QUANTITATIVE ANALYSIS OF SATELLITE ARCHITECTURE CHOICES: A GEOSYNCHRONOUS IMAGING SATELLITE EXAMPLE

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ABSTRACT

Firms operating satellites have a choice between two broad classes of satellite architectures: consolidated and distributed. In a consolidated satellite architecture multiple instruments are aggregated onto a single spacecraft. A distributed (or disaggregated) architecture separates satellite capabilities -- including payloads -- across multiple heterogeneous smaller spacecraft in the same orbit. Vehicles in a distributed satellite architecture may share a common wireless network.

For a firm that operates scientific or national security satellites, there may be four classes of potential advantages associated with a distributed architecture: (1) capabilities can be deployed incrementally instead of waiting until the last payload is ready for launch; (2) failures in orbit can be fixed more quickly and with smaller units; (3) new technologies can be inserted more efficiently by phased integration of new payloads; and (4) the system is more flexible in terms of responses to adversarial interactions in space, and may therefore provide more flexibility for deterrence. Quantitative approaches are useful to assess the value of these benefits for specific mission types. We present here a quantitative framework to assess tradeoffs between consolidated and distributed satellite architecture for national space programs.

We use optimization and risk models to show when distributed satellite architectures can provide a more resilient and valuable way of implementing certain critical space systems, such as weather satellites and strategic missile launch warning satellites. This work allows comparison of mission approaches on the basis of expected utility maximization and selection of strategies that best exploit the technical and operational characteristics of each satellite architecture. Early results allow determination of an optimal architecture based on the criticality of mission data, reliability of satellite and launch vehicles, anticipated rate of technology advancement, and risk preference of a decision maker. Sample results are provided for a fictional geosynchronous imaging system.

INTRODUCTION & BACKGROUND

Introduction

Modern commercial and government operated satellites provide a foundation for global communications,[1] navigation,[2] treaty verification,[3] intelligence and national security,[4] scientific investigation,[5] remote sensing,[6] and monitoring of global weather and climate issues.[7] There are several possible reasons for a firm to use multiple satellites to accomplish a single objective, including: (1) a physics-based requirement, such as for position, navigation and time (PNT) systems; (2) a desire to decrease revisit time or to improve coverage, such as for communications satellites; and (3) a desire to gain an operational advantage or better manage risk.[*] This paper

[*] Some systems are configured based on two or all three of these reasons. For instance, the U.S. Global Positioning System (GPS) requires multiple satellites to provide PNT services but includes extra satellites to provide better coverage and improved system reliability.

focuses on the third category: the use of multiple satellites for the collection of data that could otherwise be accomplished with an individual, large satellite, and for which further decrease of the revisit time is not a primary motivation. Most missions in this category are based on assembling data from multiple payloads simultaneously – for example, a weather satellite designed to obtain visible, infrared and microwave radiation measurements from three specialized instruments. For this weather mission, these instruments could be operated using one, two, or three spacecraft, with the payloads located together, with two paired and one separate, or all separated. Assuming that the data from all three sensors are primarily valuable to users when the sensors operate simultaneously with a similar field of view, the choice of one, two or three satellites is driven primarily by the value of the data to the decision maker -- not by a physical need or a particular desire for revisit time improvement. Potential benefits and the rationale to quantify them are discussed next. Important examples of satellites in this category include weather, Earth science, and strategic warning satellites.

We frame the choice between consolidated and distributed satellite architectures as a strategic decision for a government or private leaders, rather than a pure engineering or program-management choice. Therefore, we are interested in the value of the data derived from an entire satellite system, which includes more than the technical performance or project management of individual vehicles.

We illustrate that choice for Earth-observation space systems. We first solve for strategies that optimally exploit the technical and operational characteristics of different satellite architectures. Given the uncertainties involved, we then compare missions on the basis of "certain equivalents" as defined in decision theory. We examine how this choice depends on expected technology advancement rates, value of data, risk aversion of the decision maker, launch reliability, and other decision factors. In this paper, we demonstrate the framework using a fictional geosynchronous mission, which provides Earth observations for a national government.

Consolidated and Distributed Satellites

The design implementation of a single spacecraft or a cluster of spacecraft modules shall be referred to as the mission *architecture*. A single-spacecraft mission implementation is a *consolidated* satellite architecture; using multiple spacecraft to accomplish a similar mission is called a *distributed* satellite architecture. The terms *distributed* and *disaggregated* are used interchangeably in this paper.[†]

This analysis focuses on the distribution of payloads (as opposed to a satellite bus' basic functions) across multiple satellites for improved performance under uncertainty. We define a distributed satellite architecture more precisely as *a separation of payload capabilities, normally resident on a single spacecraft, into multiple heterogeneous satellite modules that may share a common wireless network*.

This definition can also include *fractionated spacecraft* as a special type of distributed mission architectures. A fractionated architecture distributes traditional bus subsystems, in addition to payloads, across multiple vehicles.[8] A fractionated spacecraft may thus include more specialized allocation of cross-link, computing and storage, multi-layer security, and downlink subsystem resources across a set of spacecraft modules. (This paper only considers the example of a mission with consolidated and distributed satellite architectures. The framework presented here, however, can also be applied to fractionated architectures).

[†] A note on terms: Some studies use the term *distributed* to include systems like GPS. This paper focuses only on systems that can be consolidated or distributed based on value, like weather satellites, as opposed to systems such as GPS that must be distributed by physical necessity. The term *disaggregation* was understood originally as a separation of mission requirements. Requirements disaggregation can imply a single, distributed architecture (a group of satellites essentially working together), or it can simply mean that two capabilities, such as strategic and tactical systems, will be split between different satellite programs. In practice, it is often used to describe a distributed satellite system. For this reason, this paper generally uses *distributed* and *disaggregated* interchangeably, most of the time "*distributed.*"

Debate about the wisdom of shifting to distributed satellite architectures has been underway since the mid-1990s.[9] It has gained significantly more attention, however, in recent years given the challenges of developing single-bus satellites and progress in systems analysis and design.

There are four types of potential benefits associated with distributed satellite architectures, shown in Exhibit 1. These include: (1) more cost-effective deployment of new sensor technology over time by upgrading individual sensors and using smaller satellites; (2) incremental launch of individual or sub-groups of payloads as their initial development/building is completed (this also includes potentially more cost-effective scaling of capabilities if additional payloads are needed); (3) more cost-effective responses to spacecraft failures; and (4) greater flexibility in deterring and responding to adversarial behaviors against satellite systems.

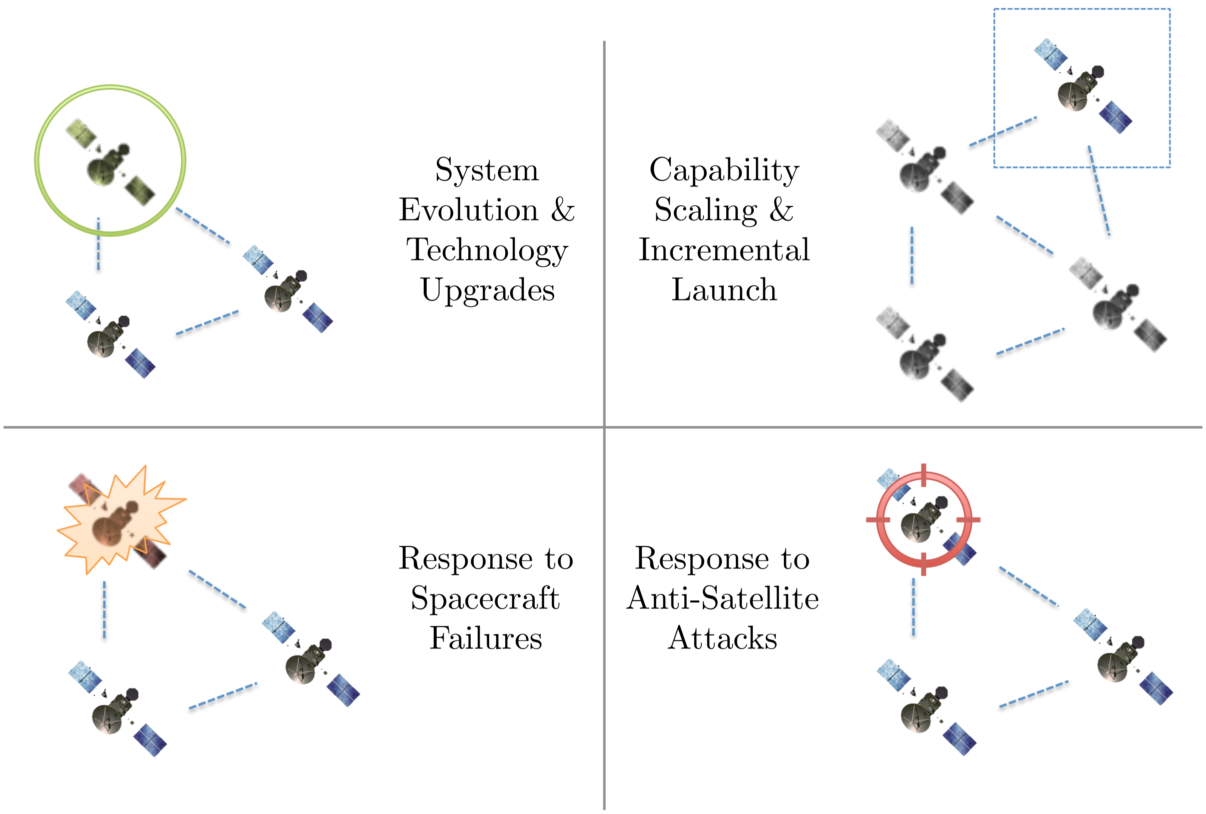

Exhibit 1: Four families of potential benefits of distributed satellite architectures for multi-payload satellites

Legend: In the green circle, a payload that can be upgraded without a system-wide recapitalization; in the square, a payload that can be launched separately; in the red flash, an element that can be replaced after a failure; and in the red circle, an element that can be replaced quickly if destroyed.

The third benefit was identified early: simulation-based studies as early as the 1990s found that distributed satellite architectures could enable more efficient system replenishment over long time periods.[10] Qualitative discussions in the U.S. government around the same time also characterized many of the benefits outlined above.[11] More recently, attention has returned to this subject with additional focus on the value of resilient and changeable attributes in distributed space systems.

