# Flexible Deployment of a Commercial Earth Imaging CubeSat Constellation

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Prepared as part of a semester-length project for
IDS.332, Engineering Systems Analysis for Design

Fall 2018

## Executive Summary

This report was prepared to detail the methodology, analysis and findings of work conducted as part of Prof. Richard de Neufville's course, Engineering Systems Analysis for Design. The project was intended to apply course topics and principles to an engineering system problem relevant to a student's field of study. These principles included engineering for uncertainty, flexibility in product design, and cost/revenue analysis for engineering systems. As a Space Systems Engineering student, I chose to investigate how these topics might be applied to the development, deployment and operation of a commercial Earth imaging CubeSat constellation.

A service satellite constellation is a complex engineering undertaking characterized by large development and deployment costs, significant technical overhead and risk, and long timetables for first revenue. Further, even a perfectly designed and deployed technical architecture is not guaranteed to be a financial success. This is determined by critical external factors which are characterized by uncertainty including demand for satellite imagery, launch costs, etc. This report describes a system model that was developed to capture the complex interactions of technical, managerial and external conditions that determine the profitability of such an architecture. A "base case" is defined which assumes perfect knowledge of the future; a rigid development and deployment strategy is created for this case. Then, uncertainty is introduced and a significant drop in expected NPV is observed. Next, a set of strategies for a flexible system are discussed and implemented. It is shown that a conditional and responsive approach to meeting realized demand with additional satellite launches is a powerful flexibility strategy.

The new and emerging paradigm of constellations of small satellites for Earth-related services, including imaging, is a promising sign for the commercialization of space. However, commercial operators must be aware of the risks that uncertainties inherent in such a new economic sector pose to the potential success of their systems. This analysis shows that, while these risks are significant, prudent managerial and architectural decisions may yet yield very profitable products.



## Acknowledgements

I would like to thank Prof. Richard de Neufville for his timely and generous guidance throughout this project. He supplemented his interesting and engaging course material with advice specific to my application. In addition, I would like to thank The Aerospace Corporation for providing me access to their Small Satellite Cost Model (SSCM14). Lastly, I would like to mention that this work was inspired by (or sprung out of) a NASA-funded research project to develop a Commercial Space Technology Roadmap (CSTR) as a companion to NASA's own Technology Roadmaps. This present work was inspired by an analysis of the Earth Imaging sector of the space economy for the CSTR.

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## Introduction and Motivation

Satellite-based remote sensing activities can be defined as those which obtain, process and provide data on terrestrial objects, phenomena and scenes as gathered by imaging technologies onboard space-based assets. Colloquially known as satellite imagery, this service is provided by both government and commercial parties to a wide range of customers including military and intelligence agencies, agriculture and resource excavation operations, humanitarian organizations. Users of Geographic Information Systems (GIS) such as mapping software, GPS visualization, and everyday applications on smart phones, are increasingly important downstream customers of satellite imagery.

A variety of architectures have been deployed which vary in terms of number, size and capability of satellite systems for gathering such imagery. This project examines a particular subset of these architectures, namely, constellations of CubeSats. CubeSats are a relatively new paradigm in satellite design which miniaturize subsystems into shoebox-sized satellites which are cheaper, albeit with lower performance. Constellations of these CubeSats are large, coordinated deployments that can present a competitive challenge to large, monolithic, low quantity remote sensing architectures.[1] However, several design and business decisions are critical in determining the success of such a constellation including: orbit selection, design lifetime, and number/cadence of satellite deployment. In addition, factors such as launch vehicle failures and demand fluctuation are external uncertainties which affect the venture's success.

The decision to deploy a constellation of CubeSats is thus a potentially lucrative but also highly risky business decision. This study performs a cost-centric analysis of an imaging CubeSat constellation constrained to a few key design decisions.

## Problem Context

In order to frame the project and provide a consistent context for the several analyses conducted as part of the course-long work, a problem statement must be defined. This statement is framed from the perspective of a hypothetical company seeking to develop and deploy an Earth-imaging satellite constellation. They must make certain design decisions to maximize the likelihood of fielding a profitable product.

### Problem Statement

*To develop an analytical model for understanding the best combination of architectural and management decisions which deliver a space-based Earth imaging CubeSat constellation that is responsive to uncertain market and technological conditions.*

The analysis will factor managerial and architectural decisions in terms of potential costs and revenues. In addition, sources of uncertainty will be considered which affect these values probabilistically. Lastly, the value of incorporating flexibility in these decisions will be investigated by using conditional statements in the system model.

## System Model

A system model was built to parametrically investigate the impacts of the various design and management decisions. This was done on Excel in modular fashion such that each module –

pertaining to a particular cost, demand, capacity, or revenue contribution – could be modified as needed. The flow of inputs and outputs is depicted in Figure 1. Some of the inputs in the model are user defined, and thus are the key decisions that a manager would be faced with. Other inputs capture uncertain parameters as probabilistic distributions. Lastly, other parameters, primarily cost and demand figures, are taken from publicly available sources, cost models, and analogous mission. Methods for determining parameter values or their distributions are discussed briefly in the following subsections.

