"System Lifecycle Cost Under Uncertainty as a Design Metric Encompassing the Value of Architectural Flexibility"

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System Lifecycle Cost Under Uncertainty as a Design Metric Encompassing the Value of Architectural Flexibility*

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In this work, we develop an alternative metric and approach for system design and acquisition decisions that encompasses system flexibility called assured system lifecycle cost under uncertainty, or simply stochastic lifecycle cost. We use this metric to compare the overall lifecycle costs of an existing monolithic satellite system to a hypothetical fractionated satellite system that provides the same service. Different approaches to fractionation are investigated. Lifecycle cost calculations are derived in a non-deterministic form using Monte Carlo simulations incorporating launch and component failure uncertainty to produce mean values with associated variances for statistical comparison. We find that the total lifecycle cost of fractionated satellite architectures are comparable to monolithic satellite architectures when the individual satellite design lifetimes are longer and are aligned with individual satellite expected mean mission durations based on component failure reliability.

I. Introduction

Since 2000, a body of research has emerged on value-based metrics for system acquisition and design decisions. Such metrics consider the net present value of the lifecycle value delivered by the system minus its lifecycle costs – where the value streams may encompass the operational utility or revenues of the system as well as other, less tangible sources such as the option value of architectural flexibility. This value-centric perspective is a significant improvement over traditional design and acquisition analysis techniques based largely on cost alone because it rewards modular, scalable, reconfigurable, and otherwise flexible designs that can substantially enhance a system's overall value to the operator with only a modest cost penalty.

In this work, we develop an alternative metric and approach as a basis for system design and acquisition decisions that encompasses system flexibility. We term this metric assured system lifecycle cost under uncertainty, or simply stochastic lifecycle cost. The underlying premise of our approach is that the cost to develop, procure, and operate a system with some assured minimum capability over its lifecycle is not a deterministic value. Instead, it is a random variable with a probability distribution resulting from a set of uncertainties introduced throughout the system's life. We argue that this random variable metric is a relevant basis for comparison between alternative system architectures and design choices. This metric alone may provide important information to decision makers, even before net lifecycle value (i.e., value delivered over a system's lifetime, minus the total lifecycle cost) can be calculated. This is important for systems, such as those purchased and fielded by the government, whose utility is not readily quantifiable through a market valuation or other measure. In this work we illustrate our approach by modeling the stochastic lifecycle cost for several different space architectures intended to accomplish the same mission.

II. The Value Offered by Satellite Fractionation

The study of the value created by system lifecycle flexibility has been the topic of recent research into alternative approaches to spacecraft architecture design. Methods offered for enhancing spacecraft flexibility have included on-orbit satellite servicing[i,ii,iii,iv], staged constellation deployment[v], and on-orbit software upgrades[vi]. Each of these methods involves one or more value-enhancing attributes, collectively known as design flexibility. Design flexibility can take the form of capability restoration, capability augmentation, risk diversification, schedule diversification, or uncoupling of system requirements.

We argue that one novel architectural approach to enhancing the lifecycle value of a spacecraft through flexibility is the adoption of a fractionated satellite architecture.[vii] A fractionated architecture is one in which the spacecraft system is decomposed into multiple modules which interact wirelessly to deliver at least the same capability as that provided by a comparable traditional, monolithic system. There are two fundamental dimensions to satellite fractionation: heterogeneous and homogeneous.

Heterogeneous fractionation is the degree to which the original spacecraft is decomposed into functionally dissimilar modules. For instance, a spacecraft with a separate payload, tracking telemetry and communications (TT&C), and computation and data handling (C&DH) modules would be considered to be fractionated into three heterogeneous modules. Conversely, homogeneous fractionation is the degree to which a spacecraft is decomposed into a number of identical modules. A hypothetical example of this could be a constellation of a dozen identical sensing satellites serving as a distributed aperture in space. With either type of fractionation, one of the critical driving factors is the level of connectivity between the separate modules.

The fractionated spacecraft design paradigm is enabled by the recent advances in wireless and network-related technologies, as well as the advent of micro-satellites. These technologies include: a) robust self forming networks; b) secure wireless communication; c) scalable and adaptable distributed computing; d) reliable and efficient wireless power transfer; e) autonomous cluster navigation; and f) effective distributed payload operations. These technologies, developed and implemented in the context of new space systems, can combine to significantly change the current paradigm of launching costly and bloated satellites that are prone to system fragility and are inflexible to uncertainties in their operating environment. Some of the numerous benefits brought about by the fractionated spacecraft architecture paradigm are:

- Diversification of launch and on-orbit failure risk.
- Reliability enhancement through emergent sharing of subsystem resources.
- Scalability in response to service demand fluctuations.
- Upgradeability in response to technological obsolescence.
- Incremental deployment of capability to orbit.
- Graceful degradation of capability on-orbit.
- Robustness in response to funding fluctuations and requirements changes.
- Reduced integration and testing due to subsystem decoupling.
- Production learning across multiple similar modules.
- Enabling spacecraft to be launched on smaller launch vehicles with shorter timescales.

It is our goal in this paper to attempt the quantification of some of these benefits, which collectively amount to value and cost enhancements, in a single metric – that of assured lifecycle cost under uncertainty.

III. Total Stochastic Lifecycle Cost Analysis Approach

In order to conduct an economic case study of satellite fractionation, we needed to baseline an existing and established satellite system that closely represented the type of monolithic space systems to which a fractionated architecture would have greatest applicability. Choosing a government asset allowed us to obtain the design data needed to conduct our analysis, but also led us to adopt a steady-state system goal of uninterrupted service utility in place of maximized profit, as would be expected if we studied a commercial system. We chose the current operational incarnation of the Geostationary Operational Environmental Satellites (GOES) system, Block I-M. We provide additional details on the GOES spacecraft, as modeled, in subsequent sections. The combination of multiple onboard payloads and enduring mission requirements made GOES an ideal case for this study. Note that the nature of the GOES system, defined by multiple disparate payloads, naturally led to modeling heterogeneous fractionation.

A. Comparing Satellite Fractionation Approaches

Our approach to evaluating the benefit of a heterogeneously fractionated GOES system involved modeling the stochastic lifecycle costs of three different space architectures intended to accomplish the same mission: monolithic, pure fractionation, and hybrid fractionation. The operating paradigm for each of these architectures is explained below.

