Integrating Spacecraft and Aircraft in Earth Observation System Architectures

by

Brandon H. Suarez
B.S., Aerospace Engineering
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ABSTRACT

The Global Earth Observation System (GEOS) is the essential data gathering network that enables the advancement of Earth science. In recent years, efforts have been made to understand the major GEOS architectural tradeoffs. Several decision support tools have been developed, including the Campaign-level Science Traceability Matrix (CSTM). The CSTM is a framework designed to trace the benefit delivered by a campaign of Earth observing systems to relevant stakeholders. This thesis first presents the CSTM v1.1, an enhanced version of the original CSTM, which updates the scientific understanding captured in the framework. This benefit tracing framework is applied to the set of satellite missions recommended by the National Research Council Earth Science Decadal Survey. To support campaign scheduling, this thesis presents and applies a multi-objective Genetic Algorithm (GA), built using the Matlab GA toolkit. The algorithm seeks to maximize "Data Value", minimize the effects of "Data Gaps", and accounts for cost, budget, and technology readiness. The results show that under the current conditions, gaps in important measurements will arise in the near future as currently operational NASA Earth observation missions age and their replacements continue to experience development issues. This result motivates a systematic rethinking of measurement gap mitigation strategies and the use of airborne observational platforms in the GEOS.

The integration of aircraft into the GEOS is explored through three case studies. Three unique modes of operation for aircraft in Earth observation are presented and characterized. Based on the results of the case studies, a quantitative framework, called CSTM v2.0, is introduced. CSTM v2.0 uses a Rule-Based Expert System (RBES) that evaluates instruments at a level of fidelity that allows for comparison between aircraft and spacecraft. The GA campaign scheduling tool is used to understand the role of aircraft in the GEOS. The results of this analysis show that aircraft provide a short-term source of high value missions and are able to fill critical measurement gaps. This thesis recommends that aircraft be considered as operational platforms in future GEOS architectures, recognizing that autonomous systems promise significant benefits for Earth observation.

Thesis Supervisor: Edward F. Crawley
Title: Ford Professor of Engineering

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1. Introduction

1.1. Motivation

The Global Earth Observation System (GEOS) is the essential data gathering network that enables the advancement of Earth science. This thesis seeks a more comprehensive understanding of how observational platforms deliver benefit to the stakeholder community interested in Earth science through campaign definition and scheduling. This section presents the relevance of this research.

1.1.1. Earth Science and Climate Change

In 2007 the Intergovernmental Panel on Climate Change released their 4th report, which thoroughly examined existing climate data and projected current and future emissions. The report stated with "High Certainty" that changes will occur to the Earth's climate with negative consequences on the environment and the world's economy. (Intergovernmental Panel on Climate Change 2007) The report also admitted that changes are uncertain and difficult to predict creating a significant need for more Earth science data. The political response to this report and ones like it reflects the lack of influence of the Earth Science community on politicians and an unwillingness to commit resources to extensive observation programs. While this response is important, it is not the concern of this thesis. Regardless of the political response, Earth and climate scientists continue to press for a more complete understanding of the Earth system.

As with all areas of Earth science, the fidelity of models built to understand the future effects of climate change are limited by the amount of relevant data available. Scientists require current data to test models, validate hypotheses, and gain understanding of how the Earth system could respond to future human activity. This large amount of data collection can only occur with the coordinating efforts of government institutions and sufficient funding to establish useful programs. The National Aeronautics and Space Administration (NASA) is one of the organizations within the United States (US) focusing on problems related to climate change and other Earth Science fields. The National Oceanic and Atmospheric Administration (NOAA) is another key organization in the US Earth science community and will also be discussed in this thesis.

The Earth Science Division (ESD) leads the efforts within NASA to build programs that effectively collect data for Earth scientists. Through the use of various observation platforms such as spacecraft, aircraft, and ground stations the engineers and scientists at ESD are able to collect relevant data for the Earth science community. This data is distributed to institutions all over the US and the world and then integrated with various models other data to help scientists gain a better understanding of the Earth system.

1.1.2. The Earth Science Decadal Survey

In an effort to bring scientists together from all of the Earth Science disciplines, the Earth Science Decadal Survey was chartered by the National Research Council (NRC) Space Science Board (SSB) in 2004. The stated objectives of the Decadal Survey were to set out goals and outline missions for Earth Science in the 2010-2020 decade. (Committee on Earth Science and Applications 2007) The Decadal Survey is the first time that scientists from a broad range of Earth science fields came together to lay out a systematic plan for the future.

To facilitate the in-depth study the entire community was broken into six (6) thematically organized "Panels". These panels are: Human Health, Ecosystems, Climate Change, Solid Earth, Weather, and Water. The panels are discussed in more detail throughout this thesis as they form the stakeholder community of interest. Each panel prepared a report with a stated list of objectives and a set of missions that they determined could best fulfill their objectives over the 2010-2020 decade. These reports were combined to form a recommended set of satellite missions that would be implemented by NASA and NOAA. The final report was published in 2007 and has acted as the guiding document for NASA's ESD since then. The document is extensively referenced throughout this thesis. (Committee on Earth Science and Applications 2007)

1.1.3.Recent Events that affect Decadal Survey

Since the report was released in 2007, many of the assumptions that went into the decision making process have changed. This was reflected in a NASA report issued in June 2010 titled "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observation and Applications in Space". (National Aeronautics and Space Administration 2010a) This report cited many issues that have come about since the publication of the Decadal Survey as well as the rising mission costs and reduced budget now faced by NASA's ESD. In particular, there have been three big events that have hurt the original recommendations set forth; the failure on launch of OCO, the reorganization of NPOESS, and the recent failure of Glory.

Orbiting Carbon Observatory

The Orbiting Carbon Observatory (OCO) was a mission designed to map the Earth's carbon sources and sinks and would have been instrumental in carbon treaty monitoring as well as understanding the Earth's carbon cycle. (D Crisp et al. 2004) The mission was critical to the Earth science community and was intended to be a precursor to the ASCENDS mission by the Decadal Survey panels. On February 24th, 2009 the OCO spacecraft failed to reach orbit due to malfunctions with the fairing separation mechanisms. NASA has proposed to refurbish an engineering unit and launch OCO-2 in February 2013. (Boland et al. 2009)

NPOESS

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) was officially dismantled in February 2011 as cost overruns and programmatic issues have plagued the multi agency project for years. (Space News 2011a) NPOESS was a major precursor for the entire Decadal Survey as many of its measurements continued long term data series required by the Earth science community. The loss of NPOESS presents a critical gap in the Global Earth Observation System that NASA and NOAA have to patch with the use of smaller single agency missions and international missions.

Glory

NASA's Glory mission was meant to fill two important roles in the study of climate change by measuring total solar irradiance and aerosols. Both of these measurements are crucial to understanding the Earth system and specifically climate monitoring. (Mishchenko et al. 2007) On March 4th, 2011 the launch vehicle carrying Glory also failed to reach orbit. At the time of this writing, a Mishap Investigation Board has been formed but no root cause has been identified.

In the Preface of the final report on page xiv, the Decadal Survey points towards the need to re-evaluate their recommendations by writing:

"Participants in the survey were challenged by the rapidly changing budgetary environment of NASA and NOAA environmental satellite programs. [...] In the present survey, the foundation eroded rapidly over the course of the study in ways that could not have been anticipated. The recommended portfolio of activities in this survey tries to be responsive to those changes, but it was not possible to account fully for the consequences of major shocks that came very late in the study, especially the delay and descoping of the NPOESS program, whose consequences were not known even as this report went to press [...] and it was in no position to consider the implications of a possible large-scale reduction in funding and later delay of the GPM mission." (Committee on Earth Science and Applications 2007)

In addition, the Decadal Survey captured a growing sentiment among scientists that non-space-based observational platforms will play a larger role in Earth observation in the future. The inclusion of airborne observational platforms in the GEOS is one of the significant contributions of this thesis.

1.1.4. Recommendation to use Airborne and Ground-based Observational Platform

The Decadal Survey recognized that a complete Global Earth Observation System (GEOS) will include space-based, airborne, and terrestrial platforms for both scientific and economic reasons. While the panels did not make specific recommendations related to aircraft, they provided general statements like those seen below. The Decadal Survey begins with broad recommendations, on page 14:

"The space-based observations recommended by the committee will provide a global view of many Earth system processes. However, satellite observations have limited spatial and temporal resolution and hence do not alone provide a picture of the Earth system that is sufficient for understanding all of the key physical, chemical, and biological processes. In addition, satellites do not directly observe many of the changes in human societies that are affected by, or will affect, the environment. To build the requisite knowledge for addressing urgent societal issues, data are also needed from suborbital and land-based platforms, as well as from socio-demographic studies. The committee finds that greater attention is needed to the entire chain of observations from research to applications and benefits. Regarding complementary observations, the committee makes the following recommendations:

*"**Recommendation**: Critical surface-based (land and ocean) and upper-air atmospheric sounding networks should be sustained and enhanced as necessary to satisfy climate and other Earth science needs in addition to weather forecasting and prediction.*

*"**Recommendation**: To facilitate the synthesis of scientific data and discovery into coherent and timely information for end users, NASA should support Earth science research via suborbital platforms: airborne programs, which have suffered substantial diminution, should be restored, and unmanned aerial vehicle technology should be increasingly factored into the nation's strategic plan for Earth science."* (Committee on Earth Science and Applications 2007)

The report talks generally about the need to integrate other observational platforms with spacecraft, on pages 67-68:

"Routine aircraft observations play an important role in operational weather forecasting (Uppala et al., 2005). They have also been important in the formulation of public-policy legislation and in the systematic testing and improvement of forecast models across broad categories in the Earth sciences. [...] Yet, strikingly, at a time when the scientific and societal need for a robust national capability in aircraft research and surveillance has never been greater, NASA's competence and resources in airborne research facilities have eroded to the point that they are now in serious jeopardy. The decline is seen in increasing limitations on aircraft available for deployment, decreased support for instrument development, lack of funds to stage missions, and a loss of technical infrastructure to execute needed objectives.

"To compound the effects of a substantially weakened airborne program, virtually every satellite instrument developed for observations of Earth from space was conceived and first tested on an aircraft platform. In addition, graduate programs in experimental science and engineering are built on a backbone of airborne research that is now collapsing. Restoring the nation's airborne research program is a prerequisite for linking the Earth sciences to emerging societal objectives and for the restoration of U.S. leadership in higher education internationally.

"The airborne programs of NASA and NOAA are in transition from conventional aircraft to unmanned aerial vehicles (UAVs). UAVs have the potential to revolutionize suborbital remote and in situ sensing with their increased range and loiter time and their ability to penetrate hazardous environments. However, issues with avionics software, flights over populated regions, high cost, and reliability have thus far limited UAVs to controlled demonstration missions. In the transition to future wide deployment of UAVs, conventional aircraft will continue to be the mainstay of the suborbital aircraft program—they are more reliable and more cost-effective to use." (Committee on Earth Science and Applications 2007)

The Decadal Survey presents a compelling motivation to consider the use of aircraft in Earth observation. This thesis uses these recommendations as motivation to work towards the integration of aircraft in a scheduling model currently used to set satellite-only campaigns.

1.1.5. Aircraft for Earth Observation

As evidenced by the recommendations in the Decadal Survey, aircraft have and will continue to play a vital role in Earth observation. NASA currently owns and operates a fleet of aircraft used for Earth observation including both large aircraft capable of carrying several tons of instrumentation and personnel and unmanned aircraft capable of carrying a single instrument. The fleet is operated by the Airborne Science Program (ASP) and released to scientists for an hourly rate. Scientists currently have the ability to integrate an instrument onto an aircraft and use it for any mission with NASA support. The Decadal Survey had an impact in aircraft for Earth observations as the Earth Venture program was established to fund 5 aircraft missions for Earth science.

Earth Venture 1

NASA's Earth System Science Pathfinder (ESSP) program within the ESD was tasked with implementing the Decadal Survey's recommendation for a series of low-cost, innovative suborbital missions. The first round of solicitations, Earth Venture-1 was announced in 2009 stating:

"This Earth Venture-1 program element solicits proposals for complete suborbital, principal investigator-led investigations to conduct innovative, integrated, hypothesis or scientific question driven approaches to pressing Earth system science issues." (NASA ESSP 2009)

The EV-1 program will be flying missions starting in the summer of 2011 and the results will set the expectations for future aircraft endeavors. The EV-1 concept and missions will be examined in detail for this thesis. One of the most ground breaking parts of the EV-1 program is that it makes extensive use of the Global Hawk Unmanned Aerial System (UAS).

Unmanned Aerial Vehicles

The Decadal Survey specifically said that Unmanned Aerial Vehicles (UAVs) have the potential to change the way airborne Earth science is done. UAVs are a relatively new technology that has been extensively developed over the past decade thanks to investments by the US Department of Defense (DOD) and the private sector. Large UAVs have been gathering Intelligence, Surveillance, and Reconnaissance (ISR) data in the Middle East in support of the US's involvement in Iraq and Afghanistan. Through this experience with complex operations, UAVs have become a mainstay in military operations. While still not widely used in civilian applications, UAVs are beginning to expand into areas of Homeland Defense (Border patrol and marine surveillance). As technology necessary for more regular flights in the national airspace, especially "Sense and Avoid", the utility of these platforms for observation will be tested.

UAVs have already found use in NASA's fleet of aircraft for Earth observation. NASA now owns and operates two Global Hawk UAS, which are now being used to fly 30 hour missions. A modified General Atomics Predator B, called Altair, is now being used for local observation flights. This thesis also introduces a new aircraft type for Earth Observation, the Optionally Piloted Vehicle (OPV).

Optionally Piloted Vehicle

An Optionally Piloted Vehicle (OPV) combines the autonomy and endurance of a UAV with the safety of manned aircraft. OPVs can be reconfigured to fly either as manned or unmanned vehicles. This allows an OPV to be flown safely in populated areas or transported through national airspace, thus avoiding certain UAV-specific drawbacks. Once at the area of interest, the vehicle can be flown as a UAV, thus gaining the advantages of an autonomous platform.

1.2. General Objective

In light of recent events surrounding the Global Earth Observation System, the objective of this thesis is to create a methodology to integrate spacecraft and aircraft in the GEOS to support decision makers in campaign architecting.

1.3. Relevant Literature

An extensive literature review was conducted in order to form the foundation for this thesis. Within the MIT Space Systems Architecture Group (SSAG) under the leadership of Professor Ed Crawley there has been work on the GEOS including stakeholder analysis, mission scheduling, and instrument packaging. Computational tools such as genetic algorithms are reviewed as a method for campaign scheduling.

Lastly, the use of aircraft in Earth observation is reviewed so that a basic understanding of aircraft technology informs this research.

1.3.1.Previous MIT Work

Stakeholder Analysis

Stakeholder analysis is an important part of the Earth Observation project. Tim Sutherland completed his thesis titled, "Stakeholder Value Network Analysis for Space-Based Earth Observation" in 2009. (Sutherland 2009) After extensive research into the nature and importance of 13 system-wide stakeholders, the graph shown in Figure 1.1 was developed. Each box represents a specific stakeholder and the lines present value flows between them. This diagram represents 190 value flows, each derived from either the Decadal Survey or other policy sources. By tracing the flow of value through stakeholders, a map is generated that identifies the importance of each stakeholder to the system as viewed by NASA.

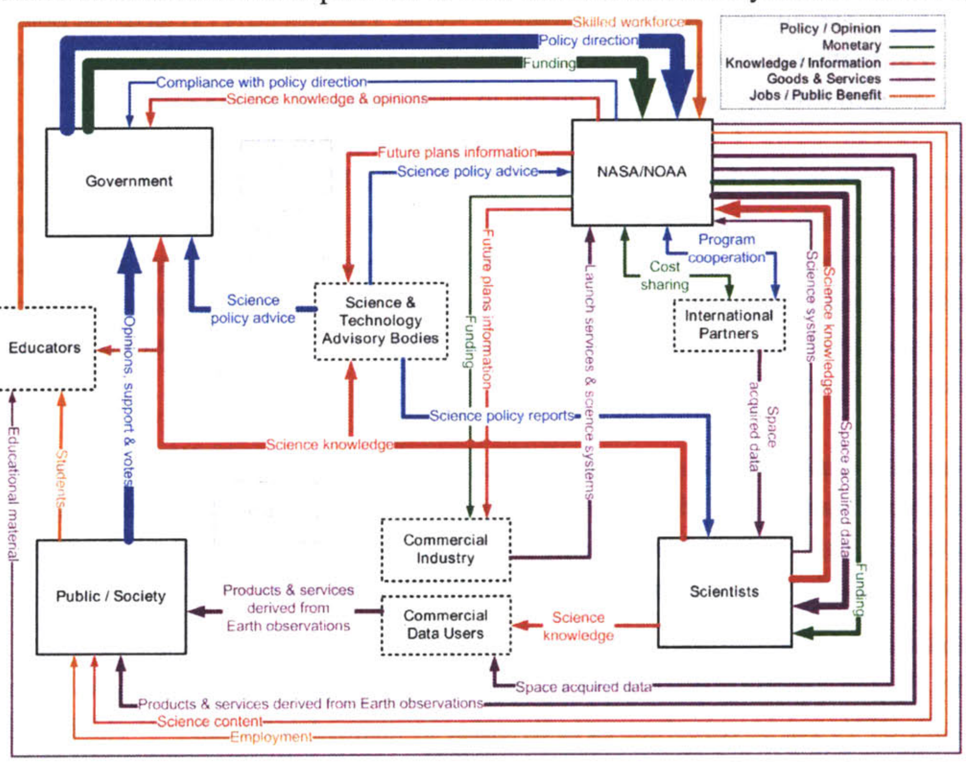


Figure 1.1: Simplified Stakeholder Value Flow Map derived from Stakeholder Analysis that determined relationship between each stakeholder and the value and strength of the flow between them. (Sutherland 2009)

The broad stakeholder model of Figure 1.1 captures the contributions to value flow of the six panels assembled for the Decadal Survey. The contributions of each panel to the value flow were evaluated. This created a relative weighting as shown in Figure 1.2 and is used as part of this work. This relative weighting represents the strength of contribution each panel makes in creating value for the entire Global Earth Observation System.

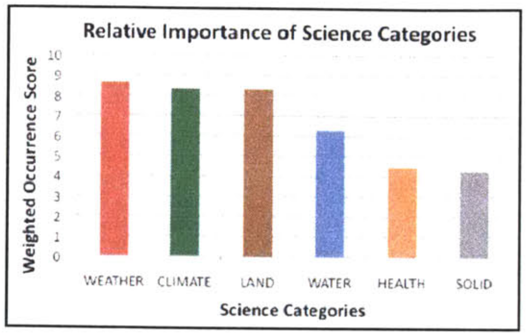


Figure 1.2: Relative Weighting of 6 Science Panels based on Stakeholder Analysis, which is used to weight Panel Objectives, as discussed in Section 2.3.2. (Sutherland 2009)

It is important to decision makers to be able to trace the flow of value to their constituents or organization, in order to justify decisions. The stakeholder analysis informs the mission benefit model presented in Chapter 2 as the CSTM v1.1. The CSTM v1.1 builds on the work of Theo Seher discussed below.

Campaign Benefit Estimation

The most recent work on mission scheduling was completed by Theo Seher in a thesis titled, "Campaign-level Science Traceability for Earth Observation System Architecting". (Seher 2009) Seher's main contribution is the Campaign-level Science Traceability Matrix (CSTM). The CSTM traces the benefit delivered to each stakeholder (Decadal Survey Panel) from missions by mapping a mission's instrument to the measurements it takes. Measurements are mapped to objectives, which fulfill specific needs of the stakeholders. An outline of this value traceability along with the constraints imposed at each step is shown in Figure 1.3.

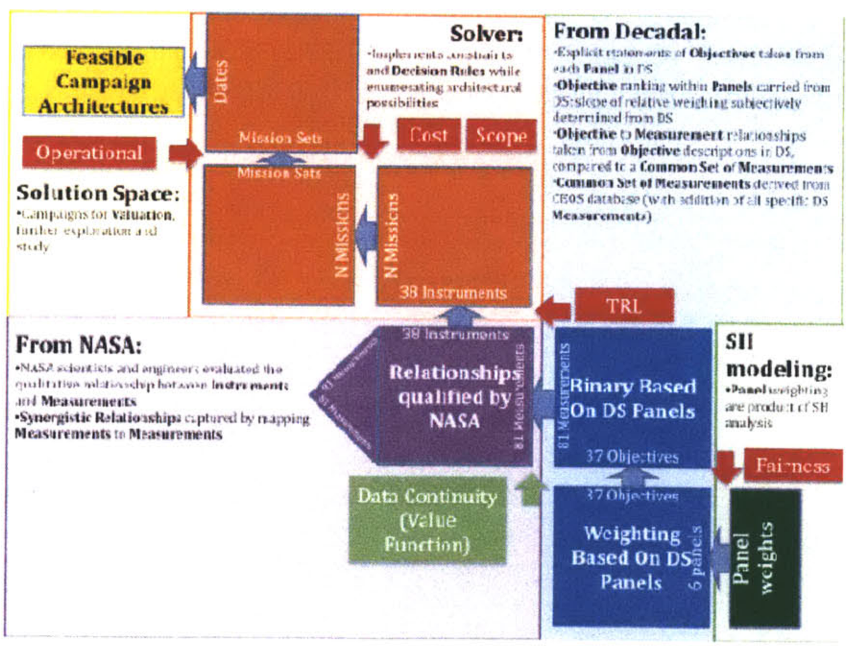


Figure 1.3: Seher's Campaign-Level Science Traceability Matrix for Decadal Survey Analysis (Constrained). CSTM is adapted as described in Section 2.2. (Seher 2009)

Campaign Scheduling

The CSTM is the framework through which Seher is able to generate campaign architectures, which is then used to inform a campaign scheduling tool. The tool displays the value being delivered to the panel stakeholders, as shown in Figure 1.4. Seher uses Excel worksheets to evaluate a small number of architectures, including the reference case as outlined loosely in the Decadal Survey, a constrained reference case, and a "free-flyer" case where all the instruments launch separately. The main limitation of this work is its inability to evaluate a large number of architectures and its lack of flexibility in mission definition. Architectures were forced to resemble the Decadal Survey due to the constraints imposed by fairness in value delivery and mission technology readiness, driving a need to loosen constraints and more exhaustively explore the trade space appeared necessary.

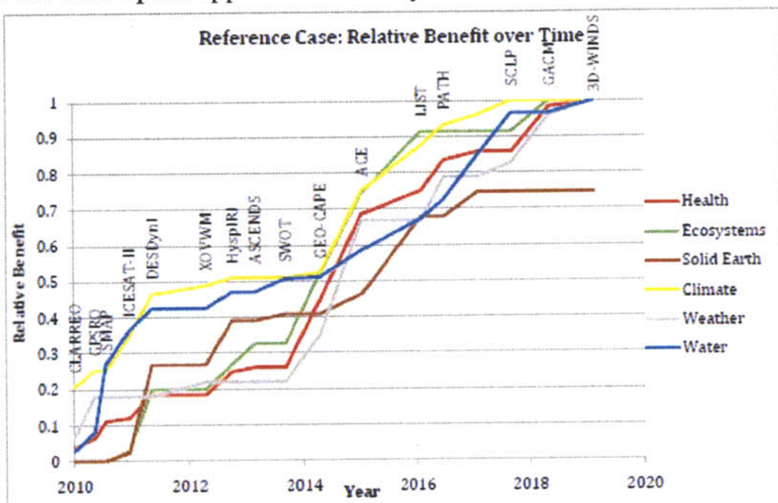


Figure 1.4: Panel Value added over time in Seher's Optimization of the Decadal Survey Campaign Schedule. Figure 3.6 shows similar Value visualization. (Seher 2009)

Seher's work was built upon the thesis work of Justin Colson titled, "System Architecting of a Campaign of Earth Observing Satellites". (Colson 2008) Colson studied the GEOS and explored architecture decisions. The outline of the methodology used to schedule Decadal Survey missions is shown in Figure 1.5.

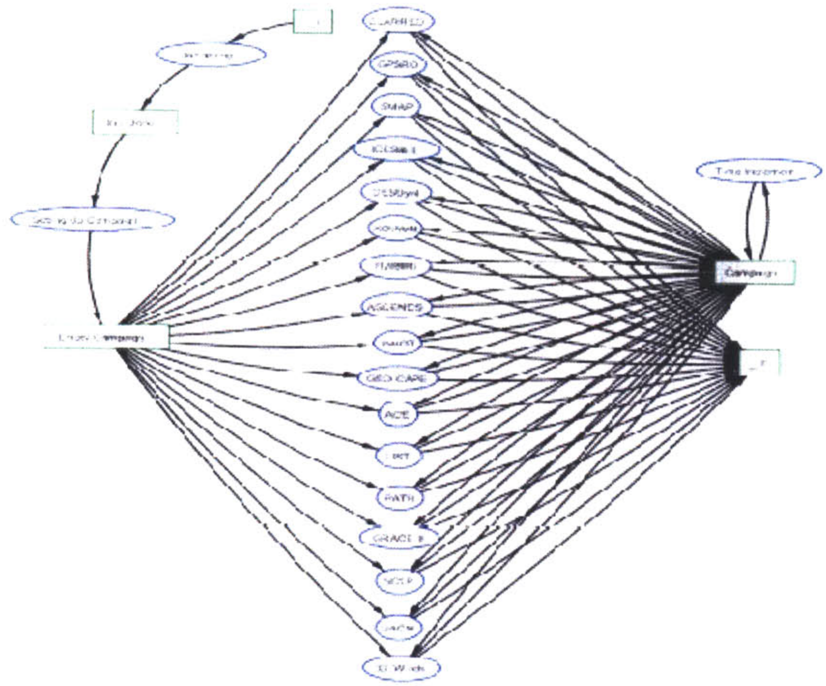


Figure 1.5: Colson's Scheduling Tool for Baseline Decadal Survey Missions, which was the first instantiation of the Campaign Scheduling Problem. (Colson 2008)

This model was constrained by several rules, which are present in some form in this thesis:

1. **Campaign Budget**: Missions within a campaign were scheduled such that the expenditure rate, carefully based on mission costs, did not exceed the prescribed budget.
2. **Technology Readiness Level**: Missions were scheduled so that no flights were cued before their technology readiness date, which were taken from the Decadal Survey.
3. **Data Gap**: The scheduler forced mission overlap and continuous measurements in the accordance with the recommendations presented in the Decadal Survey. Flights were ordered/scheduled to guarantee any required overlap in data coverage. Latest possible dates had to be enforced for some missions to ensure they launched before a recommended deadline.
4. **Value Delivery Fairness**: 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".

Colson also pointed out a relevant challenge with these types of permutation problems. They become significantly larger than practical for normal modern computers. This is shown in Table 1.1 when the 17 missions referenced in the Decadal Survey have $3.55*10^{14}$ possible permutations. Colson estimates it would take over 5,000 years to evaluate this trade space on a personal computer.

Number of Missions	Possible Mission Permutations	
2	2	
3	6	
4	24	← Low Complexity
5	120	
6	720	
7	5040	
8	40320	← Moderate Complexity
0	362000	
10	3628800	
11	39916800	← High Complexity
12	479001600	
13	6227020800	
14	87178291200	
15	1.30767E+12	
16	2.09228E+13	
17	3.55687E+14	← Decadal Survey Rec's
18	6.40237E+15	
19	1.21645E+17	← Including NPOESS Sensors as 2 Follow-ons
20	2.4329E+18	

Table 1.1: Permutations needed for Full Enumeration showing that the Campaign Scheduling Problem becomes too big for full enumeration when considering over 10 missions. This drives Heuristic methods to be considered. (Colson 2008)

The size of these studies creates a problem when full enumeration of architectures is desired. There have been two attempts to simplify the mission scheduling problem so that traditional optimization techniques can be used to solve it. Lin generalizes a Conflict-directed A* (CDA*) algorithm in his thesis, "Multi-objective Constrained Optimization for Decision Making and Optimization for System Architectures". (Lin 2010) To do this Lin casts the mission scheduling problem as a Constrained Optimization Problem (COP) and expands a single objective method to two objectives using Benefit and Unfairness as the metrics. This is cumbersome to implement in code because every constraint is hard-coded and the resulting architecture space is very limited in order to reduce the number of possible architectures to explore. Although Lin's thesis is dedicated more to problem formulation and algorithm development, his final analysis of the Earth observation problem consists of an 11 mission set evaluated to produce 7 promising schedules. The main conclusion is that while constraining the problem allows it to be solved more efficiently, limiting the trade space makes it difficult to find useful solutions. After reviewing Lin's work, the decision was made to make the formulation for this thesis as open and flexible as possible.

Instrument Selection and Packaging

The instrument packaging problem deals directly with the method and result of assigning instruments to missions. This problem becomes apparent as soon as mission architectures are flexible flexible. The premise is that there is an optimal way to package a set of potential instruments to maximize value in the GEOS. This work is being undertaken by Daniel Selva, a PhD candidate in the SSAG. In his first conference paper titled, "Integrated Assessment of Packaging Architectures in Earth Observing Programs", Selva outlines a methodology by which large numbers of satellite architectures can be enumerated and evaluated. (Selva and Crawley 2010) There is a tradeoff between packaging many instruments on a single spacecraft and dedicating spacecraft to specific instruments. Selva built a quantitative model to evaluate architectures based on Scientific Performance, Cost, Schedule, and Risk. This framework was then applied to ESA's ENVISAT mission, an Earth science mission launched in

2002.

This work has been built on and expanded to include an extensive ruled-based expert system (RBES) used to populate Design Structure Matrices (DSM's). The RBES was presented in a conference paper titled, "Exploring Packaging Architectures for the Earth Science Decadal Survey" (Selva and Crawley 2011). Selva uses interviews with Earth scientists and experts in the field to generate over 70 rules, which capture synergies between measurements and interactions between instruments. These rules were applied to the Decadal Survey set of instruments. This analysis can be applied to any given set of instruments as long as they are characterized well enough to apply the rules. This thesis will use Selva's work extensively to develop a method for integrating aircraft and satellites into campaign architectures.

1.3.2. Genetic Algorithms

This thesis solves the campaign scheduling problem using a Genetic Algorithm (GA). The GA is an optimization tool that is used because it allows for large trade space exploration and can be adapted to realistically fit the GEOS campaign scheduling problem without imposing unrealistic constraints.

The Essentials of GA

Genetic Algorithms represent a set of optimization methods designed to mimic the way biological organisms adapt to their environment. The concept was first attributed to John Holland in his book, "Adaptation in Natural and Artificial Systems", in which he outlines a set of problems notoriously hard to solve using classic optimization techniques. (Holland 1975) In this groundbreaking work, Holland lays out the algorithms with theoretical application to areas of genetics, economics, game-playing, and searches. His framework includes concepts found in nature such as reproduction, cross-over, inversion and mutation. This robust algorithm is shown to present potential for solving many problems. In general, problems that are non-convex, discontinuous, and non-differentiable are better solved using heuristic methods such as GA. (Houck, Joines, and Kay 1995) This is due mainly to the fact that a GA does not need any gradient information on the function being evaluated. The GA also has a random component in its search algorithm that reduces the chance it will get caught in a local minimum. The algorithm is able to search many different areas of the solution space in parallel. (Houck, Joines, and Kay 1995)

The methodology implemented by a GA is summarized, from "Handbook of Genetic Algorithms": (Davis 1991)

1. Initialize a population of chromosomes. Chromosomes represent individual campaign architectures in the Earth science campaign scheduling case.
2. Evaluate each chromosome in the population using a fitness function based on system metrics.
3. Create new chromosomes by mating current chromosomes; apply mutation and recombination as the parent chromosomes mate.
4. Delete members of the population to make room for the new chromosomes.
5. Evaluate the new chromosomes and insert them into the population.
6. If any of the termination criteria are triggered, stop and return the best chromosomes; if not go to 3.

By following these 6 steps, the GA is able to extensively search the trade space and converge on a solution that is generally considered near optimal.

Multi Objective GA

Many engineering problems are not evaluated on a single metric and do not have a single solution. With the GEOS campaign scheduling problem falling into this category, a multi-objective formulations of similar problem were reviewed this thesis. When evaluating multi-objective metrics, the use of Pareto analysis is necessary to distinguish non-dominated individuals within a trade space. An individual dominates another individual if it is better in all of the objectives simultaneously. Therefore a non-dominated solution is one that is not dominated by any of the other feasible solutions. This set of non-dominated individuals forms the Pareto front.

A detailed discussion of Pareto-Optimality can be found in Deb (Deb 2001) starting on page 30. For this thesis, it is sufficient to say that a Pareto Front is a commonly used method for displaying the trade-off of a multi-objective solution space. This is typically done for 2 metrics, as shown here, but in theory Pareto optimality applies to n-dimensions. Figure 1.6 shows a solution space with different Pareto fronts indicated depending on how the two metrics are defined to be optimal.

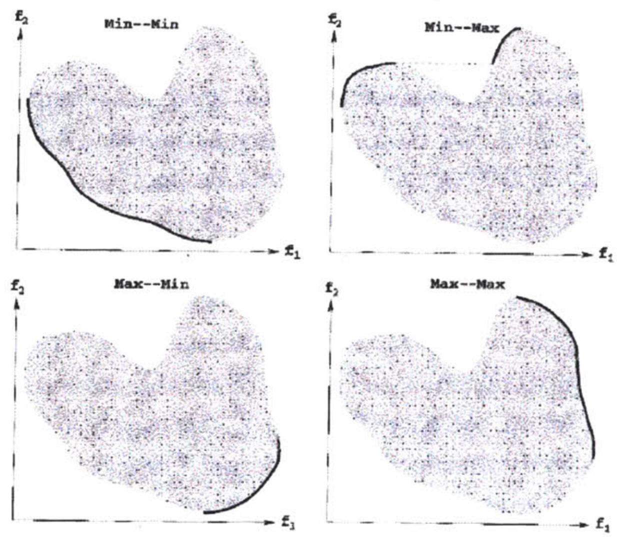


Figure 1.6: Solution space with 4 different Pareto Fronts based on the definition of optimality of the metrics. Global Earth Observation System Model will be Max-Min formulation shown on Bottom Left plot. (Deb 2001)

Multi-objective Genetic Algorithms (GA) are explained in some detail in chapter 3 of P.J. Fleming's "Genetic Algorithms in Engineering Systems". (Zalzala and Fleming 1997) A Pareto optimal set of solutions can make ranking individual solutions difficult as part of the GA selection method. One of the application chapters in "Genetic Algorithms and Evolution Strategies in Engineering and Computer Science" titled "GA Multiple Objective Optimization Strategies for Electromagnetic Backscattering" explains a ranking scheme used to distinguish individuals that are part of the Pareto front. This method is shown in Figure 1.7. (Periaux, Sefrioui, and Mantel 1997)

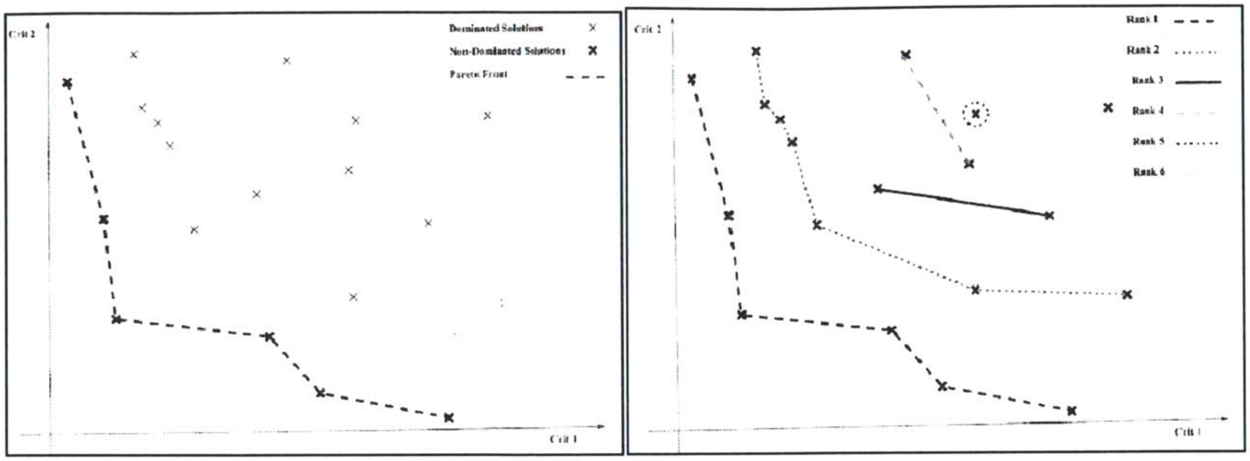


Figure 1.7: Left Panel shows a Pareto Optimal set of Solutions based on non-domination. Right Panel shows the ranking method used to select solutions based on Pareto Optimality. (Periaux, Sefrioui, and Mantel 1997)

Penalty Functions in the GA

In real engineering systems there are sources of uncertainty that make hard constraints unrealistic. This leads engineers using GA's to implement a variety of penalty schemes and cost functions. In the Third International Conference on Genetic Algorithms, Jon Richardson, described the problem in "Some Guidelines for Genetic Algorithms with Penalty Functions". (Richardson et al. 1989) In this paper, he points out that up to that point the method for finding feasible solutions in a constrained space was to apply heavy penalties so that only feasible solutions were considered. This means that valuable information from infeasible individuals is lost as they do not get selected for the next generation. In the extreme case where the feasible space is very sparse, when the algorithm finds a feasible solution it can become a "super individual" and the GA falsely converges on a non-optimal solution. Richardson proposes to use "softer" penalties as a way to keep infeasible solutions alive within the algorithm but only as a way to lead to better feasible solutions. He concludes with the statement:

"Penalties which are functions of the distance from feasibility are better performers than those which are merely functions of the number of violated constraints." (Richardson et al. 1989)

This concept has been applied to this problem in the way the algorithm handles the rules that constrain the campaign scheduling problem.

GA Applied to TSP

Conceptually, one way to formulate the campaign scheduling problem is using the example of the Travelling Salesman Problem (TSP). The TSP is a classically "hard problem" in the optimization field used to benchmark many optimization techniques. The TSP is based on a fictional salesman who must visit each city in his assigned area at least once for the least cost. This is formulated as a network problem in which the cities are represented by nodes (A-J in Figure 1.8) connected by links. Each link has a cost associated with it, which the salesman incurs when he travels between those two nodes. In Figure 1.8 the goal is to minimize the path value while visiting A-J at least once each. (Larson)

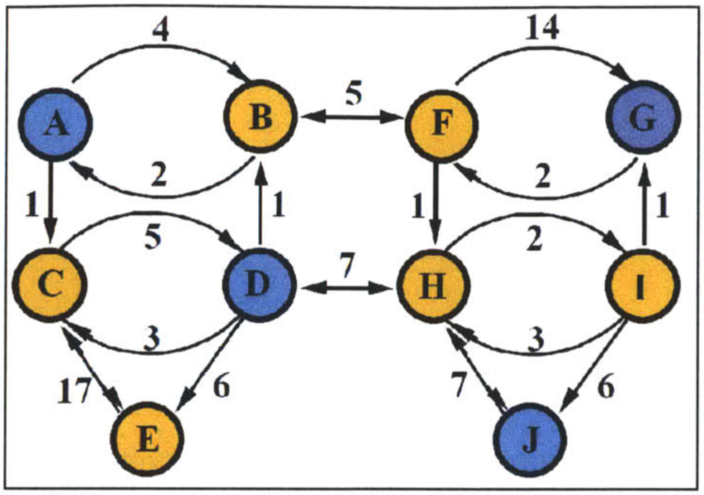


Figure 1.8: Travelling Salesman Problem Network showing Nodes A-J and Links with Weights. Scheduling Problem is formulated like TSP by treating each Mission like a Node on the Network.
(Larson)

The TSP was one of the first problems to which GA was applied, and many papers were published on the subject. In 1989 a new method for recombining parents to produce children who retain much of the parental "goodness" was described in "Scheduling Problems and Traveling Salesmen: The Genetic Edge Recombination Operator". (Whitley, Starkweather, and Fuquay 1989) The same work is found again in 1991in Lawerence Davis's book, "Handbook of Genetic Algorithms". (Davis 1991) In that work, the same type of problem was extended to scheduling order-filling on a production line with around 500 items to be scheduled. This extension makes it likely that the same approach works for the mission scheduling problem in which 15-30 missions must be sequenced and optimized.

Matlab GA Toolbox

The literature relevant to the GA shows that it has been applied to similar problems as found in this thesis. This thesis implements a GA using the Matlab toolbox. The first version of the Matlab GA toolbox is introduced in "A Genetic Algorithm for Function Optimization: A Matlab Implementation" (Houck, Joines, and Kay 1995). Houck uses both float genetic algorithm (FGA) and binary genetic algorithm (BGA) to compare solutions and runtime to a Simulated Annealing (SA) algorithm on a series of non-linear, non-convex, multi-modal functions. The FGA outperforms the other two algorithms and shows the feasibility of implementing GA in Matlab. (Houck, Joines, and Kay 1995) That report also points to the ease with which problems can be formulated and run using the GA toolbox. The Matlab Global Optimization Toolbox is summarized in Matlab software documentation (MathWorks 2010) and in more detail on the related website (Mathworks 2010). The GA toolbox is the product of many lessons learned over decades of GA research. It is a single code with a variety of options that allow the user to generate almost any permutation of GA. Both single and multi objective varieties are included. The toolbox is easy to adapt to any specific problem and adapts well to the campaign scheduling problem in this thesis.

1.3.3. Aircraft for Earth Observation

The Decadal Survey presents many solutions for Earth observation with space-based platforms. The recommended campaign includes details of the satellite missions. While mentioned, the report does not focus with such detail on potential non-space-based missions. An extensive review of applicable aircraft technology was completed but is not be presented in this thesis. This survey was used to select the airborne observational platform case studies found in chapter 4. A list of relevant aircraft and technologies can be found on the NASA Airborne Science Program website. (NASA 2011a)

The idea of using aircraft in Earth observing is not new, but in recent years technology has opened the door for Unmanned Aerial Vehicles (UAVs) to play a larger role in gathering data. This provides a relatively new observational platform to be considered for the GEOS. While there are many publications discussing specific applications of airborne observations, Roser and Schonermark summarize the general discussion in their 1996 paper titled, "Comparison of Remote Sensing Experiments from Airborne and Space Platforms". (Roser and von Schönermark 1996) They describe the spectral and temporal resolution issues associated with operating different platforms and list the advantages and disadvantages of both. Figure 1.9 shows the typical ground speed of different platforms on a log-log scale with operating altitude.

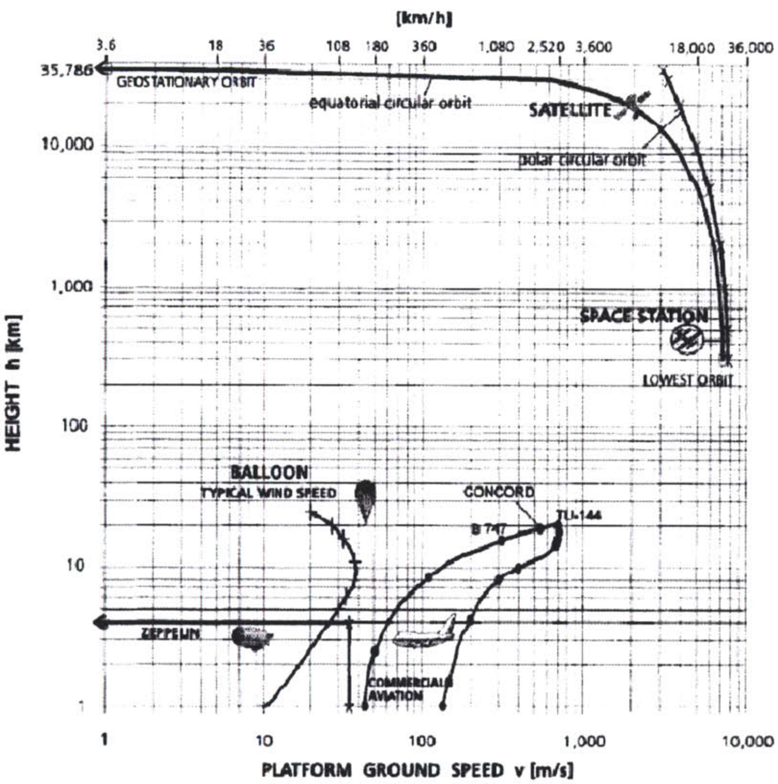


Figure 1.9: Performance Envelops for Typical Airborne and Space Platforms. Graph shows Aircraft and Balloons operating from 0-20km and Satellites operating from 30-30,000km. (Roser and von Schönermark 1996)

UAVs have applications beyond scientific Earth observation. One work that considers an example is "High-Altitude, Long-Endurance UAVs vs. Satellites: Potential Benefits for U.S. Army Applications" by William Symolon. (Symolon 2009) In his thesis, Symolon details the roles that High-Altitude, Long Endurance (HALE) aircraft could play for the US Army. Figure 1.10 show where needs and capabilities overlap, specifically in the area of GPS, Communications, and Intelligence, Surveillance, and Reconnaissance (ISR).

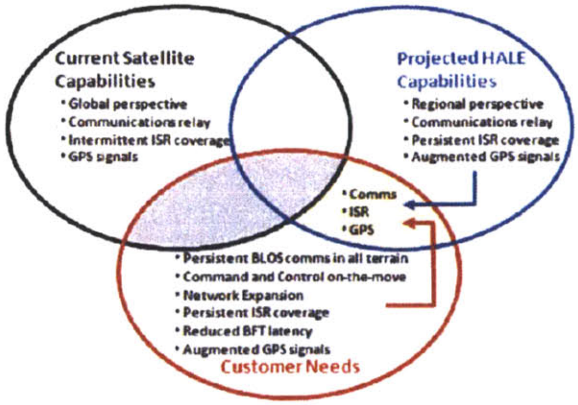


Figure 1.10: Venn Diagram of Current Capability of Satellites and High-Altitude Long Endurance Aircraft and Customer Needs. Shows Communication, GPS, and Intelligence, Surveillance, and Reconnaissance as possible overlap between aircraft and customers. (Symolon 2009)

There has been a significant amount of work done in recent years to study the potential benefits and costs to integrating UAVs into civilian airspace. Currently, UAV-based Earth observing missions are conducted in restricted airspace set up specifically for the mission. To make operations feasible any large scale use of UAVs in the GEOS would require some level of integration into the National Airspace System (NAS). Two MIT related publications are helpful in sorting out this complex issue. The first is a summary report by MIT's International Center for Air Transportation (ICAT) titled, "Safety Considerations for Operation of Unmanned Aerial Vehicles in the National Airspace System". (Weibel and Hansman 2005) This report offers insights into the safe operation of UAVs in the NAS as well as a general discussion of "sense and avoid' for varying level of UAVs as shown in Figure 1.11

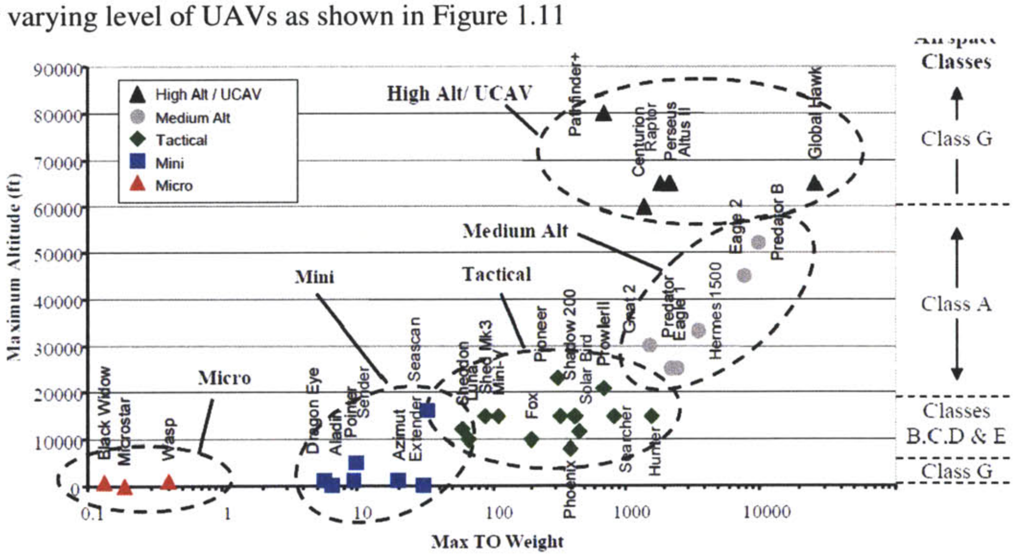


Figure 1.11: Altitude vs. Take Off Weight for Current UAVs showing 5 classes: Micro, Mini, Tactical, Medium Altitude, and High Altitude / UCAV. (Symolon 2009)

Another good discussion of integrating UAVs into the NAS comes in "Civilian Applications and Policy Implications of Commercial Unmanned Aerial Vehicles" by Kara Sprague. (Sprague 2004) Sprague looked at small UAVs operating in urban centers for applications such as police and fire department operations. She also does a thorough risk analysis given US population density and air traffic frequency to build risk maps for different size UAVs. While this is a policy paper, it is important to realize that any large scale use of aircraft for Earth observation will come with a host of non-technical issues associated with public perception and response.

There is also an extensive review of UAV technology and application published annually by The Teal Group. (The Teal Group 2011) In the most recent review titled, "World Unmanned Aerial Vehicle Systems: Market Profile and Forecast", the Teal Group profiles each country's UAV program and assesses the commercial potential of such systems. Through market analysis, they project a world market of over $64 Billion dollars in the 2011-2020 timeframe. This market includes $4.8 billion in civilian UAV applications, in which Earth science would fall. There are high expectations for UAV technology to penetrate the commercial market.

1.4. Specific Objectives

The specific objective of this thesis is to develop a decision support tool that traces scientific benefit through the GEOS and facilitates the inclusion of both spacecraft and aircraft in campaign architectures. The thesis will apply the genetic algorithm to the campaign scheduling problem to study the need for incorporating airborne Earth science missions into the GEOS. The methodology will be applied to an integrated set of space-based and airborne missions to gain insight into the main architectural tradeoffs between spacecraft and aircraft for Earth observation.

This objective breaks into five specific objectives:

- To adapt the CSTM framework with a deeper understanding of the GEOS, thus creating CSTM v1.1. Framework gives decision makers insight into system metrics.
- To develop a new Earth science campaign scheduling algorithm based on Matlab's Genetic Algorithm toolbox to examine the architectural trade-offs present in campaign scheduling. The tool will allow for large trade space exploration.
- To identify potential near-term data gaps and investigate strategies to mitigate the associated risk.
- To conduct three Case studies to qualitatively assess the capabilities of aircraft for Earth observation.
- To demonstrate a methodology, CSTM v2.0, that utilizes a rules-based expert system (RBES) to create a more precise comparison of airborne and space-based measurements.

1.5. Overview of this Thesis

This thesis is organized into 6 chapters. The remaining chapters are as follows:

- Chapter 2 presents the benefit tracing methodology provided by the CSTM v1.1. Chapter 2 also introduces the two metrics that are used for campaign schedule architecting: "Data Value" and "Data Gap". The calculation of these two metrics are presented and applied to the Decadal Survey set of satellite missions.
- Chapter 3 applies the Genetic Algorithm campaign scheduling tool to three cases of the Decadal Survey satellite campaign. The first case is the baseline case set under the assumptions present during the writing of the Decadal Survey. The second case is an updated Decadal Survey case in which mission cost estimates, campaign budget predictions, and the technology readiness assessment are updated to reflect the current Earth observation environment.
- Chapter 4 conducts three case studies to explore three fundamental modes of airborne Earth

science observation: sustained regional campaigns, local opportunity driven missions, and global in-situ data collection. The instruments explored in chapter 4 are characterized and integrated into the GEOS model.

- Chapter 5 presents an application of the CSTM v2.0 and GA campaign scheduling tool to an integrated airborne and space-based GEOS campaign. This chapter applies this methodology to the Climate panel of the Decadal Survey.
- Chapter 6 concludes the thesis with conclusions based on the presented work and specific recommendations for the future integration of aircraft into the GEOS.

2. Framework for Campaign Architecture Analysis

This chapter presents an updated Campaign-Level Science Traceability Matrix (CSTM) framework, which is used to analyze campaign architectures in this thesis. The CSTM is a value tracing framework that is applied to the space-based Global Earth Observation System (GEOS) and in later chapters is extended to the complete GEOS including suborbital systems. Chapter 3 applies the resulting CSTM framework to the Decadal Survey recommended set of satellite-only campaigns. Chapter 5 expands the framework presented in this chapter to an integrated architecture containing both suborbital and space-based observational platforms as suggested in the Decadal Survey.

When systems architecting principles are applied to show how the system is decomposed into elements of form, a value tracing methodology emerges. This value tracing methodology begins with analysis from stakeholders and follows through campaign completion. It provides quick exploration and evaluation of a large set of candidate system architectures. As part of the analysis presented in this chapter and the next, assumptions are made about key system variables. The intent is for this analysis to remain flexible, so new values and changing assumptions can be quickly assessed. This flexibility reflects a general objective of this thesis, to give decision makers a tool that can be implemented rapidly and effectively. The goal of this analytic framework is for it to be applied to other applications that require large trade space exploration at a significant level of abstraction; this will be an area of future work not addressed in this thesis.

The CSTM is introduced in section 2.1 through an architecting methodology of system decomposition. Section 2.2 presents an adapted version of the Campaign-level Science Traceability Matrix, which is the analytic framework introduced in the literature review. This enhanced methodology will be applied to the Decadal Survey set of 17 recommended missions comprised of 37 instruments nominally designed to capture up to 84 measurements. The third section of this chapter documents the Matlab genetic algorithm used to optimally schedule the set of Decadal Survey Earth observation missions.

2.1. System Decomposition

This section presents a system decomposition of the Global Earth Observation System (GEOS), resulting in a value tracing framework. The system under investigation is decomposed into elements of form, which helps to more deeply understand the interactions within the system and builds the foundation on which to analyze it. Decomposition of a complex system leads to a seemingly complicated problem being broken up into more manageable sub-problems. (Weigel 2009) Formal decomposition for the complete GEOS is shown at a high level of abstraction in Figure 2.1. The goal of this abstract form decomposition is to represent the complete system without exhaustively drawing out every possible observation platform in detail.

As Figure 2.1 shows, the GEOS is comprised of more than just the satellites that are traditionally considered to be the sole source of Earth Science data collection. The system is composed of all the platforms capable of gathering data and the infrastructure needed to handle that data. The data handling system in place for the GEOS will not be addressed in this thesis. The additional platforms that have the potential to gather Earth Science data include aircraft (both manned and unmanned), ground observation sites, balloons, and underwater vehicles, all of which provide unique observation sites in terms of the physical location and the instruments they can carry. While Figure 2.1 is not exhaustive, as instruments can be mounted on myriad observational platforms, it contains the most relevant to this program.

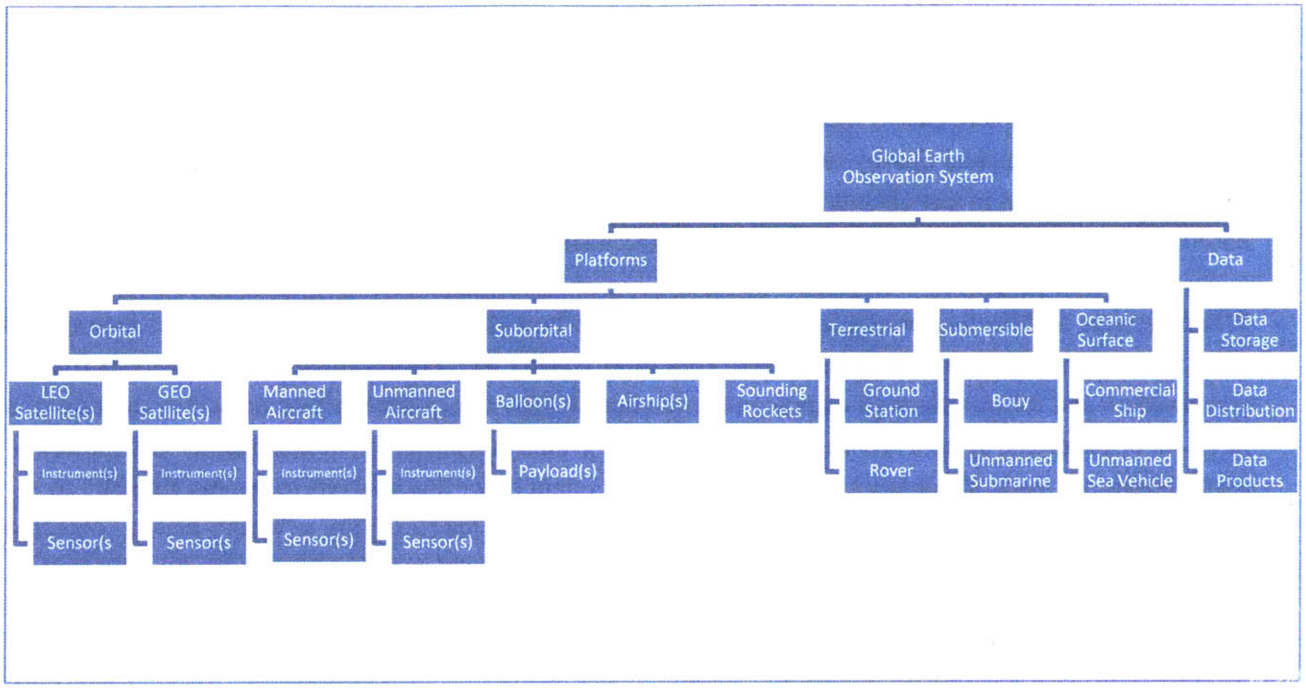


Figure 2.1: First Step in Systems Architecting: Global Earth Observation System Formal Decomposition. Observational platforms can be Orbital, Suborbital, Terrestrial, Submersible, and Oceanic Surface; each has a set of payloads that can be unique or common. Data must be handled through Storage, Distribution, and Products. Decomposition shows that Orbital platforms are only part of a much larger system.

The high level of this form decomposition of the GEOS fails to capture the variety of specific forms present in the system. This variety is evident at the instrument/sensor level where an instrument in specific terms could range from a multi-million dollar optical camera orbiting on a platform in Geostationary Earth Orbit (GEO) at an altitude of 36,000km to a thumb size pressure gauge flying on a commercial aircraft across the Atlantic Ocean at an altitude of 40,000ft. A high level view also fails to capture the complexity of individual systems within the GEOS as demonstrated in Figure 2.2 and Figure 2.3.

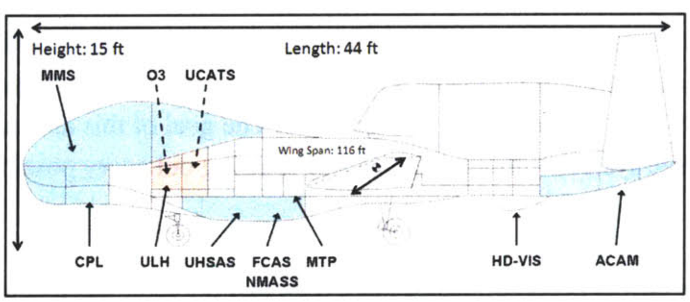


Figure 2.2: GLOPAC Global Hawk instrument layout showing the complexity of an Unmanned Aerial System (UAS) carrying 11 instruments to support weather observation science over the Pacific Ocean. (NASA Earth Science Project Office 2011)

During the winter months of 2010 a Global Hawk Unmanned Aerial System (UAS) carrying 11 different scientific instruments, as shown in Figure 2.2, flew weather observation missions out of NASA's Dryden Flight Research Center (DFRC) as part of the Global Hawk Pacific Mission (GLOPAC). (NASA Earth Science Project Office 2011) In this specific case of an unmanned aircraft, the Global Hawk gives NASA a long endurance platform on which multiple instruments can be carried and a diverse range of missions can be accomplished with minimally invasive modifications to integrate and test the instruments. This platform and other airborne vehicles will be discussed at length in Chapter 4. The idea of an adaptable platform, demonstrated by the Global Hawk, is accomplished differently in space as demonstrated by NASA's A-Train of Earth observing satellites in LEO.

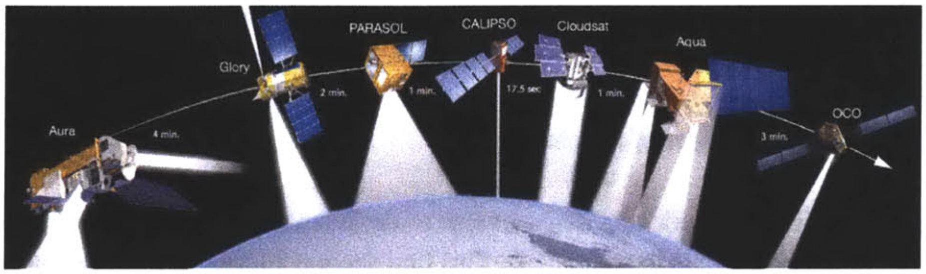


Figure 2.3: Complexity that exists within Satellite Systems of Systems: NASA's A-Train set of Earth Observing Satellites. The A-Train is a collection of 7 Satellites (6 NASA, 1 JAXA) flying in the same orbit but separated by a few minutes, which allows for cross-registration of data. (National Aeronautics and Space Administration 2009a)

NASA's A-Train is a set of Earth observing satellites in the same orbit with only seconds separating their respective ground location transits in an effort to cross-register data for scientific synergy. This complex multi-satellite system represents a case in which multiple elements of form are nearly collocated to perform a set of functions that would otherwise not be possible. The pattern of complex sensor arrangement and collocation repeats itself throughout the GEOS. This inherent complexity necessitates a comprehensive approach to for decomposition in order to establish the larger problem in more manageable sub-problems.

These elements of form are established to deliver value to the broader stakeholder community through the GEOS. The value generated by the elements of form in the GEOS is directly related to the stakeholder objectives fulfilled by measurements taken by instruments. Figure 2.4 outlines this value flow that culminates in the Campaign-level Science Traceability Matrix (CSTM) developed by Theo Seher in 2009 as mentioned in the literature review. (Seher 2009)

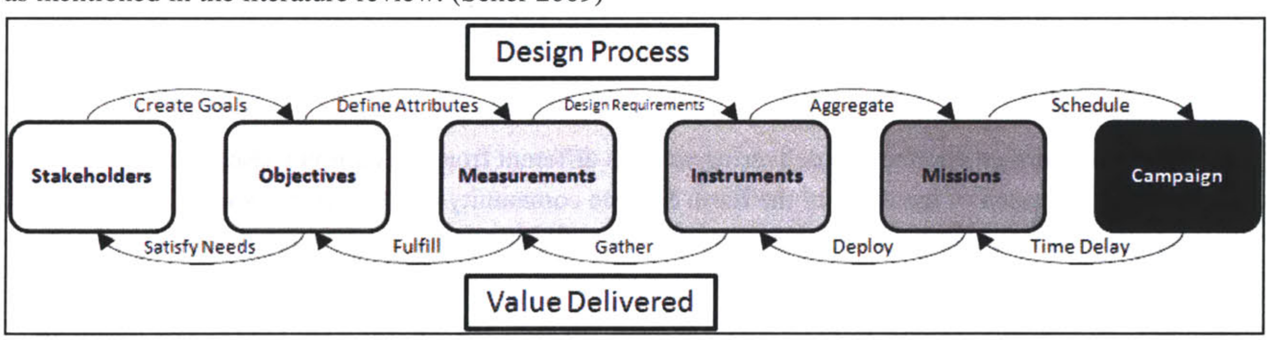


Figure 2.4: Overview of Campaign-level Science Traceability Matrix Framework. Stakeholder analysis is used to identify to identify value in the system. Stakeholders create Objectives,

Objectives define the attributes needed from Measurements, Measurements determine the design requirements of Instruments, Instrument aggregate into Missions and Missions are scheduled into campaigns. Going from left to right this value is incorporated into the system architecture and from right to left value is delivered to the stakeholders.

The design process begins with the identification of stakeholders who will ultimately be the judge of the system's benefit. Stakeholders create goals either individually or as a group, which generates objectives. For the GEOS, these objectives define the attributes of the measurements, which in turn shape the design requirements of instruments. The individual instruments aggregate to form missions, which are then scheduled into a campaign. The campaign delivers value back to the stakeholders by sequencing missions thereby introducing time delays. Missions act to deploy instruments, which gather measurements. The measurements that are actually gathered have attributes that fulfill objectives, either partially or wholly. When objectives are fulfilled stakeholder needs are met. This process of design and delivery will be examined in detail in the remainder of the chapter.

The ultimate goal of this framework is to deliver value to the stakeholder by correctly identifying how that value traces from stakeholders to campaigns. This first section attempted to show that value can be maximized if system architecting principles are applied. Keeping the CSTM framework in mind, the remainder of this chapter will describe how this thesis proposes to accomplish this value identification and optimization.