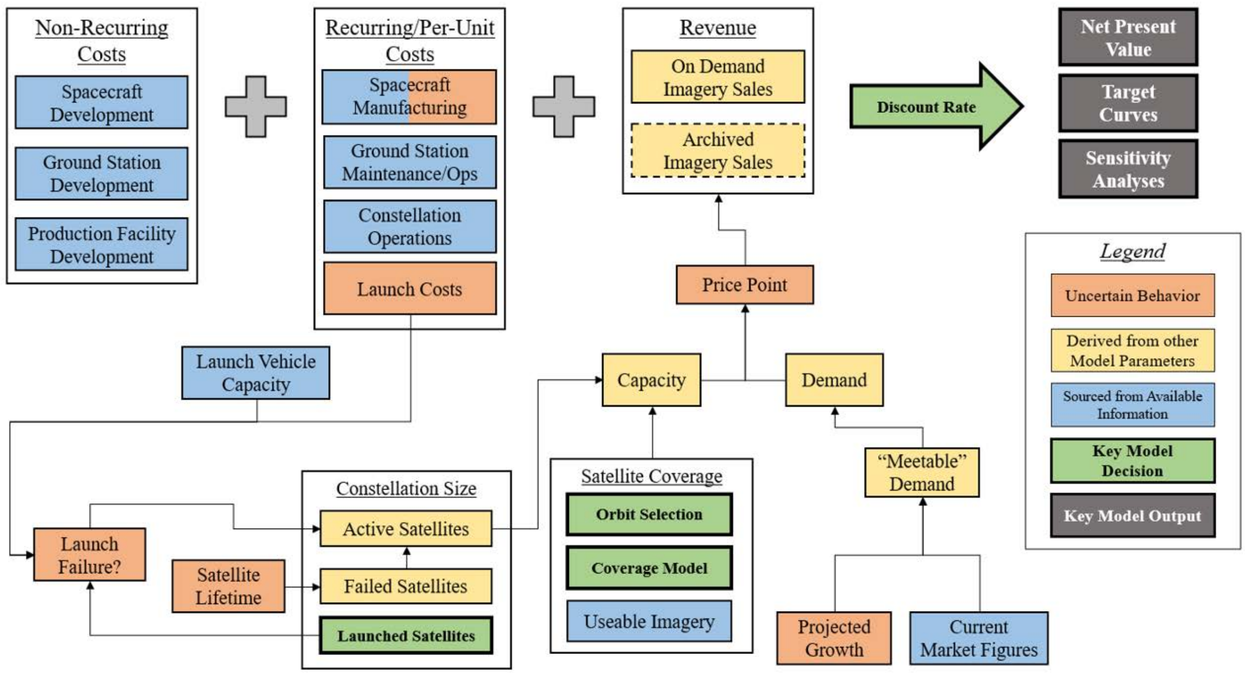


**Figure 1. Flow diagram representing the input/output parameters of the System Model for this project. The top row of boxes represents the sum of costs and revenues to arrive at a net cash-flow. The lower level boxes represent the supporting modules to arrive at final values for costs and revenues.**

## Sourcing Parameter Values from Available Information

The boxes shown in blue in Figure 1 correspond to parameters whose values were gathered mainly from publically available sources. These include market reports for the commercial remote sensing industry and data provided on company websites and spec sheets (e.g. launch vehicle capacities, manufacturing facility costs, etc.). These sources were used to arrive at most cost figures for recurring and non-recurring expenses of the satellite development, operation and maintenance lifecycle.

One additional source used was The Aerospace Corporation's Small Satellite Cost Model 2014 (SSCM 14) which was used to estimate a development and per-unit cost for the CubeSats. While it is not explicitly meant for CubeSat class missions, SSCM 14's Cost Estimating Relationship (CER) parameter bounds are those closest to values of CubeSat missions.[2] SSCM 14 estimated that the 12U CubeSat bus development (non-recurring) costs would be around $2.6M while the first unit costs would be around $3.5M.[3] In addition, a $10M imaging payload development cost was included. These costs should be seen as conservative estimates, as many CubeSat development projects are developed and launched for around $1M.[2]

Table I shows a summary of costs, divided into non-recurring and recurring/per-unit figures. Non-recurring costs can be seen as those upfront development and engineering costs needed to support the eventual "Theoretical First Unit" and subsequent copies of the first unit. The recurring costs are those that must be paid every year (or other time unit) of operation; these include facility upkeep and maintenance, employee salaries, operations costs, etc. In addition, per-unit costs are incurred with each satellite that is manufactured and lost. In the model, non-recurring costs are fixed while the recurring "Constellation Operations" cost is modulated by the number of active satellites which need to be operated. Also, satellite launch costs are modulated by an uncertain parameter and the per-unit satellite manufacturing costs are affected by the learning effect.

**Table I. Summary of nominal non-recurring, recurring and per-unit costs for the system. Note that uncertainty or learning curve effects are not included in these values.**

| | |
|---|---|
| **Non-Recurring Costs** | |
| Satellite Bus Development | $2,600,000 |
| Satellite Imager Payload Development | $10,000,000 |
| Ground Station Development | $50,000,000 |
| Manufacturing Facility Construction | $50,000,000 |
| **Recurring Costs** | |
| Ground Facilities Maintenance and Upkeep | $45,000,000 |
| Constellation Operations | $100,000,000 |
| Program Management and Systems Engineering | $14,500,000 |
| **Per-Unit Costs** | |
| Satellite Manufacturing, per Satellite | $3,500,000 |
| Satellite Launch Costs, per Satellite | $450,000 |

Key Model Decisions

The green boxes in Figure 1 represent the elements which are chosen by the mission designer and are thus the key architectural and managerial decisions that must be made. The primary decision is clearly the number and cadence of satellites deployed each year. This decision drives all aspects of the cost and revenue for the system and is thus critically important. Indeed the goal of this analysis is to determine a suitable strategy for selecting this value. Other decisions up to the manager include the selection of the discount rate, and technical facets of the mission including orbit selection and methods for estimating satellite coverage.

For this project, due to its risky nature, a high discount rate of 25% was selected. An orbital altitude of 475 km was chosen due to a variety of factors including lower atmospheric drag than lower orbits (preventing orbital decay), acceptable theoretical resolution limits of about 1.7 m, and ease of access by most launch vehicles. Lastly, a simplified coverage model assumed that each new CubeSat added to the constellation adds a constant amount of imaging capacity, as measured in km^2 per year. In reality, Earth coverage from orbit is a highly non-linear function of orbital planes, altitude, inclination, and desired coverage latitudes.[4] As such, coverage and capacity models should be taken as first order estimates.

Uncertain Parameters

Five predominant sources of uncertainty are identified in the System Model. These uncertainties are the primary causes for deviation from a deterministic view of the problem. As such, the ultimate metrics of success for the project are highly dependent on these uncertainties and how they are realized over the course of the project lifecycle.

1. *Demand for satellite imagery drastically varies* – A significant decrease in demand might be due to a rise in the capabilities (at lower cost) of the aerial or drone-based remote-sensing markets. Another scenario would be an economic downturn which might see customers deeming satellite imagery a luxury they cannot afford to have. Conversely, we could see upticks in demand during good economic conditions or during high-impact global events. As demand directly determines revenue and the need for capacity, it is likely the most important uncertain parameter in the problem.
2. *Satellite Lifetime* – Spacecraft are typically designed to operate for a particular amount of time (i.e. the satellite's lifetime). However, the hostile environment of space could lead to failures and loss of service well in advance of this lifetime. Typical causes include misbehaving hardware, random (or partly cyclic) radiation activity, and orbital debris. This introduces an uncertainty about the actual amount of time that a particular satellite in the constellation might yield revenue. A nominal CubeSat operational lifetime is assumed to be 2 years for this analysis.[5]
3. *Price-point variability* – This uncertainty captures the various factors which set the competitive price of a product. The activities of other players in the market, such as launching their own constellation or going defunct, can significantly change the price-point at which we are able to sell imagery. A nominal price point of \$1.50 per $km^2$ of image area is used. This is taken from figures provided by image brokers for the expected "medium" resolution of the imagery.[6]
4. *Launch cost variability* – This uncertainty has to do with how much we pay to deploy our constellation of satellites. We have seen revolutionary technologies and capabilities in the launch services industry that have led to a sharp decrease in launch costs (measured in \$/kg). However, various factors could lead to increases or uncertain behavior. These include manufacturing cost variability, launch failures which lead to backlogs and delays, etc. Increased launched costs would raise the deployment costs of each satellite, significantly impacting revenue and net present value.
5. *Launch Failures* – This uncertainty has to do with our ability to access space to deploy our constellation of satellites. While launch vehicles are very reliable, there are plenty of examples of launch failures leading to the loss of the payloads intended for delivery. Especially if we consider small satellites or CubeSats which are often launched many at a time from a single launch vehicle, a launch failure could lead to the loss of multiple assets. This in turn would prevent us from meeting the demand which they were launched to accommodate.
6. *Learning Effects* – we consider uncertainty in how learning effects will be realized in the spacecraft manufacturing process. Learning is a well-documented phenomenon, especially in multi-satellite systems. However, this effect is known for medium to large class satellites; it is uncertain how it will be realized in CubeSat systems of dozens or even hundreds of units.

