Ranking CubeSat Communication Systems Using a Value-centric Framework

by

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Submitted to the MIT Sloan School of Management and the Department of Aeronautics and Astronautics
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Abstract

This work focuses on the application of a streamlined version of Multi-Attribute Tradespace Exploration (MATE) as a first-order analysis tool to aid in the selection of CubeSat communication systems. As CubeSats have become more capable, their need to support ever-increasing amounts of mission data has become imperative. However, the selection of a communications system is complex endeavor with multiple competing objectives and multiple stakeholders. This already challenging environment is compounded by the fact that CubeSats often operate with miniscule budgets on reduced timelines. So, in order to aid the decision maker while maximizing value, we show that MATE can be applied as a first-order analysis tool.

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1   Introduction

The current paradigm of satellite manufacturing is to build and operate very capable, very expensive, monolithic satellites with 15-year lifetimes and 10-year development cycles. This paradigm has made the consequences of mission failure severe and has led to a no-fail environment for satellite manufacturers and operators. However, a new paradigm is starting to emerge in the satellite industry: distributed networks of low-cost small satellites with short development cycles that can enable robust, redundant, and responsive space systems. One class of these small satellites is a modular, 10 x 10 x 10 cm^3 spacecraft called a CubeSat. First launched in 2003, these small satellites have been used extensively for experimental purposes with much success. Owing to the achievements of last decade, stakeholders across the satellite industry have started to examine CubeSats for use in operational missions. But, in order for CubeSats to transition from experimental projects to operational assets, a key limitation still remains to be overcome, the communications system.

Communications are a vital part of satellite technology, both to command the spacecraft and to get mission data to the end users in a timely manner. Compared with larger, monolithic satellites, CubeSats typically communicate with a low data-rate to a limited number of receiver stations on the ground. This leads to constrained amounts of mission data that suffers from high latency, due to the long period between ground station accesses. In order to enable more sophisticated, useful, and/or operational missions, that limitation must be overcome.

However, the problem is a complex one with numerous variables and competing objectives from multiple stakeholders. The success of the CubeSat industry has led to many new commercial entrants that provide a broad range of communication solutions specifically designed for use on CubeSats. While it is certainly positive that many more options exist than did 10 years ago, this presents a new problem for decision makers. How can the value of the system be maximized with so many choices? This problem is further compounded by the limited time and budgets under which CubeSat decision makers operate. In

this environment, there is typically not enough time to explore every option in detail as might be done in a traditional engineering trade analysis.

To aid the decision maker confronted with this problem, the work herein focuses on the application of a value-centric framework to investigate, characterize, and rank these communication systems. By using a value-centric framework, as opposed to a purely technical one, decision maker preference can be included in the design process to maximize overall design utility and help quickly explore the complete set of feasible designs early on in the design process while changes are still possible. The value-centric framework chosen for this application is Multi-Attribute Tradespace Exploration (MATE) (Ross, Diller, & Hastings, 2003), which combines both technical tradespace exploration and Multi-Attribute Utility Analysis (MAUA) (Keeney & Raiffa, 1976).

In the classic application of MATE, a utility function is assigned to each decision maker-derived attribute of the system. With this input, custom software calculates and returns the overall utility of all the possible designs based on the previously input decision maker preferences, calculates the cost of each particular design, and then plots each design in the utility-cost tradespace. The results of this model can then be used to help understand the tradespace of a complicated new design, drive rapid design iteration, prevent anchoring to previous designs through design enumeration, and ultimately maximize decision maker utility (Nickel, Ross, & Rhodes, 2009).

The research performed with the MATE framework up to now has focused mainly on rigorous application to large-scale systems. While incredibly powerful, a complete application can be time consuming, and unfortunately, the constraints of CubeSat programs do not always afford the time a complete implementation of MATE deserves. However, as a holistic analysis tool, MATE is still useful to guide decision-making under such constraints. The work that follows validates this assertion through the application of a streamlined version of MATE as a first-order analysis tool for CubeSat communications system selection.

2   Motivation and History

CubeSats are quickly moving from "practical learning tool for engineering students" (Twiggs, 2008) towards becoming operational space-based assets. This can be attributed mostly to their low cost and short development cycle. These desirable attributes are achieved through the use of a common standard and limited size, which enable commercial off the shelf (COTS) components to be developed and utilized cost-effectively for a broad range of missions.

As the transition towards becoming an operational asset continues, it is important that the COTS systems selected for use in these small satellites be optimized for each mission in order to get the most out of their limited capability. In their infancy, system selection was not so difficult, as only a few component systems existed which were specifically designed for CubeSats. However, as CubeSats have proliferated over the last decade, and been called upon to perform missions of ever increasing importance, many more commercial vendors have entered the space to offer component systems for these small spacecraft. These entrants, while fantastic for the success of CubeSats, have resulted in many more system combinations than can be thought about at any one time by a decision maker or designer. So with this in mind, we seek to aid the decision maker and designer by applying a value-centric framework to the selection of one such component system: the communications package.

Before beginning any detailed analysis and a discussion of value centric methodology as it relates to CubeSat system design, we begin by presenting a brief discussion of the CubeSat standard and its history to help provide background and some common vocabulary for this work.

2.1   CubeSats in Brief

In its simplest form, a CubeSat is a 10 x 10 x 10 cm^3 fully functioning spacecraft, which weighs no more than 1 kg. This is referred to as a 1U CubeSat. Typical sizes also include 2U (10 x 10 x 20 cm^3) and 3U (10 x 10 x 30 cm^3) CubeSats. These pico or nano-satellites are quite a departure from the larger, monolithic satellites typically flown today, some of which can easily reach into the hundred of kilograms

and be tens of meters in length, width, and height. Small satellites, such as CubeSats, are comprised of a similar set of systems which can be found on their larger and much more expensive cousins, though in miniature.

With multiple commercial providers now selling components for CubeSats, one problem CubeSat users and builders face is how to select the right mix of components for a particular mission. In the following analysis, a value-centric methodology will be applied to aid in this selection. For the purposes of explanation and limiting scope, the communications system has been chosen to use as a representative case. However, it should be noted that the methodology described herein could be applied to any other subsystem or even a complete system. For brevity, descriptions of subsystems other than communications will be limited to that required for our analysis. Any further research on these subsystems will be left to the reader.

2.2   The CubeSat Standard

Much of the success of CubeSats can be attributed to the development and wide adoption of a common standard. In this section, we will discuss the history of that standard followed by its chief advantages.

2.2.1   Development History

The idea for the CubeSat standard started around 1998 with a desire on the part of Prof. Bob Twiggs of Stanford University to make student satellite programs more successful, thereby increasing interest from engineering students and giving them valuable experience with actual space hardware while still in college. He reasoned that this would require the reduction of system development timeline and launch cost. Having observed that previous student programs were challenged by these problems, Prof. Twiggs decided that limiting the size (and mass) of the satellite would reduce the number of experiments which could be flown on a single mission and would thus reduce launch cost and time.

With this in mind, he reasoned that miniaturization is really limited by the amount of power that can be produced by a recharging system (solar cells) on-orbit. At the time, in order to achieve charging of two lithium-ion batters in series, eight 1.2V GaAs solar cells had to be used which, when affixed to the six sides of a cube, measured 3.5 inches cubed. Additionally, in order to accommodate launch rails, a 0.25 inch clearance was needed all around each face, bringing the CubeSat's size up to a 4 inch cube. After looking around, a plastic "Beanie Baby" box was found and used for the initial conceptual model. Finally, in poking some fun at the Mars Lander failure suffered as a result of a metric conversion error between JPL and Lockheed Martin, it was decided that the CubeSat standard would be 10 x 10 x 10 cm^3 as this was very close to 4 inches. Finally, to complete the specification, the maximum mass was defined to be 1kg, the equivalent weight of a 1000 cm^3 volume of water and also the designated upper limit for picosat mass (Twiggs, 2008). Table 1, from Janson (2008) shows naming conventions for various sizes of small satellite. CubeSats are typically in the "nanosatellite" class of small satellite.

Table 1: Small Satellite Classification by Mass

Spacecraft Class	Mass Range
Microsatellite	10 – 100 kg
Nanosatellite	1 – 10 kg
Picosatellite	0.1 – 1 kg
Femtosatellite	0.01 – 0.1 kg

The next step was to create a standardized launcher. The first prototype was a simple 3U (10 x10 x 30 cm^3) box with a spring-loaded lid and a pusher spring to deploy the CubeSats. Prof. Twiggs brought this simple prototype launcher to Prof. Jordi Puig-Suari at Cal-Polytechnic in hopes he and his team could handle detailed design, launch vehicle integration, and qualification of the launcher. So, using the initial launcher design idea, Profs. Twiggs and Puig-Suari agreed upon a standard for the CubeSat and launcher. With that, the team at Cal-Poly created a simple, spring loaded launcher design which could fit up to three

1U CubeSats or any combination of sizes, provided it added to no more than 3U. This launcher was called

the Poly Picosat Orbiting Deployer (P-POD). It is shown in its most recent incarnation in Figure 1 and

Figure 2 (California Polytechnic State University, 2009). By investing time to qualify the launcher with a

particular launch vehicle and show that anything put inside it would remain captive, posing little or no

threat to a primary payload, the time to launch and onerous launch vehicle-specific design requirements

for a given satellite would be drastically reduced. So, from a "Beanie Baby" box and a desire to keep

engineering students interested, an entire industry has emerged and a useful standard for small satellites

has been adopted (Twiggs, 2008).