Realization of these benefits depends on the strategy for operation of the satellite system. This study therefore quantifies the values attached to these factors by identifying an optimal sequence of decisions to operate each satellite architecture alternative.[‡] The potential benefits of distributed satellite systems, outlined above, are material insofar as they affect the value of a satellite architecture given an optimal operational policy.

Status Quo

Certain space systems can only be implemented with large, individual vehicles. At present, space telescopes with large optics and interplanetary probes with significant propulsion requirements are technologically or economically infeasible by means other than individual, consolidated spacecraft. For other systems, however, such as weather satellites, one has a choice between consolidated and distributed satellite architectures.

Some have proposed that the current paradigm of consolidated satellites contributes to a feedback cycle that increases the cost and risk of government space projects over long timescales.[12] Organizational factors may have contributed to an equilibrium that has favored consolidated satellite architectures. A significant fraction of civil and military space projects in the U.S. are based on contracts between the U.S. government and a few firms that specialize in large systems integration. Government program managers often have incentives to aggregate stakeholders into individual programs.

Under current practices, there are few significant incentives for managers of major government satellite programs to consider distributed architectures without the intervention of high-level leaders. Such a major shift requires assessing the long-term costs and benefits of whole architecture alternatives in light of national objectives and risks. The analytic framework presented here provides two capabilities toward this end: first, a detailed mission analysis tool to identify optimal strategies (such as launch schedules) within a satellite program; and second, an ability to compare satellite architectures based on a detailed analysis and optimal strategy for each.

We present a strategic decision and risk analysis tool designed to synthesize the different (often uncertain) factors that high-level leaders need to consider when making choices between consolidated and distributed satellite architectures.

Quantifying the Value of Consolidated and Distributed Satellites

To analyze the availability of data from a multiple-satellite project, one standard approach is to simulate the reliability of individual satellites over its lifetime, given replenishment policies and capabilities. One such model is the Generalized Availability Program (GAP), a tool based on Monte Carlo simulations for satellite constellations.[13] GAP has been used by many U.S. government navigation, weather, and communications satellite constellations. Highly detailed satellite reliability analyses[14] can serve as inputs to GAP. Early simulation studies[15] of consolidated and distributed satellite architectures found benefits to the latter based on replenishment efficiencies, assuming that the launch capacity for potential replacements is available. The ability to evaluate other possible benefits of a distributed satellite architecture, however, also requires a quantitative consideration of the chances of technological change and component failures in a given time frame, as well as preference factors such as data value, risk preference, and, most importantly, optimal operational strategies specific to each satellite architecture.[§]

[‡] An interesting broader parallel to this exists: A 1993 memo by Andrew Marshall observes that while technology can enable a revolution or disruption in current affairs, changes actually occur when new operational practices are developed. Therefore, his advice to senior leaders was that experimentation with novel concepts of operation to exploit new technologies, and technologies likely to be available in the years ahead, is extremely important. (See: Andrew Marshall, "Some thoughts on military revolutions - second version," ONA Memorandum for the Record, Washington, D.C., August, 1993).

[§] Adapting other traditional models to quantify a choice between consolidated and distributed satellite architectures encounters the challenge that most models were not designed for this purpose. For example, the Complexity Based Risk Assessment (CoBRA) method was developed in 1999 to compare the "complexity" of a spacecraft relative to its cost and schedule. (See: *R.E. Bitten, D. A. Bearden, and D. L. Emmons, "A quantitative assessment of complexity, cost, and schedule:*

More recently, there has been a growing focus on attributes associated with changeability (modification in orbit) in attributes of engineered systems. For example, one study observes that *decentralized* systems have the characteristic that “necessary decisions are made at the point of best knowledge and information,” which, they point out, “enables the allocation of attributes or properties to the most appropriate location within the system.”[16] This observation is consistent with the early findings of replenishment efficiency of distributed satellites.

By opening the frame of analysis to an entire space project instead of particular vehicles, it is possible to conceptualize a satellite project as a service that can be changed or improved -- not just as a set of vehicles to be maintained. Several approaches have focused on various elements of changeability in engineered systems[17] as well as taxonomies related to system attributes that affect system performance over time.[18] Studies of value-based decision-making in engineering have also gained increasing attention.[19]

Recently, researchers have sought to build on these approaches to characterize the value provided by distributed (including fractionated) satellite architectures relative to more traditional mission approaches, for example, in studies relevant to DARPA's System F6 Program. Several of these studies use Monte Carlo simulations to obtain distributions of the Net Present Value (NPV) of a satellite architecture.[20] Others contributed insights using mini-max regret approaches,[21] statistical reliability analysis,[22] and mass-based value models.[23] Some studies have also compared simulation-based approaches to sequential decision models,[24] and considered the ability to change mission configurations in response to changes in demand for different mission-types.[25] Qualitative studies have also continued to suggest the value of improved flexibility and survivability with smaller and distributed satellite architectures.[26]

However, what has not been done is a synthesis of all the factors necessary to compare directly distributed and consolidated satellite architectures in a sequential decision framework based on expected utility maximization, including a computation of the effects of optimal exploitation of technological and operational characteristics of each architecture. These include technology upgrades, the duration of satellite construction, vehicle reliabilities, replenishment and deployment issues, and other factors. That is the focus of this work.

Decision and Risk Analysis

This section briefly reviews core concepts of decision and risk analyses, including the treatment of uncertainties and definitions of value, flexibility, options, hedging, risk aversion, and time-discounting as they are used in this study.

Decision analysis is based on three elements: alternatives, information, and preferences.[27] The *von Neumann-Morgenstern (VNM) axioms*[28] specify at a basic level, how a rational decision maker must be able to quantify his or her preferences and uncertainties. This logic leads to the choice of the alternative that *maximizes his or her expected utility* in a problem of resource allocations under uncertainty.

A fundamental corollary of these axioms is that the probabilities and the values that one puts on the outcomes of a decision are separate, and both are subjective. (For example, two individuals can place different values on an identical quantity of money. This idea has existed since at least 1738, when Bernoulli provided[29] an example analogous to: $100 for a beggar is not the same as $100 for a millionaire). The value of an uncertain deal is called the *certain equivalent*, defined as the amount that an individual would need to be paid to sell the deal.

Achieving a balanced approach for program success,” in 6th IAA International Low Cost Planetary Conference, 2005). The CoBRA methodology uses a measure for spacecraft complexity based on how the spacecraft's subsystems compare to past missions. CoBRA’s final input to decision-analysis, however, is designed to be mostly qualitative: CoBRA does not quantitatively characterize uncertainties (such as the chance of failure given a particular mission's complexity, cost, and schedule), represent preferences, or define alternatives. By design, a tool like CoBRA does not enable a complete quantitative basis for decision and risk analysis of satellite architecture choices.

For treatment of uncertainties, decision analysis uses probabilities based on all information available (including statistics when they exist and are relevant) in the framework of Bayesian probability theory.[30] The Bayesian approach allows updating prior information with new experience and is essential when dealing with new or poorly known systems. Probabilistic information includes *in situ* data when they exist, surrogate data (for the same components in other systems), engineering models, test results, and expert opinions. The method permits quantification of the risk-reduction benefits of new options.[31] Bayesian probability, along with the use of dollars to represent preferences ("utility") for outcomes, enables calculation of the value of new information, for example from tests, which is the maximum amount an individual should be willing to pay to gather information about an uncertain factor.[32] Bayesian methods thus allow using probability when large quantities of relevant data are not available,[33] and provide a framework for learning from new information.[**]

One of the implications of the Von Neumann axioms is the separate encoding of probability and preferences before they are combined in expected utility computation. A risk preference describes an individual's attitude toward valuing uncertain deals. If an individual's value for uncertain deal is equal to the expected value of the outcomes, she is "risk neutral." If her value for the deal is less than the expected value of the outcomes that she faces, she is "risk averse." Qualitatively, one can interpret increasing risk aversion as an increasing focus on the worst case 'tail events' of a scenario.

A time preference on rewards describes an individual's preference between receiving a monetary amount in the present or in the future. It is described in these decision support models by a discount rate.

Sequential decision under uncertainty must be analyzed "backwards," resolving first the last decisions to be made and working towards the resolution of the first, as a chess player wants to consider first where he or she will be some moves ahead to back-figure the best initial one. Three additional concepts are relevant in that context. First, an *option* can be understood as an alternative to postpone a decision until after more information has been obtained, either on a one-time or recurring basis.[34] The value of an option depends on a decision maker's risk preference, the amount of uncertainty in her decision situation and her expectation about gathering additional information. The second is *flexibility,* which, in the context of decision analysis, can be understood as the number of feasible alternatives in a decision situation. Given two otherwise equivalent decision scenarios, where one offers more available alternatives, it is considered more flexible.[35] Finally, *hedging,* in the context of decision analysis, can be understood as adding new deals to a portfolio to change the moments of the portfolio's probability distribution in a way that increases the decision maker's value.[36]

Other methods such as the Analytical Hierarchy Process and the minimization of maximum regret have also been used in the domain of aerospace engineering but can present logical problems and limitations in modeling uncertainties and preferences.[37]

[**] Note that of course, more information does not mean less uncertainty if new possibilities that were not envisioned before are discovered in the process.

MODEL

We present systems analysis and sequential decision models to show whether and when distributed satellite architectures can provide a more resilient and valuable way of implementing certain critical space systems, such as weather satellites and strategic missile launch warning satellites. This model enables a comparison of mission approaches on the basis of certain equivalent (as defined in decision theory), by first solving for a strategy that best-exploits the technical and operational characteristics of each satellite architecture alternative.

This section provides a high-level overview of the modeling steps used in this study; these steps are sufficient to understand the model perspective and to analyze the reference geosynchronous mission provided in the *Sample Scenario* section.

