrics used for evaluation are the normalized discounted benefit and the normalized undiscounted benefit. In this plot the utopia point is depicted in the upper-right corner, pointing to the right: the ideal campaign will include 100% of the possible benefit enumerated in the CSTM (by including all seventeen missions within a decade), and will be sequenced such that depreciation is minimized, although the depreciated value outweighs the nondepreciated value.

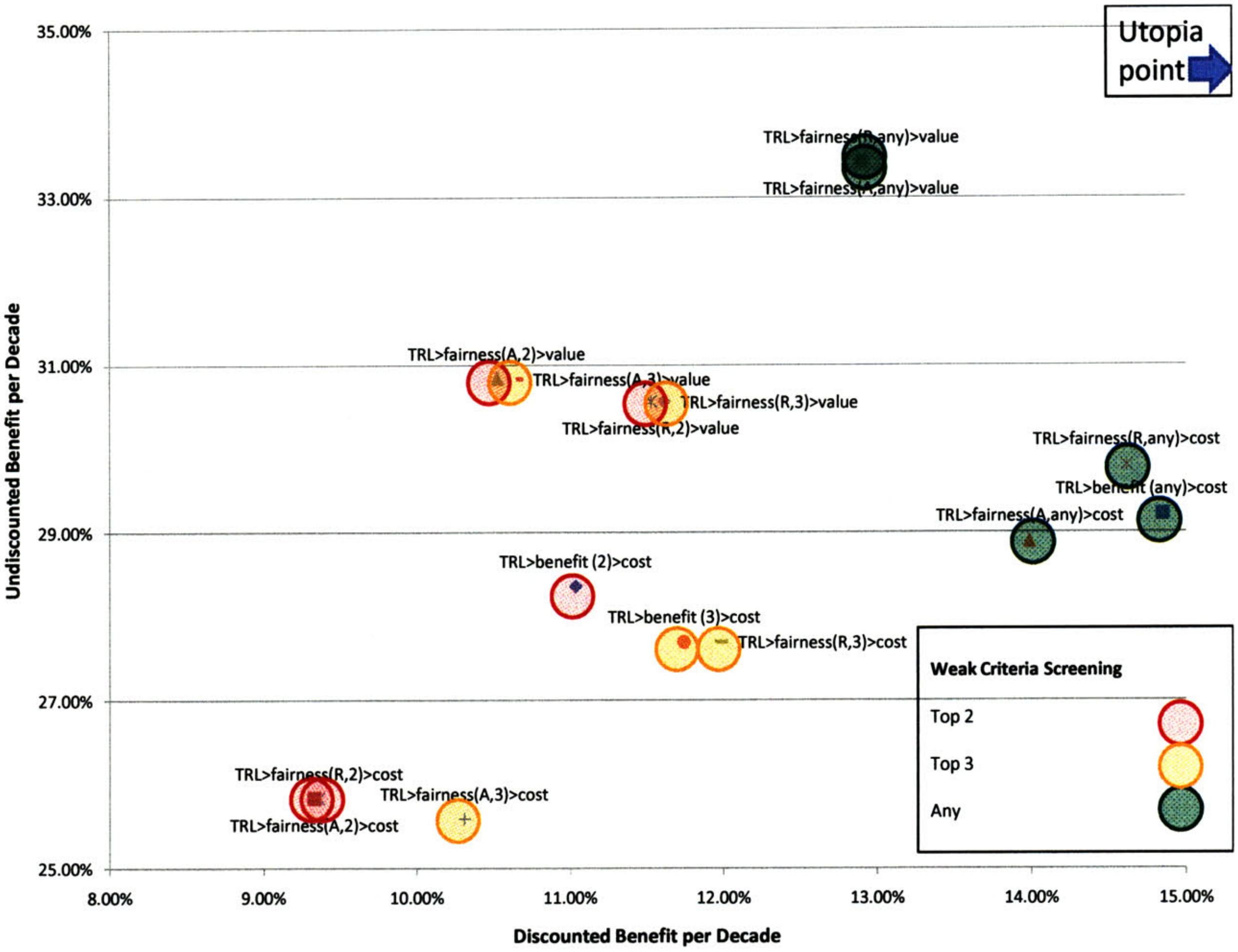


Figure 43. Second Algorithm Experiment: Screening Variations

Based upon this analysis, the final algorithm selected is represented by the second point to the right of the plot, "TRL>fairness>cost". This algorithm utilizes the strong criteria of cost and the weak criteria of fairness to the two least satisfied panels. While it does not represent the optimal discounted-benefit solution, it does implement the concept of fairness for a relatively low cost.

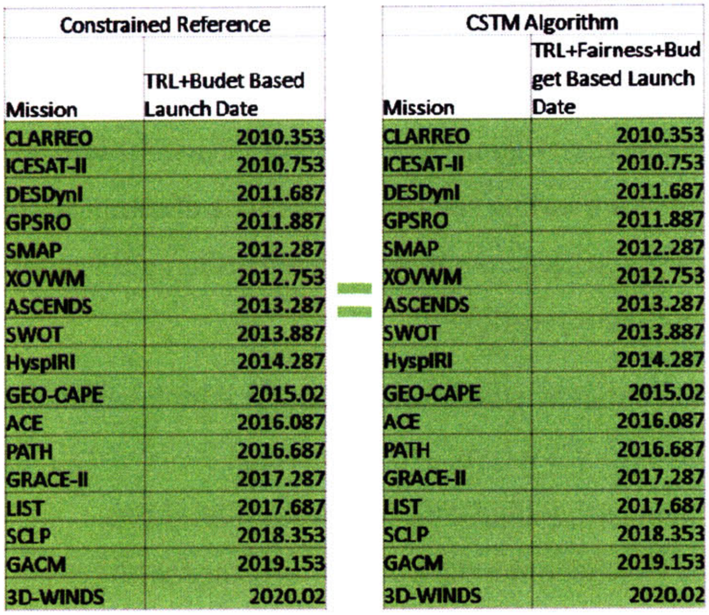
4.3.3.3 Final Algorithm Summary

The algorithm that will be used in Chapter 5 to explore rearchitecting the Decadal campaign thus closely resembles the programmatic decision strategy proposed in the Decadal Survey—scheduling on budgetary and technological risks factors, with the addition of fairness. The following outlines a simplified explanation of the algorithm:

1. First, the algorithm searches the list of available, un-flown missions. Although long-term campaign planning should incorporate the possibility of the operationalization of missions, for a first pass this algorithm assumes each mission will only fly once. This is also a necessary assumption given that the CSTM value calculations were all dependent on flying each Decadal mission only once. This is described in 4.1.3.
2. Second, the algorithm pares the list of missions down to those that are technologically ready given the date. If no missions are available, as seen in the baseline Decadal scenario, the algorithm pares the list down to those missions in the next bin of TRL dates—simulating the acceleration of the most ready technologies. This constraint is described in 4.1.2.2.
3. Third, the algorithm determines which two panels are least satisfied. It does this by computing the percentage of each panel's weighted benefit that has been accrued relative to that panel's stakeholder weighting. Hence the least satisfied panel is not necessarily the panel with the most unfulfilled absolute benefit. This process is described in 4.1.2.4.
4. Fourth, the algorithm determines which missions satisfy the two least satisfied panels. If there are no missions current available to fly that meet this restriction, the algorithm expands the field to missions that satisfy the top three panels, and so forth until at least one mission meets the criteria. No preference is given to missions that are more effective in satisfying a panel-either a mission does or does not.
5. Finally, from the missions that have passed through all the previous steps, the algorithm selects the lowest costing option. If two missions that reach the final algorithm step are of the same price, then the algorithm picks the

one best satisfies both of the least satisfied panels. If the missions are qualitative identical, the number of panels included in this calculation is expanded (by panel dissatisfaction order) until a difference is found. This mission is then added to the schedule, and time is advanced using the cost/budget assumption.

This algorithm was validated against the Decadal Survey by applying it to the first experiment scenario described in this chapter (Table 17). The schedule produced by the final CSTM algorithm was then compared against the constrained reference case (Table 21). The results were identical: given the constraints inherent in the original Decadal Survey, the final CSTM algorithm can replicate the Decadal campaign (Table 21).



Constrained Reference	
Mission	TRL+Budet Based Launch Date
CLARREO	2010.353
ICESAT-II	2010.753
DESDynl	2011.687
GPSRO	2011.887
SMAP	2012.287
XOVWM	2012.753
ASCENDS	2013.287
SWOT	2013.887
HyspIRI	2014.287
GEO-CAPE	2015.02
ACE	2016.087
PATH	2016.687
GRACE-II	2017.287
LIST	2017.687
SCLP	2018.353
GACM	2019.153
3D-WINDS	2020.02

=

CSTM Algorithm	
Mission	TRL+Fairness+Budget Based Launch Date
CLARREO	2010.353
ICESAT-II	2010.753
DESDynl	2011.687
GPSRO	2011.887
SMAP	2012.287
XOVWM	2012.753
ASCENDS	2013.287
SWOT	2013.887
HyspIRI	2014.287
GEO-CAPE	2015.02
ACE	2016.087
PATH	2016.687
GRACE-II	2017.287
LIST	2017.687
SCLP	2018.353
GACM	2019.153
3D-WINDS	2020.02

Table 21. Final Algorithm Applied to Baseline Scenario

4.4 Summary

This chapter described the use of the CSTM for campaign design. Constraints were applied to the CSTM based upon guidance from the Decadal Survey and Colson's thesis. Value functions relevant to total benefit, present value, and data continuity were described. The Decadal Survey was used to inform a reference algorithm. An improved algorithm was developed and validated against the reference algorithm. This algorithm will be used in the following chapter to explore campaign planning with post-Decadal assumptions.

5 Scheduling Simulation Results

The CSTM scheduling algorithm has been validated against the original Decadal Survey assumptions. The section presents the results of a series of scheduling simulations that apply current assumptions to the Decadal campaign: the new mission costs, the reduced annual budget, the loss and degradation of precursor missions, and the addition of international missions, as discussed in Section 1.1.

Objective of Scheduling Simulation Results

- *To examine the impacts of key changes that have occurred since the publishing of the Decadal Survey by attaining updated assumptions using surveys of NASA scientists and Engineers*

The primary problem addressed by this chapter is the issue of cost growth. The strategy of breaking apart the original Decadal survey missions into single-instrument platforms is presented as a possible solution. Variations of campaign parameters and a sensitivity analysis are presented demonstrating the utility of this approach. This chapter is organized into the following sections:

- Section 5.1: Changes to the Decadal sequence based upon new assumptions. This section presents a comparison between the constrained reference sequence and a campaign scheduled with updated assumptions.
- Section 5.2: Rescheduling the Decadal campaign with reassigned instruments. This section presents a comparison between scheduling the originally proposed Decadal missions and scheduling the instruments of the Decadal campaign as individual missions.
- Section 5.3: Completing the NASA Schedule. This section examines scheduling a limited subset of missions given the campaign decisions already made by NASA.
- Section 5.4: Budget Sensitivity. This section analyzes the sensitivity of a campaign to budgetary changes.
- Section 5.5: Summary.

5.1 Changes to the Decadal Sequence Based upon New Assumptions

5.1.1 Motivation

Chapter 4 presented a justification for the CSTM algorithm, which, given the original Decadal assumptions, could reproduce the constrained reference sequence. This section presents the application of the CSTM algorithm to scheduling, given updated assumptions, and an analysis of how they affect the sequencing of Decadal missions.

5.1.2 Parameters

For this simulation the constrained reference sequence was compared to a campaign scheduled using the CSTM algorithm and recosted missions. The scenario parameters found in Table 22 were assumed. The costs and TRL dates for both schedules can be found in Table 23. The results of this simulation are compared to the constrained reference sequence presented in Table 21 of section 4.3.3.3.