Figure 1: Six CubeSats and their deployment systems
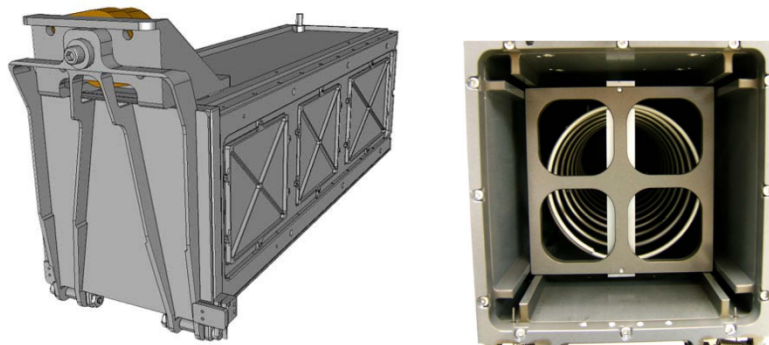
Figure 2: Poly Picosatellite Orbital Deployer (P-POD) and Cross Section

2.2.2   Advantages of the CubeSat Standard

Much of the success of CubeSats over the past decade can be attributed to the adoption of a common standard by a broad range of stakeholders. There are many advantages of designing to a standard, and we think it important to mention two in particular.

First, by designing to a standard, the process of securing a ride to orbit can be started well ahead of the actual start of satellite design, thus allowing for a much faster CubeSat design cycle. This characteristic has resulted in the rise of a middle tier (broker-like) portion of the industry in which private corporations secure rides for their P-POD like "launcher" in the spare volume of launch vehicles whose primary payload is very large. They then sell space in their launchers to groups with CubeSats at greatly reduced costs compared to that of a primary mission. In addition to private companies NASA has also gotten into the act with their CubeSat Launch Initiative (NASA, 2013a). Through this initiative, university CubeSat teams competitively propose for free launch slots aboard already planned NASA missions.

Second, by having a single standard, the technical requirements for CubeSat buses remain static across a widely varied set of missions. Thereby, commercial companies can take advantage of economies of scale and offer component systems at a reduced cost to a wide range of CubeSat builders (consumers). This removes a significant amount of cost from a CubeSat project, as not everything need be a unique and completely new design. An excellent discussion on the advantages of a CubeSat Standard can be found in (Chin, Coelho, Brooks, Nugent, & Puig-Suari, 2008)

2.2.3   Current CubeSat Missions

With these advantages and some history in our minds, let us turn our attention to the current state of the art for CubeSats. The most recent CubeSat launch aboard NROL-36 showed that CubeSats are becoming ever more advanced and are maintaining a steady pace toward becoming operational systems (CubeSat, 2012). The NROL-36 missions shown in Table 2 represent systems that could, in the not so

distant future, be relied upon by both government and commercial stakeholders for critical information across a broad range of endeavors. They include on-demand over the horizon communication[1] (USASMDC/ARSTRAT, 2012), autonomous on-orbit inspection technology[2] (Hinkley & Hardy, 2012), tracking cargo containers over the ocean[3] (University of Southern California, 2012), space weather monitoring[4] (University of Colorado Boulder - Laboratory for Atmospheric and Space Physics, 2012), cosmic X-ray background measurements[5] (Morehead State University - Space Science Center, 2012), and space debris monitoring[6] (Fury, 2012).

Table 2: NROL-36 CubeSat Missions

Mission	Name	CubeSat Size	CAD Rendering or Photo
On-demand over the horizon communication[1]	SMDC-One & SMDC-Two	3U	
Autonomous on-orbit inspection technology[2]	Aerocube 4	1U	
Tracking cargo containers over the ocean[3]	Aeneas	3U	
Space weather monitoring[4]	CSSWE	3U	
Cosmic X-ray background measurements[5]	CXBN	2U	
Space debris monitoring[6]	STARE	3U	

2.3 CubeSats vs. Large Satellites

Even with the success of these CubeSats, as well as others, it is still tough to get past the fact that CubeSats are less capable than traditional large satellites. As such, this seems like an appropriate time to discuss the tangible differences in CubeSats and large (traditional) satellites.

The current industry paradigm is to build extremely capable, monolithic satellites that can cost in excess of $1B each and can have development times well in excess of 5 years. These high development costs and long development cycles have led to a no-fail environment for satellite manufacturers, operators, and launch providers. Conversely, "the CubeSat Program is designed so that space missions can be completed in two years or less (the average collegiate lifetime of a graduate student)" (Toorian & et al, 2005) Further, the typical cost of a CubeSat is on the order of $1M. These characteristics lead to a robust, responsive system with the potential for exceptional reliability gained through redundancy. In fact, these qualities are compelling enough that Defense Advanced Research Projects Agency (DARPA), the Department of Defense (DoD) Office of Operationally Responsive Space (ORS), and NASA have put in place programs to examine the use of small satellites in responsive roles. Specifically, the DoD terms this a Tier 2 need scenario, where neither a traditional development timeline nor a current asset could deliver what the user needs when the user needs it (DoD Office of Operationally Responsive Space, 2012).

2.3.1 Responsive Space: Filling the Void between NPP and JPSS-1

One example of where a CubeSat could be useful in a responsive role is as a gap-filler for the Joint Polar Satellite System (JPSS). JPSS is the program of record under which the National Oceanic and Atmospheric Administration (NOAA) and NASA manage the United States' polar orbiting weather satellites throughout their lifecycle. This $12.9B program consists of 3 satellites, the Suomi NPOESS Preparatory Project (Suomi NPP), JPSS-1, and JPSS-2 (Office of Inspector General, 2012). This suite of satellites, of which NPP is the only one currently in orbit, is intended to provide atmospheric observations that feed numerical weather models used in storm prediction and climate monitoring, amongst other critical weather missions.

It is predicted that in the next few years, due to programmatic issues like cost over-runs and schedule delays, there may be a gap in satellite coverage. As shown in Figure 3, Suomi NPP, launched on October 28, 2011 after 10+ years of development, may die before JPSS-1 is ready to replace it in 2017 (Office of Inspector General, 2012). This is particularly distressing, as "Polar satellites provide[d] 84 percent of the data used in the main American computer model tracking Hurricane Sandy" (Cushman, 2012). So, it is reasonable to assert that this is a capability that greatly benefits the nation and one that we would rather not be without.
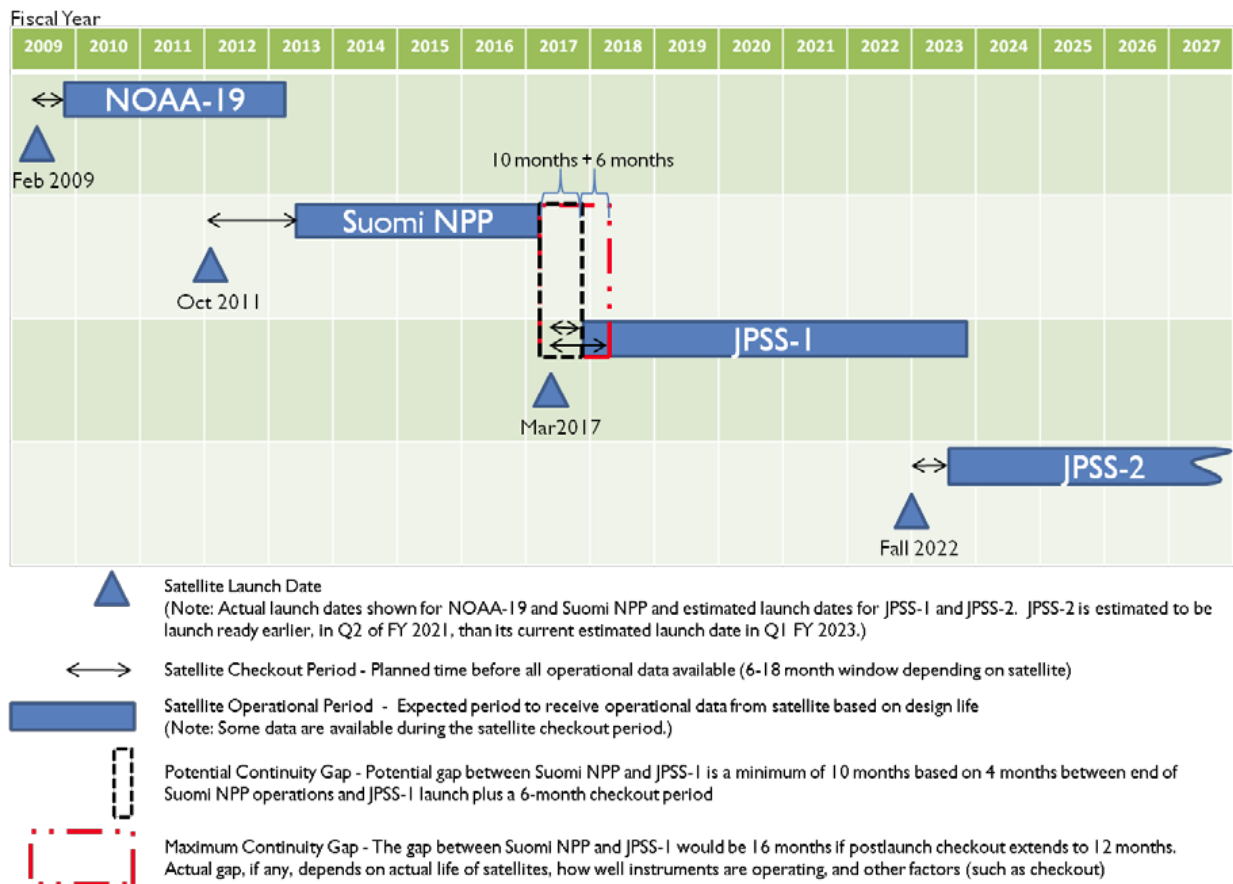
Figure 3: Potential Continuity Gaps for Polar-Satellite Operational Forecast Data (OIG, 2012)