Analysis Frame: The Firm

This research builds an analytic frame around an abstraction that shall be called the *firm*, representing either a U.S. government agency, like NASA, or a large private corporation. The firm is assumed to do three things: (1) procure satellites, meaning contract with one or more other organizations to purchase satellites and payloads; (2) operate satellites, that is, manage all operations associated with a satellite program, including replenishment launches, technology upgrades, and responses to crises; and (3) distribute data and allocate data products or data-derived analytic products to other organizations. The firm incurs costs through the first two activities; it incurs costs and derives value from the third. The firm may choose what satellites to procure from a menu of possible choices – such as a commercially-marketed list of satellite buses – but does not design its own satellites.

This restriction is consistent with how large firms operate today: outside contractors build satellites to specified requirements for all major U.S. government satellite programs, as well as for large private companies like DigitalGlobe, Iridium, and Intelsat. There is an important distinction between an organization that designs and builds satellites, and a firm that operates them and derives value from their data; these two types of organizations may not have identical preferences.

An example of a scenario for the firm is illustrated in Exhibit 2. For any satellite project, satellite health states determine the capabilities to generate data from orbit at a particular time. Decision makers can modify a satellite system by acquiring and launching new satellites; these actions can be done to respond to failures, to provide system replenishment in anticipation of failures, or to deploy new technologies. This option, of course, requires that launch capacity be available. Therefore, the launch timing – and the benefit of the new satellite – may be uncertain. For some satellite systems, external events can change the current value of the data, the likelihood of system anomalies, or both. Different satellite architectures involve different subsystem dependences, probabilities of failure for each launch vehicle, and acquisition and deployment costs. Accordingly, each satellite architecture may present different strategies for a decision maker who wants to best exploit the system's overall technical and operational properties.

Model Overview

We separate “strategic” and “tactical” decisions involved in the management of a spaceflight project. Tactical decisions include investments in a spaceflight project for which a particular architecture has already been chosen: initial deployment schedules, replenishment launches, technology upgrades, and responses to crises. Whether to use consolidated or distributed satellite architectures is a strategic decision to be made by national leaders, comparing costs and benefits of the main options, given optimal tactical allocations within each architecture. This concept, and a summary of analytic methods, is illustrated in Exhibit 3.

The first part of the model is an analysis of the tactical decisions (optimal policy) for each satellite architecture. The second is the choice of the best architecture, given the results of an optimal tactical policy for each option.

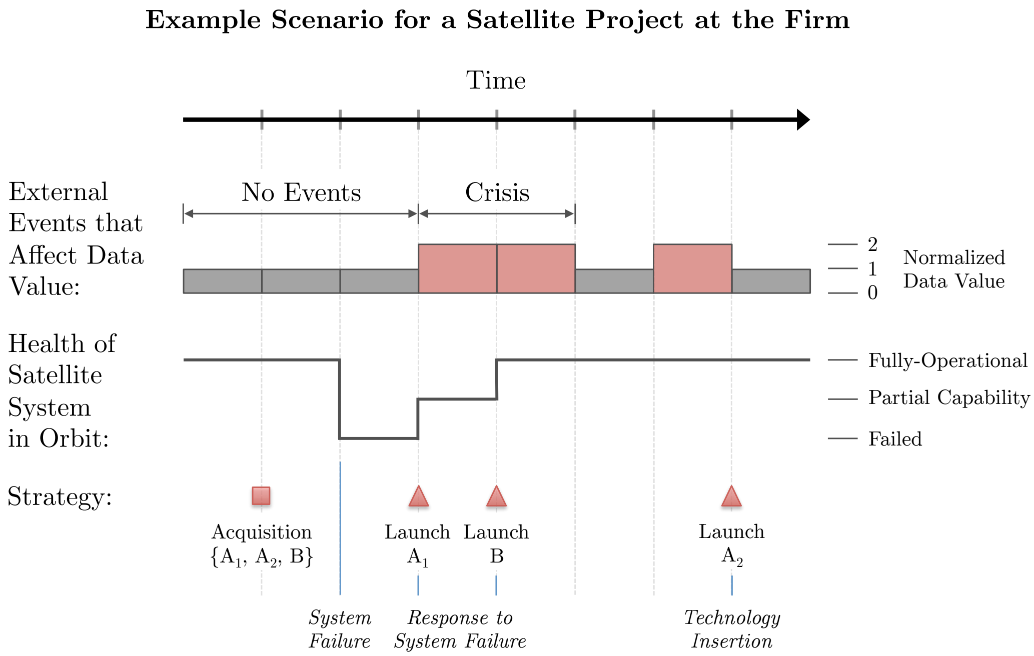

Exhibit 2: An example scenario of tactical decisions for a satellite project (given a satellite architecture).

Factors shown here include satellite health states that can affect data availability, acquisition and launch decisions by the firm, and the potential for external events that can affect data value and/or the health-evolution of satellite vehicles.

The model presented below is designed to find optimal tactical allocations based on stochastic dynamic programing (stochastic control) to solve multi-stage decisions through the lifecycle of a spaceflight program. Our approach is to quantify optimal strategies under uncertainty by modeling the lifecycle evolution of each satellite as a finite, discrete Markov process. [††] The complete method therefore frames tactical resource allocations as a risk-sensitive Markov Decision Problem with constant discounting.

System States: Satellite Lifecycle Model

The fundamental building block of this framework is a lifecycle model of an individual satellite, shown in Exhibit 4. It starts with a decision to acquire the satellite, and ends when the satellite is no longer able to operate in orbit. In between, the satellite undergoes development, build, assembly, and test (DBAT) activities on the ground, with an uncertain completion time. The satellite can then be stored on the ground or launched into orbit as soon as scheduling permits. Given a decision to launch, it may succeed or fail given the reliability of particular launch vehicles. If the satellite is deployed successfully into Earth-orbit, it operates and ages in space for an uncertain length of time. As it ages, failures become more likely. Ultimately, the depletion of consumables or orbit degradation will limit a satellite's life, even if failures do not.

To model either a consolidated or a distributed satellite architecture, multiple satellite lifecycle models are implemented in parallel. For example, for a consolidated architecture one needs at least two satellite lifecycle models to account for possible preemptive replacement launches; this is because a still-functioning older satellite may be maintained as a 'warm' in-orbit spare. In the same way, a distributed architecture divides payloads across at least two vehicles in orbit. Each vehicle can be replaced or upgraded before it fails, then maintained as a 'warm' spare. Multiple satellite lifecycle models can be used to represent this scenario.

[††] A Markov process is a type of stochastic model that approximates the probability distribution of the system's states in the next time period as depending only on the current state. Mathematically, if X_t is the system state at time t, then:
$P(X_{t+1} = y \mid X_t = x, X_{t-1} = w, X_{t-2} = z, \ldots) = P(X_{t+1} = y \mid X_t = x)$, where the sign | represents conditionality ("given that").

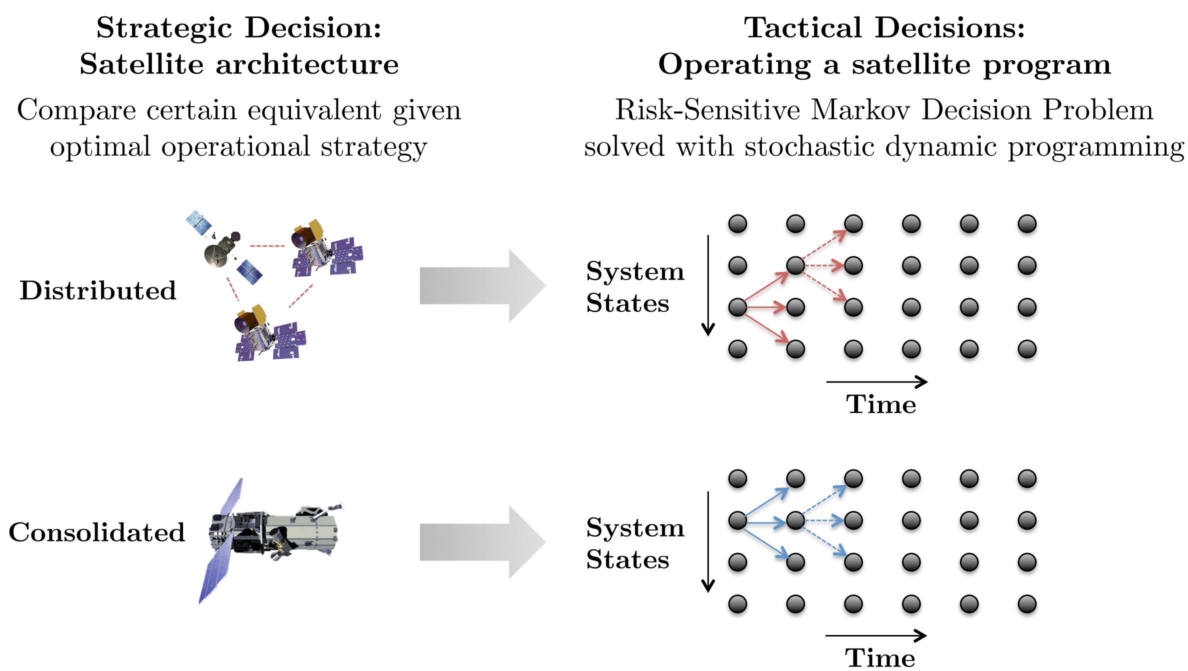

Exhibit 3: Comparison of the value of each satellite architecture given an optimal tactical strategy

Legend: The decisions within each architecture are tactical decisions. The choice between satellite architectures is a strategic decision. To solve this problem, the model provides a complete solution to 'tactical' decisions for operating each satellite architecture alternative.