In order to capture the above uncertainties, probability distributions were attached to the relevant calculations. For example, the demand forecast is modulated with uncertainty in two ways: 1) an annual demand volatility and 2) a total demand growth uncertainty figure. This captures both short-term and long-term trends. The latter case is given as a symmetric distribution around 0 of +/-

30%. An example of a non-symmetric uncertainty distribution is in the satellite lifetime figure; here, we assume that a satellite has no probability of operating beyond its lifetime, while it has a certain likelihood of failing before its intended lifetime. This is manifest as a +0/-30% distribution. The uncertainty figure for all uncertainties is shown in Table II.

**Table II. Summary of Uncertainty values/ranges for each of the parameters above.**

| Uncertain Parameter | Above Expected Value | Below Expected Value | Rationale |
|---|---|---|---|
| Demand for satellite imagery | 30% | 30% | This parameter is difficult to predict. However, we do know that "Forecasts are always wrong". This figure is for Year 10 demand. In addition, a 25% annual demand volatility is incorporated |
| Satellite Lifetime | 0% | 35% | CubeSats are not typically designed for a long lifetime. In addition, their low cost approach implies that lower reliability can be expected. |
| Price-Point Variability | 10% | 30% | A competitive price is very difficult to know in advance without knowledge of what competitors might do. However, as similar CubeSat constellations are deployed, we expect significant price to decrease. Also, a 2% price degradation per year is incorporated. |
| Launch Cost Variability | 20% | 20% | The major launch providers are being shaken awake by SpaceX and other start-up style rocket companies. We can expect it to be more likely that costs continue to fall than the to rise, however this is still to be demonstrated in the small satellite launch industry |
| Launch Failures | 5% | - | Launch failures are very rare, but devastating when they occur. The seemingly high 5% figure is due to the new class of small launch vehicles, intended for CubeSat deployments, which do not have the legacy or track record of larger vehicles. |
| Learning Curve Slope | - | 97%, fixed | Typical learning curve slopes for satellite manufacturing are within this range. It is unknown whether these will be significantly different once figures are reported for CubeSats. For this analysis, it is fixed at 97% |

Derived Parameters

An important modeling decision that was encountered was how to quantify and model demand. We want to model demand in the same units as capacity – in this case, satellite capacity is measured in terms of area imaged per year (in $km^2$).[7] However, figures for the demand of satellite imagery in these units were not readily available. Current and historical data as well as trending was available for the market value of the satellite imagery industry.[8] Therefore, a mapping was made between the two figures which 1) relates market value to revenue, 2) relates known revenue from satellite company DigitalGlobe to the stated total imaging capacity (in $km^2$) of its fleet, 3) extrapolates total U.S. demand from this relationship (assuming DigitalGlobe's capacity perfectly captures its demand) and DigitalGlobe's market share and 4) applies the market value trending to this demand as modulated by the above relationships. This yields a linear trend over the next decade for satellite imagery demand as measured in total image area captured in a year.

The final model then is a network of various inputs with a final output of net cash-flow for each year of the project. The cash-flow is then discounted to account for the time devaluation of money. The aggregate of cash-flows for each year of the project is summed into a Net Present Value (NPV) figure. The model may be run thousands of times, calling upon the probabilistic modules to vary across their potential distribution. This Monte Carlo analysis allows us to develop Target Curves of Expected Net Present Value (ENPV) for each set of decisions. Knowing the extreme values for uncertain parameters allows for sensitivity analyses, as well. The main analysis output of the model is shown in Figure 2 for the first several years of the project. The green row is the main architecture decision which specifies the number of satellites to launch each year.

| ***Net Present Value Analysis*** | | | | | |
|---|---|---|---|---|---|
| Year | 2018 | 2019 | 2020 | 2021 | 2022 |
| **Demand** | | | | | |
| Demand (Deterministic) (Mkm^2) | - | 372 | 449 | 525 | 602 |
| Demand (Uncertain) (Mkm^2) | - | 405 | 429 | 489 | 659 |
| Demand (Realized) (Mkm^2) | - | 405 | 429 | 489 | 659 |
| **Capacity** | | | | | |
| Total Satellites (at beginning of year) | 0 | 0 | 0 | 0 | 0 |
| Available Satellite Capacity (at beginning of year) | 0 | 0 | 0 | 0 | 0 |
| New Satellites to Deploy (for end of year) | | | | | |
| Launch Vehicles Needed | 0 | 0 | 0 | 0 | 0 |
| Launch Failure? | No | No | No | No | No |
| Satellites Lost in Failure (Assume 1 launch failure) | 0 | 0 | 0 | 0 | 0 |
| Successfully Deployed Satellites (for end of year) | 0 | 0 | 0 | 0 | 0 |
| Failed Satellites | 0 | 0 | 0 | 0 | 0 |
| **Revenue** | | | | | |
| Demand Met (Mkm^2) | 0 | 0 | 0 | 0 | 0 |
| Price Point (Realized) ($ per Mkm^2) | - | $ 1,420,000 | $ 1,471,000 | $ 1,442,000 | $ 1,413,000 |
| Revenue from Demand Met (requested imagery) | $ - | $ - | $ - | $ - | $ - |
| **Costs** | | | | | |
| Spacecraft Bus Development Cost (Non-Recurring) | $ 2,600,000 | 0 | 0 | 0 | 0 |
| Spacecraft Imager Development Cost (Non-Recurring) | $ 10,000,000 | 0 | 0 | 0 | 0 |
| Ground Station Development Cost (Non-Recurring) | $ 50,000,000 | 0 | 0 | 0 | 0 |
| Large Scale Production Facility Cost (Non-Recurring) | $ 50,000,000 | 0 | 0 | 0 | 0 |
| Spacecraft Development Cost, (Recurring) | $ - | $ - | $ - | $ - | $ - |
| Ground Station Maintenance and Upkeep (Recurring) | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 |
| Constellation Operations Cost (Recurring) | $ 100,000,000 | $ - | $ - | $ - | $ - |
| Program Management and Systems Engineering Cost (Recurring) | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 |
| Satellite Launch Costs (Recurring) | $ - | $ - | $ - | $ - | $ - |
| **Cashflow Analysis** | | | | | |

**Figure 2. Main model computation section; the main architecture decision is highlighted in green.**

## Base Case

With the System Model built, we can begin to investigate strategies for maximizing the value of the project. We start by ignoring the question of uncertainty temporarily in order to develop a "Base Case". This Base Case is selected as if everything will occur exactly as predicted. By deciding ahead of time on a strategy based on unrealistic expectations of perfect predictions, we arrive at a rigid strategy. We can then proceed to understand the impacts of uncertainty on this strategy and lastly devise a flexible strategy for responding proactively to this uncertainty as it is realized.