As was mentioned previously, CubeSats trade capability in exchange for reduced development time and cost. These features also increase the risk tolerance of a decision maker when it comes to allocating funds. In turn, this increases the flexibility and responsiveness of small satellites compared with large ones. So, given the relatively short development cycle that would be required and relatively limited funds

available, a CubeSat seems like a logical choice to provide at least some capability in the interim. So, let's compare Suomi NPP, the current state of the art, to a typical set of CubeSat specifications directly and see how a gap-filler satellite might stack up. Table 3 shows this comparison with a notional 1U CubeSat and a 3U CubeSat (California Polytechnic State University, 2009; ClydeSpace, 2013; NASA, 2013b).

Table 3: Large Satellite vs. CubeSat Capability Comparison

Satellite	NPP	1U CubeSat (Typical)	3U CubeSat (Typical)
Mass	2132.8 kg	1.33 kg	4kg
Dimensions	4.0 x 2.6 x 2.2 m	10 x 10 x 10 cm	10 x 10 x 30 cm
Power	2600 W	2.1 W – Body Panels Only	7.3 W – Body Panels Only
Orbit Altitude	824 km	300-900 km	300 – 900 km
Design Life	5 Years	1 Year	1 Year
Comm Bands	S, X	VHF, UHF, S	VHF, UHF, S
Comm Topology	LEO to Ground & Crosslink	LEO to Ground	LEO to Ground
Link Availability	100%	5-10%	5-10%
Data D/L Rate	300 Mbps	115 kbps	115 kbps
Cost	~$900M	~0.1M	~$1M

In examining this table, the main thing to note is that there is overall less capability on the part of a CubeSat, but at far less cost. In particular, as we will be using the communication system for a detailed example in the coming chapters, note the Link Availability and Data Downlink Rate lines. These are clearly much lower in the case of the 1U and 3U CubeSat than that of the Large (traditional) satellite. However, this does not mean that there is no value in a system with reduced performance.

We may still gain value from even a little bit of data when compared with the prospect of none. So, what if we could increase link availability and data downlink rate while still remaining in a decision maker's comfort zone? Or, more formally, what if we could design a system within a set of parameters

such that the decision maker derives value from the system? Note that a decision maker is a person involved in a program who has the power to affect change. This is a situation where defining and utilizing a value centric framework to capture as much value as possible from a complex system could be extremely useful.

2.4   Value Proposition for CubeSats

CubeSats are important and will continue to be more so in the coming decades, whether as gap-filler satellites, space qualification platforms for rapidly developing electronics technologies, or as a student learning tool to educate and excite the next generation of engineers. They are inexpensive, responsive, flexible, and robust. But, the question remains, how do we maximize the value that can be gained from any particular CubeSat given its technical limitations? For that matter, how do we select the right subsystems to go on CubeSats given all of the possible design choices? These over-arching questions frame the research that will be presented in the following chapters.

3 CubeSat Communication Technology

As missions are becoming more sophisticated, the demand to return ever-increasing amounts of data from those missions in a timely manner is increasing. In this chapter, an introductory discussion of CubeSat communications is presented.

The analysis herein will be mostly limited to data downlink from the CubeSat, which is the stressing case. Uplink scenarios tend to be less stressing due to a lower required data rate and ample available transmit power at the ground station. In other words, communicating commands is far less taxing on the system than the delivering volumes of mission data. So, if it can perform effectively during downlink, we will assume that it will also be able to perform well in uplink scenarios.

3.1 Current CubeSat Communication Systems

Generically, a CubeSat communication system is made up of a transmitter onboard the spacecraft and a receiver at a ground station, or set of receivers across a geographically diverse ground station network. For reference, Table 4 from (Klofas, Anderson, & Leveque, 2008), shows a summary of CubeSat transmitters and their capabilities as of November 2008.

Table 4: Nov 2008 Summary of CubeSat Transmitters (Klofas, 2008)

Satellite	Object	Size	Radio	Frequency	License	Power	TNC	Protocol	Baud Rate/Modulation	Downloaded	Lifetime	Antenna
AAU1 CubeSat	27846	1U	Wood & Douglas SX450	437.475 MHz	amateur	500 mW	MX909	AX.25, Mobitex	9600 baud GMSK	1 kB	3 months	dipole
DTUsat-1	27842	1U	RFMD RF2905	437.475 MHz	amateur	400 mW		AX.25	2400 baud FSK	0[1]	0 days	canted turnstile
CanX-1	27847	1U	Melexis	437.880 MHz	amateur	500 mW		Custom	1200 baud MSK	0[1]	0 days	crossed dipoles
Cute-1	27844	1U	Maki Denki (Beacon)	436.8375 MHz	amateur	100 mW	PIC16LC73A	CW	50 WPM	N/A	65+ months	monopole
(CO-55)			Alinco DJ-C4 (Data)	437.470 MHz	amateur	350 mW	MX614	AX.25	1200 baud AFSK	>10 MB		monopole
QuakeSat-1	27845	3U	Tekk KS-960	436.675 MHz	amateur	2 W	BayPac BP-96A	AX.25[2]	9600 baud FSK	423 MB	7 months	turnstile
XI-IV	27848	1U	Nishi RF Lab (Beacon)	436.8475 MHz	amateur	80 mW	PIC16C716	CW	50 WPM	N/A	65+ months	dipole
(CO-57)			Nishi RF Lab (Data)	437.490 MHz	amateur	1 W	PIC16C622	AX.25	1200 baud AFSK	>11 MB		dipole
XI-V	28895	1U	Nishi RF Lab (Beacon)	437.465 MHz	amateur	80 mW	PIC16C716	CW	50 WPM	N/A	36+ months	dipole
(CO-58)			Nishi RF Lab (Data)	437.345 MHz	amateur	1 W	PIC16C622	AX.25	1200 baud AFSK			dipole
NCube-2	28897[3]	1U		437.505 MHz	amateur			AX.25	1200 baud AFSK	0[1]	0 days	monopole
UWE-1	28892	1U	PR430	437.505 MHz	amateur	1 W	H8S/2674R[4]	AX.25	1200/9600 baud AFSK		0.75 months	end-fed dipole
Cute-1.7+APD	28941	2U	Telemetry Beacon	437.385 MHz	amateur	100 mW	H8S/2328[4]	CW	50 WPM	N/A	2.5 months	dipole
(CO-56)			Alinco DJ-C5	437.505 MHz	amateur	300 mW	CMX589A	AX.25/SRLL	1200 AFSK/9600 GMSK	<1 MB		dipole
GeneSat-1	29655	3U+	Atmel ATA8402 (Beacon)	437.067 MHz	amateur	500 mW	PIC12C617	AX.25	1200 baud AFSK		3 months	monopole
			Microhard MHX-2400	2.4 GHz	ISM	1 W	Integrated[5]	Proprietary		500 kB		patch
CSTB1	31122	1U	Commercial[6]	400.0375 MHz	Experimental	<1 W	PIC	Proprietary	1200 baud FSK	6.77 MB[7]	19+ months	dipole
AeroCube-2	31133	1U	Commercial[6]	902-928 MHz	ISM	2 W	Integrated[5]	Proprietary	38.4 kbaud	500 kB	0.25 months	patch
CP4	31132	1U	TI CC1000	437.325 MHz	amateur	1 W	PIC18LF6720	AX.25	1200 baud FSK	487 kB	2 months	dipole
Libertad-1	31128	1U	Stensat	437.405 MHz	amateur	400 mW		AX.25	1200 baud AFSK	0[8]	1 month	monopole
CAPE1	31130	1U	TI CC1020	435.245 MHz	amateur	1 W	PIC16LF452	AX.25	9600 baud FSK	0[9]	4 months	dipole
CP3	31129	1U	TI CC1000	436.845 MHz	Experimental	1 W	PIC18LF6720	AX.25	1200 baud FSK	2.0 MB[7]	19+ months	dipole
MAST[10]	31126	3U	Microhard MHX-2400	2.4 GHz	ISM	1 W	Intgrated[5]	Proprietary	15 kbps	>2 MB	0.75 months	monopole
Delfi-C3	32789	3U	Custom Beacon	145.870 MHz	amateur	400 mW	PIC18LF4680	AX.25	1200 baud BPSK	60 MB[11]	7+ months	turnstile
(DO-64)			Custom Transponder	145.9-435.55 MHz	amateur	200 mW	N/A	Linear	40 kHz wide	N/A		turnstile
Seeds-2	32791	1U	Musashino Electric (Beacon)	437.485 MHz	amateur	90 mW		CW		N/A	7+ months	monopole
(CO-66)			Musashino Electric (Data)	437.485 MHz	amateur	450 mW		AX.25	1200 baud AFSK	500 kB		monopole
CanX-2	32790	3U	Custom S-Band	2.2 GHz	Space Research[12]	500 mW	Integrated	NSP	16kbps-256kbps BPSK	250 MB	7+ months	patch
AAUSAT-II	32788	1U	Holger Eckhardt (DF2FQ)	437.425 MHz	amateur	610 mW	PIC18LF6680	AX.25	1200 baud MSK	8 MB[13]	7+ months	dipole
Cute 1.7+APD II	32785	3U+[14]	Invax (Beacon)	437.275 MHz	amateur	100 mW	H8S/2328	CW	15 WPM	N/A	7+ months	monopole
(CO-65)			Alinco DJ-C5 (Data)	437.475 MHz	amateur	300 mW	H8S/2328, CMX589A	AX.25/SRLL	1200 AFSK/9600 GMSK	21 MB[15]		monopole
Compass-1	32787	1U	BC549 (Beacon)	437.275 MHz	amateur	200 mW	PIC12F629	CW	15 WPM	N/A	7+ months	dipole
			Holger Eckhardt (Data)	437.405 MHz	amateur	300 mW	C8051F123, FX614	AX.25	1200 baud AFSK/MSK	<1 MB		dipole