The traditional approach is to employ a single large (monolithic) satellite system, and operate it until failure or a predicted end-of-life (EOL) point. Before predicted EOL is reached, a determination is made whether to replace the system. It is important to note that 'failure' in this context can occur in many forms. It can be failure to launch, failure to initially communicate with the ground, failure to deploy required appendages such as solar arrays, or a failure of internal components. Without loss of generality, our definition of 'failure' encompasses any unintended event that results in less than full mission capability of the spacecraft system. Thus the failure of one of many critical payloads is considered system failure, since the entire system can no longer function to supply the service provided by the failed payload. Restoring the functionality of the lost payload requires the launching of an entirely new monolithic spacecraft.

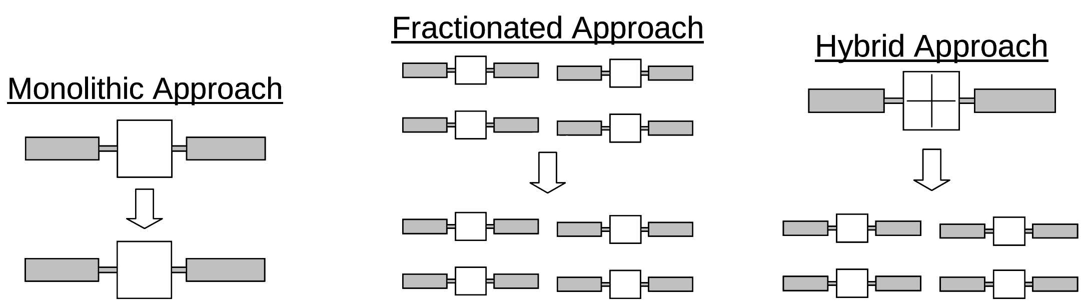


Figure 1: Comparison of approaches to Fractionation

For a purely heterogeneous fractionated spacecraft system, the operating paradigm begins with the launching of all of the individual modules, separately if possible to distribute launch risk. Once on station, the combined system functions together to supply the same utility as the monolithic system. Incremental deployment of capability is possible, but given our self-imposed requirement of complete system functionality, this situation was not modeled. The difference between the fractionated and monolithic architecture becomes apparent with the first 'failure.' This time, any specific launch failure, deployment failure, or component failure affects only one module. Instead of launching an entirely new system to regain full mission capability, only the replacement of the failed module is required. With this paradigm, each spacecraft module operates on a independent replacement schedule over time, theoretically reducing the number of fully functional subsystems that are replaced unnecessarily.

A hybrid approach combines aspects of the monolithic and fractionated paradigms. With this approach, the initial system is one satellite in its physical appearance only, but with all internal subsystems cooperating using wireless means. Thus communications between the navigation subsystem and the processor, for example, is accomplished without physical data connectivity. Launch failure still requires total system replacement, but component failure scenarios are quite different than in the monolithic case. Instead of having to replace the entire spacecraft when the failure of a critical component causes less than full mission capability, all that is required is the launch of a new module into the vicinity of the hybrid spacecraft. Once wireless communication is established between the hybrid monolith and the replacement module, full mission capability is restored. As illustrated in Figure 2, note that continued failures of this type will eventually lead to the end state of a fully fractionated architecture, where all operating functionality is distributed between small fractionated modules.

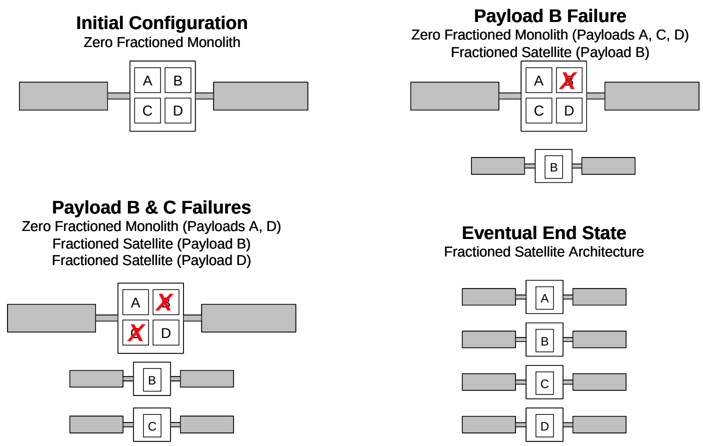


Figure 2: Fractioned Satellite Architecture Evolution

B. Analytic Stochastic Lifecycle Cost Approach

To adequately compare the three different architectural options, a key step is properly modeling the cost behavior over time. This model must take the entire operating lifecycle of the system over time into account. To do so requires considering development, launch, deployment, and operation. While some relatively innocuous assumptions can be made (e.g., fixed satellite development time), it is important to our analysis to consider non-deterministic events. That is to say that system events, such as component failure, which occur stochastically throughout the mission life.

In our analysis we incorporate lifecycle uncertainties which can readily be translated into cost impact on the overall mission. These cost-impact uncertainties include launch/deployment failure and on-orbit component failure. Lifecycle uncertainties that can be incorporated as additional value to the overall mission, but that lack a direct cost impact, are left for future analysis Examples of value-impact lifecycle uncertainties include requirements creep, funding stream volatility, technology development risk, and volatility of demand. Note that incorporating value-impact uncertainties into a larger analysis is only expected to help the case for fractionation.

Certain failures, such as launch and deployment failure, can be modeled as point event opportunities occurring when a launch is necessary. Component failures, on the other hand, can occur throughout the lifetime, and are based upon predefined reliability models. Component failures in this study are modeled using the Weibull distribution, where the characteristic life parameter is based upon the reliability of the component and the shaping parameter is fixed at 1.7, a value commonly used for satellite systems.[viii] Note that Weibull distributions do not account for 'infant mortality' failures at the beginning or the wear-out failures at the end of standard system lifetimes. Infant mortality can be reduced with thorough testing prior to launch and the use of reliable standardized designs. For ease of calculation, an infant mortality rate of 1% was incorporated into the launch and deployment failure rate. Wear-out reliability is accounted for by acknowledging that a spacecraft must be replaced upon reaching its design life, even if the internal components are still functional, due to exhaustion of expendables and extended exposure to the space environment. For this study, we initially adopted a standard design life of 10 years for all spacecraft, regardless of size or function.