### Static Base Case

With most architectural decisions fixed in this analysis (for simplicity), the central decision we need to make is the number of satellites to launch in each year. The large number of assumptions made in this model might allow us to arrive at a base case with a very high NPV; instead, we seek a more realistic strategy that resembles that employed by current players in the market. In particular we will model our base case after Planet's deployment strategy. Planet currently operates a constellation of 130+ Earth imaging CubeSats.[9] They follow an annual deployment strategy that seeks to steadily add to their total active satellite count while also replenishing failed predecessors.

One important factor of a satellite deployment strategy is having a feasible launch cadence. While building and launching dozens of large satellites is highly infeasible, doing so with CubeSats is both feasible and proven. In fact, some launch providers have demonstrated the ability to deliver up to a hundred miniature satellites in one launch. As such, our base strategy includes years with launches of 40 or more satellites. This strategy is depicted in Figure 3. Years beyond 2025 do not include any more deployments as the discounted revenue from those years does not justify additional operations. Thus, the base case effectively ends when the satellites launched in 2025 fail, nominally in 2027, with a total of 245 CubeSats deployed.

| ***Net Present Value Analysis*** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| **Demand** | | | | | | | | |
| Demand (Realized) (Mkm^2) | - | 372 | 449 | 525 | 602 | 679 | 756 | 833 |
| **Capacity** | | | | | | | | |
| Total Satellites (at beginning of year) | 0 | 10 | 40 | 45 | 55 | 60 | 70 | 75 |
| Available Satellite Capacity (at beginning of year) | 0 | 111 | 442 | 498 | 608 | 664 | 774 | 829 |
| New Satellites to Deploy (for end of year) | 10 | 30 | 15 | 40 | 20 | 50 | 25 | 55 |
| Launch Vehicles Needed | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 3 |
| Launch Failure? | No | No | No | No | No | No | No | No |
| Satellites Lost in Failure (Assume 1 launch failure) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Successfully Deployed Satellites (for end of year) | 10 | 30 | 15 | 40 | 20 | 50 | 25 | 55 |
| Failed Satellites | 0 | 0 | 10 | 30 | 15 | 40 | 20 | 50 |
| **Revenue** | | | | | | | | |
| Demand Met (Mkm^2) | 0 | 111 | 442 | 498 | 602 | 664 | 756 | 829 |
| Price Point (Realized) ($ per Mkm^2) | - | $ 1,500,000 | $ 1,471,000 | $ 1,442,000 | $ 1,413,000 | $ 1,386,000 | $ 1,359,000 | $ 1,332,000 |
| Revenue from Demand Met (requested imagery) | $ - | $ 166,000,000 | $ 651,000,000 | $ 718,000,000 | $ 851,000,000 | $ 920,000,000 | $ 1,028,000,000 | $ 1,105,000,000 |
| **Costs** | | | | | | | | |
| Spacecraft Bus Development Cost (Non-Recurring) | $ 2,600,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Spacecraft Imager Development Cost (Non-Recurring) | $ 10,000,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ground Station Development Cost (Non-Recurring) | $ 50,000,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Large Scale Production Facility Cost (Non-Recurring) | $ 50,000,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total Satellites Manufactured | 10 | 40 | 55 | 95 | 115 | 165 | 190 | 245 |
| Spacecraft Development Cost, (Recurring) | $ 31,630,000 | $ 87,420,000 | $ 42,370,000 | $ 110,780,000 | $ 54,550,000 | $ 134,680,000 | $ 66,630,000 | $ 145,300,000 |
| Ground Station Maintenance and Upkeep (Recurring) | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 |
| Constellation Operations Cost (Recurring) | $ 100,000,000 | $ 100,000,000 | $ 160,200,000 | $ 165,300,000 | $ 174,000,000 | $ 177,800,000 | $ 184,500,000 | $ 187,500,000 |
| Program Management and Systems Engineering Cost (Recurring) | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 |
| Satellite Launch Costs (Recurring) | $ 4,500,000 | $ 13,500,000 | $ 6,800,000 | $ 18,000,000 | $ 9,000,000 | $ 22,500,000 | $ 11,300,000 | $ 24,800,000 |
| **Cashflow Analysis** | | | | | | | | |
| Net Cashflow | $ (308,200,000) | $ (94,400,000) | $ 382,100,000 | $ 364,400,000 | $ 554,000,000 | $ 525,500,000 | $ 706,100,000 | $ 687,900,000 |
| Discounted Cashflow | $ (308,200,000) | $ (75,500,000) | $ 244,500,000 | $ 186,600,000 | $ 226,900,000 | $ 172,200,000 | $ 185,100,000 | $ 144,300,000 |
| **Net Present Value** | **$ 989,500,000** | | | | | | | |

**Figure 3. NPV Model with static base case satellite deployment decisions. A total of 245 satellites are launched over 7 years for a deterministic (i.e. over optimistic) NPV of around $1B.**

The static base case is promising. It suggests that, with all of our assumptions and forecasts for the future being perfect, we can expect the NPV of the project to be around $1 Billion. This would require an upfront investment (including to build and launch the first batch) of around $300 M. The base case involves operating a constellation as large as 75 satellites and launching a total of around 250 satellites over the course of 7 years. We cannot reasonably expect to have made perfect (or even remotely accurate) forecasts of the future for this highly unpredictable endeavor. We must consider the uncertainties as discussed and quantified previously.

<u>Uncertainty in the Base Case</u>

Through the Monte Carlo analysis alluded to earlier, we expect to arrive at a range of Net Present Value (NPV) which we can compare to the static base case. Before we perform this full simulation, we want to understand the relative importance of each of the uncertainty considerations. Having prudently designed the System Model in a modular fashion, we can "turn on/off" each of the uncertainties by overwriting their outputs. We can easily run the base case calculations with the extreme values of each uncertainty and develop a "Tornado Diagram". This diagram (shown in Figure 4) orders the uncertainties in terms of their independent impact on the Static NPV.