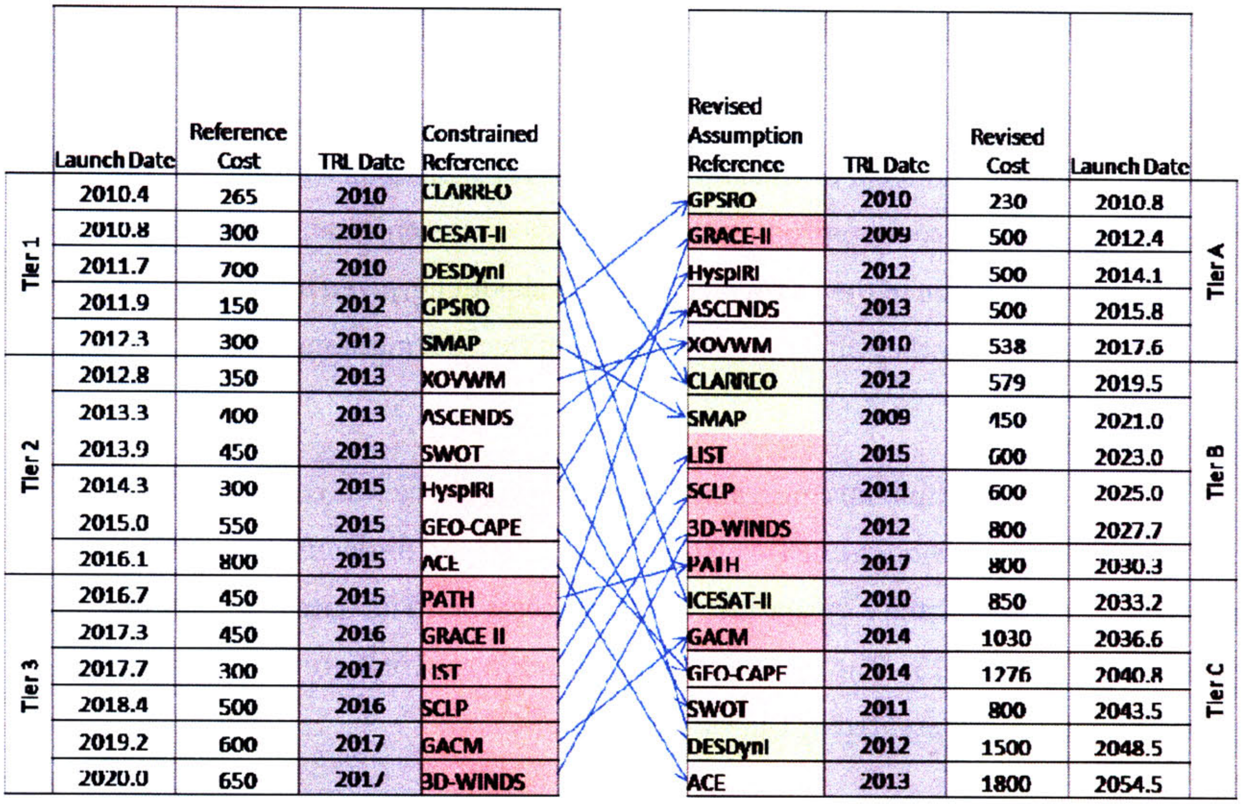
Campaign Parameter	Constrained Reference Campaign	Recosted Decadal Mission Set
Annual Budget	$750M	$300M
Mission Costs	Decadal Survey	NASA estimates 5/09
Instrument TRLs	Decadal Survey	NASA estimates 5/09

Science Panel	Total Value	Discount Rate
Weather	0.214	0.10
Climate	0.206	0.15
Ecosystems	0.206	0.10
Water	0.156	0.10
Health	0.111	0.10
Solid Earth	0.107	0.05

Table 22. New Assumption Scenario Parameters

5.1.3 Results

Table 23 displays how each mission changed in the sequence with updated assumptions. The different colors indicate the Decadal tiers. A new set of tiers, "A, B, and C" are indicated for the updated campaign.



	Launch Date	Reference Cost	TRL Date	Constrained Reference
Tier 1	2010.4	265	2010	CLARREO
	2010.8	300	2010	ICESAT-II
	2011.7	700	2010	DESDynI
	2011.9	150	2012	GPSRO
	2012.3	300	2012	SMAP
Tier 2	2012.8	350	2013	XOVWM
	2013.3	400	2013	ASCENDS
	2013.9	450	2013	SWOT
	2014.3	300	2015	HyspIRI
	2015.0	550	2015	GEO-CAPE
	2016.1	800	2015	ACE
Tier 3	2016.7	450	2015	PATH
	2017.3	450	2016	GRACE II
	2017.7	300	2017	LIST
	2018.4	500	2016	SCLP
	2019.2	600	2017	GACM
	2020.0	650	2017	3D-WINDS

Revised Assumption Reference	TRL Date	Revised Cost	Launch Date	
GPSRO	2010	230	2010.8	Tier A
GRACE-II	2009	500	2012.4	
HyspIRI	2012	500	2014.1	
ASCENDS	2013	500	2015.8	
XOVWM	2010	538	2017.6	
CLARREO	2012	579	2019.5	Tier B
SMAP	2009	450	2021.0	
LIST	2015	600	2023.0	
SCLP	2011	600	2025.0	
3D-WINDS	2012	800	2027.7	
PATH	2017	800	2030.3	
ICESAT-II	2010	850	2033.2	Tier C
GACM	2014	1030	2036.6	
GEO-CAPE	2014	1276	2040.8	
SWOT	2011	800	2043.5	
DESDynI	2012	1500	2048.5	
ACE	2013	1800	2054.5	

Table 23. Sequence Comparison

The first tier of Decadal missions spreads out evenly across the entire campaign, with GPSRO becoming the first mission scheduled, CLARREO and SMAP beginning tier "B", and ICESat-II and DESDynI falling to tier "C". The second tier of missions congregates primarily in tier "A", although the more expensive SWOT, GEO-CAPE, and ACE missions move to tier "C". The third tier of missions mostly moves forward to occupy tier "B", with the GRACE mission notably moving to second in the queue.

5.1.4 Interpretation

The first explanation for this result is that TRL is not an active constraint. In the constrained reference case, the TRL dates of each mission ensure that a diverse cross-section of mission sizes is scheduled in each tier. The original TRL dates, however, are not traceable exclusively to instrument readiness—they incorporate data continuity assumptions as well. Additionally, the TRL dates assigned to missions a posteri are functions of the campaign sequence: missions scheduled to fly in a decade do not need to be developed right now, and hence have alter readiness dates. The revised TRL dates instead assume that if a mission is prioritized first in the sequence, that date will be the earliest it will be ready to fly. The latest of the revised TRL dates, 2017, which is associated with the more expensive PATH mission. Because this constraint is not active, the primary criterion for scheduling is prioritization based upon cost.

The missions are arranged almost exactly in increasing cost order. This is reflective of the algorithms preference for low budget risk missions. However, two exceptions occur in the schedule: the SMAP and SWOT missions. This is evidence of the fairness criteria being applied, as seen by the plot of the relative nondiscounted value accrual over time (Figure 44).

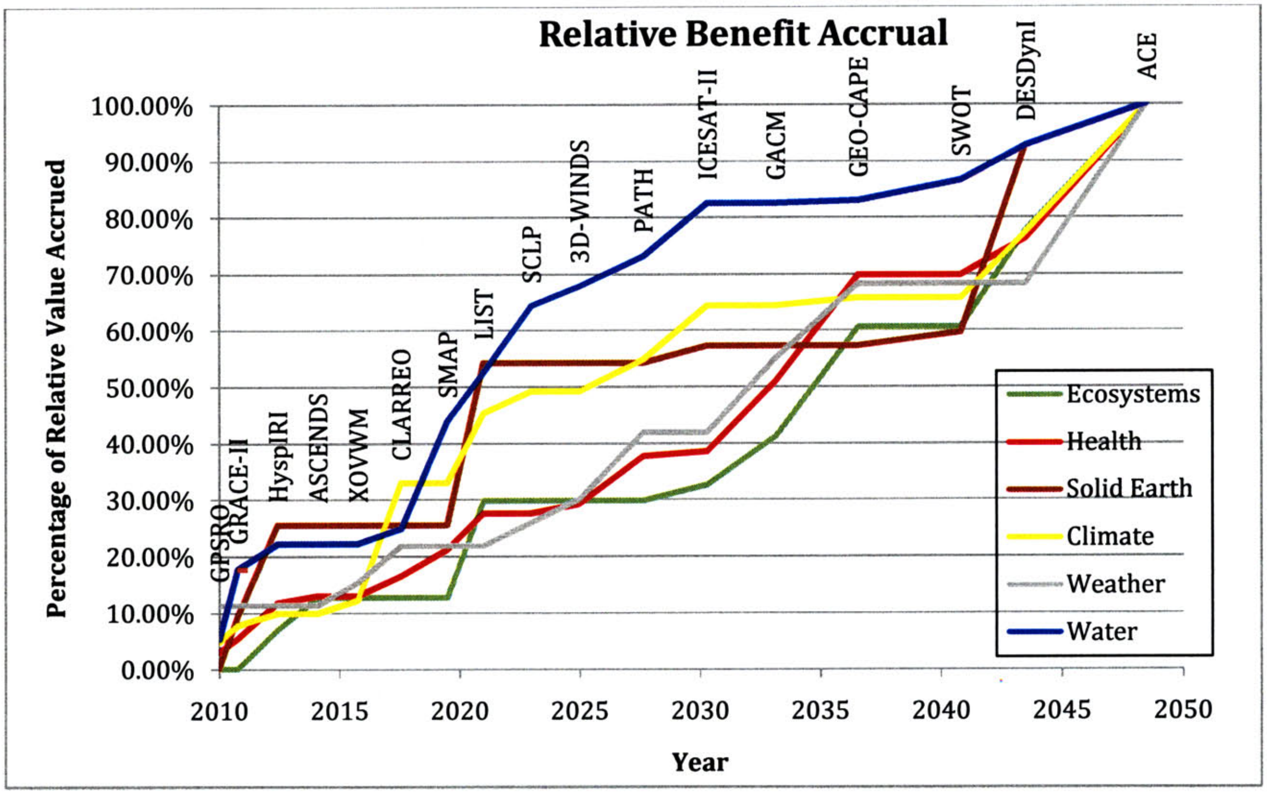


Figure 44. Fairness for New Assumption Campaign

At most points in time the Water panel is the most satisfied. A schedule with only cost-ordering would fly SMAP second; however, because the CSTM algorithm includes fairness, and SMAP is primarily a Water mission, it is moved further back in the queue . Hence, it moves to seventh in the sequence, by which time the Health panel, the only other recipient of SMAP benefit, is one of the two least satisfied missions. This effect is mirrored in the scheduling of SWOT, which delivers value to both Water and Solid Earth panels.

This comparison shows that there may be an unstated utility to maintaining the Decadal survey tiers. Although it recommended only TRL and Cost as decision criteria, even with the added conception of fairness, the Decadal tiers are not recoverable. This comparison highlights the need for further algorithm experimentation and development.

5.2 Rescheduling the Decadal Campaign with Reassigned instruments

5.2.1 Motivation

With the current mission cost and budget projections it will take more than 40 years to complete the Decadal campaign. The scope of the Decadal Survey was exactly that—a program of space missions that pushed the boundaries of technology, but could realistically be achieved in the next decade. A new approach is necessary to constrict the campaign to a reasonable size.

One of the issues presented in the Decadal Survey is that of mission size. Table 10 in Section 3.1.5 presented the number of instruments in each mission, highlighting the correlation between number of instruments and mission cost. This section presents a comparison between scheduling the original Decadal missions and scheduling the same instruments reassigned onto unique missions.

Campaigns were scheduled for both missions sets using the algorithm identified in the previous chapter. Discounting was applied to the value of both campaigns and the resultant impacts were analyzed.