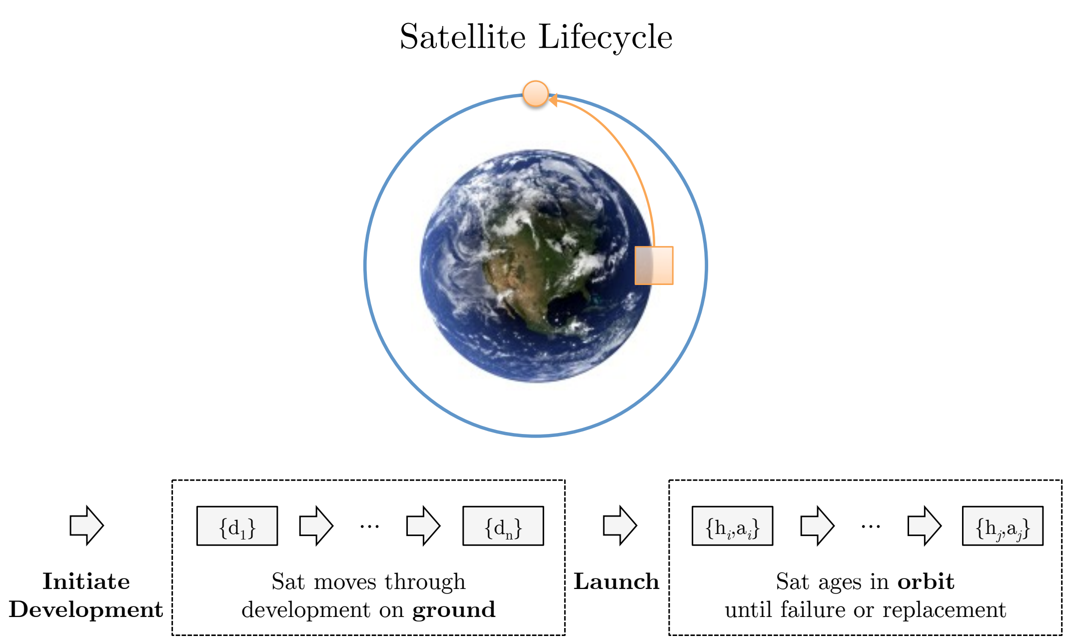

Exhibit 4: Two decisions and two periods of uncertain evolution in a satellite lifecycle.

Legend: First, a decision is made to acquire a satellite. The satellite then undergoes design, build, assembly, and test activities, which may experience delays. Once a satellite is completed, a decision can be made to launch the satellite (or retain it for a period of time as a ground spare). A launch can succeed or fail. If the satellite is delivered safely into orbit, it ages over time until it fails or gets replaced.

Lifetime in Orbit: Satellite Health States

This analysis models the uncertain evolution of each satellite in orbit as a finite, non-homogenous, discrete time Markov process. This framework uses a finite set of states to describe whether (or how well) a satellite is functioning, and a set of transition probabilities for changes between states that depend on the satellite's age. As a satellite ages, its probability of failure (or partial failure) in the next time increment increases.

State transition probabilities are generated by discretizing a reliability model, in the form of a reliability function for each vehicle. This approach enables government agencies and private firms to make use of proprietary reliability models for satellite buses and payloads, analogous to current reliability and availability analysis frameworks. The inputs for the fictional reference geosynchronous mission are provided further in the *Sample Scenario* section.

Construction Time: Satellite Development, Build, Assembly and Test (DBAT) States

The lifecycle of each satellite is modeled to include construction states on the ground and health states in orbit. Construction states represent the delay between the acquisition decision for a new satellite and its availability for launch. In more detailed studies, satellite construction states can also include programmatic delays and funding cash-flow through a program. Once an acquisition decision has been made, a satellite progresses through phases of design, building, assembly, and test (DBAT) states, and the total time is modeled using a Markov chain. To set transition probabilities, we approximate the decision maker's belief about the time associated with DBAT activities, and we use it to create a probability matrix for transitions between DBAT states.[‡‡]

Probabilistic Relevance Between Satellites in Orbit

Failures in a constellation of Earth-orbit satellites may not be independent among vehicles. We identify four types of probabilistic dependencies of anomalies among different satellite vehicles in a distributed constellation. First, external events, such as solar storms, may affect multiple vehicles. Second, common failure modes may be based on similar components or subsystem designs in multiple vehicles. This fact merits attention, mostly in very small satellites that may not undergo rigorous testing. Third, the failure of one satellite may physically cause an increase of failure risk in other vehicles. For instance, a catastrophic space debris impact may cause the breakup of the satellite that was hit, which endangers other satellites. Fourth, one satellite's failure may affect the surviving satellites' health due to re-tasking or capability re-balancing factors. For example, a satellite may need to have its orbit adjusted to compensate for the lost coverage of another satellite, reducing the surviving satellite's propellant supply, and effectively shortening its useful life.

Modeling these effects can be accomplished by super-states, i.e., additional state-elements to consider each uncertainty. Generally this modeling framework focuses on the first issue, the possibility of common external events. In this study, however, the analysis of the reference geosynchronous mission is implemented with an independence assumption for satellite failures in orbit.

[‡‡] It is helpful to first model a decision maker's beliefs about the overall duration of a satellite's development, build, assembly, and test activities. For a discrete time distribution on the length of DBAT activities, a negative binomial distribution is convenient for simulation with a Markov chain. That distribution has several useful properties: the distribution is right-skewed, reflecting the fact that for many satellites there is a relatively high likelihood of DBAT completion around the nominal completion deadline, and a right tail to account for possible delays. The shape and position of this distribution depend on the type of vehicle under construction.

Value of data and Preferences

Value of data and Technology Evolution

This study models the *firm's* value for satellite data. In this framework, design attributes of a satellite vehicle provide value only insofar as they change the quantity or quality of data from the satellite over its lifetime. This analysis assumes that the value of satellite data is time-separable, and that the total value of a satellite will equal the sum of the values provided by the data obtained in specific time periods. The calculation of value for each time period depends only on the quantity of data received in that period.

This analysis requires that a decision maker assess her value of the satellite data in each time period, or equivalently, her cost estimate of a gap in data per period. We call the first approach a *revenue value model* in which a decision maker assesses her value for a complete set of data during a specified period as positive given available technology at the start of the program. The revenue value model approach is usually most appropriate for a private firm that derives revenue from the sale of data in each period. In this approach, the data value in each period can be assessed by the firm according to a data market price given the conditions of the program.

Alternatively, a decision maker can assess her cost for a gap in data as a negative value, given available technology at the start of the program. We call this approach a *penalty value model.* This approach can be more tractable when assessing data value from a government decision maker who may be more inclined to think in terms of operational costs than prices she is willing to pay for data. For a government satellite program, the cost of data gaps in each period could be approximated at first order by the cost of obtaining the data through alternative means, such as commercial systems or non-space systems.

The reference geosynchronous mission considered in this paper (described further in the *Sample Problem* section) uses a simple *revenue value model* for illustrative purposes, with an extensive sensitivity analysis. More detailed analyses of government projects use a combination of revenue and penalty models: assessing both a subjective (positive) value of data and tracking the cost of gaps in data.

Technology advancement over time is modeled as part of the firm's value model. This study models technology evolution for the firm as would a government actor, without consideration of the influence of any market competitor. In this approach, a particular product is approximated as providing a consistent value over time as long as it functions properly; new products, constructed later, provide greater value. This approach is most valid for a firm that derives value from the *usefulness* of a product to its own activities over short to medium time scales.[§§] The simplest example of this case is a consumer buying a device for personal use: without major changes in the consumer's preferences after the purchase, and as long as the device works, the value of the device can be considered consistent while the consumer uses the device. After a period of time, however, an analogous product available for purchase may provide more utility to the consumer – and the consumer would be willing to pay a positive, finite amount to acquire the newer device, even though her older one still works.[***]

We approximate the US Government decisions using this approach (with assumptions that can be adjusted as necessary): the firm buys satellites, and derives value from the data that they produce for other activities. Newer satellites provide more utility, and so the government is willing to buy new capabilities even when older ones are still functioning. American strategic missile launch warning satellites provide an example of this: even while Defense Support Program (DSP) satellites provide effective scanning data, the value of newer sensors motivated a transition to Space Based Infrared System (SBIRS) satellites. Other researchers have used a similar approach to model the value of adding new technologies during the Hubble telescope servicing missions.[38] As newer sensors

[§§] These are time scales shorter than the changes in entire high-level standards, such as data languages.

[***] Alternatively, a different way of modeling the effects of technology evolution on a firm's value could be to represent a product as becoming 'obsolete.' This approach is likely most valid for a private firm competing to sell products in a market, as competitors are able to advance their own technology and the value of their own products.

were added to Hubble, the observatory's information throughput increased, and the resulting increase in data throughput provided a measure of the increase in 'utility' that was made possible by new technologies.

This study models technology evolution as an increase in the per-period data value achievable with newer satellites. In this approach, if a satellite acquired in year t is able to provide annual value v_t, then a satellite acquired the next year is able to provide annual value $v_{t+1} = (1+\alpha)v_t$, where $\alpha > 0$ is an annual step-increase in value available each year. Starting from an index year 0, this is generalized to $v_t = (1+\alpha \bullet t)\ v_0$, assuming a constant rate of increase in technological improvement (for example, 3%, hence $\alpha = 0.03$).

The rate of value increase for new technologies is difficult to estimate, but for some programs it can be done empirically with observations of past performance increases – such as in the study of Hubble.[39] For most cases, including in this study, the rate of value increase from newly-available technologies is treated only in a sensitivity analysis – allowing a comparison of scenarios without improving technology, with slow technology improvements, or with rapid technology improvements.

Risk & Time Preferences

The economist Kenneth Arrow argues that the government should behave as a risk neutral actor in public investments when the risks of an investment are borne by the government and that the amounts involved are small enough compared to the nation's budget.[40] He argues this because when the government bears a risk, it effectively spreads it across a very large number of people. He notes, however, that when risks in public investments are borne (in all or in part) by private individuals, it is appropriate to discount the outcomes as the individuals would.

We include the effects of risk-sensitivity on decision making to study the effect of (a very real) risk aversion on the certain equivalents of different satellite architectures, and on the choice of an optimal policy for each architecture. Recall that a *policy* is a set of tactical decisions given a particular satellite architecture, including: initial deployment schedules, replenishment launches, launches to upgrade payload technologies, whether to maintain in-orbit or ground-based spare vehicles, and other factors. In a sensitivity analysis, considering the effects of risk aversion can provide national leaders with additional insights about the optimal structure of spaceflight projects -- especially in cases where they are considered critical to national security programs. Additionally, while the financial risks of major spaceflight projects are spread across a large number of people, consistent with observations of Arrow,[41] the risks associated with losses in data may be felt in some cases by a smaller number of people (such as deployed military personnel), or the loss may be disproportionately large for a large number of people (such as loss of national strategic systems that enable missile launch warnings). We model a risk averse decision maker using an exponential utility function, which reflects a constant absolute risk aversion.