2.2. System Metrics

The second step in the system architecting process is to determine how the value that flows from campaigns to stakeholder is to be quantified in order for architectures to be evaluated. The Global Earth Observation System requires value flow metrics because no single objective governs the GEOS. This is supported by the NRC committee that was formed and the numerous compromises that were made for the Earth science community to come to agreement in the Decadal Survey. (Committee on Earth Science and Applications 2007) The committee that wrote the Decadal Survey had notional metrics in mind when making decisions but they did not explicitly detail those metrics in a traceable way. For this reason, two metrics are used to evaluate GEOS architectures: Data Value and Data Gap.

2.2.1. Campaign Benefit

The first metric this thesis uses to evaluate GEOS architectures is "Data Value", which is a measure of the benefit gained by the stakeholders with the successful operation of a given mission. The value delivered to the stakeholders is calculated by tracing campaign benefit through the CSTM as described in Figure 2.5. To deliver benefit back to the stakeholders, a mission's instruments must gather data that can be used to fulfill an objective put forward by one of the Decadal Survey panels.

This stakeholder driven approach to delivering value is different from the current technology centric mindset that puts much of the focus of the Earth Science community on developing new instruments. NASA Earth science satellite missions are currently formulated and run by a Principal Investigator (PI) who is responsible for technology development and ultimately the scientific results of the mission. This approach, which puts scientists at the forefront of each mission, has had tremendous success in creating new technology and furthering understanding of the Earth system, but it has also led to rising instrument costs and longer development cycles. The "PI model" of Earth Science missions relies on scientists proposing new instruments and missions in order to win technology development contracts from (mainly) government funding sources. The Decadal Survey represents the first time the Earth science community came together to collectively discuss priorities and objectives, which signals a more systematic approach is being sought. A stakeholder driven view of mission formulation and technology development doesn't take the scientists out of the process, but directs the community towards a strategy that has broad scientific and societal appeal. Stakeholder considerations go into the way that instrument and mission funding decisions are made but a traceable framework is created for this thesis. This traceable mission value framework will culminate in Figure 2.6 with a set of mission values.

The design and delivery steps outlined in section 2.1 are effectively summarized in Figure 2.4 and will be quantitatively explored through Figure 2.5. This framework builds on the work of Theo Seher who introduced the Campaign-Level Science Traceability Matrix (CSTM), which used a set of matrices to trace the flow of benefit through Figure 2.5. A Science Traceability Matrix (STM) is a well established tool used in mission planning to demonstrate a mission's scientific fulfillment; the Campaign-level STM applies that methodology to a series of missions that make up a campaign. This thesis uses the CSTM to determine the flow of benefit from instruments to objectives for satellite missions. The inputs to the CSTM have been updated and its scientific assumptions have been reevaluated.

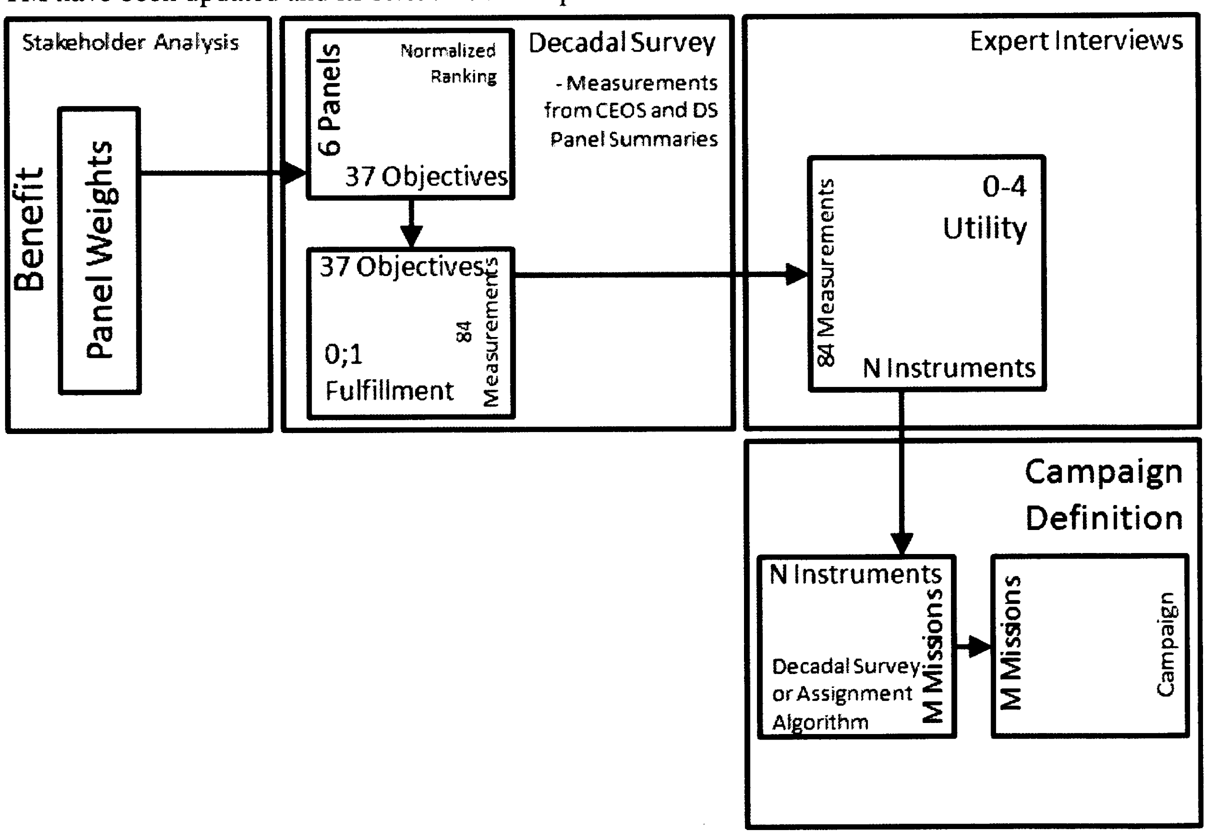


Figure 2.5: The Campaign-Level Science Traceability Matrix (CSTM) Framework version 1.1. CSTM traces benefit from Stakeholder Objectives through Measurements and Instruments using the Decadal Survey and Expert Interviews as guides. Instruments are assigned to Missions and a set of Missions form a Campaign based on a defined campaign.

Figure 2.5 lays out a graphical representation of the CSTM methodology that will be used to trace benefit flow from stakeholders to feasible architectures. The 4 large boxes represent sources of information for the matrices and mappings within them. The stakeholder analysis results in a set of panel weights, which act to define the importance of each stakeholder to the broader community. Information from the Decadal Survey is used to map the 6 panels to their 37 objectives and those objectives to the measurements that fulfill them. Expert interviews are used to determine the measurements taken by each instrument and with what quality. The instrument sets are assigned to missions and the missions are assigned into a campaign, this process is called "Campaign Definition". Within the matrices are descriptions of how the two sides are related. For instance, each panel presented a ranked list of its objectives. The result of this framework is a total benefit (B_{Total}) of the defined campaign.

Stakeholder Analysis

The first step in the CSTM value tracing process is stakeholder analysis, which was performed by Tim Sutherland (Sutherland 2009) as described in the literature review. One of the results of his thesis will act as the panel weights (w_p) in Equation 2.1. These weights were determined by quantifying the importance of each panel to the broader stakeholder community through the number and importance of their interactions. Note that the 6 panels of the Decadal Survey were meant not only to represent the interests of their respective science communities but also the wider societal and national interests associated with their work (Committee on Earth Science and Applications 2007). This broad reach means that these panels' objectives are a good proxy for the larger stakeholder community and thus will be used throughout this framework. Equation 2.1 shows how total benefit is related to the panels through the panel weights and the benefit delivered to each panel by the campaign.

$$B_{Total} = \sum_{p=1}^{\#Panels} w_p b'_p = \sum_{p=1}^{\#Panels} b_p \text{ where } b_p = w_p b'_p$$

Equation 2.1: Total Benefit as a function of Panel Benefit. Total Benefit (B_{Total}) is the sum of the benefit delivered to each of the panels by the Campaign (b'_p) weighted by each of the panel weights (w_p).

The panel weights (W_p) are given Table 2.1.

W_p	Panel	Weighting
W_5	Weather	0.214
W_4	Climate change	0.206
W_2	Ecosystems	0.206
W_6	Water	0.156
W_1	Human health	0.111
W_3	Solid Earth	0.107

Table 2.1: Weight assigned to each Panel based on Stakeholder Analysis. Panel weights (W_p) will be used to weigh the benefit delivered by the campaign to the panels.

Stakeholder analysis is crucial to developing a quantitative understanding of the benefit delivered by the GEOS because key architectural decisions must appeal to the entire stakeholder community in order to ensure support and funding for the program. More details regarding the outcomes and methods of the stakeholder analysis can be found in Sutherland's master's thesis titled, "Stakeholder Value Network

Analysis for Space-Based Earth Observations" (Sutherland 2009).

Panels Define Objectives

The stakeholders of the system, in this case the Decadal Survey panels, define objectives that satisfy their needs. The Decadal Survey panels defined and ranked their objectives in the individual panel reports within the Decadal Survey as shown in Table 2.2. The table shows the ranking given to each objective by their respective panels and the numerical value (W_{po}) that will be used to weigh the objectives in the CSTM. More precisely, the weight assigned to each objective (W_{po}) is equal if the objectives are equally ranked. If they are not equally ranked, the difference between adjacent objective is constant ($1/n^2$). If a subset of objectives is equally ranked, their combined weight is equally divided. The sum of a panel's the objective weights is always equal to 1. For the exact algorithm see the Matlab code in section **Error! Reference source not found.** of the appendix. Equation 2.2 shows how benefit is delivered to the panels through their objectives as defined in the Decadal Survey.

$$b_p = \sum_{o=1}^{\#Objectives} W_{po} q_o$$

Equation 2.2:Panel benefit (b_p) is the Summation of Objective fulfillment (q_o) weighted by the rankings assigned to each objective by the panels (W_{po}).

The objectives weights (W_{po}) are presented in Table 2.2.

Measurements Fulfill Objectives

The benefit derived from an objective (q_o) comes from measurements being taken by instruments in the campaign. The measurement to objective mapping (W_{om}) is a binary relationship that is mined from the Decadal Survey and expert interviews, as shown in Equation 2.3.

$$W_{om} = \begin{bmatrix} 1;\ if\ Measurement\ fulfills\ Objective \\ 0;\ if\ Measurement\ does\ not\ fulfill\ Objective \end{bmatrix}$$

Equation 2.3: If a Measurement fulfills an Objective, its weight is 1, otherwise it is 0 as shown in a sample in Table 2.3 below.

An objective receives benefit through measurements relative to the total number of measurements that fulfill it, as described in Equation 2.4.

$$W'_{om} = \frac{W_{om}}{\sum_{m=1}^{\#Measurement} W_{om}} \qquad q_o = \sum_{m=1}^{\#Measurement} W'_{om} q_m$$

Equation 2.4: Objective benefit (q_o) is the sum of the measurement fulfillment weighted by the measurement to objective mapping (W_{om}) normalized by the number of measurements that go into the fulfillment of each objective (provided in Table 2.2).

As shown in Equation 2.4, there is a relationship between the total fulfillment of an objective and the number of measurements that could potentially contribute to it. For instance, if in a campaign, 10 measurements could contribute to an objective then each one that is taken only fulfills 1/10 of the objective. While not completely descriptive of the benefit delivery process, it is an approximation that will be refined in Chapter 5.

Objectives	Panel Ranking	W_{po} (See Equation 2.2)	$\sum_{m=1}^{\#Measurement} W_{om}$ (See Equation 2.4)	
H1: Ozone Processes: Ultraviolet Radiation and Cancer	1	$W_{1,1}$= 0.167	21	Health
H2: Heat Stress and Drought	1	$W_{1,2}$= 0.167	4	
H3: Acute Toxic Pollution and Releases	1	$W_{1,3}$= 0.167	4	
H4: Air Pollution and Respiratory and Cardiovascular Diseases	1	$W_{1,4}$= 0.167	9	
H5: Algal Blooms and Waterborne Infectious Diseases	1	$W_{1,5}$= 0.167	4	
H6: Vector-borne and Zoonotic Disease	1	$W_{1,6}$= 0.167	6	
Eco1: Ecosystem Function	1	$W_{2,7}$= 0.280	4	Ecosystems
Eco2: Ecosystem Structure and Biomass	2	$W_{2,8}$= 0.240	3	
Eco3: Carbon Budget	3	$W_{2,9}$= 0.200	3	
Eco4: Coastal Ecosystem Dynamics	4	$W_{2,10}$= 0.160	4	
Eco5: Global Ocean Productivity	5	$W_{2,11}$= 0.120	3	
SE1: Surface Deformation	1	$W_{3,12}$= 0.280	3	Solid Earth
SE2: Surface composition and Thermal Properties	2	$W_{3,13}$= 0.240	3	
SE3: High Resolution Topography	3	$W_{3,14}$= 0.200	2	
SE4: Temporal Variation in Earth's Gravity Field	4	$W_{3,15}$= 0.140	4	
SE5: Oceanic Bathymetry	4	$W_{3,16}$= 0.140	1	
C1: Aerosol-Cloud Forcing	1	$W_{4,17}$= 0.184	12	Climate
C2: Ice Sheet and Sea Ice Volume	1	$W_{4,18}$= 0.184	6	
C3: Carbon Sources and Sinks	1	$W_{4,19}$= 0.184	6	
C4: Radiance Calibration and Time-Reference Observatory	2	$W_{4,20}$= 0.133	5	
C5: Earth Radiation Budget (ERB) Continuity	2	$W_{4,21}$= 0.133	0	
C6: Ice Dynamics	3	$W_{4,22}$= 0.102	1	
C7: Ocean Circulation, Heat Storage, and Climate Forcing	4	$W_{4,23}$= 0.082	6	
W1: Tropospheric winds	1	$W_{5,24}$= 0.194	5	Weather
W2: High temporal resolution air pollution	1	$W_{5,25}$= 0.194	6	
W3: All-weather temperature and humidity profiles	2	$W_{5,26}$= 0.153	4	
W4: Comprehensive tropospheric aerosol characterization	2	$W_{5,27}$= 0.153	5	
W5: Radio Occultation	3	$W_{5,28}$= 0.112	1	
W6: Comprehensive tropospheric O3 measurements	3	$W_{5,29}$= 0.112	7	
W7: Aerosol-cloud discovery	4	$W_{5,30}$= 0.082	12	
WA1: Soil moisture and freeze-thaw state	1	$W_{6,31}$= 0.204	2	Water
WA2: Surface water and ocean topography	2	$W_{6,32}$= 0.184	3	
WA3: Snow and cold land processes	3	$W_{6,33}$= 0.163	4	
WA4: Water vapor transport	4	$W_{6,34}$= 0.143	4	
WA5: Sea Ice thickness, glacier surface elevation and glacier velocity	5	$W_{6,35}$= 0.122	4	
WA6: Groundwater storage, ice sheet mass balance and ocean mass	6	$W_{6,36}$= 0.102	3	
WA7: Inland and coastal water quality	7	$W_{6,37}$= 0.082	4	

Table 2.2: Ranking of Panel's Objectives taken from Decadal Survey with Linear Normalized scores (W_{po}) and used in Equation 2.2.The forth column is the number of Measurements that fulfill Objectives as used in Equation 2.4 [2]

A sample of the measurement to objective matrix (W_{om}) is provided in Table 2.3 and the entire matrix can be found in the Appendix in Table 7.1. The measurements considered in this CSTM analysis are a combination of measurements found in the Decadal Survey, listed on the CEOS database (Committee on

Earth Observation Satellites 2010), and found to be important through expert interviews. The 84 resulting measurements are broken into 5 categories: Atmosphere, Land, Water, Ice, and Gravity/Magnetism.

W_{om}	1.1.1 aerosol height/optical depth	1.1.2 aerosol shape, composition, physical and chemical properties	1.1.3 aerosol scattering properties	1.1.4 aerosol extinction profiles/vertical concentration	1.1.5 aerosol size and size distribution	1.1.6 aerosol absorption optical thickness and profiles
H1: Ozone Processes: Ultraviolet Radiation and Cancer	1	1	1	1	1	0
H2: Heat Stress and Drought	0	0	0	0	0	0
H3: Acute Toxic Pollution and Releases	0	0	0	1	1	0
H4: Air Pollution and Respiratory and Cardiovascular Diseases	0	1	0	0	1	0
H5: Algal Blooms and Waterborne Infectious Diseases	0	0	0	0	0	0
H6: Vector-borne and Zoonotic Disease	0	0	0	0	0	0

Table 2.3: Binary Mapping of Measurements to Objectives (W_{om}) (Sample). Each Measurement fulfills a set of Objectives, which can be updated to reflect changes in scientific techniques or methods. Full table is located in the Appendix as Table 7.1 and associated Matlab code is located in section Error! Reference source not found. **of the Appendix.**

An example shown in Table 2.3 is the first Health Panel objective, Ozone Processes. There are 5 measurements shown in Table 2.3 that fulfill the Ozone Processes objective: 1.1.1, 1.1.2, 1.1.3, 1.1.4, and 1.1.5. All of these measurements deal with aerosols and affect the Ozone Processes objective by the way they help to understand UV reflection. By fulfilling objectives, each measurement is able to deliver benefit back to the stakeholders. In this example, if these 5 measurements were the only that fulfilled objective H1, the taking each measurement would contribute 0.2 to the fulfillment of H1.

Measurement Benefit to Panels

At this point the benefit of each measurement to each panel (b_{mp}) can be computed by summing the normalized measurement to objective mapping (W'_{om}) multiplied by the weight of that objective (W_{po}) over all of the objectives, as shown in Equation 2.5. Note that the benefit derived by panels from measurements (W_{pm}), instruments (W_{pi}), and missions (W_{pM}) will remain matrices in terms of all of the panels. This is seen in Equation 2.11 so that the designer retains the option to include or not include panel weights (w_p) in the calculation of total benefit.

$$W_{pm} = \sum_{o=1}^{\#Objectives} W_{po} W'_{om}$$

Equation 2.5: The benefit of a measurement to each panel (W_{pm}) is equal to the number of objectives it fulfills normalized by the number of measurements that go into the fulfillment of each objective multiplied by the objectives weights (W_{po}) (both provided in Table 2.2) .

Measurements are taken by Instruments

The mapping of instruments to the measurements they take (W_{mi}) is evaluated both on an absolute scale and relative to other instruments. Note the relatively low fidelity of the 0-4 scale in the instruments to measurements mapping. It will be shown later that this fidelity is not enough to incorporate non-space based instruments into the CSTM. Equation 2.6 shows the scale on which measurements are rated for each instrument. This 0-4 score captures both an instruments ability to take a given measurement, and its fidelity with respect to all of the other potential instruments in the set or available to Earth scientists.

$$W_{mi} = 0.1 \cdot 2^{(w-1)}, for \begin{bmatrix} w = 4; if\ Instrument\ i\ takes\ Measurement\ m\ with\ "Highest\ Quality" \\ w = 3; if Instrument\ i\ takes\ Measurement\ m\ with\ "High\ Quality" \\ w = 2; if\ Instrument\ i\ takes\ Measurement\ m\ with\ "Moderate\ Quality" \\ w = 1; if\ Instrument\ i\ takes\ Measurement\ m\ with\ "Low\ Quality" \\ w = 0; if\ Instrument\ i\ does\ not\ take\ Measurement\ m \end{bmatrix} = \begin{bmatrix} .8 \\ .4 \\ .2 \\ .1 \\ 0 \end{bmatrix}$$

Equation 2.6: The relationship between Instruments and Measurements is rated 0 to 4 based on the quality of the measurements taken by the instruments. This is shown as a sample in Table 2.4.

A sample of this mapping (W_{mi}) as it applies to the Decadal Survey is shown in Table 2.4 and can be seen in full in the Table 7.2 of the Appendix.

W_{mi}	SMAP_RAD	SMAP_MWR	DESD_SAR	DESD_LID	XOV_SAR	XOV_RAD	XOV_MWR
1.1.1 aerosol height/optical depth	0	0	0	**0.8**	0	0	0
1.1.2 aerosol shape, composition, physical and chemical properties	0	0	0	0	0	0	0
1.1.3 aerosol scattering properties	0	0	0	0	0	0	0
1.1.4 aerosol extinction profiles/vertical concentration	0	0	0	**0.4**	0	0	0
1.1.5 aerosol size and size distribution	0	0	0	0	0	0	0
1.1.6 aerosol absorption optical thickness and profiles	0	0	0	0	0	0	0
1.2.1 Atmospheric temperature fields	0	0	0	0	0	0	**0.8**
1.3.1 Atmospheric humidity (indirect)	0	0	0	0	0	0	**0.8**
1.3.2 Water vapor transport - Winds	0	0	0	0	0	0	**0.8**

Table 2.4: Mapping of Instruments to Measurements (W_{mi}) (Sample). Each Instruments is capable of taking a set of Measurements as designed by Scientist and Engineers. Information for this mapping comes from Instrument Documentation and Expert Interviews.

Information for this instrument to measurement matrix is derived mainly from experts at NASA and was subsequently modified through expert interviews conducted by Daniel Selva as part of his ongoing research into this area (Selva and Crawley 2011). The subjectivity with which measurements are ranked is due to the high level of abstract used in this updated version of the CSTM v1.1. This fidelity issue will be address in CSTM 2.0 and the rules-based expert system that are introduced and discussed in Chapter 5.

Instruments contribute benefit to panels (W_{ip}) through the measurements they take and the quality with which they take them (W_{mi}). Equation 2.7 shows the calculation of the benefit of each instrument to each panel.

$$W_{ip} = \sum_{m=1}^{\#Measurements} W_{mi} W_{pm}$$

Equation 2.7: The benefit delivered by each instrument to each panels (W_{ip}) is the sum of the

benefit of the measurements (W_{pm}) it takes, whether or not instrument i takes measurement m is represented by W_{mi}.

Instruments to Missions

A mission is an observational platform carrying a set of instruments designed to gather data on a given set of measurements from which benefit is derived by the science community. The assignment of instruments to missions is crucial for the delivery of benefit to the stakeholders. When missions are predefined, the assignment of instruments to missions is established; however ongoing work is exploring the optimization of instrument assignment to maximize benefit for a given cost. This work has been conducted by Daniel Selva and more can be found in his recent publications. [(Selva and Crawley 2010), (Selva and Crawley 2011)]

Regardless of the method used to populate the instrument to mission matrix, it will be a binary matrix as described in Equation 2.8.

$$W_{iM} = \begin{bmatrix} 1;\ if\ Instrument\ i\ is\ on\ Mission\ M \\ 0;\ if\ Instrument\ i\ is\ not\ on\ Mission\ M \end{bmatrix}$$

Equation 2.8: An instrument receives a 1 if Mission M carries it and a 0 otherwise.

The complete set of mission to instrument assignments is listed in Table 7.3 of the Appendix. With the relationship between instruments and the missions on which they fly, a defined set of missions constitute a campaign.

$$W_{Mp} = \sum_{i=1}^{\#instruments} W_{iM} W_{ip}$$

Equation 2.9: The benefit delivered by each Mission to each panel (b_{Mp}) is calculated by summing the instrument benefit (b_{ip}) for each instrument in a Mission (W_{iM}).

Equation 2.9 shows that the CSTM can calculate the benefit delivered to each panel by each mission (b_{Mp}), which is shown graphically in Figure 2.6. In this graph, the total benefit delivered to the GEOS by the 17 Decadal Survey missions is normalized to 1. Each panel is highlighted in a different color so that the graph shows how missions are contributing to the overall GEOS. The numerical values can be found in Table 7.4 of the Appendix.

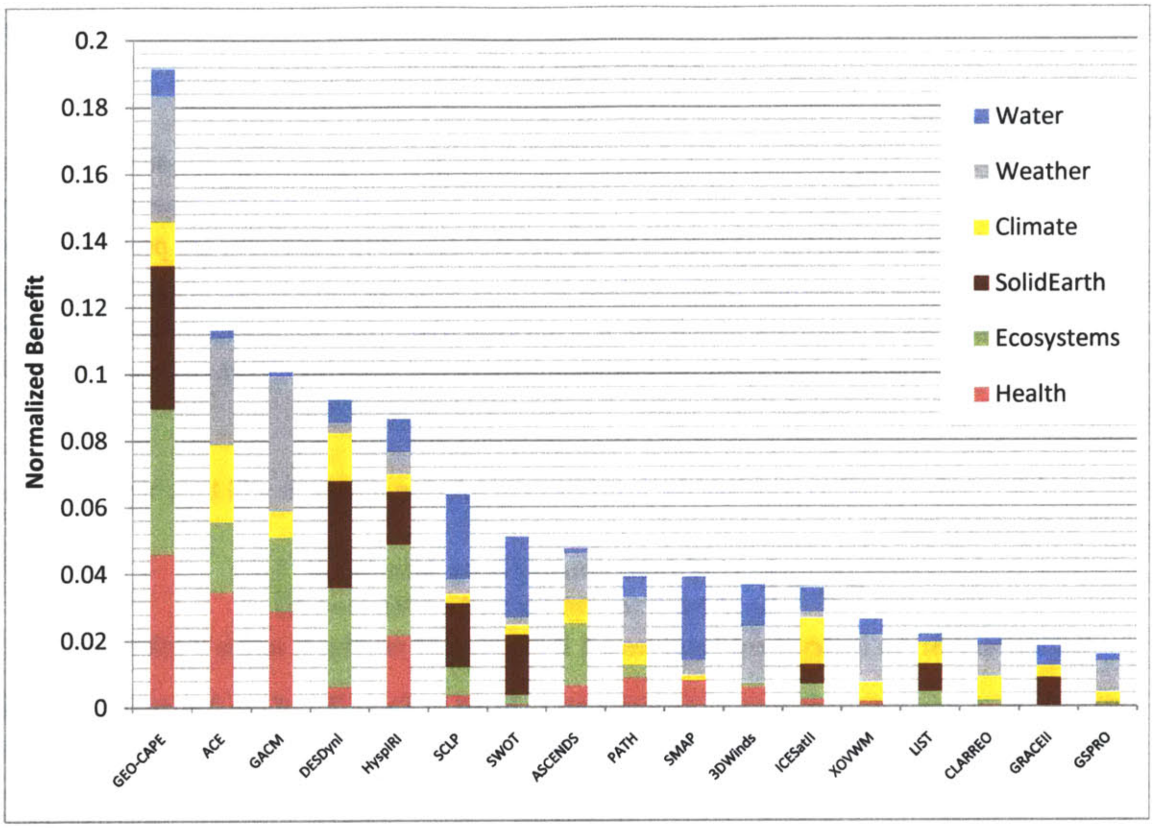


Figure 2.6: Normalized CSTM v1.1 Mission Benefit broken down by Panel (b_{Mp}) ranked in Descending order. This plot is shown numerically in Table 7.4 of the Appendix. These Mission benefits and their associated Measurements inform the scheduling algorithm described in section 2.3.

According to this analysis GEO-CAPE delivers the most total benefit by taking 34 measurements to fulfill 114 objectives. This also delivers the most benefit to 4 out of the 6 panels. For comparison, GSPRO delivers the least benefit to 4 out of 6 panels taking only 4 measurements and fulfilling only 6 objectives. This analysis also gives a decision maker the ability to compare missions based on benefit, and later by cost/benefit ratios, which is discussed in Chapter 3 when cost estimates are introduced.

Campaign Benefit

As was shown in Figure 2.5 benefit can be traced through a set of missions to the stakeholders of the system. Equation 2.10 completes the value framework by showing which missions are part of a given campaign (q_M). For the Decadal Survey case, this is the set of missions there were recommended in the final report. This will be expanded on in Chapter 5 with the addition of aircraft missions to complete the GEOS.

$$W_{MC} = \begin{bmatrix} 1;\ if\ Mission\ i\ is\ part\ of\ the\ Campaign \\ 0;\ Otherwise \end{bmatrix}$$

Equation 2.10: Campaign definition determines which missions are flown represented as $W_{M,C}$.

With the identification of the campaign's missions, a total campaign benefit can be calculated as shown in Equation 2.11 with or without panel weighting (W_p).

$$b_p = \sum_{M-1}^{\#Missions} W_{Mp} q_M W_p \quad \text{or} \quad b'_p = \sum_{M-1}^{\#Missions} W_{Mp} q_M$$

Equation 2.11: The total campaign benefit for each panel is the sum of the Mission benefits (W_{Mp}) for the Mission in the campaign (q_M). The campaign benefit can be weighted by the panel weights (W_p), which is the array b_p or it can be not weighted, which is the array b'_p.

As can be seen visually in Figure 2.6, each panel does not receive an equal amount of benefit when the benefit of each mission is summed along panel lines. The campaign benefit delivered to each panel is shown numerically in Table 2.5.

Panel	Normalized Panel Benefit $\left(\frac{b'_p}{\sum_{p=1}^{\#Panels} b'_p}\right)$	Normalized Weighted Panel Benefit $\left(\frac{b_p}{\sum_{p=1}^{\#Panels} b_p}\right)$
Health	0.176	0.116
Ecosystems	0.191	0.233
Solid Earth	0.151	0.095
Climate	0.124	0.152
Weather	0.211	0.267
Water	0.147	0.136

Table 2.5: CSTM Normalized Benefit Delivered to Panels ($b'_p/\sum(b'_p)$) by 17 Decadal Survey Missions as shown in the first column. The second column shows CSTM Normalized Benefit weighted by Stakeholder Analysis Weights ($b_p/\sum(b_p)$). Note the changes in normalized benefit based on stakeholder weighting, these CSTM benefits will become important when considering a campaigns "Fairness".

Table 2.5 shows the distribution of benefit delivered to the panels by the campaign with (b_p) and without (b'_p) panel weighting. This shows that the Weather panel receives the most benefit from the Decadal Survey campaign. The stakeholder weighting is particularly important as the panel weights shown in Table 2.1 alter the delivered benefit, shown when comparing the two columns of Table 2.5. For example, the Solid Earth panel receives 15.1% of the campaign benefit before panel weighting and 9.5% after panel weighting. This decrease is due to the low weight given to Solid Earth through stakeholder analysis. This analysis benefit delivery is important when later considering "Fairness" in chapter 3.

2.2.2. CSTM v1.1 Conclusion

Section 2.2 described the value tracing CSTM framework represented in Figure 2.5. This is an updated version of the CSTM base on the work of Seher in 2009 that includes a more thorough understanding of Earth science measurements and instruments compiled from research and interviews with experts. By mapping the panels of the Decadal Survey to their respective objectives and those objectives to measurements, a quantitative framework is created for exploring the value of any set of Earth observing instruments and missions. Using the 17 recommended Decadal Survey missions as an illustrative example, a value map of missions to panels reveals benefit received by the stakeholders from the completion of each mission. These missions are scheduled to form a campaign that delivers benefit to the stakeholders by launching the missions. Section 2.3 expands the CSTM to include a campaign architecting and evaluation component.

2.3. Campaign Scheduling

This section introduces a campaign scheduling tool used to evaluate campaign architectures based on the two objectives: "Data Value" and "Data Gap". The algorithm chosen to explore and optimize campaign schedules is a multi-objective genetic algorithm (GA). The GA is presented in this section. First the high level algorithm is introduced and justified, and then the metric calculation processes are discussed.

2.3.1. Multi-objective Genetic Algorithm

A novel approach of this thesis is the implementation of the genetic algorithm to solve this scheduling problem, it therefore requires some justification. The Earth observing mission scheduling problem displays at least 4 characteristics that make it a poor candidate for "classic" optimization.

- Highly Non-Linear: The Global Earth Observation System campaign model's non-linearity makes it unsuitable for the classic methods of optimization such as Newton Method or Sequential Quadratic Programming (SQP), which require gradient or quasi-gradient information. To obtain gradient information, a closed form solution of the problem under investigation has to be derived and to do so would require losing some fidelity and realism in the case of the GEOS campaign model. The scheduling problem can be modified to fit a linear form, but this causes an even greater sacrifice in terms of fidelity than attempting to produce a closed form solution.
- Non-Convex: By examining previous authors' attempts at optimization as described in section 1.3.1 of the literature review and by examining Pareto fronts produced by this GA it is evident that the solution space contains many local optima. The presence of many local optima makes it highly improbable that a single-solution solver could find a global optimum.
- Integer Variables: Discrete inputs are solvable for linear problems using techniques such as branch and bound or cutting plane, but non-linear integer optimization requires either dynamic programming or meta-heuristic methods, like GA. Dynamic programming is only appropriate when the problem can be expressed in a specific recursive form, which is not the here.
- Ordinal Variables: The input variables do not represent actual cardinal values but are actually ordinal values. Therefore no gradient or pseudo-gradient information can be defined.

Given these characteristics, a meta-heuristic method appears to be the best solution, the GA was chosen for its proven performance in scheduling problems. (Davis 1991)

The Genetic Algorithm (GA) toolkit in Matlab (MathWorks 2010) provides an excellent framework on which to build. In addition, the Matlab toolkit is relatively well understood and it is relatively simple to implement. This thesis will not delve into the merits or derivations of the genetic algorithm method but more can be found in the literature reviewed for this thesis outlined in section 1.3.2. (Davis 1991) For reference, the Matlab implementation of GA uses a variant of the NSGA-II algorithm found in Deb's "Multi-Objective Optimization Using Evolutionary Algorithms". (Deb 2001)

In order to implement a genetic algorithm the following elements need to be defined: the input (design vector), fitness function, and constraints. The Matlab GA toolkit contains a prewritten set of code for the necessary functions but requires adaptation to the specific problem. All of the methods presented in this section are shown in Matlab code in section **Error! Reference source not found.** of the Appendix.

Design Vector

For the scheduling problem, an "individual" is an array of mission numbers arranged in the order in which they will be launched. An example ordering is shown in Pseudocode 2.1, which shows a campaign in which Mission 5 will be launched first followed by Mission 8 and so on until Mission 14 is launched last. As described above, 1500 individuals constitute the "population" that is evaluated in each "generation".

Individual = [5,8,11,1,3,4,9,16,12,17,13,2,7,6,15,14]

Pseudocode 2.1: (Example) GA Scheduling Algorithm Individual is an ordering of Missions. Each Mission number points to Parameters such as Instruments, Cost, and Technology Readiness Launch Date and can only be contained once in an Individual.

Fitness Function

The fitness function is the method that analyzes the architecture and calculates the "Data Value" and "Data Gap" metrics. The metrics are used to evaluate "Individuals" in order to generate the next generation. The fitness function uses specific calculations for the two metrics as discussed in sections 2.3.2 and 2.3.3.

2.3.2. Objective 1: Data Value

The first objective that the GA optimizes for is "Data Value", which is calculated using a 4 step process. Missions are assigned launch dates and assessed a cost penalty based on their technology readiness. The benefit derived from each mission is discounted to reflect an urgency to deliver benefit. The discounted benefit is weighted by the panel weights derived from stakeholder analysis. The entire benefit of a mission is derived at launch and is independent of mission duration

Launch Date Estimate

The first step in the process of calculating the "Data Value" metric is to estimate the launch dates of the missions in the campaign, which is considered an estimate because it will be reassessed if the cost is penalized due to technology constraints. Launch dates are calculated using a simple formula shown in Equation 2.12. The time that it takes to launch a mission is estimated by its cost divided by the yearly budget, carried out for each mission in the campaign order. The calculation starts at a predetermined campaign start date (CapaignStart) and counts up, moving to the next mission when the entire budget is consumed by a mission's cost as shown in Equation 2.12.

$$\text{if } Year_j = CampaignStart: \quad LaunchDate^{Est}_{Miss_i} = CampaignStart + \frac{Cost^{Initial}_{Miss_i}}{Budget_{Year_j}}$$

$$\text{if } Year_j > CampaignStart: \quad LaunchDate^{Est}_{Miss_i} = LaunchDate^{Final}_{Miss_{i-1}} + \frac{Cost^{Initial}_{Miss_i}}{Budget_{Year_j}}$$

Equation 2.12: Launch Date Calculation. Each Mission's Launch Date is calculated by dividing that Mission's cost by the Budget in the Current Year and future years needed to launch the Mission. Missions are launched in serial sequence.

In order to determine mission launch dates in a deterministic way, several assumptions are made:

1. Mission costs are set at the beginning of the campaign and are considered to be known.
2. NASA budgets are known and projectable into the future.
3. Missions are developed and launched in serial sequence. In reality, missions are developed in parallel as money is allocated for their development and ramped up or down depending on

progress and other resource allocation needs. The reality of mission spending is illustrated representatively in Figure 2.7. (Seher 2009)

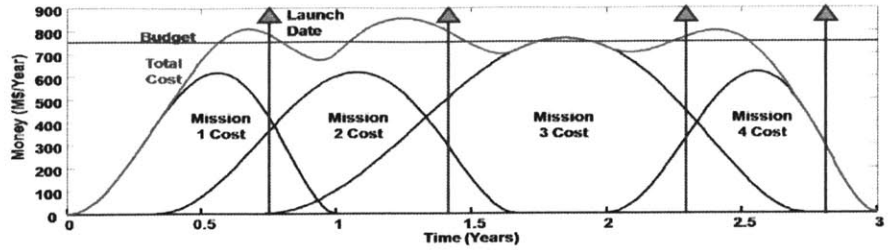


Figure 2.7: Realistic Campaign Spending graph showing parallel development, launch and operations for multiple Missions throughout Campaign. Flat budget used in GEOS model is simplified version to develop and launch missions sequentially. (Seher 2009)

Technology Readiness Level-Based Cost Penalty

The second step in the process of calculating the "Data Value" metric is to recognize, as the Decadal Survey did, the technology readiness constraints present within each mission and the general GEOS. The technology readiness constraint is present because Earth Science missions have historically involved new technology development as part of the overall mission development. In the case of Earth observation missions, it is most often a new instrument that must be developed to either gather new data or take a measurement with higher accuracy. Technology Readiness Level (TRL) is defined by Mankin's 1995 white paper titled "Technology Readiness Levels" as "a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology".(Mankins 1995). This is the method the Decadal Survey panels used when roughly evaluating which "Tier" a given mission should be launched in as shown in Table 2.6. As a surrogate, this thesis will use a date after which the mission would nominally be ready for launch.

Tier 1	**2010-2013**	GSPRO	CLARREO	SMAP	ICESat-II	DESDynl	-
Tier 2	**2013-2016**	HyspIRI	XOVWM	ASCENDS	SWOT	GEO-CAPE	ACE
Tier 3	**2016-2020**	LIST	PATH	GRACE-II	SCLP	GACM	3DWinds

Table 2.6: Decadal Survey 'Tier' structure outlined in Table ES.1 and ES.2 of the Executive Summary. Missions are arranged in ascending cost order according to Decadal Survey cost estimates (Committee on Earth Science and Applications 2007).

The most widely used method for modeling constraints in an optimization problem is to demarcate feasible and infeasible regions. Infeasible regions are not to be explored because; assuming the optimal solution must be feasible, there is no way the optimal solution can exist in an infeasible region (Bertsmias 1997). While there are conceivably many ways to model the above mentioned TRL constraint, it is assessed in this analysis as a penalty. Modeling the TRL constraint as a penalty is done for two reasons:

1. The GA uses known solutions from the previous "generation" to explore the problem's trade space and an infeasible architecture may be on the path to a feasible architecture in a way that the algorithm may never find the feasible architecture if it is not able to delve into the infeasible area. This is especially true for trade spaces on which large areas are infeasible as would be the case in highly constrained environments.
2. When a hard constraint is applied to restrict exploration of infeasible regions, it is possible for an

optimization algorithm to get "stuck" in a sub-optimal feasible region because of the barriers. A more gradual penalty allows the algorithm to explore infeasible regions and potentially find feasible regions of higher value.

The topic of penalty functions is discussed thoroughly in Chapter 7 titled, "Constrained Multi-Objective Evolutionary Algorithms" in Deb's book "Multi-Objective Optimization Using Evolutionary Algorithms" (Deb 2001). For the two reasons mentioned above and after consulting resources such as Deb's work it was determined that applying a penalty is the preferred method for implementing a TRL constraint.

The penalty applied must represent a realistic consequence of the desire to launch a mission before its predetermined TRL readiness date. If there was no penalty, launch dates would be a simple function of the benefit of the missions, their costs, and the yearly budgets. Every campaign generated from a set of missions would end on the same date as the cumulative cost of the campaign would always be the same. Instead, Equation 2.13 is applied so that for every year a mission is scheduled to launch before its "TRL Launch Date", a cost penalty is assessed. After the "TRL Cost Penalty" is applied, a new launch date is calculated as seen in Equation 2.14. The initial cost of the Decadal Survey missions is discussed in chapter 3.

$$\text{if } LaunchDate_{Miss_i}^{Est} \geq TRL\_Launch\_Date_{Miss_i}; \qquad Cost_{Miss_i}^{Final} = Cost_{Miss_i}^{Initial}$$
$$\text{if } LaunchDate_{Miss_i}^{Est} < TRL\_Launch\_Date_{Miss_i}; \quad Cost_{Miss_i}^{Final} = Cost_{Miss_i}^{Initial} * \left[(1 + TRL\_Cost\_Penalty)^{(TRL\_Launch\_Date_{Miss_i} - LaunchDate_{Miss_i}^{Est})}\right]$$

Equation 2.13: "TRL Cost Penalty" associated with breaking the "TRL Launch Date" assigned to each mission. "TRL Launch Dates" are first assigned based on Decadal Survey 'Tier' structure and then based on Campaign Analysis. Cost Penalty resembles a 'Return on Investment' financial calculation in that it determines the money necessary to advance a Mission.

The "TRL Cost Penalty" is intended to model an approach where an agency would dedicate resources to accelerate instrument development in order to launch a mission sooner than would otherwise be possible. Since the cost of a mission may increase due to the cost penalty, launch dates are recalculated as shown in Equation 2.14.

$$\text{if } Year_j = CampaignStart: \quad LaunchDate_{Miss_i}^{Final} = CampaignStart + \frac{Cost_{Miss_i}^{Final}}{Budget_{Year_j}}$$
$$\text{if } Year_j > CampaignStart: \quad LaunchDate_{Miss_i}^{Final} = LaunchDate_{Miss_{i-1}}^{Final} + \frac{Cost_{Miss_i}^{Final}}{Budget_{Year_j}}$$

Equation 2.14: The calculation of the Final Launch Date for each Mission depends on the Final Cost of that mission, which may be penalized due to TRL constraints.

Discounting Delivered Benefit

The third step in the process of calculating the "Data Value" objective is to assess a measure of urgency to data delivery. Once the launch dates have been calculated and costs penalized accordingly, they are inputs into the discounted benefit calculation. A mission's benefit is discounted based on the time between when the campaign starts and the mission's final launch date to capture the sense that "data today is better than data tomorrow", a common sentiment among scientists. The equation governing the implementation of this assumption is show in Equation 2.15. Each panel is given an annual discount rate based on work by Justin Colson (Colson 2008) shown in Table 2.7.

Panel	Depreciation rates
Weather	10%
Climate Change	15%
Land/Ecosystems	10%
Water	10%
Human Health	10%
Solid Earth	5%

Table 2.7: Yearly Depreciation Rates for each Panel used in time depreciation of the "Data Value" metric according to Equation 2.15. Climate Panel has 15% rate to reflect time sensitive nature of Climate data given the current political and scientific landscape. (Colson 2008)

The panel depreciation rates represent a judgment based on the urgency of the respective panels to receive data. Climate change is considered a topic presently relevant in the minds of various stakeholders and so data gathered today is much more valuable than data gathered in a decade. This is in contrast to the Solid Earth community, who experiences changes in their area of study on much longer time scales. These panel discount rates are applied to the number of years between the mission launch date and the campaign start date as seen in Equation 2.15.

$$Discounted\_b_{Mp} = b_{Mp} \cdot (1 - DepreciationRate_p)^{(LaunchDate_M - CampaignStart)}$$

Equation 2.15: The Data Value received by Panels from a given Mission is discounted based on the time between the Campaign Start Date and the Mission's Launch Date to reflect the time value of Data.

The value received by each panel is then weighted by its normalized weight as shown in Equation 2.16. The panel weights are found in Table 2.1 of the earlier discussion of stakeholder analysis.

$$Objective_{\text{DataValue}} = \sum_{p=1}^{\#Panels} W_{Tp} \left(\sum_{M=1}^{\#Missions} Discounted\_b_{Mp} \right)$$

Equation 2.16: The summation of discounted Data Value received by a Panel from the Campaign is weighted by that Panel's Stakeholder Analysis derived weighting shown in Table 2.1.

The weighted sum of the discounted mission benefit is the "Data Value" metric. The "Data Value" metric is the culmination of a 4 step process by which missions are assigned launch dates, assessed a penalty based on their TRL date constraint, discounted to reflect the urgency of the difference panels to receive data and weighted to include stakeholder analysis. This eagerness for data is balanced within the "Data Value" calculation by the TRL constraint and the escalating mission costs associated with it and from the "Data Gap" metric by the need to maintain measurements over long records and fill data gaps in the future.

2.3.3.Objective 2: Data Gap

This sub-section will present the second objective that the GA optimizes: "Data Gap". "Data Gap" is calculated by counting the number of gap-years present in a campaign schedule once established and then weighting those gaps by the measurement's importance. The concept of achieving data continuity is difficult to model for two primary reasons: the varying need among measurements to maintain data continuity and the ability of other observational platforms to take over the data gathering responsibility. The first difficulty is addressed by weighing each measurement gap based by its importance (I_m) to the stakeholders as calculated through the CSTM. The second difficulty is addressed more substantially in Chapters 4 and 5 as aircraft and other platforms are considered in conjunction with satellites.

This section details the accounting of data gaps by first presenting a discounting scheme similar in concept to the value discounting previously described. The measurement to mission mapping and the launch manifest will inform an accounting matrix that when summed and weighted by each measurement's importance produces the "Data Gap" objective.

Measurement Importance

Data gap is of more or less importance for certain measurements depending on the underlying science's need for long and/or uninterrupted data series. The Global Climate Observing System (GCOS) has defined 50 Essential Climate Variables (ECVs), which are crucial to support the work of United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). The ECVs should remain continuously measured if the international organizations tasked with determining the causes and effects of climate change are going to effectively fulfill their objectives. The ECVs are listed in Table 2.8 as defined in GCOS's October 2010 report to the UNFCC. (Global Climate Observing System 2010)

Domain	Essential Climate Variables
Atmospheric (over land, sea and ice)	**Surface:** Air temperature, Wind speed and direction, Water vapour, Pressure, Precipitation, Surface radiation budget. **Upper-air:** Temperature, Wind speed and direction, Water vapour, Cloud properties, Earth radiation budget (including solar irradiance). **Composition:** Carbon dioxide, Methane, and other long-lived greenhouse gases, Ozone and Aerosol, supported by their precursors
Oceanic	**Surface**: Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Surface current, Ocean color, Carbon dioxide partial pressure, Ocean acidity, Phytoplankton. **Sub-surface**: Temperature, Salinity, Current, Nutrients, Carbon dioxide partial pressure, Ocean acidity, Oxygen, Tracers.
Terrestrial	River discharge, Water use, Groundwater, Lakes, Snow cover, Glaciers and ice caps, Ice sheets, Permafrost, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Above-ground biomass, Soil carbon, Fire disturbance, Soil moisture

Table 2.8: Essential Climate Variables recognized by GCOS as critical to support work of UNFCCC and IPCC. Importance of certain measurements indicates that Data Gap must be applied selectively. (Global Climate Observing System 2010)

To capture the relative importance of data continuity on measurements (I_m), Equation 2.17 shows how it will be calculated in this thesis.

$$I_m = \sum_{o=1}^{\#Objectives} W_{mo} \left[\sum_{p=1}^{\#Panels} W_{po} \right]$$

Equation 2.17: The Importance of each measurement (I_m) is the sum of the benefit of each objective that it fulfills. W_{mo} is shown in Equation 2.3 and W_{po} is shown in Table 2.2.

The importance of each measurement (I_m) is calculated differently than the benefit of each measurement within the campaign as shown in Equation 2.17. The fundamental assumption in this calculation is that the importance of each measurement is independent of other measurements relative to the objectives it fulfills. In other words, each measurement gets the sum of all of the objectives it maps to. This is different from the calculation of b_{mp} in the CSTM benefit metric, where the number of measurement relevant to each objective is used as a normalization factor. The importance of each measurement (I_m) has been calculated and is shown in Table 7.5 through Table 7.9 by category.

Data Gap Discounting

Similar to the urgency constraint within the "Data Value" calculation, data continuity is more important in the near term then the far future. Therefore, within the "Data Gap" calculation gaps are discounted over time. Rising costs and shrinking budgets cause campaign lifetimes to stretch over several decades. There are two reasons that data gaps in the near term should be weighted more than gaps in the future. First, a data gap today is a problem that stakeholders know must be addressed or scientific value will be lost. Second, future plans are malleable enough to assume that with sound input from Earth scientists, gaps in the future can be closed. Data gaps occur most often because there is some unforeseen catastrophe, like a satellite malfunction, a launch failure, or a large cost overrun in a development project. These unexpected events cause the community to solve the problem in a rushed and inefficient way. While there is no commonly accepted rule for either of these situations, this thesis assumes a 10 year threshold for this data gap concern that tapers off linearly until the end of the campaign life time. Equation 2.18 shows how this is applied in the algorithm.

$$Measurement\_Time\_Line_{mt} = 1 \qquad for\ all\ m\ and\ 0 < t < 10$$

$$Measurement\_Time\_Line_{mt} = \frac{CampaignEnd - t}{CampaignEnd - 10} \qquad for\ all\ m\ and\ 10 < t < CampaignEnd$$

Equation 2.18: Data Gaps are discounted linearly from 10 years after the campaign start date to the end of the campaign to represent the diminishing weight put on gaps in the future.

Figure 2.8 shows Equation 2.18 applied to a 25 year campaign. The discounting scheme described in Equation 2.18 and shown graphically in Figure 2.8 contributes to the creation of a matrix called "Measurement Time Line". This matrix is used to count the measurement gaps so that each measurement has an associated number of gap-years.

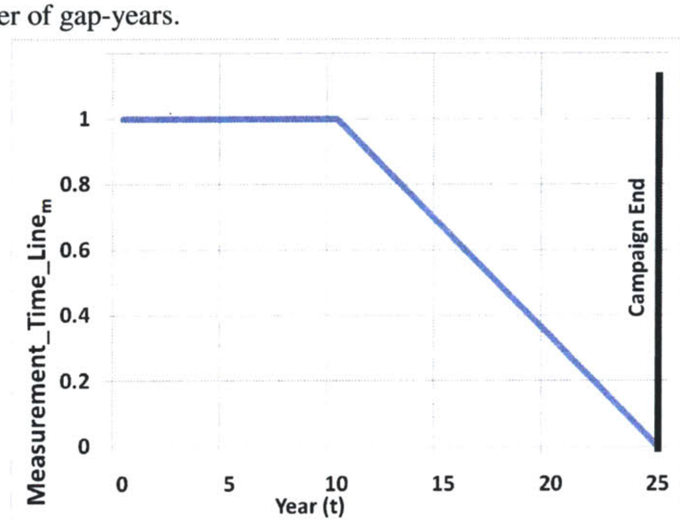


Figure 2.8: Data Gap Discounting for 25 year Campaign. Graphical representation of the weight of a Measurement_Time_Line from 0 to 25 years after Campaign Start Date.

Data Gap Accounting and Weighted Sum

The "Measurement Time Line" matrix represents the number of gap-years numerically possible for each measurement. Pseudocode 2.2 loops over all of the missions and accounts the measurements taken over that mission's lifetime to calculate a gap-year value for each measurement.

```
For i = 1:numMissions
        Find measurements in Mission(i)
        For j = 1:numMeasurements_Mission(i)
             MeasurementTimeLine(Measurement(j), MissionLaunchDate : MissionEndDate) = 0
        End
End
```

Pseudocode 2.2: Measurement Gaps are accounted for by looping through each Mission and setting entries to "covered" that correspond to the Measurements that are taken during that Mission's lifetime. The summation of each Measurement's discounted Data Gaps are weighted by that Measurement's importance to form the "Data Gap" metric.

$$MeasurementGap_m = \sum_{t=0}^{CampaignEnd} Measurement\_Time\_Line'_{mt}$$

Equation 2.19: The sum of the discounted measurement gaps (Measurement_Time_Line'$_m$) over the campaign lifetime for measurement m is MeasurementGap$_m$.

Equation 2.20 shows how the "Data Gap" metric is calculated by weighting the sum of the discounted gaps for each measurement (MeasurementGap$_m$) by that measurement's importance (I_m). The importance of each measurement is shown in Equation 2.17.

$$Objective_{DataGap} = \sum_{m=1}^{\#Measurements} I_m * MeasurementGap_m$$

Equation 2.20: Data Gap Objective is calculated by summing over all measurements the number gaps for that measurement (MeasurementGap$_m$) weighted by that measurement's importance (I_m).

Along with "Data Value", the "Data Gap" score is used to optimize for architectures that create the most value for stakeholders with the fewest data gaps. The optimal architectures form a Pareto front, which is the output of the Matlab multi-objective genetic algorithm.

2.4. Framework Conclusion

As a summary of this chapter, Figure 2.9 shows how the CSTM is used to understand the benefit delivery within the campaign. The boxes outlined in dashed line represent the decision rules that will be used to constrain the campaign architecture optimization process.

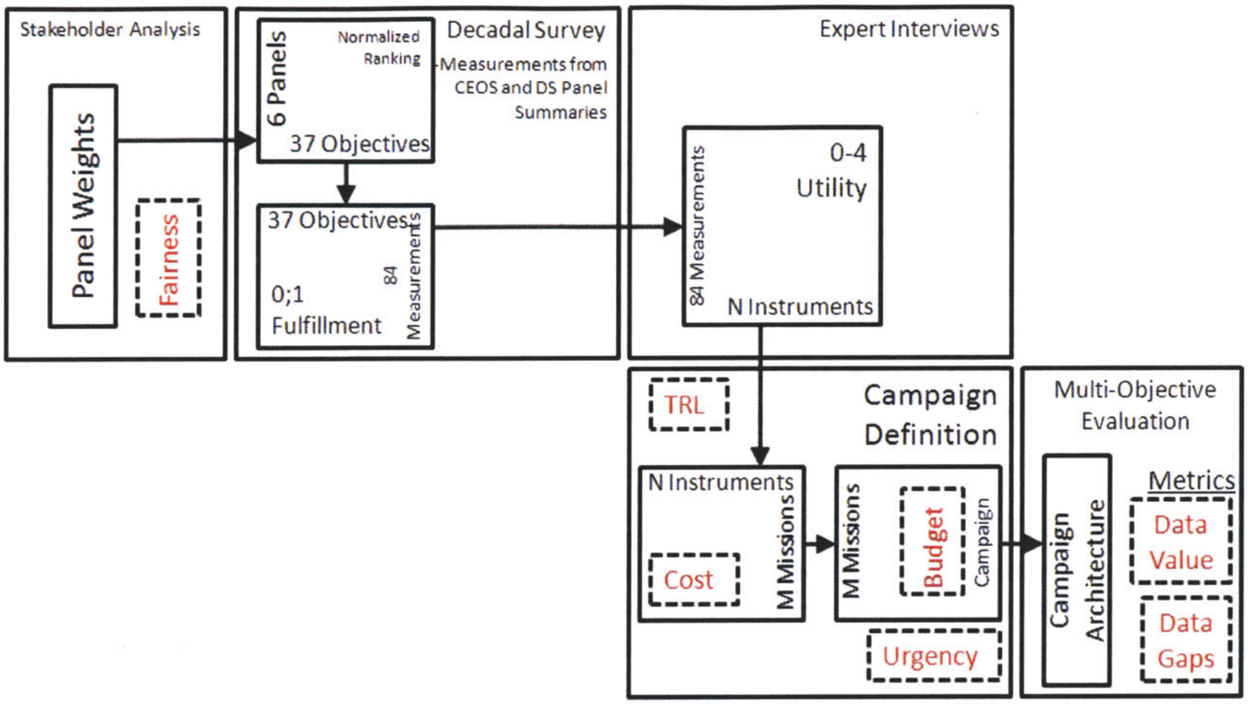


Figure 2.9: Campaign Scheduling using the CSTM framework to trace benefit and apply decision rules (red box). The Multi-Objective Evaluation tool used in this thesis is a Genetic Algorithm (GA) that will optimize the campaign architecture for "Data Value" (Section Error! Reference source not found.) **and "Data Gap" (Section 2.3.3). Decisions rules are applied to constrain the campaign and produce feasible architectures.**

The CSTM, introduced in Figure 2.5, forms the basis for analysis in Figure 2.9 as it provides the framework and the metrics. Fairness refers to the qualitative desire to deliver benefit evenly among the panels of the Decadal Survey. Each instrument will have an associated Technology Readiness Level (TRL) that will reflect the need to development new technology for Earth science. Cost estimates for each mission will force a budget to be established for the campaign. Cost and budget will determine the rate of mission deployment, which directly corresponds to an urgency to deliver benefit sooner rather than later.

This chapter developed a framework, the CSTM v1.1, to trace benefit through an Earth Science satellite mission campaign to a set of stakeholders. The entire process surrounding the CSTM shown in Figure 2.5, includes a campaign scheduling tool to optimize the benefit delivered to the science community. The framework begins with a stakeholder analysis, which generats Decadal Survey panel weights. The Decadal Survey panels produce individual lists of objectives to guide the decision making process and ensure the significance of the data collected by the satellite campaign. Objectives are fulfilled by measurements, which are taken by instruments.

The lowest element of form within the data gathering segment of the Global Earth Observation System is the instrument. The instruments are presented through a recommended set of missions within the Decadal Survey. Each instrument is designed to gather certain measurements with various degrees of fidelity, determining its value to the stakeholders. The benefit derived by the stakeholders from the set of missions that constitute the campaign is therefore traced through the CSTM and presented to the scheduling tool.

The campaign scheduling algorithm used in this thesis is a Genetic Algorithm (GA) with two objectives, "Data Value" and "Data Gap". The algorithm seeks to maximize "Data Value", which is constrained through a set of rules. A campaign budget and mission cost estimates determine the length of the campaign and the cadence of the launch dates. Technology Readiness Levels constrain the launch of instruments requiring development using a penalty on their cost. A sense of urgency is quantitatively applied to the campaign by discounting the "Data Value" metric based on the time until a mission's launch date. Fairness is qualitatively applied in Chapter 3 once campaigns are optimized along a Pareto front.

The algorithm seeks to minimize the second objective, "Data Gap". Once the schedule is determined as above, each measurement has a set of gaps. The measurement gaps are accounted for in a linearly discounted fashion after a 10 year period from the start of the campaign. The sum over the campaign length of each measurement gap is weighted by the importance of that particular measurement to the overall system. Each campaign is evaluated using the "Data Value" and "Data Gap" metrics such that as the GA explores the design space, it converges on a Pareto optimal set of architectures through evolutionary means as outlined in the literature review.

Chapter 3 utilizes this analytic framework to recreate and improve on the set of missions recommended by the Decadal Survey under the assumptions that prevailed at the time of the writing of the document in 2007 and that prevail now in 2011. This framework is expanded in Chapter 5 to integrate aircraft missions along with the satellite missions discussed in chapter 3.

3. Satellite-Only Campaign Scheduling

This chapter presents the results of scheduling the Decadal Survey set of missions using the CSTM to evaluate campaign architectures and the Genetic Algorithm (GA) to schedule them. The GA is used to generate a set of campaign architectures optimized for "Data Value" and "Data Gap". The Campaign-Level Science Traceability Matrix (CSTM), presented in chapter 2, culminates in the numerical benefits derived by stakeholders from each mission. The outputs of the CSTM framework are used to inform the adapted Matlab GA. Chapter 3 presents and analyzes this optimal set of campaign architectures under three cases: a baseline Decadal Survey case, a case updated for current cost and budget, and a case with current cost/budget and current missions added. This analysis results in a better understanding of how the GEOS performs and leads to a set of recommendations.

The adapted Genetic Algorithm (GA) is first applied to the set of missions recommended by the Decadal Survey under the assumptions and constraints present in 2007. Section 3.1 describes the mission cost estimates and Earth Science budget projections assumed by the Decadal Survey authors in order to recreate the recommended launch manifest. The CSTM and scheduling framework will be validated against the Decadal Survey 'Tier' structure so that the underlying assumptions can be updated to fit the state of the present day GEOS. Section 3.2 presents and analyzes this updated Decadal Survey case in order to make up-to-date recommendations. It also shows the need to incorporate current and near-term NASA Earth Science missions in the model. This analysis of additional satellite missions provides insights into potentially harmful data gaps and long-term technology development priorities. The case is made that the current satellite-only GEOS is unsustainable and threatens to leave large gaps in critical measurement coverage. Section 3.3 presents a case for incorporating non-space-based platforms into current GEOS models, thus introducing Chapter 4, which discusses the current use of aircraft technology in Earth observation.

3.1. Decadal Survey Recommended Baseline

The framework is first applied to the 17 Decadal Survey satellite missions (15 NASA and 2 NOAA) in order to validate the CSTM value tracing framework and the GA scheduling tool. The goal of this section is to validate this framework by recreating the 'Tier' structure presented in the Decadal Survey through modeling the report's logic. First the mission cost estimates and agency budget assumptions are discussed. With only each mission's "Data Value" score and cost, a scheduling optimization algorithm produces a campaign sequence based on mission value (benefit per cost), but violates technology readiness assumptions. A "TRL Launch Date" for each mission and the associated TRL Cost Penalty aligns the launch sequence with the Decadal Survey's notion of technology readiness. The GA results, presented in sub-section 3.1.3, show the effects of the "Data Gap" objective and introduce a qualitative "Fairness" metric. This section shows that the analysis presented in Chapter 2 and the GA tool successfully recreate the 'Tier' structure of the Decadal Survey and together provide useful insights into the GEOS.

3.1.1. Mission Costs and Campaign Budget

The first variables required for an analysis of the mission scheduling problem are mission cost estimates and a campaign budget prediction. A scheduling optimization algorithm will use these cost estimates to maximize stakeholder value over a campaign length determined by the budget. Table 3.1 shows the cost estimates taken from the mission descriptions within the panel reports of the Decadal Survey. (Committee on Earth Science and Applications 2007)

	Tier 1					Tier 2						Tier 3					
Decadal Survey Cost ($M, FY07)	GSPRO	CLARREO	SMAP	ICESatII	DESDynl	HyspIRI	XOVWM	ASCENDS	SWOT	GEO-CAPE	ACE	LIST	PATH	GRACEII	SCLP	GACM	3DWinds
	150	265	300	300	700	300	350	400	450	550	800	300	450	450	500	600	650

Table 3.1: Decadal Survey Mission Cost Estimates arranged by cost within 'Tier'. These cost estimates will be used as inputs into the GA in the Baseline Case to recreate the recommended Decadal Survey campaign. (Committee on Earth Science and Applications 2007)

To recreate their logic, this section uses the cost figures used by the committee in its decision making process. Given the mission costs and the benefit each mission delivers to the panels shown graphically in Figure 2.6, a mission value (benefit/cost) is generated, as shown in Figure 3.1.

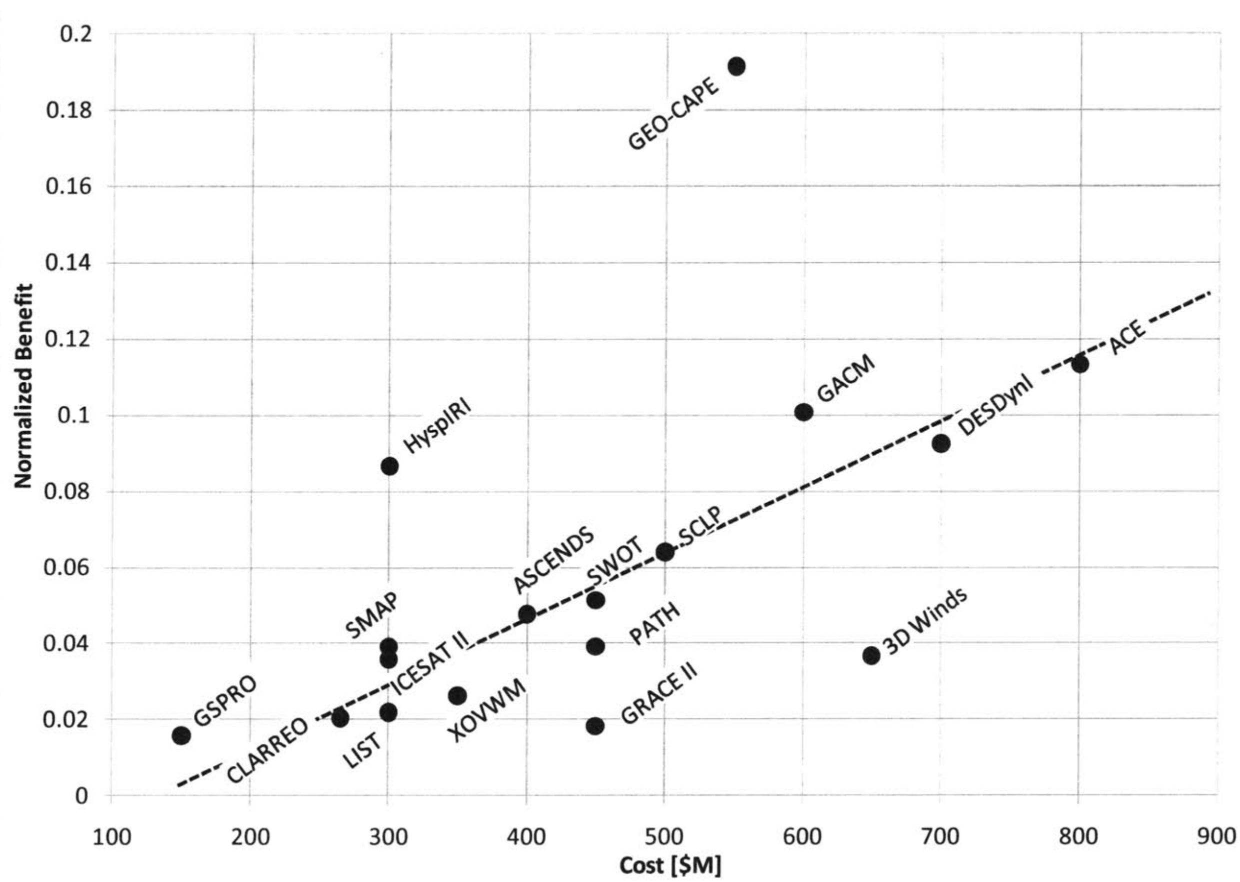


Figure 3.1: Cost/Benefit plot for recommended Decadal Survey missions with original Cost estimates and value calculated by the CSTM v1.1. There appears a general trend, marked by a dashed line, with missions such as GEO-CAPE, HyspIRI, and GACM above the line and missions such as 3DWinds, GRACE-II and PATH falling below the line.