5.2.2 Parameters

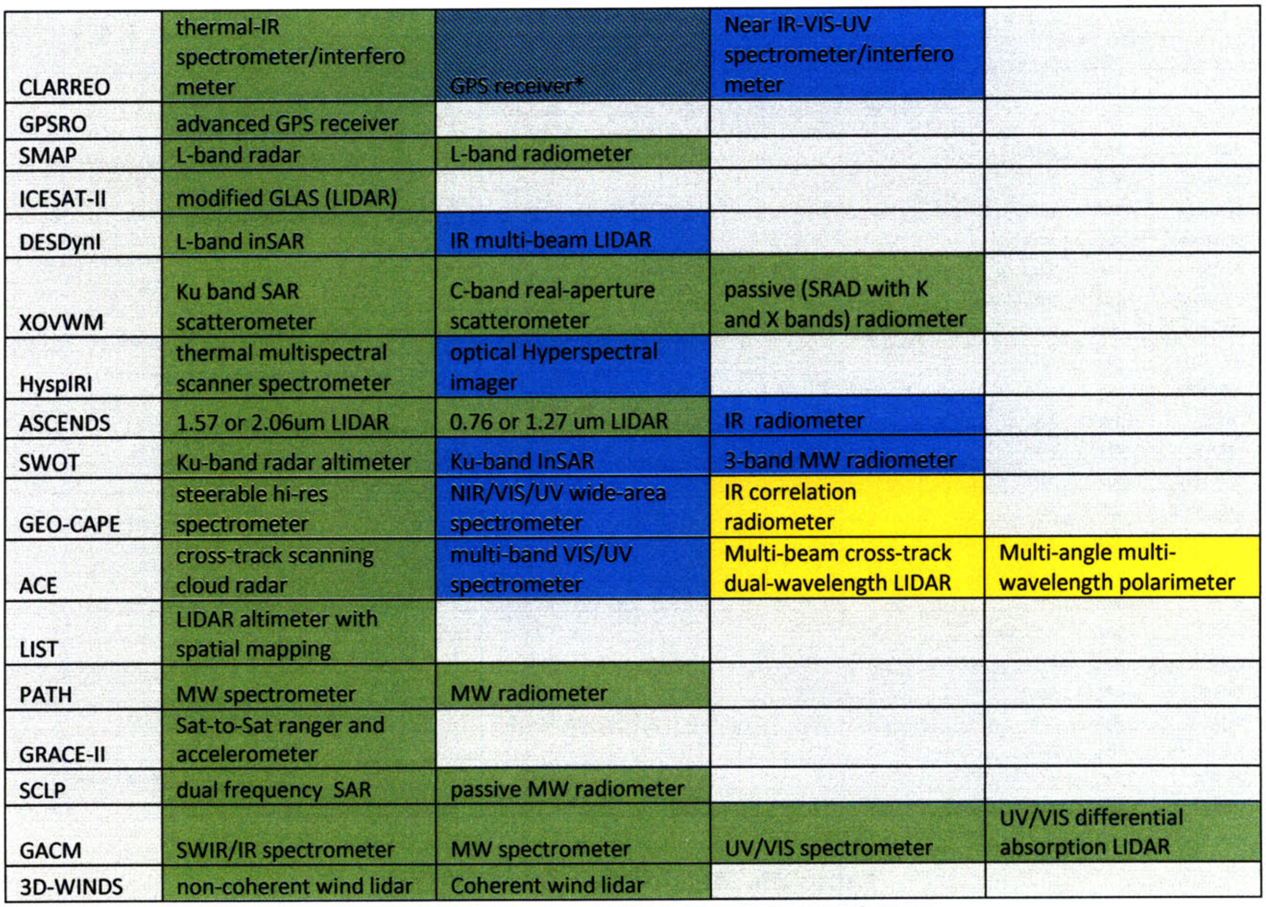
Two campaigns were scheduled: one using the original Decadal mission set and one using the reassigned set. The baseline scenario parameters are similar (Table 24). Every mission in the mission set was flown, and no time limit was placed on the campaign.

Campaign Parameter	Decadal Mission Set	Free-flyer Mission set
Annual Budget	$300 M	$300 M
Mission Costs	NASA estimates 5/09	NASA estimates 5/09
Instrument TRLs	NASA estimates 5/09	NASA estimates 5/09

Science Panel	Total Value	Discount Rate
Weather	0.214	0.10
Climate	0.206	0.15
Ecosystems	0.206	0.10
Water	0.156	0.10
Health	0.111	0.10
Solid Earth	0.107	0.05

Table 24. Baseline Scenario Parameters

Table 25 outlines how the instruments on each mission were separated. This scenario only focused on splitting apart larger missions and not reassembling different combinations. In this diagram the color of each instrument indicates if it was separated into an additional mission. Instruments with shared colors were kept together. The GPS receiver for CLARREO was assigned to both sub-missions.



CLARREO	thermal-IR spectrometer/interferometer	GPS receiver*	Near IR-VIS-UV spectrometer/interferometer	
GPSRO	advanced GPS receiver			
SMAP	L-band radar	L-band radiometer		
ICESAT-II	modified GLAS (LIDAR)			
DESDynI	L-band inSAR	IR multi-beam LIDAR		
XOVWM	Ku band SAR scatterometer	C-band real-aperture scatterometer	passive (SRAD with K and X bands) radiometer	
HyspIRI	thermal multispectral scanner spectrometer	optical Hyperspectral imager		
ASCENDS	1.57 or 2.06um LIDAR	0.76 or 1.27 um LIDAR	IR radiometer	
SWOT	Ku-band radar altimeter	Ku-band InSAR	3-band MW radiometer	
GEO-CAPE	steerable hi-res spectrometer	NIR/VIS/UV wide-area spectrometer	IR correlation radiometer	
ACE	cross-track scanning cloud radar	multi-band VIS/UV spectrometer	Multi-beam cross-track dual-wavelength LIDAR	Multi-angle multi-wavelength polarimeter
LIST	LIDAR altimeter with spatial mapping			
PATH	MW spectrometer	MW radiometer		
GRACE-II	Sat-to-Sat ranger and accelerometer			
SCLP	dual frequency SAR	passive MW radiometer		
GACM	SWIR/IR spectrometer	MW spectrometer	UV/VIS spectrometer	UV/VIS differential absorption LIDAR
3D-WINDS	non-coherent wind lidar	Coherent wind lidar		

Table 25. Simplified Mission Lysis

The following table outlines the composition of each mission set in more detail (Table 26). The Decadal mission set includes the 17 missions described in the Decadal Survey. Each of these missions, displayed vertically on the table, is attributed an updated cost and TRL. Additionally, the instrument on each Decadal mission are listed (different colors indicate different missions). The horizontal mission set includes the reassigned satellites. When reasonable, the Decadal survey missions were broken apart, resulting in 26 new missions. Recombination of Decadal instruments was not analyzed. Each free flyer includes as cost estimate provided by NASA, as well as a TRL date reflective of the instruments on board.

		DS Mission	CLARREO			GPSRO	SMAP		ICESAT-II	DESDynl		XOVWM			HyspIRI		ASCENDS			SWOT			GEO-CAPE			ACE				LIST	PATH		GRACE-II	SCLP		GACM				3D-WINDS	
		May 09 Cost	579			230	450		850	1500		538			500		500			800			1276			1800				600	800		500	600		1030				800	
		TRL	2012			2010	2009		2010	2012		2010			2012		2013			2011			2014			2013				2015	2017		2009	2011		2014				2012	
		Instrument	thermal-IR	Near IR-VIS-UV	GPS reciever	advanced GPS	L-band radar	L-band radiometer	modified GLAS	L-band InSAR	IR multi-beam	Ku band SAR	C-band real-apeture	passive (SRAD with	thermal	optical	1.57 or 2.06um	0.76 or 1.27 um	IR radiometer	Ku-band radar	Ku-band InSAR	B-band MW	steerable hi-res	NIR/VIS/UV wide-	IR correlation	cross-track scanning	multi-band VIS/UV	Multi-beam cross-	Multi-angle multi-	LIDAR altimeter	MW spectometer	MW radiometer	Sat-to-Sat ranger	dual frequency SAR	passive MW	SWIR/IR	MW spectrometer	UV/VIS	UV/VIS differential	non-coherent wind	Coherent wind lidar
Clarreo A	300	2012	X		X																																					
Clarreo B	300	2012		X	X																																					
GPSRO	230	2010				X																																				
SMAP	450	2009					X	X																																		
ICESAT II	850	2010							X																																	
DESDynl A	900	2012								X																																
DESDynl B	600	2010									X																															
XOVWM	538	2010										X	X	X																												
HYSPIRI A	350	2010													X																											
HYSPIRI B	350	2012														X																										
ASCENDS A	450	2013															X	X																								
ASCENDS B	250	2011																	X																							
SWOT A	350	2011																		X																						
SWOT B	650	2011																			X	X																				
GEOCAPE A	600	2014																					X																			
GEOCAPE B	400	2013																						X																		
GEOCAPE C	400	2013																							X																	
ACE A	900	2012																								X																
ACE B	300	2012																									X															
ACE C	600	2013																										X	X													
LIST A	600	2015																												X												
PATH A	800	2017																													X	X										
GRACE A	500	2009																															X									
SCLP A	600	2011																																X	X							
GACM A	1030	2014																																		X	X	X	X		
WINDS A	800	2012																																						X	X

Table 26. Mission Set Composition

Of the 38 Instruments originally identified, only 26 reassigned missions were created. ICESat-II, LIST, GRACE-II, and GPSRO were not separable, as they only had one instrument each. The NOAA mission XOVWM, and the NASA mission GACM were not separated due to lack of detailed instrument knowledge. SMAP, 3D-Winds, and parts of ASCENDS were not separated due to the use of a shared component by two instruments (SMAP's instruments share a 6m rotating antenna, 3D-WINDs share a set of four telescopes). PATH and SCLP, and parts of ACE and SWOT, were not separated due to need for concurrent measurements. The CLARREO mission, which utilizes three separate instruments, was split into missions, each with a different type of spectrometer and a shared GPS receiver.

5.2.3 Results

Table 27 lists the results of the simulation. The left-hand columns of the table indicate when the original Decadal missions were scheduled. The right-hand columns of the table indicate when the corresponding reassigned missions were scheduled. The colors associated with the reassigned mission are indicative of the differences in launch date from the corresponding Decadal mission, which is calculated in the far right column. Green indicates the smallest difference, followed by light green, yellow, orange, red, dark red, and black. The absolute total difference in launch dates equals 276 years, which indicates, on average, a 10.6 year deviation from the Decadal mission launch date.

Decadal Missions	Launch Date	Reassigned Missions	Launch Date	Difference (years)
3D-WINDS	2027.7	WINDS A	2047.6	19.9
ACE	2054.5	ACE A	2053.6	-0.9
	2054.5	ACE B	2014.8	-39.7
	2054.5	ACE C	2033.7	-20.8
ASCENDS	2015.8	ASCENDS A	2035.2	19.4
	2015.8	ASCENDS B	2012.8	-3
CLARREO	2019.5	CLARREO A	2013.8	-5.7
	2019.5	CLARREO B	2015.8	-3.7
DESDynl	2048.5	DESDynl A	2050.6	2.1
	2048.5	DESDynl B	2031.7	-16.8
GACM	2036.6	GACM A	2057	20.4
GEO-CAPE	2040.8	GEOCAPE A	2037.2	-3.6
	2040.8	GEOCAPE B	2019.4	-21.4
	2040.8	GEOCAPE C	2027.7	-13.1
GPSRO	2010.8	GPSRO	2010.8	0
GRACE-II	2012.4	GRACE A	2022.6	10.2
HyspIRI	2014.1	HYSPIRI A	2011.9	-2.2
	2014.1	HYSPIRI B	2018.1	4
ICESAT-II	2033.2	ICESAT-II	2044.9	11.7
LIST	2023	LIST A	2026.4	3.4
PATH	2030.3	PATH A	2042.1	11.8
SCLP	2025	SCLP A	2029.7	4.7
SMAP	2021	SMAP	2020.9	-0.1
SWOT	2043.5	SWOT A	2016.9	-26.6
	2043.5	SWOT B	2039.4	-4.1
XOVWM	2017.6	XOVWM	2024.4	6.8
			Total	276.2

Table 27. Baseline Results

The biggest change in launch dates comes from the ACE mission. As presented in Section 3.3, the ACE mission is by far the most valuable. However, it is also the most expensive, with the current estimate running at $1.8B. The CSTM algorithm will attempt to schedule the most expensive mission last, regardless of benefit delivered. Breaking ACE apart, however, allows the cheaper, yet still significantly beneficial, portions to fly earlier on in the campaign. Conversely, the GACM mission, which had been one of the more expensive of the 17 Decadal missions, became the most expensive mission because it was not reassigned, and was subsequently scheduled last in the campaign by the CSTM algorithm.