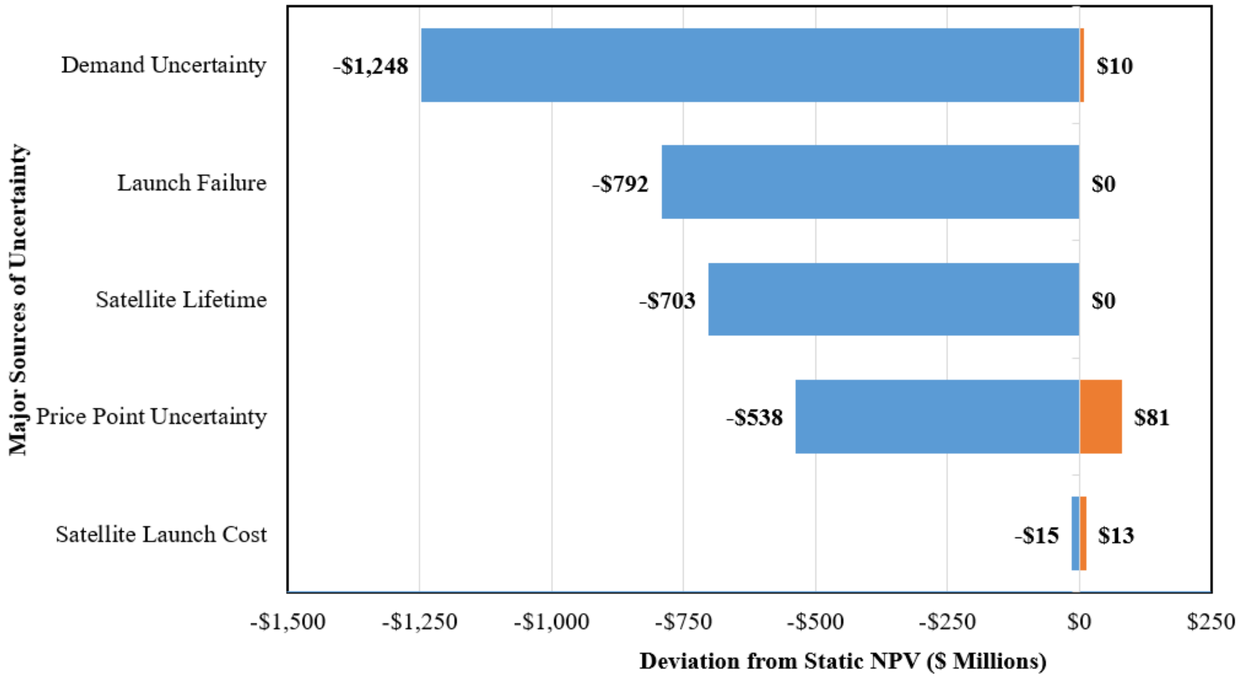


**Figure 4. Tornado diagram of the sources of uncertainty and their independent impact on NPV (as compared to the static case). Note, if the negative value is greater than the static NPV, this uncertainty may end up causing a net negative discounted cash flow.**

The impacts of uncertainty are highly asymmetric, skewed towards negative impacts. This is because in a capacity constrained rigidly deployed system, it is not possible to reap the benefits of higher demand; however, it is entirely possible to suffer the consequences of various downsides as captured by these uncertainties. Clearly the most highly impactful uncertainties as measured in difference from the static case are 1) demand not meeting expectations, 2) several launch failures, and 3) satellites underperforming in terms of lifetime. Indeed, the impacts of launch failures are not necessarily from the sunk cost of their development but from the diminished ability of the deployed constellation to meet demand. Satellite launch cost uncertainty is not highly impactful (contrary to conventional wisdom) since we assume a per kg launch cost structure and our CubeSats are very light (~9 kg). This may not be the case if we were to incorporate a discrete launch vehicle purchasing scheme.

| ***Net Present Value Analysis*** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Period | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Year | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
| **Demand** | | | | | | | | |
| Demand (Deterministic) (Mkm^2) | - | 372 | 449 | 525 | 602 | 679 | 756 | 833 |
| Demand (Uncertain) (Mkm^2) | - | 308 | 344 | 462 | 447 | 565 | 491 | 533 |
| Percent Uncertainty | - | (17.00) | (23.30) | (12.12) | (25.86) | (16.88) | (35.01) | (36.08) |
| Demand (Realized) (Mkm^2) | - | 308 | 344 | 462 | 447 | 565 | 491 | 533 |
| **Capacity** | | | | | | | | |
| Total Satellites (at beginning of year) | 0 | 10 | 38 | 35 | 40 | 37 | 50 | 45 |
| Available Satellite Capacity (at beginning of year) | 0 | 111 | 420 | 387 | 442 | 409 | 553 | 498 |
| New Satellites to Deploy (for end of year) | 10 | 30 | 15 | 40 | 20 | 50 | 25 | 55 |
| Launch Vehicles Needed | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 3 |
| Launch Failure? | No | No | No | No | No | No | No | No |
| Satellites Lost in Failure | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Successfully Deployed Satellites (at end of year) | 10 | 30 | 15 | 40 | 20 | 50 | 25 | 55 |
| Failed Satellites (at end of year) | 0 | 2 | 18 | 35 | 23 | 37 | 30 | 45 |
| **Revenue** | | | | | | | | |
| Demand Met (Mkm^2) | 0 | 111 | 344 | 387 | 442 | 409 | 491 | 498 |
| Price Point (Realized) ($ per Mkm^2) | - | $ 1,455,000 | $ 1,236,000 | $ 1,543,000 | $ 1,159,000 | $ 1,455,000 | $ 1,305,000 | $ 1,399,000 |
| Revenue from Demand Met (requested imagery) | $ - | $ 161,000,000 | $ 425,000,000 | $ 597,000,000 | $ 513,000,000 | $ 595,000,000 | $ 641,000,000 | $ 696,000,000 |
| **Costs** | | | | | | | | |
| Spacecraft Bus Development Cost (Non-Recurring) | $ 2,600,000 | $ - | 0 | 0 | 0 | 0 | 0 | 0 |
| Spacecraft Imager Development Cost (Non-Recurring) | $ 10,000,000 | $ - | 0 | 0 | 0 | 0 | 0 | 0 |
| Ground Station Development Cost (Non-Recurring) | $ 50,000,000 | $ - | 0 | 0 | 0 | 0 | 0 | 0 |
| Large Scale Production Facility Cost (Non-Recurring) | $ 50,000,000 | $ - | 0 | 0 | 0 | 0 | 0 | 0 |
| Total Satellites Manufactured | 10 | 40 | 55 | 95 | 115 | 165 | 190 | 245 |
| Spacecraft Development Cost, (Recurring) | $ 31,630,000 | $ 87,420,000 | $ 42,370,000 | $ 110,780,000 | $ 54,550,000 | $ 134,680,000 | $ 66,630,000 | $ 145,300,000 |
| Ground Station Maintenance and Upkeep (Recurring) | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 | $ 45,000,000 |
| Constellation Operations Cost (Recurring) | $ 100,000,000 | $ 100,000,000 | $ 157,978,360 | $ 154,406,804 | $ 160,205,999 | $ 156,820,172 | $ 169,897,000 | $ 165,321,251 |
| Program Management and Systems Engineering Cost (Recurring) | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 | $ 14,500,000 |
| Satellite Launch Costs (Recurring) | $ 4,000,000 | $ 12,700,000 | $ 7,400,000 | $ 15,600,000 | $ 10,700,000 | $ 26,600,000 | $ 11,400,000 | $ 23,700,000 |
| **Cashflow Analysis** | | | | | | | | |
| Net Cashflow | $ (307,700,000) | $ (98,600,000) | $ 157,800,000 | $ 256,700,000 | $ 228,000,000 | $ 217,400,000 | $ 333,600,000 | $ 302,200,000 |
| Discounted Cashflow | $ (307,700,000) | $ (78,900,000) | $ 101,000,000 | $ 131,400,000 | $ 93,400,000 | $ 71,200,000 | $ 87,500,000 | $ 63,400,000 |
| **Net Present Value** | **$ 248,900,000** | | | | | | | |