For the United States, a time preference has been established by executive policy: the White House Office of Management and Budget prescribes a real discount rate (that is updated annually) for public investments that bring costs and benefits to the general public.[42]

Optimization: Finite-Time, Risk-Sensitive Markov Decision Problem with Constant Discounting

The solution method for this model is stochastic dynamic programming (analysis of decisions in inverse chronologic order, under uncertainty). This section provides a brief overview of a sequential decision problem within the framework of a finite-time Markov Decision Process (MDP). This is shown here for a risk-neutral as well as a risk-averse decision maker with an exponential utility function in a *finite time, risk-sensitive MDP with constant discounting*.

Several assumptions are made to make this model tractable: (1) the health-state evolution of a satellite is uncertain and depends only on its age; (2) the set of possible actions depends only on the current systems state, not on the current time (for example, it is possible to launch a satellite only if a satellite has already completed construction activities, regardless of the year); (3) rewards are monetary, can be positive or negative, and depend deterministically on the current state and current actions taken at a particular time; related, the value of a program is separable and can be calculated as the discounted sum of uncertain rewards received over the course of the program; and (4) the risk preference of the decision maker is represented by an exponential utility function (described below).

To outline the formulation of an MDP model, we use the following notation: ***S*** is the state space, a finite set of possible states. $\boldsymbol{x} \in \boldsymbol{S}$ is a state vector. ***A(x)*** is the set of possible actions in state ***x***. ***T*** is the problem time horizon, defined as the total time of analysis for a satellite program. The probability of transitioning from state ***x*** to state ***y*** when action ***k*** is chosen at any time is ***P(y|x,k)***. The time-dependent reward received for being in state ***x*** and taking action ***k*** at time ***t*** is $\boldsymbol{r_t(x,k)}$. (At the final time ***T***, the immediate reward is $\boldsymbol{r_T(x)}$ and depends only on the system state).

A policy function $\boldsymbol{\mu_t}$ at each time stage describes an action as a function of a state. Therefore: $\boldsymbol{\mu_t(x) \in A(x)}$ for all $\boldsymbol{x \in S}$ and **t = 0,…,T-1**. A Policy **π** is a set of time-stage policy functions for all planning time-stages:
$\boldsymbol{\pi = \{\mu_0, \ldots, \mu_{T-1}\}}$. The expected value of a satellite program in state **x** at time **t** given policy **π** is $\boldsymbol{v_t^\pi(x)}$.

Our objective is to find a policy that yields the maximum certain equivalent for the entire program. Recall that there is only one maximum certain equivalent, but that there may be several policies that can achieve it.

Risk-Neutral Markov Decision Problem

For a risk neutral decision maker, one can use expected values to assess a policy. The expected value of being in state **x** at time **t** given policy **π** can be written in terms of the current reward and the expected value of possible subsequent states, given continued application of the policy; this is often called the Bellman recursion.[43] Using the notation above, this recursion can be written as:

$$v_t^\pi(x) = r(x, \mu_t(x)) + \beta \sum_{y \in S} P(y|x, \mu_t(x)) \; v_{t+1}^\pi(y)$$

for **t = 0,…,T-1**, where **β** is a time-discount rate. At time **T**, $\boldsymbol{v_T^\pi(x) = v_T(x) = r_T(x)}$. Our objective is to find the maximum value, $\boldsymbol{v_t^*(x)}$, and a corresponding policy $\boldsymbol{\pi^*}$ that provides it. Using the same recursion as above, this can be written as:

$$v_t^*(x) = \max_{\mu_t(x) \in A(x)} \; r(x, \mu_t(x)) + \beta \sum_{y \in S} P(y|x, \mu_t(x)) \; v_{t+1}^*(y)$$

and

$$\pi^* \in \operatorname*{arg\,max}_{\mu_t(x) \in A(x)} \; r(x, \mu_t(x)) + \beta \sum_{y \in S} P(y|x, \mu_t(x)) \; v_{t+1}^*(y)$$

for **t = 0,…,T-1** and with $\boldsymbol{v_T^*(x) = r_T(x)}$. The solution for both $\boldsymbol{v_t^*(x)}$ and $\boldsymbol{\pi^*}$ can then be obtained with dynamic programming: values are substituted in for $\boldsymbol{v_T^*(x) = r_T(x)}$ for all **x**, and then each $\boldsymbol{v_t^*(x)}$ is found by working backward from **t** = **T-1** to **t = 1**, for all ***x*** at each ***t***. For each state **x** and time **t**, the optimal action is saved. The policy $\boldsymbol{\pi^*}$ is produced when this process is complete.

Risk-Sensitive Markov Decision Problem with Constant Discounting

For a decision maker who is not risk neutral, expected values cannot be used to assess the costs and benefits of a system. Instead we assume here an exponential utility function (constant risk aversion), which can be used to model the preferences of a broad range of decision makers and has a large set of useful properties for analyzing decisions.[44] An exponential utility function takes the form:

$$u(w) = -e^{-\gamma w}$$

where **γ** is the risk aversion of a decision maker (where the utility tends towards risk neutrality as **γ** approaches 0, and increasing risk aversion is reflected by an increasing **γ**),[†††] ***w*** is the monetary value in dollars of a mission outcome, and ***u(w)*** is the utility associated with ***w*** for the considered decision maker. An exponential utility function assumes a decision maker does not consider his or her prior wealth when evaluating uncertain deals.

For a decision maker with an exponential utility function, Howard and Matheson (1972)[45] show it is possible to write the utility in this framework as:

$$\begin{aligned} u(\hat{v}_t^{\pi}(x)) &= \sum_{y \in S} P(y|x, \mu_t(x))\ u(r(x, \mu_t(x)) + \hat{v}_{t+1}^{\pi}(y)) \\ &= \sum_{y \in S} P(y|x, \mu_t(x))\ e^{-\gamma r(x, \mu_t(x))}\ u(\hat{v}_{t+1}^{\pi}(y)) \end{aligned}$$

where $\hat{v}_t^{\pi}(x)$ is the *certain equivalent* of a process currently in state ***x*** at time ***t*** given policy ***π***. This can be understood as the minimum amount a decision maker would accept instead of the uncertain value from the remainder of the program, given the current state, time, and policy. Note that for a risk neutral decision maker, $\hat{v}_t^{\pi}(x) = v_t^{\pi}(x)$. Time discounting can be included in the reward function, changing **r(x,k)** to **r_t(x,k)**. Backward induction can then proceed as in the risk neutral case. The result is the optimal certain equivalent, $\hat{v}_t^{*}(x)$, instead of an expected value, for a program in state ***x*** at time ***t***, and an optimal policy **π^*** based on the decision maker's risk aversion.

Strategic Analysis: Comparison of Satellite Architectures

For a Markov Decision Process (MDP) model of each satellite architecture, the outputs include the maximum expected utility achievable for that architecture given a defined initial state, and a policy that provides that value. These outputs can be used to inform a detailed mission analysis for each particular architecture.

For a strategic decision between consolidated and distributed satellite architectures, the final step is to select the satellite architecture that provides the maximum expected utility, given its optimal policy for operation. This can be done by selecting the architecture with greatest certain equivalent, then operating the architecture according to the optimal procedures found in its detailed mission analysis.

[†††] Recall that an increasing risk aversion can be understood qualitatively as an increasing focus on the worst-possible outcomes in a scenario.

SAMPLE SCENARIO: REFERENCE GEOSYNCHRONOUS SATELLITE MISSION

In this paper, we consider a sample scenario called the *reference geosynchronous mission (RGM)* to examine the results of a long-term Earth observation project in geosynchronous orbit. Table 1 provides overall inputs for the mission. The RGM is a project that collects data from two primary payloads as well as multiple smaller secondary ones. The consolidated satellite architecture places both primary payloads on a single satellite. The distributed satellite architecture divides the two primary payloads onto two vehicles.

	GEO Reference Mission	Sensitivity Analysis?
Mission planning period	30 years	No
Annual data value	$1.3 B [‡‡‡]	Yes
Risk Aversion	Risk Neutral and Risk Averse	Yes
Discount Rate	5%	Yes

Table 1: Scenario parameters for the GEO reference mission.

	Consolidated Satellite Architecture: (One Satellite)	Distributed Satellite Architecture: (Two Satellites)	Notes
Total satellite mass in orbit: Bus + Payload(s)	10,000 lb (4,500 kg)	4,000 lb (1,800 kg)	
Primary payloads per vehicle	2	1	
Orbit	Geosynchronous	Geosynchronous	
Design life for each vehicle	12 years	6 years	Consolidated similar to SBIRS.[46]
Reliability for Design Life	0.62	0.51	See Exhibit 5.
Total cost *per satellite*	Approx. $1,000 M	Approx. $450 M (x 2)	Used as order-of-magnitude estimates.[§§§]
Time required for satellite design/build/assembly/tests	6 years	4 years	
Launch Vehicle	Evolved Expendable Launch Vehicle (EELV)	Evolved Expendable Launch Vehicle (EELV)	
Launch cost *per satellite* (incl. integration, facilities)	$250 M	$250 M (x 2)	Approximated from public NASA OIG report.[47]
Probability of successful launch and deployment	0.98	0.98	
Total <u>initial</u> deployment cost for each architecture	$1,250 M	$1,400 M	Sum of vehicle and launch costs.

Table 2: Fictional vehicle parameters used as inputs for consolidated and distributed satellite architectures.

This analysis makes several simplifying assumptions to use publicly available input data. To approximate data value, we use a simple revenue model, for the RGM, approximated $1.3 Billion USD, based on an average of recent annual U.S. expenditures for the SBIRS Program.

[‡‡‡] The annual data value of input is chosen by comparison with SBIRS. The annual expenditures on SBIRS are taken as the 2008-2013 average, approximately $1.3 Billion USD (see: "Program Acquisition Costs by Weapon System," U.S. Department of Defense Comptroller, years 2008-2014. Available online: http://comptroller.defense.gov/). The annual U.S. Government expenditure on SBIRS is used as an initial coarse estimate as the amount that the U.S. is willing to pay for SBIRS data. SBIRS annual expenditures correspond to multiple orbital locations; here we use the average annual expenditure of recent years to consider the value of a single data set – one GEO slot. This is meant to be illustrative, and an order-of-magnitude sensitivity analysis is performed for this value.