The schedules were then evaluated with respect to the discounted value of the campaign. As both mission sets included every instrument proposed in the Decadal Survey, the total non-discounted value for both campaigns was identical. The depreciation of value over time is presented in Figure 45.

In this figure the depreciation of a mission value is a function of the panel discount rates (Table 24) and the value of the mission as determined through the CSTM. The black line represents the cumulative benefit actually captured by a campaign—realized when a mission launches. Value depreciation stops once a mission has been launched, hence it is desirable that the scheduler capture as much benefit as possible before it depreciates. The length of time between steps on the black line is indicative of the cost of the mission, and the scheduler preference for low-cost mission first is seen in the elongated steps later on in both campaigns.

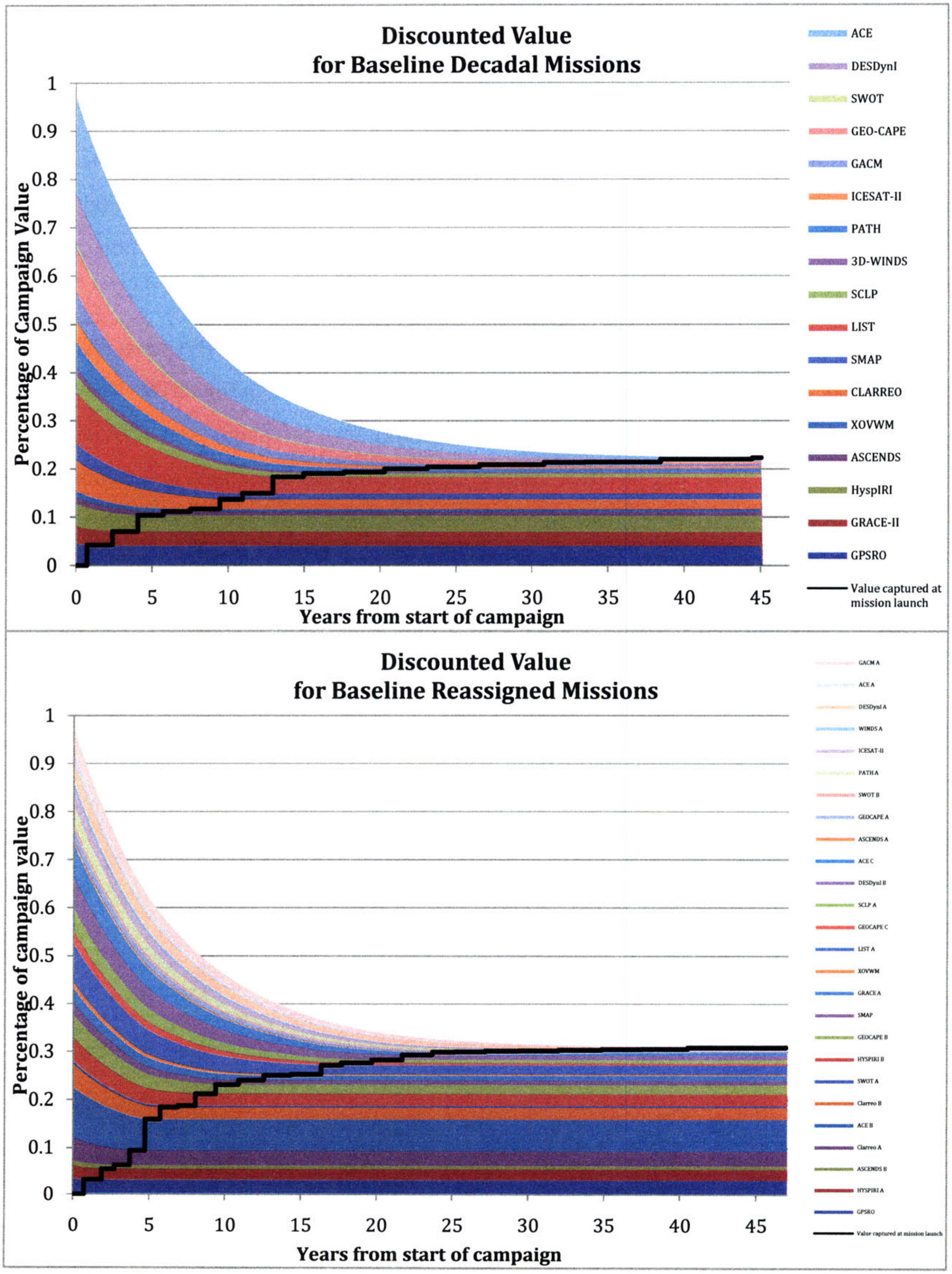


Figure 45. Discounted Value over Time

The reassigned mission set, although more expensive overall, is more effective at accruing benefit quickly (Figure 46). The biggest separation occurs 4 years into the campaign when the reassigned campaign schedules the ACE-B mission. A significant portion of ACE's value is accrued early on in the campaign, as opposed to the Decadal campaign, which schedules the entire ACE mission 40 years later.

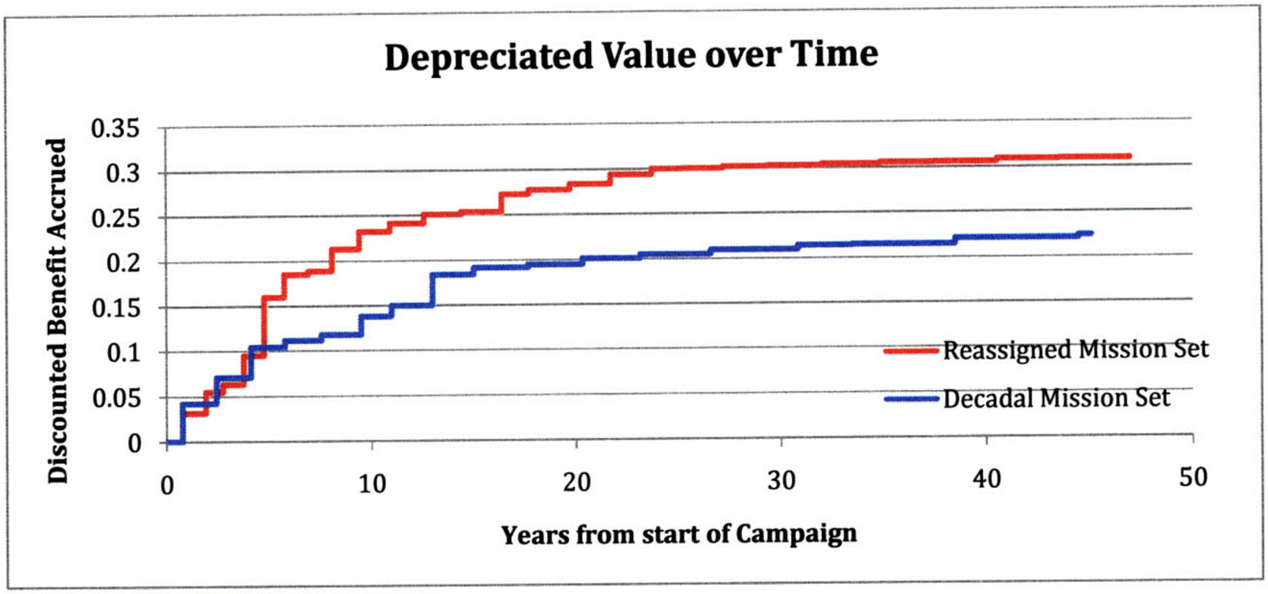


Figure 46. Comparison of Discounting

The key difference between mission sets campaigns are summarized in Table 28. The Decadal mission set is slightly less expensive, and its campaign will complete a few years earlier; however there is a huge difference in discounted value. The reassigned campaign accrues as much value in 9.5 years as the Decadal campaign accrues in 44.5.

	Discounted Campaign Value	Final Launch Date	Total Cost ($M)
Decadal Mission Set	0.22	2054.5	13353
Reassigned Mission Set	0.31	2057.0	14098

Table 28. Simulation Results Summary

5.2.4 Interpretation

The reassigned campaign is much more effective because breaking apart missions changes their cost to benefit ratios (Figure 47). Missions in is set on average accrue more benefit per dollar than missions in the Decadal set. The most valuable campaign (the least discounting) will schedule the high benefit-to-cost missions first.

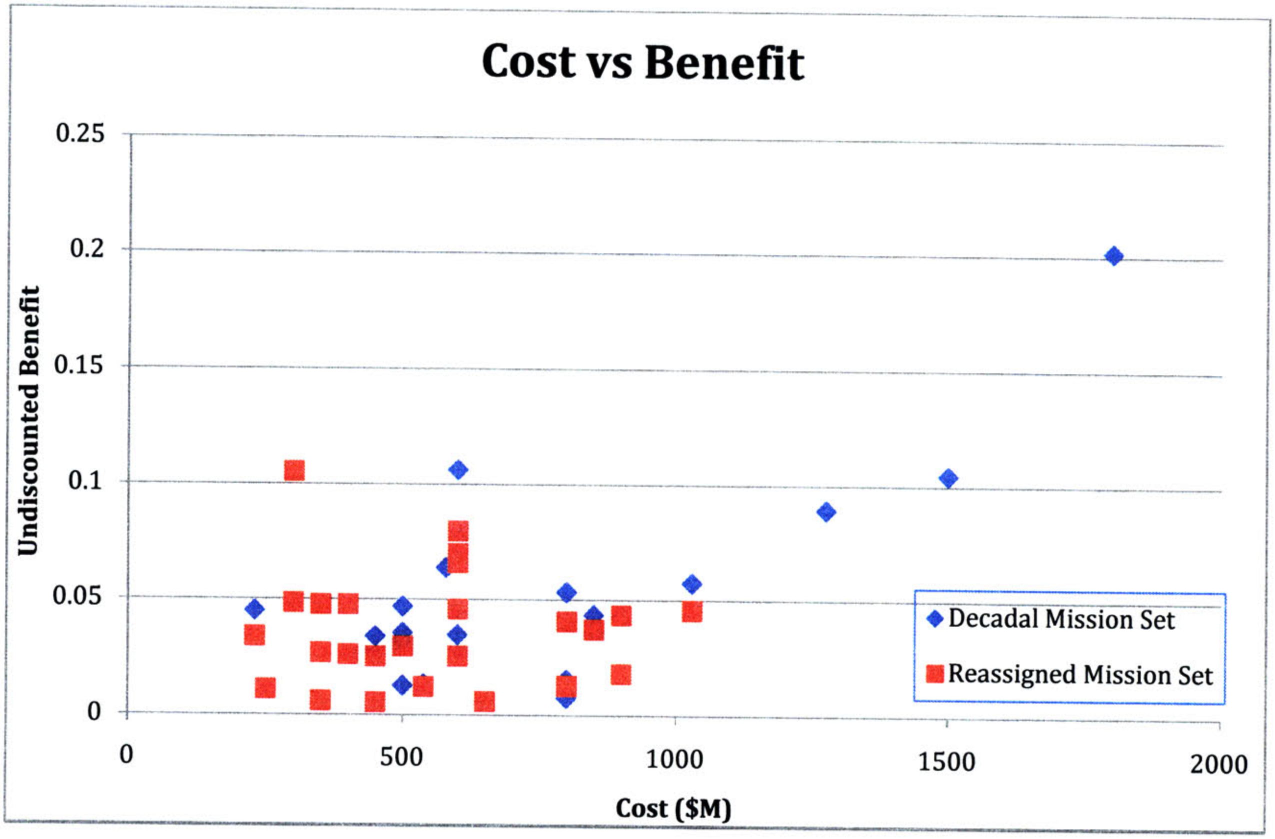


Figure 47. Cost to Benefit

The algorithm chosen for scheduling, however, does not take into account the benefit of each mission, as the Decadal Survey had no explicit system for enumerating value when it designed the Decadal campaign. Breaking the campaign into a series of smaller missions allows a campaign to accrue benefit before discounting takes a significant toll.