The component failure reliability models developed for each spacecraft – whether a monolith or a fractionated module – drive lifecycle replacement schedules. Since the failures occur stochastically based upon these predefined models, executing a large number of sample runs using the replacement paradigms discussed in Section III A above yielded a mean (expected) replacement schedule for each architecture. The cost for each individual replacement satellite was determined using cost estimating relationships (CER). The CERs provided by the 2005 edition of the Aerospace Corporation's Small Satellite Costing Model (SSCM) and the 8th edition of the Air Force Space and Missile Center's Unmanned Space Vehicle Cost Model (USVCM) provide an estimate of the recurring and non-recurring costs associated with a satellite's development based upon some basic system parameters such as subsystem size, mass, and power. Since these CERs are based on actual data from past small satellite programs, the numbers – while debatable in the accuracy of their absolute magnitude – are acceptable estimates upon which to base system-to-system comparisons. Note that no conclusions in this study are based on the absolute cost values themselves.

C. Stochastic Lifecycle Cost Estimation Process

Our estimation of the stochastic lifecycle cost for each of the different architectures consisted of a three step process. The first step was to establish spacecraft design metrics, in terms or mass, power and failure reliability, down to the subsystem level. This yielded two key pieces of information: a model of the overall spacecraft failure reliability over time in the form of a probability distribution function (PDF), and a detailed understanding of the size, weight, and power metrics of each of the satellites, including the monolith and the fractionated modules.

The second step was to develop a spacecraft replacement strategy by performing a forward looking schedule analysis. This schedule analysis attempts to anticipate, in a non-deterministic fashion, when elements of the spacecraft architectures will encounter failures. Since launch, deployment and infant mortality failures can only occur at the beginning of the timeline and at discrete points immediately following prior satellite failures, they were modeled with a combined simple point probability of success. Steady state component failures were modeled using the individual satellite PDFs developed in step one above. The different failure models and sequences were analyzed using the Crystal Ball software package based on the driving constraint of assured uninterrupted service. Uninterrupted service implied that a replacement satellite would be designed and launched at least prior to its predecessor's failure, thus assuring no gaps in service. This process yielded expected failure occurrences per satellite throughout the overall mission lifetime, and thus an expected value of how many satellites of each type would be required to ensure uninterrupted service over the mission lifetime. Note that all results were random variables with normal probability distributions represented by mean values with associated variances.

The third and final step was to incorporate estimates for the development, procurement, payload, launch, and operations costs. The cost estimates for development and procurement for each of the satellites were derived using the USVCM or the SSCM, as appropriate based on spacecraft mass. CERs generated estimates of non-recurring and recurring costs for each satellite based on size, weight and power metrics (determined as above). Studies of actual government programs on the scale and complexity of satellite systems show that cost estimates such as these are rarely the actual cost figure.[ix] The actual cost figures tend to be lognormal distributions about some mean value higher than the initial estimate. To account for the probability of cost growth, we transformed the CER estimates into lognormal probability distributions using mean and variance statistics applicable to development (non-recurring) and procurement (recurring) costs, respectively. Since the CERs from both models do not estimate payload costs, the NRE and RE cost estimates for payload elements were included as normal distributions about a mean value.

Launch costs were added to the costing model as point values using a commonly accepted ratio based on the mass of the satellite to be launched. Satellite operations costs were modeled differently for the monolithic and fractionated cases. For both the monolithic and hybrid monolithic cases, we started with a fixed annual value and then transformed it using cost growth statistics, in the same manner as applied to the satellite development and procurement costs, resulting in a lognormal distribution. For the fractionated case, the total operations cost of the system was determined by using the same fixed amount used for the monolithic cases for the first satellite. Successive satellite operations cost was assumed to be a 50% increment on the operations cost increment of the previous satellite. This approach captured the savings to be gained from the use of common facilities, personnel, procedures across the networked system of satellites. As with the monolithic case, a lognormal probability distribution was applied to model cost growth.

The end result of this three step process was two-fold. The first product was a stochastic estimate of the expected replacement timeline for each element of each spacecraft architecture. A product such as this is ideal for spacecraft projects at their initial stages since it helps designers consider full lifetime mission capability. The second product was a stochastic estimate of the overall lifecycle costs of the entire system for each of the spacecraft architectures studied. Both sets of data were produced with mean values and variances for use in statistical comparisons. The aspect that sets this overall approach apart from other work using deterministic values that ignore uncertainties is the stochastic nature of the analysis.

To compare the monolithic, purely fractionated, and hybrid architectures, we designed and executed a stochastic analysis to determine representative mission event schedules and overall estimates of lifecycle cost required to provide assured mission capability over a planned time frame. The statistical comparison of the resulting cost data, termed system lifecycle cost under uncertainty, or simply stochastic lifecycle cost, is the basis of our conclusions.

IV. GOES Test Case

The National Oceanic & Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES) provide persistent collection of weather-related data over the continental United States. Normally two GOES satellites operate in geosynchronous orbit and provide coverage of almost a third of the Earth's surface. One satellite monitors North and South America and most of the Atlantic Ocean, while the second covers North America and the Pacific Ocean basin.

GOES data is used for accurate and timely weather forecasts and advanced warnings of thunderstorms, flash floods, hurricanes, and other severe weather. The GOES mission is carried out by two primary instruments, the Imager and the Sounder. The Imager is a multi-channel sensor that collects radiant energy and reflected solar energy from the Earth's surface and atmosphere. The Sounder is a multi-channel radiometer that collects data related to the vertical temperature and moisture profile of the atmosphere, surface and cloud top temperatures, and ozone distribution. Other instruments on board the spacecraft are a Search and Rescue (SAR) transponder, a data collection and relay system for ground-based data platforms, and a Space Environment Monitor (SEM). The SEM consists of a magnetometer, an X-Ray Sensor (XRS), a high energy proton and alpha detector, and an Energetic Particles Sensor (EPS).[x]

As noted previously, GOES provides an excellent test case to apply our stochastic modeling approach to predicting the total lifecycle costs of a fractionated spacecraft architecture because of the (presumed) constant value of the mission service delivered by the space vehicles, and its reliance upon multiple simultaneous functioning payload modules. In this section we examine the total lifecycle costs of sustaining a single GOES satellite mission contingent upon the simultaneous operation of the GOES Imager, Sounder, and a SEM consisting of the XRS and EPS systems. This study incorporates the magnetometers into the XRS and the proton and alpha detector into the EPS. We also consider the SAR transponder and data collection and relay system to be part of the overall communications subsystem.