The overall objective, at least for the purposes of this study, is to get as much mission data to a user as possible. It is also desirable to do so in as timely a manner as possible, but we will address this second objective in Chapter 5. In order to determine our performance against the first objective, we can begin by measuring how much data the system is able to transmit. Total data volume can be calculated by multiplying the transmit rate and the access time of the satellite to a receiver station. At first glance, it would seem that if we want to maximize the amount of data that is getting to the ground, then all we have to do is increase access time and increase the transmit rate. This sounds easy enough, but on a CubeSat both access time and data rate are inherently limited. So, let us turn our attention to the elements of the communication system that affect the data rate and access time and discuss how these two elements might be maximized.

3.1.1   Maximizing Data Rate

At this point, we will assume that we are talking about digital communication. As such, data is encoded onto an analog signal via a modulation scheme. In the case of CubeSats, this modulation scheme is typically rather simple, and thus limits how much data can be transmitted in a given amount of time. However, by using higher order modulation, packing the signal with more information over constant bandwidth, it is possible to achieve higher data throughput for the system. But, this idea has a problem. The more data encoded onto a signal, the more energy is needed in order to ensure that encoded data is not lost. Formally, this is termed E_b/N_0 (bit energy to noise ratio). So, there is a tradeoff between spectral efficiency and power. That is, the more efficiently we use a given section of bandwidth, the more power must be used during transmission (Wertz, Everett, & Puschell, 2011).

Given that the transmit power emitted by CubeSat is limited, typically around 1W (Selva & Krejci, 2012), the alternative is to use a spectrally inefficient (simple) modulation scheme which includes a great deal of forward error correction. But, this requires a greater amount of bandwidth. While such a plan could work in theory, the radio spectrum, shown in Figure 4 (Office of Spectrum Management, 2011), is already densely packed and tightly regulated by the Federal Communications Commission

(FCC) in the United States and internationally by the International Telecommunication Union (ITU) (Maral & Bousquet, 2009).
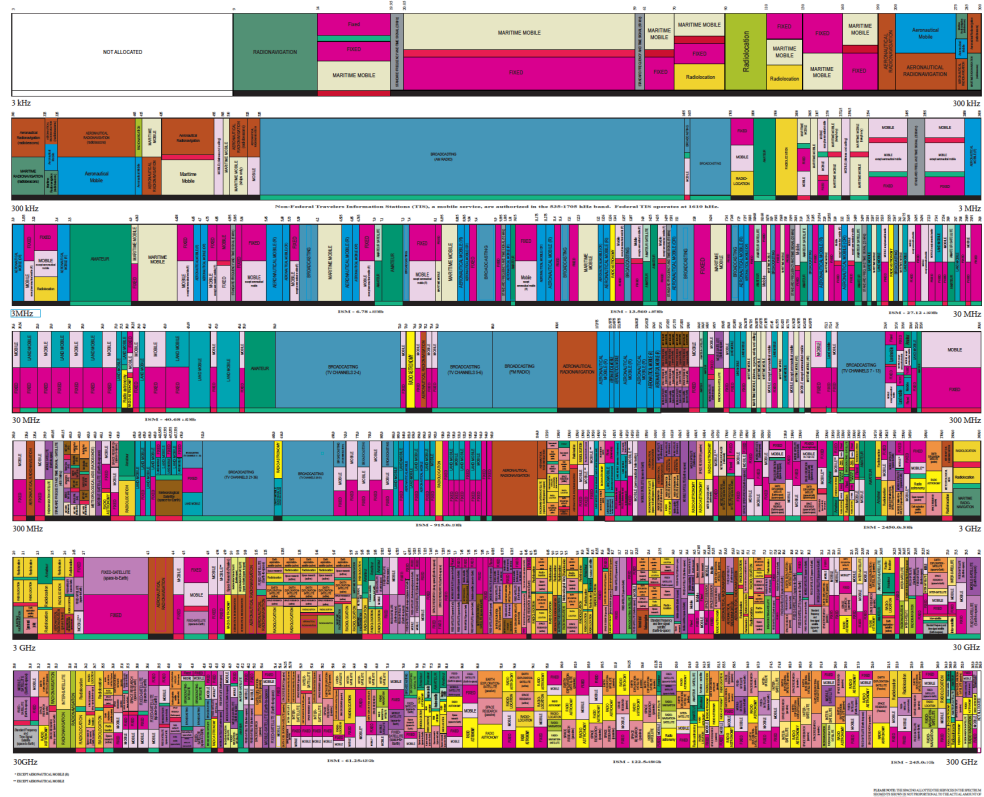
Figure 4: United States Frequency Allocation Spectrum (Office of Spectrum Management, 2011)

It should be noted that this is a greatly simplified description of the trade analyses required to effectively design or select a satellite communication system. The takeaway from this discussion should be that this problem is inherently a complex one with many variables and multiple competing objectives. During the design process, these technical considerations are accounted for through a link budget. This budget accounts "... for increases and decreases in power through each part of the link from the transmitter and its antenna, and through space to the receiver antenna and electronics where the signal is measured and decoded" (Wertz, Everett, & Puschell, 2011).

3.1.2 Access Time

For the purposes of analysis, let us assume for a moment that increasing the data rate to increase the overall data volume isn't possible. This could be because of physical (technical) restrictions or maybe because of bandwidth limits from a regulatory body. So, let us focus on another option, increasing access time.

Typically, CubeSats fly in Low Earth Orbit (LEO) from just outside the upper atmosphere to a few hundred kilometers in altitude, and communicate to receiver stations on the ground of varying size and performance. These receiver stations can range from an amateur radio operator with a simple Yagi antenna to advanced parabolic antennas that are 10s of meters in diameter, like those of the National Aeronautics and Space Administration (NASA) Deep Space Network (DSN) (NASA, 2006; Tuli, Orr, & Zee, 2006).

Irrespective of the capability of an individual ground station, receiver access time is dominated by geographic location of the receiver and the orbit geometry of the CubeSat. For a single ground station in an optimal location and the CubeSat in an optimal orbit, we can assume that a typical ground station pass for a CubeSat will last approximately 10 minutes and occur once every 90 minutes. In reality, things aren't quite so perfect. The precession of the CubeSat, assuming it is in an inclined orbit, constrains the number of passes where data can be downloaded. So, what can be done about that?

Assuming that CubeSats are going to continue being launched into LEO orbit, and not higher orbits with longer dwell times and higher path loss, then there are two options to increase overall access time. First, increase the number of ground stations to which the CubeSat can communicate. This idea certainly has merit and is currently being actively pursued through various collaborative endeavors, like the Global Educational Network for Satellite Operators (GENSO) (Kief, 2011). Second, we could choose a completely different network topology. By that, we mean some form of satellite cross-linking to a larger dedicated communications satellite that could then forward data to the user on the ground through its own

already established communication network. Some of the main advantages and disadvantages of each

option are presented in Table 5.