5.3 Completing the NASA Campaign

5.3.1 Motivation

A second simulation was conducted to consider rearchitecting the Decadal campaign from the perspective of NASA planners. This analysis was conducted to inform campaign design decisions given the high-level decisions that have already been made.

5.3.2 Parameters

In this more limited experiment the same set of mission and scenario parameters described in the previous section were utilized with three significant changes:

1. First, this simulation only allowed the scheduling of the 15 NASA missions and not the two NOAA missions. It is not known at this time how integrated NASA and NOAA efforts will be in completing the Decadal Survey; hence it is assumed that the NOAA missions will be handled independently.
2. Second, the SMAP and ICESat-II missions are already assigned launch dates. Currently these two missions are the most well-developed and have been tentatively scheduled to launch in 2013 and 2015, respectively. For this simulation it is assumed that SMAP will launch in 2013.5, and that ICESAT-II will launch next, with the exact date being a function of the annual budget, as discussed in 4.1.2.1. Once again, the budget is assumed to be $300M/year.
3. Third, the campaign is limited to a 20-year span, starting in 2010. No missions are scheduled after 2030 because it is unknown if NASA has the capability for such far-horizon planning.

Because of these parameters, the value remaining to be accrued is different than in previous simulations (Figure 48). The contributions of NOAA to the entire campaign are represented by the top purple area—this is not eligible for NASA campaign planning. The contributions to campaign benefit from SMAP and ICESat-II are already fixed, as represented by the black line. At the time of ICESat-II launch (6.3 years into the campaign), only 45% of the total benefit is still available to be scheduled.

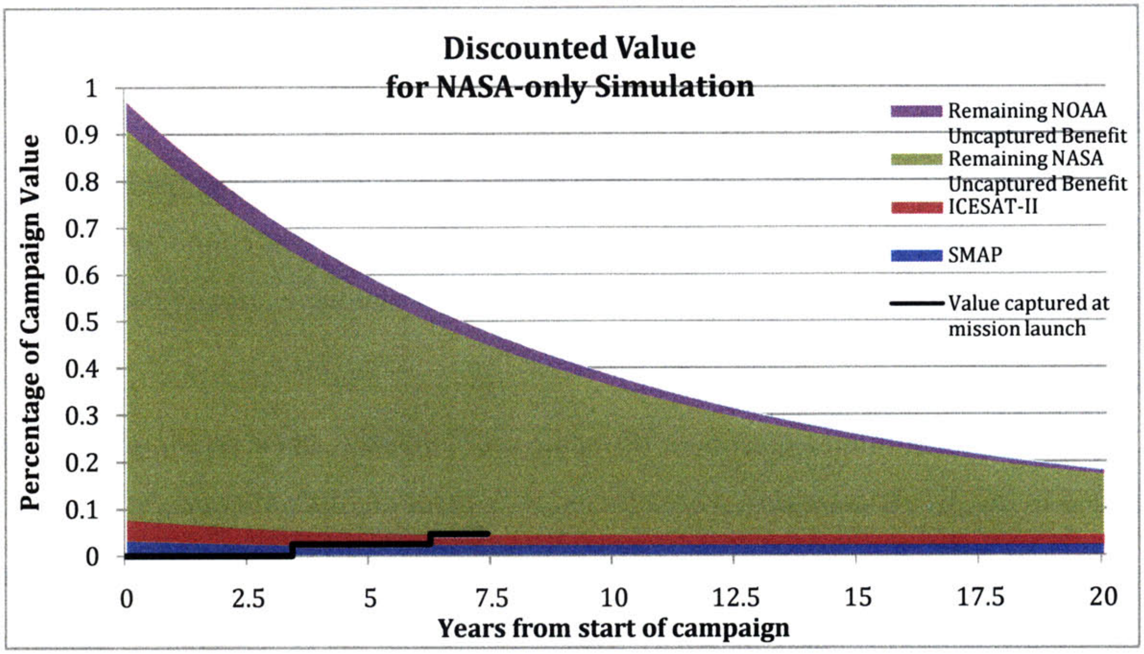


Figure 48. Uncaptured Benefit at start of NASA-only simulation

5.3.3 Results

The results of the simulations are displayed in Table 29. In this table, missions are divided into three tiers: those that were fixed in the simulation, those launching between 2017 and 2023, and those launching between 2024 and 2030. The fixed missions are highlighted in green. Reassigned missions that also appear in the original mission set schedule are boxed in pink. Missions that are not represented by both schedules are depicted in gray.

	Reassigned Mission Set		Original Mission Set	
Fixed	SMAP	2013.5	SMAP	2013.5
	ICESAT-II	2016.3	ICESAT-II	2016.3
2017-2023	ASCENDS B	2017.2	HyspIRI	2018.0
	ACE B	2018.2	ASCENDS	2019.7
	CLARREO A	2019.2	GRACE-II	2021.3
	CLARREO B	2020.2	CLARREO	2023.3
	HYSPIRI B	2021.3		
	HYSPIRI A	2022.5		
	SWOT A	2023.7		
2024-2030	GEOCAPE B	2025.0	LIST	2025.3
	GEOCAPE C	2026.3	SCLP	2027.3
	GRACE A	2028.0	PATH	2029.9
	ACE C	2030.0		

Table 29. NASA-only Campaign Schedules

All of the 2017-2023 missions from the Decadal mission set are at least partially represented in the free-flyer sequence. The only instrument missing is ASCENDS A, which contains the two LIDAR instruments from the original mission concept. None of the 2024-2030 missions are represented. Instead, free flyers from SWOT, GEOCAPE, and ACE are included in the campaign. Each of these missions were originally represented in the tier "C" of the original Decadal resequencing (5.1.3, Table 23).

As was seen in the previous section, a comparison of the discounted value of each campaign indicates the reassigned, smaller mission set is more valuable (Table 30). The depreciation of value over time for both campaigns can be found in Figure 49, but as in the previous analysis, the high benefit-to-cost missions of the reassigned campaign make it better suited to accruing value. This is particularly evident in the scheduling of the originally large ACE and GEOCAPE components early on—the Decadal missions provide significant benefit, more of which can be realized when the missions are split into smaller pieces.

NASA-only campaign			
	Discounted Campaign Value	Final Launch Date	Total Cost ($M)
Decadal Mission Set	0.143	2029.9	5379
Reassigned Mission Set	0.184	2030.0	5400

Table 30. NASA-only Results

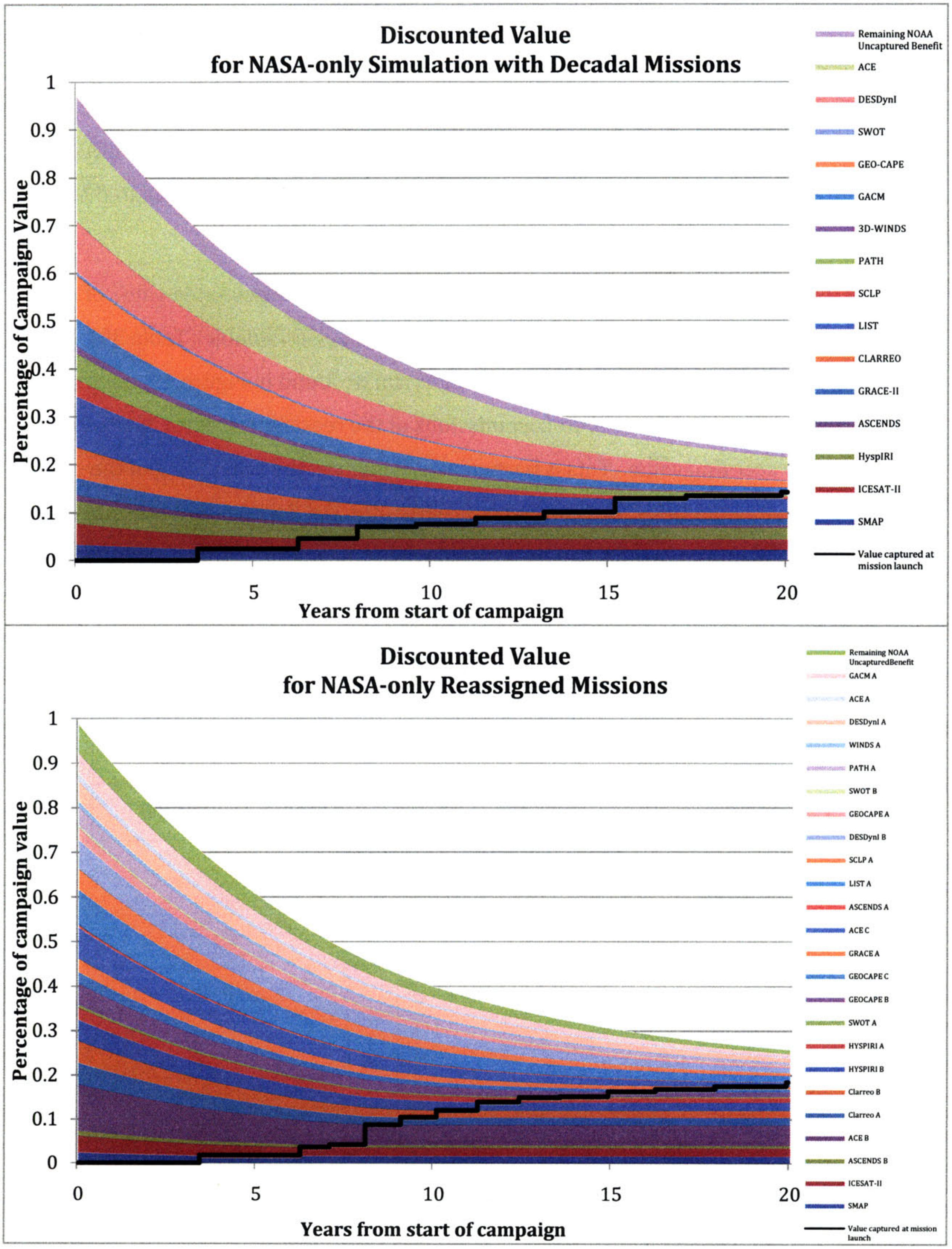


Figure 49. NASA-only Discounted Value over Time

5.3.4 Interpretation

The results in Table 29 indicate that there are a number of missions that should be flown first. The HyspIRI, ASCENDS, GRACE-II, and CLARREO missions all deliver value at lower costs. Additionally, larger missions such as GEOCAPE and ACE should be considered for decomposition—their instruments are too valuable to tie up in budget risk factors and schedule at the end of the campaign.

5.4 Budget Sensitivity

5.4.1 Motivation

As a final analysis, the sensitivity of the NASA-only free-flyer campaign to budget variations was analyzed. Understanding the impacts of changes enables dialog between the campaign architect and policy makers.