Figure 3.1 shows an obvious general trend of increasing cost with more delivered benefit. The dashed line approximately represents the average capability to deliver benefit at cost. As technology and instruments are inherently different, missions that fall below the line are not necessarily bad as they may provide specific needs, but their reduced benefit at cost will affect scheduling. There are several missions that land above this cost-benefit curve, such as GEO-CAPE, HyspIRI, and GACM, all of which provide above-average value. Missions such as 3DWinds, GRACE-II and PATH fall below the curve and represent below average value either due to high expense or lower total benefit.

Due to the time-discounting of mission benefit within the algorithm, as shown in Equation 2.15, mission value sets the campaign sequence in an unconstrained optimization, as seen in Table 3.2. The algorithms seeks to launch the highest benefit missions first to capture the maximum discounted value.

Mission development and launch are constrained by the budget, which ultimately sets the campaign length. The Decadal Survey campaign budget for this baseline case is defined in the report's second chapter titled, "The Next Decade of Earth Observations from Space", which states on pages 45 and 46:

"The overall cost to implement the recommended NASA program (~$7 billion over 12 years for the 15 [NASA] missions) is estimated to exceed currently projected program resources but fits well within funding levels provided to NASA Earth science as recently as 2000. [...] Accordingly, the committee sees a need for rapid growth in the NASA Earth science budget from about $1.5 billion per year to $2 billion per year beginning in 2008 and ending no later than 2010." (Committee on Earth Science and Applications 2007)

The budget desired by the Decadal Survey committee is admittedly optimistic but recognizes a perceived, or at least desired, national reprioritization of Earth Science. Based on this budget assumption, the baseline model uses an annual Decadal Survey campaign budget of $750M, derived from the total campaign cost spread over 10 years. Figure 3.2 shows the budget that would have been required starting in 2007 to successfully launch the 15 proposed NASA missions within the 2010-2020 decade.

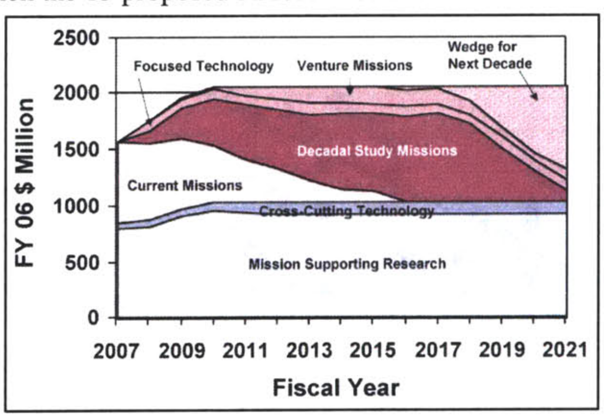


Figure 3.2: NASA Earth Science Budget Recommended by the Decadal Survey in order to launch all 15 proposed NASA-specific Missions within the Decade. Budget ramps back to FY2000 ($2M/Year) level from 2007-2010. This recommended budget did not materialize as the FY2010 ESD budget was $1.4M. (Committee on Earth Science and Applications 2007)

The Decadal Survey recommended a ramp up to FY00 spending levels between 2007 and 2010, as shown in Figure 3.2. The "Decadal Study Missions" budget shows growth in the 2010-2015 timeframe and decline in the 2017-2021 timeframe. This rise and decline in Decadal Survey mission spending is not captured in a flat $750M/year budget model but the total cost of the campaign is accounted for and the simplification is reasonable. The budget sets the length of the campaign when costs are fixed.

At this point it is interesting to show the optimal campaign launch sequence when only benefit and cost are considered. Table 3.2 show the resulting campaign schedule, with the last mission being launched in 2020.

Benefit/Cost (10^{-4})	Mission	Launch Date	Decadal Survey 'Tier'
3.48	GEO-CAPE	2010.74	2013-2016
2.89	HyspIRI	2011.14	2013-2016
1.68	GACM	2011.94	2016-2020
1.41	ACE	2013.01	2013-2016
1.32	DESDynl	2013.95	2010-2013
1.30	SMAP	2014.35	2010-2013
1.28	SCLP	2015.02	2016-2020
1.19	ICESatII	2015.42	2010-2013
1.19	ASCENDS	2015.96	2013-2016
1.14	SWOT	2016.56	2013-2016
1.05	GSPRO	2016.76	2010-2013
0.87	PATH	2017.36	2016-2020
0.77	CLARREO	2017.72	2010-2013
0.75	XOVWM	2018.19	2013-2016
0.73	LIST	2018.59	2016-2020
0.56	3DWinds	2019.46	2016-2020
0.40	GRACEII	2020.06	2016-2020

Table 3.2: Campaign optimized for Mission Benefit/Cost in Decadal Survey Baseline Case without Technology constraints. The color of the mission name represents the assigned Decadal Survey "Tier" of that mission. Plot shows that when unconstrained by Technology, the optimization algorithm will order the missions according to benefit/cost due to the time discounting of benefit.

The missions listed in Table 3.2 are color-coded according to the 'Tier' structure found in the Decadal Survey. Green colored missions are 'Tier 1', orange colored missions are 'Tier 2' and red colored missions are 'Tier 3'. Thus, it is shown that the campaign optimized for benefit/cost, shown in Table 3.2, violates the Decadal Survey ideas of technology readiness by ordering the missions outside of their assigned 'Tiers'. The technology readiness logic will be captured in the next sub-section with "TRL Launch Dates" and a TRL Cost Penalty.

3.1.2. TRL Launch Date and TRL Cost Penalty

This sub-section defines a set of penalties to align the campaign architectures more closely with the Decadal Survey's idea of technology readiness. Sub-section 3.1.1 shows that a set of mission values and a campaign budget will determine an optimal launch manifest, but does not capture the role technology readiness plays in the Decadal Survey logic. The Decadal Survey placed missions into three 'Tiers' based on a perceived level of mission maturity. To capture this logic in this model, technology readiness is modeled as a launch date ("TRL Launch Date") and a cost penalty associated with advancing ahead of that date. Equation 3.1 shows how this cost penalty is applied if the estimated launch date of a mission is before its "TRL Launch Date".

$$
\begin{aligned}
&if\ LaunchDate^{Est}_{Miss_i} \geq TRL\_Launch\_Date_{Miss_i}; && Cost^{Final}_{Miss_i} = Cost^{Initial}_{Miss_i} \\
&if\ LaunchDate^{Est}_{Miss_i} < TRL\_Launch\_Date_{Miss_i}; && Cost^{Final}_{Miss_i} = Cost^{Initial}_{Miss_i} * \left[(1 + TRL\_Cost\_Penalty)^{\left(TRL\_Launch\_Date_{Miss_i} - LaunchDate^{Est}_{Miss_i}\right)} \right]
\end{aligned}
$$

Equation 3.1: Cost Penalty associated with breaking the TRL Launch Date assigned to each mission. "TRL Launch Dates" are first assigned based on Decadal Survey 'Tier' structure and then based on Campaign Analysis.

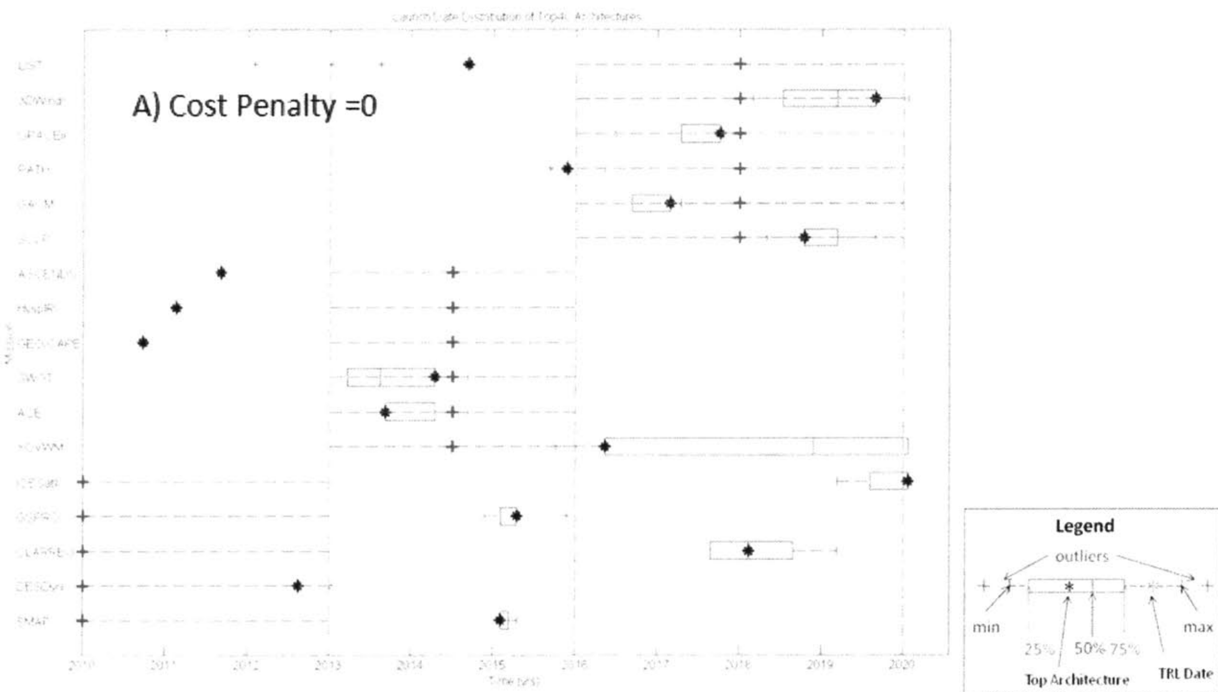
The cost penalty affects the total stakeholder value of the architecture by propagating cost-induced delays throughout the campaign. These delays lengthen the time until launch of every mission manifested after the mission that breaks its assigned "TRL Launch Date". Table 3.3 illustrates the penalty scheme through an example in which GEO-CAPE (A 'Tier 2' Mission) is launched first but has a "TRL Launch Date" of 2014.5.

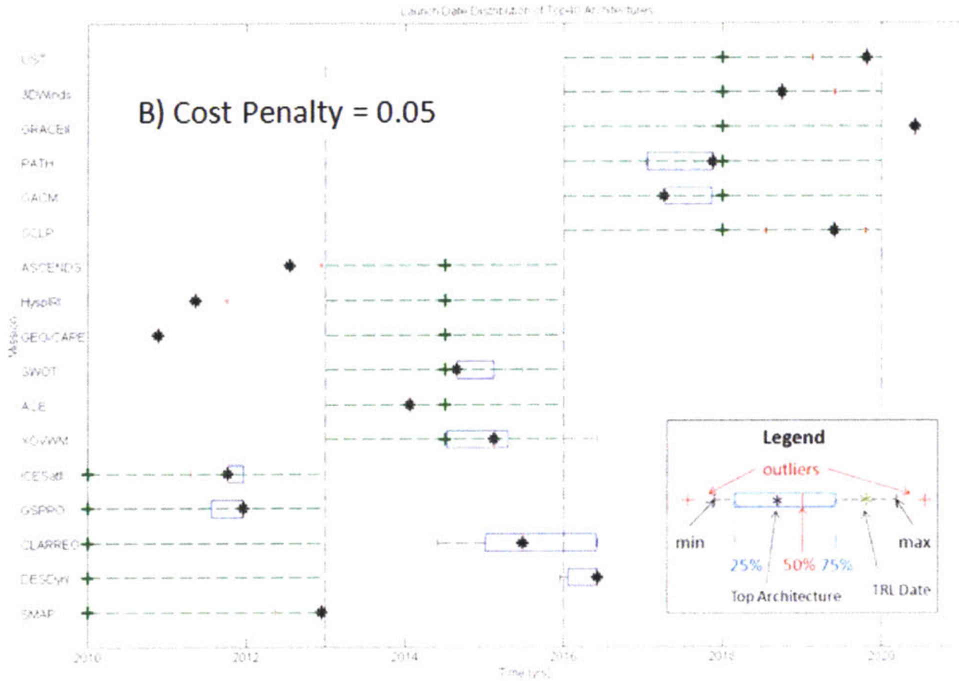
Variable	Amount	Units
Mission Cost	550	$M
Yearly Campaign Budget	750	$M
Campaign Start Date	2010	-
Estimated Launch Date (Sec. 2.3.2)	2010.73	-
Mission TRL Date	2014.50	
TRL Date Break	3.77	years
Cost Penalty	30%	-
Penalized Mission Cost (Sec. 2.3.2)	1,477.57	$M
Penalized Launch Date	2011.97	-
Campaign Years Increased	1.24	years
Panel Value Penalty (10% Discount Rate)	12.2%	(2.3.2)

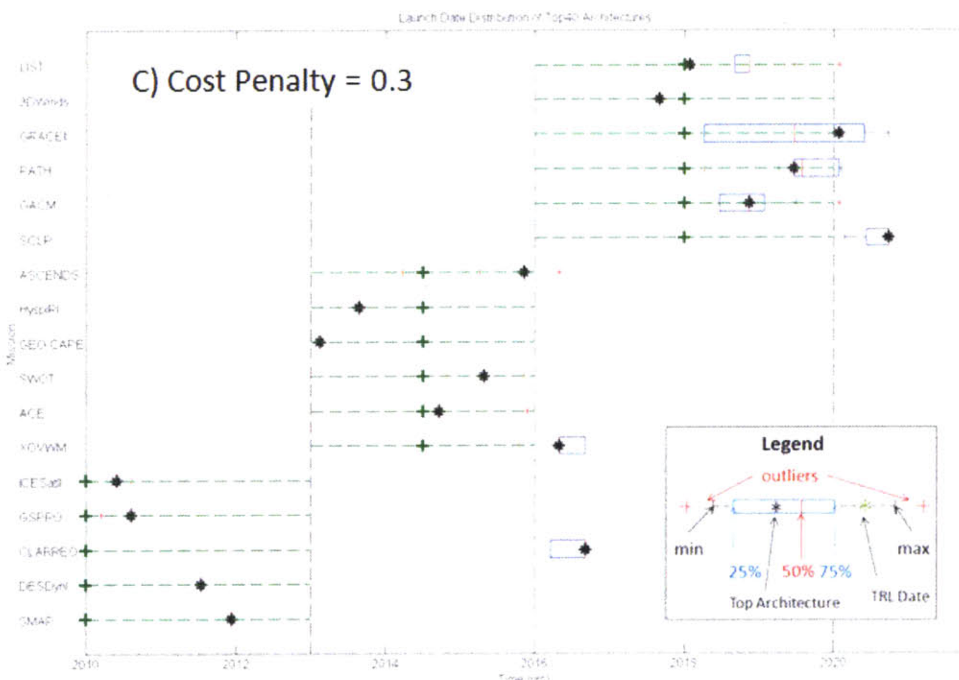
Table 3.3: GEO-CAPE Launch Penalty Example. The effects of a TRL Launch Date break by GEO-CAPE are shown by estimating the launch date without a penalty, applying the penalty based on the length of the break, recalculating launch date based on penalized mission cost, and propagating that extra time through the campaign.

As an illustrative example, Table 3.3 considers the effects on the GEOS in a case where GEO-CAPE launched first at a cost of $550M with a yearly campaign budget of $750M. In this case, the estimated launch date would be 2010.73 and would cause a "TRL Launch Date" break of 3.77 years. With a cost penalty of 0.3, launching GEO-CAPE first would increase the cost of the mission by $927.6M so as to reflect the anticipated cost of advancing the mission's technology 2-3 years ahead of originally estimated by the Decadal Survey. With a total mission cost of $1,477.57M, GEO-CAPE's new launch date would be 2011.97, thus costing the entire campaign 1.24 years. This penalty-induced campaign extension causes a decrease in the "Data Value" metric of $1-(1-\text{rate})^{\Delta t}$, where Δt is the launch delay. In this example for a launch delay of 1.24 year, the panels that experience a 10% yearly discount rate (Weather, Ecosystems, Water and Health) receive a 12.2% decrease in "Data Value", an 18.2% decrease for the Climate panel (15% rate) and a 6.1% decrease for the Solid Earth panel (5% rate). Therefore, the example shown in Table 3.3 illustrates the importance of the technology readiness considerations used by the Decadal Survey. There is balance that exists between delivering high value missions early in the campaign and scheduling within the TRL constraint.

To determine an effective cost penalty, an experiment was conducted in which the penalty was varied from 0% to 300% while keeping the other parameters of the GA constant. These experiments are optimized using both "Data Value" and "Data Gap". Figure 3.3 displays the results (the 0, 5, 30, and 75% data points) of this experiment in which cost and budget were set as described above and "TRL Launch Dates" were set to [2010, 2014.5, 2018] for 'Tier' 1, 2, and 3 missions respectively. For better visualization, the statistics of the top 40 campaigns are displayed in a "Whisker Plot" and missions are arranged bottom to top within each plot according to their 'Tier'. A "whisker plot" (Also known as a box plot) allows for visual representation of mission launch dates across a set of campaigns. This visualization can be useful for seeing trends in the top architectures and observing missions that tend to break their "TRL Launch Date". The top ranking campaign is called out in a large black "*" and the statistical data is shown with a blue box showing the 25-75%and black "whiskers" showing the 5-95% ranges. The green lines represent a mission's 'Tier' and the green '+' shows the "TRL Launch Date" specified in the model.




Launch Date Distribution of Top40 Architectures
B) Cost Penalty = 0.05
Legend
outliers
min
max
25%
50% 75%
Top Architecture
TRL Date


Launch Date Distribution of Top40 Architectures
C) Cost Penalty = 0.3
Legend
outliers
min
max
25%
50% 75%
Top Architecture
TRL Date

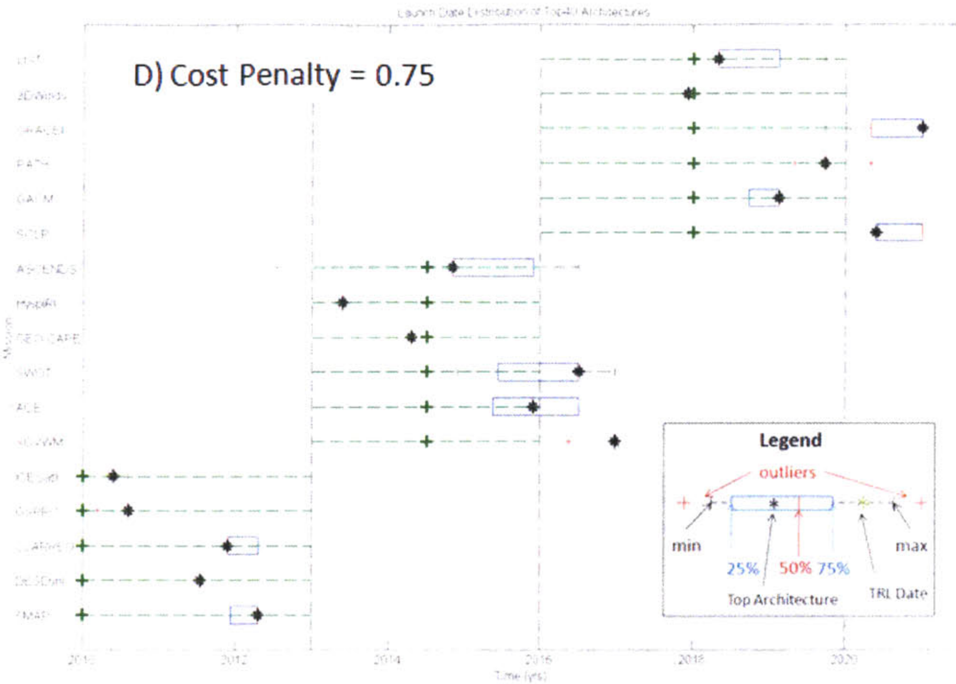


Figure 3.3: Statistical view ("Whisker Plot") of Launch Dates for multi-objective GA determined Pareto Optimal Campaign Architectures with different Cost Penalties for TRL Launch Date Break. See Section 3.1.2 for Explanation of TRL Launch Date Cost Penalty. Pane A shows no TRL Cost Penalty as Missions arrange in Benefit/Cost order, Pane B shows 5% TRL Cost Penalty as 'Tier 2' Missions move back and 'Tier 1' Missions move forward, Pane C shows 30% TRL Cost Penalty as 16/17 Missions align with the 'Tier' Structure and Pane D shows 75% TRL Cost Penalty. Experiment show that a 30% TRL Cost Penalty aligned the mission with the 'Tier' structure and was selected.

Through analysis of Figure 3.3 several key insights emerge that will determine an appropriate TRL cost penalty. The first insight, shown in pane (a), is that when no cost penalty is applied, the optimal schedule is closer to a descending benefit/cost order because it is not limited by TRL constraints, as described in sub-section 3.1.1 above. With no cost penalty the campaign begins with GEO-CAPE and HYSPIRI and 9 out of the 17 missions launch in the 'Tier' windows prescribed by the Decadal Survey. The result of the GA with a TRL Cost Penalty of 5% is shown in pane (b) of Figure 3.3 with 12 out of the 17 missions launching within their respective 'Tiers'. Pane (b) also clearly shows the effect of the cost penalty as ICESat-II and GPSRO move into the first 'Tier' and the campaign lengthens due to additional costs. Across the 4 experiments, shown in Figure 3.3, it can be seen that campaign length remains within 2-3 years of the non-penalized scenario, which is a reaction to the discounted returns of a mission launched further away from the Campaign Start Date, as described in Table 3.3. Pane (c) of Figure 3.3 reveals that a TRL Cost Penalty of 30% is appropriate because it generates a set of optimal campaign architectures with 16/17 missions in their assigned 'Tier'. This cost penalty would signal to decision makers that the desire to move a mission 1 year prior to its designated "TRL Launch Date" incurs a 30% cost increase due to accelerated technology development. The TRL cost penalty is best described as a "Return on Investment", which is the basis for dismissing pane (d). A 75% cost penalty, while aligning the missions well, represents an unreasonable investment for limited benefit. As shown in the GA results, a TRL cost penalty of 30% has the effect of producing a balance between Pareto optimal results that conform to the

Decadal Survey 'Tier' structure and results that indentify high value missions worth advancing.

Thus far, the rationale for the "TRL Launch Dates" and a "TRL Cost Penalty" has been established and a reasonable cost penalty determined empirically. The third aspect of the TRL constraint is assigning "TRL Launch Dates" for each mission that reflects an assessment of a reasonable date after which each mission can be launched. In the second chapter of its report, the Decadal Survey states that mission development must occur before 2010 if the aggressive set of 'Tier 1' missions is to launch before 2013. This model, however, has a 2010 Campaign Start Date in order to compensate for the flat budget projection over the 2010-2020 timeframe.

Baseline Scheduling Assumptions	
Budget	750 ($M/year)
Costs	Decadal Survey (See Table 3.1)
Campaign Start Date	2010
TRL Launch Dates	
Tier 1	2010
Tier 2	2016
Tier 3	2018
TRL Cost Penalty	30%
Current US Missions	None

Table 3.4: Global Earth Observation System Model Assumptions for the Baseline Case to be used in the GA. GA results shown in Section 3.1.3 below.

The set of baseline assumptions laid out in Table 3.4 attempts to match the assumptions used by the Decadal Survey committee. 'Tier 1' missions are given a "TRL Launch Date" of 2010 so that any one of them could launch first given the right technology investment over the 2007-2010 timeframe. 'Tier 2' and 'Tier 3' missions are given "TRL Launch Dates" later then 'Tier 1' missions to reflect the perception of the Decadal Survey committee that those missions should not be considered until later in the decade. 'Tier 2' missions are given a "TRL Launch Date" of 2016, which will most likely increase the cost of at least some of those 6 missions. Placing the "TRL Launch Date" at the end of the 'Tier' window may better reflect reality given the initial uncertainty in technology maturity assumptions. 'Tier 3' missions are given a TRL date in the middle of their 'Tier' window, which may have the affect of artificially increasing the cost of some missions while not effecting those that launch after 2018. This compromise between cost increase and assuming a mature technology level reflects the expectation that during the 2010-2018 timeframe technology that contributes to 'Tier 3' missions will be maturing independent of the launch dates assigned to them. The "TRL Launch Dates" have a tremendous impact on mission sequencing and thus effort was spent to qualitatively and empirically justify the baseline assumptions used in this section and updated assumptions used in section 3.2.

Given the previously described assumptions, the GA explores the mission ordering trade space in order to maximize the "Data Value" metric and minimize the "Data Gap" metric to produce a Pareto optimal set of campaign architectures.

3.1.3. Baseline Decadal Survey GA Results

The inputs for the GEOS model, shown in Table 3.4, and the GA parameters discussed in section 3.1 allow the algorithm to run with performance results shown in Table 3.5. The GA was run with a population size of 1,500 and a generation limit of 200, which takes less than an hour on a laptop computer with 2GB of RAM and a 2.53GHz Core™ 2 Duo processor. The specific GA tuning parameters can be found in the Matlab code shown in section **Error! Reference source not found.** of the Appendix.

Genetic Algorithm Results	
Generation to Terminate	107
Architectures Evaluated	162,001

Table 3.5: Algorithm Performance for Baseline Case shows that GA converged on a Pareto Optimal Solution after having evaluated over 160,000 Campaign Architectures.

In this baseline case, the genetic algorithm terminates after 107 generations due to solution convergence. The output of the GA is a set of Pareto optimal campaign architectures and the associated metrics. The GA output acts as the input to a post-processor, which generates two Excel sheets (Table 7.11 and Table 7.12 of the Appendix), plots data shown in Figure 3.4 through Figure 3.6 below, and saves the manipulated data for further use. An important aspect of this method is the ability to keep a human in the loop to guide and understand the results. This gives the campaign designer the ability to see many high level results while maintaining the ability to mine the detailed data. The Matlab code for this post-processing step is shown in section **Error! Reference source not found.** of the Appendix.

The concept of a Pareto front is described in section 1.3.2 of the literature review as a method for displaying and ranking a multi-objective set of non-dominated solutions. The campaign architectures in the final population of the baseline case are shown in Figure 3.4. These points are color coded to indicate each architecture's adherence to the Decadal Survey 'Tier' assignments. Points colored blue represent architectures that fall completely into Decadal Survey 'Tiers'. In general, "*" indicates an architecture is on the Pareto front and "." indicates it was part of the final "population" but not the Pareto front. Points colored green represent architectures with two missions breaking their respective 'Tiers', an example of which would be a campaign where a 'Tier 1' mission launches after a 'Tier 2' mission such that both break their 'Tier' constraints. Points colored red represent architectures along the Pareto front where 3 or more missions break their Decadal Survey 'Tiers' and points colored black represent the 3 or more break class of architectures that are part of the final population but not the Pareto front. The GA attempts to optimize for two objectives: maximize "Data Value" shown on the x-axis and minimize "Data Gap" seen on the y-axis.

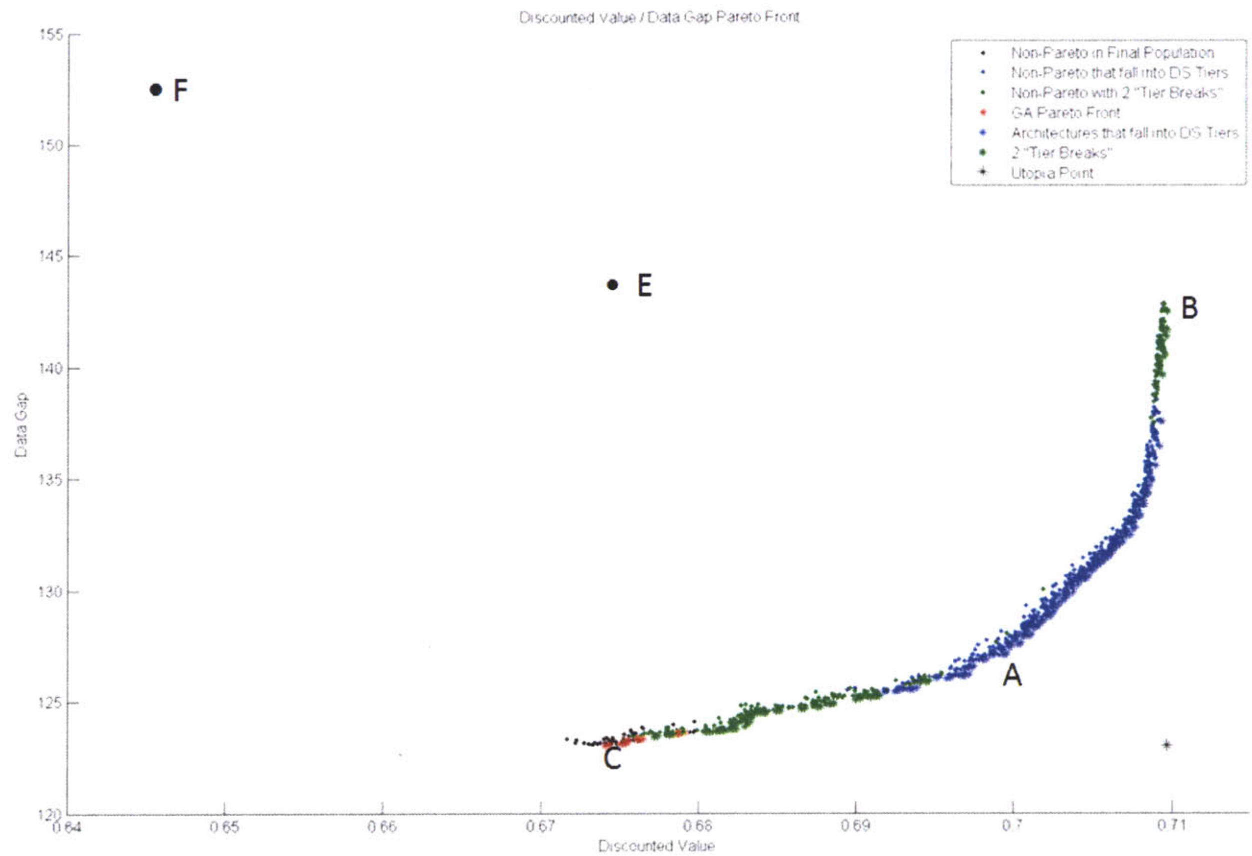


Figure 3.4: GA Results for Baseline Case presented as Pareto Optimal Campaign Architectures (*) and Campaign Architectures that are part of the Final Population (.). Architectures are color-coded to represent adherence to Decadal Survey 'Tiers' where Blue marks mean all of the Missions fall into assigned 'Tiers', Green marks mean there are two Missions that break assigned 'Tiers' and Black/Red marks mean there are three or more Missions that break assigned 'Tiers'. Points A, B, and C are shown in Table 3.6. Point D is shown in Table 3.6 but does not fit on this plot, point E is Seher's "optimal" campaign and point F is Colson's "optimal" campaign

From the 1500 individuals of the final population 148 are unique architectures along the Pareto front, but this number varies as the genetic algorithm carries duplicates within a population. The "*" point colored black at the bottom right of the plot, called the "Utopia Point", has the minimum "Data Gap" score and maximum "Data Value" score found on the Pareto front. Given that the number of architectures on the Pareto front is still too high for detailed study, a selection criterion is applied to rank them. This selection criterion is based on Euclidean distance to the "Utopia point", as described in Equation 3.2.

$$Distance_i = \sqrt{\left(1 - \frac{DV_i - DV_{min}}{DV_{max} - DV_{min}}\right)^2 + \left(\frac{DC_i - DC_{min}}{DC_{max} - DC_{min}}\right)^2}$$

Equation 3.2: Normalized Euclidean Distance from "Utopia" Point (Minimum Data Gap and Maximum Value) is used to rank Campaign Architectures for further analysis. Within Post-Processing Step (Code shown in Section Error! Reference source not found. **of Appendix) Pareto Front Campaign Metrics are normalized and sorted based on Euclidean Distance to find "Top Ranking" Campaign.**

An examination of the Pareto optimal set of campaigns reveals interesting trends and patterns in the solution space reflecting dynamics of the GEOS. In order to further explore the Pareto front, Table 3.6 lists the mission names and launch dates of the "Top Ranked" campaign, the campaign with the highest "Data Value" metric, the campaign with the lowest "Data Gap" metric, and the benefit/cost campaign shown in Table 3.2. The top ranked campaign falls into the Decadal Survey 'Tier' structure with ICESat-II being launched first. As value increases along the Pareto front SWOT falls back in launch order, which allows GACM, the most valuable 'Tier 3' mission, to move closer to the Campaign Start Date and therefore be less discounted. Likewise, as the "Data Gap" score decreases along the Pareto front, GEO-CAPE moves up with its high value measurements as CLARREO and ASCENDS fall back. Note that the benefit/cost campaign architecture does not fit onto Figure 3.4 since it has a "Data Value" of 0.58 and a "Data Gap" of 194.6. The top ranking campaign in Figure 3.4 represents a 21% improvement in "Data Value" and a 34% reduction in "Data Gap" over the benefit/cost campaign shown in Table 3.2.

a) Top Ranking Campaign		b) Max "Data Value"		c) Min "Data Gap"		d) Without TRL Penalty	
ICESatII	2010.40	GSPRO	2010.20	ICESatII	2010.40	GEO-CAPE	2010.74
GSPRO	2010.60	CLARREO	2010.56	GSPRO	2010.60	HyspIRI	2011.14
DESDynI	2011.54	ICESatII	2010.96	DESDynI	2011.54	GACM	2011.94
CLARREO	2011.90	DESDynI	2011.90	SMAP	2011.94	ACE	2013.01
SMAP	2012.30	SMAP	2012.30	GEO-CAPE	2013.70	DESDynI	2013.95
GEO-CAPE	2013.90	GEO-CAPE	2013.90	HyspIRI	2014.36	SMAP	2014.35
HyspIRI	2014.53	HyspIRI	2014.53	SWOT	2015.15	SCLP	2015.02
ACE	2015.72	ACE	2015.72	ACE	2016.22	ICESatII	2015.42
SWOT	2016.32	ASCENDS	2016.26	XOVWM	2016.69	ASCENDS	2015.96
ASCENDS	2016.86	XOVWM	2016.73	3DWinds	2017.67	SWOT	2016.56
XOVWM	2017.33	GACM	2017.64	GRACEII	2018.27	GSPRO	2016.76
3DWinds	2018.20	PATH	2018.24	LIST	2018.67	PATH	2017.36
LIST	2018.60	SCLP	2018.91	CLARREO	2019.03	CLARREO	2017.72
GACM	2019.40	SWOT	2019.51	ASCENDS	2019.57	XOVWM	2018.19
PATH	2020.00	3DWinds	2020.38	PATH	2020.17	LIST	2018.59
GRACEII	2020.60	LIST	2020.78	GACM	2020.97	3DWinds	2019.46
SCLP	2021.27	GRACEII	2021.38	SCLP	2021.64	GRACEII	2020.06

Table 3.6: Pareto Front Exploration for Baseline Decadal Survey Case shows Missions ordered by Launch Dates and color-coded to reflect Decadal Survey assigned 'Tier'. Pane (a) is "Top Ranking" Campaign Architecture, which matches the 'Tier' structure of the Decadal Survey. Pane (b) is the Campaign Architecture to deliver the most Value to the Stakeholder Community by moving 4 'Tier 3' Missions sooner in the Decade. Pane (c) is the Campaign Architecture with the lowest Data Gap score, which is achieved by slipping CLARREO and ASCENDS near the end of the Decade and absorbing come additional Cost Penalties. Pane (d) shows the results from Table 3.2, Campaign Architecture does not fit on plot metrics = (0.58, 194.6).

The last launch date shown in the "Top Ranked" campaign is 2021.27, which indicates that the TRL cost penalty had a non-trivial effect on the cost of several missions. This campaign's length is 1.21 years longer than in the non-TRL-constrained case shown in section 3.1.1. Inspection of Table 7.12 of the Appendix, the detailed launch results of the GA, reveals that three missions suffered penalties that increased their cost. In the top ranked campaign architecture, the final cost of GEO-CAPE rose $645.7M to $1,195.7M, the final cost of HyspIRI rose $168.6M to $468.6M and the final cost of ACE rose $88.5M to $888.5M.

The balance between delivering value to the stakeholders and covering a decade of measurements is seen by comparing pane (b) and pane (c) of Table 3.6 graphically in Figure 3.5 below. The most effective visualization of the "Data Gap" metric is shown in Figure 3.5, which compares the data gap plots of the maximum "Data Value" and minimum "Data Gap" campaigns. This tool plots measurements on the y-axis and years on the x-axis where a blue line indicates that measurement is being taken in that given year. Using this scheme, white areas represent times when a measurement is not being taken by any mission. Note that there are some measurements that are not taken at any time in the campaign. The numbers on the y-axis are identifiers for the each of the 84 measurements and can be seen in Table 7.5-Table 7.9 of the Appendix. This graphic representation allows for a quick assessment of where major measurement gaps are present and will be expanded in section 3.2 to include current and near-term NASA missions.

(a) Maximum "Data Value" (b) Minimum "Data Gap"

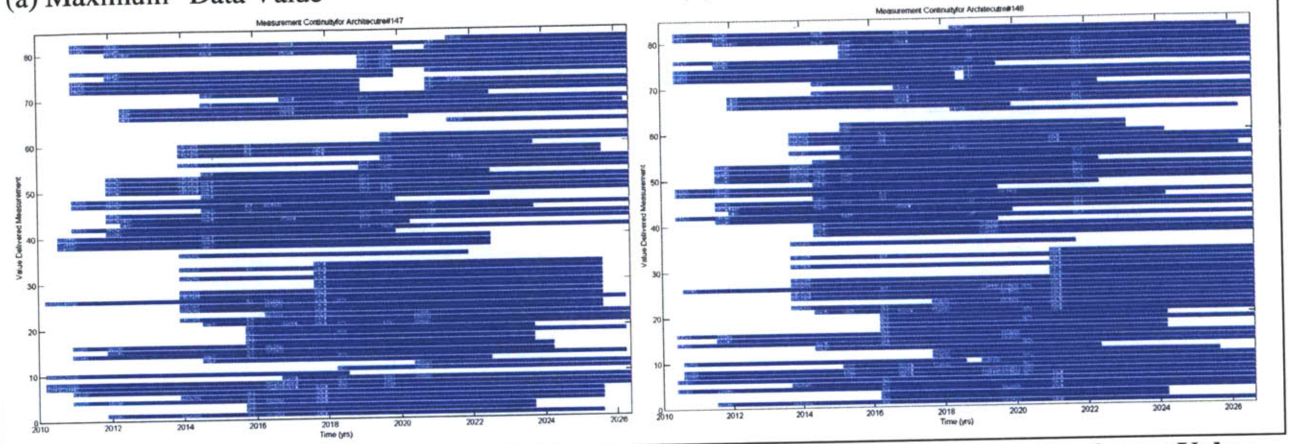


Figure 3.5: Data Gap Visualization for Baseline Decadal Survey Case compares Maximum Value Campaign Architecture (Pane (a)) with Minimum Data Gap score Campaign Architecture (Pane (b)). Campaign (b) is able to close Data Gaps by shifting ICESat-II forward and GACM/SCLP back. This tool plots measurements on the y-axis and years on the x-axis where a blue line indicates that measurement is being taken in that given year. Using this scheme, white areas represent times when a measurement is not being taken by any mission.

The first difference between the two campaigns shown in Figure 3.5 is the sequence of the 'Tier 1' missions; GPSRO and CLARREO launch first in the high value campaign while ICESat-II launches first in the low data gap campaign. ICESat-II being launched first allows for an extra six months of high value measurements to be taken. The campaign with a low "Data Gap" score pushes GACM back in the decade, thus stretching the measurements taken between them and GEO-CAPE/ACE. A third difference between these two campaigns is the movement of CLARREO from 'Tier 1' to the last years of the campaign so as to distance it from the missions it overlaps with, namely HyspIRI. The two campaign architectures shown in Figure 3.5 have "Data Gap" scores of 123.0 and 142.5, an increase of 15.7%.

The visualization of the "Data Value" metric is shown in Figure 3.6 where each panel is a color coded line that indicates the benefit delivered to it by the missions, which displayed vertically with launch dates. Benefit is added to the panels discounted in time but not weighted by stakeholder importance. Accumulated benefit is normalized to the highest panel benefit at the end of the campaign, which is the Weather panel in the baseline case. In section **Error! Reference source not found.** it was shown that the total unweighted benefit (b'$_{Cp}$ Equation 2.9) delivered by the Decadal Survey campaign is not equal for all the panels. Table 2.5 showed that Weather receives the most benefit as it does in the top ranked baseline campaign architecture.

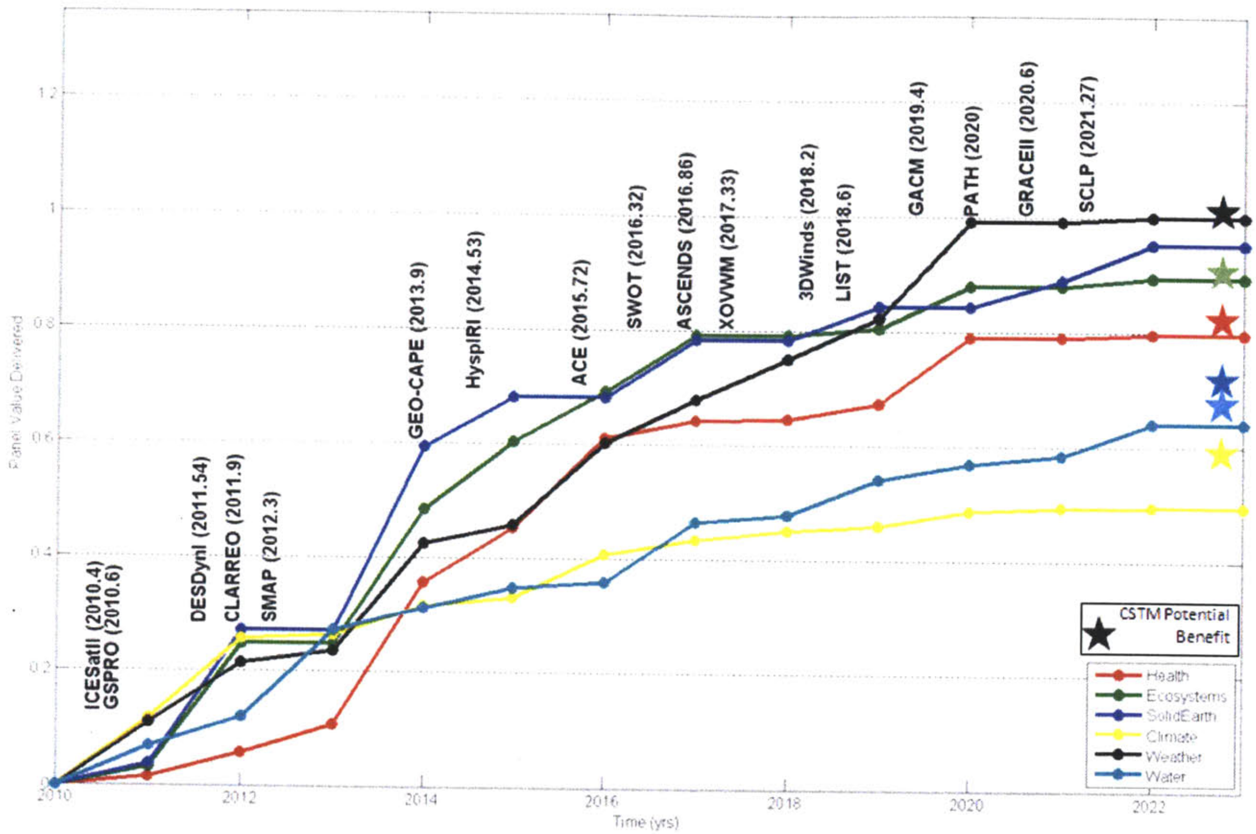


Figure 3.6: Discounted Benefit Accumulation for "Top Ranking" Campaign Architecture of the Baseline Decadal Survey Case shows how the non-panel-weighted "Data Value" metric builds over time. Benefit is discounted as described in Section 2.3.2 so that Panels do not realize all of their Potential Benefit (Marked by Star) as shown in Table 2.5, which leads to a Qualitative Metric for Fairness. The Weather Panel receives the most Benefit from the Baseline Case because it relies on Missions throughout the Campaign for Benefit Delivery.

This plot is helpful for understanding the GEOS because it gives decision makers a qualitative sense of the fairness with which value is being delivered to the panels. Fairness is captured in Figure 3.6 through the difference in delivered discounted value between the six panels, for instance, 'Climate' receives 49.5% as much value as 'Weather' by the end of the campaign. In the baseline case 'Water' and 'Solid Earth' receive the most value from the 'Tier 1' missions while during the same period 'Weather' and 'Human Health' receive the least. But as the campaign goes on 'Weather' becomes the panel to receive the most value and 'Climate' ends up with the least. The resulting total panel values can be compared to Table 2.5, which shows the potential value of each panel from the CSTM. When undiscounted potential value is compared to discounted campaign value it becomes clear that panels that rely on 'Tier 2' and 'Tier 3' missions to deliver all of their value finish the campaign worse off. In contrast, the weather panel receives value from every mission and as a result, its value accumulates steadily throughout the campaign so that it receives the most value over the campaign lifetime.

A "Top 10" plot, as shown in Figure 3.7, is generated by using the Euclidean distance from the "Utopia point" as a ranking method, as described in Equation 3.2, and arranging the manifests so they can be read from bottom to top in launch order.

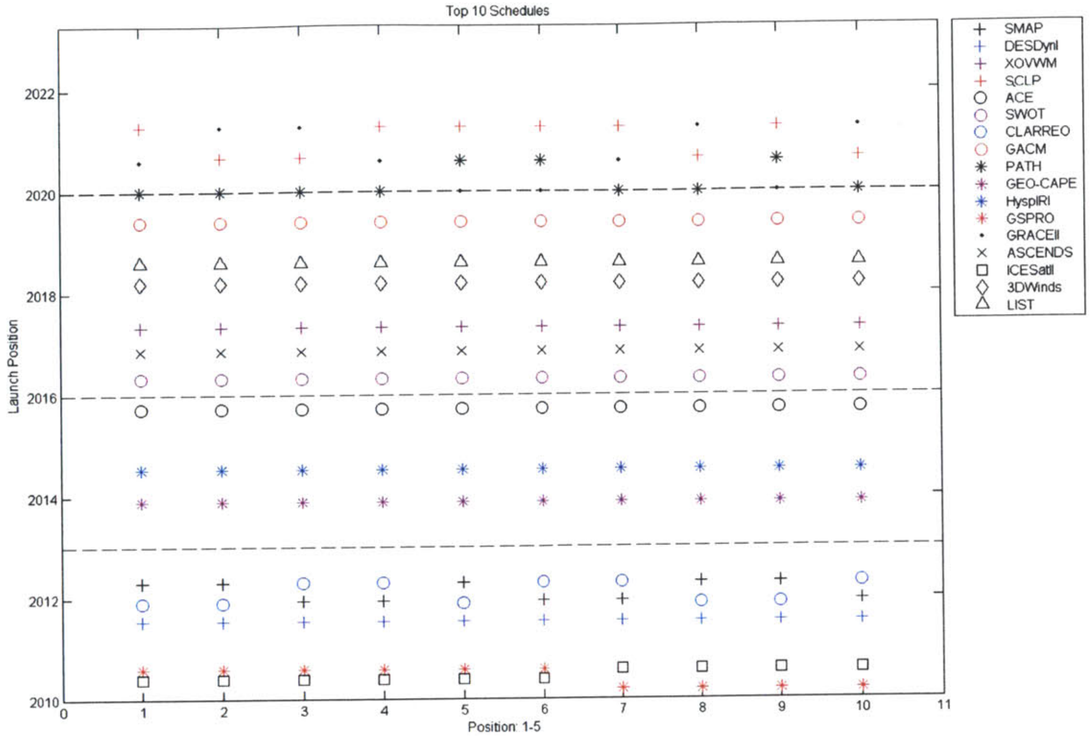


Figure 3.7: Top 10 Manifests for the Baseline Decadal Survey Case shows a robust 'Tier 2' Mission ordering and 5 'Tier 1' Missions launching in the 2010-2013 timeframe.

Evaluating the ten highest ranking campaigns in Figure 3.7, it can be seen that in all cases, the 'Tier 1' missions launch before 2013. There is a 1.5 year gap between the first 5 missions and GEO-CAPE, which launches right before 2014 followed by the same sequence of 8 missions. Only 3/6 'Tier 2' missions are able to launch in the 'Tier 2' window (2013-2016) but in all cases they launch before any 'Tier 3' missions.

Given the amount of variability, a statistical representation of launch dates helps to understand patterns and better visualize the Pareto front. Figure 3.8 shows the top 80 architectures displayed on a "whisker plot". A "Whisker Plot" is explained in detail in before Figure 3.3 and in the legend below.

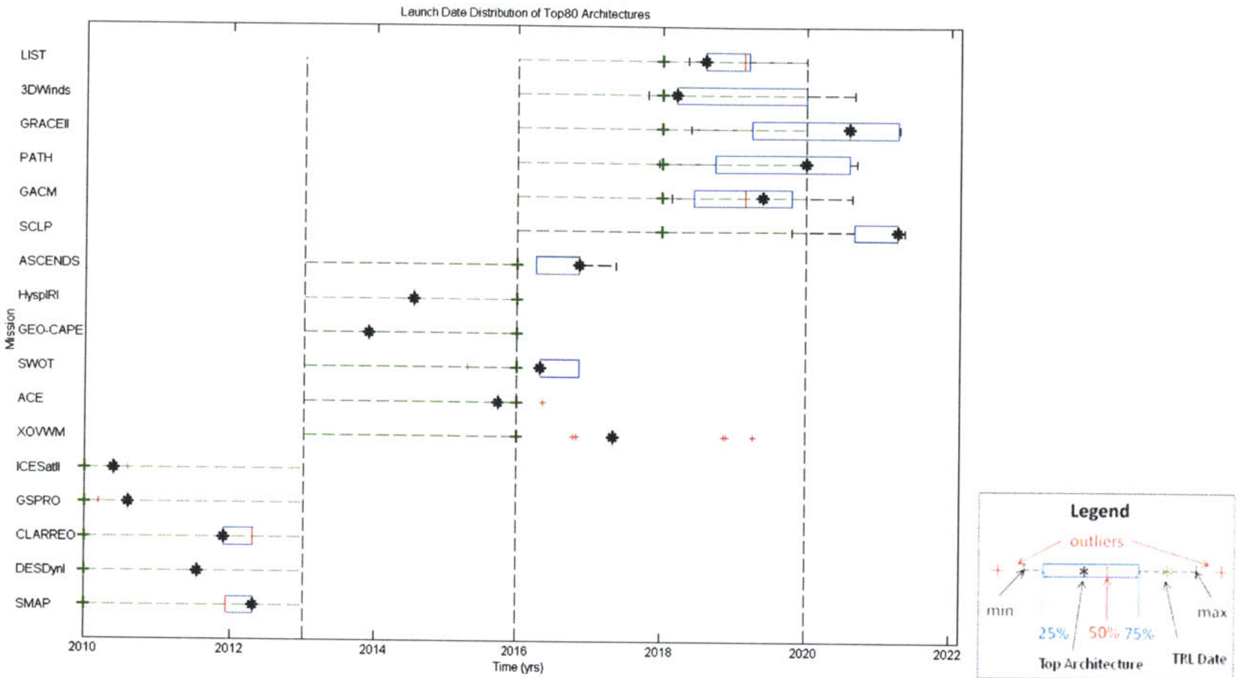


Figure 3.8: Statistical View ("Whisker Plot") of Top 80 Campaign Architectures for the Baseline Decadal Survey Case. Robustness of Pareto Optimal Architectures shown through variability in Launch Dates, which indicates 'Tier 1' and 'Tier 2' ordering is robust and 'Tier 3' is flexible. GEO-CAPE, HyspIRI, and ACE consistently break TRL Launch Dates indicating potential Technology Investment Areas.

Evaluating the top 80 architectures reveals GEOS scheduling dynamics such as the set of missions that consistently break a "TRL Launch Date" because the benefit they deliver is worth the resulting cost penalty. The 'Tier 3' missions are the most variable due to their positions late in the campaign. The later a mission is launched, the less effect it has on the system level metrics due to time discounting. The only missions to get penalized for breaking "TRL Launch Dates" lie within the 'Tier 2' set, which leads to a relatively stable launch order. For the top ranked campaign, GEO-CAPE is assessed a cost penalty of 117.4%, HyspIRI is assessed a 56.2% penalty and ACE an 11.1% penalty. This plot also shows architectures that fall out of line with the Decadal Survey 'Tier' structure, corresponding to green or red points on the Pareto front plot in Figure 3.4. An example of such a campaign is shown in the red "+" marker along XOVWM where it moves back to 13th in the flight order as 3DWinds moves to 11th. The "Whiskers Plot" can also be useful for showing where technology development money could be invested to help deliver the most value to the stakeholders. In the case of GEO-CAPE some early investment in instrument development might mitigate the 117.4% cost overrun associated with moving the mission closer to the 1st 'Tier'. The significant 'Tier' breaks also signal architectures that could absorb cost overruns. For example, if CLARREO slips and affect all subsequent missions, money can be channeled to GEO-CAPE changing the architecture while maintaining Pareto optimality.

3.1.4. Previous Analysis

This sub-section compares the results presented above to previous scheduling algorithm created within the MIT Space System Architecture Group (SSAG). The Decadal Survey 'Tier' structure is used to validate the GA in section 3.1.3 by showing that it could be reproduced given similar missions cost estimates, campaign budget predictions, and technology readiness assumptions. The scheduling problem has been evaluated two other times by the SSAG as mentioned in sub-section 1.3.1 of the literature review.

Table 3.7 shows the top ranking results from the three different algorithms compared using the algorithm presented in this thesis. The internal algorithms of the GA calculate launch dates and the "Data Value" and "Data Gap" metrics under two different TRL penalty cases. (Colson 2008) (Seher 2009) The first case was executed using a cost penalty of 30% (TRL CP .3) and the second case evaluated the same campaigns without a cost penalty (NO TRL CP). The mission cost estimates and campaign budget predictions are consistent within all three cases but the metrics used in arriving at each optimum are different. The most noticeable difference between the three sets of analysis is how each values missions. Although Seher uses the CSTM framework to value missions, many of the values he used were changed for this thesis to reflect a deeper understanding of the instrument to measurement relationship. It is demonstrated that more simple algorithms and previous work do not outperform the GA used for this analysis. Not that the associated Launch Dates are under the baseline parameters with a "TRL Cost Penalty" of 30%

Suarez Results			Seher Results (E in Figure 3.4)			Colson Results (F in Figure 3.4)			Benefit/Cost Order		
	TRL CP .3	No TRL CP		TRL CP .3	No TRL CP		TRL CP .3	No TRL CP		TRL CP .3	No TRL CP
Data Value	0.70	0.74	**Data Value**	0.67	0.70	**Data Value**	0.65	0.67	**Data Value**	0.56	0.82
Data Gap	127.60	110.77	**Data Gap**	144.98	124.89	**Data Gap**	153.53	132.88	**Data Gap**	194.62	123.79
Mission		**Launch Dates**	**Mission**		**Launch Dates**	**Mission**		**Launch Dates**	**Mission**		**Launch Dates**
	ICESatII	2010.4		CLARREO	2010.3		CLARREO	2010.4		GEO-CAPE	2012.9
	GSPRO	2010.6		ICESatII	2010.8		ICESatII	2010.8		HyspIRI	2013.7
	DESDynl	2011.5		DESDynl	2011.7		DESDynl	2011.7		GACM	2015.7
	CLARREO	2011.9		GSPRO	2011.9		GSPRO	2011.9		ACE	2016.8
	SMAP	2012.3		SMAP	2012.3		SMAP	2012.3		DESDynl	2017.7
	GEO-CAPE	2013.9		XOVWM	2013.4		SWOT	2013.7		SMAP	2018.1
	HyspIRI	2014.5		ASCENDS	2014.3		ASCENDS	2014.5		SCLP	2018.8
	ACE	2015.7		SWOT	2015.1		XOVWM	2015.1		ICESatII	2019.2
	SWOT	2016.3		HyspIRI	2015.6		HyspIRI	2015.6		ASCENDS	2019.7
	ASCENDS	2016.8		GEO-CAPE	2016.3		ACE	2016.7		SWOT	2020.3
	XOVWM	2017.3		ACE	2017.4		GRACEII	2017.4		GSPRO	2020.5
	3DWinds	2018.2		PATH	2017.9		SCLP	2018.1		PATH	2021.1
	LIST	2018.6		GRACEII	2018.6		PATH	2018.7		CLARREO	2021.5
	GACM	2019.4		LIST	2018.9		LIST	2019.1		XOVWM	2021.9
	PATH	2020		SCLP	2019.7		GEO-CAPE	2019.8		LIST	2022.4
	GRACEII	2020.6		GACM	2020.5		GACM	2020.6		3DWinds	2023.2
	SCLP	2021.2		3DWinds	2021.3		3DWinds	2021.5		GRACEII	2023.8

Table 3.7: Comparison of Results from three Space Systems Architecture Group (SSAG) studies on Earth Science Decadal Survey Scheduling Problem. Campaigns considered "Optimal" by individual algorithms are evaluated using framework and methods described in Sections 2.2 and 2.3. "TRL CP .3" is the evaluation using the baseline parameter and "No TRL CP" is the

evaluation using the same parameters but without a TRL Cost Penalty. The associated Launch Dates are under the baseline assumptions (TRL CP .3). Results show that GA outperforms Seher's and Colson's results. Benefit/Cost Ordering is shown in far right table for comparison.

This cross-algorithm analysis shows that the GA outperforms the other two methods in both the "Data Value" and "Data Gap" metrics by finding solutions that still fall within the Decadal Survey 'Tier' structure. In all cases, the campaign ranked highest by the GA outperforms the solution found in Seher's work, which in turn outperforms the solution found in Colson's work. All three solutions outperform the benefit/cost ordering, shown on the far right, as the first three missions in that campaign are heavily penalized for breaking their respective "TRL Launch Dates".

These results also show the sensitivity of the GEOS model to initial assumptions as three different "optimal" solutions were found. It is important for future decision makers to involve key stakeholders in the process of architecting so that all parties can agree to the foundational aspects of the system model.

Justification for an Updated Evaluation

Section 3.1 shows how the GA informed by the CSTM can replicate the logic of the Decadal Survey and produce optimal architectures in line with those recommended by the Decadal Survey 'Tier' structure. Admittedly, the system being modeled in this baseline case has been out of date since the time the Decadal Survey was published. In the Preface of the final report on page xiv, the Decadal Survey actually points towards the need to re-evaluate their recommendations by writing:

"Participants in the survey were challenged by the rapidly changing budgetary environment of NASA and NOAA environmental satellite programs. [...] In the present survey, the foundation eroded rapidly over the course of the study in ways that could not have been anticipated. The recommended portfolio of activities in this survey tries to be responsive to those changes, but it was not possible to account fully for the consequences of major shocks that came very late in the study, especially the delay and descoping of the NPOESS program, whose consequences were not known even as this report went to press [...] and it was in no position to consider the implications of a possible large-scale reduction in funding and later delay of the GPM mission." (Committee on Earth Science and Applications 2007)

In light of this admission by the Decadal Survey itself, section 3.2 explores a GEOS scenario with updated mission cost estimates, campaign budget predictions, and technology assessments.

3.2. Current Satellite-Only Architecture

This section applies the methodology presented above to evaluate the Decadal Survey set of missions in an updated scenario. The GA scheduling tool used in section 3.1 to assess the baseline Decadal Survey case was validated by recreating the 'Tier' structure and is used in this section as well. Now almost 4 years after the release of the Decadal Survey final report, many of the assumptions and predictions that went into the logic of the report have changed. It is necessary to revisit the Decadal Survey in light of recent events, current realistic budget predictions, updated cost assumptions, and the reprioritization of the nation's Earth science interests. There have been several major changes to the GEOS since the Decadal Survey was written in 2007:

- Missions that were considered precursors have either been cancelled, have failed or are significantly delayed. Major setbacks have been the cancellation of NPOESS, the failure of OCO and Glory, and the slip of NPP, GPM and LDCM. More detail can be found in section 1.1.3.

- The Decadal Survey's optimistic budget predictions did not materialize and NASA's future Earth Science budget is uncertain. Section 3.2.2 will present recent Earth Science Division budgets and create a reasonable prediction of the future funding stream.
- Decadal Survey recommendations were not implemented in the 2007-2010 timeframe so that now the closest Decadal Survey mission launch date is still at least 3 years away. This mission gap that grew over the past 4 years is a consequence of delays to current missions and overoptimistic TRL launch date assumptions in the Decadal Survey.

The increase in mission costs is explored in sub-section 3.2.1 and the changes to NASA's Earth Science Division (ESD) budget are examined in sub-section 3.2.2. Sub-section 3.2.3 reassesses the technology readiness assumptions and presents an updated set of results. In light of these results, a budget sensitivity analysis is presented in sub-section 3.2.4.To complete the satellite-only system analysis, current and near-term NASA missions are added to the model and the whole set is optimized using the GA. The results of this complete model, presented in sub-section 3.2.5, identify key measurement gaps that are likely to occur under the current trajectory. The results also open the discussion to possible mitigation strategies.

3.2.1. Updated Mission Cost Estimates

The first step in the process of updating the Global Earth Observation System (GEOS) model, used to solve the campaign scheduling problem, is to update mission cost estimates. Estimating the cost of satellite missions is a difficult task that continues to be studied in the systems engineering community. Therefore, it is fully recognized that the Decadal Survey's task of estimating the cost of under-defined missions (5 to 15 years before launch) was a difficult and highly uncertain one. The motivation for this reevaluation comes from the Decadal Survey when, on page 43 it states:

"The panels believe that cost estimates for the recommended missions vary within ±50 percent for the smallest missions and within ±30 percent for the larger missions. The cost estimates will depend directly on the exact measurement requirements for the eventual missions, and the cost uncertainty rises for missions scheduled later in the next decade and for missions requiring the most technology development." (Committee on Earth Science and Applications 2007)

In this effort, Theo Seher, acquired updated cost estimates from knowledgeable sources at NASA's Goddard Space Flight Center (GSFC) for his thesis in 2009. These estimates are shown in Table 3.8 along with the original cost estimates from the Decadal Survey. (Seher 2009) The updated cost for ICESat-II and SMAP are based on current NASA budget reports.

	Tier 1					Tier 2						Tier 3						
Missions	GSPRO	CLARREO	SMAP	ICESatII	DESDynl	HyspIRI	XOVWM	ASCENDS	SWOT	GEO-CAPE	ACE	LIST	GRACEII	PATH	SCLP	GACM	3DWinds	Total
Decadal Survey Cost (FY07)	150	265	300	300	700	300	350	400	450	550	800	300	450	450	500	600	650	7,515
Cost Est. (FY11)	154.8	1,000	635.6	628.2	1,680	452	361.2	473	698	1,276.2	1,627.8	609.9	471.4	521	512	1,036.9	797.7	12,935
Increase (%)	3.2	277.4	111.9	109.4	140.0	50.7	3.2	18.3	55.1	132.0	103.5	103.3	4.8	15.8	2.4	72.8	22.7	72%

Table 3.8: Updated Decadal Survey Mission Costs based on NASA GSFC Estimates and FY2012 ESD Budget Request (SMAP and ICESat-II). Row 2 will be used for Updated Case.