Table 5: Comparison of Options for Increased Access Time

Option	Description	Advantages	Disadvantages
1	More Ground Stations	Simplicity, Control	Regulation (Multiple Countries) Need to Staff Multiple Locations Initial Set-up Cost
2	Alternate Network Topologies (Satellite Cross-link)	Greatly increased access time	Various Technical Challenges: e.g. Free-space loss, Beam Handover, Doppler shift, Reduced Data Rate, Need for Directional Antenna on CubeSat

3.1.2.1   Option 1: More Ground Stations

At first glance, it would seem that a good solution to the problem of not enough access time

would be to add a lot of geographically diverse ground-based receiver stations to the mix. They are

relatively simple, compared with a space-based receiver, and can be controlled directly by the operations

team, assuming they are networked together. However, there are a few disadvantages that make the

implementation not so simple.

First, each country has its own set of complex regulations for bandwidth allocation. As such,

bandwidth allocation can be a costly and time-consuming process. Second, there is a need to staff each

location, which is a recurring cost. Though a single ground station might only cost a few tens of

thousands of dollars to set up, the cost of a staff to maintain that ground station could quickly exceed the

budget of a CubeSat program intended to minimize cost. It should also be pointed out that even graduate

student labor is not free.

The arguments being made here pertain to an operational system. That is, a system which is

fulfilling a critical need and which must achieve a high reliability. So, the assumption has been made that

the communications link must be a controllable and reliable one. Therefore, a solution like partnering with the amateur radio community, though incredibly valuable on a research and development basis, would not be appropriate for an operational CubeSat system.

3.1.2.2   Option 2: Alternate Network Topologies

Now, let us discuss an alternate solution to creating a complex network of ground stations. Designers of larger satellites have often solved the problem of increasing access time by selecting a communication system that utilizes another satellite already in orbit. This is termed a satellite cross-link and can be performed through a variety of on-orbit network topologies, which are shown Figure 5.
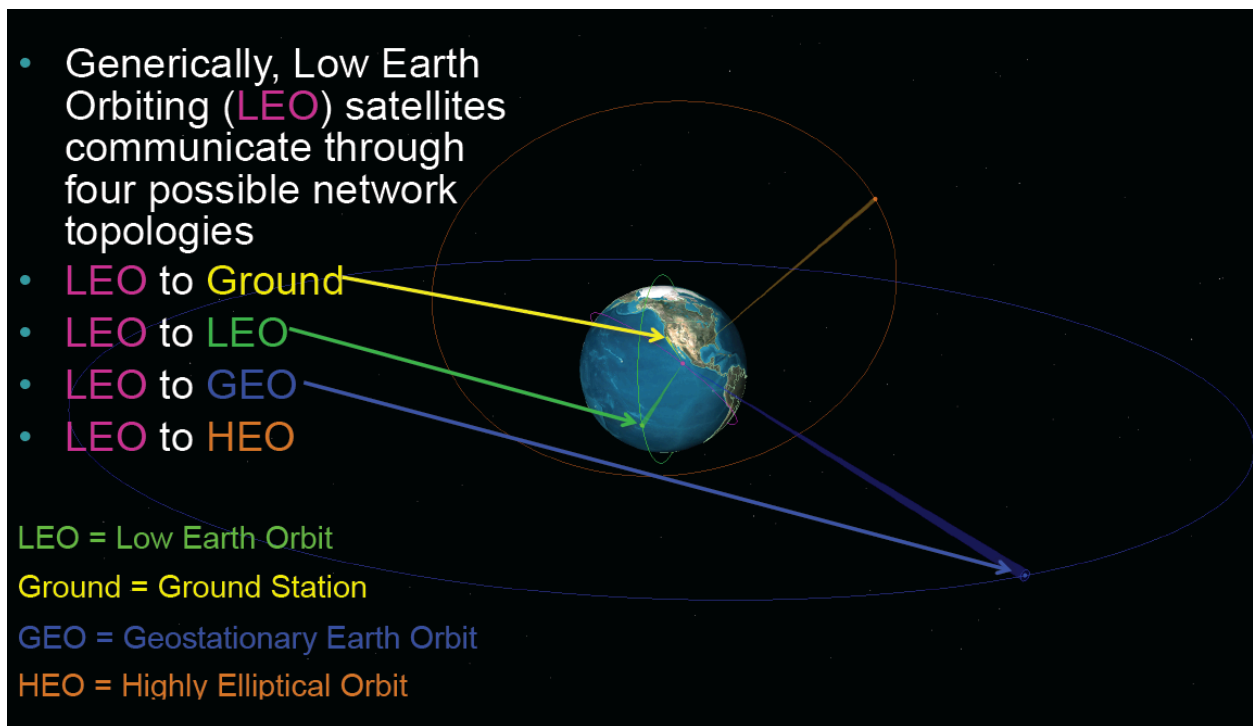
Figure 5: Various Satellite Network Topologies

There are several commercial and government entities that operate satellite networks that perform cross-link communication, like the Iridium satellite telephone constellation or NASA's Tracking Data and Relay Satellite System (TDRSS) (Iridium, 2013; NASA, 2008). These systems are a scarce resource, and as such are not always available to operators of small satellite missions. However, there is commercial interest in increasing this resource for use by small satellites, though no transceivers are yet appropriately

miniaturized for use on CubeSats. Many of the technical challenges associated with utilizing this set of network topologies can be more easily solved on a larger platform than a CubeSat. These include the need for a directional antenna to overcome free-space loss, active attitude control for pointing, performing spot-beam handover, and compensating for Doppler frequency shift.

While no active system to perform CubeSat communication to a commercial asset via cross-link exists, the technology is ever advancing. So, we can think about what such a system might look like and start to analyze how such a system would stack up against ground-based systems. This could reveal the parameters required by such a system to make it feasible and motivate future system development.

3.2 Stakeholders for CubeSat Communication Systems

The selection of a communication system is a complex task with many competing objectives. One might expect that this is where the complexity ends. However, in addition to the technical trades, stakeholders who may have competing interests are involved. There are many groups that have a stake in satellite communications and not just those interested in CubeSats. Table 6 summarizes a few of the varying stakeholder viewpoints associated with this endeavor in order to give a broad sense of what each group cares about before we continue with more detailed analysis in Chapter 5.

Table 6: Stakeholder Summary

Stakeholder	Stakeholder Motivation/Need
End User of CubeSat Mission Data *(Likely a Decision Maker)*	Wants a lot of data, quickly, and at minimum cost.
CubeSat Development Program Manager *(Likely a Decision Maker)*	Wants to manage the creation of a functioning system to get the user his/her data, but at a reasonable cost and in a reasonable time.
Satellite/Communication System Designer	Wants to design the best system possible. Typically optimizes on performance and not cost. The design is typically constrained by requirements set by the program manager or other decision maker.
Regulators (ITU – FCC)	Are legally responsible for ensuring that all users of the finite radio spectrum operate harmoniously. Note: Authorization for spectrum use can take a year or more.
Other Users of the Radio Spectrum **(Not limited to sat. comm.)**	Want to be able to perform communications without interference from other users. Typically desire to have as much bandwidth allocated to them as possible.
CubeSat Operator	Wants to ensure proper operation and reliability of the space vehicle while maintaining positive control. Want to get user his/her data quickly and efficiently.
Other Satellites in Orbit	Want to operate free of restriction from other space users. In other words, want to avoid conjunctions or radio interference.
Relay Communication Satellite Operator	Wants to handle as much traffic as possible so that profit can be maximized. Pricing structure is by the minute or by the kilobit.
Ground Station Operator	Wants to support satellite operations while maintaining minimal staffing to reduce cost.

3.3   Summary

In summary, it has been shown that the design, selection, and operation of CubeSat communication systems are complex endeavors with no simple solutions. There are multiple competing technical parameters that must be selected to yield the maximum benefit across a number of competing objectives, which are defined by myriad competing stakeholders. In short, complexity is everywhere. In the next chapter, in order to bring some order to this complexity, a value-centric framework called Multi-Attribute Tradespace Exploration (MATE) will be introduced.

4 Multi-Attribute Tradespace Exploration

Multi-Attribute Tradespace Exploration (MATE) is a value-centric framework, developed by Adam Ross and Nathan Diller while completing their graduate work at MIT (Diller, 2002; Ross, 2003). This framework combines multi-attribute utility analysis and tradespace exploration to aid the system design process through design enumeration and design ranking in the face of complex problems. MATE does this by incorporating decision maker preference across important attributes early in the design process, thus maximizing utility and overall value to the stakeholder community. The inclusion of preference is what sets this methodology apart from traditional engineering trade studies.

There have been several successful applications of this framework on large systems, e.g. networks of satellites (Ross, Diller, Hastings, & Warmkessel, 2002) and Transportation Infrastructure Planning (Nickel, Ross, & Rhodes, 2009). While large-scale systems present good applications for MATE, we would like to show that MATE can also be applied effectively to deliver value quickly to problems under increased time pressure with reduced resources. This will be shown in Chapter 5 by using MATE in the selection of a CubeSat communication system.

4.1 Value vs. Utility

Before discussing the details of MATE, it is worthwhile to take a moment and discuss the difference in value and utility, as it is a central point in understanding this framework. Informally, **value** can be determined only when a decision maker can make a direct preference ranking of attributes in the presence of all relevant information. This is seldom the case in real-world design, so **utility** allows us to actually arrive at an objectively good solution utilizing the decision-maker's preference to drive the creation of an objective function (e.g. to maximize or minimize an attribute) that can be used to benchmark a large set of design options. The formal definitions as they appear in (Ross, 2003) are presented here:

Value: A preference measure that captures the ordered ranking of bundles over all outcomes.