**Figure 5. Screenshot of the NPV analysis for a particular run of the Monte Carlo uncertainty analysis. Note the drastically lower NPV.**

Now "turning on" all of the uncertainties, we arrive at a truly randomized base case calculation, depicted in Figure 5. We can run this simulation 2500 times in a Monte Carlo analysis. This analysis yields a probabilistic distribution of Net Present Values (shown in Figure 6). This is complemented by Table III which shows the key statistical values including minimum, maximum, and mean NPV. The maximum expected value of the randomized case (i.e. everything going as predicted or better) approaches the static NPV of around $1B; however, as the CDF plot shows, this is unlikely to occur. We have at most a 5% chance of making above $600M, as measured by the Value at Gain, P95 value. That means we have a 95% chance of making 60% or less of the Static NPV. On the other end, there is at most a ~10% chance of losing, as suggested by the Value at Risk, P10 value. There is less than a 5% chance of losing more than ~$70M.

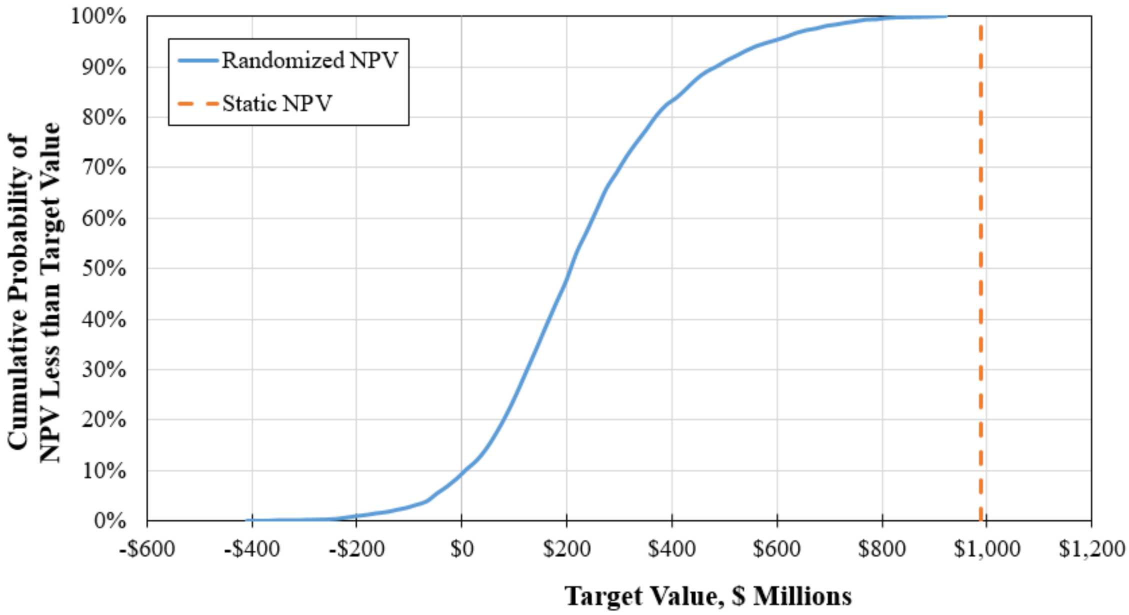


**Figure 6. Target curve for the randomized static case, including the 5 source of uncertainty.**

**Table III. Tabulation of approximate statistical measures of the randomized base case example.**

| Statistical Parameter | Value, $ Millions |
|---|---|
| Maximum NPV | $960 |
| Minimum NPV | ($440) |
| Average NPV | $230 |
| Value At Risk, P5 | ($70) |
| Value At Risk, P10 | $0 |
| Value at Gain, P90 | $500 |
| Value at Gain, P95 | $600 |

## Incorporating Flexibility

While the figures in the base case analysis suggest that the odds of breaking even, or making money are greater than ~90%, we would like to design a strategy that optimizes NPV by deploying a system that is responsive to uncertainty. This can be done in two ways: 1) maximizing the upside by capturing more demand, if present and 2) minimizing the downside by avoiding or mitigating situations which lead to losses. This is the motivation for developing a flexibility strategy.

### Flexibility Options

We can envision a variety of actions that we might take depending on the realization of uncertainty as the project develops. Table IV details a few of these actions as well as the rationale behind them and the type of effect the option might have.

**Table IV. Summary of possible flexibility actions in the development and deployment of the CubeSat constellation**

| Flexibility Action | Rationale | Effect of Action |
|---|---|---|
| Conditional satellite launch to meet realized demand trends | Significant variations in demand might require us to reconsider further launches or to schedule even more of them. | Maximize Upside |
| Distribute batch launches across multiple launch vehicles | Since we saw that Launch Failures are one of the highest impact uncertainty, we should not "put all our eggs in one basket" when it comes to launching large amounts of satellites. This might offset the cost of purchasing additional vehicles. | Minimize Downside |
| Upgrade investment for high-reliability CubeSats | To address the highly impactful uncertainty of potential shorter-than-expected lifetime. | Minimize Downside |
| Conditional move to higher orbit for subsequent launches | Higher orbit results in higher coverage area (and greater capacity to meet Demand)…however, this comes at the cost of lower resolution for the same system and potential radiation issues. | Maximize Upside |
| Flexibly incorporate payloads which deliver higher priced imagery | This is to take advantage of potential upsides in imagery prices that might come from higher quality images (in terms of resolution or spectral composition). | Maximize Upside |

For the scope of this analysis, we investigate one flexibility action from each of the "Effect" categories. First, a flexible launch strategy determines the number and timing of satellite launches based off of the demand that was realized; this is in contrast to the "Rigid Case" in which we deploy satellites in pre-determined numbers based off of forecasted annual demand. Such a strategy allows us to fully take advantage of higher than expected demand. Conversely, it allows us to scale back when demand is less than anticipated over several years. The upfront costs for enabling this option are covered by the constellation specific costs including ground station, production facility and launch which are modulated by the number of satellites in the constellation.

Secondly, a reactive approach is employed to address high satellite failure rates (i.e. lower than expected satellite lifetimes). The "High Reliability CubeSat" strategy is activated in Year 1 if the lifetime uncertainty value (failure rate) is above 20%. In this case, a secondary development period is initiated to "upgrade" all phases of the CubeSat development cycle to deliver higher reliability units. This includes additional expenditures on Payload development, Bus development, production facility upgrades, and ground station development – this assumes that the initial design of the system allowed for easily (i.e. cheaply) upgradeable systems. The end result of these additional costs is a new satellite lifetime uncertainty value of 10%. The two implemented strategies are summarized in Table V below.