Table 3.8 shows that only two years after the release of the Decadal Survey, total campaign costs had increased on average by 72% and some missions, like CLARREO, more than tripled in cost. These estimates are substantiated by examining the ICESat-II and SMAP budget outlays in the Fiscal Year (FY) 2010, FY11, and FY12 NASA ESD budgets. Recent budgets for these two missions are shown in Figure 3.9 below and Table 7.13 in the Appendix. Figure 3.9 shows the ICESat-II budget requests and expenditures for the 2008-2016 time period, which even in the most conservative request (FY12), total over \$628 million. (National Aeronautics and Space Administration 2009b) (National Aeronautics and Space Administration 2010b) (National Aeronautics and Space Administration 2011) NASA's own budgets reveal that ICESat II has experienced a 109% cost increase while at the same time experiencing a launch date slip to 2016.

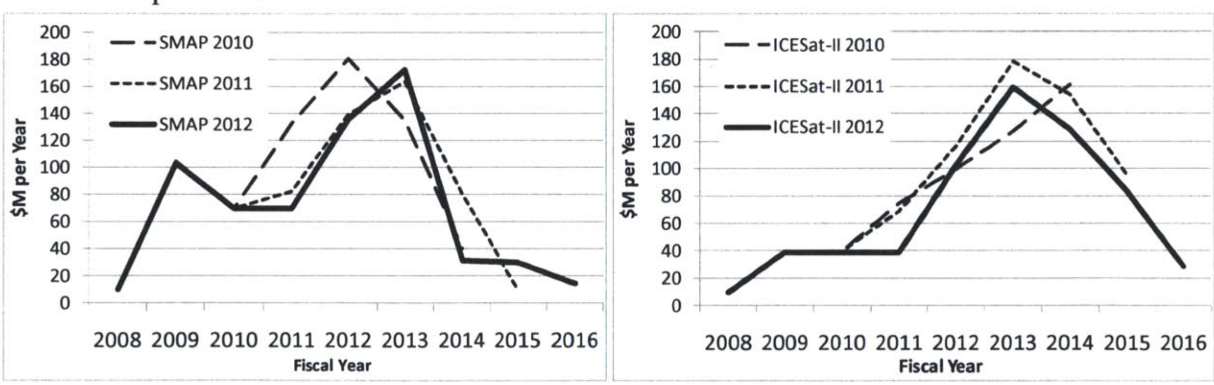


Figure 3.9: ICESat II and SMAP Budget Outlays based on NASA ESD FY09-FY12 Budget Requests. Figure shows original Decadal Survey cost estimates severely underestimated Mission costs, 112% increase for SMAP and 109% increase for ICESat-II from Decadal Survey to current spending.

SMAP, shown in the dashed line in Figure 3.9, experienced the same cost growth with a budget estimate that indicates a 112% increase from the \$300M originally proposed in the Decadal Survey to \$635.6M in the 2008-2016 timeframe. The numerical analysis extracted from the FY09-FY12 NASA budget requests is shown in Table 7.13 in the Appendix. This simple cost analysis for two 'Tier 1' missions shows that there is a serious mismatch between Decadal Survey estimates and the actual costs of missions. The difficulty of estimating mission cost shows another limitation of planning campaigns far into the future. The remainder of this analysis will use the cost figures shown in Table 3.8 while recognizing that future large planning studies require more realistic cost estimations.

3.2.2. Updated Campaign Budget

The second step in the process of updating the GEOS model is to predict a more realistic budget outlay. As discussed in sub-section 3.1.1, the Decadal Survey recommended that the NASA Earth Science Division (ESD) budget be restored to FY00 levels ($2Billion/Year) by 2010. Since the writing of the Decadal Survey, NASA's ESD budget has fluctuated (The federal stimulus included a $325M boost in FY09) but remains well below the recommendations of the Decadal Survey at $1.4B in FY10. (National Aeronautics and Space Administration 2009b) In general, ESD budgets are broken up into 6 sections as shown in Figure 3.10: Earth Science Research, Applied Sciences, Earth Science Multi-Mission Operations, Earth Systematic Missions, Earth System Science Pathfinder, and Earth Science Technology. Figure 3.10 shows this breakdown for FY06-FY16, assuming that FY11 is the same as FY10 and FY12-FY16 follow the projections of the FY12 budget request. The table used to create Figure 3.10 can be found in the Appendix as Table 7.13.

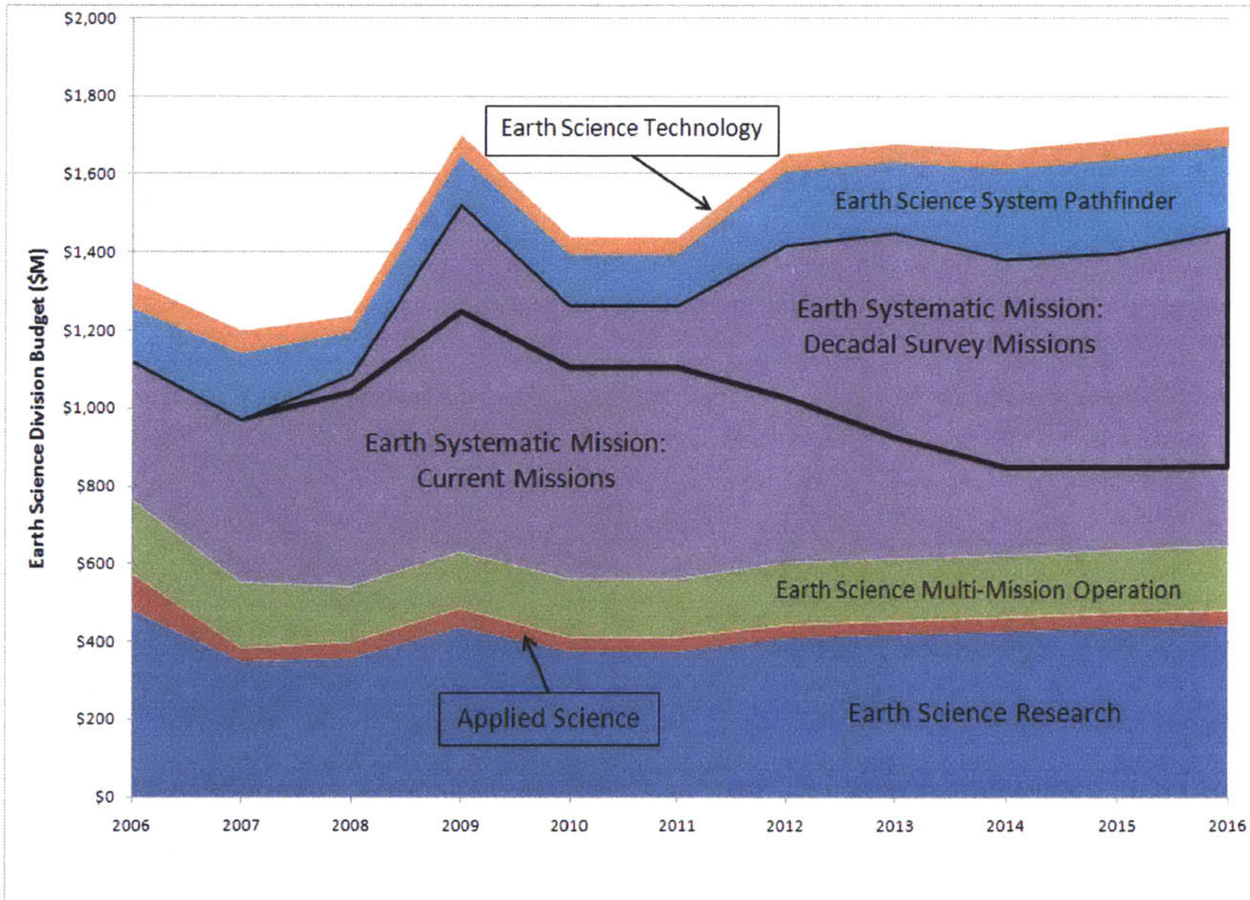


Figure 3.10: NASA Earth Science Division Budget FY06-FY16 (Projected) broken into categories. Decadal Survey Mission Budget is calculated by adding ESM pre-FY08 "Other" Category to the Budgets specifically calling for SMAP, ICESat-II or "Decadal Survey". Graph shows that Decadal Recommendation of returning ESD to FY2000 Budget levels ($2B/year) did not materialize. Table 7.13 in the Appendix shows budget numbers.

Figure 3.10 shows that NASA is optimistically projecting that budgets will return to FY09 levels in FY12 after having taken a short-term dip in the last two years. It can be seen that the largest percentage of the

ESD budget is given to Earth Systematic Mission (ESM), the branch that handles the large Earth Science space missions. The section of the ESM budget outlined in black is an estimate of the amount of money ESM could dedicate to Decadal Survey missions over the FY09-FY16 timeframe. This 'Decadal Survey Mission' portion was calculated using specific ICESat-II and SMAP outlays in addition to part of the "Other" budget category. It is assumed that the ESM's "Other" category in FY06 is required to operate the current Earth Science satellite missions and remains part of the expenditures at least before FY16. Therefore, the remainder of the ESM's "Other" budget category is assumed to be available for Decadal Survey missions. This plot is intended to mirror Figure 3.2, which was used in the Decadal Survey to show NASA budget trend, but updated to include relevant FY budgets.

In addition to the ESM, the Earth System Science Pathfinder (ESSP) program contributes to the design, testing, and operation of Earth science satellite missions of smaller size, scope, and cost. Within the ESM and ESSP budgets, there is a breakdown for specific missions, which is shown in Figure 3.11 below with the same assumptions as Figure 3.10 above.

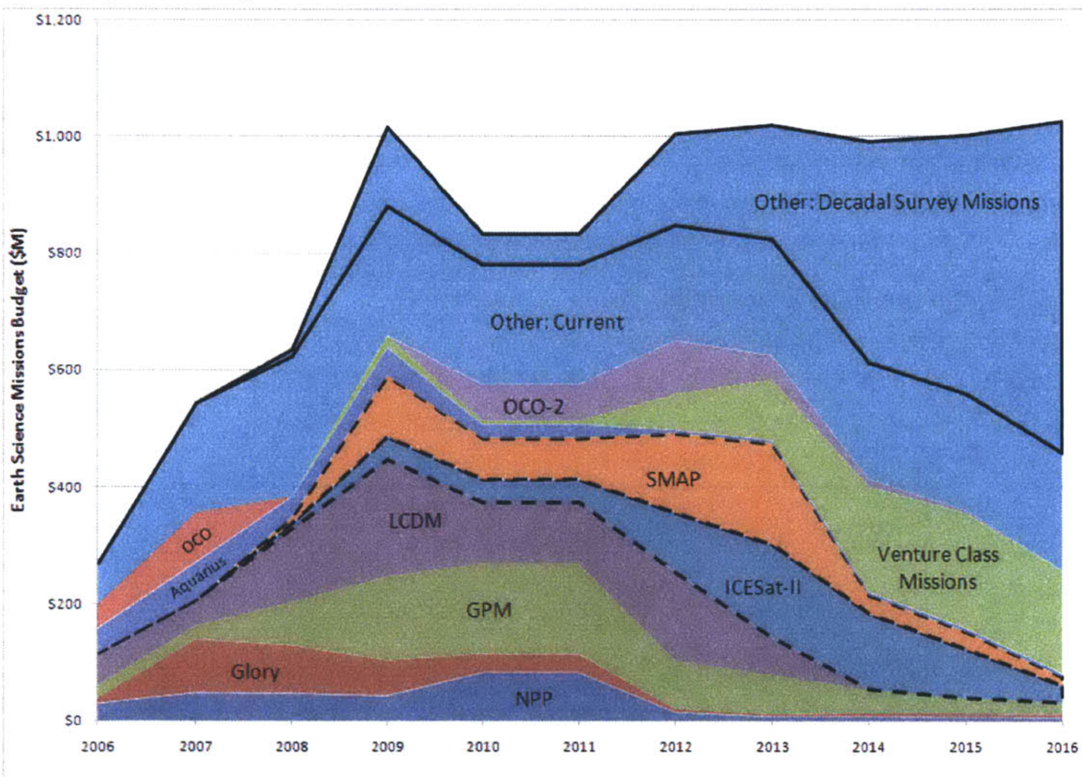


Figure 3.11: NASA ESD Upcoming Mission Budgets FY06-FY16 (Projected) from Earth Systematic Missions (ESM) and Earth System Science Pathfinder (ESSP). Decadal Survey Mission Budget is ESM pre-FY08 "Other" Category. Table 7.13 in the Appendix shows budget numbers.

Highlighted in Figure 3.11 is the high level of uncertainty within NASA's Earth Science satellite missions and their future costs. With several large missions scheduled to be launched within the next 2 years (NPP, GPM, and LDCM) a large "Other" category emerges that fills the gap between planned spending and appropriate spending levels. This practice of using a large "Other" category does not appear to be unusual for ESD budget requests since previous requests displayed the same magnitude of uncertainty 3-4 years into the future. It does show that there is room to still influence and define the course of the ESD.

A Decadal Survey campaign budget is estimated by subtracting known mission expenditures, NPP, GPM, LDCM, and "Other" (before Decadal Survey missions were relevant), from the full ESM budget. This results in Table 3.9, shows the projection that is used in subsequent schedule optimizations.

Year	2011	2012	2013	2014	2015	2016	FY11-FY16	Beyond 2016
Decadal Survey Campaign Budget ($M/year)	161.70	393.20	527.00	537.60	553.90	608.90	2,782.30	500.00

Table 3.9: Decadal Survey Campaign Budget for FY11-FY16 (Projected) used in Updated Case. Campaign Budget predictions based on FY09-FY12 ESD Budget documents with a more realistic estimate for the timeframe beyond 2016.

The increasing trend shown in Table 3.9 for FY11-FY16 is not carried beyond 2016 as the following analysis assumes a $500M budget, in real FY11 terms, for years after 2016. While conservative, this forward projection represents a budget landscape where additional funding is going to be increasingly difficult to attain as US federal budgets shrink and NASA budgets contract in turn. Another area of uncertainty is in regards to funding for future Glory operations since that particular mission failed to reach orbit. The accident report is yet to be published at the writing of this thesis. This simplistic approach to budget projection is examined with a budget sensitivity analysis in sub-section 3.2.4. Table 7.13 of the Appendix shows the numerical data taken from the ESD budget documents. (National Aeronautics and Space Administration 2008) (National Aeronautics and Space Administration 2009b) (National Aeronautics and Space Administration 2010b) (National Aeronautics and Space Administration 2011)

3.2.3. Updated Model Assumptions and GA results

This sub-section presents an updated assessment of technology readiness and the results of the updated campaign scheduling. Table 3.10 presents the assumptions that are used as inputs into the GA optimization. This analysis shows the consequences of running the same manifest as outlined in the Decadal Survey in the current GEOS situation.

Updated Case Assumptions		
Budget	See Table 3.9	
Costs	FY11	See Table 3.8, row 3
Campaign Start Date	2011	-
TRL Launch Dates		
Tier 1	2014, 2015, 2018	
Tier 2	2022	-
Tier 3	2022	-
TRL Cost Penalty	30%	-
Current US Missions	None	

Table 3.10: Global Earth Observation System Model Assumptions for the Updated Decadal Survey Case. TRL Launch Dates chosen to reflect scheduled Launch Dates of ICESat-II and SMAP, the Mission Definition work done on other 'Tier 1' Missions and a 10 year development horizon for the remaining Missions. GA results presented below.

After mission cost and campaign, the assignment of "TRL Launch Dates" to the various recommended missions has budget with the most impact on the model outcome. Within the 'Tier 1' missions, SMAP has a "TRL Launch Date" of 2014 because its scheduled launch date is November 2014 according to its mission website and ICESat-II has a "TRL Launch Date" of 2015 because its scheduled launch date is late 2015/early 2016 according to the most recent publically available documentation. (NASA JPL) (Mclennan 2010) A TRL launch date of 2018 is used for the other 'Tier 1' missions to reflect the small amount of mission definition and technology development that has been completed for them. The TRL launch date for the other Decadal Survey recommended missions is, at this time, highly speculative as very little work has been done on 'Tier 2' or 'Tier 3' missions besides mission definition as part of the Decadal Survey. In order to model these missions a TRL launch date of 2022 was chosen because it reflects a 10 year development path from 2012 should NASA decide to make a commitment and begin technology development now. Setting all of the 'Tier 2' and 'Tier 3' missions to the same TRL launch date also gives the algorithms flexibility to assign launch dates according to the optimal campaign, thus giving insight into technology priorities and possible technology development roadmap.

Using all of the same algorithms and GA parameters as in the baseline case, performance is shown in Table 3.11.

Genetic Algorithm Results	
Generation to Terminate	116
Architectures Evaluated	175,501

Table 3.11: Algorithm Performance for the Updated Decadal Survey Case shows that GA converged on a Pareto Optimal Solution after having evaluated over 175,000 Campaign Architectures.

The results of this updated GEOS campaign scheduling optimization are shown through the Pareto front in Figure 3.12, the exploration of that Pareto front shown in Table 3.12 and Figure 3.16, and the "Data Gap" and "Data Value" metrics shown in Figure 3.13 and Figure 3.14 respectively.

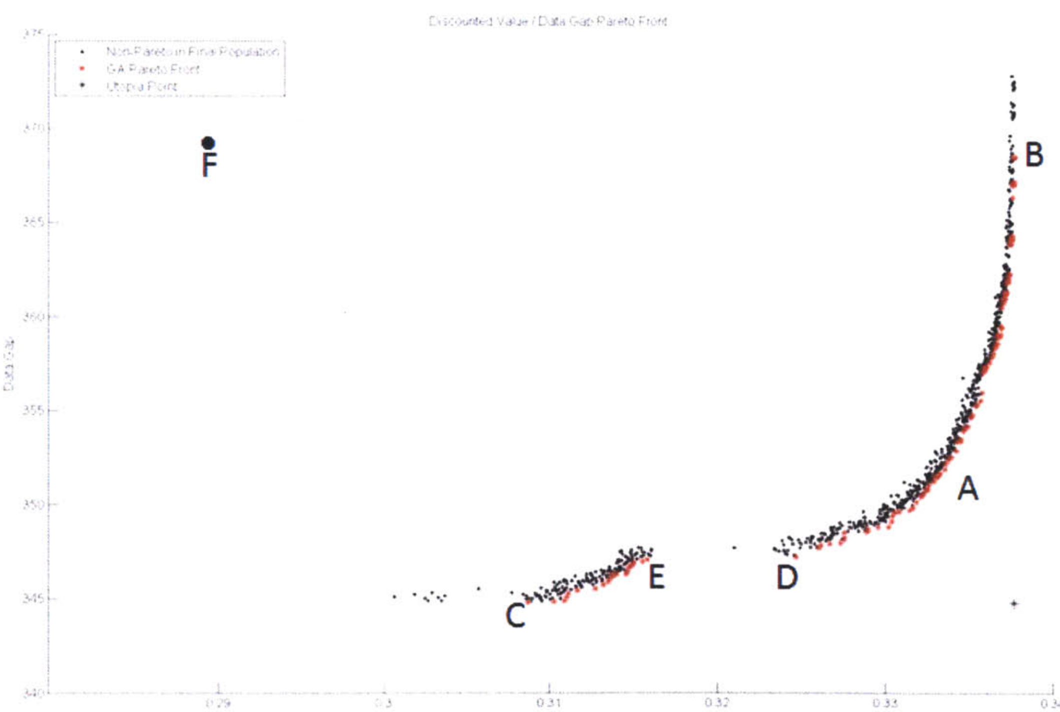


Figure 3.12: GA Results for Updated Decadal Survey Case presented as Pareto Optimal Campaign Architectures. Gap in Pareto Front is explained through the coupling of high value Missions

(GACM and GEO-CAPE) so that they are always separated in the launch order. Architectures A-E (Not exact as shown) are explored in Table 3.12. Architecture F is the top ranked campaign from the Baseline case shown in Table 3.6.

The color coding in Figure 3.12 shows that none of the campaign architectures on the Pareto front fall within the "Tier" structure, which indicates that the launch sequence suggested in the Decadal Survey does not completely apply to the updated scenario. In order to explore the Pareto front adequately, Table 3.12 shows 5 campaign architectures corresponding to architectures shown in Figure 3.12: the "top ranked" campaign (pane A), the highest "Data Value" campaign (pane B), the lowest "Data Gap" campaign (pane C), and campaigns on either side of the large gap in the Pareto front (panes D and E). Pane A, which is the top ranked campaign architecture, has the majority of the missions aligned with the Decadal Survey 'Tiers' with the exception of ACE and CLARREO. For all of the campaigns along the Pareto front SMAP, ICESat-II, GSPRO and DESDynl are in the top four, which aligns with the "Tier" structure.

Another interesting feature is the large gap in the Pareto front around a "Data Value" of 0.32, which is explored in Table 3.12 in pane D showing the architecture that falls directly to the right of the gap and in pane E showing the architecture that falls directly to the left of the gap. Upon further inspection of the Excel sheets, written by the post processing step as explained in sub-section 3.1.3, it can be seen that for all of the architectures on the right of the gap in the Pareto front GEO-CAPE is in the 5^{th} or 6^{th} launch spot, CLARREO is in the 17^{th} launch position and GACM is in the 9^{th}, 10^{th}, 11^{th}, or 12^{th} position. Architectures to the left of the gap have GEO-CAPE as the 12^{th} mission to launch, CLARREO in the 5^{th} position and GACM in the 6^{th} position. There is an apparent trade between GEO-CAPE and GACM, which are very similar missions in terms of the measurements they take. Due to the influence of the "Data Gap" metric, these missions separate. Higher "Data Value" is achieved when GEO-CAPE launches first between the two missions but GACM is pushed back to spread valuable measurements over the campaign. When GACM launches first between the two missions, CLARREO fills a budget gap that becomes present because GACM is less expensive than GEO-CAPE. This is shown in Table 3.12 through pane B as the maximum value case, which falls on the top right corner of the Pareto front and through pane C as the minimum data gap campaign, which falls on the bottom left of the Pareto front.

Top Ranked Campaign		Max "Data Value"		Min "Data Continuity"		Campaign #45		Campaign #78	
SMAP	2013.15	SMAP	2013.15	SMAP	2013.15	ICESatII	2013.7	SMAP	2013.15
ICESatII	2014.42	ICESatII	2014.42	ICESatII	2014.42	SMAP	2014.55	ICESatII	2014.42
GSPRO	2015.1	GSPRO	2015.1	GSPRO	2015.1	GSPRO	2015.21	GSPRO	2015.1
DESDynl	2018.15	DESDynl	2018.15	DESDynl	2018.15	DESDynl	2018.27	DESDynl	2018.15
GEO-CAPE	2021.74	HyspIRI	2020.11	CLARREO	2020.15	GEO-CAPE	2021.74	CLARREO	2020.15
HyspIRI	2022.65	GEO-CAPE	2022.67	GACM	2022.23	HyspIRI	2022.65	GACM	2022.23
XOVWM	2023.38	ASCENDS	2023.62	PATH	2023.28	XOVWM	2023.38	HyspIRI	2023.14
ASCENDS	2024.33	XOVWM	2024.35	GRACEII	2024.23	GRACEII	2024.33	SCLP	2024.17
SWOT	2025.73	GACM	2026.43	SCLP	2025.26	ASCENDS	2025.28	PATH	2025.22
PATH	2026.78	SCLP	2027.46	ASCENDS	2026.21	PATH	2026.33	ASCENDS	2026.17
GRACEII	2027.73	PATH	2028.51	HyspIRI	2027.12	LIST	2027.55	GRACEII	2027.12
GACM	2029.81	SWOT	2029.91	GEO-CAPE	2029.68	GACM	2029.63	GEO-CAPE	2029.68
SCLP	2030.84	3DWinds	2031.51	LIST	2030.9	SCLP	2030.66	XOVWM	2030.41
ACE	2034.1	ACE	2034.77	ACE	2034.16	ACE	2033.92	ACE	2033.67
LIST	2035.32	GRACEII	2035.72	XOVWM	2034.89	SWOT	2035.32	SWOT	2035.07
3DWinds	2036.92	LIST	2036.94	SWOT	2036.29	3DWinds	2036.92	LIST	2036.29
a) CLARREO	2038.92	b) CLARREO	2038.94	c) 3DWinds	2037.89	d) CLARREO	2038.92	e) 3DWinds	2037.89

Table 3.12: Pareto Front Exploration for Updated Decadal Survey Case shows Missions ordered by

Launch Dates and color-coded to reflect Decadal Survey assigned 'Tier'. Pane (a) shows "Top Ranking" Campaign with GEO-CAPE breaking the TRL Launch Date and CLARREO slipping to the end of the Campaign. Pane (b) and (c) show the extremes of the Pareto Front, Pane (d) is the first Pareto Optimal Campaign to the right of the Gap (Around Data Value of 0.295) and Pane (e) is the first Pareto Optimal Campaign to the left of the Gap.

Table 3.12 can also inform decision makers without having to point to a complete scheduling solution. For instance, this analysis shows that ICESat-II and SMAP should always be launched first. This is logical given the amount of money that has already been spent on technology and instrument development for those missions. Both ICESat-II and SMAP have had instrument prototypes fly on aircraft in separate efforts to mitigate risks and develop technology. This money should not go to waste and both of these valuable missions should be flown, even if later missions are cancelled. The analysis, that pushes CLARREO to the end of the campaign in most cases, is also in line with the current actions of NASA leadership as CLARREO development activity has been cancelled. (Space News 2011b) In the near-term, this analysis suggests that if NASA leadership and the Earth Science community decide to continue with the Decadal Survey missions, funding should be reinstated to DESDynl if it has the potential to launch before 2020. Otherwise investments should be made in 'Tier 2' missions such as GEO-CAPE, HyspIRI, and ACE. Through some further post-processing steps, architectures that align with the Decadal Survey 'Tiers' were compared to the optimal campaign architectures found with the GA. Architecture F in Figure 3.12 shows the position of the top ranked architecture from the baseline case as described in Table 3.6. This analysis shows that simply following the Decadal Survey recommendations given the current situation would be sub-optimal. Compared to the to the top ranked architecture in the updated case, described in Table 3.12, the baseline top ranked solution delivers 12.6% less "Data Value" and receives a 5.6% worse "Data Gap" score.

Figure 3.13 displays the measurement gaps that are foreseeable when considering the Decadal Survey missions alone. This "Data Gap" visualization plot uses the same technique as Figure 3.5.

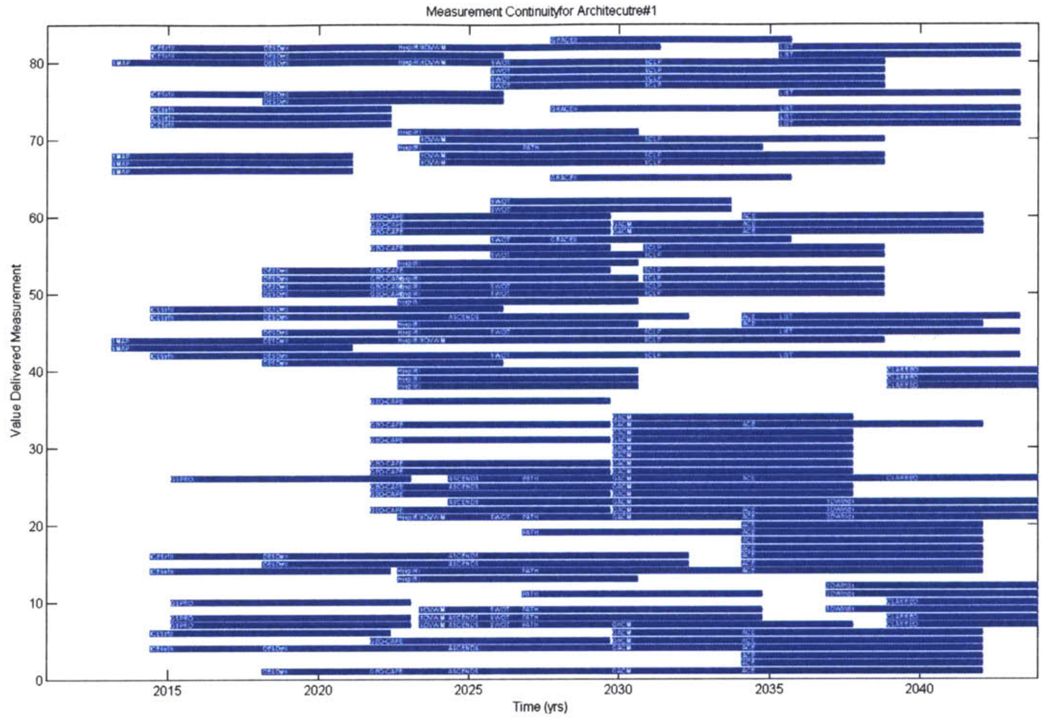


Figure 3.13: Data Gap Graph for "Top Ranking" Campaign of the Updated Decadal Survey Case shows how gaps in Measurement Continuity form when Campaign is stretched to 35+ years. 8 year Mission Lifetime opens scientific community to significant failures that could affect Data Gap. Blue signifies a measurement is being taken and white that it is not.

Analysis of the baseline Decadal Survey case shown in Figure 3.5 confirmed that when launched within the decade as intended, the recommended set of Decadal Survey missions covers the key Earth science measurements and in most cases has substantial overlap. In the updated Decadal Survey case the campaign is spread over 35+ years, as shown in Figure 3.13 and the obvious measurement gaps begin to emerge. With an 8 year mission lifetime, the water/ice missions (ICESat-II, SWOT and SCLP) are able to cover many of the gaps near the top of the plot. Some measurements, especially those associated with CLARREO, show gaps in the middle of the campaign. Figure 3.13 also clearly highlights the need for gap filler missions, a need that wasn't obvious when all of the missions were being launched in the same decade and most gaps were filled, as in the baseline case. The 8 year lifetime assigned to each mission also opens the possibility of failures having large consequences for data continuity. This risky reliance on long lifetimes is especially true for missions that cover a wide range of measurements like GEO-CAPE, ACE, or GACM. Failures in those missions leave large multi-year holes in the record that would need to be filled with quick reaction platforms.

When evaluating the updated Decadal Survey case, an obvious fact emerges: under current budget and cost estimates the 17 recommended missions will take more than 35 years to complete. The effect of this 35+ year campaign length can be seen in Figure 3.14. It shows the accumulation of the "Data Value" metric in the same way as Figure 3.6 above.

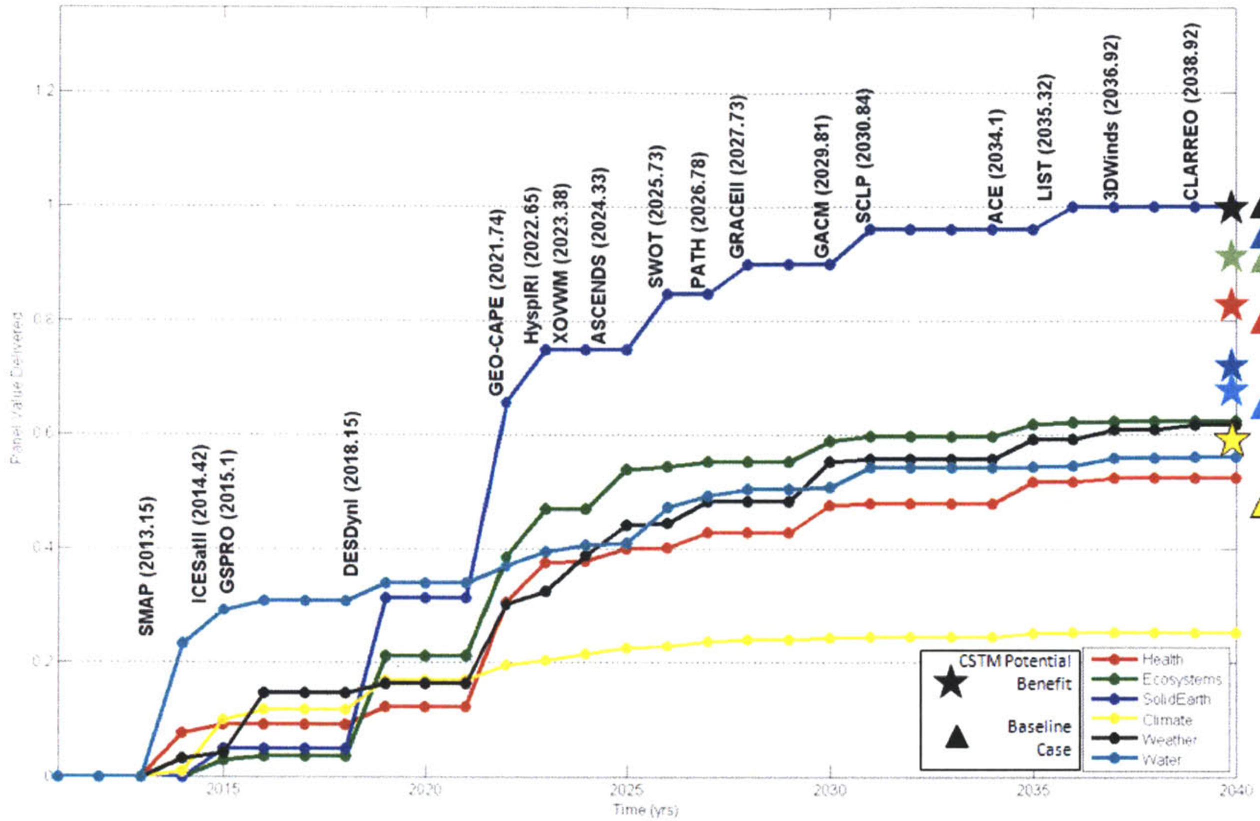


Figure 3.14: Discounted Benefit Accumulation for "Top Ranking" Campaign of Updated Decadal Survey Case shows how discounting benefit delivery over a 30+ year campaign produces Panel Values that are highly penalized from Potential Benefit (Table 2.5) as shown in Figure 3.15 below. Fairness becomes an issue as the Climate Panel loses 66% of its Baseline value (Marked by ▲) while the Water Panel only loses 30%.

To illustrate the effect of time on the value delivered to the stakeholders, as formulated by the "Data Value" metric, SMAP, SWOT and SCLP are compared. SMAP, SWOT, and SCLP have potential value deliveries to the water panel of 0.326, 0.317, and 0.332 respectively but as can be seen on the above plot, through the launch sequence they deliver very different values. In the top ranking campaign architecture, shown in Figure 3.14, SMAP launches in 2013.15 delivering 0.137 units of value to "Water", SWOT launches in 2025.73 delivering 0.038 units of value to "Water" and SCLP launches in 2030.8 delivering 0.020 units of value to "Water". This effect is more clearly captured in Figure 3.15, which compares the raw non-panel-weighted "Data Value" score for the potential value of each panel given by the CSTM to the discounted value delivered to each panel in the baseline Decadal Survey case, and the discounted value delivered to each panel in the updated Decadal Survey case.

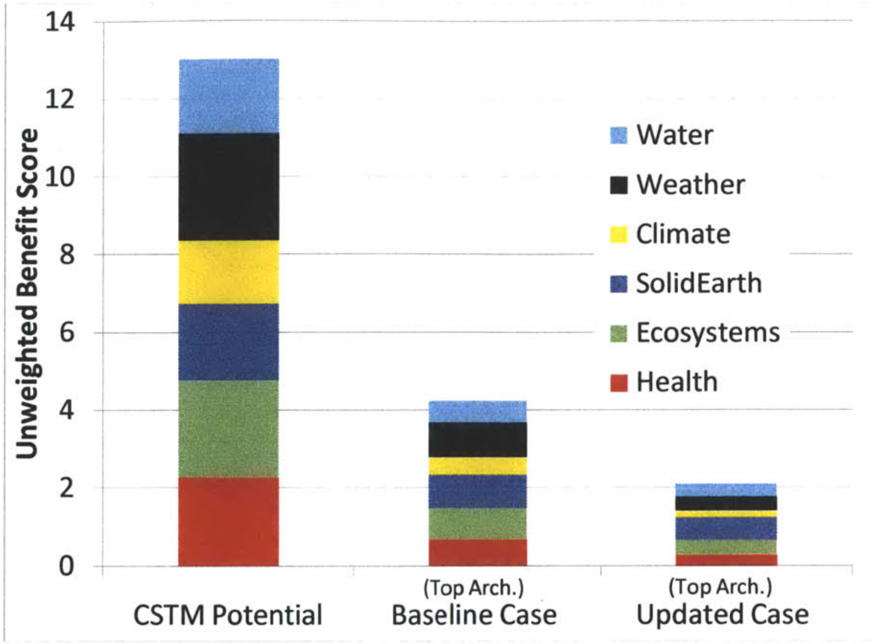


Figure 3.15: Delivered non-panel-weighted Benefit each Panel receives from the campagin Comparison between CSTM Potential Value (Table 2.5), Baseline Decadal Survey Case (Figure 3.6) and Updated Decadal Survey Case (Figure 3.14). Panels are heavily affected by Time Discounting of Data Value but not evenly.

Previous discounted value accumulation graphs (Figure 3.6 and Figure 3.14) and Figure 3.15 show that not all panels are affected equally by the time discounting of data value. Figure 3.15 can be understood to show that the difference in total benefit between the CSTM potential (sum of undiscounted, unweighted benefit delivered by the campaign) and the baseline case is due to the time discounting of benefit. Similarly, the difference between the baseline and updated cases is due to increased mission costs and decrease campaign budget. When compared to the CSTM potential, the Ecosystems panel loses 52% of its value in the baseline case because of the time discounting and it loses 84% in the updated case. For comparison, in the baseline case the Water panel only loses 26% of its value compared to the CSTM potential and it loses 48% in the updated case compared to the CSTM potential. The entire stakeholder community loses 42% of the potential value from the CSTM results to the baseline case and 73% of the potential value when the parameters are updated. The calculation displayed in Figure 3.15 may also be a measure of fairness since each panel is compared to its own potential cumulative value and therefore is a measure of how each campaign architecture affects the realized total value of each panel. The level of knowledge captured here gives decision makers unprecedented understanding of the system and its dynamics. The influence of the TRL constraints is shown in Figure 3.16. Figure 3.16 displays the 80 highest ranked campaign architectures in a "Whisker Plot" similar to Figure 3.8.

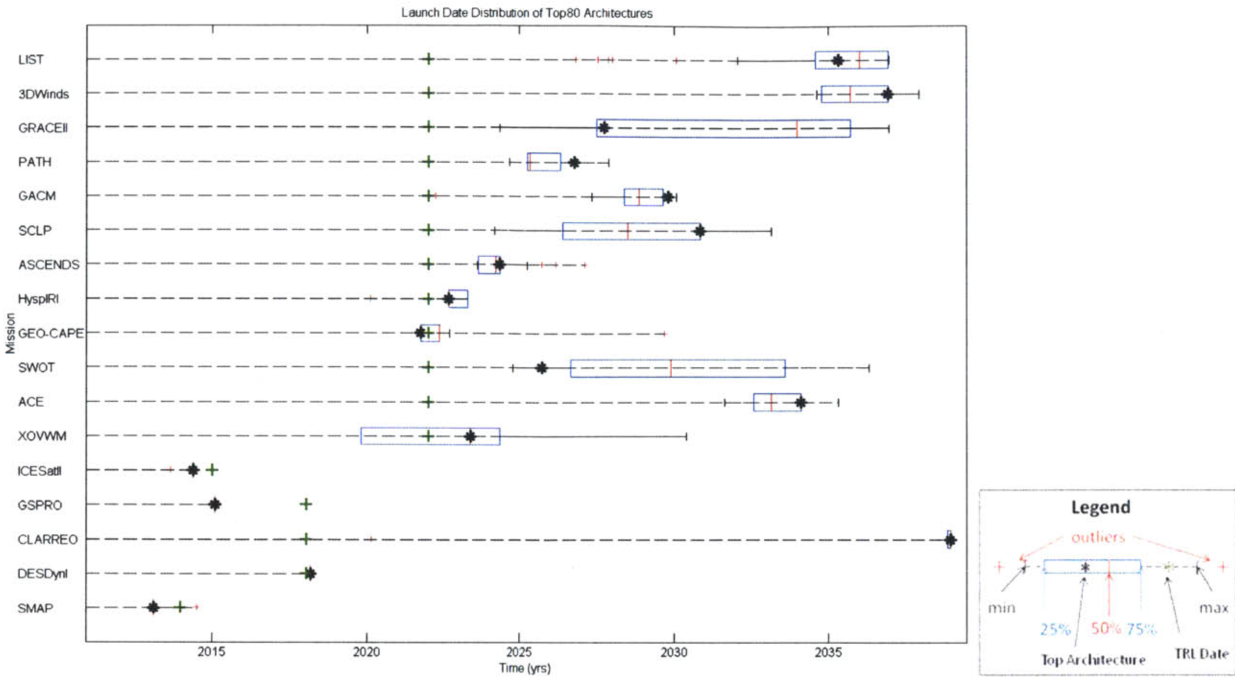


Figure 3.16: Statistical View ("Whisker Plot") of Top 80 Campaign Architectures for the Updated Decadal Survey Case. Plot of Launch Dates shows stability for Missions in which investment has already been made (SMAP and ICESat-II), high value 'Tier 2' missions (GEO-CAPE and HyspIRI) and Missions at the end of the Campaign (CLARREO and 3DWinds).

The range of launch dates shown in Figure 3.16 for each mission could inform a decision about that mission's ability to be accelerated or slipped in the launch order given extraneous circumstances such as mission failure, an observation opportunity, or changing national/scientific priorities. The flexibility of the mission launch date to the optimal solution is seen in the blue box that surrounds the optimal point. Missions such as SCLP and SWOT have large flexible ranges for their optimal launch date, which indicates that both of those missions would be likely candidates to slip in the launch order. This slip might occur if a precursor mission was performing better than expected or if another mission could be accelerated to fill a gap or opportunity in its place. The algorithm has found that GEO-CAPE and HyspIRI should always launch as soon as possible despite their low TRL and high costs and that GACM and ACE should launch to fill the major measurement gaps as soon as GEO-CAPE and/or HyspIRI fail. In addition to the missions that are shown to be important and of high priority by the algorithm results, there are some missions such as CLARREO and 3DWinds that consistently fall to the back of the optimized campaign architectures. In reality, unless there is a strong commitment to the Decadal Survey recommended set of missions, these missions at the end of the campaign will eventually be superseded by the next generation of Earth observation missions designed to address more relevant scientific and societal needs. To address this, a budget sensitivity analysis is conducted in the next sub-section.

3.2.4. Budget Sensitivity Analysis

Given the uncertain nature of NASA's Earth Science Division projected budget and the high degree of non-linearity displayed by the GEOS model in sections 3.1 and 3.2.3 it is necessary to examine how this complex system will deliver value in different budget scenarios. The analysis presented here consists of running the GA under all of the same assumptions as in Table 3.10 for the various budgets as shown graphically in Figure 3.17 and numerically in Table 7.14 of the Appendix. The "baseline" budget represents the budget presented in the updated case in section 3.2.2 on page 70. A 'Low' budget case assumes that in 2012 the Decadal Survey mission budget gets a small boost and then stays at half that predicted level into the future. The 'Medium Low' budget case assumes a similar stagnation as in the 'Low' case but beginning in 2013 at $400M a year. Similarly, a 'Medium High' scenario assumes a stagnate budget starting in 2017. The 'High' case continues to grow by 10% until 2020 and then levels off at $1B/year, twice the baseline case.

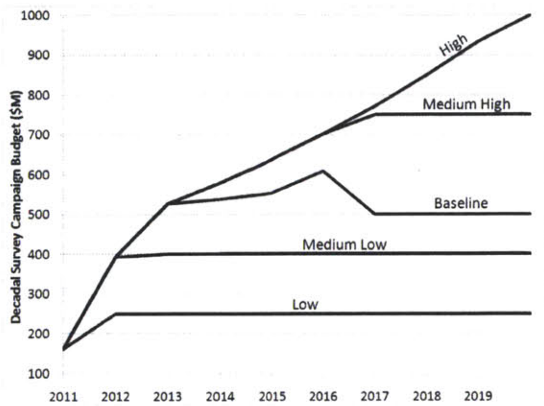


Figure 3.17: Graphical Representation of Budget Analysis Scenarios. Baseline follows Table 3.9, 'Low' levels at $250M or Half of Baseline, 'Medium Low' follows Baseline and stagnates in 2012 at $400M, 'Medium High' grows to stagnate at $750M, and 'High' grows at 10% until reaching $1,000M.

Investigating the budget sensitivity of the GEOS model showed that the TRL launch dates set in Table 3.10 for the updated case could not be used for every budget scenario. For instance, in the 'Low' budget case, the campaign takes more than 35 years to launch. TRL dates had to be moved back to reflect how the pace of technology development slows as the funding and launch rate slows. Due to computer memory issues, campaigns were stopped after 35 years so that all of the remaining missions had a launch date of 2046, but this situation only occurred in the 'Low' budget case. Table 3.13 shows the numerical results of the budget analysis. The maximum "Data Value" and minimum "Data Gap" metrics in relation to the budgets are on the top half of the table and the top ranking campaign architectures are on the bottom half. All changes (Δ) are relative to the 'Baseline' case, which is the updated scenario presented in this section.

Budget	2020 Budget and Beyond	Change (Δ) from Baseline	Max "Data Value"	Δ from Baseline	Minimum "Data Gaps"	Δ from Baseline
High	1000	100.0%	0.345	20.8%	294.9	-18.7%
Medium High	750	50.0%	0.326	14.2%	313.5	-13.6%
Baseline	500	0.0%	0.285	0.0%	362.9	0.0%
Medium Low	400	-20.0%	0.252	-11.6%	423.5	16.7%
Low	250	-50.0%	0.191	-33.0%	482.2	32.9%
		Top Ranking Campaign				
Budget	Value	Δ	Data Gaps	Δ	Campaign Length (years)	
High	0.343	22.0%	297.991	-18.9%	17	
Medium High	0.324	15.2%	316.363	-13.9%	20	
Baseline	0.281	0.0%	367.450	0.0%	28	
Medium Low	0.251	-10.8%	431.992	17.6%	34	
Low	0.190	-32.6%	487.528	32.7%	35+	

Table 3.13: Results of the Budget Analysis compare Budget to Maximum Value and Minimum Data Gaps in the Top Half of the Table. This comparison shows that doubling the long-term budget only increases Data Value by 20.8% and at best could decrease Data Gaps by 18.7%. This shows that later investment cannot make up for the lack of early funding. Conversely, cutting the budget in half still allows for 67% of the Value to be delivered as 8/17 Missions would be launched in the Campaign length of the Baseline Case.

The top half of the analysis presented in Table 3.13 shows that there is not a linear relationship between the amount of money spent on the campaign and the resulting metrics. For the 'High' case, a doubling of the budget beyond 2020 leads to only a 20.8% increase in the value delivered to the stakeholder community and a 18.7% decrease in the occurrence of data gaps. Increasing the long-term budget outlook does not have a drastic effect on the objectives of the system because many of the effects occur later in the campaign lifetime, beyond 2020, and therefore are discounted more strongly then would be the case if budgetary changes were put into effect now. This is consistent with the recommendation of the Decadal Survey, which stated that Earth Science Division budgets should be ramped back up to FY00 levels no later than 2010. The Decadal Survey authors recognized that in order to see drastic effects in the performance of the GEOS, the time to invest more heavily in Earth science was before the decade under investigation began, not after 2020. For the 'Low' budget case, in which the actual budget is half of requested levels starting in 2013, the value that would be delivered to the stakeholders decreases by 33% and total score of the "Data Gap" metric increases by 32.9%. In addition, the top ranking 'Low' budget campaign launches the 8 highest value missions within the same time period as the entire campaign in the 'Baseline' case. By launching 8/17 missions in the same time that the 'Baseline' case launches 17/17, the 'Low' scenario is able to capture most of the value and fill many of the resulting data gaps. The budget presented in the 'High' case results in a campaign with its last missions launching in 2028, 11 years before the end of the 'Baseline' scenario but still well outside of the decade originally envisioned for the Decadal Survey set of missions. This means that even under optimistic budget predictions, it is not possible for the set of missions proposed by the Decadal Survey to all launch within the 2010-2020 decade originally envisioned. In light of this, chapter 4 begins to explore other means to observe the Earth in an effort to fulfill the objectives of the various Earth Science communities.

The results of the updated case, especially the small number of missions to realistically be launched in the coming decade, shows that there is a need to consider not just the Decadal Survey missions but also the NASA/NOAA missions currently and soon-to-be in orbit. By considering the missions that the Decadal Survey committee took as a foundation, the system can be better understood and new insights are gained.

3.2.5. Current NASA/NOAA Missions

The future Global Earth Observation System of satellites does not operate without consideration for the missions that are currently collecting data and those missions that NASA is planning to launch soon. NASA is currently operating 15 satellites in orbit, which are listed in Table 3.14 with their launch dates and currently estimated "End of Life" (EOL) dates (Committee on Earth Observation Satellites 2010). These dates are best estimates but do not necessarily reflect reality. Missions tend to be extended as long as they are gathering useful data leading to highly uncertain mission lifetimes. These current missions must be taken into account when evaluating architectures in the larger GEOS context because within the CSTM framework, the "Data Gap" metric is heavily affected by the presence or absence of a mission currently gathering data and its lifetime.

Mission Name Short	Mission Name Full	Mission Agencies	Launch Date	EOL Date
ACRIMSAT	Active Cavity Radiometer Irradiance Monitor	NASA	20-Dec-99	2012
Aqua	Aqua (formerly EOS PM-1)	NASA / JAXA / BNISS / INPE	4-May-02	2014
Aura	Aura (formerly EOS Chemistry)	NASA / NSO / FMI / NIVR / BNSC	15-Jul-04	2014
CALIPSO	Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observations	NASA / CNES	28-Apr-06	2016
CloudSat	CloudSat	NASA / CSA	28-Apr-06	2016
GRACE	Gravity Recovery and Climate Experiment	NASA / DLR	17-Mar-02	2015
Jason	Ocean surface topography	NASA / CNES	7-Dec-01	2013
Landsat-5	Landsat-5	USGS / NASA	1-Mar-84	2012
Landsat-7	Landsat-7	NASA / USGS	15-Apr-99	2015
NMP EO-1	New Millenium Program Earth Observing-1	NASA	21-Nov-00	2013
OSTM	Ocean Surface Topography Mission	NASA / NOAA / CNES / EUMETSAT	20-Jun-08	2017
QuikSCAT	Quick Scatterometer	NASA	19-Jun-99	2014
SORCE	Solar Radiation and Climate Experiment	NASA	25-Jan-03	2014
Terra	Terra (formerly EOS AM-1)	NASA / JAXA / CSA	18-Dec-99	2014
TRMM	Tropical Rainfall Measuring Mission	NASA / JAXA	27-Nov-97	2014

Table 3.14: Currently Operational NASA Missions listed in Alphabetical Order with Full Name, Participating Agencies, Launch Date and Estimated End of Life Date. Missions are considered for "Data Gap" Metric as fixed assets.

In addition to the current missions listed in Table 3.14, there are also a series of missions that are scheduled to launch in the coming years. The Decadal Survey panels were considering a set of missions based on the assumption that the near-term NASA missions listed in Table 3.15 would be launched on time. Unfortunately, none of these missions have been launched by the date originally predicted. Missions that are not included in Table 3.15 and Table 3.14 that the Decadal Survey panels considered precursors were NPOESS, OCO and Glory. In February of 2009 the launch vehicle carrying OCO failed to deploy the satellite and in March of 2011 a similar failure caused the Glory mission to not reach orbit either. The

OCO failure caused NASA to refurbish an engineering unit (National Aeronautics and Space Administration 2010a) and rebrand it as OCO-2 because the measurements taken by OCO, namely the mapping of carbon sources and sinks, are of value to the international community. NPP is a precursor mission to the larger NPOESS, which has recently been cancelled and parts have been reassigned to different agencies, as discussed in section 1.1.3.

Mission Name Short	Mission Name Full	Mission Agencies	Launch Date	EOL Date
Aquarius		NASA	Jun-11	2018.5
GPM Constellation	Global Precipitation Measurement Mission Constellation spacecraft	NASA / JAXA	Nov-14	2020.5
GPM Core	Global Precipitation Measurement Mission Core spacecraft	NASA / JAXA	Jul-13	2020.5
LDCM	Landsat Data Gap Mission	NASA / USGS	Dec-12	2020
NPP	NPOESS (National Polar-orbiting Operational Environmental Satellite System) Preparatory Project	NASA / NOAA / DoD (USA)	Dec-11	2019
OCO-2	Orbiting Carbon Observatory	NASA	Feb-13	2019

Table 3.15: Near-Term NASA Missions listed in Alphabetical Order with Full Name, Participating Agencies, Launch Date and Estimated End of Life Date. Missions are considered for "Data Gap" Metric as fixed assets.

Each of the missions listed in Table 3.14 and Table 3.15 has a set of instruments as outlined in the CEOS database and inferred from mission documentation. The CSTM framework, presented in section 2.2, was applied to the current and near-term NASA missions. Note that this analysis could also done for international missions, but doing so raises questions regarding data sharing and openness of US scientist to receiving international data as a gap filler. Considering international partners could be an area of future work.

The two sets of missions (Current/Near and Decadal Survey) are combined to produce Figure 3.18 using color coordination to distinguish panels. Figure 3.18 presents the current and near-term NASA missions alongside the recommended Decadal Survey missions to show the relative value assigned to each. From plot it can be seen that the Decadal Survey missions are in line with current missions in terms of the value they provide to the stakeholder base, which shows the consistency of the CSTM framework and its ability to equally assess missions.

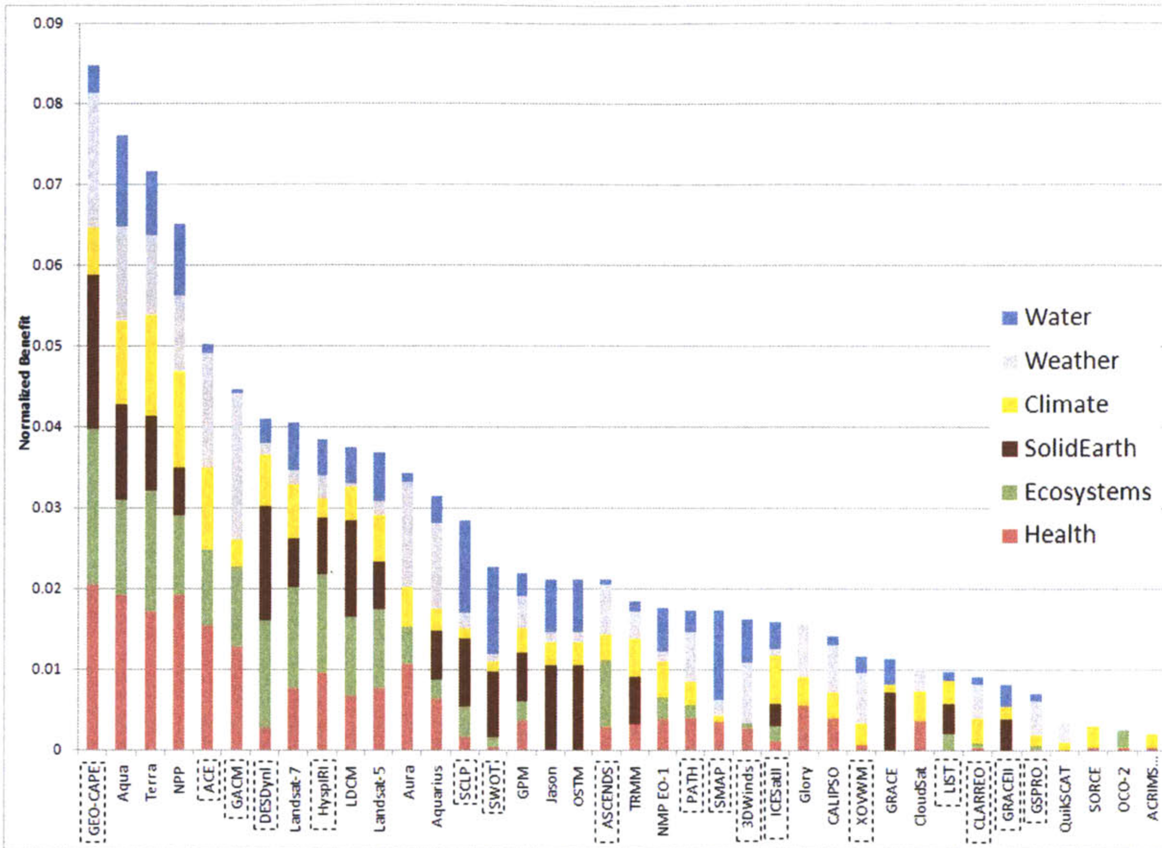


Figure 3.18: Normalized CSTM Mission Value for Decadal Survey Mission, Current NASA Missions, and Near-Term Missions broken down by Panel ranked in Descending order. Plot shows the output of the CSTM, which is the "Data Value" delivered to each Panel from each Mission. Decadal Survey Missions are well distributed among entire set and two (2) categories emerge fitting well with the ESM and ESSP structure within NASA ESD.

Several features emerge from Figure 3.18 that help to understand the Decadal Survey set of missions in the larger GEOS context. First, the Decadal Survey missions, highlighted on the x-axis, are well distributed among the current and near-term missions. This distribution means that the Decadal Survey recommended a set of missions that is well aligned with the current scope present in the Earth observing system of satellites. Second, within this large set of missions two groups emerge: larger missions represented by GEO-CAPE through ASCENDS and smaller highly specialized missions represented by PATH through ACRIMSAT. This two tiered structure is very much in line with the organizational structure of NASA's Earth Science Division as shown through the budgets in Figure 3.10 and Figure 3.11. Within ESD, ESM accounts for one or two large facility-class missions and several medium sized missions and ESSP accounts for the small technology demonstration or specialty measurement missions. The third interesting feature is that only 3 out of the top 7 missions are currently in orbit, which may reflect the growing complexity and the ambitious nature of the set recommended by the Decadal Survey.

With the stakeholder values and measurement set of 38 missions shown in Figure 3.18, the same GA tools are applied. By scheduling the Decadal Survey mission in the context of the current missions, a better picture of the upcoming data gap environment emerges.

3.2.6. Complete Satellite GEOS Model Assumptions and GA Results

The analysis of the current operational and near-term Earth observation satellites presented in sub-section 3.2.5 are added to the updated Decadal Survey case shown in section 3.2.3 using the same Decadal Survey mission costs presented in section 3.2.1 and the GEOS campaign budget estimate presented in section 3.2.2. The current and near-term missions are added as fixed assets with start and end dates, thus no cost is associated with them. The fixed stakeholder value associated with the additional missions is added equally to each architecture in the algorithm therefore the added missions are only considered within the "Data Gap" metric. The GA analysis was run using the assumptions shown in Table 3.16, which are identical to the assumptions shown in Table 3.10 with the addition of "Current US Missions" parameters set to include the current and near-term missions outlined in section 3.2.5.

Updated Case Assumptions		
Budget	See Table 3.9	
Costs	FY11	See Table 3.8, row 3
Campaign Start Date	2011	-
TRL Launch Dates		
Tier 1	2014, 2015, 2018	
Tier 2	2022	-
Tier 3	2022	-
TRL Cost Penalty	30%	-
Current US Missions	Included	

Table 3.16: GEOS Model Assumptions for the Updated Case with Current and Near-Term NASA Missions, which is the same as for the Updated Case but with all missions shown in Figure 3.18.

Using all of the same algorithms and GA parameters as in the baseline case, algorithm performance is shown in Table 3.17.

Genetic Algorithm Results	
Generation to Terminate	104
Architectures Evaluated	157,501

Table 3.17: Algorithm Performance for the Updated Case with Current and Near-Term NASA Missions shows that GA converged on a Pareto Optimal Solution after having evaluated over 150,000 Campaign Architectures.

The results of the GA are shown graphically through the Pareto front of the optimal solutions in Figure 3.19, the top 80 architectures are displayed in a "Whisker Plot" in Figure 3.20, and the data continuity visualization is shown in Figure 3.21. The Pareto front of this GA analysis shows that there are no architectures that fall into the 'Tiers' outlined by the Decadal Survey and that the minimum "Data Gap" metric drops 34% from 344.8 to 227.6, a direct effect of the additional missions.

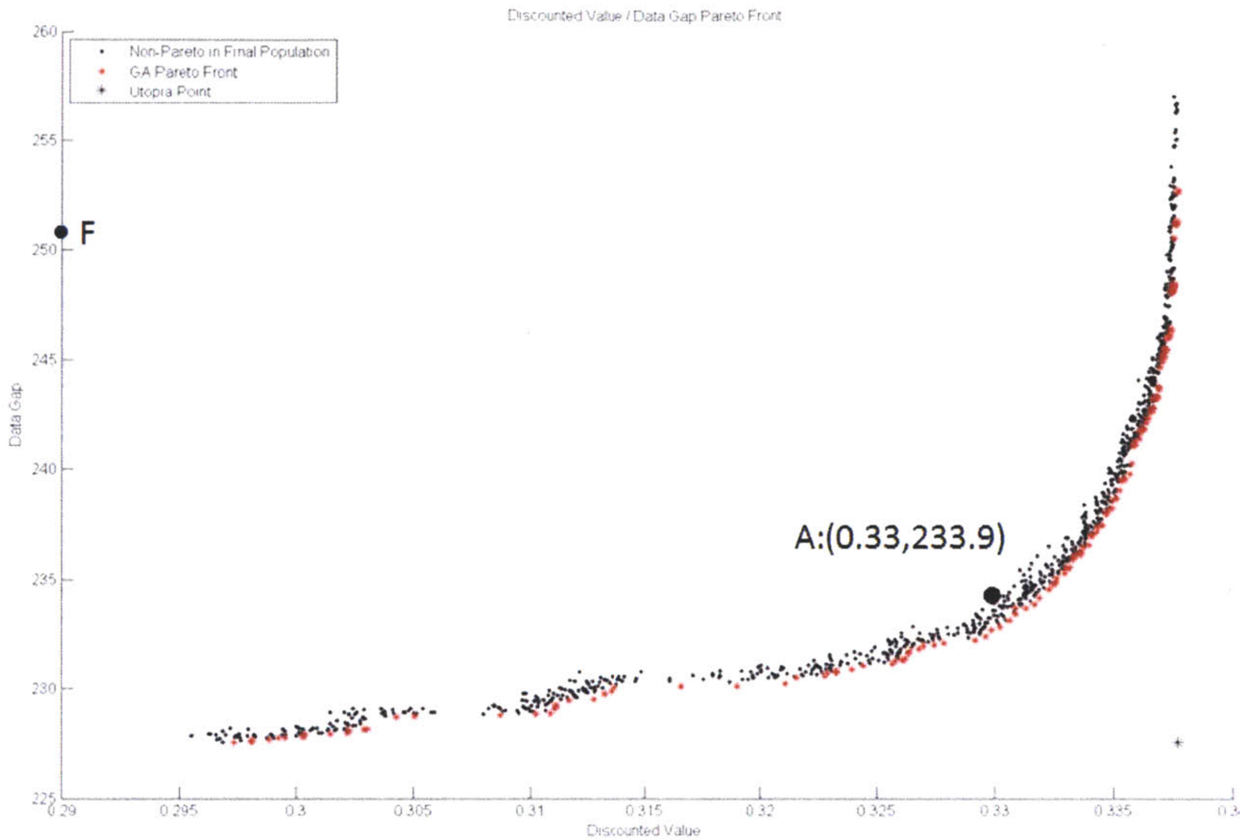


Figure 3.19: GA Result displayed as Pareto Front for the Updated Case with Current and Near-Term NASA Missions. Red colored markers are Pareto Optimal Architectures and black markers were individuals in the final population but not on the Pareto front, none of the final architectures fit into the Decadal Survey 'Tier' assignments. Point A is the top ranked campaign from the Updated Case shown in Table 3.12. Point F is the top ranked campaign from the baseline case shown in Table 3.6.

Similar to Figure 3.12, none of the Pareto optimal campaign architectures fall within the 'Tier' structure. Figure 3.20 displays the 80 highest ranking campaign architectures in a statistical form and can be compared to Figure 3.16 above to observe major differences between schedules with and without the current and near-term NASA missions.