[§§§] Consolidated vehicle cost is within an order of magnitude of a SBIRS satellite costs at about $1.3 B (see for example: http://www.bloomberg.com/news/2011-05-07/u-s-air-force-launches-1-3-billion-missile-defense-satellite.html, accessed 4/8/2014). For distributed vehicle, a simple correlation with mass is used to provide a coarse estimate.

The value of the data is derived from the two primary payloads only, and we assume that each primary payload provides half this value independently of the other payload's state. A sensitivity analysis is also performed to consider the case where value is only obtained when both payloads are operational.

Reliability input data for consolidated and distributed satellite vehicles are shown in Exhibit 5. The consolidated satellite reliability curve corresponds to a vehicle with a design life of approximately 12 years. The reliability curve for each distributed satellite corresponds to a vehicle design life of about 6 years. Both reliability curves are obtained based on engineering judgment; detailed analyses with propriety or non-public reliability (or cost) data can be done simply by substituting different input data.

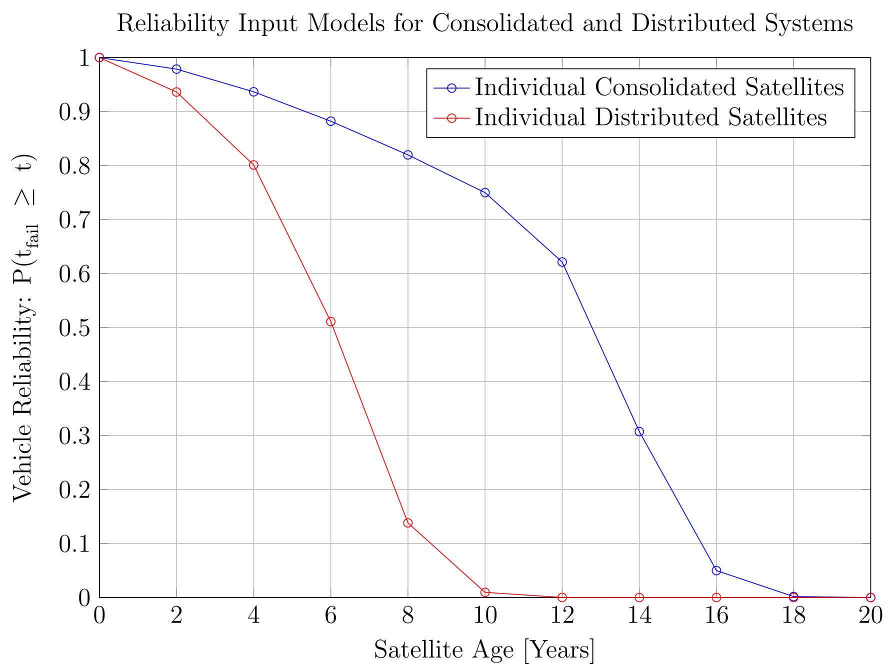

Exhibit 5: Reliability curves for individual vehicles in consolidated and distributed satellite architectures.

In addition, this sample scenario is based on several assumptions: (1) distributed satellite modules are launched separately, each incurring a full launch cost; (2) there is no schedule constraints on launch vehicle availability; this factor will have to be included in further studies and will depend on the circumstances at the time; (3) each vehicle operates self-sufficiently relative to the payload(s) that it carries; payload data can be downlinked directly from each satellite, and a cross-link is not necessary; (4) the distributed architectures will not require or use close-proximity formation flight operations; the physical separation of distributed spacecraft modules is sufficient for intra-constellation collision probabilities to be very low; (5) the total value of satellite data (see Table 1) is provided by the two primary payloads; each primary payload provides half of this value independently of the other payload's state; and (6) partial vehicle failures are not considered in this model of the reference geosynchronous mission.

RESULTS & DISCUSSION

High-Level Observations

For a 30-year planning horizon, using the base case inputs of Tables 1 and 2 and assuming *no technology advancements* and *a risk neutral decision maker,* MDP solutions indicate that a consolidated satellite architecture provides a slightly higher value ($12.93 B) than a distributed satellite architecture ($12.82 B). In all scenarios that include *technology advancements*, however, the distributed satellite architecture has a higher value than the consolidated architecture because the system can be upgraded more efficiently. In the same way, for a very risk-averse decision maker, even with no technology advancements, a distributed satellite architecture has a higher value because failed satellites can be replaced more quickly and at lower cost. These results can be seen in Exhibits 8 and 9 and are discussed further below.

Insights can also be gained through Monte Carlo simulations of both architectures, with an optimal operational policy applied for each. Simulation results of program value given optimal policies are shown for a risk neutral decision maker assuming first no technology improvement (Exhibit 6), then a small annual technology advancement (Exhibit 7). Two observations can be made from Exhibits 6 and 7: first, a consolidated satellite architecture with these inputs, tends to have a relatively high value (the most likely outcome). Even with an optimal operational policy, however, the consolidated satellite architecture has a longer downside tail on its value distribution than a distributed architecture. By contrast, a distributed satellite architecture, with an optimal policy, tends to have a more Gaussian (symmetric) distribution of value, with a smaller mode and a shorter left tail.

These results provide a quantitative confirmation of an intuitive idea: even with the best possible operational policies, a low-probability, high-consequence gap in data is more likely for a consolidated satellite architecture than for a distributed architecture, provided that some launch capability is available within a reasonable time. Less intuitively, these results highlight the fact that a distributed satellite architecture, using smaller, individually less-reliable vehicles, can be a better solution for a decision maker who is highly risk-averse about gaps in data. (This result is confirmed empirically with a sensitivity analysis on risk aversion, discussed below and shown in Exhibit 8).

This result applies to cases where partial value can be obtained from each payload independently of other payloads (recall that for the reference geosynchronous mission, half the value is provided by each sensor). This approach is applicable for most mission types that face a risk-based choice between consolidated and distributed satellite architectures. The exception to this result would be the case of a mission that requires data from both payloads to obtain any value. In this case, under the inputs in Tables 1 and 2, a consolidated architecture provides a higher value than a distributed architecture over a broader set of scenarios.

The second observation, based on Exhibit 7, is that both satellite architectures provide more value in a scenario involving technology advancements over time, but the distributed satellite architecture performs better overall. This is because technology insertions can be done more cost-effectively for distributed satellite architectures, even with a simple division of payloads across two satellites.

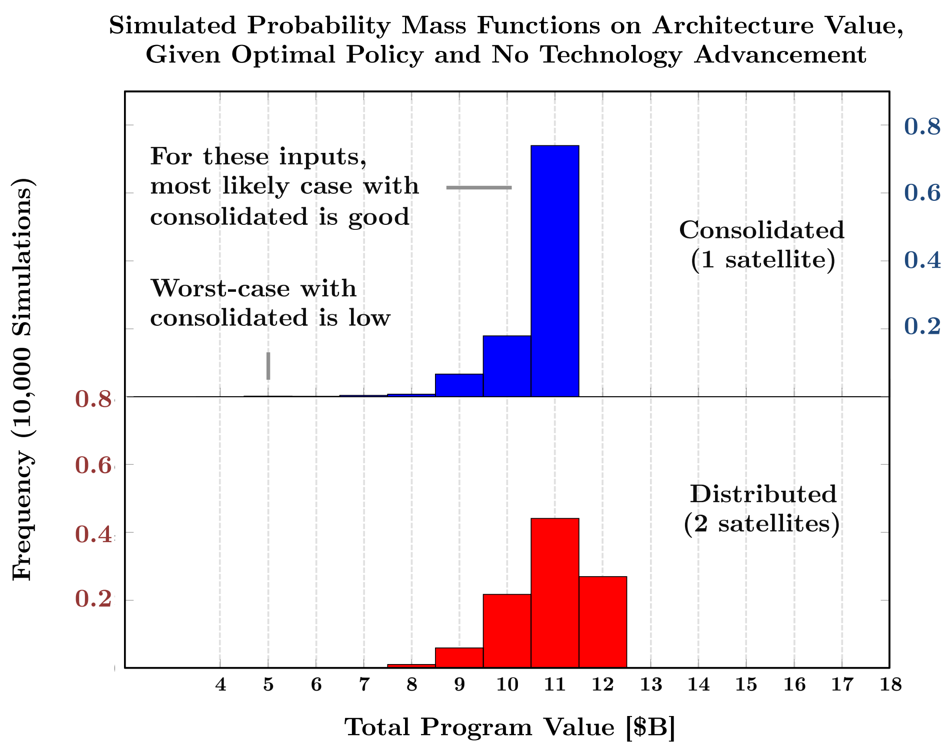

Exhibit 6: Distribution over value for GEO reference mission with no technology advancement.

For 30-year GEO reference mission, risk neutral decision maker, given an optimal policy for each architecture.

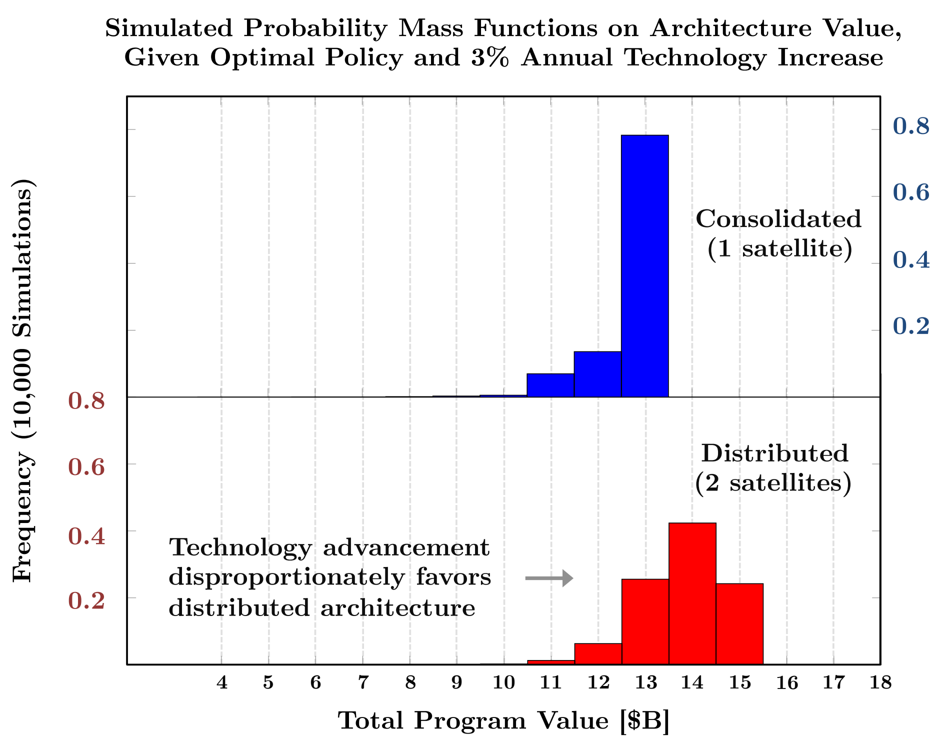

Exhibit 7: Distribution over value for GEO reference mission with 3% annual technology value increase.