A. Fractionated GOES Spacecraft Model

The first step in examining the total lifecycle cost of a fractioned approach to the GOES mission is the logical decomposition of the GOES spacecraft into multiple spacecraft modules. In this analysis we examine four (4) modular test cases for accomplishing the GOES mission with increasing degrees of fraction (Dfrac). The Dfrac is simply the number of spacecraft modules required to form a system equivalent to the monolith. These test cases were developed by decomposing the GOES monolith into the following modules:

Case 1) Payload (Imager/Sounder/SEM) and Communications (Dfrac = 2)
Case 2) Imager/EPS, Sounder/XRS, and Communications (Dfrac = 3)
Case 3) Imager, Sounder, SEM, and Communications (Dfrac = 4)
Case 4) Imager, Sounder, SEM, Communications, and TT&C (Dfrac = 5)

Actually decomposing the GOES monolith spacecraft into the modular cases focused primarily on developing rational and defensible approximations for the subsystem level mass, power and reliability required to accomplish a GOES-like mission. For the purpose of this study, a GOES mission was assumed to require a geosynchronous orbit and design life of 10 years, a value approximately 150% of its planned mean mission duration (MMD) of 7 years. Mass and power estimates for each spacecraft module were determined from analysis of sub-system level requirements. Each subsystem was analyzed to determine how much residual capability from the original GOES monolith was needed in each of the independent modules to accomplish the same sensing missions. As expected, some duplication was necessary across the modules. For example, a mass and power allotment for a backup TT&C subsystem was incorporated into each module, even though the normal operation of satellite control would be accomplished using communication through the one module containing the full TT&C package. Thus the expected 'overhead' inherent in fractionation was designed into the different modular versions of GOES.

Costs estimates for each spacecraft design were determined by applying their mass and power metrics to the CERs from the SSCM and USVCM, and then transforming them into lognormal distributions to account for cost growth probability. Note that this process produces estimated recurring and non-recurring cost distributions for the entire spacecraft, except for internal sensor payloads. Actual costs for the GOES Imager, Sounder, and SEM were not available for this study. Since payload development costs typically provide a significant impact to the overall spacecraft cost, cost estimates of the individual GOES payloads were modeled as a normal distribution where three standard deviations were assumed to cover +/- 50% of the estimated mean cost. Table 1 provides the costs estimates used for the GOES Imager, Sounder and SEM systems. For the Dfrac = 3 case where the SEM is split into separate XRS and EPS payloads, the total SEM cost was evenly distributed between the XRS and EPS.

Table 1. GOES Payload Costs Estimates

	Non-recurring ($K FY07)			Recurring ($K FY07)		
Element	**Lower 1-sigma**	**Mean**	**Upper 1-sigma**	**Lower 1-sigma**	**Mean**	**Upper 1-sigma**
Imager	7,500	15,000	22,500	5,000	10,000	15,000
Sounder	7,500	15,000	22,500	5,000	10,000	15,000
SEM (XRS/EPS)	2,500	5,000	7,500	1,500	3,000	4,500

Tables 2 - 5 describe the mass, power, and CER cost (not including payload cost) estimates for the baseline GOES monolith, the initial "wireless" monolith, and the four-fractionated module cases. These estimates were derived using proportionate scaling from the monolith to the extent practicable, but incorporate mass and power penalties that arise from necessary duplication across fractionated modules. Note that the RE and NRE figures listed in Tables 2-5 are the cost estimates prior to being corrected for cost growth, as described in Section III C.

Table 2. Monolithic Satellite Architecture Mass Breakdown

	Monolithic GOES		Wireless GOES Monolith			
Element	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Delta (Kg)**	**Power (W)**	**Delta (W)**
TT&C	31.5	28.1	31.5	0	28.1	0
Attitude Control	83.8	155.1	83.8	0	155.1	0
Electrical Power	41.3	10.0	41.3	0	10.0	0
Propulsion	88.9	4.7	88.9	0	4.7	0
Thermal	68.8	210.4	68.8	0	210.4	0
Communications	71.5	228.3	71.5	0	228.3	0
SEM	56.9	86.0	56.9	0	86.0	0
Imager	129.0	188.0	129.0	0	188.0	0
Sounder	129.0	187.0	129.0	0	187.0	0
Structure	168.1	11.0	168.1	0	11.0	0
Mechanical Integration	57.6	0.0	69.1	+ 11.5	0.0	N/A
Electrical Integration	67.0	0.0	80.4	+ 13.4	10.0	+ 10
Solar Array	59.1	0.0	59.1	0	0.0	N/A
Station keeping Fuel	160.0	0.0	160.0	0	0.0	N/A
Orbit Insertion Fuel	1,065.0	0.0	1,065.0	0	0.0	N/A
Bus Dry Total	737.6	N/A	762.5	+ 24.9	N/A	N/A
Spacecraft Dry Total	1,052.5	N/A	1,077.4	+ 24.9	N/A	N/A
Spacecraft Wet Total	2,277.5	1,108.6	2,302.4	+ 24.9	1,118.6	+ 10
	NRE	**RE**	**NRE**	**RE**	**Delta-NRE**	**Delta-RE**
($K FY07)	$237,893	$78,247	$237,937	$78,262	$ 44	$ 15

Table 3. Fractioned Satellite Architecture Mass Breakdown (DFrac = 2, 3)