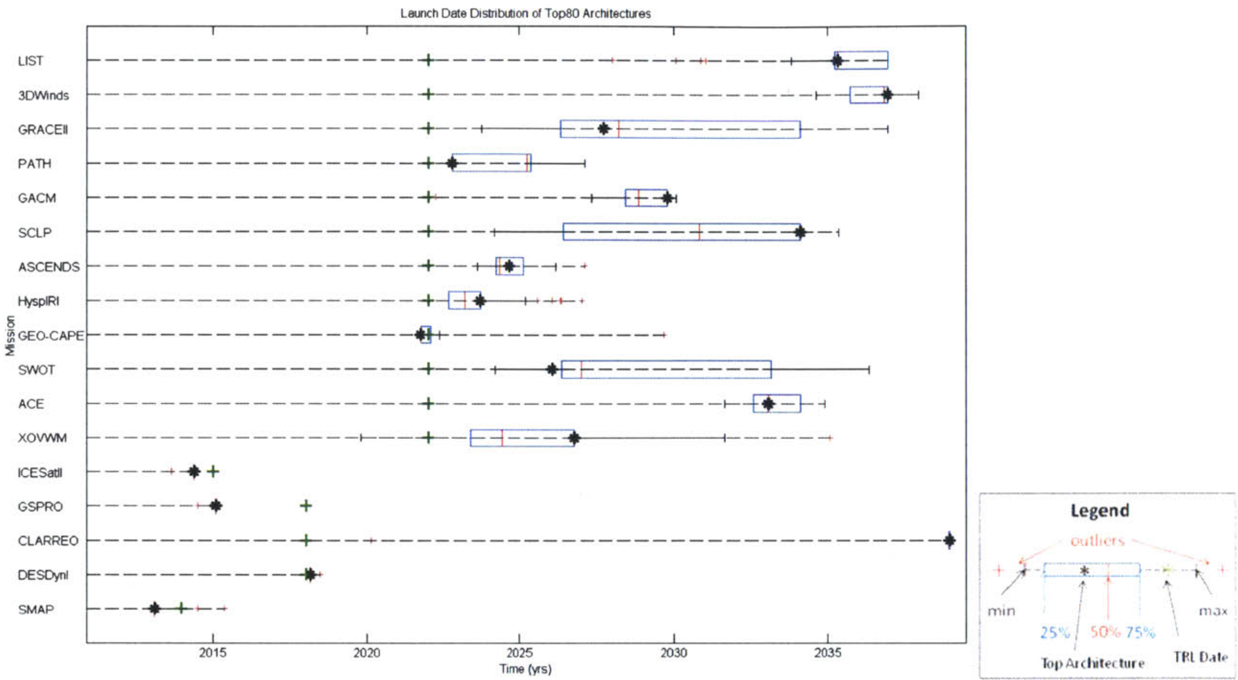


Figure 3.20: Statistical View ("Whisker Plot") of Top 80 Campaign Architectures for the Updated Decadal Survey Case with Current and Near-Term NASA Missions. Plot of Launch Dates shows results similar to Updated Case (Figure 3.16) with less flexibility in general.

By examining the top 80 campaign architectures along the Pareto front, the flexibility of each mission's launch date and the effect of adding the current and near-term NASA missions is shown. Figure 3.20 shows that in relation to the GA results without the NASA missions, the campaign sequence of the Decadal Survey missions becomes less flexible along the Pareto optimal front. GEO-CAPE and HyspIRI remain important missions in terms of technology development and receive an early launch date and CLARREO and 3DWinds remain scheduled at the end of the campaign. While the ordering of missions is not generally effected by the addition of current and near-term missions, significant changes are shown in the data continuity plot. Figure 3.21 shows the current NASA missions in red and overlap between Decadal Survey and NASA missions in pink.

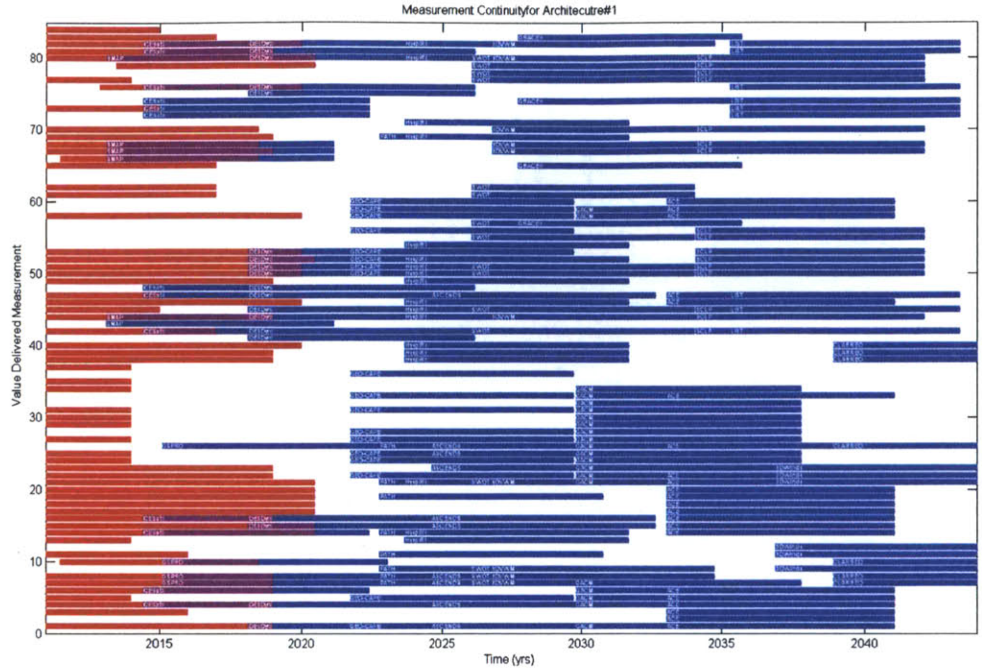


Figure 3.21: Data Gap Graph for "Top Ranking" Campaign of the Updated Decadal Survey Case with Current and Near-Term NASA Missions shows foreseeable Measurement Gaps between current Missions and later Decadal Survey Mission GEO-CAPE and SWOT. Visual representation of Measurements also makes the case for considering less expensive gap-fillers to mitigate Data Gap risk.

The data continuity graph gives visual insight into the near-term measurement gaps, which could inform current mitigation strategies. For example, there is a gap in the measurement of atmospheric SO_2, CH_4, NO_x and CO between the end of the Aura mission, 2014 in this model, and the launch of GEO-CAPE in 2021, according to the highest ranking campaign architecture. Another example is the sea level height and sea floor topography measurements currently taken by Jason, with an end of life date of 2013, for which there will be a gap until the SWOT mission is launched in 2024 according to the campaign architecture displayed in Figure 3.21. Other examples can be seen in the plot above and show that unless mitigation steps are taken, large gaps in measurement continuity will appear in the GEOS due to the effects that decreased budgets and increased costs have on campaign schedules. One step to mitigate the coming measurement gaps is by using other observational platforms for gathering data as discussed below.

3.3. Justification for Aircraft Measurements

This section justifies the inclusion of aircraft missions by using the results of the updated campaign architecture to examine measurements that are especially in danger of gaps. Section 3.2 showed that even with an optimistic outlook on current and near-term NASA mission lifetimes, serious gaps in Earth Science measurements are foreseeable. Mitigation strategies must be undertaken now in order to minimize the impact of these gaps on the Earth science community. These potential gaps were also seen by the Decadal Survey as they made recommendations to further incorporate aircraft measurements into the GEOS.

The visual representation of the "Data Gap" metric, shown in Figure 3.21, displays times when a measurement is taken in blue (or red for current and near-term missions) and gaps in a measurement as white. The "Data Gap" metric, explained in sub-section 2.3.3, is calculated so as to determine measurements that might be in danger of gaps. Table 3.18 is a collection of measurements that are part of the ten worst in terms of data gap length and/or weighted "Data Gap". As explained in sub-section 2.3.3, the gaps are discounted after ten years so that the total discounted number of gap-years in this 36 year campaign is 22.96. Each measurement's gap-year total is weighted by its measurement importance (I_m), shown in Equation 2.20, so that the total "Data Gap" score of this campaign architecture is 232.4.

#	Measurement	Meas. Importance (I_m)	Data Gap Years	"Data Gap" Objective
2	1.1.2 aerosol shape, composition, physical and chemical properties	0.75	20.09	15.10
3	1.1.3 aerosol scattering properties	0.59	15.09	8.83
5	1.1.5 aerosol size and size distribution	0.92	8.26	7.58
11	1.4.1 atmospheric wind speed	0.50	10.89	5.48
12	1.4.2 atmospheric wind direction	0.34	21.10	7.11
25	1.8.5 CO	0.84	9.48	7.96
27	1.8.7 NOx(NO, NO2), N2O5, HNO3	0.64	9.48	6.06
28	1.8.8 CH2O and non-CH4 VOC	0.64	12.48	7.98
32	1.8.12 Vulcanic SO2, OCS and other vulcanic aerosols	0.00	18.76	0.00
35	1.8.15 Upper-troposphere/stratosphere - Polar Stratospheric Clouds	0.00	19.96	0.00
37	1.9.1 Spectrally resolved solar irradiance	0.13	19.96	2.65
54	2.6.5 surface composition	0.24	16.69	4.01
60	3.1.3 Extended ocean color - NIR (atmospheric correction)	0.71	13.54	9.64
63	3.2.4 thermal plumes	0.00	22.96	0.00
64	3.2.5 river plumes/sediment fluxes	0.33	22.96	7.50
71	3.7.2 coral reef health/extent	0.28	16.69	4.67
84	5.1.2 magnetic field variations	0.00	18.96	0.00

Table 3.18: Measurements with Costly Gap Potential due to ten worst Data Gap lengths in "Top Ranking" Campaign (Figure 3.21) or ten worst in Data Gap Score. Data Gap Calculation is shown in Equation 2.20. Many critical Measurements now taken by Aura, Aqua, or Terra could end without a replacement until GEO-CAPE or GACM early next decade.

Analysis of the 17 measurements considered 'high risk' in terms of their potential data gaps, shown in Table 3.18, reveals that 14 have gap-year totals over 10 and that there are several groups of measurements that are linked to a single critical mission. The first three measurements of Table 3.18 are all linked to the ACE mission and represent high value measurements that will not be taken once the currently operational Aura, Aqua, and Terra missions end. Another 'high risk' group of measurements is the atmospheric chemistry group represented on Table 3.18 by CO, NO_x, CH_2O and Volcanic Aerosols, which are associated with GEO-CAPE and GACM. These will also no longer be taken once the Aura, Aqua, and Terra missions end. It can also be seen here that several measurements with large gap-year totals are considered by the CSTM to not provide any value to the Earth science community. This lack of value delivery could either be due to the Decadal Survey panels not recognizing certain measurements or simply reflects the recognition by the panels that since these measurements are less important. Either way, no weight was placed on gaps in their measurement and long gap-year totals resulted. These measurements are included here for completeness. This detailed gap analysis along with the broader view provided by Figure 3.21 show that this campaign scheduling tool points to substantial gaps in key measurements in the years to come. These gaps will not be filled using traditional space-based means given the budget situation explored previously. This framework also proves useful for the identification of potentially damaging gaps across a range of campaign architectures under changing assumptions. The insights gained from this data gap analysis motivate and inform the discussion of the role of aircraft in the Global Earth Observation System presented in Chapters 4 and 5.

3.4. Conclusion

This chapter presented a multi-objective genetic algorithm (GA) to solve the Global Earth Observation System (GEOS) scheduling problem under campaign budget, mission cost, and technology readiness assumptions. Pareto optimal campaign architectures were generated using "Data Value" and "Data Gap" as metrics. These campaign architectures show that serious measurement gaps are going to occur unless other observation platforms are considered for gathering data.

Results for a baseline case are presented in section 3.1 that show that the logic of the Decadal Survey can be recreated so that the 17 recommended missions fit into the 'Tier' structure originally envisioned for the 2010-2020 manifests. Statistical analysis of Pareto optimal results shows how the 'Tier' structure can be broken to improve either data value or data gap and where key technology investments can move certain missions forward in the campaign to increase the performance of the system. Given recent events effecting the U.S. Earth science satellite environment an updated scenario was analyzed. New cost estimates were added to a realistic budget outlook to produce a campaign architecture that can fit into current plans. Section 3.2 presents a case for substantially rethinking the GEOS mission architecture in light of the low value delivery and worse data gap observed when the campaign is stretched out over 25 years. Again, through statistical analysis of the Pareto optimal set of campaign architectures, the flexibility of the campaign to changes in mission order was shown and missions were identified that could add more value to the system through early technology development. This chapter motivates looking into NASA's future ability to close large gaps in key measurements that are foreseeable given the current age of operational missions.

Limitations and Future Work

There are ways this GA model can be improved to better reflect the reality of satellite development and better represent the current and near-term budgetary and cost inputs. Below are four key improvements for the GA model that could produce more realistic results.

- The model presented in Chapter 2 and Chapter 3 is both deterministic and simple in terms of campaign budget and mission costs but neglects some aspects of the real problem. Future work could focus on generating more realistic budget conditions in conjunction with NASA personnel. The same is true for the mission cost figures, which are outdated and would require a more detailed analysis with the use of a real cost estimating model. The cost penalty associated with TRL launch date break could be informed by real development projects and mission specific technology costs.
- As was noted in section 2.3.3, the weighting of measurement gaps should be done using a more realistic assessment of the scientific benefit of each measurement. The Essential Climate Variables outlined in Table 2.8 could inform a consensus of the importance of data gap to each measurement for different communities, which could lead to a more informative "Data Gap" metric.
- Section 2.3.2 noted the desire to develop missions in parallel rather than in series.

- Work by Selva has been done in the area of optimizing instrument packaging to more effectively allocate resources by launching a subset of instruments on platforms of varying size. This area should be explored more and done in conjunction with the development of the model presented here so that the two can eventually be integrated.

Building on section 3.3, in which a case was laid out for the inclusion of non-space-based platforms in the Global Earth Observation System model, chapter 4 explores the ways that NASA is currently using aircraft to gather Earth Science data. This includes discussions of specific programs, such as the first round of Earth Venture missions, and 3 case studies to look at distinct spatial and temporal observation environments.

4. Aircraft for Earth Observation

This chapter explores NASA's airborne capability by conducting three case studies that represent the three fundamental modes of operation for aircraft in the future integrated Global Earth Observation System (GEOS). A satellite-only view of the GEOS, as explored in Chapter 3, is not sufficiently comprehensive to show how NASA and international partners can deliver the most benefit to the science community. The satellites currently gathering Earth Science data are ageing and their replacements continue to be descoped or experience schedule slip. This thesis studies the options to fill the critical gaps in the GEOS capability exposed in chapter 3 with airborne observational platforms. The Decadal Survey made this recommendation in its final report:

"To facilitate the synthesis of scientific data and discovery into coherent and timely information for end users, NASA should support Earth science research via suborbital platforms: airborne programs, which have suffered substantial diminution, should be restored, and unmanned aerial vehicle technology should be increasingly factored into the nation's strategic plan for Earth science" (Committee on Earth Science and Applications 2007)

This thesis recognizes the need to think systematically about integrating aircraft into the larger GEOS. Aircraft are often seen as cheap missions to develop technology or as gap fillers that fly until a spacecraft is ready to take over. This is beginning to change as NASA and NOAA have made a concerted effort in the past decade to bring aircraft into mainstream Earth observation program. Section 4.1 introduces the current capability maintained by NASA's Airborne Science Program (ASP) and describes the impact the Decadal Survey has had on suborbital platforms. As a direct result of recommendations made in the Decadal Survey, the Earth Ventures program was established and will begin flying missions in the summer of 2011.

A survey of available literature on aircraft Earth science missions reveals that there are at least three (3) fundamental modes of operation for aircraft in the future integrated GEOS: sustained regional campaigns, local opportunity driven missions, and global in-situ data collection. By examining these three modes of operation through case studies in sections 4.2 through 4.4, a broad view is taken of the issues and opportunities associated with airborne observational platforms. This chapter concludes by using the case studies to formulate a discussion of the comparative advantages and disadvantages of suborbital platforms in scientific and programmatic terms. This leads to chapter 5, in which an integrated model is used to assess the value delivered to the 'Climate' community using both aircraft and spacecraft in the coming decade.

4.1. Airborne Science Introduction

This introduction section familiarizes the reader with the current state of NASA's aircraft fleet and show ways that the Decadal Survey has had an impact on airborne Earth science. Satellites have come to dominate the GEOS with clear advantages in coverage and campaign life time, however aircraft still play a critical role in Earth observation. The Decadal Survey recommended that aircraft should play a larger role in the future of the GEOS, but no specific plan was formulated. This general sentiment of the committee members reflects a broader feeling among Earth scientist that aircraft are necessary to achieve high levels of scientific performance. The recommendation made the by committee to expand the role aircraft play in the future GEOS has been implemented through the Earth Venture program.

ESSP Earth Venture

The largest impact the Decadal Survey has had on the airborne Earth science program was to propose the introduction of a competitively selected and well defined Earth science mission campaign. NASA's Earth System Science Pathfinder (ESSP) program within the ESD was tasked with implementing the Decadal Survey's recommendation for a series of low-cost, innovative suborbital missions. The first round of solicitations, Earth Venture-1 was announced in 2009 stating, "This Earth Venture-1 program element solicits proposals for complete suborbital, principal investigator-led investigations to conduct innovative, integrated, hypothesis or scientific question driven approaches to pressing Earth system science issues." (NASA ESSP 2009) The solicitation also lists four characteristics that all selections must share, and reflect a general notion of how aircraft can be leveraged for Earth Science:

- **Sustained, science-based data acquisition**
  - *NASA Definition*: The investigations must advance Earth system science objectives through temporally sustained regional or larger-scale measurements sufficient and necessary to prove/disprove a scientific hypothesis or address scientific questions.
  - This characteristic specifically calls for regional or larger campaigns because that's the geographic scale for which airborne platforms are most well suited. This is in contrast to space-based platforms, which in most cases (in LEO) provide global coverage even if the area of interest is not global. Satellites continue to operate as long as in orbit and functioning properly, while aircraft campaigns must be sustained either through programmatic/science requirements or advocacy within the agency. This means that the ability to sustain an airborne mission is a concerted effort on the part of managers and scientists.
- **Mature technology**
  - *NASA Definition*: The investigations must use mature system technology where, at a minimum, there has been a system/subsystem model or prototype demonstration in a relevant environment (Technology Readiness Level (TRL) of 6 or greater).
  - While aircraft provide a great platform for technology development, this requirement presents the objective of cost reduction. By focusing on mature technology, the EV program is trading off gaining technological advances for cost/risk reduction.
- **Competitive selection**
  - *NASA Definition*: The investigations are selected in an open competition to ensure broad community involvement and encourage innovative approaches.
  - While spacecraft missions are also competitively selected, the degree of competition displayed in EV-1 is much higher due to the low cost and quick cycle times. Airborne platforms also open the competition to a broader community since many groups have the ability to develop an aircraft instrument but not a more expensive space-based one. By receiving many more proposals then they could possibly fund, ESSP was able to pick the most valuable missions. They were also able to assure those not selected that they would have another chance in the next round.
- **Cost and schedule constraints**
  - *NASA Definition*: Each suborbital Venture-class investigation must have a life cycle of less than or equal to 5 years and the total investigation cost cannot to exceed $30 million.

- This is to limit cost and schedule slip of EV-1 missions. After the recent proliferation of cost overruns and schedule slips, there is an effort to reign in this problem. It also shows that 2-4 years worth of science can be accomplished for less than $6M a year. This is a small fraction of the cost for the equivalent time in a satellite, however for a much different product.

The 5 selections were announced in May 2010 spanning a range of measurements and aircraft shown in Table 4.1. It is important to note that of the 5 selections; only one PI is from academia with the other 4 PI's spread around 4 separate NASA centers. The 5 missions also utilize 5 different aircraft, all of which are NASA owned and operated. (BD Allen, Braun, et al. 2010)

Mission	Acronym	Measurement	PI	Aircraft	Flight
Airborne Microwave Observatory of Subcanopy and Subsurface	AirMOSS	Root zone soil moisture at 100m resolution, sub-weekly, seasonal, and annual time scales.	Mahta Modhaddam, University of Michigan	DFRC Gulfstream-III	Spring-Fall campaigns in Canada, Central-Eastern US, Western US, and Central America sequentially for 3 years
Airborne Tropical TRopopause Experiment	ATTREX	Movement of halogen-containing compounds, stratospheric ozone, the size and shape of cloud particles, water vapor, and winds through the Tropical Tropopause Layer.	Eric Jensen, NASA Ames	Global Hawk UAS	24-28 hour flights from DFRC, Guam, Hawaii, and Darwin over 2 years
Carbon in Arctic Reservoirs Vulnerability Experiment	CARVE	Soil moisture, freeze/thaw state, surface temperature, and atmospheric columns of CO_2, CH_4 and CO on Artic-region scales with seasonal resolution	Charles Miller, NASA JPL	DHC-6 Twin Otter	Spring-Fall campaigns from Fairbanks, AK for 3 years
Deriving Information on Surface Conditions from Column and VERtically Resolved Observations Relevant to Air Quality	DISCOVER-AQ	Column-integrated, surface, and vertically-resolved distributions of aerosols and trace gases relevant to air quality as they evolve throughout the day	James Crawford, NASA Langley	NASA P-3B, B200	30-day deployments over Baltimore-DC, Houston, Sacramento, and a TBD city over 4 year period

Hurricane and Severe Storm Sentinel	HS3	Measurements associated with clouds, wind and precipitation	Scott Braun, NASA Goddard	Global Hawk UAS	Ten 30-hour sorties over each of three one-month deployments from Wallops, VA

Table 4.1: Earth Venture-1 Selections announced May 2010, 5 campaigns selected cover a wide range of science, observational platforms, and knowledge centers. (BD Allen, Braun, et al. 2010)

The nature of these aircraft missions forced the ESSP to rethink the way in which these missions are managed. In a conference paper written by several members of the ESSP they stated,

"Traditional orbital procedures, processes and standards used to manage previous ESSP missions, while effective, are disproportionally comprehensive for suborbital missions. Conversely, existing airborne practices are primarily intended for smaller, temporally shorter investigations, and traditionally managed directly by a program scientist as opposed to a program office such as ESSP." (BD Allen, Denkins, et al. 2010)

The resulting management structure is a hybrid between the front loaded, risk adverse satellite plan and the one time, customized aircraft plan. EV-1 missions will span multiple years and like satellite missions they must be relatively sure of success at the start. Like an aircraft mission however, they have the ability to modify and fix mistakes along the way. This leads to a cyclic structure where after every deployment, a reevaluation is performed to see what areas can be improved and/or fixed. It also means that there is less upfront risk reduction making it possible for the missions to start on a tight schedule. Depending on the success of the EV-1 missions, this may serve as a model for future larger scale aircraft campaigns.

The first round of Earth Ventures shows that NASA is advancing ideas put forward in the Decadal Survey and paving the way for future airborne operational Earth science. The program builds on key advantages aircraft have over spacecraft, namely, the ability to accomplish iterative science inexpensively. NASA has the potential to accomplish much more in the future with its comprehensive fleet of aircraft, introduced in this chapter.

Current NASA Aircraft Fleet

NASA currently has the capability to perform Earth science from more than 12 aircraft it owns and operates. Each of these aircraft has the ability to be tasked on a month to month basis and carry a variety of payloads. NASA maintains this set of aircraft with large fixed acquisition costs already paid so that science teams only pay for integration and hourly operation. This fleet is run through the Airborne Science Program (ASP), which is part of the Science Mission Directorate (SMD). Table 4.2 lists the aircraft that are useful in this study due to their payload capacity, range, and utility in observation missions.

Platform	Flight Altitude (ft)	Flight Range (nm)	Flight Speed (kts)	Endurance (hrs)	Payload (lbs)	Engines	Flight Cost ($/hr)	Location
DC-8	1,000-42,000	5,400	450	12	30,000	4 Jet	6,500	DFRC
P-3B	500-30,000	3,800	330	12	16,000	4 Turbo Prop	3,500	WFF
WB-57	60,000	2,500	410	6.5	6,000	2 Jet	3,500	JSC
Twin Otter	25,000	500	160	7	5,000	2 Turbo Prop	---	WFF
ER-2	>70000	>5,000	410	12	2,900	2 Jet	3,700	DFRC
Gulfstream-III	45,000	3,400	459	7	2,610	2 Jet	2,500	DFRC
B200	500-32,000	1,800	250	6.75	2,000	2 Turbo Prop	2,000	WFF
Ikhana (Predator B)	500-40,000	3,500	171	24	2,000	1 Turbo Prop	3,500	DFRC
Global Hawk	65,000	11,000	335	31	1,500	1 Jet	3,502	DFRC

Table 4.2: Current NASA-Owned Fleet of Aircraft used for Earth Science arranged by Payload Capacity. This set of aircraft will be described in detail throughout this chapter as their role in airborne missions is explored. (Airborne Science Program 2011)

The observational platforms listed in Table 4.2 provide NASA a comprehensive set of aircraft to accomplish a wide range of Earth science missions. The DC-8 is an older aircraft that NASA has modified to carry a number of instruments with investigators on board. The benefit of this large platform is it can easily accommodate instruments and equipment that have not been miniaturized from lab set-ups and that require human operation. This allows for relatively immature instruments to fly in a pressurized compartment with the ability for their operators to be collocated and perform adjustments mid-flight. On the other end of the spectrum is the Global Hawk, which as an unmanned platform requires instruments to be smaller, use less power, and work in an unpressurized environment at an altitude of 70,000 feet. Instruments flying on the Global Hawk must also operate autonomously and subject to stricter requirements for integration onto a modern and expensive aircraft. The fleet of aircraft is professionally maintained and supported by ASP staff.

Case Studies and Methodology

A common methodology is used to examine three modes of operations for these airborne platforms through case studies. These three modes of operation are: sustained regional campaigns, local opportunity driven missions, and global in-situ data collection. The goal is to gain a broad view of the issues and opportunities associated with airborne platforms so that generalizations can be made to facilitate the integration of suborbital and space-based operations in campaign architectures. Each case study introduces the mode of operation, describes the platforms and the payloads of one or more missions, discusses the mission's concept of operation, and draws specific conclusions.

More specifically, an introduction to each mission includes the notional mode of operation for which each was selected and how it exemplifies a way that airborne platforms can add unique capabilities to the GEOS. Each mission is introduced in particular to show why it was created and how it fits the case study description. The platforms and payloads participating in the mission are described in detail to gain an understanding of the aircraft and the science it accomplishes. For each mission, a concept of operations is examined in an effort to set aircraft apart from their space based counterparts. These mission analyses highlight the exceptional role NASA's aircraft play or could play in the future GEOS. Specific conclusions are drawn from each case study and the combination of all three lead to general conclusions at the end of the chapter.

4.2. Case Study 1: Sustained Regional Campaigns

The first case study looks at two examples of missions that operationally gather data over large regions for multiple years. Both Operation Ice Bridge (OIB) and the Airborne Robotic Radar Greenland Observing System (ARRGOS) propose to study water, ice and the regional balance between them. On a regional scale, the location and movement of ice sheets and sea ice contributes to population issues and industrial operations. From a scientific perspective, ice formation, melting, and movement constitute an ongoing field of research that may hold keys to better understanding Earth's climate and water cycle.

OIB fills the gap between the now de-orbited ICESat satellite mission and its replacement, the Decadal Survey 'Tier 1' ICESat-II. Section 4.2 shows that the instruments flying on OIB's fleet of aircraft contribute to a more detailed understanding of both the Greenland and Antarctic ice systems. ARRGOS is a proposal aimed at operational snow and ice measurements over Greenland using an Optionally Piloted Vehicle (OPV). ARRGOS represents the future application of unmanned technology to operational Earth observation in its duration and scope. By examining these examples of airborne campaigns across regional areas of interest, key insights are gained into the larger comparison between aircraft and spacecraft.

4.2.1. Operation Ice Bridge (OIB): Introduction

The first example in this case study is Operation Ice Bridge (OIB), a 6+ year mission to fill the gap between the ICESat and ICESat-II satellite missions. NASA's ICESat mission was launched on January 12, 2003 as the first satellite mission dedicated to measuring ice-related variables. (Abdalati et al. 2010) ICESat carried the Geoscience Laser Altimeter (GLAS) instrument, which contained three 1064 nm Nd-YAG lasers designed for a 5 year mission. The system was engineered so that one laser would be used at a time, thus if one failed the 2nd, and then 3rd, could be turned on to continue the mission. After 37 days of operation the first laser failed pre-maturely and the mission switched from a continuous observation mode to a more conservative campaign mode. The science team decided to scale back the measurement schedule as it was determined that the first laser failed because of a peak power problem. This allowed the second laser to operate in less risky power conditions while gathering as much scientifically relevant data as possible. (Abdalati et al. 2010) The 3rd laser stopped firing in 2009 and plans to fill the measurement gap between ICESat and ICESat-II began. As of August 17, 2010 ICESat has been decommissioned and will begin to reenter the atmosphere after 15 de-orbit burns. (NASA GSFC 2010)

ICESat has made so many contributions to Earth science despite its altered mission, plans for a second ICESat mission were part of the Decadal Survey (RFI 111). (Committee on Earth Science and Applications 2007) ICESat-II is currently being funded and plans are for an early 2016 launch. Based on lesson learned from ICESat, one of the major modifications is a change to the instrumentation from a single beam laser to a micro-pulse, multi-beam, photon-counting laser. This allows for a lower power laser to more accurately measure surface features like slopes at higher spatial resolutions. (Mclennan 2010) Figure 4.1 shows the ground tracks for ICESat and ICESat-II over Jacobshavn Glacier in western

Greenland. It is important to note that because of ICESat's scaled back mission, it was only able to capture 1/3 of the ground tracks shown in panel (a).

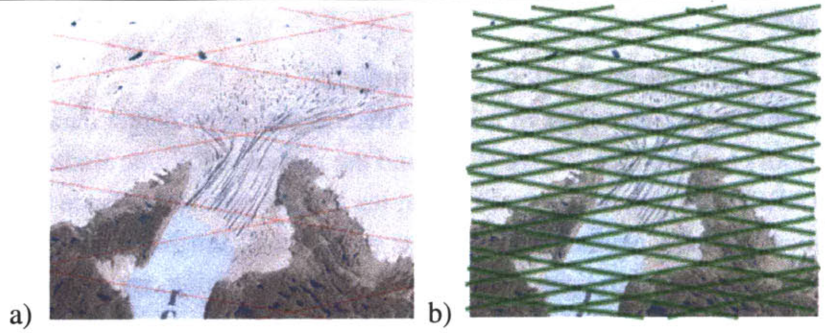


Figure 4.1: Planned ICESat (panel a) and planned ICESat-II (panel b) ground tracks over Jacobshavn Glacier in Western Greenland (T. Markus 2010) **ICESat-II is able to cover more ground with higher accuracy due to its more advanced multi-beam laser, which was designed to combat peak power issues that led to ICESat's premature failure.**

There is going to be at least a 7 year gap between ICESat and ICESat-II. In 2008 a study was commissioned to investigate the effectiveness of an aircraft gap-filler. (Fladeland and Martin 2009) The report issued in January 2009 led to the creation of NASA's Operation Ice Bridge, which has been flying missions over both poles for almost 3 years now. OIB is primarily designed to mimic the campaign-mode being flown by ICESat, conducting operations during the Northern Hemisphere Fall in Antarctica and in the Northern Hemisphere Spring in Greenland. To do this, OIB uses multiple airborne platforms at different stages in the 6 year campaign carrying an array of ice measuring instruments.

Ice Bridge has two main scientific objectives:

1. Provide surface elevation data now that the ICESat-1 mission has ended, focused on areas undergoing rapid change that are critical to characterizing select areas of sea ice and modeling the processes that determine the mass balance of the terrestrial ice sheets. Due to the non-linear, time variable changes that these areas undergo, repeated monitoring is required. IceBridge also allows more detailed studies over these smaller areas. (NASA 2011b)

2. Support complementary measurements critical to ice models such as bed topography, grounding line position, and ice and snow thickness. These parameters cannot be accurately measured by satellite, but can be measured from aircraft. They are significant unknowns in understanding the ice and developing predictive models of sea level rise in response to climate change.(NASA 2011b)

These objectives state clearly that OIB's mission is to fill this critical gap both in measurements taken during ICESat and in understanding general ice dynamics. The report titled, "An Analysis and Summary of Options for Collecting ICESat-like data from Aircraft through 2014" outlines the gaps that should be filled in the 2009-2014 timeframe with 2-3 options to accomplish that mission. (Fladeland and Martin 2009) Table 4.3 lists 5 areas of interest indentified by cryospheric scientists where measurements from aircraft could have significant impact in the field. Scientists are able to split a global mission (ICESat) into distinct regional ones and in the process gain measurement precision and the ability to explore new areas in detail.

Area of Interest	Science Priority	Features
Greenland	Glacial Outlets along Northwest and Southeast coasts	Bases in either Thule, Greenland or Iceland from which to launch long endurance aircraft
Arctic and Antarctic Sea Ice	Sea Ice thickness and inter-annual variability, ice mass balance	Requires extended missions over long distances
Coastal Antarctica	Coastal Glacial outlets along Antarctic Peninsula and Amundsen Sea	Base in Punta Arenas, Chile to reach Peninsula and South Pole
Antarctic Sub-Glacial Lakes and Interior Features	Water under large glaciers should be observed twice per year along ICESat lines	Requires long endurance aircraft to reach interior
Southeast Alaska Glaciers	Yakutat Icefield, Bering/Bragley and Malaspina/Seward Glaciers and Hubbard Glacier are all changing rapidly	Many bases from which to launch close to areas of interest, known missions for NASA teams.

Table 4.3: Regions of Interest and Science Requirements for ICESat Continuity show that when forced to narrow science requirements, the snow/ice mission can be accomplished with sustained regional campaigns to the Arctic and Antarctic in opposite seasons. (Fladeland and Martin 2009)

The scientific priorities shown in Table 4.3 are not exhaustive but it represent areas that scientists believe aircraft are well suited. By design ICESat took measurements all along its orbit even though certain regions are of particular importance. This continuous stream of data from ICESat was used to measure things for which it was not necessarily designed. For example, forest cover and vegetation height were measured. These secondary measurements, while valuable were not considered in this report. These 5 areas are also interesting because they are not necessarily mutually exclusive but can be grouped into larger regions to be explored. All of the Arctic areas (Greenland, Sea Ice, and Alaska) can be measured during the same campaign as can all of the Antarctic areas. This means that platform and instrument selections are not only a matter of schedule and cost but also range and the ability to reach multiple areas of interest. Due to the relatively quick reaction time necessary to go from campaign definition to data collection, mature instruments are given priority as seen in the following section.

4.2.2. OIB Observational platforms and Payloads

NASA's Operation Ice Bridge (OIB) uses 4 different aircraft platforms carrying at least 7 instruments to fill the gaps in measurements associated with ICESat and ICESat-II. Over the course of a year, OIB uses 7 mature instruments during two separate two month missions in the Arctic and Antarctic involving over 50 scientists from NASA, NOAA and academia. This section explores the observational platforms and instruments to fill these critical gaps in ice and water measurements along with the impact they have had. Figure 4.2 shows the two main aircraft that will be used for the majority of OIB; the DC-8 and P-3B.

Figure 4.2: DC-8 (left) and P-3B (right) are two of the four observational platforms used in Operation Ice Bridge. They contribute substantially to the NASA fleet because as manned aircraft with flight heritage, they can easily accommodate new instruments and the passengers to run them in real-time.

NASA's DC-8 can carry an array of instruments as well as the personnel to run them onboard, which makes it well suited for initial deployment and instrument testing. The P-3B acts as slower and lower flying counterpart perfect for the shorter missions in Greenland. The DC-8 with its extended range, has been used primarily in Antarctica where missions are launched from Chile and in Greenland during long flights over sea ice. In addition to the aircraft shown above, the Global Hawk and B-200 will be used at various point in the campaign. Currently, the B-200 is flying the LVIS instrument over the glaciers in Greenland. Table 4.4 lists the instruments flying in OIB and describes the measurements they take.

Instrument	Short Name	Type	Measurements	Platform	Notes
Airborne Topographic Mapper	ATM	Scanning LIDAR	2.2.2 Hi-Res Topography 4.1.2 Glacier Surface Elevation 4.1.5 Ice Sheet Topography 4.3.2 Sea Ice Cover	DC-8 P-3B	WFF, Flying over Greenland since 1993, <1,500 ft AGL Source: (Brock et al. 2002)
Laser Vegetation Imaging Sensor	LVIS	Laser Altimeter	2.2.2 Hi-Res Topography 2.2.1 Surface Deformation 2.4.1 Vegetation Type and Structure 2.4.3 Vegetation Height 2.7.1 River and Lake Elevation 4.3.2 Sea Ice Cover 4.1.5 Ice Sheet Topography 2.4.4 canopy density	DC-8 P-3B B-200	GSFC, >30,000 ft AGL Source: (Blair 1999)
Multichannel Coherent Radar Depth Sounds	MCoRDS	Radar Altimeter	4.1.1 Ice Sheet Volume 4.1.5 Ice Sheet Topography 4.1.2 Glacier Surface Elevation 4.1.4 Ice Sheet Velocity 4.1.3 Glacier Mass Balance	DC-8 P-3B	KU CReSIS, Measures bedrock elevation, ice thickness, and internal layering Source: (Shi et al. 2010)
Snow Radar	--	Radar Altimeter	4.2.4 Snow Cover 4.2.2 Snow Depth	DC-8 P-3B	KU CReSIS, Snow thickness for sea ice and glaciers Source: (Center for Remote Sensing of Ice Sheets 2011)
Ku-Band Radar	--	Radar Altimeter	3.2.1 Sea Level Height 4.3.1 Sea Ice Thickness 4.2.2 Snow Depth 4.1.1 Ice Sheet Volume	DC-8 P-3B	KU CReSIS, sea ice and ice sheets elevation, sea surface height Source: (Center for Remote Sensing of Ice Sheets 2011)
Gravimeter	--	Gravimeter	5.1.1 Gravity Field Variations	DC-8	Columbia SDL/LDEO, Differentiate rock, ice, water Source: (Bell, Childers, and Arko)
Digital Mapping System	DMS	Camera System	4.3.2 Sea Ice Cover 2.6.1 Land Use	DC-8	NASA ARC, 1/10Hz nadir pointing

Table 4.4: The 7 Instruments used in Operation Ice Bridge to collect data specific to understanding ice dynamics. These instruments will continue to collect data until at least 2014.

Based on reports online and in publications, Ice Bridge is fulfilling its mission to take measurements associated with ICESat and ICESat-II. The ATM instrument flying on the DC-8 and P-3B is gathering high quality topography data over Greenland and Antarctic glaciers and ice sheets to help scientist better understand those freshwater sources of sea level rise. WFF's LVIS instrument is generating large amounts of altimetry data especially over sea ice areas to better predict the disappearance of Arctic sea ice both around Greenland and Alaska. The KU CReSIS set of snow/ice penetrating radars is actually taking a measurement not possible with ICESat or ICESat-II. The information on bedrock and snow layers is unique to OIB because both ICESat missions carry LIDAR, which is not capable of penetrating ice layers. OIB has also been able to calibrate and validate ICESat and ESA's CryoSat measurements by flying the same ground tracks. These flights represent satellites and aircraft working together to gather more useful and ultimately higher quality data. The next sub-section explores the concept of operations required to accomplish OIB's goals.

4.2.3. OIB Concept of Operations

A description of a typical OIB concept of operations highlights be important differences between aircraft and satellite operations. OIB officially began in the fall of 2009 with NASA's DC-8 flying a two month mission over Antarctica carrying a suite of laser altimeters, radar sounders, gravimeters, and cameras. The campaign continues today as the "Greenland 2011" mission flies NASA's P-3B and B-200 over glaciers in Greenland and the sea ice of the Arctic Ocean. The flight plan presented here is representative of a typical mission because it uses the base as a starting point and then flies across the country to take racetrack-like scientific measurements. Figure 4.3 shows the view from Google Earth overlaid with data from OIB's ATM instrument. (NASA GSFC/WFF 2011)

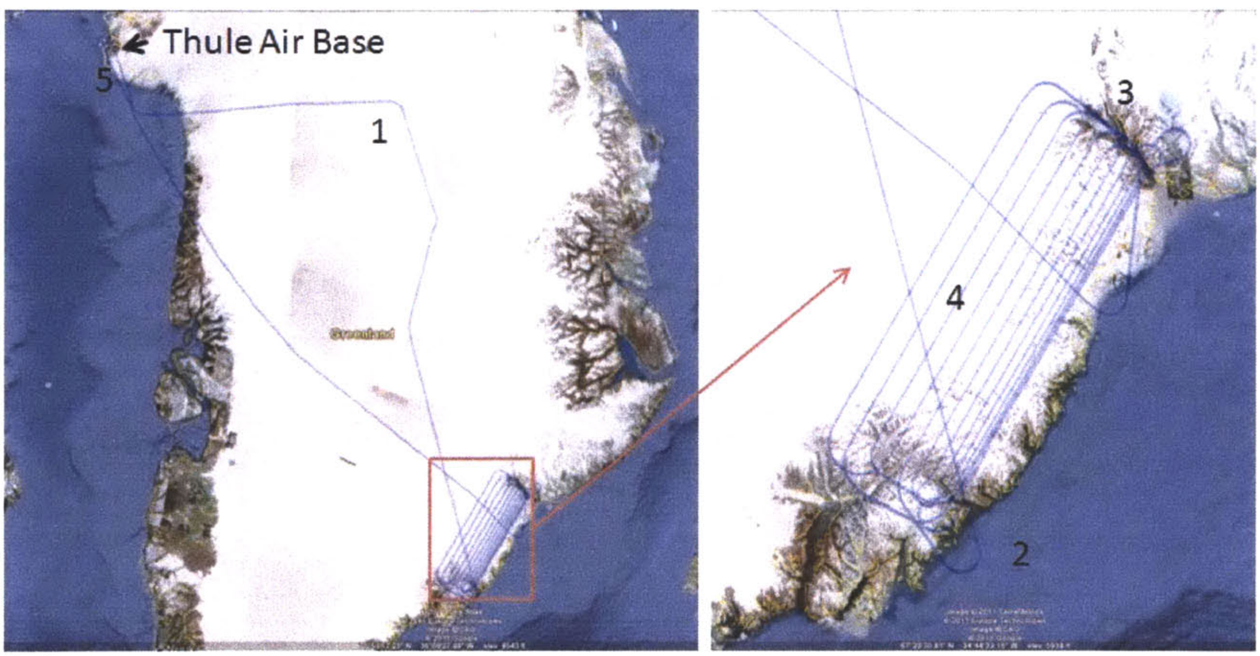


Figure 4.3: Flight from Thule Air Base to Southeastern Greenland glaciers for LVIS Science flight. The P-3B traverses Greenland (Left) and flies a racetrack pattern over the Area of Interest (Right) on the Southeastern Glacier front. (NASA GSFC/WFF 2011)

The mission is designed to use the LVIS instrument over one of Greenland's coastal glaciers in order to retrieve precise topography and velocity data. Table 4.5 describes the mission in detail with leg distances and point locations, which correspond to points on the map above.

Altitude:	24,000 ft	Range:	5,143 mi	
Base:	**Thule Air Base**	**Leg Distance**	**Total Distance**	**Description**
Point 1	Central Greenland	537	-	Climb out, check out instruments, secondary science objectives related to central glaciers
Point 2	Southeastern Glaciers	780	1,317	Transit to Area of Interest for LVIS Science Flight, Enter racetrack pattern
Point 3	First Track	235	1,552	Racetrack pattern over glacier, track spacing decreases as path gets closer to the coast
Point 4	13 Tracks Complete	2,523	4,075	Tracks complete, Aircraft turns to return to Thule
Point 5	Land at Thule	1,068	5,143	Route back to Thule is directly over center of the Island

Table 4.5: Mission Description for flight path shown in Figure 4.3. Flight is part of Operation Ice Bridge's Spring 2010 campaign in Greenland. P-3B is carrying ATM and LVIS stationed out of Thule Air Base on March 14th, 2010.

The mission begins at Thule Air Base (a current United States Air Force base) and climbs out over the interior of the country. The P-3B cruises at 24,000 feet for the entire flight, which is the preferred operating altitude of the LVIS instrument. Once over the area of interest in southeastern Greenland, the aircraft turns to perform racetrack patterns flying over 2,500 miles. These racetrack patterns are characteristic of glacial mapping flights, as seen in point 4, because they traverse the region in straight lines (GPS navigated) and bunch closer near the coast. This bunching is done to measure the speed of the glacial movement, which is faster closer to the coast. The trip back to Thule in a straight line is a little over 1,000 miles and the P-3B lands with all systems functioning normally. By flying over 5,000 miles the mission is able to deploy out of a central location (Thule) and achieve high quality precise measurements over a key area of interest for scientists.

In an effort to reduce costs and increase mission frequency, some companies are proposing autonomous systems to act as platforms for Earth observation. One such company, Aurora Flight Science, responded to the Earth Venture solicitation discussed in section 4.1. The system to be examined in the next sub-section promises to reduce operating costs by an order of magnitude while accomplishing all of the major snow/ice science goals using an autonomous observational platform.

4.2.4. Aurora Flight Science's ARRGOS Introduction

This sub-section introduces Aurora Flight Sciences' (AFS) Airborne Robotic Radar Greenland Observing System (ARRGOS), a proposal for the NASA Earth Venture-1 solicitation. The goal of the project is to use an Optionally Piloted Vehicle (OPV) to carry the Pathfinder Advanced Radar Ice Sounder (PARIS) instrument built by Johns Hopkins' Applied Physics Laboratory (APL) in order to measurement ice sheet thickness and topography over the course of a three year mission. ARRGOS proposed to fly 6,000 hours of observations over Greenland glaciers using up to 3 Diamond Aircraft 42 Multi-purpose platforms (DA42M) at a cost of $25.7 million, fitting under the $30 million cap of Earth Venture Missions. (Aurora Flight Sciences 2009) ARRGOS was not selected for the first round of Earth Venture programs.

This mission architecture promises to reduce operational costs by an order of magnitude, proposing to fly for $200/hour when fully operational, while fulfilling major science objectives. ARRGOS also represents the movement towards unmanned systems for the long tedious operations that usually characterize Earth science missions. The vehicle and the radar it proposes to carry are examined in the next sub-section.

4.2.5.ARRGOS Platform and Payload

ARRGOS utilizes an OPV, which is a manned aircraft that has been modified in order to allow it to fly fully autonomously without a pilot via satellite link to a ground station. OPV's have several advantages over traditionally manned aircraft and traditional Unmanned Aerial Vehicles (UAV):

- OPV's overcome one of the current limitations of UAV's, which is that UAV's are currently restricted to special airspace. In a manned configuration OPV's can be flown in civilian airspace because a pilot can fly the aircraft under a standard Federal Aviation Authority (FAA) authorization. Current FAA regulations state that a UAV can only operate under a Certificate of Authorization (COA), which only applies to a specific time and airspace. The COA restriction makes flights across long distances within the US impossible because UAV flights are restricted to a section of airspace separate from manned aircraft.
- At the destination, a pilot can fly a route once, which the aircraft can then replicate in an unmanned configuration. Current restrictions on pilot performance and the limits of human fatigue make it impossible to fully utilize a DA42M's endurance, which can be up to 11 hours at a time and 22 hours within a 24 hour period. FAA limits on pilot endurance do not allow a human pilot to maintain that schedule.
- A fleet of OPV's requires fewer pilots for the same sortie rate because the pilot is flying fewer or none of the missions. This is especially advantageous in a remote basing situation like ARRGOS envisions where the cost of maintaining a large number of pilots and crew members would be a significant portion of the mission cost.

Figure 4.4 shows the proposed DA-42M and highlights the modifications necessary to turn this manned aircraft into an OPV. A new DA-42M costs $860,201 according to Aurora's estimate but with modifications and instrument integration, two aircraft would be delivered for a fixed cost of $3,025,300. APL estimates the instruments to have a fixed cost of $1,138,100 not including labor costs. According to Aurora's concept of operations and engineering estimates, once delivered to Greenland, the DA42M would cost $200 per flight hour to operate and maintain. This low cost represents an order of magnitude savings compared to similar manned and unmanned aircraft as shown in Table 4.2. Aurora attributes these cost savings to the DA42M's reliability and other OPV-related advantages.

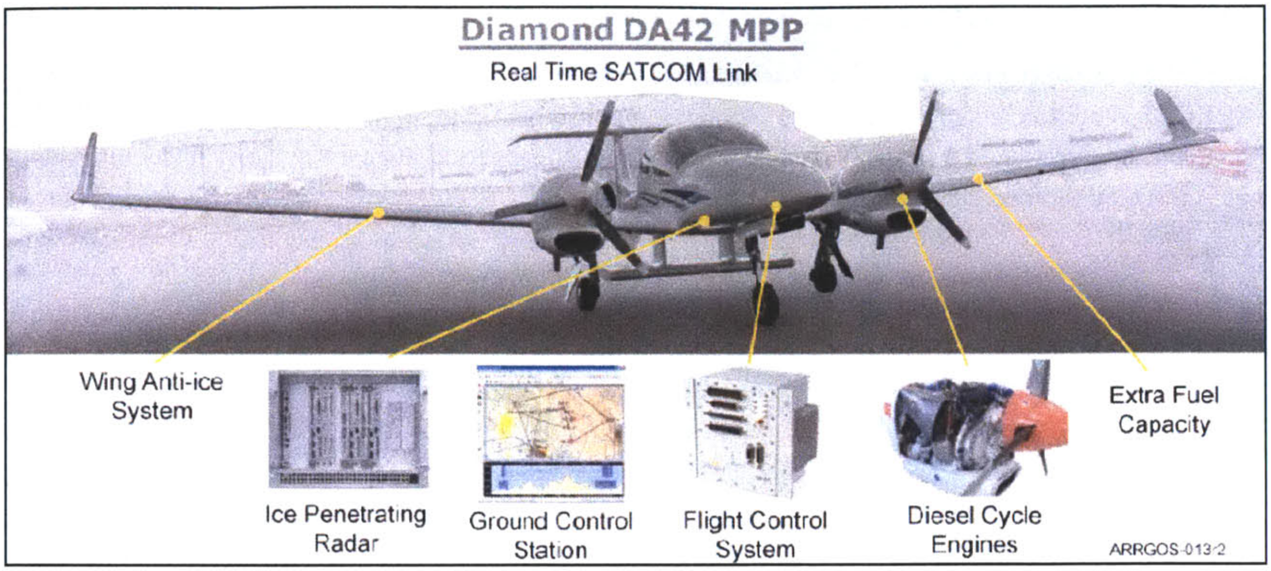


Figure 4.4: Aurora's D42MPP is a modified version of the manned DA-42 with the ability to fly autonomously. This Optionally Piloted Vehicle can carry a pilot in ferry flights on experimental missions then reconfigured to fly autonomously beyond-line-of-sight.

The DA-42M platform has a reduced payload capacity and will only carry one radar antenna. This is compared to the large P-3B and DC-8 aircraft currently used in OIB, which routinely carry 3 or 4 antennas. This advanced radar is able to capture most of the important snow/ice measurements, as seen below.

Pathfinder Advanced Radar Ice Sounder (PARIS)

The instrument proposed for this mission is APL's PARIS radar, whose specifications are seen in Table 4.6. PARIS weighs over 50kg total and requires 500W of power, less than the 840W made available through the DA42M systems.

Instrument	Short Name	Type	Measurements	Platform	Notes
Pathfinder Advanced Radar Ice Sounder	PARIS	Ice Penetrating Radar	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 4.2.2 snow depth 4.3.1 Sea ice thickness 4.3.2 Sea ice cover 4.2.4 snow cover	P3-B DA-42	Design and Developed by JHU APL, proposed as Earth Ventures 1 instrument Source: (Aurora Flight Sciences 2009)

Table 4.6: ARRGOS Instrument, Pathfinder Advanced Radar Ice Sounder (PARIS) Specifications. Radar has the ability to penetrate snow and ice in a small enough package to fit as a payload on the DA-42M.

The PARIS instrument is designed to penetrate up to 3km of ice with a 3% standard deviation on thickness measurements. The radar is comparable to the MCROSIS system currently being flown in OIB. In fact, PARIS was considered in the initial trade studies of OIB because it has been used to measure ice and snow over Greenland in the past.

4.2.6.ARRGOS Concept of Operations

ARRGOS is considered an operational mission because it proposes to stay in Greenland year round to complete its objective of flying 6,000 flight hours over a 3 year period. Figure 4.5 shows the composite of the science mission possible using an OPV platform.

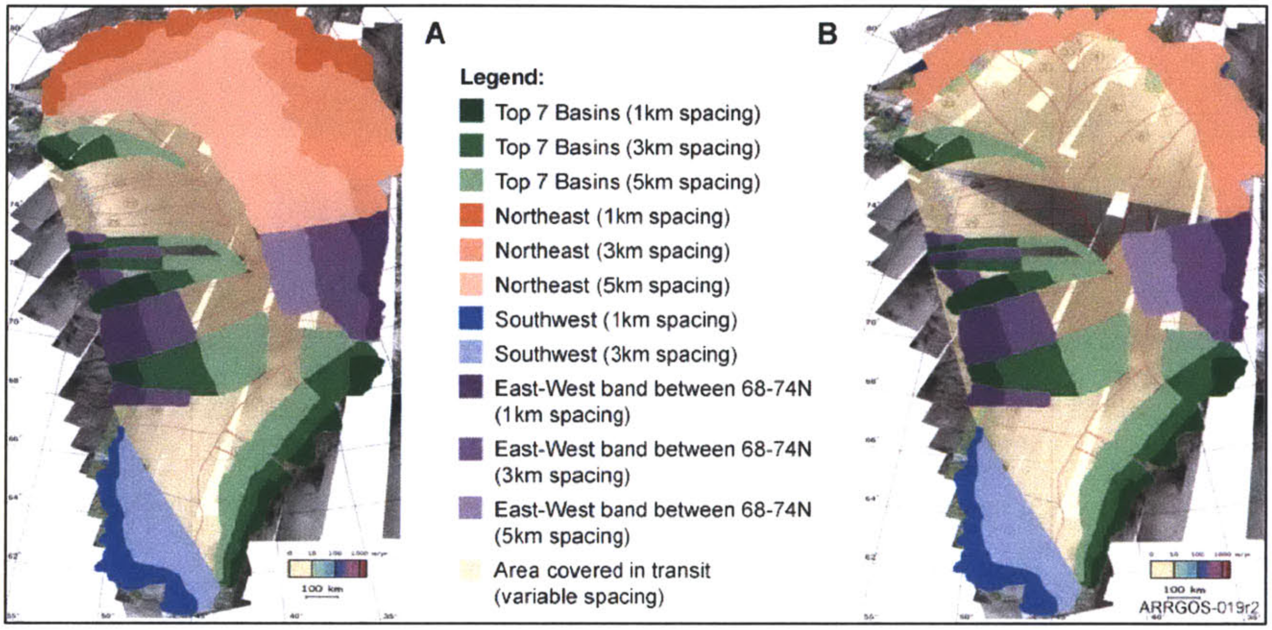


Figure 4.5: Panel A: 3-year composite of science coverage and track spacing. Panel B: Science Floor

Panel (a) of Figure 4.5 shows the best case scenario for data collection over Greenland. The darker colors represent 1km spacing lines similar to the race tracks shown in Figure 4.3 flown for the OIB LVIS instrument. 3km spacing is shown with a medium tone color in each of the four main areas of interest and 5km spacing reaches into the interior. These ground track spacing differences are related to the speed of the glacier at different distances from the coast. ARRGOS is able to cover most of the island over a three year period because it traverses so much of the inland area flying from bases in the south and west to areas of interest in the mid latitudes and the north. Figure 4.6 shows a typical flight profile with two aircraft flying autonomously with command and control links to satellites for beyond-line-of-sight operations.

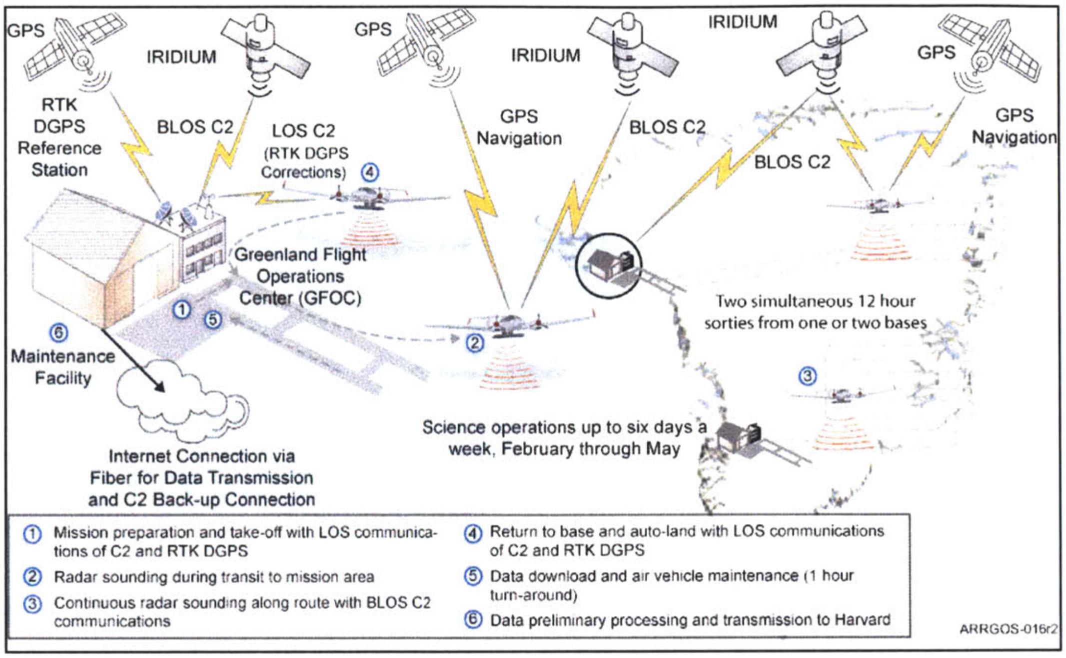


Figure 4.6: Concept of Daily Operations for ARRGOS DA-42M platform flying autonomous missions. One or two bases can support one or two aircraft flying up to 12 hour missions over areas spanning all of Greenland. Satellite relays allow for beyond-line-of-sight communications.

In addition to advancing autonomous operations for Earth Science, ARRGOS expands the current operational paradigm by seeking to fly multiple aircraft from two bases in a single mission. Figure 4.6 shows this by outlining a typical day of operations. The DA42M platform is capable of an autonomous takeoff using line-of-sight communications and differential GPS. Satellite communications provide command and control to the vehicles as they traverse the country and carry out a science mission. Minimal operator input is desired so that the two aircraft can operate simultaneously and reduce operational costs. These operations would continue 6 days a week for the high interest seasons.

4.2.7. Sustained Regional Campaign Conclusions

This case study examined sustained regional aircraft campaigns that contribute to ice/snow measurements. Since these measurements are very similar to those taken by the ICESat family of spacecraft, the two platforms can be directly compared. Table 4.7 shows the unique set of measurements taken by ICESat (I and II) and OIB, with the higher quality measurement displayed in cases of overlap.

		Coverage		Horz. Spatial Res.		Temp. Res.		Accuracy		Swath	
	Measurement	Space-Based	Airborne	Space-Based	Airborne	Space-Based	Airborne	Space-Based	Airborne	Space-Based	Airborne
Space-based Only	1.1.4 Aerosol extinction profiles	Global	-	High	-	Very Low	-	Medium	-	None	-
	1.1.6 Aerosol absorption	Global	-	High	-	Very Low	-	Medium	-	None	-
	1.5.2 Cloud type	Global	-	High	-	Very Low	-	Medium	-	None	-
	1.6.1 cloud height	Global	-	High	-	Very Low	-	Medium	-	None	-
Space-based and Airborne	2.2.2 Hi-res topography	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	None
	2.4.3 vegetation height	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	None
	2.4.4 canopy density	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	None
	4.1.1 ice sheet volume	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	Narrow-10km
	4.1.2 Glacier surface elevation	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	Narrow-10km
	4.1.3 glacier mass balance	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	Narrow-10km
	4.1.5 Ice Sheet topography	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	Narrow-10km
	4.3.1 Sea ice thickness	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	Narrow-10km
	4.3.2 Sea ice cover	Global	Most	High	Highest	Very Low	Medium	Medium	High	None	None
Airborne Only	2.2.1 surface deformation	-	Most	-	Highest	-	Medium	-	High	-	None
	2.4.1 vegetation type and structure	-	Most	-	Highest	-	Medium	-	High	-	None
	2.7.1 river and lake elevation	-	Most	-	Highest	-	Medium	-	High	-	None
	4.1.4 Ice sheet velocity	-	Most	-	Highest	-	Medium	-	High	-	Narrow-10km
	4.2.4 snow cover	-	Most	-	Highest	-	Medium	-	High	-	Narrow-10km
	4.2.2 snow depth	-	Most	-	Highest	-	Medium	-	High	-	Narrow-10km
	3.2.1 Sea level height	-	Most	-	Highest	-	Medium	-	High	-	Narrow-10km
	5.1.1 gravity field variations	-	Most	-	High	-	Medium	-	Medium	-	Narrow-10km
	2.6.1 land use	-	Most	-	Medium	-	Medium	-	Medium	-	Narrow-10km

Table 4.7: Comparison between ICESat-II and Operation Ice Bridge measurements and measurement qualities. This comparison shows measurements that are taken by space-based platforms only, measurements that are taken by both space-based and airborne platforms, and

measurement taken from aircraft only.

The specific differences in Table 4.7 are representative of more general differences between spacecraft and aircraft. In all cases, the coverage of satellites is global whereas the coverage of aircraft is of "most of the area of interest". Spacecraft have the distinct advantage of being able to take global measurements, which provides utility to more stakeholders. While missions are directed by a few scientists, the data is available to the general community and different groups find different uses for it. Another key difference occurs in horizontal spatial resolution and accuracy. Low altitude observational platforms deliver more precise measurements and allow for the operation of snow and ice penetrating radar. Ice-penetrating radar instruments cannot operate from space due to peak power constraints. Satellites can carry LIDAR, but certain measurements remain airborne-only. Temporal resolution is also different between platforms. A space-based instrument with a narrow swath will overfly the same location infrequently whereas an airborne mission is able to tailor its flight profile and can fly over a site of interest as often as necessary.

Some other conclusions from this case study include general observations. With current technology aircraft campaigns are generally less expensive than large space missions. While satellite missions cost on the order of $500M, an aircraft campaign may be only $10M. Airborne campaigns have the potential to save costs in the long run as integration is the key cost driver and systems can be prepackaged for future missions. These benefits will increase as autonomous platform technology is advanced. Ice related missions will exploit the autonomous aircraft and be able to operate with remote deployments and repeated flights. The second case study examines an area where new technology is being used to exploit some of the advantages of airborne observations.

4.3. Case Study 2: Local Opportunity-driven Missions

The second case study examines missions that are driven by specific local scientific opportunities that arise in the Earth Science field. This category of Earth science studies is particularly important in the discussion of airborne platforms for several reasons. The first is that events with high importance on a local level, such as air pollution over a city or remote region, do not require the global coverage provided by satellites. These local cases often only benefit a few stakeholders so that the low cost nature of aircraft platforms can make the science value obtainable. The second reason airborne platforms are interesting in these situations is that events, such as disaster monitoring, often require many resources for a short period of time. A satellite mission currently requires years of development and testing before it is ready for launch, while an aircraft platform can be outfitted with instruments and tested several times in the timeframe of weeks and months.

Section 4.3 introduces the Global Hawk Pacific Mission (GLOPAC), which is a campaign aimed at better understanding the aerosol-cloud forcing problem over the Pacific Ocean and testing new instruments for Earth observation. The Genesis and Rapid Intensification Processes (GRIP) mission is exploring rapidly forming hurricanes and tropical storms over the Atlantic Ocean using a suite of airborne platforms. Both of the missions described in this case study use the Global Hawk UAS.

The Global Hawk Unmanned Aerial System

Both examples in this case study use the Global Hawk Unmanned Aerial System (UAS), a vehicle that has the potential to improve suborbital Earth observation. The Global Hawk has been operating successfully for the US Air Force (RQ-4) since the early 2000's and more recently for the US Navy (BAMS) but NASA did not receive its first Global Hawk until 2009. NASA received two of the initial development versions of the high altitude long endurance vehicle after the Air Force decided it could no longer use them. In order to explore the impact of the Global Hawk on the Global Earth Observation System, two missions are considered in detail. The Global Hawk Pacific (GLOPAC) mission was the first operational Earth science use of the Global Hawk and was designed to gather aerosol and cloud data over the Pacific Ocean. The Genesis and Rapid Intensification Processes (GRIP) mission used a Global Hawk in conjunction with two other aircraft to gather data in the Atlantic Ocean during hurricane season in 2010. Both of these missions use the Global Hawk platform in order to understand local events with high global impact.

4.3.1. Global Hawk Pacific Mission (GLOPAC) Introduction

The first example of a local event well suited for a suborbital observational platform is the Global Hawk Pacific (GLOPAC) mission. In general terms the mission focused on gaining a better understanding of the cloud-aerosol climate forcing phenomenon, which plays a major and poorly understood role in regional weather and global climate change. The campaign was the first time one of NASA's Global Hawks had flown operational Earth science missions and thus has paved the way for further suborbital data collection. The campaign goal of covering the Pacific Ocean, as stated in the title, is ambitious for a suborbital campaign but is possible because of the unique capabilities offered by the Global Hawk platform. The campaign has three high level science objectives:

1. Validation and scientific collaboration with NASA earth-monitoring satellite missions. This is primarily the Aura satellite mission, which is discussed in sub-section 4.3.3.
2. Observations of stratospheric trace gases in the Upper Troposphere / Lower Stratosphere (UT/LS) from mid-latitudes to the tropics.
3. Measurements of dust, smoke, and pollution that cross the Pacific travelling eastward from Asia and Siberia.