For 30-year GEO reference mission, risk neutral decision maker, given an optimal policy for each architecture.

Risk Aversion

Exhibit 8 provides a sensitivity analysis for the value (certain equivalent) of each satellite architecture as a function of increasing risk aversion **γ**. Each point represents the best-achievable value of a satellite architecture (based on the inputs of Tables 1 and 2) given an optimal policy for the 30-year program with risk aversion **γ**. The X-axis is shown as $\mathbf{Log_{10}(\gamma)}$: the left side, $\boldsymbol{\gamma=10^{-11}}$, approaches a risk neutral preference for this scenario, while moving rightward toward $\boldsymbol{\gamma=10^{-7}}$ approaches a high degree of risk aversion relative to the expenditures of the reference geosynchronous mission.[****]

As risk aversion increases, the optimal policy for sequential decisions within each satellite architecture changes. In the limit of very high risk aversion, the optimal policy becomes never to acquire or launch satellites – rather than to launch and risk failures. At this level of risk aversion, the value of each satellite architecture given the optimal policy approaches zero (fixed costs identical to both mission architectures are excluded from the analysis).

At intermediate levels of risk attitude, as a decision maker becomes increasingly risk averse, the distributed satellite architecture provides greater value than the consolidated satellite.

Technology Advancement Rate

Exhibit 9 provides a sensitivity analysis for the value of consolidated and distributed architectures given a risk neutral decision maker and an optimal policy for each configuration. As technology change accelerates, the value of a distributed satellite architecture increases significantly faster than the value of a consolidated satellite architecture. For example, comparing a scenario with *no technology improvement* to a scenario with a *5% linear annual improvement*, the expected value of a distributed satellite architecture over 30 years increases by 54% ($6.9 B) compared to 43% ($5.5 B) for a consolidated satellite architecture. This is because a distributed satellite architecture, with shorter development times and lower acquisition costs, makes launching new systems before old ones have failed more practical.

Other factors

Sensitivity analysis for both the data value (Exhibit 11, Appendix 2) and the time-discount rate (Exhibit 12, Appendix 2) are also performed. Varying either factor does not significantly change the preferred alternative between consolidated and distributed satellite architectures. For the reference geosynchronous mission, risk aversion and technology advancement rates have the largest effects on the relative value of the two architectures.

[****] These values of **γ** can be understood as follows: changing **γ** effectively changes the shape of the utility function. As **γ** becomes larger, a decision maker is approximated as more risk averse. In the limit of being very risk averse, a decision maker focuses on the worst-possible outcomes of a scenario, and acts accordingly.

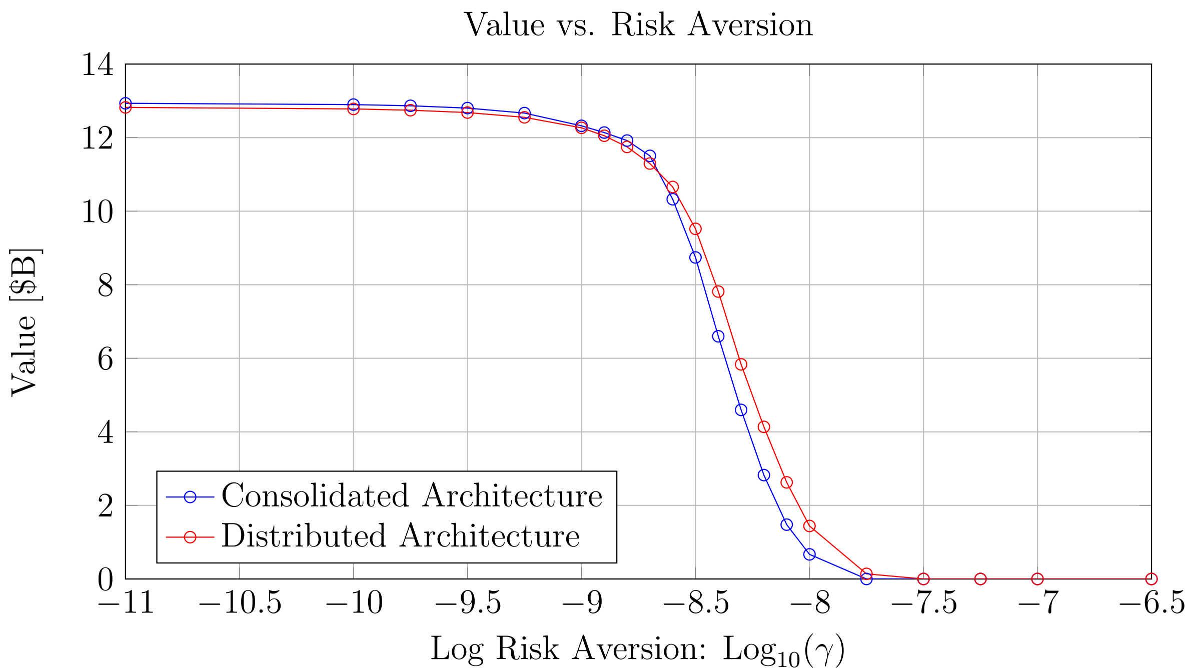

Exhibit 8: Certain equivalent of distributed and consolidated satellite architectures as a function of risk aversion. A high level of risk aversion favors distributed satellite architectures. Each point is a complete MDP solution: the certain equivalent of 30-year GEO reference mission, assuming no technology growth, starting with no satellites, and given an optimal management policy.

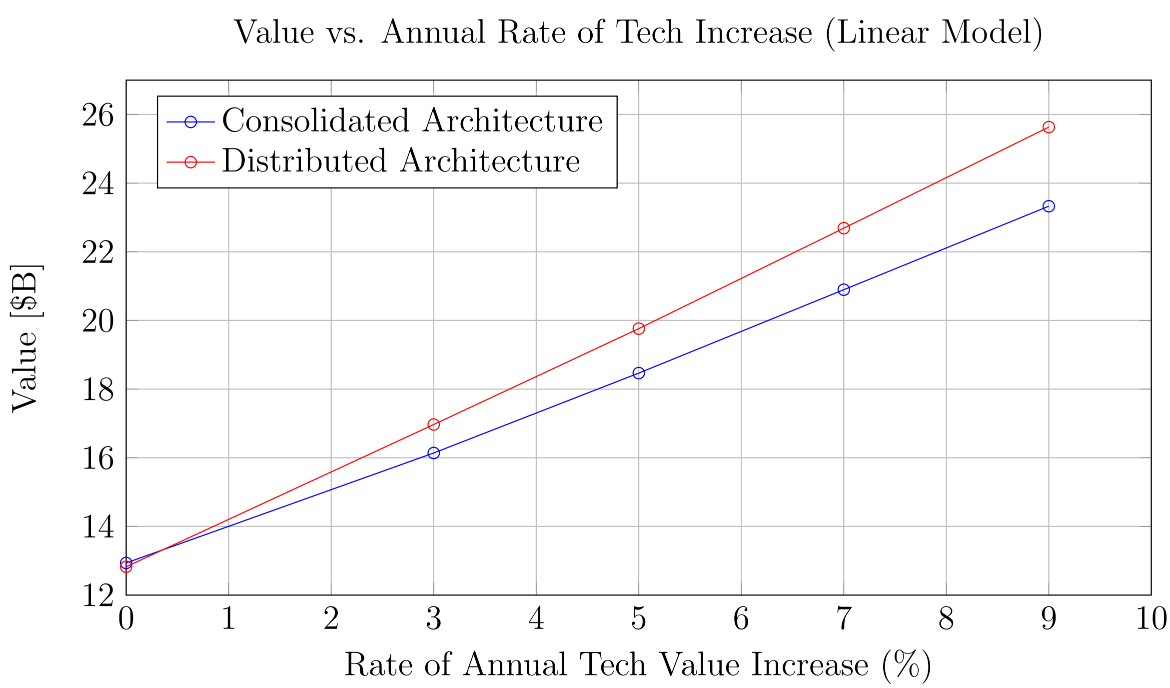

Exhibit 9: Certain equivalent of different satellite architectures as a function of annual technology value increase Scenarios with technology advances over time favor distributed satellite architectures. Each point is a complete MDP solution: the certain equivalent of a 30-year GEO reference mission, for a risk neutral decision maker, starting with no satellites, and given an optimal policy.

CONCLUSIONS

There is no satellite architecture that is clearly the 'best' in all cases: an optimal satellite architecture depends on the specifics of a mission, relevant uncertainties, the risk preference of a decision maker, and the anticipated rate of technology advancement. This paper provides a quantitative foundation for analyzing strategic architecture decisions for national Earth-observation satellite programs. It synthesizes all the elements necessary to analyze this decision in an expected-utility maximization framework, considering the value of optimally exploiting the technical and operational characteristics of each architecture alternative. Within any satellite architecture, this framework can also be used for detailed mission analysis, including optimal launch and acquisition schedules, orbit- or ground-spare choices, and other relevant factors.