	DFrac = 2				DFrac = 3					
	Imager/Sounder/ SEM		**Communications**		**Imager/EPS**		**Sounder/XRS**		**Communications**	
Element	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**
TT&C	10.4	9.3	31.5	28.1	10.4	9.3	10.4	9.3	31.5	28.1
Attitude Control	62.9	116.3	33.5	62.0	41.9	77.6	41.9	77.6	33.5	62.0
Electrical Power	31.0	7.5	16.5	4.0	20.7	5.0	20.7	5.0	16.5	4.0
Propulsion	66.7	3.5	35.6	1.9	44.5	2.4	44.5	2.4	35.6	1.9
Thermal	51.6	157.8	27.5	84.2	37.8	115.7	37.8	115.7	27.5	84.2
Communications	7.2	22.8	78.7	251.1	7.2	22.8	7.2	22.8	78.7	251.1
SEM	56.9	86.0	0.0	0.0	28.5	43.0	28.5	43.0	0.0	0.0
Imager	129.0	188.0	0.0	0.0	129.0	188.0	0.0	0.0	0.0	0.0
Sounder	129.0	187.0	0.0	0.0	0.0	0.0	129.0	187.0	0.0	0.0
Structure	130.6	8.5	53.6	3.5	76.7	5.0	76.7	5.0	53.6	3.5
Mechanical Integration	53.7	0.0	22.0	0.0	31.5	0.0	31.5	0.0	22.0	0.0
Electrical Integration	62.5	7.8	25.6	3.2	36.7	4.6	36.7	4.6	25.6	3.2
Solar Array	42.0	0.0	23.1	0.0	25.0	0.0	25.0	0.0	23.1	0.0
Stationkeeping Fuel	123.8	0.0	51.6	0.0	72.7	0.0	72.7	0.0	51.6	0.0
Orbit Insertion Fuel	823.8	0.0	343.6	0.0	484.2	0.0	484.1	0.0	343.6	0.0
Bus Dry Total	518.5		347.6		332.4		332.3		347.6	
Spacecraft Dry Total	833.4		347.6		489.8		489.8		347.6	
Spacecraft Wet Total	1,780.9	794.6	742.8	438.0	1,046.7	473.3	1,046.6	472.3	742.8	438.0
	NRE	**RE**	**NRE**	**RE**	**NRE**	**RE**	**NRE**	**RE**	**NRE**	**RE**
($M FY07)	$72,083	$92,264	$63,741	$47,903	$47,468	$54,580	$47,462	$54,571	$63,741	$47,903

Table 4. Fractioned Satellite Architecture Mass Breakdown (DFrac = 4)

	Imager		Sounder		SEM		Communications	
Element	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**
TT&C	10.4	77.6	10.4	9.3	10.4	9.3	31.5	28.1
Attitude Control	41.9	4.5	41.9	77.6	21.0	38.8	33.5	62.0
Electrical Power	18.6	2.1	18.6	4.5	10.3	2.5	14.5	3.5
Propulsion	40.0	115.7	40.0	2.1	22.2	1.2	35.6	1.9
Thermal	37.8	0.0	37.8	115.7	17.2	52.6	27.5	84.2
Communications	7.2	22.8	7.2	22.8	7.2	22.8	78.7	251.1
SEM	0.0	188.0	0.0	0.0	56.9	86.0	0.0	0.0
Imager	129.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sounder	0.0	4.5	129.0	187.0	0.0	0.0	0.0	0.0
Structure	68.3	0.0	68.3	4.5	34.8	2.3	53.1	3.5
Mechanical Integration	28.1	4.1	28.1	0.0	14.3	0.0	21.8	0.0
Electrical Integration	32.7	0.0	32.7	4.1	16.7	2.1	25.4	3.2
Solar Array	22.6	0.0	22.6	0.0	11.5	0.0	23.1	0.0
Stationkeeping Fuel	64.8	0.0	64.8	0.0	33.0	0.0	51.2	0.0
Orbit Insertion Fuel	431.6	77.6	431.6	0.0	219.9	0.0	340.6	0.0
Bus Dry Total	307.6		307.6		165.5		344.6	
Spacecraft Dry Total	436.6		436.6		222.4		344.6	
Spacecraft Wet Total	933.1	428.5	933.0	427.5	475.3	217.5	736.4	437.4
	NRE	**RE**	**NRE**	**RE**	**NRE**	**RE**	**NRE**	**RE**
($K FY07)	$43,922	$49,558	$44,540	$49,966	$26,833	$27,157	$63,665	$47,702

Table 5. Fractioned Satellite Architecture Mass Breakdown (DFrac = 5)

	Imager		Sounder		SEM		Communications		TT&C	
Element	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**	**Mass (Kg)**	**Power (W)**
TT&C	10.4	9.3	10.4	9.3	10.4	9.3	10.4	9.3	31.5	28.1
Attitude Control	41.9	77.6	41.9	77.6	21.0	38.8	25.1	46.5	16.8	31.0
Electrical Power	18.6	4.5	18.6	4.5	10.3	2.5	14.5	3.5	10.3	2.5
Propulsion	40.0	2.1	40.0	2.1	22.2	1.2	26.7	1.4	22.2	1.2
Thermal	37.8	115.7	37.8	115.7	17.2	52.6	20.6	63.1	17.2	52.6
Communications	7.2	22.8	7.2	22.8	7.2	22.8	51.0	162.7	34.9	111.3
SEM	0.0	0.0	0.0	0.0	56.9	86.0	0.0	0.0	0.0	0.0
Imager	129.0	188.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sounder	0.0	0.0	129.0	187.0	0.0	0.0	0.0	0.0	0.0	0.0
Structure	68.3	4.5	68.3	4.5	34.8	2.3	35.6	2.3	31.9	2.1
Mechanical Integration	28.1	0.0	28.1	0.0	14.3	0.0	14.6	0.0	11.0	0.0
Electrical Integration	32.7	4.1	32.7	4.1	16.7	2.1	17.0	2.1	12.5	1.5
Solar Array	22.6	0.0	22.6	0.0	11.5	0.0	15.4	0.0	8.9	0.0
Stationkeeping Fuel	64.8	0.0	64.8	0.0	33.0	0.0	34.3	0.0	22.4	0.0
Orbit Insertion Fuel	431.6	0.0	431.6	0.0	219.9	0.0	228.2	0.0	140.1	0.0
Bus Dry Total	307.6		307.6		165.5		230.8		197.1	
Spacecraft Dry Total	436.6		436.6		222.4		230.8		197.1	
Spacecraft Wet Total	933.1	428.5	933.0	427.5	475.3	217.5	493.3	291.0	359.5	230.3
	NRE	**RE**	**NRE**	**RE**	**NRE**	**RE**	**NRE**	**RE**	**NRE**	**RE**
($K FY07)	$43,922	$49,558	$43,916	$49,549	$26,833	$27,157	$44,529	$33,192	$37,276	$29,290

It is important to note that the costs listed under the Monolithic GOES are not its actual costs, but rather estimated costs derived through parametric cost modeling. Since the cost comparison, and not the absolute cost, is the critical factor in this study, all costing numbers are derived using the same model. All conclusions are based on how the costs relate to each other, rather than on the magnitude of the costs themselves.