These primary science objectives will be supplemented by the secondary operational objectives of demonstrating the 24+ hour flight capability of the Global Hawk, the ability to under-fly a satellite track, and the ability to over-fly another manned aircraft (NCAR GV). GLOPAC will use an extensive suite of instruments, described in sub-section 4.3.2, on missions spanning the Pacific Ocean. One example mission is explored in sub-section 4.3.3.

4.3.2. GLOPAC Platform and Payloads

The GLOPAC mission is the first operational Earth science mission for the Global Hawk UAS. Figure 4.7 shows the Global Hawk in a diagram outlining the location of all 10 of its instruments. The Global Hawk has the ability to fly for over 30 hours while carrying up to 2,000 pounds of payload distributed across the vehicle. The high altitude long endurance jet is operated via satellite communication link from Dryden Flight Research Center in southern California but soon will have the ability to be operated from a mobile ground station that the Airborne Science Program is purchasing. (Suarez)

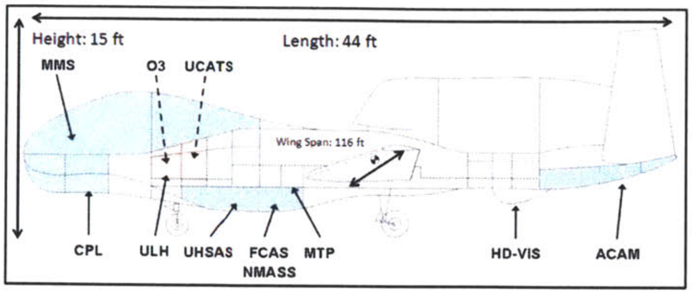


Figure 4.7: Global Hawk Unmanned Aerial System. Global Hawk can carry up to 2,000 lbs for over 30 hours at 50,000-65,000 ft with a range of 11,000 nm. The Global Hawk can fly autonomous flight plans requiring very little human oversight. (NASA ESPO 2010a)

The 10 instruments carried aboard the Global Hawk for this campaign are listed in Table 4.8 along with the type of instrument, the measurement taken, the platforms on which they fly, and brief notes. This group of instruments represents a comprehensive set capable of remotely sensing cloud and aerosol particles while taking in-situ measurements of the atmosphere. These instruments come from a variety of NASA centers, academic institutions and private companies representing a working relationship built by NASA to accomplish difficult missions.

Instrument Name	Short Name	Type	Measurements	Platform	Notes
Airborne Compact Atmospheric Mapper	ACAM	Miniature Spectrometer and HD Camera	1.8.7 NOx(NO, NO2), N2O5, HNO3 1.8.2 O3 1.1.3 aerosol scattering properties 3.1.1 Ocean color - 410-680nm 1.8.11 SO2 1.8.8 CH2O and non-CH4 VOC 2.6.2 landcover status	Global Hawk WB-57	Designed to take air quality measurements over cities, also useful for calibrating Aura satellite data Source: (Kowalewski and Janz 2009)
Cloud Physics LIDAR	CPL	LIDAR	1.1.3 aerosol scattering properties 1.5.3 Cloud amount/distribution 1.6.1 cloud height/optical thickness 1.1.1 aerosol height/optical depth 1.6.3 Cloud particle phase - ice/water transition 1.1.4 aerosol extinction profiles/vertical concentration	Global Hawk ER-2	Uses similar low-energy, photon-counting LIDAR technique as ICESat-II Source: (M McGill et al. 2002), (MJ McGill et al. 2007)
Focused Cavity Aerosol Spectrometer / Nuclei Mode Aerosol Size Spectrometer	FCAS NMASS	Aerosol Spectrometer	1.1.3 aerosol scattering properties 1.1.4 aerosol extinction profiles/vertical concentration 1.1.5 aerosol size and size distribution	Global Hawk ER-2 WB-57 DC-8	University of Denver built instrument, has flown extensively around the world Source: (J. Michael Reeves 1995) (J.M. Reeves 2011)
Meteorological Measurement System	MMS	High-Acuracy Atmospheric Probe	1.2.1 Atmospheric temperature fields 1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction	Global Hawk DC-8 WB-57	Designed to fly on any aircraft, captures same data as flight system but with higher accuracy for

				ER-2	scientific use. Source: (Bui 2011)
Microwave Temperature Profiler	MTP	Microwave Radiometer	1.2.1 Atmospheric temperature fields 1.5.1 cloud top temperature 2.5.1 Surface temperature (land) 3.5.1 Surface temperature (ocean)	Global Hawk DC-8 ER-2 WB-57	Since the 1970s, variations of the MTP have been deployed 51 times on more than 800 flights. Source: (Mahoney 2003)
Ozone Photometer	O3	In-Situ UV Photometer	1.8.2 O3	Global Hawk	Samples air to directly measure UV absorption Source: (National Instruments)
UAS Chromatograph for Atmospheric Trace Species	UCATS	2-channel gas chromatograph (GC), Dual-beam ozone photometer (OZ), Tunable diode laser (TDL) spectrometer for water vapor (WV)	1.3.1 Atmospheric humidity (indirect) 1.8.1 H2O 1.8.2 O3 1.8.7 NOx(NO, NO2), N2O5, HNO3 1.8.4 CH4 1.8.9 CFCs/HFCs	Global Hawk	Designed specifically for autonomous operation on Predator class vehicle, has 3 >20 hour flights on Global Hawk Source: (NOAA ESRL)
Ultra High Sensitivity Aerosol Spectrometer	UHSAS	Aerosol Spectrometer	1.1.5 aerosol size and size distribution 1.1.3 aerosol scattering properties	Global Hawk	Collects air samples, commercially available instrument Source: (Droplet Measurement Technologies)
UAS Laser Hygrometer	ULH	Laser Hygrometer	1.3.1 Atmospheric humidity (indirect) 1.8.1 H2O	Global Hawk ER-2 WB-57 DC-8	Directly measures air next to fuselage with high accuracy. Source: (Gettelman 2004)
High-Definition Video System	HDVIS	Camera System	1.5.2 Cloud type	Global Hawk	Provides forward looking HD video for post processing and real time navigation and targeting

Table 4.8: GLOPAC Instrument Descriptions. GLOPAC flew over the Pacific Ocean in the Spring of 2010 to measure properties relevant to weather monitoring and air quality. All of these instruments flew on a Global Hawk for GLOPAC so any other platforms listed are within design specifications.

While GLOPAC is the first operational Earth science campaign for the Global Hawk platform, many of the instruments are mature and have been validated on other platforms. The Cloud Physics LIDAR (CPL) was originally designed for use on the ER-2 manned platform as described in a 2002 paper discussing the instrument and its initial scientific results. (M McGill et al. 2002) The CPL instrument has been used on numerous missions since its first flight in 1983. It was even used to validate LIDAR data from the CALIPSO satellite mission. (MJ McGill et al. 2007) The 2007 paper presents results from an airborne campaign of the ER-2 in which CPL data was used as the baseline for calibrating CALIPSO. Scientists were interested in doing this comparison because CPL has a vertical resolution of 30m compared to

CALIPSO's 60m and a spatial resolution of 2m compared to CALIPSO's 88m.While the paper notes difficulties in directly comparing aircraft and spacecraft data, it is able to directly compare an over-flight over western Kentucky from 2006. In the conclusion, the authors note that CALIPSO data can be assumed to be correct because it agrees with CPL data, and shows the superior quality of airborne measurements in this case. (MJ McGill et al. 2007) The Airborne Compact Atmospheric Mapper (ACAM) has also been validated against satellite data in a 2009 paper comparing the NOVICE flight campaign to the Ozone Monitoring Instrument (OMI) aboard the Aura spacecraft. (Kowalewski and Janz 2009) The study qualitatively confirmed ACAM's accuracy in measuring NO_2 column concentrations over the greater Houston area and stated a goal of "sub-5%" accuracy for the GLOPAC mission. In-situ instruments like the ULH, UCATS, and UHSAS have all been calibrated and tested using known samples in the laboratory. They face the biggest challenges for accuracy because of operational issues. For these air sampling instruments, the risk of operational malfunctions is limited due to a long history of in-situ data collect on other manned airborne platforms.

4.3.3. GLOPAC Concept of Operations

To explore the concept of operations for the GLOPAC campaign, the second science flight is examined in detail. The flight shown in Figure 4.8 is important because it demonstrates the Global Hawk's ability to fly for more than 24 hours over a 9,500 mile range while accomplishing several science objectives. In addition to this platform milestone, the mission under-flew the Aura satellite by following a 2,600 mile track. This would not be possible without the Global Hawk's endurance. This flight took place on April 11th, 2010 and is documented here thanks to the pre-flight and post-flight documentation prepared by mission planners. (Newman 2010)

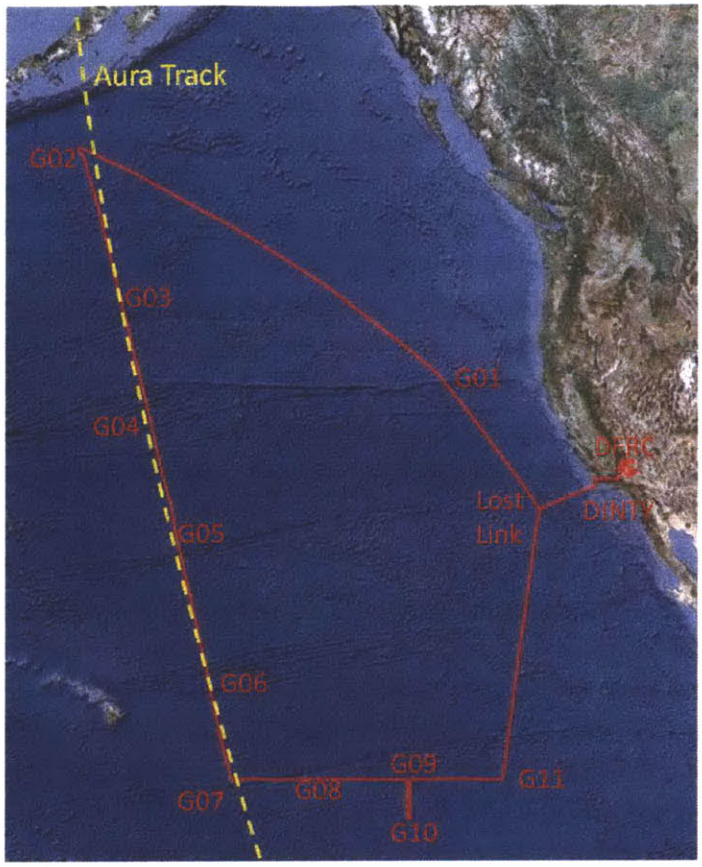


Figure 4.8: GLOPAC 2nd Science Mission over Pacific Ocean deploying from DFRC on April 11th, 2010. Mission Objectives include under-flying the Aura satellite, over-flying NCAR G5, and flying first Global Hawk mission over 24 hours. Images are taken from Google Earth overlaid with GPS data from the onboard navigation systems. (Newman 2010)

Table 4.9 describes the way points in Figure 4.8 by showing the distance between each one and the significance of each point. It's important to note that the flight path had the ability to change in flight, with point G01 shifting north in flight due to a takeoff delayed by approximately 50 minutes.

Way Point	Name	Distance (mi)	Alt (ft.)	Description
DFRC	Takeoff from Dryden	-	2,300	
DINTY	System Check and Instruments ON	656.77	56,622	Climb out of DFRC, Turn Instruments on over Pacific Ocean, Check Systems out and Continue
LOSTLINK	Lost Link Return Point	117.73	56,714	If Link to Global Hawk is lost the vehicle will automatically fly back to this point
G01	Maneuvers Point	1,781.82	58,094	Perform MMS maneuvers to check out systems
G02	Start of Aura Track	408.12	58,394	Begin underpass of Aura Satellite for Science validation
G07	End of Aura Track	2,631.08	60,211	Turn East after Aura track pass
G09	15N Tracer Sample	865.19	60,765	Extended pass along 15 deg N to sample trace gases
G10	Southern California Tracer	187.45	60,881	Stratosphere to the south of California has tracer mixing processes occurring
G11	Begin Return	974.09	61,283	Turn North for flight home
LOSTLINK	Begin Return Descent	1,244.42	62,019	Power down all of the instrument and prepare to land
DFRC	Land at Dryden	674.17	2,300	Safety check all instruments and hangar GH

Table 4.9: GLOPAC Global Hawk Mission Profile deploying from DFRC with 24+ hour mission over Pacific Ocean. UAS flies over 9,500 miles at a cruising altitude of over 60,000 feet while under-flying Aura spacecraft and over-flying NCAR G5 aircraft. (Newman 2010)

The Global Hawk took off from NASA's Dryden Flight Research Center at 6:56am local time, almost an hour behind schedule due to local flight operations. All of the instruments begin the mission powered on except for ACAM and shortly after the climb out they are all checked for functionality. One important aspect of this suborbital flight is the ability for the vehicle to return to the base if instruments are not functioning properly. There is a pre-flight and in-flight criterion that the majority of the instruments must be functioning properly according to the data being retrieved and processed in real-time. Point G02 marks the beginning of a flight over an Aura ground track that corresponds to an over-flight by the satellite. While the satellite traverses the 2,631 mile track in 9.4 minutes, the Global Hawk flying at 385 mph traverses in 6.8 hours. This difference in speed and time over a target exemplifies one of the biggest differences between the platforms. The aircraft mission is able to execute multiple science objective as it investigates an area along the 15 degree northern latitude known for unique mixing of trace gases in the stratosphere. This in-situ sampling provides another example of capabilities unique to airborne platforms. Instruments are powered down and the aircraft touches down at 7:12am local time one day after takeoff. On this particular mission, all of the instruments gathered science data. (Newman 2010)

GLOPAC demonstrated the utility of the Global Hawk platform for Earth science. Its next use was in Genesis and Rapid Intensification Processes, an Atlantic Ocean campaign to study hurricanes.

4.3.4. Genesis and Rapid Intensification Processes (GRIP) Introduction

The next campaign to use the Global Hawk platform for Earth Science after GLOPAC was the Genesis and Rapid Intensification Processes (GRIP) mission. GRIP sought to capitalize on the unique capability of NASA airborne platforms to carry 14 instruments over hurricanes and tropical storms in the Atlantic Ocean from August 15th to September 30th, 2010. This required several first achievements for the Earth Science community as 3 different aircraft were deployed from 3 separate locations to gather in-situ measurements and remote sensing data on storms that can develop in a matter of days. The mission was run jointly by scientists at NASA's GSFC and project managers from NASA's Ames Research Center with solicitations from around NASA, academia and industry. GRIP follows in a sequence of Convection and Moisture Experiment (CAMEX) field campaigns and as such used a prescripted instrument selection process. 26 proposals were received and 11 selected to investigate new techniques for remote sensing of wind and temperature, improve hurricane structure characterization, and develop more responsive models for early warning and prediction. (Kakar 2009)

The following sub-sections introduce the observational platforms and payloads required to achieve this mission investigate a typical deployment.

4.3.5. GRIP Observational platforms and Payloads

The GRIP mission uses three aircraft deployed from three different locations: the DC-8 will fly out of the Ft. Lauderdale airport where the National Hurricane Canter stages its aircraft, the Global Hawk will fly out of DFRC where NASA's only ground station is located, and the WB-57 will fly out of its base near Johnson Space Center due to maintenance and field requirements. The DC-8 was introduced with Operation Ice Bridge as a platform that can easily accommodate large instruments along with the personnel necessary to operate them. The Global Hawk was introduced with the GLOPAC mission as NASA's newest high altitude platform.

Figure 4.9: WB-57 high-altitude research aircraft. The WB-57 can carry up to 6,000 lbs for 6.5 hours at an altitude of 60,000 ft for a 2,500 nm range. Instruments are easily integrated onto the WB-57 due to its standard wing pods and manned configuration. (NASA ESPO 2010b)

The WB-57 has been flying high altitude manned flights, similar to the ER-2, for nearly 40 years. The Air Force transferred the aircraft to NASA in 1974 to conduct Earth science research NASA has maintained and utilized the platform ever since. (NASA JSC 2011) The benefit of the WB-57 is that it does not have stringent integration requirements like the Global Hawk or ER-2 yet still provides the same basic high altitude functionality. Table 4.10 lists the set of instruments used in GRIP along with the measurements each takes, the platform for which it is designed, and some brief notes. One instrument, the Lightening Instrument Package, does not take any of the measurements relevant to the GEOS. The LIP measures the charge built up on the Global Hawk and senses lightening strikes through a set of instruments distributed around the fuselage. These lightening measurements add value to the severe storm science accomplished with GRIP and also represent a measurement that can not be taken in the same manner from space based platforms. The instrument not listed in Table 4.10 is the Meteorological Measurement System (MMS), which is described in Table 4.8 as part of the GLOPAC mission.

Instrument Name	Short Name	Type	Measurements	Platform	Notes
Airborne Second Generation Precipitation Radar	APR_2	Dual-Polarization Doppler Radar	1.7.1 Cloud liquid water and precipitation rate 1.7.2 Cloud droplet size	DC-8	Designed as a precursor for a Satellite Instrument Source: (NASA JPL 2003)
Cloud Aerosol and Precipitation Spectrometer	CAPS	Cloud and Aerosol particle Spectrometer and Imaging probe	1.1.2 aerosol shape, composition, physical and chemical properties 1.1.5 aerosol size and size distribution 1.1.3 aerosol scattering properties 1.2.1 Atmospheric temperature fields 1.3.1 Atmospheric humidity (indirect) 1.7.1 Cloud liquid water and precipitation rate	DC-8	Commercially available Instrument (dropletmeasurement.com) but program run through NCAR Source: (Droplet Measurement Technologies)
Cloud Spectrometer and Impactor	CSI	Cloud Spectrometer via Impactor	1.6.3 Cloud particle phase - ice/water transition 1.7.2 Cloud droplet size 1.7.1 Cloud liquid water and precipitation rate	DC-8	In-Situ measurements from fuselage mounted probe Source: (Kok, Twohy, and Baumgardner 1997)
Precipitation and Imaging Probe	PIP	Imaging Probe	1.6.3 Cloud particle phase - ice/water transition 1.7.1 Cloud liquid water and precipitation rate 1.7.2 Cloud droplet size 1.1.4 aerosol extinction profiles/vertical concentration 1.1.5 aerosol size and size distribution	DC-8	Works together with CAPS and CSI to get total picture of Cloud and Properties Source: (Droplet Measurement Technologies 2011)
Doppler Aerosol Wind LIDAR	DAWN	Doppler LIDAR	1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction	DC-8 WB-57	Work is aplicable to 3DWinds DS mission Source: (Kavaya et al.)
DC-8 Dropsonde	Dropsonde	In-Situ Measurements as device falls through atmosphere	1.2.1 Atmospheric temperature fields 1.3.1 Atmospheric humidity (indirect) 1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction	DC-8	Vaisala RD-93 Dropsonde is standard since 1997, commercially available Source: (Vaisala 2009)
Langley Aerosol Research Group Experiment	LARGE	In-Situ Aerosol Laser	1.1.3 aerosol scattering properties 1.1.5 aerosol size and size distribution 1.1.6 aerosol absorption optical thickness and profiles 1.1.1 aerosol height/optical depth 1.1.4 aerosol extinction profiles/vertical concentration	DC-8	In situ aerosol sensors including condensation nuclei counters, optical particle spectrometers, an aerodynamic particle sizer, multi-wavelength particle-soot absorption photometers, and integrating nephelometers

LIDAR Atmospheric Sensing Experiment	LASE	Differential Absorption LIDAR (DIAL)	1.1.3 aerosol scattering properties 1.3.2 Water vapor transport - Winds 1.8.1 H2O	DC-8 ER-2 P3-B	Example of technology development that has been useful for many satellite applications and continues to return airborne science Source: (NASA LARC)
Global Hawk Dropsonde	Dropsonde	In-Situ Measurements as device falls through atmosphere	1.2.1 Atmospheric temperature fields 1.3.1 Atmospheric humidity (indirect) 1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction	Global Hawk	Miniaturized version of RD-93, System holds >20 dropsondes in the back of the GH
High Altitude MMIC Sounding Radiometer	HAMSR	Microwave Atmospheric Sounder	1.2.1 Atmospheric temperature fields 1.3.1 Atmospheric humidity (indirect) 3.5.1 Surface temperature (ocean) 1.8.1 H2O 2.5.1 Surface temperature (land)	Global Hawk DC-8 ER-2	Developed by JPL under NASA's Instrument Incubator Program Source: (Lambrigtsen 2011)
High-Altitude Imaging Wind and Rain Airborne Profiler	HIWRAP	Ku/Ka Band Radar	1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction 1.7.1 Cloud liquid water and precipitation rate 1.6.2 cloud ice particle size distribution	Global Hawk WB-57	Developed especially for Global Hawk as technology development for future 3DWinds mission Source: (Heymsfield et al.)
Lightning Instrument Package	LIP	Electric Field Mills and Conductivity Probe		Global Hawk ER-2	Detects and measurements lightening and atmospheric charge but doesn't apply directly to any measurements Source: (Blakeslee)
Hurricane Imaging Radiometer	HIRAD	C-Band Radiometer	1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction 1.7.1 Cloud liquid water and precipitation rate	WB-57	Newest instrument, Flying on WB-57 for operational ease Source: (Ruf et al. 2008)

Table 4.10: GRIP Instrument Descriptions. GRIP flew over the Atlantic Hurricanes of 2010 using a DC-8, Global Hawk, and WB-57. Mission was designed to take Wind and Precipitation measurements to better understand hurricane intensification.

The instruments flown on GRIP are unique to airborne platforms. Several of these instruments (HIRAD, HAMSR, HIWRAP, and APR-2) are being developed to push the state of the art in remote sensing with the goal of becoming space-based instruments in the future. The High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is being developed as part of NASA's Instrument Incubator Program (IIP). The goal of the HIWRAP program is to develop smaller less expensive Doppler radars to improve on precipitation radars currently in orbit, such as the Tropical Rain Measuring Mission (TRMM). (Heymsfield et al.) The DC-8 and Global Hawk also carry dropsondes, which they deploy directly into the storm to gather in-situ measurements of temperature, pressure, wind, and humidity. These direct measurements of severe storms can only be accomplished with aircraft and also represent unique measurements. (Vaisala 2009)

Operationally GRIP was a unique mission in that it flew manned and unmanned aircraft simultaneously.

4.3.6. GRIP Concept of Operations

The GRIP mission required flexibility in its mission planning due to the uncertainty surrounding severe storm formation. The 3 aircraft had to be ready for deployment for the whole 1.5 month campaign so that when a storm formed, they could be deployed together. Figure 4.10 shows the mission on September 2nd to investigate Hurricane Earl as it passed the east coast of Florida. The aircraft tracks and satellite imagery were made available via a data visualization portal established by NASA JPL. (NASA JPL 2010)

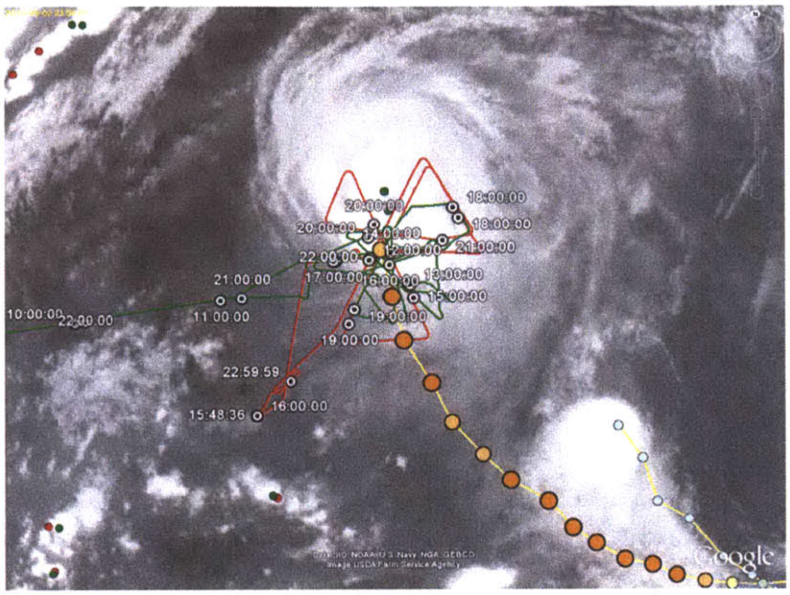


Figure 4.10: GRIP Mission to study Hurricane Earl on September 2nd, 2010. DC-8 (red) deployed from Fort Lauderdale, Global Hawk UAS (green) deployed from DFRC and Storm Track (orange) show Hurricane Earl in top center from NOAA GOES imagery. (NASA JPL 2010)

Figure 4.10 shows a typical GRIP mission flight plan for the Global Hawk (green) and the DC-8 (red) overlaid on satellite imagery from NOAA's geostationary GOES. This flight plan shows the DC-8 flying out of the Ft. Lauderdale international airport where the National Hurricane Center has a flight operation for its investigations. The DC-8 is joined by the Global Hawk taking off from DFRC in California, flying across the continental US, investigating Hurricane Earl, and flying back. The storm track is shown in orange with the larger circle following the eye of the storm as it tracks across the Atlantic Ocean. Also visible in Figure 4.10 is Tropical Storm Fiona in the lower right corner with its track in yellow and blue.

While no science has been published as a result of GRIP yet due to its recent occurrence, it is a clear example of both the unique capability of aircraft to respond with flexibility and the Global Hawk's range and autonomy. As the Global Hawk represents a new era of efficient, automated airborne Earth observation, specific conclusions from these two implementations is discussed below.

4.3.7. Local Opportunity-driven Missions Conclusion

GLOPAC and GRIP were two missions responding to local events that required flexible observational platforms that can handle a variety of instruments in different stages of development. Table 4.11 lists some of the advantages and disadvantages uncovered through this case study.

Comparison for Local Opportunities	Advantages	Disadvantages
Space-based Missions	Observational platforms, such as NOAA GOES, retain ability to observe multiple local events from the same vantage point. Once on orbit, satellites provide a ready-to-use platform without need to deploy a new mission.	Technology does not change or adapt to advances or new methods of study. Once an instrument is in orbit, it cannot be changed. LEO satellites are not capable of maintaining coverage over local events. Without a knowledge of when or where the opportunity might occur, LEO platforms could be out of place. The cost of satellite missions may not be justifiable for local opportunity missions.
Aircraft Missions	Quick response to opportunities and events due to fast integration and deployment times. New instruments and observation methods can be rapidly incorporated. Aircraft can gather in-situ measurements through instruments on the platform or dropsondes. Airborne platforms currently have significant lifecycle cost advantage because aircraft are funded on an operational basis and instrument integration is less expensive. Multiple aircraft can work together to observe the same event in order to accomplish more complex missions.	Each mission has to justify the expense of deploying the aircraft, which may change the threshold of opportunity based on budget. Cannot maintain continuous coverage as aircraft have to refuel and pilots have to rest. Aircraft can be restricted by weather or other extraneous circumstances like an instrument or platform being used somewhere else.

Table 4.11: Advantages and Disadvantages for Local Opportunity driven observation missions from Space-based and airborne observational platforms.

This case study also revealed some interesting conclusions about the new Global Hawk UAS. The Global Hawk is a powerful platform capable of providing more than 24 hours of coverage over an area of interest at a near satellite-like altitude. GH can be deployed from one location and reach events all over the Western hemisphere. This reduces costs due to deployment. These missions also show that Global Hawk can be used for Earth Science over uninhabited locations with minimal human intervention. NASA now has a platform that can fly for over 30 hours and carry a suite of Earth science instruments.

The first two case studies have been related to NASA, while the third one explores where NOAA and the airline industry collaborate.

4.4. Case Study 3: Global In-Situ Data Collection

The third unique case in which aircraft may be better suited for Earth observation is in large scale in-situ measurements of atmospheric properties. This is best exemplified with the Aircraft Meteorological DAta Reports (AMDAR) system, which uses the temperature, pressure, and wind speed data already collected by commercial aircraft to initialize and update Numerical Weather Prediction (NWP) models. AMDAR is now a world-wide consortium of national systems all following the same standards. These instruments are described in more detail in sub-section 4.4.2 and the operation of the system is described in sub-section 4.4.3. It is shown that if systematically utilized, the AMDAR system has the potential to gather scientifically useful data on a global scale.

4.4.1. AMDAR Introduction

The Meteorological Data Collection and Reporting System (MDCRS) system first became operational in the United States in the late 1980's when individual airlines were using aircraft data in their own weather forecasting models. Since then it has grown to include international airlines and partners to become generally known as Aircraft Meteorological DAta Reports (AMDAR). AMDAR uses the instrumentation that is already on commercial aircraft as part of their flight systems and reports it back to the large NWP models. Today AMDAR is an international program coordinated through the World Meteorological Organization (WMO) with country/region specific programs in Europe and Canada and more countries ready to join. (NOAA ESRL/GSD 2010a) Several years ago, the system was updated to include regional aircraft in an attempt to gain better data on troposphere regions (TAMDAR) and smaller airports where regional air traffic operates. The latest upgrade to the system has come in the form of humidity measurements taken by the Water Vapor Sensing System (WVSS), which is currently being deployed to a fleet of United Parcel Service (UPS) and South West Airlines (SWA) aircraft.

Figure 4.11 shows the international reports for the 24 hour period starting at 19:00 on May 3rd, 2011 and ending at 20:00 on May 4th, 2011.

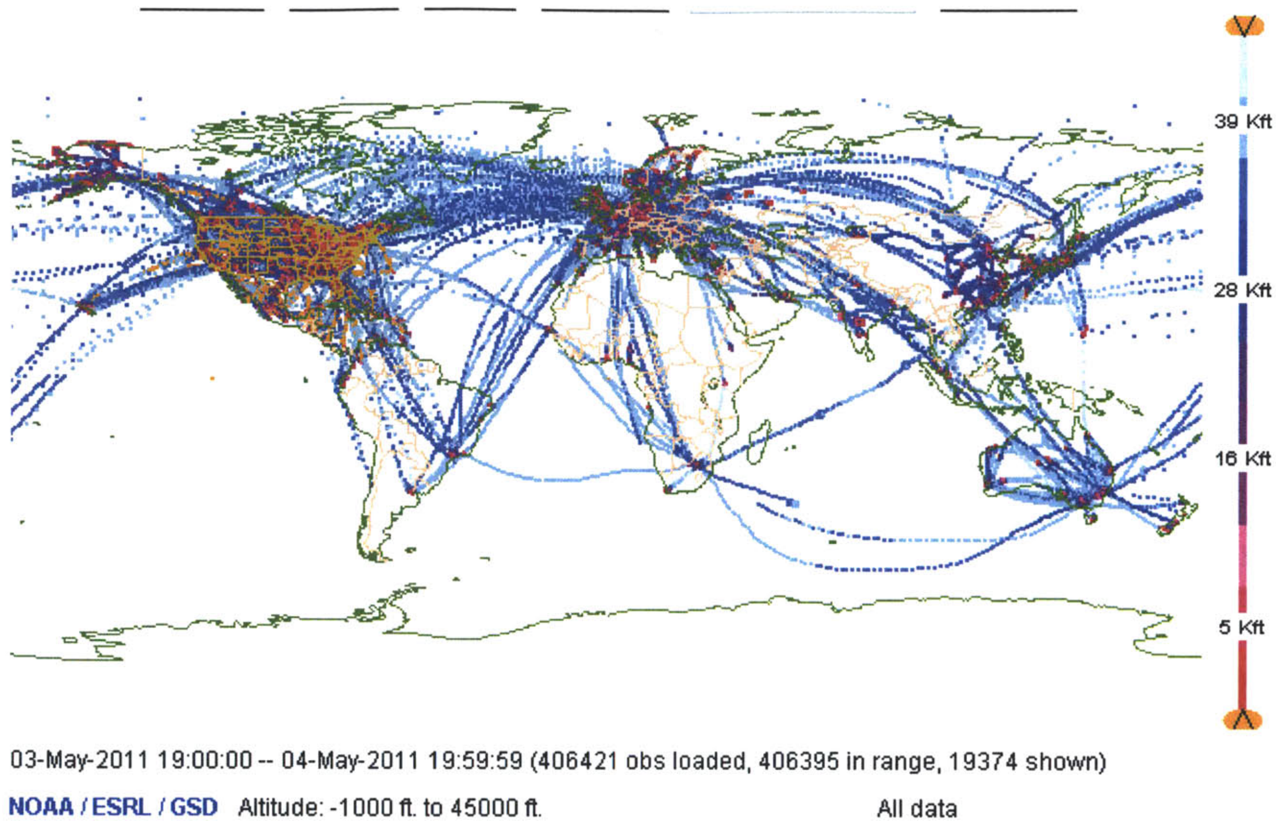


Figure 4.11: Global AMDAR reports for May 3rd-4th, 2011. The altitude of the report is shown with the color scale on the right. 406,421 observations were taken by AMDAR equipped aircraft but only 19,374 are shown in plot above. (NOAA ESRL/GSD 2010b)

According to the NOAA ESRL website, there are over 4,000 aircraft currently equipped to report to the AMDAR system. The use of cargo aircraft from FedEx and UPS allows for observations to be taken during night time hours around the globe. While seemingly comprehensive, this plot shows that a majority of the observations are coming at altitudes over 15,000 ft. While this has use for in-flight weather, it limits the applicability of the data to non-aviation sectors. In an effort to improve the tropospheric data set over the United States, Troposphere AMDAR (TAMDAR) equips regional jets and smaller turboprop aircraft with the same systems. Figure 4.12 shows the observations taken over the continental US under 15,000ft altitude. The plot shows that this method is especially effective in gathering data in the northeast corridor and in the Great Lakes region.

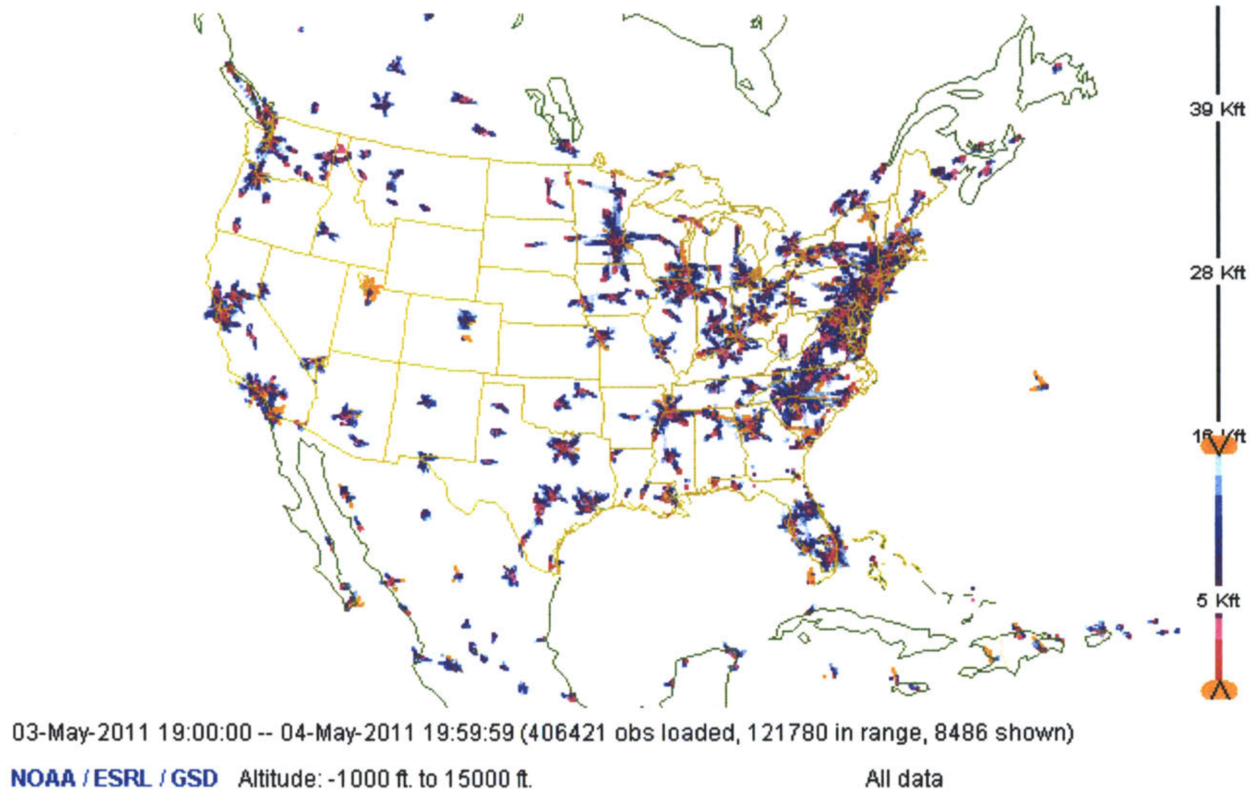


Figure 4.12: AMDAR reports below 15,000 ft over CONUS on May 3rd-4th, 2011. This includes TAMDAR data from regional jets, which allows for atmosphere readings at small airports and at lower altitudes, especially in areas of the country with high commuter traffic like the Northeast or Great Lakes regions. (NOAA ESRL/GSD 2010b)

The low altitude observations shown in Figure 4.12 are mainly taken during take offs and landings, meaning that the lowest observations are concentrated around airports. This airport centric observation structure is useful for weather predictions in the vicinity of the airports but limits the applicability on a mesoscale. Mesoscale meteorology refers to the state-size areas of most interest for weather forecasting operations. These scales are needed to accurately predict large storm systems or fronts and therefore AMDAR observations cannot be the sole source of in-situ observations.

4.4.2. AMDAR Observational platforms and Payloads

Since the AMDAR system utilizes commercial aircraft, the platforms are a variety of aircraft operated by major airlines. Figure 4.14 shows the WVSS-II instrument and the way in which the humidity data it gathers would be received by NOAA and assimilated into NWP models. Using existing commercially operated aircraft gives the AMDAR system an advantage on cost and deployment but limits the control scientists have on collection.

Instrument Name	Short Name	Type	Measurements	Platform	Notes
Aircraft Meteorological DAta Reports	AMDAR	Atmospheric Probe	1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction 1.2.1 Atmospheric temperature fields	Commercial Jet	Uses environmental data aircraft is already gathering and reports it back through ACARS for use in NWP
Tropsheric Aircraft Meteorological DAta Reports	TAMDAR	Atmospheric Probe	1.2.1 Atmospheric temperature fields 1.4.1 atmospheric wind speed 1.4.2 atmospheric wind direction	Turbo Prop	AMDAR deployed on Regional Jets and Truboprops in order to obtain Troposheric measurements between airports
Water Vapor Sensing System II	WVSS-II	Laser-Diode	1.3.1 Atmospheric humidity (indirect) 1.8.1 H2O	Commercial Jet	Spectra Sensors, Deployed on 25 UPS 757's with 31 new SWA 737's to be deployed soon

Table 4.12: AMDAR Instrument Descriptions. All of these instruments report data through current ARINC Communications Addressing & Reporting System (ACARS) which is distributed to participating airlines and NOAA.

There has been a lot of success within the weather modeling community incorporating these in-situ measurements and several studies have attempted to understand the results. These studies are both quantitative and qualitative and are explored below.

Impact of AMDAR

Several studies have been conducted to quantitatively assess the impact of AMDAR on weather forecasting and aircraft operations. Most recently, weather forecasters at NOAA's ESRL/GSD have done retroactive NWP model experiments and published the results in the *Monthly Weather Review*. (Benjamin et al. 2010) The study examines a ten-day period in 2006 and another in 2007 using the Rapid Update Cycle (RUC) model/assimilation system. The RUC model is used for mesoscale short range (3-12 hours) forecast for wind, temperature, and relative humidity at different altitudes with 20km resolution. Table 4.13 shows the observation platform type used in the study along with the measurements each takes and the frequency of the observations. The experiment column clusters the measurements into the categories used in Figure 4.13. A more detailed explanation of the observation data types is found in the study itself. (Benjamin et al. 2010)

Exp	Type	Data Source	Measurements	Approx. # of hourly Obs.
D	Air	Radiosonde	Pressure (P),Z , T , Horz. Vel. (V), Relative Humidity (RH)	80–85
B	Ground	NOAA profilers—404MHz	V (by Height (Z))	30
	Ground	Boundary layer profilers - 915 MHz, RASS	V (by Z), Virtual Temperature (Tv) (by Z)	25, 14
C	Ground	Velocity Azimuth Display (VAD) winds	V	100–130
A	Air	Aircraft (AMDAR, not TAMDAR)	V, Temperature (T)	1400–7000
	Air	TAMDAR aircraft	V, T, RH	0–800
H	Space	GOES AMV's (cloud-drift winds)	V	1000–2500
	Space	GOES cloud-top pressure, temp.	P, T	10-km resolution
	Space	GOES precipitable water	Precipitable Water (PW)	10-km resolution-clear areas
F	Space	GPS PW	PW	250–300
E	Ground	Surface—METAR	P, T, V, Dewpoint Temperature (Td)	1800–2000
G	Ground	Mesonet	P, T, Td, V	7000

Table 4.13: AMDAR impact study RUC NWP model input type, measurements, and frequency for 12 variables. The results of a retroactive study that assessed the impact of AMDAR by denying the model certain variables is shown in Figure 4.13. (Benjamin et al. 2010)

This set of heterogeneous observations is used to inform the forecasting model and each contributes to the accuracy of the resulting forecast. Figure 4.13 shows one of the results of the study, the differences between forecast and actual average wind speed for 3, 6, and 12 hour forecasts on a national scale. Each of the 8 data sets shown in the graphs (A-H) is a collection of measurements as shown in Table 4.13. These experiments show the RUC model with a particular data set (A-H) withheld versus the control model. The control model includes all of the possible data sets listed in Table 4.13. The left and right halves of the graph are displaying the same data rearranged for easier comparison. The left two graphs are showing how each input affects the resulting forecast shown in increasing forecast horizon left to right so that a variable can be compared across time. The right two graphs are showing the full set of experiments for each forecast time period so that a time period can be compared across measurement.

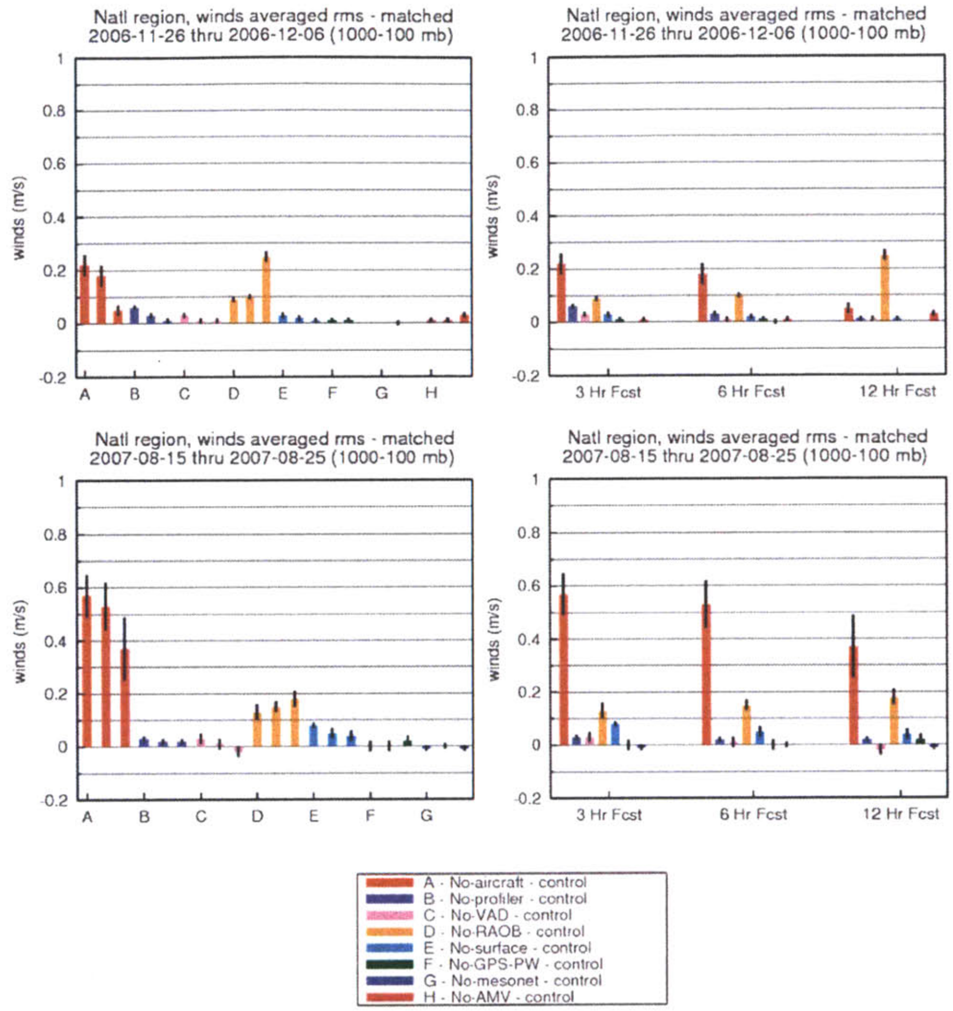


Figure 4.13: A retrospective experiment on the effects of wind forecasting in the absence of 8 data sources, as shown in Table 4.13, versus a control model with all of the variables included. These numerical experiments show that of all the inputs, AMDAR data plays the largest role in wind forecast accuracy of any model input. (Benjamin et al. 2010)

The result of this study, displayed in Figure 4.13, shows that aircraft observations play the largest role among NWP model inputs in short term wind speed foresting. For the experiment conducted retroactively on the summer day in 2007 (bottom two graphs), when aircraft observation (red bar) are removed from the model an overall error of .4-.6 m/s occurs. The bottom right graph shows that as the time horizon of the forecast is increased, the significance of the aircraft observations decrease, showing that aircraft observations are most important for very short term forecasting. For both experiments, winter 2006 and summer 2007, the aircraft observations are the most important input for 3 and 6 hour forecasts.

4.4.3. AMDAR Concept of Operations

This sub-section presents the method used to communicate data taken by aircraft to weather forecasters. The case is made that most of the US would be covered in a year if a substantial percentage of the aircraft in the US fleet was properly equipped. Figure 4.14 shows the current operational routine for transferring weather data gathered by aircraft to NOAA and air traffic controllers.

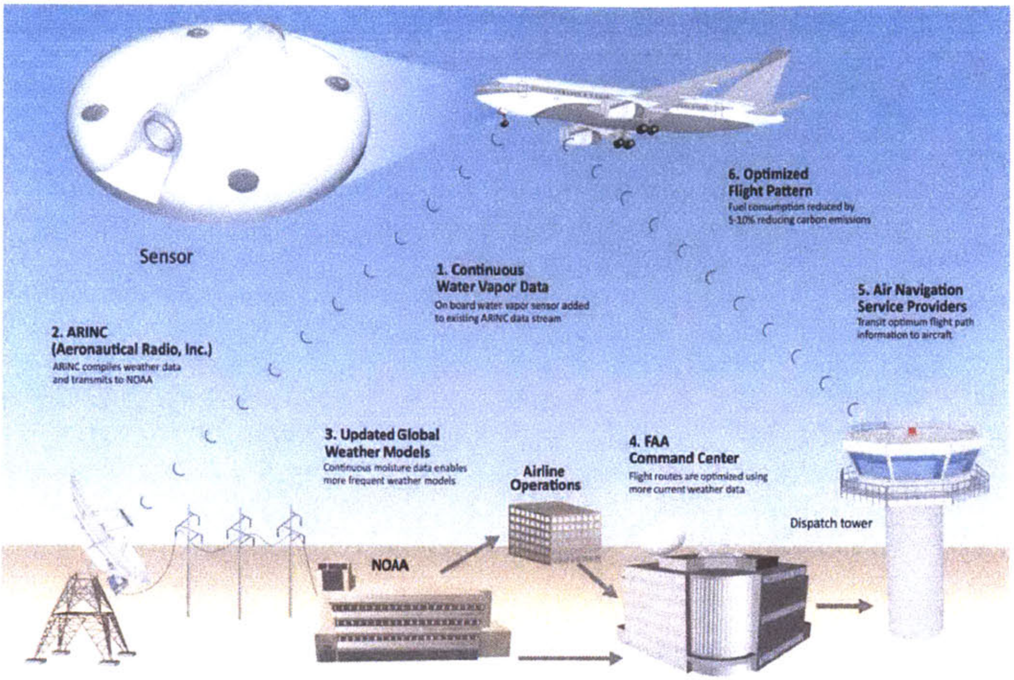


Figure 4.14: The AMDAR and WVSS-II sensor collect data aboard commercial aircraft. Aircraft communicate with ARINC per normal operations, in-situ data is fed into NWP models, models help to predict poor weather events, and planners use better weather data to optimize flight plans.
(Spectra Sensors 2010)

In this example shown graphically in Figure 4.14, humidity data is collected via the WVSS-II system and information is transmitted through the existing ARINC system. Along with temperature, pressure, and wind velocity, the data is used to update weather models. These weather models are passed from NOAA to airlines and controllers around the world as international data is used for larger scale models. Higher fidelity weather predictions influence aircraft operations in a number of ways. Information about convective storms helps to reroute flight plans around weather or reroute aircraft to avoid delays. Wind data helps airlines optimize flight paths to catch tail winds and save on fuel. Humidity data also contributes to decisions about de-icing aircraft depending on when moist air is moving into a region. The success of AMDAR can be attributed both to the large benefit it gives to the aviation community and the way it seamlessly integrates into the existing operational system. The natural extension of AMDAR into the GEOS is to consider the impact other observations could have if other instruments could be integrated onto commercial aircraft.

In order to assess the possible impact of a global fleet of commercial aircraft observations, the remainder or this section focuses on the coverage that could be achieved over the continental US. Figure 4.15 shows the results of a study aimed at finding the radar floor for every 1nm by 1nm section of the country. (Kunzi 2011) The map on the left is color coded by the lowest observed aircraft in that sector over the course of a 1 year period. The map on the right is the same data projected in a binary fashion so that areas covered in white have an aircraft fly over them at some point during the year.

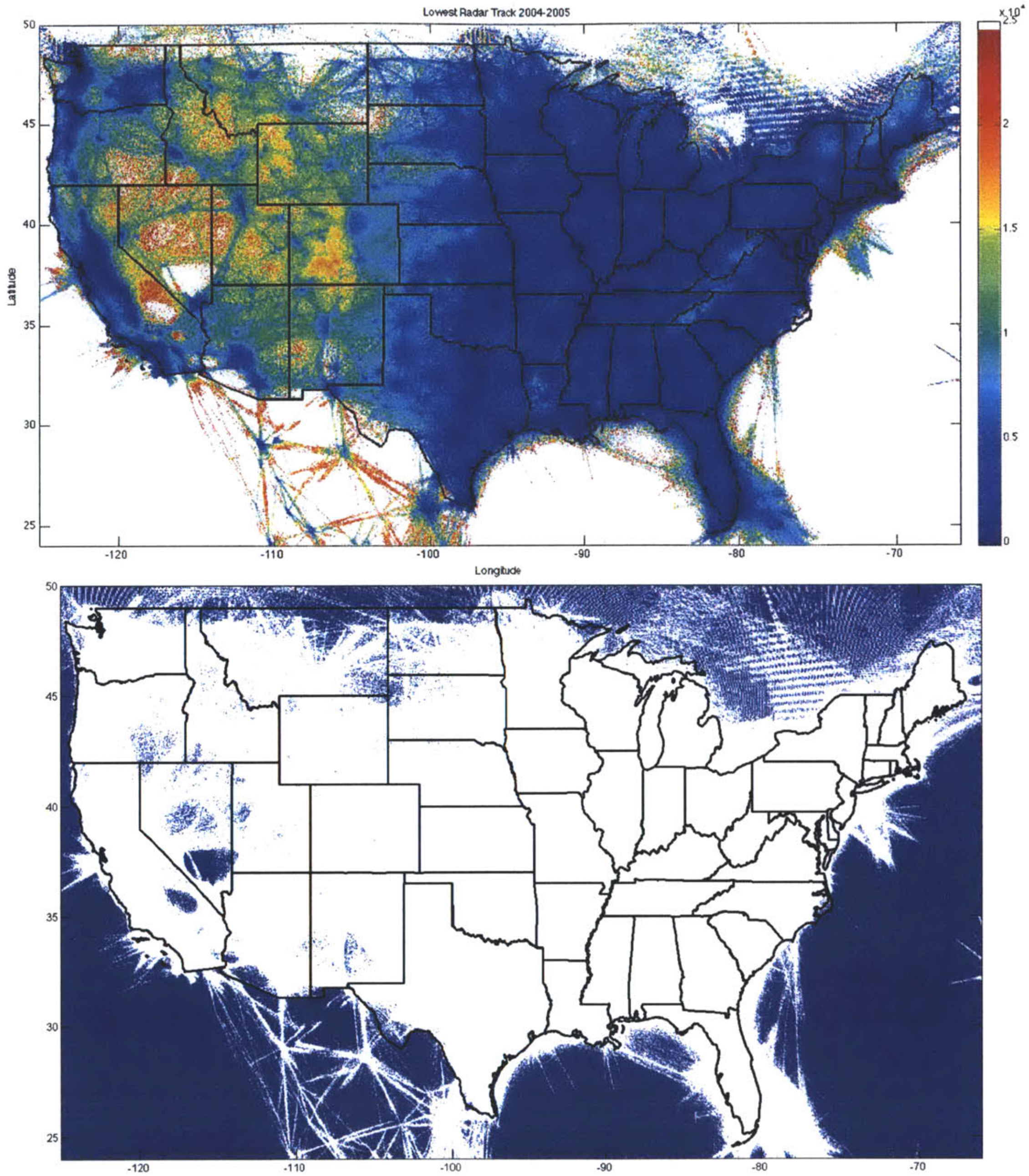


Figure 4.15: Lowest Observed Radar over the contiguous US color coded with altitude (top) and the aggregate showing whether or not an area is overflown (bottom). This theoretical data coverage represents a best case scenario in which every aircraft is equipped with AMDAR and WVSS-II. (Kunzi 2011)

As can be seen in Figure 4.15, almost the entire contiguous United States is flown over in a year. According to the NOAA tool that displays aircraft observation data, there were 406,421 observations/ day in May, 2011. This means that there could be on the order of 150 million observations in a year. WVSS-II is currently being added to aircraft because airlines recognize the benefits to be gained from a more comprehensive understanding of the weather. The same reasoning shuld be applied to remote sensing measurements that could be taken from small instruments. For instance, a miniaturized laser altimeter could provide nearly total coverage and contribute to geological studies, while also helping airlines gather better altitude readings. A small spectrometer could contribute significantly to the understanding of clouds and aerosols by gathering measurements relevant to both aviation and the Earth science communities. This thesis does not explore these ideas in detail but the general concept of remote sensing from commercial aircraft has significant promise.

4.4.4. Global In-Situ Data Collection Conclusions

This section examines the third mode of airborne observation, global in-situ measurements, which in this case were gathered using commercial aircraft. Examining a system that has been operational for over a decade is helpful for understanding how a future operational GEOS could function. By examining the current system, it is shown global coverage is nearly impossible to achieve with aircraft, even at the high volume of current air travel. This is because the standard flights taken internationally by airlines follow certain patterns and do not cover the entire globe. The exception to this is the contiguous US, which is flown over almost entirely in a year as shown in Figure 4.15.

The success of commercial aviation data collection shows usefulness of in-situ measurements for weather forecasting. In fact, given the studies done to assess the impact of aircraft observations, it appears that the current system relies on AMDAR. In a similar manner WVSS-II has the potential to improve weathering forecasting on a large scale. If the WVSS-II system can be matured and expanded to commercial airlines, benefits to both the weather community and aviation industry will follow.

It should also be noted that AMDAR is an example of a science/operational community using available resources to partially fulfill its objectives. Ideally the weather community would have the resources to launch more satellites to achieve better coverage with higher accuracy but in lieu of those resources, using existing data streams is a cost effective alternative. This resourcefulness could be an example to other scientific communities seeking creative solutions due to budget cuts and a general lack of resources.

4.5. General Observations of Airborne versus Space-Based Platforms

General Observations fall into two categories: science related and program related. Science related observations deal with the quality, quantity, and usefulness of the data collected by airborne platforms compared to space-based ones. These observations deal with performance of the platform from a science perspective, data assimilation, and calibration/validation. Programmatic observations deal with the fundamental differences between observational platforms and the way they are operated. These break down into the iron triangle of cost, schedule, and risk. Operation Ice Bridge is used to show that airborne science can be accomplished at a lower cost based on numbers estimated in a NASA internal trade study. Flexibility and responsiveness are clear advantages of aircraft in scheduling. There are several types of risk that are mitigated with airborne campaigns. The risk to instrument or platform failure is mitigated through the aircraft's ability to return to a base in most cases. The launch risk is almost eliminated by the operational frequency and heritage of most of NASA's aircraft. Aircraft can also be used as development test beds for spacecraft instruments, thus mitigating a technology risk.

Category	Aircraft	Spacecraft
Science	Airborne instruments achieve a higher spatial resolution than space-based ones due to the lower altitude at which they fly. Airborne platforms move over a target at a slower speed, so instruments are able to gather higher data integration times when integrating a column of CO_2 for example Many instruments achieve a higher accuracy from an airborne platform due to altitude and in some cases because more power is available to perform the measurement. Aircraft missions are able to focus on areas of interest, such as in the OIB concept of operations where the P-3B is able to fly racetrack patterns of the glacier it was studying Airborne instruments can take in-situ measurements of atmosphere, either through instruments on the platform or dropsondes. Airborne instruments can take measurements of the lower troposphere, which are normally unavailable to space-based instruments due to atmospheric interference. Aircraft generally place fewer size and power constraints on instruments, which aids in instrument development Long endurance aircraft, especially the newer Global Hawk, are able to sustain operation over areas of interest so that more detailed measurements can be preformed. In this way, aircraft are able to perform like low altitude GEO satellites. High precision in-situ aircraft measurements can be used to calibrate remote sensing spacecraft.	Satellites in low Earth orbit achieve global coverage, which allows space-based instruments to gather data from all over the world including areas that are not necessarily within their designed areas of interest. Space-based platforms are better suited for homogeneous and systematic data collection because orbits are predictable. Scientists can know for certain when and where a measurement is taken. Space-based instruments achieve a much wider swath due to altitude. Swath is related to the field of view of an instrument and the altitude from which it is observing. Certain measurements such as Earth Radiation Budget, Upper stratosphere, Space weather, Gravity and Magnetic fields, can only be taken from spacecraft. Space-based platforms generally provide continuous observation because they do not have to be maintained like aircraft. There are exceptions to this for instruments that require operational cycles. Spacecraft have some environmental advantages, such as 'cold space' that can be used to calibrate instruments on orbit.

	Aircraft	Spacecraft
Campaign Costs	Development costs are generally low for airborne platforms because aircraft can be tested in their operational environment cost effectively. Aircraft are also generally produced on a large scale so that the incremental cost of an aircraft is relatively low. The cost to integrate an instrument is low because there are fewer constraints in terms of size and power as compared to spacecraft. Some platforms allow engineers to fly with the instrument, which allows for real-time trouble shooting and tuning. The fixed mission costs are generally low for aircraft. Much of the infrastructure (airports, control systems, and maintenance hubs) are already commercially available. Aircraft do not have the large launch vehicle costs that are associated with spacecraft. Airborne instruments have low development costs which are related to the fact that they do not have to undergo space qualification. All of the previous comments results in aircraft missions generally having lower campaign cost than spacecraft missions. This is evidenced not only in the bottom-up cost estimation approach shown here but also in the programs of record where aircraft missions consistently display lower campaign cost than equivalent spacecraft missions.	Spacecraft are designed to remain in orbit for their entire lifetime so, they inherently have low maintenance costs.

	Aircraft	Spacecraft
Schedule	Aircraft missions consistently display a lower time to deployment compared to spacecraft missions. This gives aircraft the potential to quickly incorporate new technology and respond to fill data gaps NASA's current fleet of aircraft are available for new flight opportunities on a month to month basis. They maintain the ability to respond to mission opportunities that may only be relevant for a month or two. Aircraft mission planners have the ability to re-plan a mission mid-flight. This gives aircraft missions the ability to investigate targets of opportunity because they are not limited by orbital mechanics like spacecraft. Given the previous observations, aircraft generally have shorter mission development times than spacecraft. This allows for programs such as EV-1 where data collection begins 6 months to a year after the contracts are awarded.	From orbit, spacecraft maintain the ability to respond quickly to opportunities that vary on a global scale. For instance, a satellite could be re-tasked to observe an earthquake on the other side of the world from an area of interest, while an aircraft is limited to a range from its deployment site. Due to the high fixed cost and design requirements, satellite missions generally have much longer lifetimes than aircraft missions. As a result, once a satellite is gathering data and functioning properly, it becomes much more difficult to remove funding from the operational project. Once operational, satellites are always available. They do not need to be deployed to gather data. This gives mission planners the ability to rely on a spacecraft being able to take a measurement when needed.

	Aircraft	Spacecraft
Risk	An aircraft deployment carries a much lower risk compared to a spacecraft launch. From an instrument perspective, the ability to return "home" in the event of a failure greatly reduces the risk of completely losing the instrument. For instance, during the last mission of the GLOPAC campaign there were electrical issues that required the Global Hawk to return to its base. While this cut the mission short, none of the instruments were adversely affected. Aircraft retain the ability to come back for repairs. This occurred during the Arctic 2011 campaign of OIB when the P-3B returned to WFF in the middle of the campaign for repairs that could not be made in the field. The aircraft returned to flying a mission over Greenland in less than a week. Airborne campaigns have the ability to do planned maintenance between deployments as suggested in the EV-1 documentation. Aircraft can fly low TRL instruments without the risk of a single instrument compromising the entire mission. The low cost nature of airborne missions allows for a less demanding approval process. This reduces the barrier for new science and unproven technology leading to a more competitive environment.	Due to their higher costs and longer lifetimes, satellites generally have funding stability. As a large mission develops it becomes harder to justify cancelling the mission due to cost overruns or schedule slips. Once on orbit, the satellite will generally be funded for as long as it is returning valuable science data.

Table 4.14: Comparative advantages of aircraft and spacecraft for Earth observation missions.

These comparative advantages are expanded through the implementation of aircraft and spacecraft instruments and missions in Chapter 5.

5. Integrated Campaign-Level Science Traceability Matrix

This chapter presents a method for creating an integrated Campaign-level Science Traceability Matrix (CSTM) by using a Rules-Based Expert System (RBES). This chapter uses the framework presented in Chapter 2 and the information discussed through the set of case studies in Chapter 4 to form a complete model of the Global Earth Observation System (GEOS). The genetic algorithm (GA) used here for campaign scheduling is the same as was applied in the satellite-only Decadal Survey set of missions in Chapter 3.

As shown in Figure 3.21, the "Data Gap" plot for the updated case with current US missions, serious data continuity issues arise if a more holistic approach to Earth science is not taken. NASA is currently operating a fleet of airborne platforms for Earth Science, as discussed in Chapter 4, but they are being used on a monthly basis. This chapter lays out a methodology that helps decision makers design a more completely integrated GEOS, one which delivers more value to scientists and avoids dangerous gaps in measurement continuity.

To form a link between orbital and suborbital observation platforms, this chapter introduces the Rules-Based Expert System (RBES). The RBES maps instruments to stakeholders through a set of engineering and science rules that govern stakeholder objective fulfillment. The RBES methodology is applied without detailed explanation, however more information on this methodology is found in the works of Daniel Selva. (Selva and Crawley 2011) Due to the limited scope of this thesis, the CSTM framework integrated with the RBES, called CSTM v2.0, is only applied to the Climate panel. Application to the Climate panel is a model for the other 5 panels and thus is a step to completing the entire GEOS. This chapter considers only a sample of aircraft instruments, those studied in chapter 4, with the goal of developing the method and some results relevant to the climate science community.

The CSTM v2.0 is introduced and discussed in section 5.1 with a sample instrument characterization and evaluation by the RBES. A set of candidate aircraft missions is established, with campaign benefit scores from the RBES and cost estimates based on the case studies. The GA is applied to a campaign consisting of both the Decadal Survey set of satellite missions and a set of aircraft mission with results presented in section 5.2. The general issues associated with integrating observation platforms are discussed throughout the chapter and recommendations for incorporating aircraft into the GEOS are presented.

5.1. Integrating Spacecraft and Aircraft Measurements

The methodology for integrating airborne and space-based instruments is centered on the idea that the real determinant of value delivery is how the realized measurements resulting from a campaign align with the measurements required by the objectives. The objectives outlined in the panel reports of the Decadal Survey form the basis for comparison between every platform and instrument with the potential for Earth observation. If an instrument fulfills a science or societal objective, it doesn't matter what platform it is on. Therefore, the key to relating all Earth observing instruments and platforms is to map their value to the stakeholders through the panel objectives. This idea is capture graphically in Figure 5.1, which shows the CSTM v2.0.