Utility: A dimensionless parameter that reflects the 'perceived value under uncertainty' of an attribute. Often used in economic analysis, utility is the intangible personal goal that each individual strives to increase through the allocation of resources.

Utility exists on a cardinal scale and has no absolute zero, only relative zero. This can be very powerful in that utility values "have meaning relative to another since they consider both weighting due to the attribute and to continuous uncertainty" (Ross, 2003). Put more succinctly, by using a framework that includes utility, user preference may be included in a system model.

4.2   MATE Framework

The MATE framework is rather complicated and has many steps. So, in order to facilitate understanding, the explanation contained herein will begin at a high level and then progress to a more detailed explanation of each component.

At the highest level, MATE has 3 phases: need identification, architecture solution exploration, and architecture evaluation. Need identification occurs when a problem is formalized and put on the table for action and analysis. Architecture solution exploration and architecture evaluation are accomplished using models and simulations to transform a large set of design vectors to attributes and then evaluating each set of attributes in utility-cost space (Ross, 2003). Application of this framework results in a distinct set of design vectors whose overall utility and cost may be plotted for comparison to look for a Pareto curve from which to conduct further analysis and, ultimately, design iteration. This is shown graphically in Figure 6, which has been adapted from (Nickel, 2010).

$(X_1, X_2, \ldots, X_n)$
Attributes

Technical and cost models based on design variables yield attribute value

Utility is a function of attribute values and is created based on decision-maker interviews

Parametric Modeling

Multi-Attribute Utility Theory

$(DV_1, DV_2, \ldots, DV_n)$
Design Variables

Tradespace Exploration

$U(X)$
$E(X)$
Utility
Expense

Pareto Frontier

1

Utility U(X)

Each point represents a complete system design

0

0   Expense E(X)   1

Figure 6: MATE Process

4.2.1   MATE Steps

Now, with the broad concept in mind, each step may be presented in more detail. This set of steps is derived from the original work done by Ross (2003). However, for the purposes of this analysis, in order to show that MATE can be used to generate a first-order solution for enhanced tradespace awareness, the steps of classical MATE have been combined and reduced in number. This adaptation is appropriate, as Adam Ross (2003) points out, "MATE is more a way of thinking than an explicit set of steps to follow." The application of these steps is shown in the next chapter.

4.2.1.1   Identify Need

As might be expected, the process begins with the identification of a need. This step defines overarching continuum in which the system will operate or the objective it will seek to satisfy.

4.2.1.2   Define Mission

Next, the mission of the system is broadly defined, e.g. satellite communications for operational CubeSats. Typically, this mission will have complex value trade-offs and no clear answer, hence the need for MATE.

4.2.1.3   Define Scope

Following need identification and mission definition, it is necessary to define the scope of the mission itself. In other words, how far-reaching will the analysis be? Scope should be large enough to not limit the solution space, but no so large as to overwhelm the analyst and decision maker.

4.2.1.4   Identify Decision Makers

This is a key step in the MATE process, and should be carefully considered by the analyst. The decision maker will ultimately play a key role in that their input will drive the determination of utility. So, a careful stakeholder analysis should be performed, from which the decision makers (those empowered to make decisions, either through control of funds or other sources of power). Decision makers can be differentiated from stakeholders in that stakeholders, though they might care about a system's attributes, will likely not have much power to affect change.

4.2.1.5   Identify Constraints

Once the decision makers are identified, it is important to formalize the constraints on the system as well as the analysis itself. Constraints further define the space in which a model may be valid and in which a solution may be possible. A key strength of MATE is the ability to quickly analyze all feasible design choices and present them in an ordered way. By doing so, this framework helps to prevent

cognitive bias on the part of the decision maker from adversely affecting the final system solution. As such, care should be taken not to over-constrain the model so as not to negate this strength.

4.2.1.6   Work with Decision Makers to Define Attributes

In Multi-Attribute Utility Analysis (MAUA), the "…attribute is a decision maker-perceived metric that measures how well a decision maker-defined objective is met" (Ross, 2003). For example, we could say that an attribute of a communication system is data rate. For later notation, this will be defined as a set of decision maker derived attributes, **X**, consisting of several single attributes, X_1, X_2, X_3, … According to Keeney and Raiffa (1976), who developed MAUA as the multi-attribute expansion to Von Neumann and Morganstern's (1944) single-attribute utility theory, each attribute must have a decision maker defined definition, units, range, and a direction of increasing value. Further, according to Keeney and Raiffa (1976), a set of attributes must be complete, operational, decomposable, non-redundant, minimal, and perceived independent. Finally, research has shown that the typical human mind can only keep track of 7 ± 2 items at any given time (Miller, 1956). As such, in order to obtain a meaningful result, the number of attributes under consideration should be less than or equal to 7 ± 2.

4.2.1.7   Generate System Concepts

In this step, the analyst works with the decision makers and other stakeholders to create a set of system concepts. By this, we mean a set of example systems that will be used in the initial development of the tradespace. They will also be helpful in framing the problem so that the decision maker can reasonably assess his/her preferences when creating utility functions.

4.2.1.8   Define Utility Functions

The next step in MATE is to work with the decision maker to define a utility function for each attribute in order to capture how much utility that decision maker finds for each attribute across a range of values. This is a function whose value is, strictly for convenience, from 0 to 1 based on decision maker preference such that a utility function value of 0 represents the least acceptable value for a system

attribute and a value of 1 represents the most acceptable value. To be clear, a utility function value of 0 is still valuable. It is just derived from an attribute at a value below which the decision maker perceives no utility whatsoever. Adopting the notation from Keeney and Raiffa (1976), an attribute at its minimum value will be represented as X^o with its associated utility function $U(X^o) = 0$ and an attribute at its maximum value will be represented as X^* with its associated utility function $U(X^*) = 1$.

4.2.1.8.1 Capturing Decision Maker Preference

The use of a utility function is predicated on the idea that decision maker preferences can be captured and transformed into utility functions, which can then be plotted on a graph. The reality is, that capturing true decision maker preference is a non-trivial problem. This is due to the fact that decision makers are humans who, despite their best efforts at analytical thinking, are subject to a considerable number of cognitive biases.

Von Neumann and Morganstern, who developed single attribute utility theory, describe a method for capturing decision maker preference over a single attribute in Theory of Games and Economic Behavior (Von Neumann & Morgenstern, 1944). They made the problem tractable by utilizing some simple assumptions, shown here informally as presented in (Ross, 2003).

1. *The decision maker knows what he/she likes (existence of preference and indifference)*

2. *The decision maker is transitive in his/her preferences. (If A is preferred to B and B is preferred to C, then A is preferred to C.) (Transitivity property)*

3. *If the decision maker is equally happy with either of two sure outcomes, then he/she is also willing to substitute one for the other in a lottery. (Substitution property)*

4. *The decision maker will always accept a lottery between the best and worst outcome in preference to a sure intermediate outcome, provided the probabilities are adjusted properly. (Archimedean property)*

Once single attribute utility is known, these attributes can be combined into multi-attribute utility functions by making the assumptions of preferential independence and utility independence.

Preferential independence - The preference of a decision maker for an attribute at one level over the same attribute at a different level is independent of the level of any other attribute.

Utility independence - The shape of the utility function of a single attribute is the same up to a positive linear transformation, independent of any other attribute.

With these two assumptions in place, the multiplicative form of the multi-attribute utility function can be used. It is presented here as shown in (Keeney & Raiffa, 1976) to maintain consistent notation.

The Multiplicative Utility Function

$$u(x) = \sum_{i=1}^{n} k_i u_i(x_i) + k \sum_{\substack{i=1 \\ j>i}}^{n} k_i k_j u_i(x_i) u_j(x_j) +$$

$$k^2 \sum_{\substack{i=1 \\ j>i \\ \ell>j}}^{n} k_i k_j k_\ell u_i(x_i) u_j(x_j) u_\ell(x_\ell)$$

$$+ \cdots + k^{n-1} k_1 k_2 \dots k_n u_1(x_1) u_2(x_2) \dots u_n(x_n)$$

where

1. *u is normalized by* $u(x_1^o, x_2^o, \dots, x_n^o) = 0$ *and* $u(x_1^*, x_2^*, \dots, x_n^*) = 1$.

2. u_i *is a conditional utility function of* X_i *normalized by* $u_i(x_i^o) = 0$ *and* $u_i(x_i^*) = 1$, i = 1, 2, …, n.

3. $k_i = u(x_i^*, \bar{x}_i^o)$.

4. k *is a scaling constant that is a solution to*

$$1 + k = \prod_{i=1}^{n} (1 + k k_i)$$

This is an immensely powerful result, which Keeney and Raiffa show holds across a wide range of conditions. However, even they note that its application can be exceedingly complex. So, for the purposes of this work, we will make use of another simplifying assumption in creating the multi-attribute utility function, additive independence.