**Table V. Flexibility Action implementation in NPV model**

| Flexibility Action | Implementation in Model | Result |
|---|---|---|
| Conditional satellite launch to meet realized demand trends | Sats_To_Deploy_YearX = Base_Case_Sats_To_Deploy_YearX* (1+ Annual_Percent_Change_In_Demand_Due_To_ Uncertainty_YearX) | Satellite launch numbers that attempt to follow demand trends |
| Upgrade investment for high-reliability CubeSats | If (Sat_Lifetime_FailureRate > 20%)<br>Payload Upgrade Cost = $10M<br>Bus Upgrade Cost = $10 M<br>Ground Station Upgrade Cost = $2.5M<br>Facility Upgrade Cost = $12.5 M<br>New Sat_Lifetime_FailureRate = 10%<br>Else<br>Do Nothing | Reduced satellite failure rates |

An example of the effects of implementation of the flexible launch strategy is shown in Figure 7 below. This case considered no other uncertainty effects, such as launch failure or lifetime uncertainty. In this example of demand uncertainty, the realized demand is typically larger than what is forecasted. As such, the launched capacity (based on number of satellites launched) attempts to capture this additional demand, and garners additional revenue as a result. The NPV of the flexible case for this one run is around $1.2 B, around $300 M more than the max NPV of the Base Case With Uncertainty ("Rigid Case") Monte Carlo analysis.

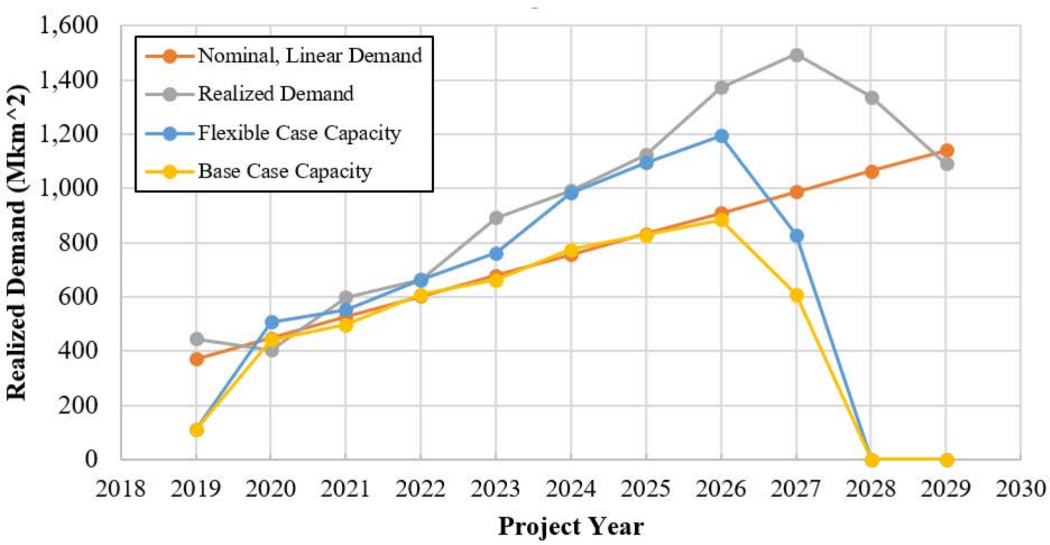


**Figure 7. Capacity deployment to meet demand, for the Flexible Case and the Base Case.**

<u>Flexible Case</u>

The next step is to conduct a Monte Carlo analysis of a flexible deployment and development strategy similar to the one done for the Base Case with Uncertainty. Four cases are compared: 1) The Base Case Strategy ("Rigid Case"), 2) The High Reliability CubeSat Strategy, 3) the Flexible Launch Strategy, 4) Full Flexibility which combines the High Reliability and Launch Flexibility Strategy.

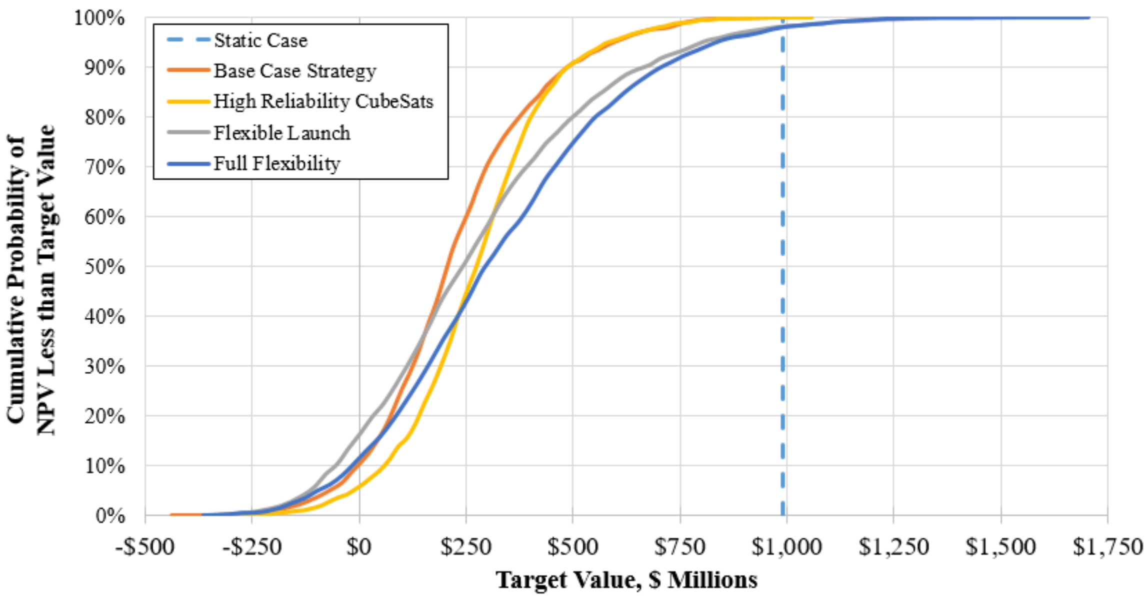


**Figure 8. NPV Cumulative Distribution for each of the cases investigated.**

**Table VI. Approximate values of statistical parameters for each of the cases investigated.**

| Statistical Parameter | Base Case | High Reliability CubeSats | Flexible Launch | Full Flexibility (High Reliability + Flexible Launch) |
|---|---|---|---|---|
| Maximum NPV, $ M | $960 | $1,050 | $1,500 | $1,700 |
| Minimum NPV, $ M | ($440) | ($350) | ($350) | ($360) |
| Average NPV, $ M | $230 | $275 | $240 | $300 |
| Value At Risk, P5, $ M | ($70) | ($10) | ($120) | ($100) |
| Value At Risk, P10, $ M | $0 | $60 | ($50) | ($10) |
| Value at Gain, P90, $ M | $500 | $480 | $680 | $700 |
| Value at Gain, P95, $ M | $600 | $580 | $800 | $840 |

Figure 8 shows the cumulative probabilities for NPV Target Values for each strategy along with the deterministic "static case" value discussed previously. Table VI shows the statistical parameters for each of the cases examined. As can be seen on the plot and read from the statistics, each flexibility option yields certain benefits, along with certain drawbacks as well.