Additional lifecycle costs incorporated in this study include launch and operations costs. Launch costs were calculated using a $K/kg metric, which was modeled by fitting a log-normal distribution (Mean = $29.85K/kg, Std Dev = $12.89K/kg) against the Geosynchronous Transfer Orbit (GTO) $K/kg for commercially available launch vehicles.[xi] Satellite operational costs were approximated to be $2M annually per satellite[xii] regardless of whether the satellite was monolithic, fractioned, or ‘hybrid.’

All lifecycle costs were converted to FY07 constant year dollars. Based upon guidance from the U.S. Government's Office of Management and Budget (OMB) for 30+ year programs, a nominal discount rate of 5.10%, inflation rate of 2.04%, and real discount rate of 3.00% was assumed.[xiii]

Table 6. GOES Payload Reliability Parameters (Weibull Distribution Parameters)

Sub-Systems	α (years)	β
Monolith and "Wireless" Monolith		
Bus	108.36	1.70
Payload	15.25	1.70
Dfrac = 2		
Bus	108.42	1.70
Payload	15.25	1.70
Comm	874.69	1.70
Dfrac = 3		
Bus	108.41	1.70
Imager	21.012	1.70
Sounder	19.89	1.70
Comm	874.69	1.70
Dfrac = 4		
Bus	108.41	1.70
Imager	27.62	1.70
Sounder	25.38	1.70
SEM	37.50	1.70
Comm	874.69	1.70
Dfrac = 5		
Bus	108.41	1.70
Imager	27.62	1.70
Sounder	25.38	1.70
SEM	37.50	1.70
Comm	874.69	1.70
TT&C	190.20	1.70

B. Stochastic Lifecycle Cost Estimate

The approach that was used to derive the total lifecycle cost involved examining the variations in satellite replacement schedules, such that all modules critical to maintaining the GOES mission were in continuous operation throughout the mission lifetime. Variations in replacement schedules were based upon estimated failure dates for the individual GOES modules: Imager, Sounder, SEM, Comm., TT&C, and the satellite bus.

Reliability estimates for these sub-systems were based upon an actual numerical reliability assessment of the GOES-L spacecraft[xiv]. Reliability of the individual fractioned GOES modules was modeled using a Weibull distribution with probability characteristics presented in Table 6.

In addition to module failure, it was assumed that any and all spacecraft have a 93.9% probability of success over the period of time including launch, deployment, and initialization. This probability of success assumes a 2.0% launch vehicle failure rate, a 3.1% probability of incorrect orbital insertion[xv], and a 1.0% infant mortality rate during initial orbital operations.

No uncertainties in spacecraft development timelines were modeled in this study. It was assumed that all satellites/modules required 2 years for development, integration, and launch as well as an additional month for on-orbit check-out and positioning. In addition, the analysis was constrained so that no satellite or satellite module could remain in operation greater than a 10 year design life. This was done in order to capture the operational lifetime constraint imposed by on-board expendables, such as thruster propellant. This 10 year value was chosen as a reasonable number given the GOES monolith MMD duration of 7 years.

To examine the variation in the total lifecycle costs resulting from the range of possible replacement schedules for each satellite architecture, a Monte Carlo simulation was performed on each of the four fractioned spacecraft modular cases and the monolithic case. In each case it was assumed that the initial satellite in the modular cases consisted of a 'wireless' monolith, i.e., a spacecraft capable of subsequent incorporation of additional free-flying modules. This decision was made because of the available option to migrate to a heterogeneous architecture and the low increase in cost over the traditional monolithic. For the monolithic and modular cases 200,000 simulation runs were performed.

V. Results

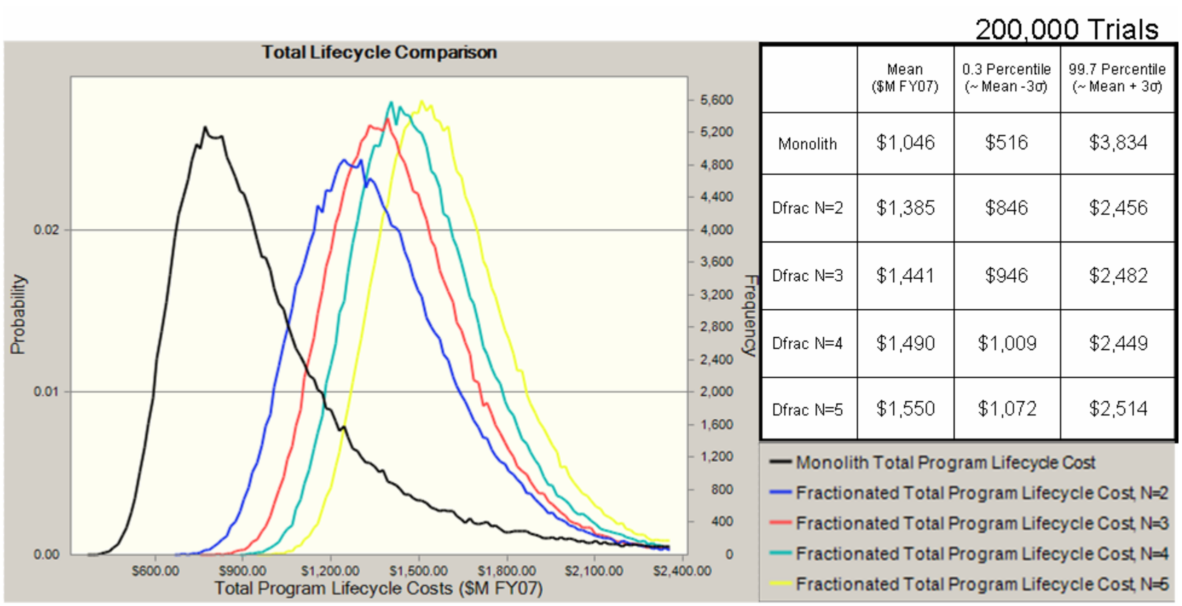
A first order comparison of the three types of system architectures for the GOES test case was performed by examining the initial cost of each of the approaches; monolithic, hybrid fractionated (i.e., "Wireless" Monolith), and 4 scenarios of purely fractionated. The mean values for the NRE and RE costs for each of the overall systems are provided in Table 7. The total column represents the estimated cost for initiating GOES services under each architectural approach, and does not provide conclusive information on the overall lifecycle cost. Note that the monolith and "wireless" monolith figures were generated using the UVSCM due to the mass of their related satellites. The costing figures for all of the fractionated scenarios were generated using the SSCM due to the smaller masses of their component satellites. While the non-recurring costs are higher for the monolithic and hybrid fractionated cases, these two designs offer a significantly lower recurring unit production cost compared to the other approaches. Given this result and the fact that the hybrid fractionated approach offers architectural flexibility at virtually no additional cost, we believe a program manager would consider the monolithic and hybrid fractionated approaches for their satellite architecture.