This graphic is identical to Figure 2.5 except that the RBES has replaced the objective to measurement and measurement to instrument relationships. These relationships have been replaced with the RBES because the CSTM v1.1 does not have the fidelity to capture the distinctions between airborne and space-based observation platforms. In the satellite only campaign scheduling model presented in Chapter 3, instruments are mapped to measurements using a 0-4 scale. Since all of the missions orbit with global coverage on roughly the same time scales (except for the GEO mission), it was useful to compare instruments with the rough 0-4 scale. But integrating airborne platforms presents problems surrounding operating conditions. The end of Chapter 4 discusses the comparative advantages and disadvantages that arise from aircraft being closer to the area of interest but limited in scope. These issues are far more complicated than what can be captured reasonably on a 0-4 scale. In order to solve this problem, measurements have to be characterized by their attributes. Measurement attributes reflect the quantity and quality with which a measurement is taken, which varies between aircraft and spacecraft platforms. Measurement attributes are used to define objectives with more precision thus allowing for a more complete comparison.

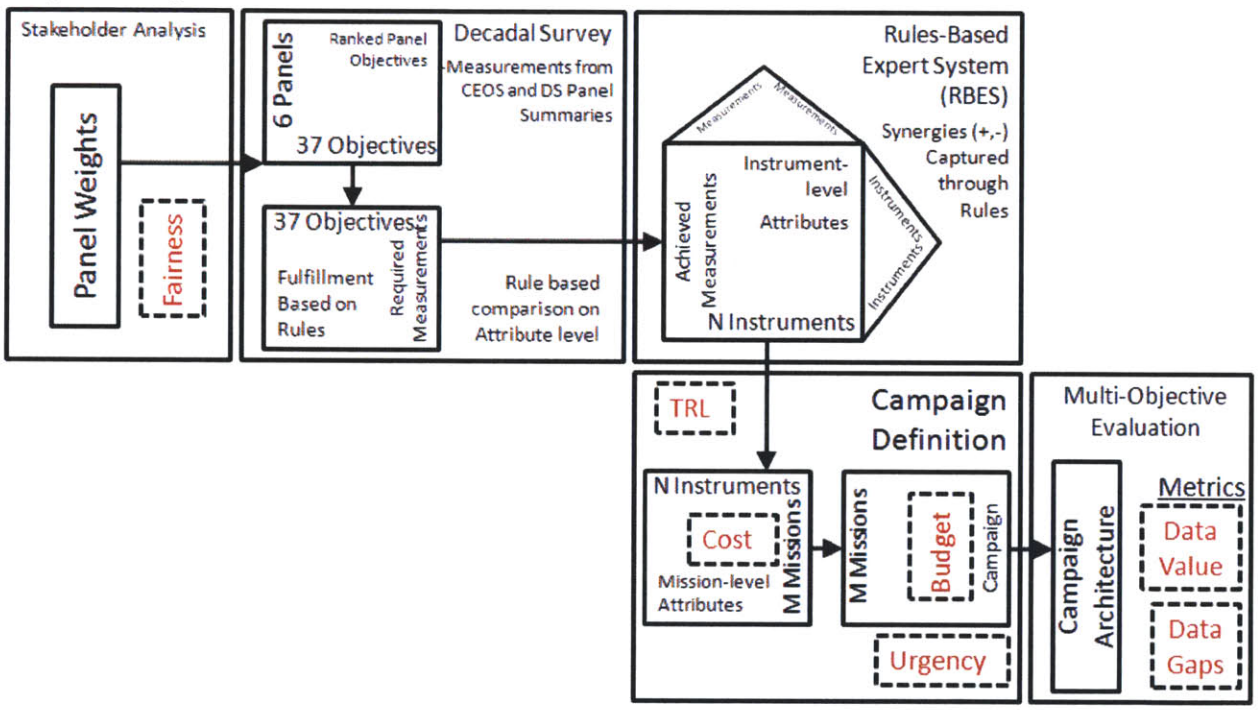


Figure 5.1: The Campaign-Level Science Traceability Matrix (CSTM) framework version 2.0. CSTM v2.0 uses a Rules-Based Expert System (RBES) to create a higher fidelity expression of objective fulfillment through instruments taking measurements. The addition of the RBES will enable the integration of non-space-based missions.

The RBES is a new method to compare instruments and measurements across this wide and varied landscape of possible platforms. This method requires not only more detail about the system under investigation, but also a more intimate knowledge of the needs of the science community in fulfilling their objectives. Sub-section 5.1.1 presents multiple layers of the RBES.

5.1.1.Rules-Based Expert System for Scientific Value

This section defines how the rules-based expert system is used to define scientific value. The work of Daniel Selva resulted in a novel rules based approach to determining stakeholder value derived from

Earth Science campaigns. Selva's work is ongoing as part of his doctoral studies and will be summarized here. More can be found in his recent publications. (Selva and Crawley 2011)

Objective Definition

The first step to the Rules Based Expert System (RBES) is the identification of stakeholder objectives. The mapping of stakeholder objectives to measurements is shown in Figure 5.2. This is done differently then was described for the CSTM v1.1, presented in Table 2.3. In the RBES, there is not a binary mapping between objectives and measurements, instead they are linked via a set of rules that govern objective fulfillment. These rules are applied at the attribute level of each measurements, comparing what an objective requires and what the set of instruments achieves.

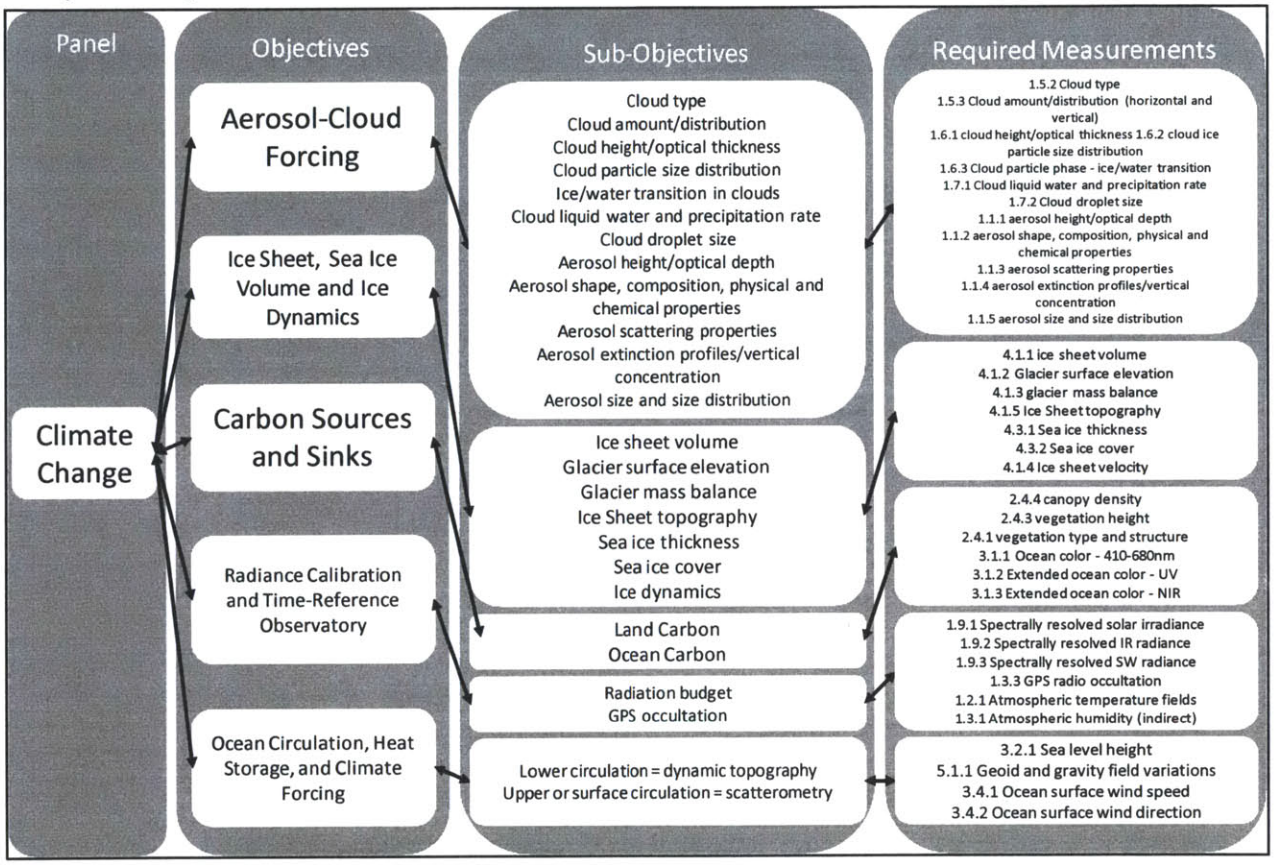


Figure 5.2: Rules-Based Mapping of Climate Panel Objectives to Required Measurements. The Climate panel objectives are broken into sub-objectives, which map directly to one or more measurements. Each of these sub-objective to measurement mappings is based on measurement attributes. Objective fulfillment is a weighted sum of the sub-objective fulfillment. The rules are used to compare the required measurements with the actual measurements taken by the instruments in the campaign.

In this case the climate panel objectives are taken from the Decadal Survey. The objectives are then broken into sub-objectives, which fulfill some part of the larger objective. Sub-objectives are fulfilled by one or more measurements as defined by the rules for that sub-objective. This mapping of measurements to sub-objectives is based on the attributes present in each measurement as defined. Therefore, by characterizing the instruments and the measurements that each takes, a rule is satisfied within a sub-objective thus adding value to the stakeholder. It follows then that for an instrument to be evaluated by the RBES, the measurements it takes must be characterized at the attribute level.

Characterization of Instruments and Measurements

The first step to integrating the new platforms is to characterize each instrument based on the measurements it takes and the mission it flies in. The characterization of the instruments was accomplished by reading literature and documents related to each. For each instrument 10 pieces of information were needed, with possible values shown in Table 5.1. Note that some of the measurement attributes depend on the instrument characteristics (i.e. Field of View and Spectral Sampling) whereas others depend on the mission definition (i.e. Coverage and Horizontal Spatial Resolution).

Source	Category	------------------------------------Attribute	--------------------------------			
Instrument Attributes	**Measurements**	See Table 7.5 -	Table 7.9			
	Spectral Sampling	Hyperspectral	Multispectral	Multiband	Single-band	N/A
	Accuracy	High	Medium	Low		
	Polarimetry	yes	no			
	Field of View	Very-wide	Wide	Medium	Narrow	None
	On Board Calibration	Advanced	Some	None		
	Radiometric Resolution	High	Medium	Low		
Mission Attributes	**Coverage**	Global	All	Most	Some	None
	Temporal Resolution	Highest	High	Medium	Low	Lowest
	Horizontal Spatial Resolution	Highest	High	Medium	Low	Lowest

Table 5.1: Instrument and Measurement Characterization. Each new instrument has to be characterized based on the measurements that it is designed to take and the quality of those measurements based on their design operating conditions. Information was taken from documentation specific to each instrument.

Within the RBES, this characterization occurs for both the measurements required to fulfill the objectives and the measurements achieved by the instruments in the campaign. If an instrument takes a measurement to the full extent required by a sub-objective then it would receive all of the possible value from that sub-objective. On the other hand, if the instrument took the measurement without all of the attributes achieving the required characteristics, then the instrument would receive a degraded score. This is best shown through an example in which the LVIS instrument is examined.

RBES Instrument Example

To illustrate the RBES methodology and its application to aircraft instruments, LVIS is used as an example. As described in the Operation Ice Bridge case study presented in section 4.2, LVIS is a laser altimeter used in studies of both ice and vegetation. The instrument is designed to fly at a medium altitude, around 35,000 feet, and is currently being integrated to fly on the Global Hawk UAS. Of the set of 84 measurements being used to describe the GEOS, LVIS covers 8 of them in its current configuration. For each of the 8 measurements, the characterizations required by the RBES are listed in Table 5.2.

Name	Measurements	Coverage	Horiz. Res.	Temp. Res.	Spectral Sampling	Acc.	Pol.	FOV	On Board Calibration	Radio. Res.
LVIS	2.2.2 Hi-res topography	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	2.2.1 surface deformation	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	2.4.1 vegetation type and structure	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	2.4.3 vegetation height	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	2.7.1 river and lake elevation	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	4.3.2 Sea ice cover	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	4.1.5 Ice Sheet topography	Most	Highest	Medium	Single-band	High	no	Narrow	None	High
	2.4.4 canopy density	Most	Highest	Medium	Single-band	High	no	Narrow	None	High

Table 5.2: Laser Vegetation Imaging Sensor (LVIS) Measurement Characterization, required for RBES. For each measurement coverage is considered to be most of the area of interest with high spatial resolution and medium temporal resolution associated with a weekly aircraft mission. LVIS has a 2km swath with high accuracy compared to space-based laser altimeters.

Some explanation of these attributes is required. Coverage is "Most" based on the fact that this suborbital instrument cannot cover the globe but is designed to gather data from all of the areas of interest. Horizontal resolution is the highest value because of the combination of a very narrow field of view and a low platform altitude. Accuracy is the highest value because LVIS achieves centimeter accuracy on an airborne platform, which would not be achievable from a spacecraft in its current configuration. The instrument is said to have medium temporal resolution, which means it is capable of an observation every few days for the entire area of interest. This mission tempo will have consequences for the number of flight-hours in a year for missions carrying LVIS, which is taken into account in the cost model. Several characterizations do not apply to LVIS, for instance "spectral sampling" and "radiometric accuracy", but are listed so that the same set of rules can be applied to all of the instruments.

When LVIS is fed through the RBES, 4 sub-objectives are triggered for application. One of these sub-objective is C2.4, "Ice Sheet Topography" and requires measurement "(4.1.5) Ice Sheet Topography" with specific attributes to fulfill it as shown in Table 5.3. Note that in this example the sub-objective and measurement have the same name, this is not always the case.

Sub-Objective	Measurements	Coverage	Horizontal Res.	Temporal Res.	Acc.
Ice Sheet Topography (C2.4)	Ice Sheet Topography (4.1.5)	Global	High	Medium	High

Table 5.3: Required measurement attributes for sub-objective C2.4. LVIS achieves all of these attributes except for Global Coverage. The result of this sub-objective fulfillment is shown in Table 5.4.

The lack of global coverage appears for all four sub-objectives, as shown in Table 5.4 and results in only 2/3 of the full value being assigned (Sub-Objective Score). The two sub-objective scores corresponding to objective 2 (C2.4 and C2.6) are weighted and summed to produce the objective score. The same process is applied to objective 3 and finally the two objective scores are weighted by their respective objective weighting and summed to produce the Climate Score for LVIS. Objective weightings are shown in Table 2.2 and sub-objective weighting are determined through expert interviews. Table 5.4 shows the calculations used to generate the matrix of instruments to objectives and the final Climate score.

Sub-Objective Fulfilled	Meas. Required	Degraded Fulfillment Rationale	Sub-Obj. Fulfill	Sub-Objective Weighting	Objective Fulfillment	Objective Weighting
C2.4: Ice Sheet Topography	4.1.5	"Most" Coverage	0.67	0.10	0.133	0.24
C2.6: Sea Ice Cover	4.3.2	"Most" Coverage	0.67	0.10		
C3.1: Canopy Density	2.4.4	"Most" Coverage	0.67	0.17	0.222	0.24
C3.3: Vegetation Type and Structure	2.4.1	"Most" Coverage	0.67	0.17		
					Climate Benefit	
						0.085

Table 5.4: Calculations of LVIS Climate Benefit. The 4 sub-objectives listed here are only partially fulfilled by LVIS due to the lack of global coverage. Each sub-objective is given a 2/3 score and then weighted (1/10 for C2 and 1/6 for C3) to calculate an objective fulfillment score. These objective scores are weighted according to their objective rank weighting to generate a Climate Panel Score.

The result of this table is that LVIS fulfills 8.5% of the climate panel in one year on its own while generating 13.3% satisfaction of objective 2 and 22.2% satisfaction of objective 3. The most important aspect of this calculation is the reasoning behind the degradation shown in column 3 of Table 5.4. By assigning 2/3 of the sub-objective fulfillment to a "Most" coverage measurement, a crucial value judgment is being made. There are a few criteria for assigning "Most" to LVIS's coverage in this case. The first is that LVIS cannot achieve "Global" coverage due to the nature of the airborne platform it flies on. An aircraft mission that covers the globe with a single instrument is impractical but the key measurements that LVIS takes are confined to "Areas of Interest". Based on the literature available, the "Area of Interest" for LVIS is the ice covered regions of the world and large forested areas requiring detailed study. With this in mind, LVIS is capable of covering all of these areas with a reasonable aircraft campaign. The coverage is still considered "Most" because true global coverage suggests that unforeseen benefits that come from space-based data will be exploited in new ways after the campaign definition.

RBES Applied to Case Study Instruments

The RBES process that is presented in Table 5.2-Table 5.4 has been completed for the five objectives of the climate panel and for all of the aircraft instruments presented in chapter 4. The results of this analysis for the climate panel are shown in Figure 5.3. The attribute values for each instrument are shown in Table 7.18 of the Appendix.

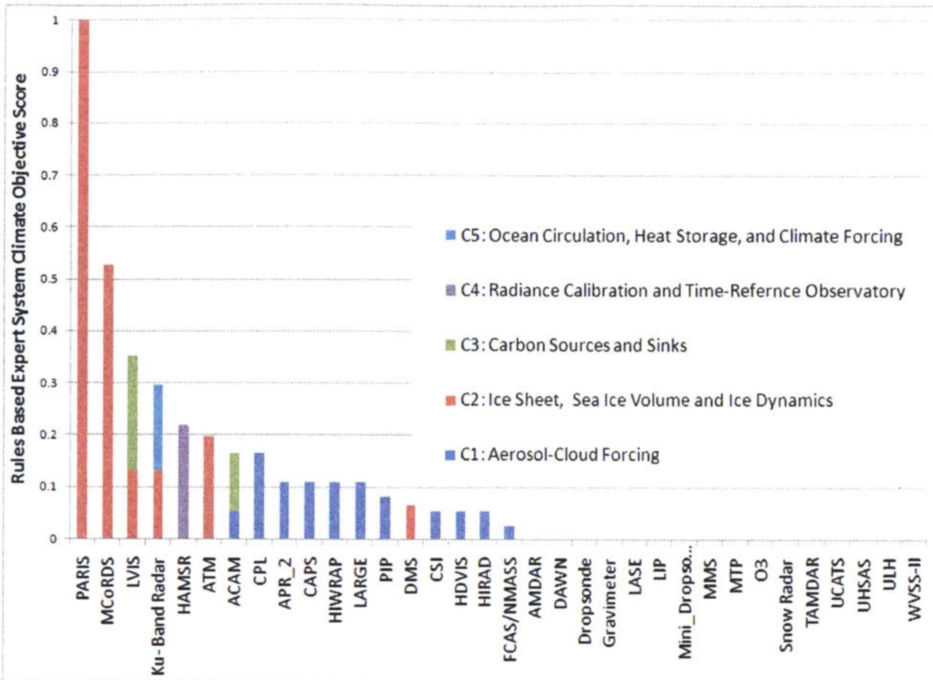


Figure 5.3: Rules-Based Expert System Climate Objective Score for each Aircraft Instrument. Objective score is based on the percentage of the objective that is fulfilled by the instrument through the measurements that it takes and their characteristics.

Figure 5.3 shows the climate objective score for the instruments in the case studies and presented here for integration into the CSTM v2.0. The plot has several interesting features that show the strengths and weaknesses of this approach. A noticeable feature of this graph is that 16/34 instruments receive no value. Within the RBES there is an explanation for each score, which displays the satisfied and broken rules. For example AMDAR and TAMDAR do not receive any value even though they take temperature measurements around the world. The Climate panel requires onboard calibration for the atmospheric temperature measurement, which they both lack. In other words, since AMDAR and TAMDAR are designed to fulfill weather-related objectives, and therefore the way in which they take measurements does not satisfy the Climate panel.

This plot shows that he RBES can be intuitively understood. ATM, LVIS, and MCoRDS are all part of Operation Ice Bridge, a mission explored in Chapter 4 dedicated to fulfilling Climate objective 2. This plot demonstrates how these instruments work together to fulfill varies aspects of objective C2. A weakness demonstrated by this plot is that although the method has captured many of the objectives and rules of the climate panel, it hasn't captured all of them. This is partly due to the method by which the Decadal Survey broke into panels and ranked objectives. By examining the whole set of objectives within for all 6 panels, there are some objectives that fall under other panels but would have influence on the Climate panel. Even though the climate panel listed these objectives as a complete list, there are objectives that belong to other panels that clearly have some stake in the climate panel's fulfillment.

5.1.2. Aircraft Mission Cost Estimates

The benefit/cost relationship is the most important part of formulating aircraft missions but compared to expected benefit, estimating cost can be much more uncertain. Modeling benefit through the RBES, ideally, involves gathering rules from a broad set of stakeholders and gaining buy-in through participation. Estimating cost requires detailed analysis of aspects of the NASA structure, which are not possible through publicly available documentation. For instance, integration costs and instrument costs are not generally public information. Hourly operating costs for the airborne platforms NASA operates are posted on the Airborne Science Program (ASP) website, but campaigns must also pay for the instrument integration and science team associated with each instrument. Some detailed cost information is available for Operation Ice Bridge, as shown in Table 7.24, and those estimates are extrapolated to the remaining missions. In addition to cost per flight hour and cost per instrument estimates, other features must be standardized, such as campaign length and flight hours associated with a mission. Defining these two sets of variables will give a baseline from which to generate cost estimates that are reasonable, despite the associated uncertainty.

This analysis assumes that all of the benefit that results from the RBES model is for one year's time. By standardizing the length of time benefit is calculated for, missions of different lifetimes can be compared. All of the aircraft missions are defined to have medium temporal resolution meaning that there are at least 100 flights per year, a relatively fast operations tempo. Missions that are only 6 months long are given half of the RBES determined value. Therefore, mission cost estimates are based on 100 flights, assuming an average flight length consistent with the endurance of the platform. Cost per hour figures are applied to both the vehicle time as advertised by the ASP and operations expense as calculated by looking at OIB cost estimates. OIB cost estimates are from an internal NASA report from 2008 that looked at options for filling the measurement gaps between ICESat and ICESat-II using aircraft. Within the report are estimates of the flight and operational per hour costs as well as fixed integration and science team costs. (Fladeland and Martin 2009)

Vehicle	Flight Cost ($/hr)	Operations Cost ($/hr)	Integration Costs		Science Team Costs	
DC-8	6,500	13,000	$1,000,000	per Instrument	$8,000	($/hr)
P-3B	3,500	1,400	$200,000	per Instrument	$8,000	($/hr)
Global Hawk	3,500	6,000	$2,000,000	Flat Fee	$9,000	($/hr)

Table 5.5: Baseline Cost Estimates for 3 Earth Observing Aircraft. (Fladeland and Martin 2009) **Flight costs based on published figures on ASP website, Operations costs based on OIB report, Integration costs based on OIB report and used as fixed cost per mission, and Science team costs based on OIB report.**

While these estimates are based on the Operation Ice Bridge documentation, in the absence of more applicable estimates, they are used for the Global Hawk missions. This includes the GRIP and GLOPAC missions for which there is no publicly available cost information.

The ARRGOS proposal has detailed cost figures, which are used for those mission estimates. Detailed cost estimates for a 3 year ARRGOS mission with highlights for recurring and non-recurring costs are shown in the Appendix in Table 7.23. Since so much of the cost of the ARRGOS mission is in vehicle purchase and modification, the proposed operations are very inexpensive making a 6 month mission cost nearly the same as a 1 year mission. (Aurora Flight Sciences 2009) For the expanded ARRGOS mission estimate (Greenland and Antarctica) the fixed costs associated with vehicle purchase, integration and operation costs are doubled to reflect the need for a second set of aircraft.

Spacecraft and Aircraft Cost Discussion

Attempting to estimate airborne mission costs revealed an interesting flaw in NASA's current operational structure. Satellite platforms are seen as large investments with many years of payoff after launch, therefore hundreds of millions of dollars are spent every year on satellite missions. Aircraft on the other hand, receive little upfront investment and are operated on an hourly basis. The majority of the costs are absorbed by the science teams operating the aircraft at high cost/hr. In fact, many of NASA's aircraft are donated or deemed inappropriate for other uses and refurbished for science flights. In Aurora's proposal for the ARRGOS mission, one of the advantages they list is their low operating costs, which they claim to be more than an order of magnitude lower than current platforms. Like the DA-42 platform sued in ARRGOS, if NASA invested in new or more modern airborne platforms, operating costs could be drastically reduced. The biggest obstacle to this strategic investment is perceived lack science return and therefore a lack of willingness to invest. Satellites are seen as the premiere platforms and flagship missions of the agency. They therefore get the most investment. The current observation paradigm views aircraft as test beds or "opportunity" platforms, performing missions because there is a short term need. Aircraft are not considered long term operational platforms, a view that keeps them from being considered in long term campaign design.

While this thesis does not delve into the political and strategic nature of platform acquisition, it should be noted that if the cost of Earth observing missions is going to be reduced to an acceptable level, upfront investments in new aircraft must be made. One of the main results in Chapter 3 was the extremely long campaign length that accompanied the increase in satellite mission cost and the decrease in Earth science budget. The original Decadal Survey campaign was only possible because of the optimistic increase in funding expected by the Decadal Survey. Without these resources, NASA must explore new way of gathering the same data. This analysis makes the case that a new way to effectively gather the same data is by investing in modern airborne platforms.

5.1.3. Additional Programmatic Considerations

There are additional considerations discussed in the conclusion to Chapter 4 that are mentioned here but not quantitatively integrated into the model. As demonstrated by the recent failure of OCO and Glory, satellite missions carry with them significant risks. Some of these risks are mitigated on airborne platforms that have the inherent flexibility of maintenance or to simply end a mission early. This risk, of course, is offset by the high value of spacecraft given success. In a budget constrained and risk adverse environment, aircraft gain an advantage.

A second consideration is the timeframe in which missions can be developed and launched. Spacecraft carry with them a long development time, during which components and instruments are space certified. Aircraft on the other hand, can go from laboratory to platform integration comparatively quickly. This is due to both the environment in which the instrument operates, and the ability for the designers to troubleshoot flight hardware curing operation. This is especially clear on an aircraft like the DC-8 where the scientist and engineers can be deployed with the instrument to gather initial data and troubleshoot issues that arise, even in flight. Taking advantage of this capability is a tradeoff between autonomous operation and a quick development time because although satellite instruments take years to develop, they also ideally operate for years without intervention. This distinct advantage for airborne platforms may be reduced if aircraft missions are seen as operational rather than opportunistic. An operational approach to airborne campaigns requires more substantial systems engineering approach and more pre-flight testing.

Neither of these interesting considerations are explicitly incorporated in the CSTM v2.0, although the responsiveness of the aircraft missions is implicitly captured in their low-cost nature.

5.2. Campaign Scheduling using the CSTM v2.0

This chapter presents a method for integrating space-based and airborne platforms and instruments through a Rules-Based Expert System in order to generate optimal Global Earth Observation System schedules. The genetic algorithm (GA) presented in chapter 2 and validated in chapter 3 is used here to gain new insights. The climate panel objectives are used in this optimization as representative of the entire system and a model for future implementation.

5.2.1. "Data Value" Metric

The first objective to consider is "Data Value", which requires that instruments be combined into missions and assigned a cost. Mission cost estimates determine launch dates, which are used to discount value as seen in Chapter 2. The output of the RBES is a score based on the percentage of each objective that each instrument fulfills. This process then follows the CSTM v2.0, shown in Figure 5.1 so that each mission, and thus the campaign, delivers benefit to the stakeholders.

Aircraft Missions

For the climate panel application of the CSTM v2.0, the aircraft missions presented in chapter 4 are used. For each mission, a one year version and a 6 month version are generated to capture the timeframes over which the mission could run. Specifically for ARRGOS, a 2 year and a 3 year mission are also added to better model the proposed mission. The one year mission (1, 2, or 3 year mission for ARRGOS) is considered an operational mission while the 6 month mission could act as more of a gap filler. As shown in Figure 5.3, the instruments associated with the global retrieval of temperature, pressure, wind speed and humidity by commercial aircraft does not fulfill any of the climate panel objectives. Therefore, the AMDAR system is not included in this optimization, but should be considered for future applications with all 6 Decadal Survey panels. The airborne missions used for this campaign scheduling exercise are shown in Table 5.6.

Mission Name	GLOPAC	GRIP		OIB	ARRGOS
RBES Benefit	**0.10**	**0.19**		**0.33**	**0.24**
Platform	**GH UAS**	**DC-8**	**GH UAS**	**DC-8**	**DA-42M**
Instruments	ACAM	APR_2	Mini_Drop	ATM	PARIS
	CPL	CAPS	HAMSR	LVIS	
	FCAS/NMASS	CSI	HIWRAP	MCoRDS	
	MMS	PIP	LIP	Snow Radar	
	MTP	DAWN	HIRAD	Ku- Band Radar	
	O3	Drop	MMS	Gravimeter	
	UCATS	LARGE		DMS	
	UHSAS	LASE			
	ULH				
	HDVIS				

Table 5.6: Aircraft Missions chosen based on case studies in Chapter 4 and RBES results. Each

mission is defined by the instruments associated with it and the aircraft on which they will fly. The 5th case studied in Chapter 4 was AMDAR, which generates no value for the Climate Panel according to the RBES and is not included here.

Benefit for the 4 aircraft missions shown in Table 5.6 is derived from the instrument value discussed in sub-section 5.1.1 and an assumed one year mission. GLOPAC remains an aerosol and cloud mission utilizing the Global Hawk on 24 hour flights. GRIP is a multi-platform mission and instruments are broken up according to the case study presented in Chapter 4 with the exception of HIRAD flying on the Global Hawk instead of the WB-57. Operation Ice Bridge has gone through many platform/instrument combinations depending on availability of aircraft at any given time, but this analysis assumes all of the instruments fly on the DC-8. This is a reasonable configuration for OIB because the DC-8 flew all of the instruments in the Spring of 2009 over Antarctica. ARRGOS is the mission proposed by Aurora Flight Sciences as presented in the case study in Chapter 4. Cost estimation for ARRGOS is accomplished using the estimates presented in the proposal, as shown for the 3 year mission in Table 7.23. Cost estimates are generated from the methodology outlined in sub-section 5.1.2 based on the mission profile assumed for each aircraft platform. The final cost estimates for each mission and length is shown in Table 5.7. The calculations for each cost estimate are shown in Table 7.19 through Table 7.22.

Mission	Life Time	Cost	
GLOPAC	6 month	$	24,200,000
	12 month	$	46,400,000
GRIP	6 month	$	29,350,000
	12 month	$	48,700,000
OIB	6 month	$	22,500,000
	12 month	$	39,000,000
ARRGOS	36 months	$	49,907,000
	24 months	$	44,893,000
	12 months	$	39,994,000
	6 months	$	36,440,000

Table 5.7: Mission Cost Estimates based on platform estimates found in Table 7.19, Table 7.20, Table 7.21, and Table 7.22. In general, 6 month missions are not half the cost of 1 year missions due to the large fixed costs associated with instrument integration.

From a qualitative perspective, the figures in Table 5.7 seem high, which is due to several factors. For the missions utilizing the Global Hawk UAS, there is a high integration cost ($2M) for each mission, when in reality once an instrument has been integrated, the cost for subsequent missions should be much lower. For missions utilizing the DC-8 platform, there is a very high operational cost ($13,000/FH), which reflects the maintenance costs associated with the older aircraft. For ARRGOS the 3 year mission cost is 66% higher than the quoted proposal cost due to the need to open operations in Antarctica and therefore purchase and integrate another DA-42M and PARIS instrument. So, while these mission cost estimates are conservative, they represent a justifiable estimate.

The Complete Mission Set

The complete set of missions including both Decadal Survey spacecraft and the chapter 4 case study aircraft; are evaluated using the RBES. Each instrument's objective score is weighted by the appropriate normalized ranking and then summed to give the instrument a Climate panel score. Each mission's instruments are summed and the total score is multiplied by the mission's lifetime. Figure 5.4 shows the normalized final Climate Panel benefit for each mission.

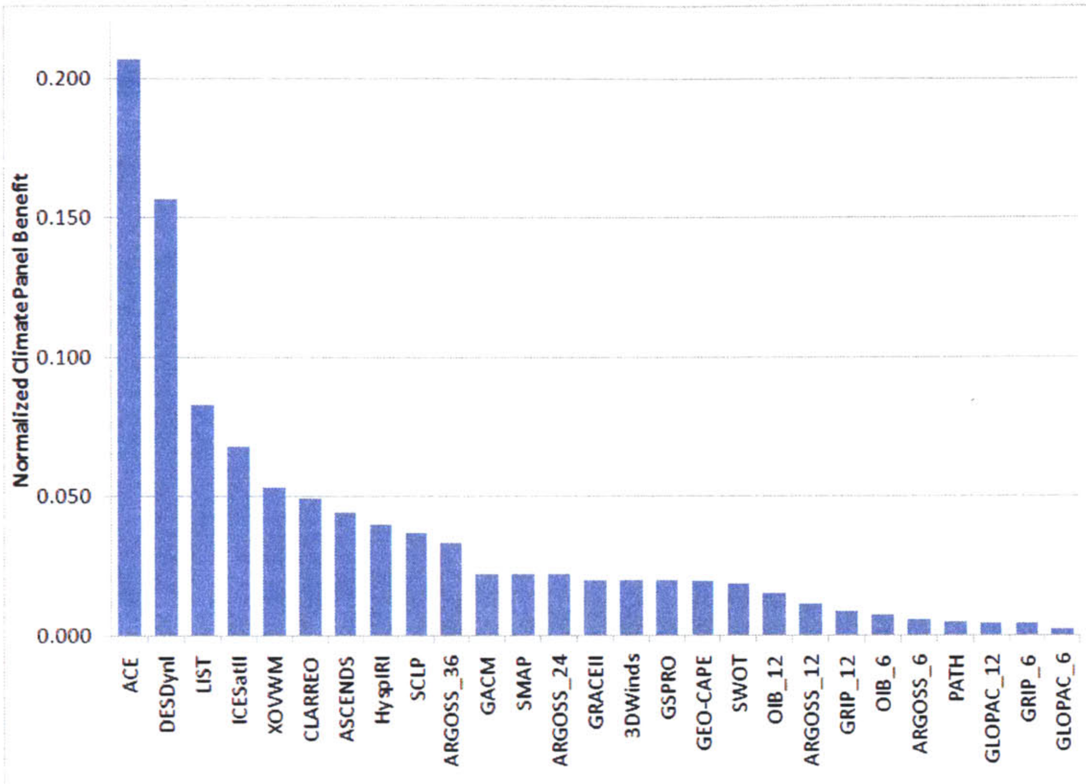


Figure 5.4: Normalize Climate Panel Benefit for all 27 Earth Observing Missions. Climate Panel benefit is calculated by weighting the RBES objective scores and summing for each mission. Scores are then multiplied by mission lifetimes and shown here.

Figure 5.4 shows that according to the RBES, in general satellite missions produce more benefit for the Climate panel. This makes sense from a qualitative view since climate scientists prefer a global perspective. Each sub-objective is fully fulfilled when its measurements have global coverage. Satellites also have a lifetime advantage over aircraft missions. Each satellite RBES score is multiplied by its lifetime (8 years) and each aircraft RBES score is multiplied by its lifetime (.5, 1, 2, or 3 years).

With both space-based and airborne missions evaluated by the RBES and cost estimates shown in Table 3.8 and Table 5.7, a benefit/cost comparison is shown in Figure 5.5.

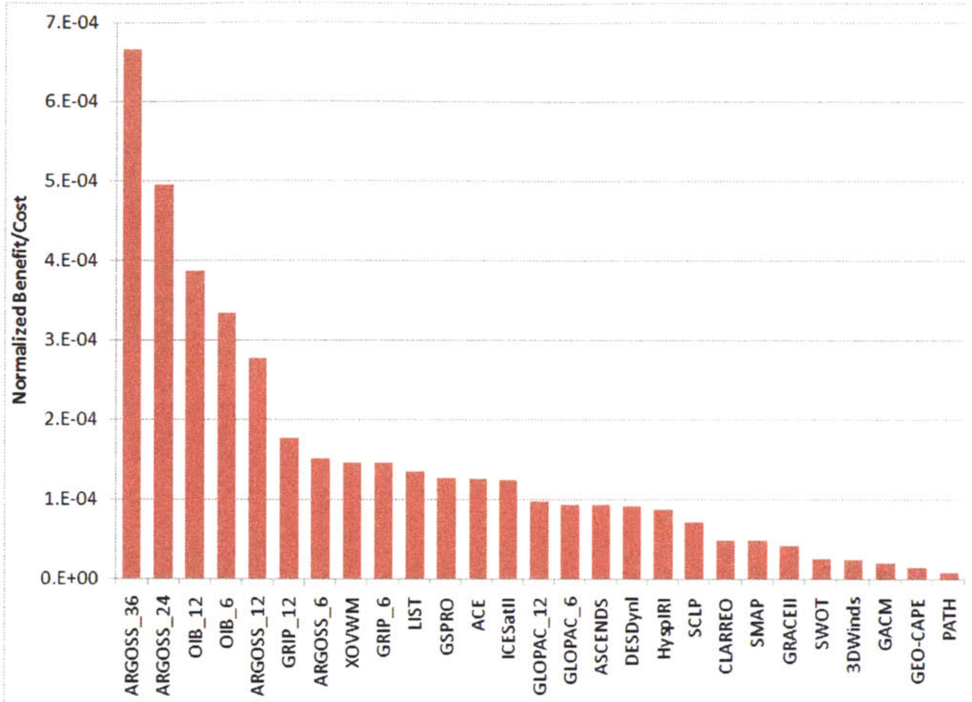


Figure 5.5: Benefit/Cost based on Lifetime-weighted Benefit to Climate Panel shown in Figure 5.4 and Cost shown in Table 3.8 and Table 5.7. Analysis shows that aircraft missions are significantly more cost effective than space-based missions due to the inflated cost of space-based platforms.

The results in Figure 5.5 show that aircraft missions have a clear advantage in terms of value. It is important to note that this is only examining the Climate panel, therefore many of the measurements that are taken by the missions are unaccounted for because they are not relevant to the Climate panel objectives. The Decadal Survey missions were chosen based on their ability to satisfy many panels so by only analyzing one panel, most of the value is lost. The aircraft missions on the other hand were chosen because they deliver value to the Climate panel (AMDAR not included at this point). They do not have as much to gain from a more broad analysis as the satellite missions do. There is also an inherent cost difference because satellite missions have to pay for the launch vehicle and satellite; both are expensive items that are fixed costs for every mission. Aircraft, on the other hand (except for ARRGOS) are simply operating the vehicle for a short time, which means that their short term value is artificially increased because someone else paid for the platform. Based on these observations the benefit and cost analysis are used as inputs into the schedule optimization shown below.

5.2.2.Data Gap Metric

The second objective in the optimization is "Data Gap". The "Data Gap" metric uses the importance of each measurement as the weighting function to determine an overall metric. In the absence of the binary measurements to objectives matrix, the RBES calculates this climate panel score for each measurement. To do this, each measurement is run through the RBES with the highest attributes utilized by the objectives. In this way, each measurement is given a score based on how it contributes to the overall Climate Panel. 35 out of 84 measurements add value to the Climate panel as shown in Table 5.8.

#	Measurement	RBES Importance
1	1.1.1 aerosol height/optical depth	0.083
2	1.1.2 aerosol shape, composition, physical and chemical properties	0.083
3	1.1.3 aerosol scattering properties	0.083
4	1.1.4 aerosol extinction profiles/vertical concentration	0.083
5	1.1.5 aerosol size and size distribution	0.083
6	1.1.6 aerosol absorption optical thickness and profiles	0.167
7	1.2.1 Atmospheric temperature fields	0.167
9	1.3.2 Water vapor transport - Winds	0.167
13	1.5.1 cloud top temperature	0.083
14	1.5.2 Cloud type	0.083
15	1.5.3 Cloud amount/distribution	0.083
16	1.6.1 cloud height/optical thickness	0.083
17	1.6.2 cloud ice particle size distribution	0.083
18	1.6.3 Cloud particle phase - ice/water transition	0.083
19	1.7.1 Cloud liquid water and precipitation rate	0.083
36	1.8.16 Visible atmospheric plumes	0.167
37	1.9.1 Spectrally resolved solar irradiance	0.167
38	1.9.2 Spectrally resolved IR radiance (200-2000cm-1)	0.167
44	2.3.2 soil moisture	0.167
46	2.4.2 vegetation state	0.167
47	2.4.3 vegetation height	0.167
57	2.7.3 groundwater storage	0.167
58	3.1.1 Ocean color - 410-680nm (Chlorophyll absorption and fluorescence, pigments, phytoplankton, CDOM)	0.167
59	3.1.2 Extended ocean color - UV (enhanced DOC, CDOM)	0.167
60	3.1.3 Extended ocean color - NIR (atmospheric correction)	0.250
66	3.3.1 Ocean salinity	0.250
67	3.4.1 Ocean surface wind speed	0.250
71	3.7.2 coral reef health/extent	0.100
72	4.1.1 ice sheet volume	0.150
73	4.1.2 Glacier surface elevation	0.100
74	4.1.3 glacier mass balance	0.400
75	4.1.4 Ice sheet velocity	0.100
80	4.2.4 snow cover	0.100
81	4.3.1 Sea ice thickness	0.100
82	4.3.2 Sea ice cover	0.250

Table 5.8: List of Measurements that add value to the Climate Panel according to the RBES evaluation. The importance shown here is used to weigh the number of measurement gap years found within the "Data Gap" objective calculation described in section 2.3.3.

The most valuable measurement according to the RBES is "Glacier Mass Balance" based on how it contributes to the "Ice Sheet, Sea Ice Volume, and Ice Dynamics" objective. With the system metrics defined, the campaign scheduling genetic algorithm is run and the results are presented below.

5.2.3. Campaign Optimization

The campaign optimization algorithm is easily adapted to accommodate the aircraft missions because they are evaluated using the same metrics as the satellite missions. The one integration issue that arises is due to a desire to potentially launch the aircraft missions more than once. A mode of operation for the aircraft missions is as a gap filler between satellites, which could require the mission to deploy multiple times over a 10+ year period. Therefore, each aircraft mission is included 5 times within the mission list so that the algorithm could potentially schedule the same mission up to 5 times. If the algorithm schedules the aircraft missions with some overlap, it creates an unrealistic scenario where missions are using the same platform in parallel. This could not happen in reality given the current fleet. This problem was addressed through the cost estimation of aircraft missions. Integration costs are included in every mission so as to maintain the potential for a single aircraft flying with multiple missions. In future work a constraint could be added so that the cost of buying an extra aircraft is added or so that aircraft missions using the same vehicle cannot overlap.

Table 5.9 shows the assumptions used for the optimization algorithm. Aircraft missions are set with TRL Launch Dates of 2011 because all of the missions are real and have flown with the exception of ARRGOS. ARRGOS is a technologically mature mission that was ready to receive funding in 2009. Campaign budget remains the same as in the updated Decadal Survey case presented in section 3.2.6 on page 70. Satellite mission costs and "TRL Launch Dates" also remain the same as the updated Decadal Survey case. The current US satellite missions are also included in the model as presented in section 3.2.5 on page 82.

Integrated Case Assumptions		
Budget	See Table 3.9	
Costs	FY11	See Table 3.8
		See Table 5.5
Campaign Start Date	2011	-
TRL Dates		
Tier 1	2014, 2015, 2018	
Tier 2	2022	-
Tier 3	2022	-
Aircraft	2011	
TRL Cost Penalty	30%	-
Current US Missions		Included

Table 5.9: CSTM v2.0 integrated campaign scheduling assumptions.

The algorithm is run with a population of 3000 individuals per generation and a maximum of 100 generations. Given that each individual has 67 missions to evaluate, the algorithm takes about 5 hours to run with these performance characteristics on a laptop computer with 2GB of RAM and a 2.53GHz Core™ 2 Duo processor.

Genetic Algorithm Results	
Generation to Terminate	100
Architectures Evaluated	303,001

Table 5.10: Campaign Optimization performance.

Figure 5.6 shows the resulting Pareto front and final population when the algorithm was terminated. This plot indicates that the algorithm is close to converging, as the final population points are all bunched around the Pareto front. One of the problems with population convergence in this case is that the algorithm considers each aircraft mission separately when in reality each is repeated 5 times. This means that although the algorithm is still exploring "optimal" solutions, it may just be switching identical missions that happen to have different mission numbers.

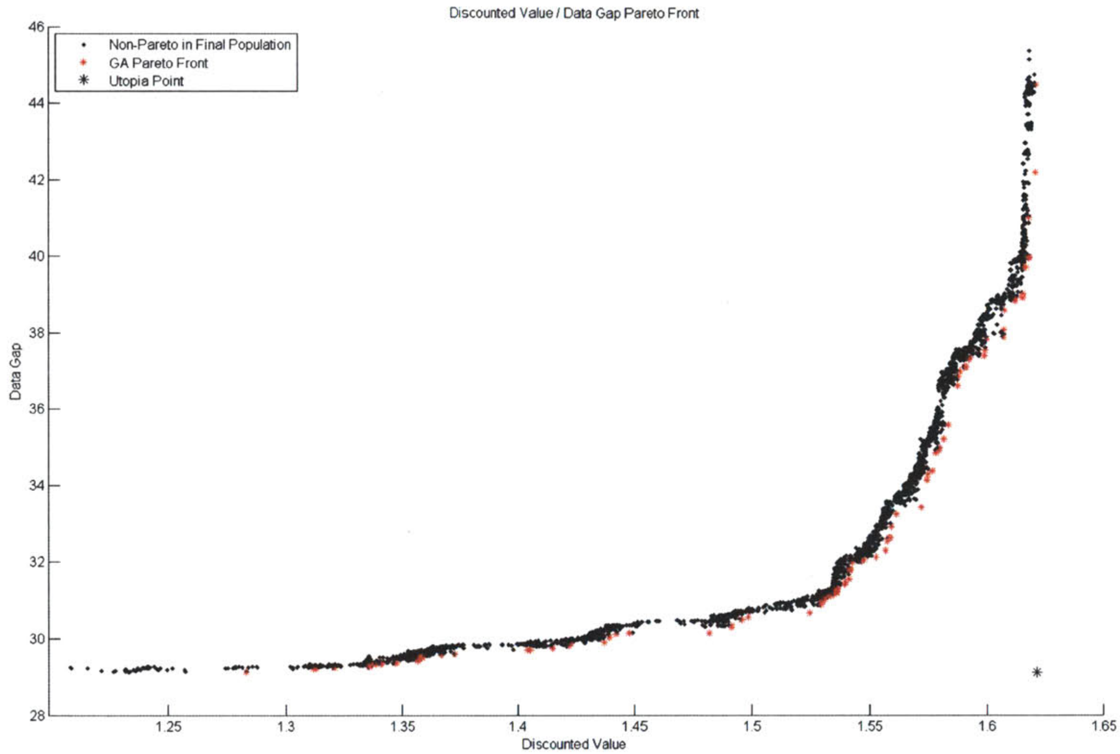


Figure 5.6: GA Results displayed Pareto front for Integrated CSTM v2.0 case. Although the metrics used here are similar to Figure 3.19, they cannot be compared numerically given the different benefit determination methods.

Figure 5.6 looks very similar to the GA results for the updated satellite case with the current US mission shown in Figure 3.19 but the solutions are different numerically. While similar, this Pareto front shows the metrics as determined using the RBES as part of the CSTM v2.0.

Figure 5.7 shows the "Whisker Plot" or statistical representation of the launch dates associated with the top 50 architectures along the Pareto front. Compared to the satellite-only results shown in Figure 3.20, the "Whisker Plot" for the integrated case has the aircraft missions added to the top of the graphic. Since each aircraft mission is launched 5 times, the 5 instances of each mission are combined on the plot to make it easier to read. Because of this, the top ranked campaign, designated by the "*", shows the position of each of the 5 missions for a given aircraft.

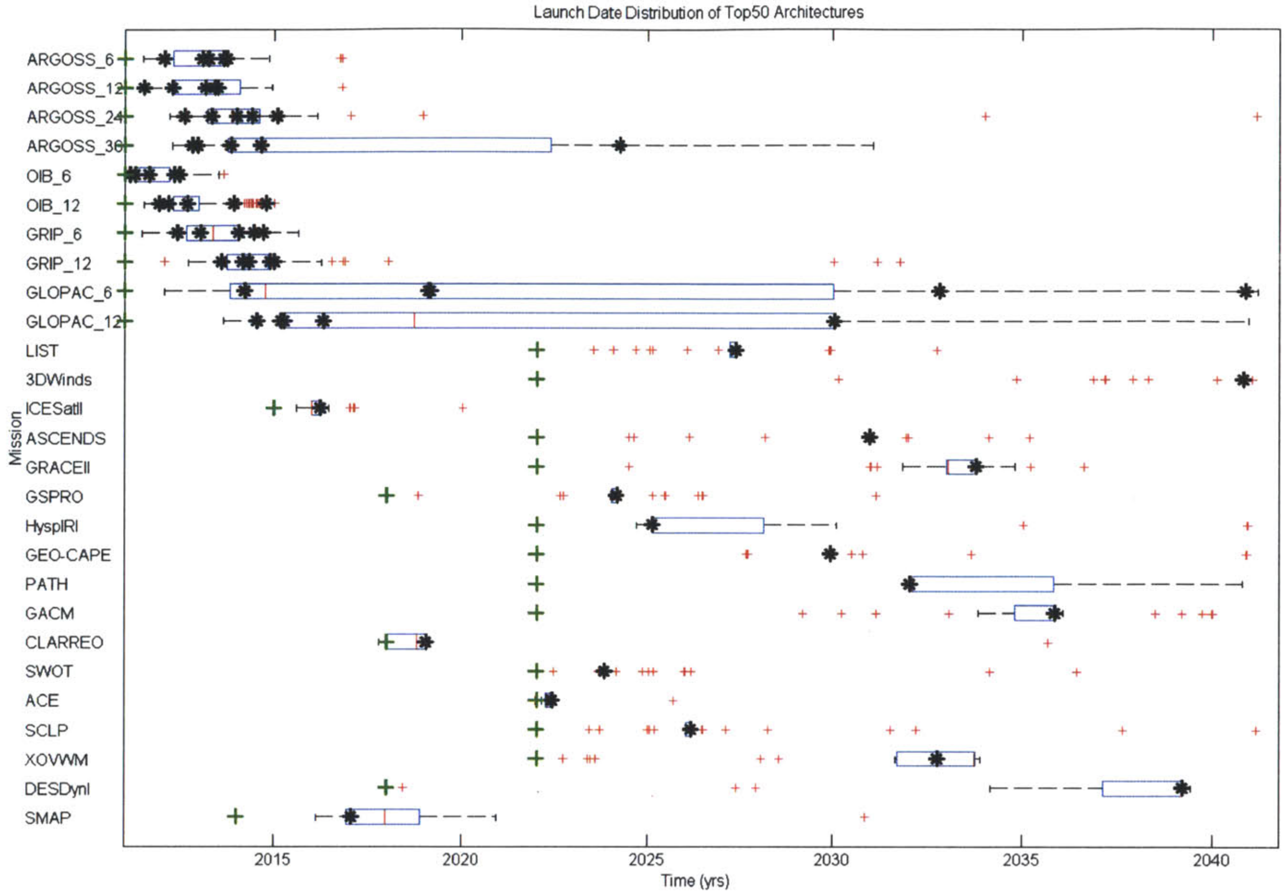


Figure 5.7: Statistical representation of the Launch Dates based on the top 50 Pareto optimal campaigns. All 5 instantiations of the aircraft missions are combined for each aircraft mission name.

The first feature of Figure 5.7 is that almost all of the aircraft missions launch first. This is primarily due to the value of the aircraft missions outweighing benefit lost from the satellite missions being pushed back in the campaign. One of the aircraft missions that doesn't launch in the beginning of the campaign is GLOPAC, which is a lower benefit aircraft mission. Because GLOPAC fills a primarily gap filler role, its launch dates are spread out over the campaign, filling measurement gaps. Note that launch dates among the satellite missions are not directly compared to the satellite only case in Figure 3.20 because this analysis is for the climate panel alone. Despite this, ICESat-II and SMAP still launch first and second in the majority of the campaigns. The final interesting feature is that there appear to be many more "outliers" among the satellite missions than in previous analysis. This is due to the high variability within the aircraft missions so that for the same number of campaign architectures, a satellite with one or two launch dates out of its most likely spot will show on the plot as "outliers".

Figure 5.8 shows the first 27 years of the data gap visualization plot for the top ranked integrated campaign. Decadal Survey satellite missions and aircraft missions are represented by blue lines and current US missions by red lines, with their overlap represented in pink. The names of the aircraft missions are not shown on the plot.

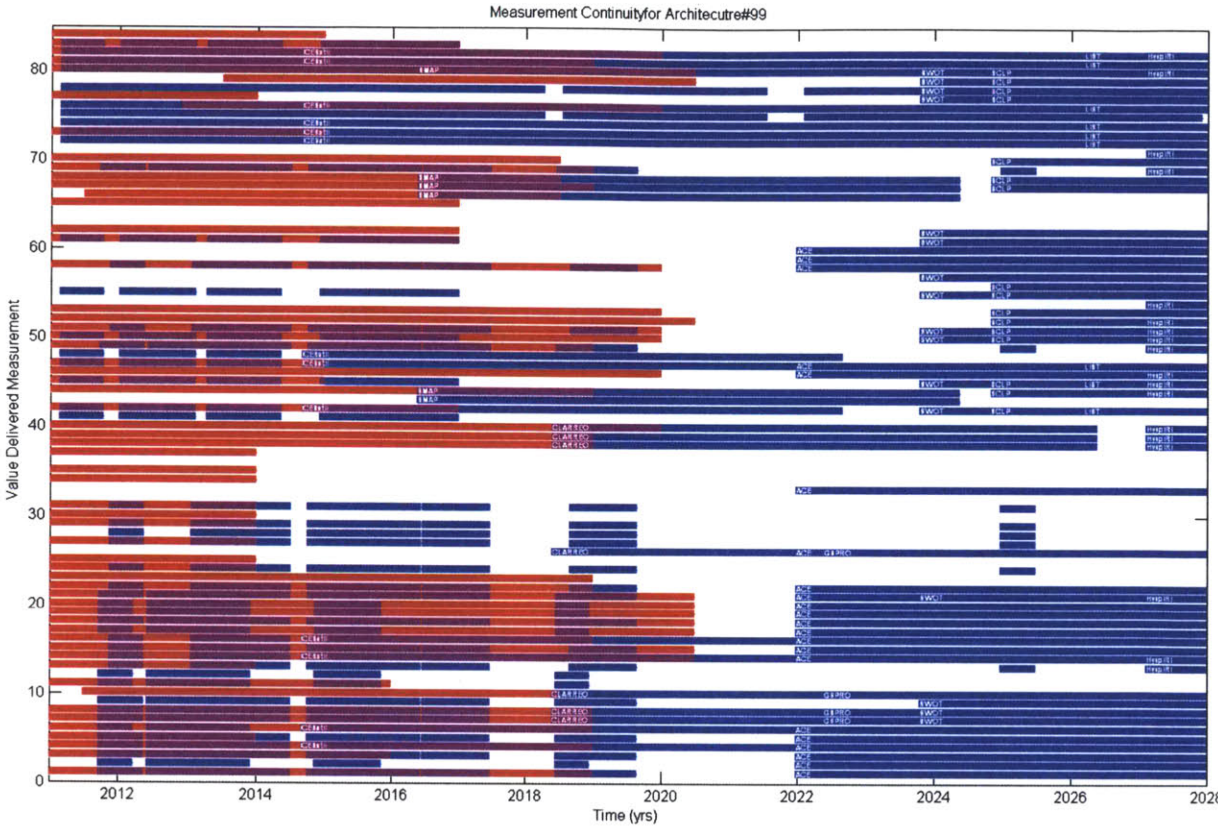


Figure 5.8: "Data Gap" Visualization shows the measurement gaps associated with the integrated campaign for the first 27 years (2011-2028). Note that only 35 of these 84 measurements were taken into account in the "Data Gap" metric calculation because of their importance to the Climate Panel. Decadal Survey satellite missions and Case Study aircraft missions are shown in blue, current and near-term mission in red, and the overlap is in pink.

Figure 5.8 shows that the aircraft missions are filling measurement gaps during the most important time of the campaign. This is best represented on the plot by the series of short missions gathering measurements 27-29 and 31. There is substantial overlap between aircraft missions and current US missions. This shows that with the addition of aircraft missions, the Climate panel becomes less dependent on currently operational and precursor satellite missions. This plot is useful as a decision support tool for campaign planners as it makes clear which measurements require a satellite mission extension and which ones can be covered by aircraft until the next satellite mission is ready to launch. This is especially important as currently operational satellite missions enter their extended campaigns. On a similar note, this tool provides support when deciding whether to advance development for a satellite mission to prepare for an unexpected gap or launch an aircraft mission to fill it. Overall the results of the campaign scheduling tool provide insight into the application and value of aircraft missions.

5.2.4. Conclusion

This chapter presents a methodology for integrating space-based and airborne observational platforms by using the Campaign-Level Science Traceability Matrix v2.0 with a Rules-Based Expert System. All of the instruments are characterized based on the measurements that they take and the attributes of those measurements. This allows for a comparison of the benefit that each mission provides to the Climate panel. The set of Decadal Survey satellite missions and the aircraft missions presented in the case studies are integrated using the GA for campaign scheduling. The results of this campaign scheduling algorithm show that the majority of aircraft missions launch before satellite missions. According to the model, the benefit from aircraft missions is lower but comparable to spacecraft missions. Since the cost of aircraft missions is lower, they offer better of value and thus contribute to optimizing the "Data Value" metric when scheduled first.

The analysis shows the potential of aircraft to fill data gaps for a fraction of the cost of satellite missions. It also shows that a robust campaign aircraft missions can mitigate the risk associated with aging operational missions and near-term missions whose launch dates slip.

Through application of the RBES method, more modeling complexities are uncovered. This chapter offers solutions to the problems of comparing missions with inherently different operating lifetimes and costs. The presented methodology can be extended to the full Decadal Survey panel set to gain futher insight into the entire GEOS.

The results of this analysis are subject to all of the assumptions that have been described. Some recommendations for future work are provided in the following section.

Future Work and Limitations

The first step in future work is to create rules for the other panels. This will lead to a more complete understanding of the GEOS and a more complete answer to the scheduling problem. Creating new rules requires significant input from scientists and system engineering experts.

The benefit/cost relationship discussed in sub-section 5.1.1 must be revisited with more fidelity added to the calculations. This could include creating mission simulations to determine actual coverage over an area of interest compared to actual coverage of a satellite system. The Satellite Tool Kit (STK) is a useful tool for this effort. A higher fidelity model of campaign cost could also be created with input from mission planners. The method presented here provides sufficient results given the resources available for this thesis, but more detailed cost estimates could be possible through collaboration with NASA personnel.

The next key step is extending the RBES to consider aircraft more specifically. This step would lead to the ability to create rules to capture synergies between measurements and instruments on the same platform. A detailed model could pair satellites and aircraft to create mission sets with more value. This requires a more complete set of Earth Science instruments to be characterized and considered.

With the RBES, including more rules in the analysis creates more realistic outcomes. As the set of instruments and possible missions expands, the number and depth of rules will as well. This is possible with the RBES because of its flexibility and the ease with which rules can be added. While the RBES is complex, it offers designers a way to trace their design drivers to their final results.

6. Conclusion and Recommendations

6.1. Conclusions

This thesis has shown that a benefit tracing framework, CSTM v1.1, can be applied to the set of satellite missions recommended by the Earth Science Decadal Survey. The CSTM v1.1 provides an assessment of the benefit each mission delivers to the scientific community. A Genetic Algorithm (GA) can be combined with the CSTM to support campaign scheduling. By modeling the assumptions used by the Decadal Survey, the GA campaign scheduling tool was able to recreate the campaign architecture proposed by the Decadal Survey.

An important result of this analysis is that if a technology readiness date is enforced using penalties applied to mission cost instead of hard constraints, certain low TRL missions are scheduled early in the campaign. Through such insights, it is shown then that the campaign scheduling algorithm can be used as a decision support tool not only for campaign architecting but for identifying priorities for technology investment.

After validation of the GA by reproducing the Decadal Survey campaign schedule, the assumptions were updated to reflect the current GEOS environment. The baseline campaign architecture is found to be highly sub-optimal when evaluated with the current mission costs, campaign budget, and technology readiness. In particular, when the campaign is spread over several decades due to budget constraints, long data gaps appear. These data gaps are harmful to the scientific community; therefore alternative mitigation strategies using airborne observational platforms were explored.

A survey of aircraft used in Earth observation was conducted in the form the three case studies. These case studies examined three modes of operation that are likely to be found in future airborne Earth science missions: sustained regional campaigns, local opportunity driven missions, and global in-situ data collection. Unmanned Aerial Vehicle (UAV) technology was found to be particularly promising due to its operating cost reduction potential and long endurance capability.

Integrating aircraft and spacecraft observations requires a level of fidelity not present in the CSTM v1.1. CSTM v2.0, which includes a Rule-Based Expert System (RBES), was successfully applied to the set of Decadal Survey satellite missions as well as the airborne missions examined in the case studies.

Due to the relatively low cost associated with airborne missions, they were found to be much more cost effective than space-based missions even when conservative cost estimates were used. As a consequence, aircraft are able to both produce a short-term source of high value missions and fill critical data gaps. Near-term aircraft missions also decrease the dependence of Earth scientists on current satellite missions with uncertain end-of-life dates and near-term satellite missions with uncertain launch dates.

6.2. Recommendations

Based on the analysis presented in this thesis, recommendations for the GEOS and NASA are presented below.

6.2.1. Space-based Global Earth Observation System

- Given the current GEOS environment, the baseline architecture proposed by the Decadal Survey should be reconsidered. Rescheduling certain missions will help to close expected data gaps and deliver more short-term value to the science community.
- Resources should be allocated to accelerate the development of technologies relevant to high value Decadal Survey 'Tier 2' missions such as GEO-CAPE.

6.2.2. Airborne Global Earth Observation System

- Airborne Earth observation missions should be considered for operational data collection. This recommendation is supported by several factors that have recently increased the value proposition of airborne observational platforms.
  - Budgets for Earth Science have stagnated and even decreased in some areas. This means that more cost effective solutions are required. While satellites deliver the most benefit to the science community, this analysis shows that aircraft provide better value (benefit at cost) up to a certain level of performance.
  - UAV technology was first used for operational Earth observation in the summer of 2010 when a Global Hawk UAS flew a 24 hour mission over the Pacific Ocean.
- Airborne missions should be considered to fill the near-term data gaps likely to occur. The next US Earth Science Decadal Survey should make specific recommendations for non-space-based observational platforms along these lines.
- Decision makers should consider, in particular, unmanned observational aircraft platforms. The use of UAVs will become more cost effective as experience is gained in operation and civilian applications increase.

6.2.3. NASA

- The Earth Venture series of Earth science missions, should be monitored closely. Lessons learned from its success or failure must be considered in architecting the future GEOS.
- Investment should be made in new aircraft to increase the value of airborne science. Operational costs of newer aircraft promise to be much lower than the aging aircraft now used around the world.

6.3. Future Work

This thesis builds on the CSTM benefit tracing framework to develop the CSTM v1.1 and v2.0. CSTM v2.0 integrates the higher fidelity RBES and allows for evaluation of a diverse set of observation platforms. Future work should focus on expanding this capability. The following list provides specific guidelines for future work.

- Complete the RBES framework by creating rules for the other panels. This will lead to a more complete understanding of the GEOS and a more complete answer to the scheduling problem. Creating new rules requires significant input from scientists and system engineering experts.
- Revisit the benefit/cost relationship of missions including more fidelity for both the benefit model and cost model. This could include creating mission simulations to determine actual coverage over an area of interest for both aircraft and satellite systems. The Satellite Tool Kit (STK) could be useful in this effort. A higher fidelity model of campaign cost could also be created with input from mission planners.

- Extend the RBES to consider synergies between aircraft and spacecraft. A detailed model could pair satellites and aircraft to create synergistic mission sets with more value. An example of this would be using an aircraft mission to calibrate a spacecraft instrument.
- Increase the breadth (number of instruments) and depth (number of attributes) of aircraft instrument characterization. This thesis presents a methodology for integrating airborne and space-based instruments into a single campaign scheduling framework, but it is limited by the extent of instrument selection. A more complete analysis will require a more complete set of instruments.
- Incorporate a more flexible instrument packaging algorithm so that new satellite and aircraft missions can be generated. This thesis used the Decadal Survey and case studies to define missions, but future work could generate missions based on the available instrument set to maximize stakeholder benefit for a given campaign budget.