5.4.2 Parameters

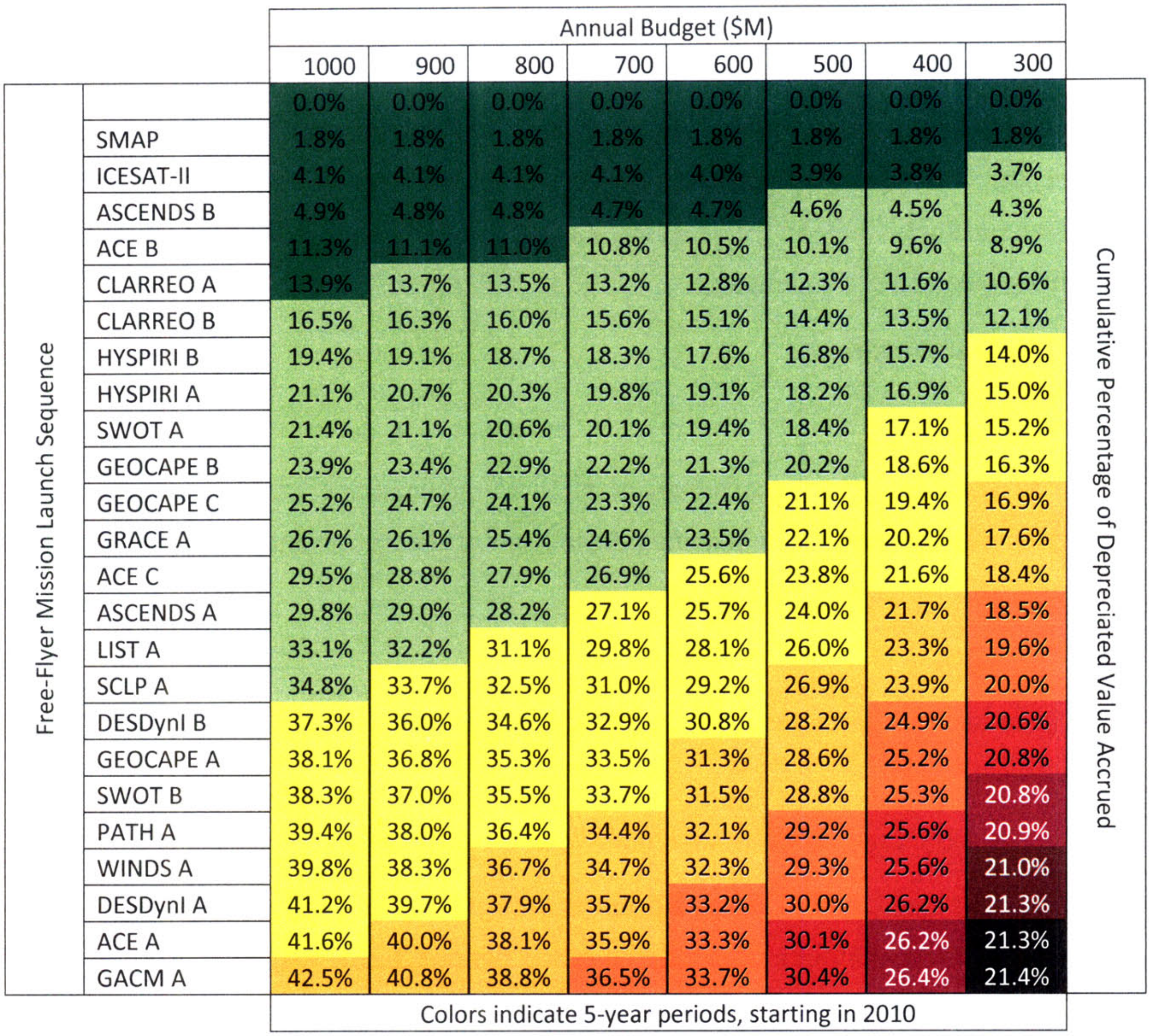
The scenario parameters discussed in the previous section were applied with the following exception:

- The campaign was not limited to a 20 year duration

For this simulation changing the budget did not actually change the sequence of missions—only the timing and depreciated value. Hence, only one sequence is presented.

5.4.3 Results

The results of the simulation are presented in Table 31. In this table the sequences of free-flyer missions is presented on the left. Each mission is mapped to an annual budget amount varying from $300-1000M/year. The percentage located in each box is the cumulative discounted value that has been captured at the time of that particular missions launch for that given budget. Additionally, the color scheme represents five-year increments in the actual schedule: dark green missions fly within the first 5 years of 2010, light green within 10 and so forth through black missions, which fly within 45 years.



Annual Budget ($M)

Free-Flyer Mission Launch Sequence	1000	900	800	700	600	500	400	300
	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SMAP	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%
ICESAT-II	4.1%	4.1%	4.1%	4.1%	4.0%	3.9%	3.8%	3.7%
ASCENDS B	4.9%	4.8%	4.8%	4.7%	4.7%	4.6%	4.5%	4.3%
ACE B	11.3%	11.1%	11.0%	10.8%	10.5%	10.1%	9.6%	8.9%
CLARREO A	13.9%	13.7%	13.5%	13.2%	12.8%	12.3%	11.6%	10.6%
CLARREO B	16.5%	16.3%	16.0%	15.6%	15.1%	14.4%	13.5%	12.1%
HYSPIRI B	19.4%	19.1%	18.7%	18.3%	17.6%	16.8%	15.7%	14.0%
HYSPIRI A	21.1%	20.7%	20.3%	19.8%	19.1%	18.2%	16.9%	15.0%
SWOT A	21.4%	21.1%	20.6%	20.1%	19.4%	18.4%	17.1%	15.2%
GEOCAPE B	23.9%	23.4%	22.9%	22.2%	21.3%	20.2%	18.6%	16.3%
GEOCAPE C	25.2%	24.7%	24.1%	23.3%	22.4%	21.1%	19.4%	16.9%
GRACE A	26.7%	26.1%	25.4%	24.6%	23.5%	22.1%	20.2%	17.6%
ACE C	29.5%	28.8%	27.9%	26.9%	25.6%	23.8%	21.6%	18.4%
ASCENDS A	29.8%	29.0%	28.2%	27.1%	25.7%	24.0%	21.7%	18.5%
LIST A	33.1%	32.2%	31.1%	29.8%	28.1%	26.0%	23.3%	19.6%
SCLP A	34.8%	33.7%	32.5%	31.0%	29.2%	26.9%	23.9%	20.0%
DESDynI B	37.3%	36.0%	34.6%	32.9%	30.8%	28.2%	24.9%	20.6%
GEOCAPE A	38.1%	36.8%	35.3%	33.5%	31.3%	28.6%	25.2%	20.8%
SWOT B	38.3%	37.0%	35.5%	33.7%	31.5%	28.8%	25.3%	20.8%
PATH A	39.4%	38.0%	36.4%	34.4%	32.1%	29.2%	25.6%	20.9%
WINDS A	39.8%	38.3%	36.7%	34.7%	32.3%	29.3%	25.6%	21.0%
DESDynI A	41.2%	39.7%	37.9%	35.7%	33.2%	30.0%	26.2%	21.3%
ACE A	41.6%	40.0%	38.1%	35.9%	33.3%	30.1%	26.2%	21.3%
GACM A	42.5%	40.8%	38.8%	36.5%	33.7%	30.4%	26.4%	21.4%

Cumulative Percentage of Depreciated Value Accrued

Colors indicate 5-year periods, starting in 2010

Table 31. Budget Sensitivity

5.4.4 Interpretation

Budget plays a huge role in the actual benefit accrued by each mission. In comparing the original mission set to the free-flyer set in section 5.2 it was noted that in less than ten years the free-flyer campaign accrued as much value as the entire Decadal campaign in 45 years. Similarly, doubling the budget from $300M to $600M results in the larger-budget campaign capturing as much benefit in less than ten years than the smaller budget captures in 45 years.

6 Conclusions and Future Work

Chapter 6 provides conclusions and recommendations for Decadal campaign architecture development using the CSTM. Additionally, areas for future work and model improvement are identified.

6.1 Conclusions

This thesis has shown that system architecting of the Decadal campaign can realistically reproduce the decision logic of the Decadal Survey, while accurately capturing the necessary constraints and value functions in an automated manner. This capability provides decision makers a key tool for dealing with uncertainty by enabling to evaluate the impacts of decisions with respect to the entire campaign.

This thesis illustrated a technique for tracing stakeholder value to campaign architecture decisions through the use of science traceability. A framework for campaign analysis was presented and applied to the Decadal campaign. Relationships between campaign elements were enumerated using stakeholder modeling, the Decadal Survey, and surveys of NASA scientists and engineers. This model for tracing value, the CSTM, was then validated against the Decadal Survey.

The CSTM led to several observations about the Decadal campaign. First, although each of the 17 proposed missions are "research" missions, there are significantly differences in the level of benefit expected from each mission. While the Decadal Survey does not explicitly consider the value of each mission, it may be desirable to apply the value traceability as a constraint in scheduling. Secondly, there is a disconnect between the objectives of the Decadal Survey and the missions proposed to accomplish those objectives.

Additionally, this thesis presented a refinement for a technique for scheduling space-based earth observation campaigns. The decision logic of the Decadal Survey was captured through the development of constraints and value functions, which, applied by an algorithm, allow the systematic design and evaluation of a large number of possible solutions. This algorithm was validated against the logic and sequence proposed in the Decadal Survey.

The CSTM scheduling algorithm reflects three primary criteria: TRL, cost, and fairness. TRL is used to ensure individual instrument development does not negatively affect the entire campaign. Cost is used to mitigate the risks of mission cost overruns. Fairness is used to ensure that different sciences communities are equally satisfied over the course of the campaign.

Finally, this thesis examined the impacts of key changes that have occurred since the publishing of the Decadal Survey to provide insight and recommendations for the earth observation program. Several Scenarios were presented:

- The campaign sequence proposed by the Decadal Survey was compared to the sequence generated using the latest cost and TRL assumptions with the CSTM algorithm. This simulation revealed the need to consider benefit in campaign design.
- The campaign generated with the latest cost and TRL assumptions of the 17 Decadal missions was compared to a campaign of missions in which the instrument pairing of the 17 missions were broken apart. This simulation revealed that there are significant benefits associated with flying smaller missions.
- The campaign generated with the updated set of 17 missions was compared to a corresponding campaign generated from the repaired instruments mission set to analyze the impacts of campaign decision that have already been made. This simulation revealed that the current choice of missions may not be optimally suited to the delivery of value.
- The sensitivity of value delivery to campaign budget was analyzed. This quantified the desirability of an increased budget by presenting the loss to campaign value implicit in having a smaller annual budget.

6.2 Future Work with Earth Observation Systems

This section describes the areas for future work identified in previous chapters. Preliminary approaches are suggested.

Revise measurements and measurement mappings: The instrument-measurement mapping process revealed several areas where the common set of measurements could be expanded or improved. Several areas were identified where measurements can be combined, such as the vegetation measurements; and several new measurements were identified. Additionally, the GACM instrument mapping needs to be completed. Revised surveys can be complete by working in conjunction with NASA Goddard.

Investigate the contributions of International space programs: The CSTM methodology allows for the easy inclusion of international mission through the measurement framework. The CEOS database can be utilized to identify substitute instruments which capture the requisite measurements. This information can be utilized to inform synergistic scheduling, and in some cases, allow for the demanifestation of a particular mission to constraint the size of the campaign

.

Expand the solution space through instrument-mission architecting: This thesis only analyzed two hand-crafted mission sets, a process which can be automated. Given a known understanding of both instrument properties and requirements, and measurement synergies, a separate mission set generator can be developed which parametrically estimates cost parameters for new missions. This could be combined with the scheduling algorithm to identify the globally optimum missions set and schedule.

Explore the implementation of synergistic measurement qualities: In this thesis the quantification of measurement synergies was identified as an area for immediate research. First the specific relationships amongst measurements must be captured. Then they can be incorporated into the CSTM as a value function reflective of both instrument-mission relationships and mission scheduling. A survey has already been developed to quantify these relationships, although it has not been completed.

Expand campaign elements to include ground and air networks: The CSTM framework in this thesis is only applied to space-mission campaign elements. It is desirable to expand the framework to include other resources, such as ground and air observation campaigns. This will require the development of separate value functions and constraints, but having multiple campaign elements in a common framework will allow a robust generation of campaign architectures.

Algorithm experimentation: The results in Chapter 5 indicate that even the explicit Decadal decision rules do not necessarily reflect the tacit Decadal logic. The binning of missions into three tiers, and the breakdown of those tiers when considered with updated assumptions indicates a more sophisticated decision process. Although the CSTM algorithm was validated against the Decadal schedule with the Decadal assumptions, it is desirable to revisit different algorithmic considerations, such as benefit or even limited sequences position shifting.

Computational techniques: The results generated in Chapter 5 were all products of a manual implementation of the CSTM algorithm. Several techniques are being explored to automate the process and process large batches of possible solutions. This includes multi-objective optimization, linear programming, and the use of genetic algorithms to schedule missions. It is desirable to be able to both enumerate and evaluate large numbers of feasible solutions, so that the global maximum can be identified.

7 Appendix A: NASA Worksheet Instructions

Questionnaire

There are three parts to this questionnaire. The first section is designed to understand the Decadal Survey Missions as originally proposed. The second section is designed to understand which measurements individual instruments are taking. The third section is designed to understand the synergistic effects of taking certain measurements concurrently.