Table 7: Theoretical First Unit Cost Comparison

Architecture	Mean First Unit Cost Estimates NRE ($M FY07)	RE ($M FY07)	Total ($M FY07)
Monolith	$376	$112	$488
Hybrid Fractionation	$376	$112	$488
Pure Fractionation (Dfrac = 2)	$215	$202	$417
Pure Fractionation (Dfrac = 3)	$251	$226	$477
Pure Fractionation (Dfrac = 4)	$283	$251	$534
Pure Fractionation (Dfrac = 5)	$310	$272	$582

Based on this assumption, the remainder of the analysis focused on comparing the total lifecycle costs of the monolithic architecture to the "wireless" monolithic architectures for the GOES test case. Recall that the evolution of the "wireless" monolith will eventually lead to a fully fractionated system. Therefore the evaluation of the four fractionated replacement strategies (Dfrac = 2-5) are still valid; the main difference being that first unit in each of these strategies will consist of a "wireless" monolith instead of a fully fractioned architecture. We refer to this replacement strategy as Hybrid Dfrac.

The resulting overlay of the total lifecycle cost distributions and statistics for the monolith and each "wireless" monolith case (Hybrid Dfrac = 2-5) can be found in Figure 2. From this figure one can clearly see that the monolithic satellite approach has the lowest mean total lifecycle costs and that mean lifecycle costs increase proportionally to the degree of fractionation. Part of the reason for the increase in mean total lifecycle cost with the degree of fractionation is that the probability of successful mission operation is not limited by the component failure reliability. As with the monolithic satellites, the lifetime of fractionated satellites is still limited by design life, thus adding to the cost of fractionation. Additionally, the data in Figure 2 reveals that the variability of costs, particularly for the cost overrun risk at the high end, is significantly higher for the monolith than for the fractionated cases.



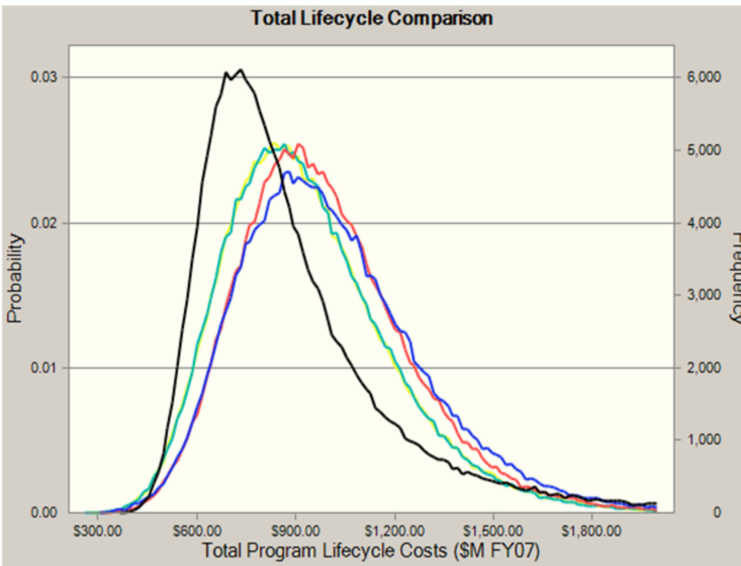
	Mean ($M FY07)	0.3 Percentile (~ Mean -3σ)	99.7 Percentile (~ Mean + 3σ)
Monolith	$1,046	$516	$3,834
Dfrac N=2	$1,385	$846	$2,456
Dfrac N=3	$1,441	$946	$2,482
Dfrac N=4	$1,490	$1,009	$2,449
Dfrac N=5	$1,550	$1,072	$2,514

Figure 2: Total Stochastic Lifecycle Cost distributions (Constrained Design Life)

After examining the results of the design life constrained evaluation, the analysis was re-run without the 10 year design life constraint imposed. The 10-year design life limitation was based on the MMD of the monolithic satellite, and was imposed on all of the fractionated modules to avoid modeling wear-out reliability. In actuality, it is quite reasonable to expect that each of the individual fractionated modules will have a different sub-set of the monolith's demands placed on them, and thus could be developed for longer design lives to suit their expected on-orbit failure rates. Indeed, as a monolith's components are decoupled to form fractionated modules, the MMD durations of these modules are necessarily higher than for the monolith, and thus can support longer design lives given that expendables are appropriately increased.

Figure 3 shows the results of the unconstrained satellite lifecycle cost estimate. Here it evident that there is a narrower difference between the distributions in total lifecycle costs of all satellite architecture approaches. Additionally the lifecycle cost variability is still significantly higher for the monolith case than for any of the fractionated cases.