7. Appendix

7.1. CSTM v1.1

Objective	Measurements
H1 Ozone Processes, Ultraviolet Radiation, and Cancer	[illegible]
H2 Heat Stress and Drought	[illegible]
H3 Acute Toxic Pollution and Releases	[illegible]
H4 Air Pollution and Respiratory and Cardiovascular Diseases	[illegible]
H5 Algal Blooms and Waterborne Infectious Diseases	[illegible]
H6 Vector-borne and Zoonotic Disease	[illegible]
Eco1 Ecosystem Function	[illegible]
Eco2 Ecosystem Structure and Biomass	[illegible]
Eco3 Carbon Budget	[illegible]
Eco4 Coastal Ecosystem Dynamics	[illegible]
Eco5 Global Ocean Productivity	[illegible]
SE1 Surface Deformation	[illegible]
SE2 Surface Composition and Thermal Properties	[illegible]
SE3 High Resolution Topography	[illegible]
SE4 Temporal Variation in Earth's Gravity Field	[illegible]
SE5 Oceanic Bathymetry	[illegible]
C1 Aerosol-Cloud Forcing	[illegible]
C2 Ice Sheet and Sea Ice Volume	[illegible]
C3 Carbon Sources and Sinks	[illegible]
C4 Radiance Calibration and Time-Reference Observatory	[illegible]
C5 Earth Radiation Budget (ERB) Continuity	[illegible]
C6 Ice Dynamics	[illegible]
C7 Ocean Circulation, Heat Storage, and Climate Forcing	[illegible]
W1 Tropospheric winds	[illegible]
W2 High temporal resolution air pollution	[illegible]
W3 All-weather temperature and humidity profiles	[illegible]
W4 Comprehensive tropospheric aerosol characterization	[illegible]
W5 Radio Occultation	[illegible]
W6 Comprehensive tropospheric O3 measurement	[illegible]
W7 Aerosol-cloud discovery	[illegible]
WA1 Soil moisture and freeze thaw state	[illegible]
WA2 Surface water and ocean topography	[illegible]
WA3 Snow and cold land processes	[illegible]
WA4 Water vapor transport	[illegible]
WA5 Sea ice thickness, glacier surface elevation and glacier velocity	[illegible]
WA6 Groundwater storage, ice sheet mass balance and ocean mass	[illegible]
WA7 Inland and coastal water quality	[illegible]

Table 7.1: The mapping of Measurement to Objective for CSTM v1.1 as discussed in section Error! Reference source not found. **and a sample of which was presented in Table 2.3.**

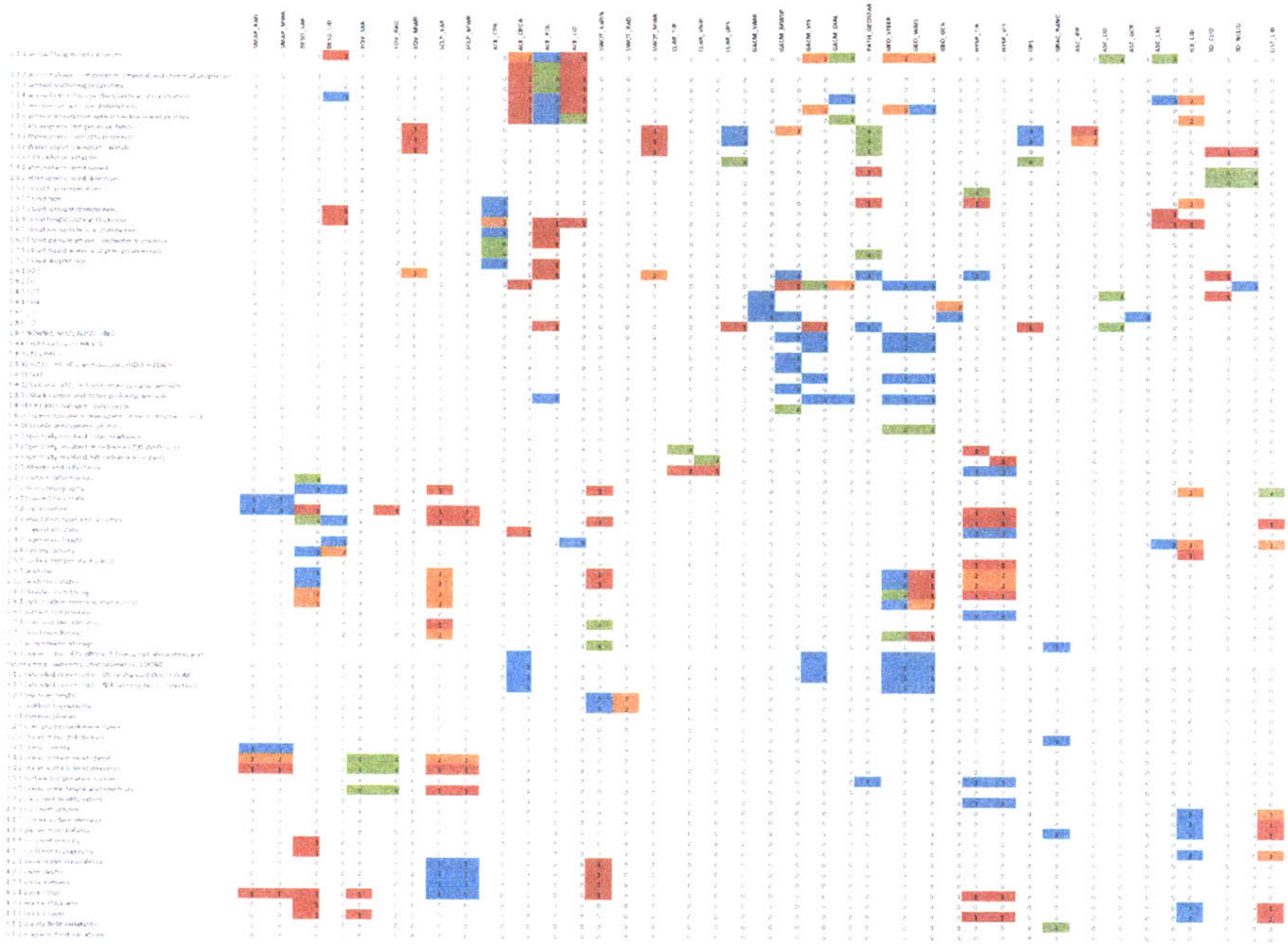


Table 7.2: Decadal Survey Instruments to Measurements mapping for CSTM v1.1 as discussed in section Error! Reference source not found. **and a sample of which was presented in Table 2.4.**

	SMAP	DESDynl	XOVWM	SCLP	ACE	SWOT	CLARREO	GACM	PATH	GEO-CAPE	HyspIRI	GSPRO	GRACEII	ASCENDS	ICESatII	3DWinds	LIST
SMAP_RAD	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SMAP_MWR	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DESD_SAR	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DESD_LID	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
XOV_SAR	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
XOV_RAD	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
XOV_MWR	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SCLP_SAR	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
SCLP_MWR	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ACE_CPR	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ACE_ORCA	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ACE_POL	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ACE_LID	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
SWOT_KaRIN	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
SWOT_RAD	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
SWOT_MWR	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
CLAR_TIR	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
CLAR_VNIR	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
CLAR_GPS	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
GACM_SWIR	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
GACM_MWSP	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
GACM_VIS	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
GACM_DIAL	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
PATH_GEOSTAR	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
GEO_STEER	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
GEO_WAIS	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
GEO_GCR	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
HYSP_TIR	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
HYSP_VIS	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
GPS	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
GRAC_RANG	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
ASC_IRR	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ASC_LID	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ASC_GCR	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ASC_LAS	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ICE_LID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
3D_CLID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3D_NCLID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
LIST_LID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 7.3: Missions to Instruments mapping for Decadal Survey as discussed in section Error! Reference source not found..

	GEO-CAPE	ACE	GACM	DESDynl	HyspIRI	SCLP	SWOT	ASCENDS	PATH	SMAP	3DWinds	ICESatII	XOVWM	LIST	CLARREO	GRACEII	GSPRO	Normalized Panel Score
Health	0.046	0.035	0.029	0.006	0.022	0.004	0.001	0.007	0.009	0.008	0.006	0.002	0.002	0.000	0.001	0.000	0.000	0.176
Ecosystems	0.044	0.021	0.022	0.030	0.027	0.008	0.003	0.019	0.004	0.000	0.001	0.005	0.000	0.005	0.001	0.000	0.001	0.191
Solid Earth	0.043	0.000	0.000	0.032	0.016	0.019	0.018	0.000	0.000	0.000	0.000	0.006	0.000	0.008	0.000	0.009	0.000	0.151
Climate	0.013	0.023	0.008	0.014	0.005	0.003	0.003	0.007	0.006	0.002	0.000	0.014	0.006	0.006	0.007	0.004	0.003	0.124
Weather	0.038	0.032	0.041	0.003	0.007	0.004	0.002	0.014	0.014	0.004	0.017	0.002	0.014	0.000	0.009	0.000	0.009	0.211
Water	0.008	0.002	0.001	0.007	0.010	0.025	0.024	0.001	0.006	0.025	0.012	0.007	0.005	0.002	0.002	0.006	0.002	0.147
Total Normalized Benefit	**0.191**	**0.113**	**0.101**	**0.092**	**0.087**	**0.064**	**0.051**	**0.048**	**0.039**	**0.039**	**0.037**	**0.036**	**0.026**	**0.022**	**0.020**	**0.018**	**0.016**	**1.000**

Table 7.4: Normalized Benefit for Decadal Survey Missions, which was shown graphically in Figure 2.6.

Measurements related to the atmosphere are shown in Table 7.5.

#	Measurement	Measurement Benefit (b_m)
1	1.1.1 aerosol height/optical depth	0.585
2	1.1.2 aerosol shape, composition, physical and chemical properties	0.752
3	1.1.3 aerosol scattering properties	0.585
4	1.1.4 aerosol extinction profiles/vertical concentration	0.752

5	1.1.5 aerosol size and size distribution	0.918
6	1.1.6 aerosol absorption optical thickness and profiles	0.000
7	1.2.1 Atmospheric temperature fields	0.133
8	1.3.1 Atmospheric humidity (indirect)	0.276
9	1.3.2 Water vapor transport - Winds	0.337
10	1.3.3 GPS radio occultation	0.112
11	1.4.1 atmospheric wind speed	0.503
12	1.4.2 atmospheric wind direction	0.337
13	1.5.1 cloud top temperature	0.167
14	1.5.2 Cloud type	0.432
15	1.5.3 Cloud amount/distribution	0.432
16	1.6.1 cloud height/optical thickness	0.432
17	1.6.2 cloud ice particle size distribution	0.432
18	1.6.3 Cloud particle phase - ice/water transition	0.432
19	1.7.1 Cloud liquid water and precipitation rate	0.752
20	1.7.2 Cloud droplet size	0.265
21	1.8.1 H2O	0.320
22	1.8.2 O3	0.639
23	1.8.3 CO2	0.367
24	1.8.4 CH4	0.446
25	1.8.5 CO	0.839
26	1.8.6 O2	0.353
27	1.8.7 NOx(NO, NO2), N2O5, HNO3	0.639
28	1.8.8 CH2O and non-CH4 VOC	0.639
29	1.8.9 CFCs/HFCs	0.000
30	1.8.10 H2O2, OH, HO2 and isotopes (HDO, H218O)	0.167
31	1.8.11 SO2	0.473
32	1.8.12 Vulcanic SO2, OCS and other vulcanic aerosols	0.000
33	1.8.13 Black carbon and other polluting aerosols	0.473
34	1.8.14 ClO, BrO, halogen compounds	0.167
35	1.8.15 Upper-troposphere/stratosphere - Polar Stratospheric Clouds	0.000
36	1.8.16 Visible atmospheric plumes	0.167
37	1.9.1 Spectrally resolved solar irradiance	0.133
38	1.9.2 Spectrally resolved IR radiance (200-2000cm-1)	0.299
39	1.9.3 Spectrally resolved SW radiance (0.3-2um)	0.133

Table 7.5: Atmosphere Measurements with Measurements Scores (b_m).

Land use and ecosystem measurements are related to how the land or water surrounded by land is being used or is reacting to the environment.

#	Measurement	Measurement Benefit (b_m)
40	2.1.1 Albedo and reflectance	0.000
41	2.2.1 surface deformation	0.280
42	2.2.2 Hi-res topography	0.200
43	2.3.1 Freeze/thaw state	0.204
44	2.3.2 soil moisture	0.537
45	2.4.1 vegetation type and structure	0.424

46	2.4.2 vegetation state	0.613
47	2.4.3 vegetation height	0.424
48	2.4.4 canopy density	0.424
49	2.5.1 Surface temperature (land)	0.333
50	2.6.1 land use	0.082
51	2.6.2 landcover status	0.528
52	2.6.3 disaster monitoring	0.800
53	2.6.4 hydrocarbon reservoir monitoring	0.520
54	2.6.5 surface composition	0.240
55	2.7.1 river and lake elevation	0.184
56	2.7.2 flood monitoring	0.200
57	2.7.3 groundwater storage	0.242

Table 7.6: Land/Ecosystem Measurements with Measurements Scores (b_m).

These measurements also open the possibility of using non-traditional platforms like submersibles or surface ships.

#	Measurement	Measurement Benefit (b_m)
58	3.1.1 Ocean color - 410-680nm (Chlorophyll absorption and fluorescence, pigments, phytoplankton, CDOM)	0.879
59	3.1.2 Extended ocean color - UV (enhanced DOC, CDOM)	0.464
60	3.1.3 Extended ocean color - NIR (atmospheric correction)	0.712
61	3.2.1 Sea level height	0.265
62	3.2.2 seafloor topography	0.324
63	3.2.4 thermal plumes	0.000
64	3.2.5 river plumes/sediment fluxes	0.327
65	3.2.6 Ocean mass distribution	0.324
66	3.3.1 Ocean salinity	0.000
67	3.4.1 Ocean surface wind speed	0.276
68	3.4.2 Ocean surface wind direction	0.276
69	3.5.1 Surface temperature (ocean)	0.401
70	3.6.1 Ocean wave height and spectrum	0.000
71	3.7.2 coral reef health/extent	0.280

Table 7.7: Ocean Measurements with Measurements Scores (b_m)

Ice covered regions also tends to be in relatively remote locations like Antarctica or Greenland, which provide unique operating environments and will be discussed in the first case study presented in Chapter4

#	Measurement	Measurement Benefit (b_m)
72	4.1.1 ice sheet volume	0.184
73	4.1.2 Glacier surface elevation	0.306
74	4.1.3 glacier mass balance	0.426
75	4.1.4 Ice sheet velocity	0.224
76	4.1.5 Ice Sheet topography	0.184
77	4.2.1 snow-water equivalence	0.163
78	4.2.2 snow depth	0.163
79	4.2.3 snow wetness	0.163

80	4.2.4 snow cover	0.163
81	4.3.1 Sea ice thickness	0.306
82	4.3.2 Sea ice cover	0.306

Table 7.8: Ice Measurements with Measurements Scores (b_m).

Measurements related to gravity and magnetism find applications on a local level with reservoir detection and tracking whereas most of the science is conducted on a large scale..

#	Measurement	Measurement Benefit (b_m)
83	5.1.1 gravity field variations	0.222
84	5.1.2 magnetic field variations	0.000

Table 7.9: Gravity/Magnetism Measurements with Measurements Scores (b_m).

1.1.6 aerosol absorption optical thickness and profiles
1.8.9 CFCs/HFCs
1.8.12 Vulcanic SO2, OCS and other vulcanic aerosols
1.8.15 Upper-troposphere/stratosphere - Polar Stratospheric Clouds
2.1.1 Albedo and reflectance
3.2.4 thermal plumes
3.3.1 Ocean salinity
3.6.1 Ocean wave height and spectrum
5.1.2 magnetic field variations

Table 7.10: Non-Value Adding Measurements

7.2. Matlab Code

For Matlab code, email Brandon Suarez at brandons@alum.mit.edu

7.3. Satellite-only Campaign Architectures

Schedule :	Normalize(	Normalized	Data Gap	SMAP	DESDy	XOVWI	SCLP	ACE	SWOT	CLARR	GACM	PATH	GEO-C	HyspIR	GSPRC	GRACE	ASCEN	ICESatl	3DWinc	LIST
1	0.700451	127.6012	0.349869	5	3	11	17	8	9	4	14	15	6	7	2	16	10	1	12	13
2	0.701124	127.9903	0.350379	5	3	11	16	8	9	4	14	15	6	7	2	17	10	1	12	13
3	0.700915	127.9194	0.351817	4	3	11	16	8	9	5	14	15	6	7	2	17	10	1	12	13
4	0.700242	127.5303	0.351833	4	3	11	17	8	9	5	14	15	6	7	2	16	10	1	12	13
5	0.699553	127.1412	0.354354	5	3	11	17	8	9	4	14	16	6	7	2	15	10	1	12	13
6	0.699344	127.0703	0.356952	4	3	11	17	8	9	5	14	16	6	7	2	15	10	1	12	13
7	0.700546	127.8818	0.357813	4	3	11	17	8	9	5	14	15	6	7	1	16	10	2	12	13
8	0.701428	128.3419	0.358176	5	3	11	16	8	9	4	14	15	6	7	1	17	10	2	12	13
9	0.699857	127.4928	0.358825	5	3	11	17	8	9	4	14	16	6	7	1	15	10	2	12	13
10	0.701219	128.2709	0.359258	4	3	11	16	8	9	5	14	15	6	7	1	17	10	2	12	13
11	0.701656	128.4782	0.359499	5	3	11	17	8	10	4	14	15	6	7	2	16	9	1	12	13
12	0.701447	128.4073	0.360402	4	3	11	17	8	10	5	14	15	6	7	2	16	9	1	12	13
13	0.699648	127.4218	0.361068	4	3	11	17	8	9	5	14	16	6	7	1	15	10	2	12	13
14	0.701834	128.6188	0.362095	5	3	11	17	8	9	4	13	15	6	7	2	16	10	1	12	14
15	0.702329	128.8673	0.364263	5	3	11	16	8	10	4	14	15	6	7	2	17	9	1	12	13
16	0.70212	128.7964	0.364649	4	3	11	16	8	10	5	14	15	6	7	2	17	9	1	12	13
17	0.702508	129.0079	0.367478	5	3	11	16	8	9	4	13	15	6	7	2	17	10	1	12	14
18	0.698697	127.06	0.371605	4	3	10	17	8	9	5	14	16	6	7	2	15	11	1	12	13
19	0.702633	129.2188	0.374731	5	3	11	16	8	10	4	14	15	6	7	1	17	9	2	12	13
20	0.698266	126.906	0.377485	5	3	11	17	8	9	4	14	16	6	7	2	13	10	1	12	15
21	0.702811	129.3503	0.377911	5	3	11	16	8	9	4	13	15	6	7	1	17	10	2	12	14
22	0.698057	126.835	0.3806	4	3	11	17	8	9	5	14	16	6	7	2	13	10	1	12	15
23	0.70283	129.4248	0.380943	4	3	11	17	8	10	5	13	15	6	7	2	16	9	1	12	14
24	0.703039	129.4957	0.381191	5	3	11	17	8	10	4	13	15	6	7	2	16	9	1	12	14
25	0.703059	129.5868	0.385016	4	3	11	16	8	9	5	14	12	6	7	2	17	10	1	15	13
26	0.703268	129.6578	0.385436	5	3	11	16	8	9	4	14	12	6	7	2	17	10	1	15	13
27	0.697188	126.2237	0.387423	5	3	11	17	8	9	4	15	16	6	7	2	14	10	1	12	13
28	0.697492	126.5753	0.387866	5	3	11	17	8	9	4	15	16	6	7	1	14	10	2	12	13
29	0.703504	129.8139	0.389572	4	3	11	16	8	10	5	13	15	6	7	2	17	9	1	12	14
30	0.703712	129.8848	0.390287	5	3	11	16	8	10	4	13	15	6	7	2	17	9	1	12	14
31	0.696979	126.1528	0.391242	4	3	11	17	8	9	5	15	16	6	7	2	14	10	1	12	13
32	0.697283	126.5043	0.391384	4	3	11	17	8	9	5	15	16	6	7	1	14	10	2	12	13
33	0.696765	126.129	0.396264	4	3	11	17	8	9	5	15	16	6	7	2	13	10	1	12	14
34	0.703801	130.1467	0.401467	5	3	11	17	8	10	4	14	12	6	7	2	16	9	1	15	13
35	0.703807	130.1563	0.40185	4	3	11	16	8	10	5	13	15	6	7	1	17	9	2	12	14
36	0.70381	130.1664	0.402294	4	3	11	17	8	9	5	13	12	6	7	2	16	10	1	15	14
37	0.704016	130.2272	0.402828	5	3	11	16	8	10	4	13	15	6	7	1	17	9	2	12	14
38	0.704019	130.2373	0.403276	5	3	11	17	8	9	4	13	12	6	7	2	16	10	1	15	14
39	0.704264	130.464	0.411425	4	3	11	16	8	10	5	14	12	6	7	2	17	9	1	15	13
40	0.704473	130.5349	0.412703	5	3	11	16	8	10	4	14	12	6	7	2	17	9	1	15	13
41	0.696118	126.1186	0.412786	4	3	10	17	8	9	5	15	16	6	7	2	13	11	1	12	14
42	0.704482	130.5547	0.413568	4	3	11	16	8	9	5	13	12	6	7	2	17	10	1	15	14
43	0.704691	130.6256	0.414967	5	3	11	16	8	9	4	13	12	6	7	2	17	10	1	15	14
44	0.695979	126.0671	0.415382	4	3	11	17	8	9	5	16	15	6	7	2	14	10	1	12	13
45	0.695764	126.0433	0.420533	4	3	11	17	8	9	5	16	15	6	7	2	13	10	1	12	14
46	0.704794	130.8312	0.423998	4	3	11	17	8	9	5	12	14	6	7	2	16	10	1	15	13
47	0.705003	130.9021	0.425606	5	3	11	17	8	9	4	12	14	6	7	2	16	10	1	15	13
48	0.705019	130.9868	0.429609	5	3	11	16	8	9	4	12	15	6	7	2	17	10	1	14	13
49	0.705224	131.1145	0.434185	5	3	11	17	8	10	4	13	12	6	7	2	16	9	1	15	14
50	0.705284	131.1461	0.435262	4	3	11	17	8	9	5	12	13	6	7	2	16	10	1	15	14
51	0.705493	131.2171	0.437149	5	3	11	17	8	9	4	12	13	6	7	2	16	10	1	15	14
52	0.695117	126.0329	0.437313	4	3	10	17	8	9	5	16	15	6	7	2	13	11	1	12	14
53	0.705676	131.2912	0.439485	5	3	11	16	8	9	4	12	14	6	7	2	17	10	1	15	13
54	0.705687	131.4318	0.446408	4	3	11	16	8	10	5	13	12	6	7	2	17	9	1	15	14
55	0.694655	125.949	0.448046	5	3	13	17	8	9	4	15	16	6	7	2	12	10	1	11	14
56	0.705896	131.5028	0.448516	5	3	11	16	8	10	4	13	12	6	7	2	17	9	1	15	14
57	0.705957	131.5352	0.449735	4	3	11	16	8	9	5	12	13	6	7	2	17	10	1	15	14
58	0.706166	131.6062	0.45197	5	3	11	16	8	9	4	12	13	6	7	2	17	10	1	15	14
59	0.694446	125.878	0.452393	4	3	13	17	8	9	5	15	16	6	7	2	12	10	1	11	14
60	0.706208	131.7791	0.460412	5	3	11	17	8	10	4	12	14	6	7	2	16	9	1	15	13
61	0.694128	125.8595	0.460554	4	3	14	17	8	9	5	15	16	6	7	2	12	10	1	11	13
62	0.693881	125.6177	0.463959	5	3	11	17	9	8	4	15	16	6	7	2	14	10	1	12	13
63	0.706224	131.8638	0.464573	5	3	11	16	8	10	4	12	15	6	7	2	17	9	1	14	13
64	0.706261	131.8776	0.465059	4	3	11	16	8	9	5	12	13	6	7	1	17	10	2	15	14
65	0.70647	131.9486	0.467466	5	3	11	16	8	9	4	12	13	6	7	1	17	10	2	15	14
66	0.693652	125.5467	0.468571	4	3	11	17	9	8	5	15	16	6	7	2	14	10	1	12	13
67	0.706489	132.0231	0.471128	4	3	11	17	8	10	5	12	13	6	7	2	16	9	1	15	14
68	0.706698	132.094	0.473641	5	3	11	17	8	10	4	12	13	6	7	2	16	9	1	15	14
69	0.693438	125.5237	0.474034	4	3	11	17	9	8	5	15	16	6	7	2	13	10	1	12	14
70	0.706881	132.1682	0.476525	5	3	11	16	8	10	4	12	14	6	7	2	17	9	1	15	13
71	0.707162	132.4122	0.48771	4	3	11	16	8	10	5	12	13	6	7	2	17	9	1	15	14
72	0.707371	132.4831	0.490514	5	3	11	16	8	10	4	12	13	6	7	2	17	9	1	15	14
73	0.692794	125.5142	0.491377	4	3	10	17	9	8	5	15	16	6	7	2	13	11	1	12	14
74	0.692656	125.4614	0.494438	4	3	11	17	9	8	5	16	15	6	7	2	14	10	1	12	13

Table 7.11: Listed Rank and Metrics for Campaign Architectures with Mission Position (Sample)

Rank	Normalizec	Normalizec	Normalizec	SMAP	DESDynl	XOVWM	SCLP	ACE	SWOT	CLARREO	GACM	PATH	GEO-CAP	HyspIRI	GSPRO	GRACEII	ASCENDS	ICESatII	3DWinds	LIST
1	0.700451	127.6012	0.349869	5	3	11	17	8	9	4	14	15	6	7	2	16	10	1	12	13
0	0	0	0	2012.3	2011.54	2017.33	2021.27	2015.72	2016.32	2011.9	2019.4	2020	2013.9	2014.53	2010.6	2020.6	2016.86	2010.4	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
2	0.701124	127.9903	0.350379	5	3	11	16	8	9	4	14	15	6	7	2	17	10	1	12	13
0	0	0	0	2012.3	2011.54	2017.33	2020.67	2015.72	2016.32	2011.9	2019.4	2020	2013.9	2014.53	2010.6	2021.27	2016.86	2010.4	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
3	0.700915	127.9194	0.351817	4	3	11	16	8	9	5	14	15	6	7	2	17	10	1	12	13
0	0	0	0	2011.94	2011.54	2017.33	2020.67	2015.72	2016.32	2012.3	2019.4	2020	2013.9	2014.53	2010.6	2021.27	2016.86	2010.4	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
4	0.700242	127.5303	0.351833	4	3	11	17	8	9	5	14	15	6	7	2	16	10	1	12	13
0	0	0	0	2011.94	2011.54	2017.33	2021.27	2015.72	2016.32	2012.3	2019.4	2020	2013.9	2014.53	2010.6	2020.6	2016.86	2010.4	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
5	0.699553	127.1412	0.354354	5	3	11	17	8	9	4	14	16	6	7	2	15	10	1	12	13
0	0	0	0	2012.3	2011.54	2017.33	2021.27	2015.72	2016.32	2011.9	2019.4	2020.6	2013.9	2014.53	2010.6	2020	2016.86	2010.4	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
6	0.699344	127.0703	0.356952	4	3	11	17	8	9	5	14	16	6	7	2	15	10	1	12	13
0	0	0	0	2011.94	2011.54	2017.33	2021.27	2015.72	2016.32	2012.3	2019.4	2020.6	2013.9	2014.53	2010.6	2020	2016.86	2010.4	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
7	0.700546	127.8818	0.357813	4	3	11	17	8	9	5	14	15	6	7	1	16	10	2	12	13
0	0	0	0	2011.94	2011.54	2017.33	2021.27	2015.72	2016.32	2012.3	2019.4	2020	2013.9	2014.53	2010.2	2020.6	2016.86	2010.6	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
8	0.701428	128.3419	0.358176	5	3	11	16	8	9	4	14	15	6	7	1	17	10	2	12	13
0	0	0	0	2012.3	2011.54	2017.33	2020.67	2015.72	2016.32	2011.9	2019.4	2020	2013.9	2014.53	2010.2	2021.27	2016.86	2010.6	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
9	0.699857	127.4928	0.358825	5	3	11	17	8	9	4	14	16	6	7	1	15	10	2	12	13
0	0	0	0	2012.3	2011.54	2017.33	2021.27	2015.72	2016.32	2011.9	2019.4	2020.6	2013.9	2014.53	2010.2	2020	2016.86	2010.6	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
10	0.701219	128.2709	0.359258	4	3	11	16	8	9	5	14	15	6	7	1	17	10	2	12	13
0	0	0	0	2011.94	2011.54	2017.33	2020.67	2015.72	2016.32	2012.3	2019.4	2020	2013.9	2014.53	2010.2	2021.27	2016.86	2010.6	2018.2	2018.6
0	0	0	0	300	700	350	500	888.5202455	450	265	600	450	1195.735	468.6245	150	450	400	300	650	300
				300	700	350	500	800	450	265	600	450	550	300	150	450	400	300	650	300
								11%					117%	56%						

Rank	Mission_1	Launch Dε	Mission_5	Launch Dε	Top Value Architecture	Mission	Launch Dε	Top Data Gap Architecture	Mission	Launch Dates
1	ICESatII	2010.4	ICESatII	2010.4	0	GSPRO	2010.2	0	ICESatII	2010.4
2	GSPRO	2010.6	GSPRO	2010.6	0	CLARREO	2010.56	0	GSPRO	2010.6
3	DESDynl	2011.54	DESDynl	2011.54	0	ICESatII	2010.96	0	DESDynl	2011.54
4	CLARREO	2011.9	CLARREO	2011.9	0	DESDynl	2011.9	0	SMAP	2011.94
5	SMAP	2012.3	SMAP	2012.3	0	SMAP	2012.3	0	GEO-CAP	2013.7
6	GEO-CAP	2013.9	GEO-CAP	2013.9	0	GEO-CAP	2013.9	0	HyspIRI	2014.36
7	HyspIRI	2014.53	HyspIRI	2014.53	0	HyspIRI	2014.53	0	SWOT	2015.15
8	ACE	2015.72	ACE	2015.72	0	ACE	2015.72	0	ACE	2016.22
9	SWOT	2016.32	SWOT	2016.32	0	ASCENDS	2016.26	0	XOVWM	2016.69
10	ASCENDS	2016.86	ASCENDS	2016.86	0	XOVWM	2016.73	0	3DWinds	2017.67
11	XOVWM	2017.33	XOVWM	2017.33	0	GACM	2017.64	0	GRACEII	2018.27
12	3DWinds	2018.2	3DWinds	2018.2	0	PATH	2018.24	0	LIST	2018.67
13	LIST	2018.6	LIST	2018.6	0	SCLP	2018.91	0	CLARREO	2019.03
14	GACM	2019.4	GACM	2019.4	0	SWOT	2019.51	0	ASCENDS	2019.57
15	PATH	2020	GRACEII	2020	0	3DWinds	2020.38	0	PATH	2020.17
16	GRACEII	2020.6	PATH	2020.6	0	LIST	2020.78	0	GACM	2020.97
17	SCLP	2021.27	SCLP	2021.27	0	GRACEII	2021.38	0	SCLP	2021.64

Table 7.12: Formatted List of Top 5 Campaign Architectures with Launch and Cost Details (Sample)

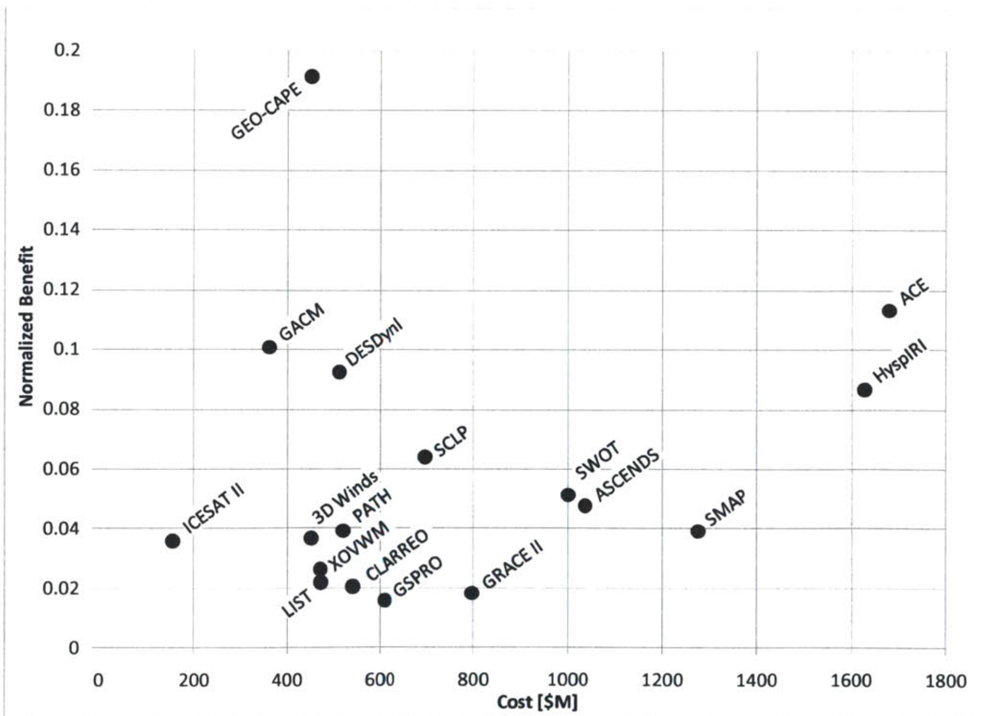


Figure 7.1: Benefit/Cost for Updated Case

Category	Sub-Category	Mission	Prior Spent	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Total FY06-FY16	FY11-FY16
Earth Science				1,325.60	1,198.50	1,237.40	1,702.30	1,439.30	1,439.30	1,653.00	1,679.20	1,665.30	1,691.40	1,727.30	16,758.60	9,855.50
	Earth Science Research		-	**481.00**	**349.50**	**358.30**	**437.40**	**375.80**	**375.80**	**409.60**	**419.00**	**427.30**	**436.70**	**444.60**	**4,515.00**	**2,513.00**
	Applied Sciences		-	**94.80**	**33.90**	**40.20**	**47.80**	**35.30**	**35.30**	**33.10**	**34.30**	**35.50**	**36.70**	**36.90**	**463.80**	**211.80**
	Earth Science Multi-Mission Operations		-	**190.40**	**168.00**	**143.00**	**146.00**	**149.00**	**149.00**	**159.90**	**158.80**	**159.40**	**162.90**	**166.60**	**1,753.00**	**956.60**
	Earth Systematic Mission		-	**356.10**	**420.90**	**546.10**	**893.70**	**705.20**	**705.20**	**816.50**	**838.70**	**761.60**	**763.20**	**810.70**	**7,617.90**	**4,695.90**
		Current Missions		**356.10**	**420.90**	**498.70**	**616.70**	**543.50**	**543.50**	**423.30**	**311.70**	**224.00**	**209.30**	**201.80**		
		Decadal Survey Missions				**47.40**	**277.00**	**161.70**	**161.70**	**393.20**	**527.00**	**537.60**	**553.90**	**608.90**		
		NPP	492.10	28.80	47.30	46.10	42.20	82.10	82.10	13.60	6.40	6.30	6.00	5.50	858.50	119.90
		Glory	70.80	8.50	91.80	82.30	61.00	31.80	31.80	5.30	3.80	6.10	5.90	6.00	405.10	58.90
		GPM	-	23.40	23.80	74.40	143.80	155.00	155.00	83.80	68.70	41.40	27.20	20.10	816.60	396.20
		LDCM	-	56.60	45.90	127.30	200.90	106.00	106.00	152.00	64.10	1.50	1.50	1.60	863.40	326.70
		OSTM	-	-	42.80	-	-	-	-	-	-	-	-	-	42.80	-
		ICESat-II	-	-	-	9.60	38.80	38.90	38.90	102.10	159.40	128.80	83.10	28.60	628.20	540.90
		SMAP	-	-	-	9.60	103.30	70.00	70.00	135.20	172.30	31.10	29.60	14.50	635.60	452.70
		Decadal Survey Missions	-	-	0.60	16.80	-	-	-	-	-	-	-	-	17.40	-
		Other	-	21.20	168.70	180.10	303.60	221.50	221.50	324.60	364.00	546.40	609.90	734.50	3,696.00	2,800.90
	Earth System Science Pathfinder		-	**133.40**	**167.90**	**106.80**	**122.10**	**128.40**	**128.40**	**187.80**	**180.60**	**229.50**	**238.40**	**214.30**	**1,837.60**	**1,179.00**
		Aquarius	35.60	40.90	62.40	33.40	46.90	22.30	22.30	4.90	4.60	4.90	5.10	5.20	288.50	47.00
		OCO	72.80	40.80	84.80	-	-	-	-	-	-	-	-	-	198.40	-
		Venture Class Missions	-	-	-	-	21.00	6.30	6.30	61.50	103.90	179.70	196.60	175.70	751.00	723.70
		OCO-2	-	-	-	-	-	62.00	62.00	91.00	41.00	13.00	4.00	-	273.00	211.00
		Other	-	51.70	20.60	73.40	54.30	37.90	37.90	30.50	31.10	31.90	32.70	33.40	435.40	197.50
	Earth Science Technology		-	**69.90**	**58.40**	**43.00**	**55.30**	**45.60**	**45.60**	**46.10**	**47.90**	**51.90**	**53.60**	**54.20**	**571.50**	**299.30**

Table 7.13: Earth Science Division FY06-FY16 Budget Analysis

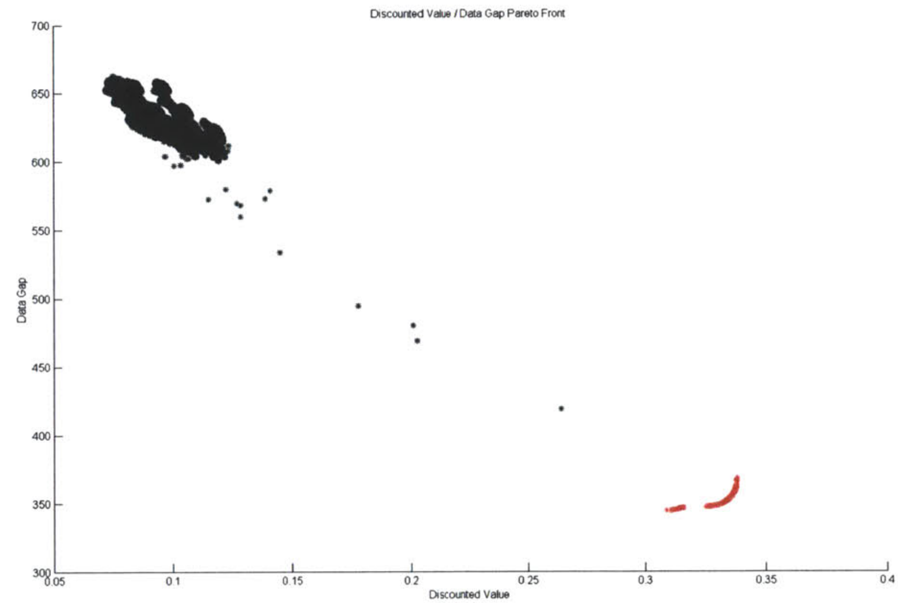


Figure 7.2: Decadal Survey 'Tier' Architectures Compared to GA Results, Updated Case

7.3.1. Budget Analysis

Budget Analysis	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020 and Beyond
High	161.7	393.2	527.0	579.7	637.6	701.4	771.6	848.7	933.6	1000.0
Medium High	161.7	393.2	527.0	579.7	637.6	701.4	750.0	750.0	750.0	750.0
Baseline	161.7	393.2	527.0	537.6	553.9	608.9	500.0	500.0	500.0	500.0
Medium Low	161.7	393.2	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0
Low	161.7	250.0	250.0	250.0	250.0	250.0	250.0	250.0	250.0	250.0

Table 7.14: Budget Analysis Scenarios

a)		b)		c)		d)		e)	
ICESatII	2014.55	SMAP	2013.19	SMAP	2013.15	SMAP	2013.15	SMAP	2013.15
SMAP	2016.37	ICESatII	2014.72	ICESatII	2014.42	ICESatII	2014.39	ICESatII	2014.39
GEO-CAPE	2022.23	GSPRO	2015.55	GSPRO	2015.1	GSPRO	2015.03	GSPRO	2015.03
HyspIRI	2024.04	DESDynI	2019.75	DESDynI	2018.15	DESDynI	2017.81	DESDynI	2017.8
ASCENDS	2025.94	GEO-CAPE	2023.96	CLARREO	2020.15	GEO-CAPE	2019.74	HyspIRI	2018.64
GACM	2030.09	HyspIRI	2025.09	GEO-CAPE	2023.74	HyspIRI	2020.35	GEO-CAPE	2020.04
SCLP	2032.14	ASCENDS	2026.28	HyspIRI	2024.65	ASCENDS	2020.99	SWOT	2020.74
ACE	2038.66	SWOT	2028.03	ASCENDS	2025.6	XOVWM	2021.48	ASCENDS	2021.22
XOVWM	2040.11	XOVWM	2028.94	SWOT	2027	SWOT	2022.42	XOVWM	2021.59
SWOT	2042.91	GACM	2031.54	XOVWM	2027.73	ACE	2024.6	ACE	2023.22
GRACEII	2044.8	PATH	2032.85	ACE	2030.99	GRACEII	2025.23	3DWinds	2024.02
GSPRO	2045.42	GRACEII	2034.03	GRACEII	2031.94	PATH	2025.93	GRACEII	2024.5
DESDynI	2046	SCLP	2035.31	GACM	2034.02	GACM	2027.32	LIST	2025.11
PATH	2046	ACE	2039.38	SCLP	2035.05	SCLP	2028.01	PATH	2025.64
CLARREO	2046	3DWinds	2041.38	PATH	2036.1	LIST	2028.83	GACM	2026.68
LIST	2046	LIST	2042.91	LIST	2037.32	3DWinds	2029.9	SCLP	2027.2
3DWinds	2046	CLARREO	2045.41	3DWinds	2038.92	CLARREO	2031.24	CLARREO	2028.2

Table 7.15: Budget Analysis Top-Ranked Campaign Exploration

7.4. Airborne Case Studies

Flight Configurations	2009	2010	2011	2012	2013	2014
Greenland	1L,1M, 3H; 1L	1L; 1L	1L,4N; 1L,4N	1L; 1L	1L; 1L	1L; 1L
Arctic Sea	1L, 8D; 1L	1L; 1L	1L; 1L	1L; 1L	1L; 1L	1L; 1L
Antarctic sub-glacial	0; 0	2L; 6AB	6AB; 5L	5L; 5L	5L; 5L	5L; 5L
Antarctic coastal	0; 2L	2L; 6AB	6AB; 5L	5L; 5L	5L; 5L	5L; 5L
Alaska SE	7A, 3K; 7A, 3K	7A; 7A	7A; 7A	7A; 7A	7A; 7A	7A; 7A

Table 7.16: Operation Ice Bridge Trade-Off Configurations

Code	Instrument	Type	PI
A	ATM	Laser altimeter	Krabil
B	LVIS	Laser altimeter	Blair
C	MFFL	Laser altimeter	Dobbs/ITT
D	Ice Roughness profilometer	Laser altimeter	Maslanik
E	SIMPL	Laser altimeter	Harding
F	PCL	Laser altimeter	Gogineni
G	Mapping Laser altimeter	Laser altimeter	Yu
H	Ka-band UAVSAR	Radar Sounder	Moller
I	PARIS	Radar Sounder	Raney
J	Ku-Radar Sounder	Radar Sounder	Jezek/Gogineni
K	ultrawideband KU	Radar Sounder	Gogineni
L	ATM, LVIS, KuRadar Sounds/PARIS	Combination	Team
M	LVIS, KuRadar Sounds/PARIS	Combination	Team
N	SIIMPL, SMLA, MFLL, PCL	Combination	Team
O	KuRadar Sounds/PARIS	Combination	Team
Code	**Platform**		
1	P-3		

2	DC-8
3	Gulfstream 3 (G-3)
4	S-3
5	Global Hawk (GH)
6	HAIPER (NSF) (G5)
7	B/200/Twin Otter
8	SUAS
9	L-1011
10	Lear 25

Table 7.17: OIB Configuration Key

7.5. Integrating Aircraft

Aircraft has been done in the past with NASA's fleet of manned and unmanned aircraft that perform Earth science missions on a monthly basis. NASA's Airborne Science Program (ASP) is responsible for this asset that has gained wide acceptance as a vital set of platforms for Earth Science. Furthermore, the science community has come to expect the flexibility and ease of access that these aircraft provide, meaning that any future GEOS architecture should systematically include them.

Instrument	Acronym	Measurement(s)	Coverage	Horizontal Spatial Resolution	Temporal Resolution	Spectral Sampling	Accuracy	Polarimetry	Swath	On Board Calibration	Radiometric Accuracy	Aircraft	Campaign
Airborne Compact Atmospheric Mapper	ACAM	1.8.7 NOx(NO, NO2), N2O5, HNO3	Most	Medium	Medium	Hyperspectral	High	yes	Narrow-10km	Some	High	Global Hawk	GLOPAC
		1.8.2 O3	Most	Medium	Medium	Hyperspectral	High	yes	Narrow-10km	Some	High	WB-57	
		1.1.3 aerosol scattering properties	Most	Medium	Medium	Hyperspectral	High	yes	Narrow-10km	Some	High		
		3.1.1 Ocean color - 410-680nm (Chlorophyll absorption and fluorescence, pigments, phytoplankton, CDOM)	Most	Medium	Medium	Hyperspectral	High	yes	Narrow-10km	Some	High		
		1.8.11 SO2	Most	Medium	Medium	Hyperspectral	High	yes	Narrow-10km	Some	High		
		1.8.8 CH2O and non-CH4 VOC	Most	Medium	Medium	Hyperspectral	High	yes	Narrow-10km	Some	High		
		2.6.2 landcover status	Most	Medium	Medium	Single-band	High	yes	Narrow-10km	None	High		
Cloud Physics LIDAR	CPL	1.1.3 aerosol scattering properties	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	High	Global Hawk	GLOPAC
		1.5.3 Cloud amount/distribution	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	High	ER-2	
		1.6.1 cloud height/optical thickness	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	High		
		1.1.1 aerosol height/optical depth	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	High		
		1.6.3 Cloud particle phase - ice/water transition	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	High		
		1.1.4 aerosol extinction profiles/vertical concentration	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	High		
Focused Cavity Aerosol Spectrometer / Nuclei Mode Aerosol Size Spectrometer	FCAS/NMASS	1.1.3 aerosol scattering properties	Some	Highest	Medium	Single-band	High	no	None	None	High	Global Hawk	GLOPAC
		1.1.4 aerosol extinction profiles/vertical concentration	Some	Highest	Medium	Single-band	High	no	None	None	High	ER-2	
		1.1.5 aerosol size and size distribution	Some	Highest	Medium	Single-band	High	no	None	None	High	WB-57	
			Some	Highest	Medium							DC-8	
Meteorological Measurement System	MMS	1.2.1 Atmospheric temperature fields	Some	Highest	Medium	N/A	High	no	None	None	High	Global Hawk	GLOPAC
		1.4.1 atmospheric wind speed	Some	Highest	Medium	N/A	High	no	None	None	High	DC-8	GRIP
		1.4.2 atmospheric wind direction	Some	Highest	Medium	N/A	High	no	None	None	High	WB-57	
					Medium							ER-2	
Microwave Temperature Profiler	MTP	1.2.1 Atmospheric temperature fields	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	Medium	Global Hawk	GLOPAC
		1.5.1 cloud top temperature	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	Medium	DC-8	
		2.5.1 Surface temperature (land)	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	Medium	ER-2	
		3.5.1 Surface temperature (ocean)	Most	Medium	Medium	Multiband	High	no	Narrow-10km	None	Medium	WB-57	
Ozone Photometer	O3	1.8.2 O3	Some	Highest	Medium	Single-band	High	no	None	Advanced	High	Global Hawk	GLOPAC
UAS Chromatograph for Atmospheric Trace Species	UCATS	1.3.1 Atmospheric humidity (indirect)	Some	Medium	Medium	Single-band	High	no	None	Some	High	Global Hawk	GLOPAC
		1.8.1 H2O	Some	Highest	Medium	Single-band	High	no	None	Some	High		
		1.8.2 O3	Some	Highest	Medium	Single-band	High	no	None	None	High		
		1.8.7 NOx(NO, NO2), N2O5, HNO3	Some	Highest	Medium	Single-band	High	no	None	None	High		
		1.8.4 CH4	Some	Highest	Medium	Single-band	High	no	None	None	High		
		1.8.9 CFCs/HFCs	Some	Highest	Medium	Single-band	High	no	None	None	High		
Ultra High Sensitivity Aerosol Spectrometer	UHSAS	1.1.5 aerosol size and size distribution	Most	Highest	Medium	Single-band	High	no	None	None	High	Global Hawk	GLOPAC
		1.1.3 aerosol scattering properties	Most	Highest	Medium	Single-band	High	no	None	None	High		
UAS Laser Hygrometer	ULH	1.3.1 Atmospheric humidity (indirect)	Some	Highest	Medium	Single-band	High	no	None	None	High	Global Hawk	GLOPAC
		1.8.1 H2O	Some	Highest	Medium	Single-band	High	no	None	None	High	ER-2	
					Medium							WB-57	
					Medium							DC-8	
High-Definition Video System	HDVIS	1.5.2 Cloud type	Most	High	Medium	Single-band	High	no	Narrow-10km	None	High	Global Hawk	GLOPAC
Airborne Second Generation Precipitation Radar	APR_2	1.7.1 Cloud liquid water and precipitation rate	Most	Medium	Medium	Multiband	High	yes	Narrow-10km	None	High	DC-8	GRIP
		1.7.2 Cloud droplet size	Most	Medium	Medium	Multiband	High	yes	Narrow-10km	None	High		
Cloud Aerosol	CAPS	1.1.2 aerosol shape, composition, physical and chemical properties	Some	Medium	Medium	Single-band	High	yes	None	None	High	DC-8	GRIP

and		1.1.5 aerosol size and size distribution	Some	Medium	Medium	Single-band	High	yes	None	None	High		
Precipitation		1.1.3 aerosol scattering properties	Some	Medium	Medium	Single-band	High	yes	None	None	High		
Spectrometer		1.2.1 Atmospheric temperature fields	Some	Medium	Medium	Single-band	High	yes	None	None	High		
		1.3.1 Atmospheric humidity (indirect)	Some	Medium	Medium	Single-band	High	yes	None	None	High		
		1.7.1 Cloud liquid water and precipitation rate	Some	Medium	Medium	Single-band	High	yes	None	None	High		
Cloud	CSI	1.6.3 Cloud particle phase - ice/water transition	Some	Medium	Medium	Single-band	High	no	None	None	High	DC-8	GRIP
Spectrometer		1.7.2 Cloud droplet size	Some	Highest	Medium	Single-band	High	no	None	None	High		
and Impactor		1.7.1 Cloud liquid water and precipitation rate	Some	Medium	Medium	Single-band	High	no	None	None	High		
	PIP	1.6.3 Cloud particle phase - ice/water transition	Some	Medium	Medium	Multiband	High	no	None	Some	High	DC-8	GRIP
Precipitation		1.7.1 Cloud liquid water and precipitation rate	Some	Medium	Medium	Multiband	High	no	None	Some	High		
and Imaging		1.7.2 Cloud droplet size	Some	Medium	Medium	Multiband	High	no	None	Some	High		
Probe		1.1.4 aerosol extinction profiles/vertical concentration	Some	Medium	Medium	Multiband	High	no	None	Some	High		
		1.1.5 aerosol size and size distribution	Some	Medium	Medium	Multiband	High	no	None	Some	High		
Doppler	DAWN	1.4.1 atmospheric wind speed	Most	Highest	Medium	Single-band	High	no	Medium-100km	Some	High	DC-8	GRIP
Aerosol WiNd LIDAR		1.4.2 atmospheric wind direction	Most	Highest	Medium	Single-band	High	no	Medium-100km	Some	High	WB-57	
	Dropsonde	1.2.1 Atmospheric temperature fields	Some	Highest	Medium	Single-band	High	no	None	None	High	DC-8	GRIP
DC-8		1.3.1 Atmospheric humidity (indirect)	Some	Highest	Medium	Single-band	High	no	None	None	High		
Dropsonde		1.4.1 atmospheric wind speed	Some	Highest	Medium	Single-band	High	no	None	None	High		
		1.4.2 atmospheric wind direction	Some	Highest	Medium	Single-band	High	no	None	None	High		
Langley	LARGE	1.1.3 aerosol scattering properties	Some	Highest	Medium	Multiband	High	yes	None	None	High	DC-8	GRIP
Aerosol		1.1.5 aerosol size and size distribution	Some	Highest	Medium	Multiband	High	yes	None	None	High		
Research		1.1.6 aerosol absorption optical thickness and profiles	Some	Highest	Medium	Multiband	High	yes	None	None	High		
Group		1.1.1 aerosol height/optical depth	Some	Highest	Medium	Multiband	High	yes	None	None	High		
Experiment		1.1.4 aerosol extinction profiles/vertical concentration	Some	Highest	Medium	Multiband	High	yes	None	None	High		
LIDAR	LASE	1.1.3 aerosol scattering properties	Most	High	Medium	Single-band	High	no	Medium-100km	None	High	DC-8	GRIP
Atmospheric		1.3.2 Water vapor transport - Winds	Most	High	Medium	Single-band	High	no	Medium-100km	None	High	ER-2	
Sensing Experiment		1.8.1 H_2O	Most	High	Medium	Single-band	High	no	Medium-100km	None	High	P3-B	
	Mini_Dropsonde	1.2.1 Atmospheric temperature fields	Some	Highest	Medium	Single-band	High	no	None	None	High	Global Hawk	GRIP
Global Hawk		1.3.1 Atmospheric humidity (indirect)	Some	Highest	Medium	Single-band	High	no	None	None	High		
Dropwindsonde		1.4.1 atmospheric wind speed	Some	Highest	Medium	Single-band	High	no	None	None	High		
		1.4.2 atmospheric wind direction	Some	Highest	Medium	Single-band	High	no	None	None	High		
	HAMSR	1.2.1 Atmospheric temperature fields	Most	Low	Medium	Multispectral	High	no	Medium-100km	Advanced	High	Global Hawk	GRIP
JPL High		1.3.1 Atmospheric humidity (indirect)	Most	Low	Medium	Multispectral	High	no	Medium-100km	Advanced	High	DC-8	
Altitude MMIC		3.5.1 Surface temperature (ocean)	Most	Low	Medium	Multispectral	High	no	Medium-100km	Advanced	High	ER-2	
Sounding		1.8.1 H_2O	Most	Low	Medium	Multispectral	High	no	Medium-100km	Advanced	High		
Radiometer		2.5.1 Surface temperature (land)	Most	Low	Medium	Multispectral	High	no	Medium-100km	Advanced	High		
High-Altitude	HIWRAP	1.4.1 atmospheric wind speed	Most	Low	Medium	Multiband	High	yes	Medium-100km	None	High	Global Hawk	GRIP
Imaging Wind		1.4.2 atmospheric wind direction	Most	Low	Medium	Multiband	High	yes	Medium-100km	None	High	WB-57	
and Rain		1.7.1 Cloud liquid water and precipitation rate	Most	Low	Medium	Multiband	High	yes	Medium-100km	None	High		
Airborne Profiler		1.6.2 cloud ice particle size distribution	Most	Low	Medium	Multiband	High	yes	Medium-100km	None	High		
Lightning	LIP	N/A										Global Hawk	GRIP
Instrument Package												ER-2	
Hurricane	HIRAD	1.4.1 atmospheric wind speed	Most	Low	Medium	Hyperspectral	High	yes	Medium-100km	Advanced	High	WB-57	GRIP
Imaging		1.4.2 atmospheric wind direction	Most	Low	Medium	Hyperspectral	High	yes	Medium-100km	Advanced	High		
Radiometer		1.7.1 Cloud liquid water and precipitation rate	Most	Low	Medium	Hyperspectral	High	yes	Medium-100km	Advanced	High		
Aircraft	AMDAR	1.4.1 atmospheric wind speed	Most	High	Medium	Single-band	High	no	None	None	High	Commercial Jet	AMDAR
Meteorological		1.4.2 atmospheric wind direction	Most	High	Medium	Single-band	High	no	None	None	High		
DAta Reports		1.2.1 Atmospheric temperature fields	Most	High	Medium	Single-band	High	no	None	None	High		
	TAMDAR	1.2.1 Atmospheric temperature fields	Some	High	Medium	Single-band	High	no	None	None	High	Turbo Prop	AMDAR
Tropospheric AMDAR		1.4.1 atmospheric wind speed	Some	High	Medium	Single-band	High	no	None	None	High		
		1.4.2 atmospheric wind direction	Some	High	Medium	Single-band	High	no	None	None	High		
Water Vapor	WVSS-II	1.3.1 Atmospheric humidity (indirect)	Some	Highest	Medium	Single-band	Medium	no	None	None	High	Commercial Jet	AMDAR
Sensing System II		1.8.1 H_2O	Some	Highest	Medium	Single-band	Medium	no	None	None	High		
	ATM	2.2.2 Hi-res topography	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High	DC-8	OIB
Airborne		4.1.2 Glacier surface elevation	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High	P3-B	OIB
Topographic		4.1.5 Ice Sheet topography	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High		
Mapper		4.3.2 Sea ice cover	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High		
	LVIS	2.2.2 Hi-res topography	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High	DC-8	OIB
		2.2.1 surface deformation	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High	P3-B	OIB
Laser		2.4.1 vegetation type and structure	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High	B-200	OIB
Vegetation and		2.4.3 vegetation height	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High	Global Hawk	OIB
Ice Sensor		2.7.1 river and lake elevation	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High		
		4.3.2 Sea ice cover	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High		
		4.1.5 Ice Sheet topography	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High		
		2.4.4 canopy density	Most	Highest	Medium	Single-band	High	no	Narrow-10km	None	High		
Multichannel	MCoRDS	4.1.1 ice sheet volume	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High	P3-B	OIB
Coherent		4.1.5 Ice Sheet topography	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High	DC-8	OIB
Radar Depth		4.1.2 Glacier surface elevation	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High		
Sounds		4.1.4 Ice sheet velocity	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High		
		4.1.3 glacier mass balance	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High		
Snow Radar	Snow Radar	4.2.4 snow cover	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High	DC-8	OIB
		4.2.2 snow depth	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High	P3-B	OIB
	Ku- Band Radar	3.2.1 Sea level height	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High	DC-8	OIB
Ku-Band Radar		4.3.1 Sea ice thickness	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High	P3-B	OIB
Altimeter		4.2.2 snow depth	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High		
		4.1.1 ice sheet volume	Most	Highest	Medium	Multiband	High	no	Narrow-10km	None	High		
Gravimeter	Gravimeter	5.1.1 gravity field variations	Most	High	Medium	N/A	Medium	no	Narrow-10km	Some	High	DC-8	OIB
					Medium							P3-B	OIB
Digital	DMS	4.3.2 Sea ice cover	Most	Medium	Medium	Single-band	Medium	no	Narrow-10km	None	Medium	DC-8	OIB
Mapping System		2.6.1 land use	Most	Medium	Medium	Single-band	Medium	no	Narrow-10km	None	Medium	P3-B	OIB
	PARIS	4.1.1 ice sheet volume	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High	P3-B	OIB
Pathfinder		4.1.2 Glacier surface elevation	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High	DA-42	ARGOSS
Advanced		4.1.3 glacier mass balance	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High		
Radar Ice		4.1.4 Ice sheet velocity	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High		
Sounder		4.1.5 Ice Sheet topography	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High		
		4.2.2 snow depth	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High		
		4.3.1 Sea ice thickness	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High		

4.3.2 Sea ice cover	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High
4.2.4 snow cover	All	Highest	Medium	Single-band	High	yes	Narrow-10km	None	High

Table 7.18: Complete Attribute list for Aircraft Instruments examined in the Case Studies of Chapter 4.

Mission	Vehicle	Instruments	1 Year	6 Months	Cost Category
GLOPAC	Global Hawk	ACAM	100	50	Flights
		CPL	24	24	hours/flight
		FCAS/NMASS	2400	1200	Total Flights
		MMS	$8,400,000	$4,200,000	Flight cost
		MTP	$14,400,000	$7,200,000	Operational costs
		O3	10	10	Instruments
		UCATS	$2,000,000	$2,000,000	Integration Costs
		UHSAS	$21,600,000	$10,800,000	Science Team Costs
		ULH			
		HDVIS	**$46,400,000**	**$24,200,000**	**Campaign Costs**

Table 7.19: GLOPAC Campaign Cost Estimate

Mission	Vehicle	Instruments	1 Year		6 Months		Cost Category
GRIP	DC-8	APR_2	Global Hawk	DC-8	Global Hawk	DC-8	Vehicle
		CAPS	50	50	25	25	flights
		CSI	24	12	24	12	hours/flight
		PIP	1200	600	600	300	Total Flights
		DAWN	$4,200,000	$3,900,000	$2,100,000	$1,950,000	Flight cost
		Dropsonde	$7,200,000	$7,800,000	$3,600,000	$3,900,000	Operational costs
		LARGE	6	8	6	8	Instruments
		LASE	$2,000,000	$8,000,000	$2,000,000	$8,000,000	Integration Costs
	Global Hawk	Mini_Dropsonde	$10,800,000	$4,800,000	$5,400,000	$2,400,000	Science Team Costs
		HAMSR					
		HIWRAP	**$48,700,000**		**$29,350,000**		**Campaign Costs**
		LIP					
		HIRAD					
		MMS					

Table 7.20: GRIP Campaign Cost Estimate

Mission	Vehicle	Instruments	1 Year	6 Months	Cost Category
OIB	DC-8	ATM	100	50	flights
		LVIS	12	12	hours/flight
		MCoRDS	1200	600	Total Flights
		Snow Radar	$7,800,000	$3,900,000	tota cost
		Ku- Band Radar	$15,600,000	$7,800,000	Operational costs
		Gravimeter	6	6	Instruments
		DMS	$6,000,000	$6,000,000	Integration Costs
			$9,600,000	$4,800,000	Science Team Costs

	$39,000,000	$22,500,000	Campaign Costs

Table 7.21: Operation Ice Bridge Campaign Cost Estimates

Mission	Vehicle	Instruments	Life Time	Cost
ARRGOS	DA-42M	PARIS	3 year	$49,907,000
			2 year	$44,893,000
			1 year	$39,994,000
			6 months	$36,440,000

Table 7.22: ARRGOS Campaign Cost Estimates

3 Year Mission: FY costs in Real Year Dollars

WBS #	Proposed Cost to NASA / WBS Element	FY10	FY11	FY12	FY13	FY14	FY15	Total (Real Yr.)
1	Project Management	$544	$1,326	$722	$724	$734	$508	$4,558
2	Systems Engineering	$123	$180	$-	$-	$-	$-	$303
3	Safety & Investigation Assurance	$40	$22	$-	$-	$-	$-	$62
4	Instruments	$4,714	$3,774	$40	$-	$-	$-	$8,528
5	Flight System and Services	$10,672	$4,024	$-	$-	$-	$-	$14,696
6	Investigation operations	$88	$1,242	$1,402	$2,446	$2,474	$96	$7,748
7	Science Data Processor	$87	$169	$34	$-	$-	$-	$290
8	Integration and Test	$28	$2,096	$622	$-	$-	$-	$2,746
9	Science Team	$289	$1,136	$1,180	$1,176	$1,239	$943	$5,963
	Reserves (16.53%)	$1,412	$1,277	$434	$456	$470	$206	$4,255
	Total Proposal Cost to NASA	$17,997	$15,246	$4,434	$4,802	$4,917	$1,753	$49,149
	Co-Investigators Contributions	$77	$77	$77	$77	$77	$77	$462
	Harvard Principle Investigator Contributions	$20	$20	$20	$20	$20	$20	$120
	Harvard Data Analysis HW Contributions	$88	$88	$-	$-	$-	$-	$176
								0
	Total Contributions	$185	$185	$97	$97	$97	$97	$758
	Total Investigation Cost	$18,182	$15,431	$4,531	$4,899	$5,014	$1,850	$49,907

Vehicle and Payload Costs
Non Recurring Cost
Recurring Cost

Table 7.23: Greenland and Antarctica ARRGOS Operational Mission Cost Estimate. Based on proposal with extra set of aircraft and payloads with doubling of operational estimates.

ROM Mission Costs	2009 ($k)	2010	2011	2012	2013	2014	Total
Greenland	4,495	3,259	5,047	3,492	3,636	3,744	**23,673**
Arctic sea Ice	580	596	602	620	640	658	**3,696**
Antarctica	6,549	7,505	6,487	5,268	5,426	5,588	**36,823**
Alaska SE	2,066	796	820	844	870	896	**6,292**
Additional Costs	5,750	10,875	5,250	2,500	2,500	2,500	**29,375**
Reserves (15%)	2,916	3,455	2,731	1,909	1,961	2,008	**14,979**
Totals by Year	**$22,356**	**$26,486**	**$20,937**	**$14,633**	**$15,033**	**$15,394**	**$114,838**

Table 7.24: Operation Ice Bridge proposed cost structure for the 2009-2014 campaign. This includes the instrument integration, vehicle modifications, campaign deployments, and science team costs.

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