Section 1: Decadal Baseline

Instructions:

The attached spreadsheet contains a matrix of the 17 Decadal Survey Missions and a list of proposed measurements. Using a scale of 0-4 (see table below) please rate the usability of data produced by this Mission with regards to a specific measurement. You are answering the question "How well does this Mission produce measurements of this type", so please consider the output of the Mission as a whole.

The usability of data produced is a combination of both amount and quality. If a Mission produces a combination of amount and quality not listed, pick the lower scoring option. Presumably, most of the Decadal Survey Missions are optimized to produce large amounts of high quality data for the specific measurements they were designed to produce; however it is possible they can produce secondary measurements in a sub-optimal manner. You will notice that the measurements are decomposed into three layers of abstractions:

Science categories	(i.e. 1. Atmosphere, 2. Land, 3. Ocean, etc)
General measurements	(i.e. 1.1 Aerosol Properties, 1.2 Atmospheric temp fields etc)
Specific measurements	(i.e. 1.1.1 Aerosol height/optical depth, etc)

Please rate each mission to the lowest level of abstraction that you are able. If you feel a measurement is missing from the list, please add it to the bottom of the matrix and fill in accordingly for all 17 Missions, as well as annotating where it should fall into this hierarchy.

Usability of Data Produced	Score
This Mission produces **no data** for this measurement	0
This Mission produces **low quality data** for this measurement **OR** this Mission produces **a small amount of data** for this measurement	1
This Mission produces **moderate quality data** for this measurement **OR** this Mission produces **a moderate amount of data** for this measurement	2
This Mission produces **high quality data** for this measurement **OR** this Mission produces **a large amount of data** for this measurement	3
This Mission produces **the highest possible quality data** for this measurement **AND** this Mission produces **a large amount of data** for this measurement	4

Part 2: Instrument Baseline

Instructions:

The second tab on the spreadsheet contains a matrix of the individual instruments proposed in the Decadal Survey Missions and a list of measurements. Using a scale of 0-4 (see table below) please rate the usability of data produced by this Instrument with regards to a specific measurement. You are scoring Instruments as isolated things: consider only the measurements produced by this specific Instrument. You are answering the question "How well does this Instrument produce measurements of this type". The usability of data produced is a combination of both amount and quality. If an Instrument produces a combination of amount and quality not listed, pick the lower scoring option.

Unlike in Section 1, it may be unlikely that these Instruments are optimized for certain measurements, and instead rely upon synergistic effects (which will be captured in section 3) to create an optimal measurements. Please do your best to capture the Usability of each instrument in isolation. If you added any measurements in Section 1, please add them to this list as well.

Additionally, for each instrument please record the expected per unit cost of the instrument. Space has been provided to do this.

Usability of Data Produced	core
This Instrument produces **no data** for this measurement	
This Instrument produces **low quality data** for this measurement **OR** this Instrument produces **a small amount of data** for this measurement	
This Instrument produces **moderate quality data** for this measurement **OR** this Instrument produces **a moderate amount of data** for this measurement	
This Instrument produces **high quality data** for this measurement **OR** this Instrument produces **a large amount of data** for this measurement	
This Instrument produces **the highest possible quality data** for this measurement **AND** this Instrument produces **a large amount of data** for this measurement	

Part 3: Measurement Synergies

Instructions:

The following pages contain matrices of measurements correlated against other measurements. This section is intended to capture the synergistic science benefits to having concurrent measurements. Using a scale of 0-4 (see table below) please rate the increase in usability of data of one measurement when complimentary measurements are made. You are answering the question "How does this measurement benefit from the presence of another measurement".

If you added any measurements in Sections 1 and 2, please add them to this matrix as well. Looking at the matrices, you are evaluating the affects of the columns upon the rows, that is, "assuming you have the measurement in a particular horizontal row, and someone were to give you the data from the measurement is the vertical column, how would it change the usability of your measurement". Because of the different layer of abstraction being used in this survey, once again please fill in the lowest level possible. We'd ideally like every single white colored cell to be filled in, even if they are mostly zeros.

It is expected that most Measurements will not be affected by Complimentary Measurements (i.e. 3.3.1 Ocean salinity is not affected by 4.1.4 Ice sheet velocity) and will score zeros, however, some Measurements may be entirely derived from combinations of Complimentary Measurement (and would hence score fours). Please choose the score that best captures the positive complimentary effects.

Usability of Measurement	core
This Measurement is **not affected** by this Complimentary Measurement	
This Measurement is **slightly more useable** with the addition of this Complimentary Measurement	
This Measurement is **moderately more useable** with the addition of this Complimentary Measurement	
This Measurement is **significantly more useable** with the addition of this Complimentary Measurement	
This Measurement **completely requires** the addition of this Complimentary Measurement	

8 Appendix B: Reference Sequence

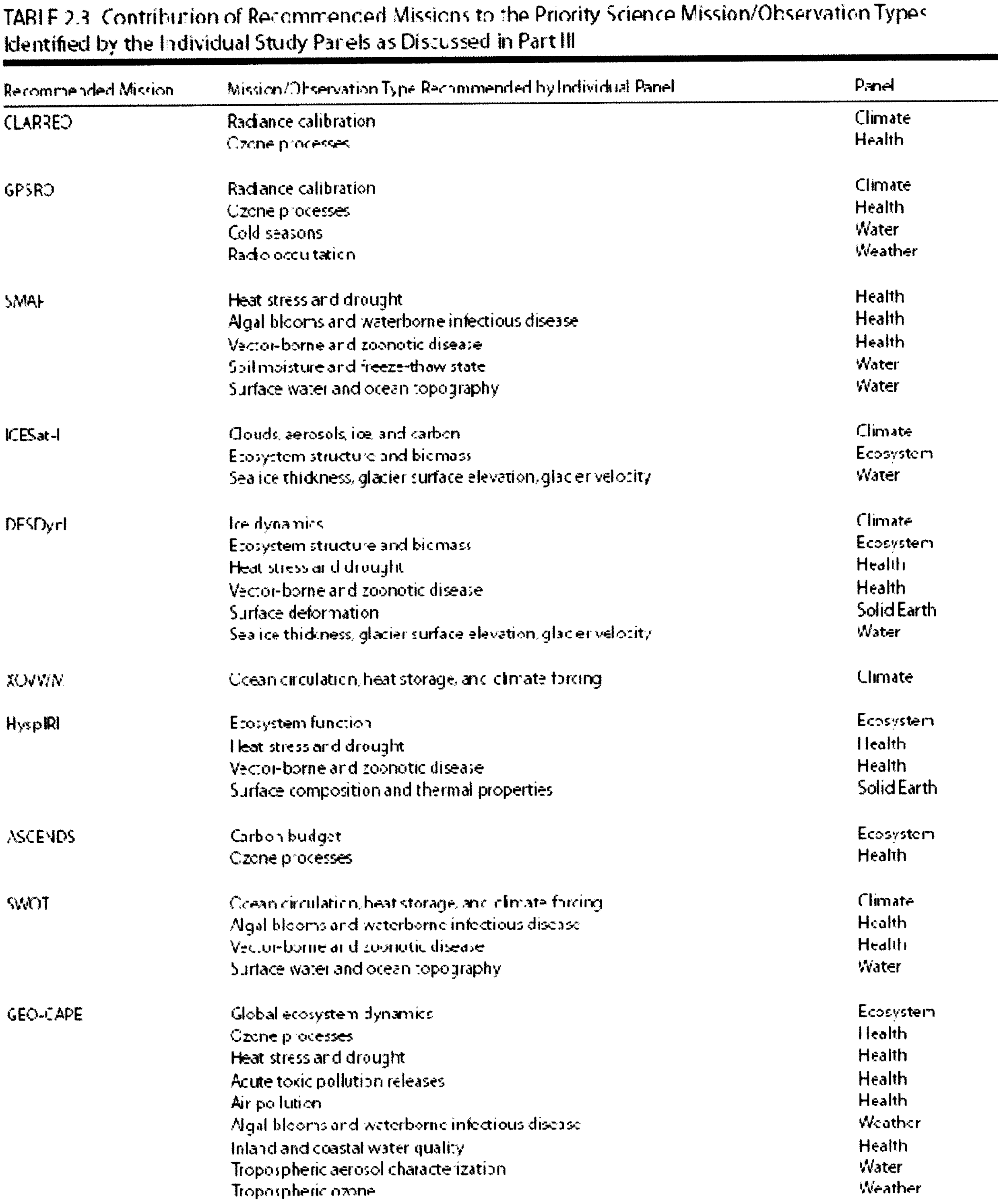


TABLE 2.3 Contribution of Recommended Missions to the Priority Science Mission/Observation Types Identified by the Individual Study Panels as Discussed in Part III

Recommended Mission	Mission/Observation Type Recommended by Individual Panel	Panel
CLARREO	Radiance calibration	Climate
	Ozone processes	Health
GPSRO	Radiance calibration	Climate
	Ozone processes	Health
	Cold seasons	Water
	Radio occultation	Weather
SMAP	Heat stress and drought	Health
	Algal blooms and waterborne infectious disease	Health
	Vector-borne and zoonotic disease	Health
	Soil moisture and freeze-thaw state	Water
	Surface water and ocean topography	Water
ICESat-II	Clouds, aerosols, ice, and carbon	Climate
	Ecosystem structure and biomass	Ecosystem
	Sea ice thickness, glacier surface elevation, glacier velocity	Water
DESDynI	Ice dynamics	Climate
	Ecosystem structure and biomass	Ecosystem
	Heat stress and drought	Health
	Vector-borne and zoonotic disease	Health
	Surface deformation	Solid Earth
	Sea ice thickness, glacier surface elevation, glacier velocity	Water
XOVWM	Ocean circulation, heat storage, and climate forcing	Climate
HyspIRI	Ecosystem function	Ecosystem
	Heat stress and drought	Health
	Vector-borne and zoonotic disease	Health
	Surface composition and thermal properties	Solid Earth
ASCENDS	Carbon budget	Ecosystem
	Ozone processes	Health
SWOT	Ocean circulation, heat storage, and climate forcing	Climate
	Algal blooms and waterborne infectious disease	Health
	Vector-borne and zoonotic disease	Health
	Surface water and ocean topography	Water
GEO-CAPE	Global ecosystem dynamics	Ecosystem
	Ozone processes	Health
	Heat stress and drought	Health
	Acute toxic pollution releases	Health
	Air pollution	Health
	Algal blooms and waterborne infectious disease	Weather
	Inland and coastal water quality	Health
	Tropospheric aerosol characterization	Water
	Tropospheric ozone	Weather