The data in Figure 3 also shows that there is virtually no decrease in mean lifecycle cost or cost



200,000 Trials

	Mean ($M FY07)	0.3 Percentile (~ Mean -3σ)	99.7 Percentile (~ Mean + 3σ)
Monolith	$911	$464	$3,239
Dfrac N=2	$1,009	$438	$2,094
Dfrac N=3	$989	$455	$1,990
Dfrac N=4	$939	$427	$1,941
Dfrac N=5	$940	$429	$1,942

Figure 3: Total Stochastic Lifecycle Cost distributions (Un-Constrained Design Life)

variability between the Hybrid Dfrac = 4 case and the Hybrid Dfrac = 5 case. This behavior is caused by the manner in which this final level of fractionation was accomplished – by pulling out the TT&C components into a separate module from the existing high reliability communications module. Fractionating this highly reliable module simply exposed two different modules to the uncertainties related to launch and orbit insertion. The lower probability of mission success led to an overall increase in the need for additional fractionated satellites for that module, resulting in no cost improvements. In all cases prior to this, only payloads with lower reliabilities were fractionated. These findings highlight the fact that fractionation must be accomplished intelligently if it is to achieve a desired benefit.

VI. Conclusions

Three main conclusions can be drawn from the our examination of the stochastic lifecycle cost of fractionating the GOES architecture.

1) The total lifecycle cost of heterogeneous fractionated satellite architectures are comparable to monolithic satellite architectures when the individual satellite design lifetimes are longer and are allowed to be aligned with individual satellite expected mean mission durations based on component failure reliability.

2) The variability of the total lifecycle costs, particularly for the cost overrun risk, is higher for the monolith than for all the fractionated cases.

3) The low option price and overall total lifecycle costs make hybrid fractionation of satellites very attractive. Hybrid fractionation results in:

- Marginal additional initial cost over an monolithic approach.
- Similar mean total lifecycle costs compared to monolithic approach.
- Smaller variance in total lifecycle costs than with a monolithic approach.

In this study, the authors only examined fractionation with an eye towards mission lifecycle costs. We highly recommend future work related to how value gained through fractionation can be added to the cost-only comparison to develop a more comprehensive analysis. We suspect that quantifying value and incorporating it into this cost-only analysis will significantly strengthen the case for fractionation. Potential sources of value to satellite systems through fractionation include the ability to:

- Upgrade satellite components.
- Adapt to changing mission requirements.
- Adjust to changing levels of service demand.
- Reduce exposure risk to external threats (ASATs, etc).
- Be flexible in response to funding uncertainties.
- Be flexible in response to scheduling uncertainties.

A second area for potential future work is a grass roots-level cost estimation scheme that can be applied to all systems such that systems engineering and integration cost are decoupled from the total cost in more granular detail than the sub-system level analysis accomplished here. This method would capture the value of a simplified integration process inherent with fractionation. A third area for future work is the development of a multi-attribute utility analysis approach to quantify value so different sources of value can be incorporated in decision making for commercial applications. Our approach attempts to forecast future failures over a mission lifetime. A real time execution strategy would have to quantify the loss in system-level value caused by unplanned events such as failures.

With this study we have attempted to introduce an alternative figure of merit for spacecraft design that may prove a desirable complement to the emerging methodology of value-centric design. While the value of government systems is not readily quantified – thereby complicating such approaches as real options for valuing flexibility – the stochastic assured lifecycle cost metric developed here encompasses system flexibility (and other “-ilities” such as survivability, scalability, maintainability, etc.) while requiring only models of system cost and exogenous and endogenous uncertainties that may affect it.

References

[i] Saleh, J., Lamassoure, E., Hastings, D., and Newman, D., “Flexibility and the Value of On Orbit Servicing—A Customer Perspective,” *Journal of Spacecraft and Rockets*, Vol. 40, No. 2, March-April 2003, pp. 279-291.

[ii] Long, A., “Framework for Evaluating Customer Value and the Feasibility of Servicing Architectures for On-Orbit Satellite Servicing,” Dual Master’s Thesis, Department of Aeronautics and Astronautics and Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, 2005.

[iii] Reynerson, C., “Spacecraft Modular Architecture Design for On-Orbit Servicing,” AIAA-99-4473, Albuquerque, NM, Sept. 1999

[iv] Joppin, C., and Hastings, D., “On-Orbit Upgrade and Repair: The Hubble Space Telescope Example,” *Journal of Spacecraft and Rockets,* Vol. 43, No. 3, May-June 2006, pp. 614-625.

[v] deWeck, O., deNeufville, R., and Chaize, M., “Enhancing the economics of communications Satellites via Orbital Reconfigurations and Staged Deployment”, AIAA Space 2003 Conference, AIAA-2003-6317, Long Beach, CA, September 2003.

[vi] Nilchiani, R.N., Measuring the Value of Space Systems Flexibility: A Comprehensive Six-element Framework, Doctor of Philosophy Dissertation, Aeronautics and Astronautics, MIT, September 2005.

[vii] Brown, Owen & Eremenko, Paul, “The Value Proposition for Fractionated Space Architectures,” AIAA-2006-7506, *AIAA Space 2006*, San Jose, CA, 2006.

[viii] Dezelan R. W., "Mission Sensor Reliability Requirements For Advanced GOES Spacecraft," 23 December 1999, The Aerospace Corporation

[ix] Arena, Mark V., et. al., "Impossible Certainty: Cost Risk Analysis for Air Force Systems," RAND Corporation, Project Air Force

[x] Office of Satellite Operations, NOAA. *"GOES Satellites."* URL: http://www.oso.noaa.gov/goes/.

[xi] "Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000." Futron, Corp., Bethesda, MD, September 6, 2002.

[xii] "GEO Commercial Satellite Bus Operations: A comparative Analysis," Futron, Corp., Bethesda, MD, August 13, 2003.

[xiii] OMB Circular No. A-94: Appendix C, "*Discount Rates For Cost-Effectiveness, Lease Purchase, And Related Analyses,*" URL: http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html. Revised January 2007.

[xiv] "GOES L Numerical Reliability Summary," Feb 7, 2000, Document not in circulation, but available from authors upon request

[xv] Sullivan, B. and Akin, D., "A Survey of Serviceable Spacecraft Failures," AIAA-2001-4540, Aug. 2001.