> ***Additive Independence -*** *Attributes X_1, X_2, ..., X_n are additive independent if preferences over lotteries on X_1, X_2, ..., X_n depend only on their marginal probability distributions and not on their joint probability distribution* (Keeney & Raiffa, 1976).

This assumption, while considerably more restrictive, allows the use of the additive form of the multi-attribute utility function, the application of which is significantly less difficult. It is presented here as shown in (Keeney & Raiffa, 1976).

> ***The n-attribute additive utility function***

$$u(x) = \sum_{i=1}^{n} u(x_i, \overline{x}_i^o) = \sum_{i=1}^{n} k_i u_i(x_i)$$

is appropriate if and only if the additive independence condition holds among attributes X_1, X_2, ..., X_n, where:

1. u *is normalized by* $u(x_1^o, x_2^o, \ldots, x_n^o) = 0$ *and* $u(x_1^*, x_2^*, \ldots, x_n^*) = 1$.

2. u_i *is a conditional utility function of* X_i *normalized* by $u_i(x_i^o) = 0$ and $u_i(x_i^*) = 1$, i = 1, 2, ..., n.

3. $k_i = u(x_i^*, \overline{x}_i^o)$, i = 1, 2, ..., n.

Scaling the Utility Function

Finally, special mention should be made to scaling the single-attribute utility functions for inclusion in the multi-attribute utility function. Denoted k_i, the scaling constant is found by assessing the overall utility of a single attribute at its most acceptable value while holding the other attributes fixed at their least acceptable value.

4.2.1.9   Define Design Variables and Their Ranges

Once the attributes have been agreed upon, a set of design variables needs to be created, with appropriate ranges, over which to conduct the analysis. These design variables constitute the tradespace to be explored. Single design variables are denoted DV_1, DV_2, …, DV_n and a group of design variables which compose a unique, complete design are termed a design vector. It should be carefully noted that attributes and design variables are not the same thing. For example, an attribute might be system data rate, whereas a design variable that affects that attribute might be transmit power, modulation scheme or some other independent parameter. Further, there will be many more design variables than attributes in the system.

> *Design Variable* – *"A designer-controlled quantitative parameter that reflects an aspect of a concept. Typically these variables represent physical aspects of a design, such as orbital parameters, or power subsystem type. Design variables are those parameters that will be explicitly traded in analysis"* (Ross, 2003).

> *Design vector* – *"A set of design variables that taken together uniquely define a design or architecture. The vector provides a concise representation of a single architecture, or design. Spans the tradespace when enumerated"* (Ross, 2003).

4.2.1.10   Map Design Variables to Attributes

Now that design variables and attributes have been created, the contribution of the design variables must be mapped to the attributes. This allows the analyst, various stakeholders, and decision makers to better understand which design variables will have an effect on various system attributes.

4.2.1.11   Model the System

With the elements of the system fully documented, it is now appropriate to model the system in software. This will include technical and cost models to translate design vectors into attribute values and

multi-attribute utility function models to translate those attribute values into utility values. Each design vector will then be plotted in utility cost space.

It should be noted that the technical and cost models could be tremendously complex, potentially representing entire spacecraft or entire transportation systems. So, it is up to the analyst to determine the amount of software development effort that is appropriate for a given problem.

4.2.1.12 Simulate the System

Once the system model is in place, the simulation should be exercised. This is included as a separate step due to the large size of the tradespace which will likely result from the previous steps. It is possible that the simulation could be computationally intensive, thus taking many days to yield a solution. If this is the case, it is up to the analyst to either pare down the set of design variables to reduce run time or re-engage with the decision makers to re-define the scope of the problem to something more manageable in the time allotted.

4.2.1.13 Analyze the Output

In this step, the analyst should engage with the decision makers and begin to iterate. At least to first order, the design vectors that compose the Pareto frontier in the utility-cost tradespace are a reasonable place to start. By examining the tradespace and searching for sensitivities it may be possible to, at the very least, better understand the interactions present in the system (value trade-offs), and at best select a design for further consideration which could maximize decision-maker utility.

4.2.1.14 Next Steps

Hopefully, at the completion of the MATE process, a candidate design will have been selected. The next step is to proceed to detailed design and then build a working system. This is covered through several design methodologies, which are beyond the scope of this analysis.

4.3   Tradespace Exploration

Tradespace exploration is the process of enumerating and analyzing a large set of design variables on the part of the designer to help understand and select the best possible design for a given problem. There are many well-established methodologies in place to accomplish this task, such as Generalized Information Network Analysis (GINA) (Shaw, Miller, & Hastings, March-April 2001) or parametric tradespace analysis. However, while these methods have their place, they are inherently limited and do not allow for the inclusion of decision maker preference under uncertainty. They require the assumption that all information is known and thus seek to maximize to an objective function without a clear upper bound.

Conversely, MAUA, the other element of MATE, does not completely explore the design space available to solve a given problem. The inclusion of tradespace exploration is what enhances MATE beyond traditional MAUA. By including this additional step, the creators of MATE link the relatively abstract ideas of utility functions and attributes to practical engineering design while providing an upper bound to which the design team can work. As such, MATE is a useful tool to maximize overall utility to decision makers as well as overall value to all stakeholders.

5   Application of MATE to the CubeSat Communication Problem

It is easy to imagine a situation in which there is little money for trade studies, but a group of decision makers would like to make a more informed decision. In the author's experience this situation is distressingly common and is the cause of considerable consternation on the part of many decision makers. We make the assertion that MATE could be used in a first iteration sense to guide decision-making under real-world time pressure to problems which are more tactical than those typically thought about in the MATE framework. In order to show empirically that such an application is possible and useful, a streamlined version of the MATE analysis process, outlined in Chapter 4, has been applied to the problem of selecting a CubeSat communication system. That application is detailed in this chapter.

5.1   Identify Need

CubeSats have been used effectively as teaching tools and scientific research platforms for more than a decade. As the technology has progressed and these small satellites have become more capable assets, the time is rapidly approaching when they will be used as operational assets. However, in order to make the leap into the operational asset domain, which demands reliability, robustness, and responsiveness, an effective communications system must be selected.

To this point, CubeSat communication has been inherently limited by its reliance on ground based network topologies. Further, in the age of reduced budgets, an increased number of component suppliers, and multiple competing stakeholders, selection of the right communication system can be a daunting task with no clear ideal outcome. So, this seems an ideal candidate for the application of MATE.

5.2   Define Mission

For the purposes of this analysis, the mission will be generally defined as any operational CubeSat in Low Earth Orbit. Various scenarios can easily be imagined, but they all have a common need for reliable, robust, and responsive communication.

5.3   Define Scope

Scope will be limited to the selection of a communication system for an operational CubeSat. Further, the stressing part of the communication system, at least from a technical perspective, is that of downlink. Since this is the limiting case, the assumption will be made that if reliable downlink is possible, then uplink will be possible. Whereas downlink typically includes large volumes of mission data, uplink is relatively more limited to transmitting commands for the spacecraft to execute. So the scope will be further limited to data downlink.

5.4   Identify Decision Makers

Were this model to be exercised in a real world scenario, the decision makers would likely be a program manager, spectrum management official, and/or chief engineer. Note that there is a distinction here between stakeholder and decision maker, as described in the previous chapter. There are surely more stakeholders involved than decision maker, but at least at this early stage in the streamlined process, consideration will be limited to the decision makers.

This is a key point in the traditional MATE process, just as it is in this abbreviated process. However, owing to various limitations and the desire to show the usefulness of this process in an abbreviated context, no outside decision makers were used.

5.5 Identify Constraints & Assumptions

First, we must identify the constraints and assumptions for the system and the analysis. This step is used to make the problem tractable. Table 7 shows the results of this step from the application to CubeSat communication system selection.

Table 7: System and System Model Constraints and Assumptions

ID	Constraint/Assumption
1	Assume a 3-axis stable, pointable cubesat (pointing error < 0.25°) *Note: A real system would require a reaction wheel assembly or similar advanced attitude control technology to obtain the best possible pointing accuracy. This high level of accuracy is required in the case of long-distance transmission with high gain antenna, as used in the GEO network topology.*
2	Hardware and capabilities must coincide with CubeSat specifications
3	Data collection (mission ops) is unaffected by satellite orientation *Note: No claims are made about how this might be possible*
4	The CubeSat is operating in Low Earth Orbit
5	The transmitter operates at only one transmit rate
6	The transmitter operates at its max rate (assuming a cutoff link margin) while connected
7	The transmitter is limited to single channel communication
8	Transmit path latency is always negligible
9	Transmit line loss is negligible
10	Total pointing loss is no more than 0.5dB *Note: 0.5dB loss results from a pointing error of ~20% of the 3dB beam-width*
11	The Spacecraft is capable of instantaneous reorientation
12	No bandwidth limitation exists
13	Transmission is allowed on any frequency
14	All data collected must be downlinked
15	Telemetry is included in "collected data"
16	Network topologies may not be combined

5.6 Define Attributes

With the need identified and the problem appropriately scoped, though hopefully not over-constrained, the next step is to define the system attributes. They are each listed along with an explanation in this section. Per the previous chapter, only 7 attributes have been chosen so as not to overwhelm the decision maker.