Input data can be provided by simple estimates or by detailed reliability and cost input models. This paper uses a fictional *reference geosynchronous mission* to examine tradeoffs and risks for a simple scenario that has order-of-magnitude similarity to U.S. government projects under consideration for deployment to GEO. Results for the reference geosynchronous mission demonstrate that distributed satellite architectures can provide increasing advantages over consolidated satellite architectures when a high rate of technology evolution is expected and for programs that merit risk-averse decision-making. This result can be counter-intuitive for program managers who may regard the status-quo in major space programs as reflecting risk aversion. In fact, these results indicate that a risk-averse leader for the reference geosynchronous mission should prefer a distributed satellite architecture because in general, the system could be more easily fixed in orbit by replacing a failed satellite. This result is even stronger if improving technologies can provide more valuable data products over time – in which case an optimal operation of distributed satellite systems provides better conditions for deploying sensor improvements.

Additional distributed architecture benefits that are not addressed here

Several additional benefits of distributed satellite architectures may appear over time, under the following circumstances:

- More frequent launches with more predictable schedules may lower launch costs over time.
- More frequent satellite acquisitions, less complex individual satellites, and more predictable satellite acquisition cycles may all contribute to lower satellite acquisition costs over time.
- If there is an increased risk tolerance for individual satellites in a distributed architecture, new technologies may be deployed earlier than current testing and space-qualification practices would permit.

These factors are not addressed quantitatively in our model. They are, however, important issues that should be considered in decisions and may show larger benefits of distributed satellite architectures.[††††]

[††††] Two additional areas will be the subject of longer-term future work: first, the distribution of satellites into multiple orbital regimes with modules in different orbits, such as GEO and MEO; second, an extended decision model involving other actors (adversaries) to test our beliefs about the deterrent effects of distributed satellite architectures.

APPENDIX 1: DETAILED SENSITIVITY ANALYSIS ON RISK AVERSION AND TECHNOLOGY ADVANCEMENT

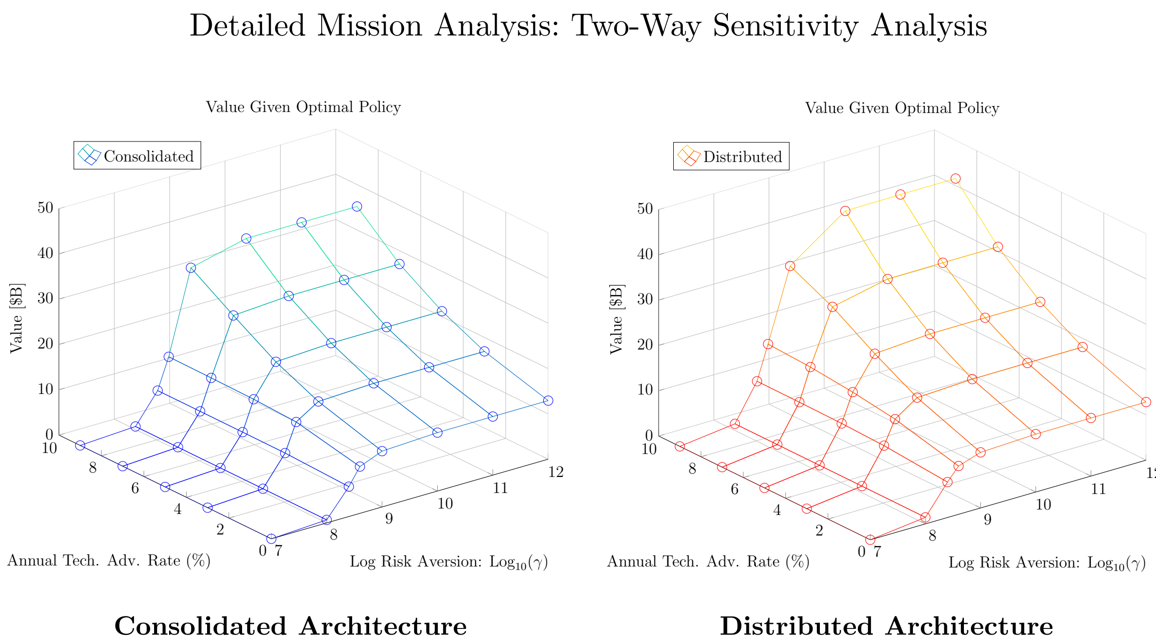

Exhibit 10: Value of consolidated (left) and distributed (right) satellite architectures as a function of the annual rate of technological advancement and risk aversion. Each point is a complete MDP solution: the certain equivalent of 30-year GEO reference mission, for a risk neutral decision maker, with no anticipation of technology advancement, starting with no satellites, and given an optimal policy.

APPENDIX 2: ADDITIONAL SENSITIVITY ANALYSES, DATA VALUE AND TIME-DISCOUNTING

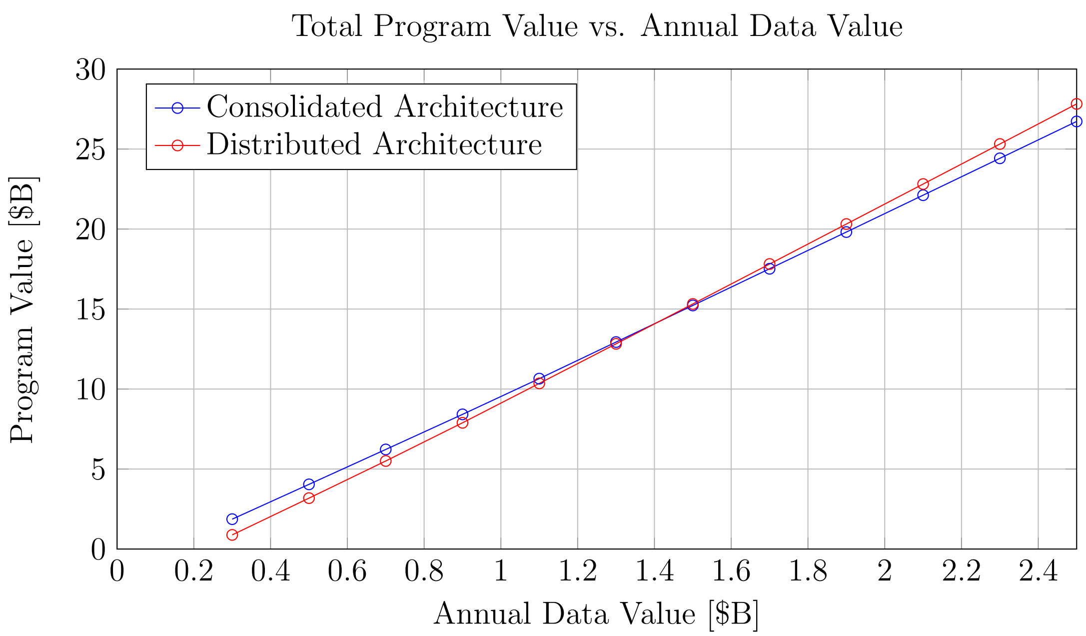

Exhibit 11: Certain equivalent of distributed and consolidated satellite architectures as a function of data value. Changing the value of data does not strongly affect the preferred satellite architecture given these input data. Each point is a complete MDP solution: the certain equivalent of 30-year GEO reference mission, for a risk neutral decision maker, with no technology advancement, starting with no satellites, and given an optimal policy.

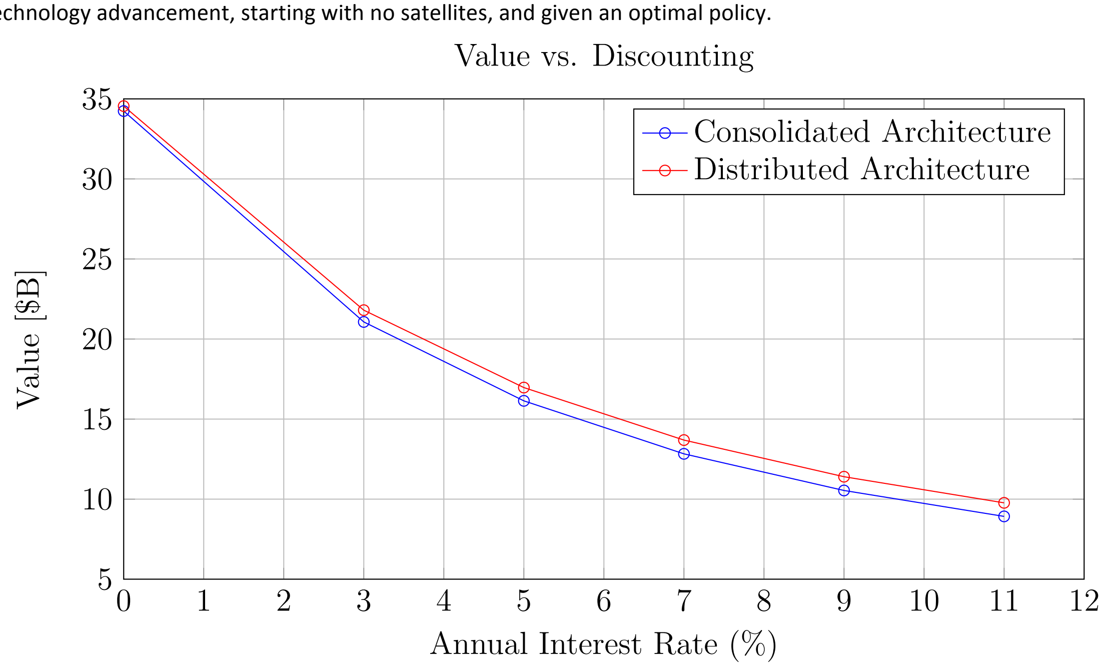

Exhibit 12: Certain equivalent of distributed and consolidated satellite architectures as a function of discount rates (shown here as annual interest rate). Changing the discount rate does not strongly affect the relative value of the two alternatives. Each point is a complete MDP solution: the certain equivalent of 30-year GEO reference mission, for a risk neutral decision maker, with no technology advancement, starting with no satellites, and given an optimal policy.

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[10] e.g., see: *R.K. Raney, G.H. Fountain, E.J. Hoffman, P.F. Bythrow, and R.H. Maurer, R.H., "Small Satellites and NOAA: A Technology Study," Proceedings AIAA/Utah State University Conference on Small Satellites, Logan, UT, 1995*. Other studies were done internally for the U.S. government with analogous results.

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