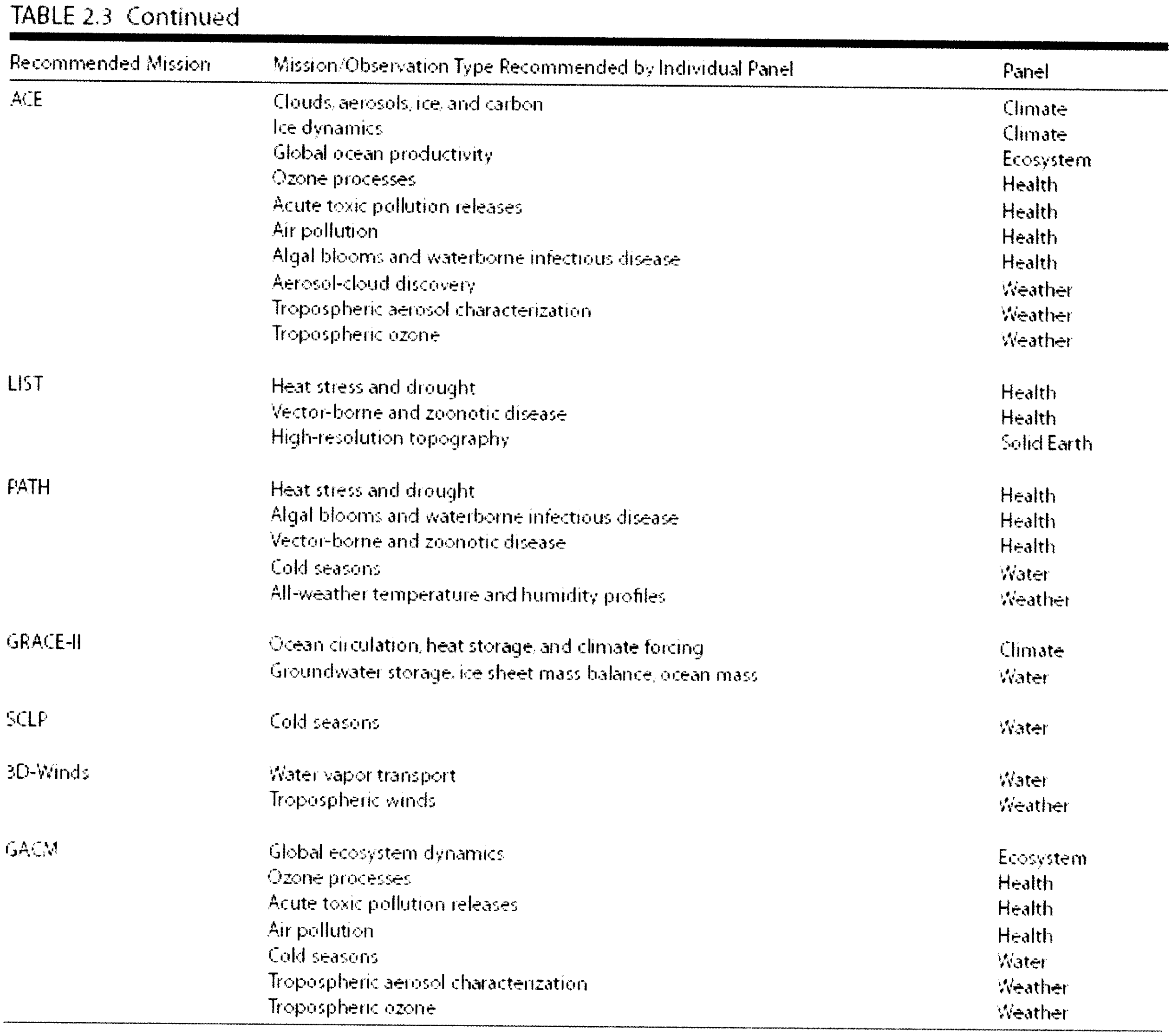


TABLE 2.3 Continued

Recommended Mission	Mission/Observation Type Recommended by Individual Panel	Panel
ACE	Clouds, aerosols, ice, and carbon	Climate
	Ice dynamics	Climate
	Global ocean productivity	Ecosystem
	Ozone processes	Health
	Acute toxic pollution releases	Health
	Air pollution	Health
	Algal blooms and waterborne infectious disease	Health
	Aerosol-cloud discovery	Weather
	Tropospheric aerosol characterization	Weather
	Tropospheric ozone	Weather
LIST	Heat stress and drought	Health
	Vector-borne and zoonotic disease	Health
	High-resolution topography	Solid Earth
PATH	Heat stress and drought	Health
	Algal blooms and waterborne infectious disease	Health
	Vector-borne and zoonotic disease	Health
	Cold seasons	Water
	All-weather temperature and humidity profiles	Weather
GRACE-II	Ocean circulation, heat storage, and climate forcing	Climate
	Groundwater storage, ice sheet mass balance, ocean mass	Water
SCLP	Cold seasons	Water
3D-Winds	Water vapor transport	Water
	Tropospheric winds	Weather
GACM	Global ecosystem dynamics	Ecosystem
	Ozone processes	Health
	Acute toxic pollution releases	Health
	Air pollution	Health
	Cold seasons	Water
	Tropospheric aerosol characterization	Weather
	Tropospheric ozone	Weather

Figure 50. Reference Sequence (National Research Council, 2007)

9 Appendix C: Measurement Weights

1) Atmosphere	17.8451909
1.1. Aerosol properties	4.17064599
1.1.1 aerosol height/optical depth	1.18693182
1.1.2 aerosol composition, physical and chemical properties	1.01646373
1.1.3 aerosol scattering properties	0.47539336
1.1.4 aerosol extinction profiles	0.47539336
1.1.5 aerosol size and size distribution	1.01646373
1.2. Atmospheric temperature fields	0.96094872
1.2.1 Atmospheric temperature fields	0.96094872
1.3. Water vapor	2.07790028
1.3.1 Water vapor profiles	1.54489052
1.3.2 Water vapor transport	0.53300977
1.4. Atmospheric winds	1.18114774
1.4.1 atmospheric wind speed	0.59057387
1.4.2 atmospheric wind direction	0.59057387
1.5. Cloud type, amount, and top temp.	0.68854312
1.5.1 cloud top temperature	0.2125
1.5.2 Cloud type	0.20923951
1.5.3 Cloud amount/distribution	0.26680361
1.6. Cloud particle properties and profile	0.71086668
1.6.1 cloud height/optical thickness	0.20923951
1.6.2 cloud particle size distribution	0.29238766
1.6.3 ice/water transition in clouds	0.20923951
1.7. Liquid water and precipitation rate	0.84506002
1.7.1 Precipitation rate	0.72700641
1.7.2 droplet size	0.11805361
1.8. Ozone	0.87325499
1.8.1 stratospheric ozone	0.08314815
1.8.2 tropospheric ozone	0.62376068
1.8.3 ozone precursors	0.16634615
1.9. Radiation budget	2.37740456
1.9.1 total solar irradiance	0.833
1.9.2 spectrum of earth IR radiance	0.97371225
1.9.3 GPS radio occultation	0.57069231
1.10. Trace gases (excluding ozone)	3.9594188
1.10.1 short-lived reactive species (OH, HO2, NO2, ClO, BrO, IO, HONO2, HCl, CH2O)	0.08314815
1.10.2 isotope observations (HDO, H218O, H2O)	0.08314815
1.10.3 tropospheric column SO2, NO2, formaldehyde	0.62376068

2) Land	11.47027
2.1. Albedo and reflectance	0
2.1.1 Albedo and reflectance	0
2.2. Land topography	0.889365
2.2.1 surface deformation	0.307857
2.2.2 Hi-res topography	0.581508
2.3. Soil moisture	2.139607
2.3.1 Freeze/thaw state	0.901429
2.3.2 soil moisture	1.238179
2.4. Vegetation	3.55655
2.4.1 vegetation type	0.2125
2.4.2 vegetation state	1.58625
2.4.3 vegetation height	0.8789
2.4.4 canopy density	0.8789
2.5. Surface temperature (land)	0.667673
2.5.1 Surface temperature (land)	0.667673
2.6. Multi-purpose imagery (land)	3.15516
2.6.1 land use	0.060095
2.6.2 landcover status	0.792862
2.6.3 disaster monitoring	1.421156
2.6.4 hydrocarbon reservoir monitoring	0.564405
2.6.5 surface composition	0.256548
2.6.6 inland water quality	0.060095
2.7 Surface water distribution	1.061918
2.7.1 river and lake elevation	0.500794
2.7.2 flood monitoring	0.273651
2.7.3 groundwater storage	0.287474
3) Ocean	6.65481
3.1. Ocean colour/biology	1.294709
3.1.1 Ocean color	1.294709
3.2. Ocean topography/currents	3.024277
3.2.1 surface circulation	0.907817
3.2.2 seafloor topography	0.407024
3.2.3 coastal upwelling	0.444267
3.2.4 thermal plumes	0.187083
3.2.5 river plumes/sediment fluxes	0.691445
3.2.6 Ocean mass distribution	0.38664
3.3. Ocean salinity	0

1.10.4 Benchmark tracer data (CO2, CO, HDO/H2O, NOy, N2O, CH4, halogen source molecules)	0.08314815
1.10.5 visible atmospheric plumes	0.0575641
1.10.6 pollutant particle size	0.0575641
1.10.7 pollutant gross vertical structure	0.0575641
1.10.8 vertically resolved CO (Daytime only)	1.04026068
1.10.9 CO vertically resolved CO (Day/Night)	1.04026068
1.10.11 C02 concentrations	0.4165
1.10.12 02 concentrations	0.4165
4) Snow and Ice	4.29579696
4.1. Ice sheet topography	2.09974537
4.1.1 ice sheet volume	0.371875
4.1.2 Glacier surface elevation	0.49707341
4.1.3 glacier mass balance	0.65934854
4.1.4 Ice sheet velocity	0.19957341
4.1.5 Ice Sheet topography	0.371875
4.2. Snow cover, edge and depth	1.49940476
4.2.1 snow-water equivalence	0.37485119
4.2.2 snow depth	0.37485119
4.2.3 snow wetness	0.37485119
4.2.4 snow cover	0.37485119
4.3. Sea ice cover, edge and thickness	0.69664683
4.3.1 Sea ice thickness	0.49707341
4.3.2 Sea ice cover	0.19957341

3.3.1 Ocean salinity	0
3.4. Ocean surface winds	0.863718
3.4.1 Ocean surface wind speed	0.431859
3.4.2 Ocean surface wind direction	0.431859
3.5. Surface temperature (ocean)	0.831442
3.5.1 Surface temperature (ocean)	0.831442
3.6. Ocean wave height and spectrum	0
3.6.1 Ocean wave height and spectrum	0
3.7. Multi-purpose imagery (ocean)	0.640664
3.7.1 visible hydrospheric pollution plumes	0.057564
3.7.2 coral reef health/extent	0.5831
5) Gravity and Magnetic fields	0.153929
5.1. Gravity, magnetic and geodynamic	0.153929
5.1.1 gravity field variations	0.153929
5.1.2 magnetic field variations	0

10 Works Cited

Bretherton, F. P. (1985). Earth System Science and Remote Sensing. *PROCEEDINGS OF THE IEEE*.

CBO. (2009). *The Budgetary Implications of NASA's Current Plans for Space Exploration.* Washington D.C.: Congressional Budget Office.

CNA. (2007, April). *National Security and the Threat of Climate Change.* Retrieved April 18, 2009, from http://www.cna.org/nationalsecurity/climate/report/

Colson, J. (2008). *System Architecting of a Campaign of Earth Observing Satellites.*

Connerton, R. (2008, July). Chief Engineer. (T. Seher, Interviewer)

Elachi, C., & Van Zyl, J. (2006). *Introduction to the Physics and Techniques of Remote Sensing (2nd Edition).* Hoboken, New Jersey: John Wiley & Sons.

GAO. (2009). *NASA: Assessment of Selected Large-Scale Projects.* Government Accountability Office.

Larson, W. J., & Wertz, J. R. (1999). *Space Mission Analysis and Design (Third Edition).* El Segundo, CA: Microcosm Press.

Murman, E. e. (2002). *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative.* New York: Palgrave .

NASA. (2009, January 12). Climate Observing & Prediction System Data Gap Analysis v12.

NASA. (2006). *Earth Observation Handbook.* Washington D.C.: National Aeronautics and Space Administration.

NASA. (1989). *Earth system science: A program for global change.*

NASA. (2008). *Fiscal Year 2009 Budget Estimates.* National Aeronautics and Space Administration.

NASA. (2007). *Systems Engineering Handbook.* Washington D.C.: National Aeronautics and Space Administration.

National Research Council. (2007). *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* National Academies Press.

Public Law 111 - 5 - American Recovery and Reinvestment Act of 2009. (2009, Februray 17). Retrieved April 18, 2009, from Government Printing Office: http://www.gpo.gov/fdsys/pkg/PLAW-111publ5/pdf/PLAW-111publ5.pdf

REMOTE SENSING. (n.d.). Retrieved April 20, 2009, from REMOTE SENSING TUTORIAL: http://www.fas.org/irp/imint/docs/rst/Sect2/Sect2_1a.html

Sutherland, T. A. (2009). *Stakeholder Value Network Analysis for Space-Based Earth Observations.*

Volz, S. (2008, February 7). NASA Earth Science New Mission Concepts for the Future.

Weiss, J. R., Smythe, W. D., & Lu, W. (2005). *Science Traceability.* Pasedena: Jet Propulsion Laboratory.