The High Reliability CubeSat case significantly lowers the risk of the lower end of the NPV values. It has the best VAR performance, meaning the 5% and 10% lowest performing runs in its Monte Carlo analysis yield the best results (i.e. smallest losses). In fact, its P10 value is positive, meaning that we have a 90% or better chance of being net positive with this case. The mean NPV in this case is also around 20% better than the Base Case. However, on the upper end, it is the worst performing of the flexibility strategies, yielding P90 and P95 values actually lower than the Base Case. This may be a result of the added expenses of the CubeSat upgrades (totaling $35 M) tied with lower than expected demand, reducing the effective value of the upgrades.

Conversely, the Flexible Launch strategy performs poorly in the high risk regime; that is, it has the worst VAR performance. This may be a result of the possibility of significantly greater launch numbers tied with higher than expected launch costs and multiple launch failures. The plot shows that in fact, up to around the 30% cumulative probability mark, this case performs worse than the Base Case. On the other hand, the upside performance of this strategy is drastically better than the previous options. Its maximum potential NPV is nearly 60% greater than the Base Case and there is a 10% chance of making $680 M, nearly $200 M more than either the Base Case or the High Reliability case at that same cumulative probability. At most, the flexible Launch cases sees a deployment of 350 satellites, over 100 more than the Base Case.

The data suggests that adopting both flexibility strategies can significantly outperform either one individually. Per the statistical data, the Full Flexibility strategy inherits the drastic upper end improvements of the Flexible Launch strategy. It seems that the lower end benefits of the High Reliability case temper some of the poorly performing aspects in this regime of the Flexible Launch strategy. While the P5 and P10 VAR values are worse than the Base Case, Figure 8 shows that after the 20% value, the Full Flexibility case begins to statistically outperform the Base Case. Beyond 50% cumulative probability, the Full Flexibility case outperforms all the others. This is well captured by its Average NPV being higher than any other case.

### Selecting a Flexibility Strategy

We have discussed the performance, drawbacks and benefits of three flexibility strategies. It is another thing altogether to decide on pursuing one or the other. This decision must be based on the priorities of the stakeholders. For example, while the Full Flexibility case might have the highest possible NPV and even the highest Average NPV, it also has a poor P10 VAR. As such, a highly risk or loss intolerant decision maker may not be willing to take on a project with a 10% chance of losing $10 M. This fact would also prevent them from opting for the Flexible Launch plan with an even worse P10 VAR. They might instead choose to sacrifice potential value with the High Reliability strategy which performs very well in the P5 and P10 figures. Conversely, a risk-taking decision maker or one insensitive to loss (say, an eccentric billionaire) might go for the Full Flexibility strategy to maximize his potential revenue. Particularly since none of the strategies statistically dominate any other, a case might be made for any of them.

## Limitations, Findings and Conclusions

### Limitations

To properly take advantage of the results of this analysis, we must understand the key assumptions and limitations of the approach. In terms of the technical details of the constellation, we made several simplifying assumptions which may reduce the fidelity of the model. As discussed previously, a linear coverage model was used to estimate the constellation capacity with each new added satellite. In reality, Earth coverage is a non-linear function with input including desired latitude of coverage, number of orbital planes and geometric relationships between the various planes. The linear model thus loses some of this fidelity while allowing for an order of magnitude estimate of coverage. The capacity model also contains a few correction terms to account for: clouded imagery, errors in data downlinking and “desirable imagery”. Clouded imagery accounts for up to 40% of all imagery gathered and is useless – the capacity model uses an optimistic figure of 30% useful images in this sense. Data downlink is the key gateway between gathered imagery and imagery that can be sold; it is assumed that 75% of imagery gathered by a satellite is successfully transmitted to the ground without error and before being overwritten. Lastly, it is assumed that only 10% of imagery transmitted without cloud cover is considered useful. This accounts for the 70% of the Earth that is ocean (limited sale potential) and the over 90% of global land that is considered remote or uninhabited.

For imagery pricing, it was assumed that the CubeSat imaging payloads were capable of capturing imagery at a resolution equal to the theoretical maximum resolution for a particular combination of orbital altitude and aperture diameter. This physical limit is given by the Rayleigh criterion and is valid for highly specialized optical systems. In reality, CubeSat imaging payloads may not yet be at this level of quality to deliver the maximum possible resolution. Thus we can expect the pricing of our imagery to be more optimistic than realistic.

Additional assumptions were required in terms of cost figures. While cost models were used for the spacecraft bus and payload non-recurring and recurring costs, other figures were estimated from analogous missions and publically quoted sources. Perhaps the most important figure that was assumed was the recurring $100 M constellation operations and maintenance cost. As this is a substantial recurring cost, the value of the project is closely tied to the accuracy of this figure. This speaks to the broader sensitivity of the model and the outcome to various inputs whose values had to be estimated. Thus, the model and these assumptions requires validation before its results can be thought credible.

Lessons Learned

*What have you learned through the process of doing the application?*

It is always useful to learn the theory and rationale behind an analysis method, but it is best to see it applied to a real world example. Throughout the course, we saw simple examples of flexibility analyses, particularly the Garage Case. However, over this course-long project I have applied the same methods to a practical case related to my field of interest. While it has helped me get a better grasp of the concepts, it also shows the significant complexities that arise in nearly every aspect of the problem from quantifying and modeling demand and capacity to determining the conditional situations for implementing flexibility. The simplifying assumptions and limitations identified for this problem reinforce the notion that highly complex models are difficult and time-consuming endeavors. On the other hand, we can get qualitative insights on a particular strategy through simpler, lower fidelity, models. I would be confident of the high level trends and qualitative outcomes of this analysis while not lending such confidence to the actual quantitative outcomes. Here lies the distinction between screening models and high-fidelity models.

*Where do you see the most use for the flexible approach to design?*

As discussed previously, determining the most valuable flexible approach is dependent on the relevant stakeholder(s)'s priorities in terms of risk tolerance, short-term or long-term concerns, and other subjective considerations. However, the flexibility analysis conducted here can give decision makers critical insights into the various strengths and weaknesses of flexibility approaches in complex socio-technical systems. As such, it can help decision makers trust or refine their high impact decisions.

Conclusion

This analysis can be leveraged to make informed decisions on the deployment of the CubeSat constellation. We have found that our uncertain knowledge in how the future might unfold is a key consideration when developing an endeavor as risky as a satellite constellation. After performing the statistical analysis, it is clear that the ~$1 B NPV of the deterministic case (which does not consider uncertainty at all) is highly unlikely. As such, it would be fundamentally wrong to make decisions based on a deterministic (i.e. average value) case alone. We found that by considering uncertainty, the expected NPV of our deployment plan was significantly reduced. Reacting to this uncertainty with a flexible and responsive plan of attack was shown to be the most prudent strategy. However, selection of a particular flexibility strategy is dependent on the priorities of the stakeholder or decision maker. In the end, the profitability of such an undertaking is as dependent on design and managerial decisions as on the realization of an uncertain future. Thus, our best course of action is to understand these uncertainties and design flexible systems which allow us to easily modify our plans as the future unfolds.

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