X_1 Data Throughput

Data throughput is the amount of data that, assuming continuous downlink, could be collected and sent to the ground without loss. It is also the average data rate with which the system can communicate with the ground.

X_2 Transmit Power

Transmit power is the amount of power the communication system uses to transmit data. This attribute is important, as it is an indication of how much power the communications system will draw from the limited supply onboard the CubeSat.

$X_{3,4}$ Regulatory Difficulty (RD)

Regulatory difficulty, or the difficulty of the process of working with the ITU and/or FCC, is captured here. In order to maintain the additive independence condition, this has been separated into two categories, topology and bandwidth.

X_3 RD – Topology

Here, the regulatory difficulty associated with a given topology is considered. In general it is assumed that it is more difficult to obtain regulatory approval for a ground-based topology than a space-based topology.

X₄ RD – Bandwidth

A second component of regulatory difficulty is that of bandwidth allocation. In general, the amount of bandwidth requested is directly proportional to the difficulty one might have obtaining regulatory approval for that bandwidth.

X₅ Onboard Storage Required

This attribute accounts for the possibility that data must be collected and then stored prior to contact with a receiver station.

X₆ Data Latency

Data latency refers to how long a particular bit of data must wait before being sent to a user. Latency is calculated as an average using Little's Law (Little, 2011) as stated below.

$$L = \lambda W$$

where:

L = Average number of items in a queuing system (data stored in bits)

λ = Average arrival rate of items into the system (collection rate in kbps)

W = Average waiting time of an item (latency in seconds)

X₇ Access Percent

Access percent refers to the percent of time that the CubeSat is in contact with a control station. A decision maker might care about this attribute because it is a measure of how well he/she can actively monitor and command the spacecraft.

5.7 Generate System Concepts

Various system concepts can be imagined, but only a few are listed here as a starting point for the creation of design variables later in the analysis.

Concept 1 - The first concept under consideration might be a baseline of what is done today. That is to say, a low power, low data rate transmitter onboard a CubeSat that communicates to a single

Continental United States (CONUS) ground based control station. This has the advantages of simplicity and ample design heritage information. It is also a good way to benchmark the analysis to be done.

Concept 2 - Next a slightly more outside of the box solution might be considered. For instance, a system with increased power and increased data rate could be considered that remains well within the limits of reason. This might be a mid-level power, medium data rate CubeSat to communicate to a network of equatorial ground stations.
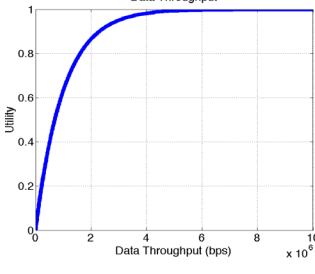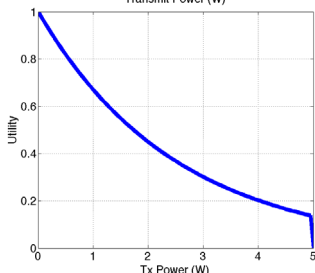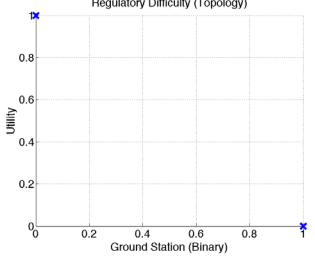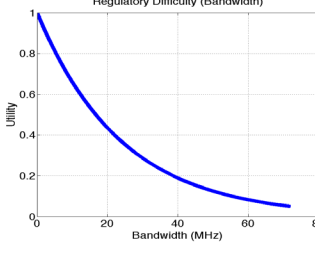
Concept 3 - Finally, a concept that is considered way outside the box should be considered to determine how well it might perform, despite any cognitive bias that might prevent its incarnation. This could be a CubeSat with a high-power, high data rate experimental transmitter that communicates to a GEO based satellite.

Ultimately, the creation of these concepts comes down to picking high, middle, and low values of each variable that might matter as well as brainstorming possible network topologies that could be utilized. This step need not be exhaustive as its purpose is to create a starting point.

5.8   Define Utility Functions

For the purposes of this exercise, generic risk-averse or risk-neutral utility functions of various forms have been chosen. In order to further explore the utility cost tradespace, the functions chosen could have also been created using risk-seeking equations, but that is left for future work. The exact functions chosen as well as the least and most acceptable values of each attribute are shown in Table 8. A logical next step would be to engage the decision maker in structured utility interviews. Utility functions could then be generated by curve fitting to the captured data so as to accurately reflect the decision maker's true preference space. However, for the purposes of enumerating the tradespace and achieving a first order solution that could then be used to motivate informed discussion amongst decision makers, these functions will suffice.

Table 8: Attribute to Utility Mapping

Attributes X	Least Acceptable Attribute Value X_i^o $Utility = 0$	Most Acceptable Attribute Value X_i^* $Utility = 1$	Utility Equations	Plot of Utility for All Attribute Values
X_1 - Data Throughput (Mbps)	$X_1^o = 0\ Mbps$	$X_1^* = 1\ Mbps$	$U(X_1) = 1 - e^{\frac{(-4)X_1}{X_1^*}}$	
X_2 – Transmit Power (W)	$X_2^o = 5\ Watts$	$X_2^* = 0\ Watts$	$U(X_2) = e^{\frac{(-2)X_2}{X_2^o}}$	
X_3 – Regulatory Difficulty – Topology (Binary)$^+$	$X_3^o = 1$	$X_3^* = 0$	$U(X_3) = 1 - X_3$	
X_4 – Regulatory Difficulty – Bandwidth (MHz)	$X_4^o = 72\ MHz$	$X_4^* = 0\ MHz$	$U(X_4) = e^{\frac{(-3)X_4}{X_4^o}}$	

Attributes X	Least Acceptable Attribute Value X_i^o $Utility = 0$	Most Acceptable Attribute Value X_i^* $Utility = 1$	Utility Equations	Plot of Utility for All Attribute Values
X_5 – Onboard Storage Required (Giga-Bytes)[#]	$X_5^o = 4\ GB$	$X_5^* = 0\ GB$	$U(X_5)$ $= \begin{cases} 1, X_5 < 2 \\ e^{\frac{(-3)X_5 - 2}{X_5^o}}, X_5 \geq 2 \end{cases}$	
X_6 – Data Latency (seconds)	$X_6^o = 604800\ s$	$X_6^* = 0\ s$	$U(X_6) = e^{\frac{(-2.5)X_6}{X_6^o}}$	
X_7 – Access Percent (%)	$X_7^o = 0\%$	$X_7^* = 100\%$	$U(X_7) = \dfrac{X_7}{100}$	

[+] X_3 is a binary attribute such that $X_3 = 1$ indicates a topology with a ground station.
[#] In the case of X_5, please note that constant maximum utility results from attribute values between 0 and 2 GB.

5.8.1.1.1 Assessing the Multi-Attribute Utility Function

For the purposes of this analysis, again adopting the notation from (Keeney & Raiffa, 1976), the additive form of the multi-attribute utility function, $\mathbf{u}(\mathbf{x}) = \sum_{i=1}^{n} \mathbf{u}(\mathbf{x_i}, \bar{\mathbf{x}}_i^o) = \sum_{i=1}^{n} \mathbf{k_i u_i}(\mathbf{x_i})$, will be used. While the required assumptions of preferential, utility, and additive independence are rather restrictive, the implementation of this form is less complex than the multiplicative form and thus may be implemented in a more expedient manner. Also, the single attribute utility functions which comprise the additive multi-attribute utility function have been equally weighted such that $k_i = 1/7\ \forall\ i$. As the goal of this analysis is to obtain a first-order solution, this seems a reasonable course of action.

5.9   Define Design Variables and Their Ranges

With the utility functions defined, design variables must be chosen to fill out the tradespace. The design variables chosen here are those that are most important in the selection of a CubeSat communication system. However, this is by no means an exhaustive listing. Each design variable, along with its range and rationale, is presented in Table 9.

Table 9: Design Variables for Simulation

Design Variable	Value	Rationale
CubeSat Orbit	Inclination: 45°, Altitude: 400 km	Typical CubeSat Orbit
Transmit Power	0.5W, 1W, 2W	These 3 levels chosen to represent a typical power level, a high power level, and an extremely high power level beyond current regulatory allowance.
Transmit Antenna Gain	1dB, 5dB, 10dB	These 3 levels chosen to represent an omni-directional antenna, a relatively achievable antenna, and a high gain antenna, respectively.
Transmit Frequency	2.4GHz, 14.5GHz, 24GHz, 60GHz	S, K_u, K_a, and V-Bands were chosen to give a broad range of frequencies.
Receive Antenna Size (Assume Parabolic)	Space Based: 0.25m, 1m, 2m, 5m Ground Based: 2m, 5m, 18m	Chose parabolic for simplicity. Could use many different types of antennas. Sizes represent a spectrum from reasonably attainable to rarely attainable for each topology.
Transmit Data Rate	100kbps, 250kbps, 500kbps, 1Mbps	A wide range of transmit rates were chosen which might be high enough to support an operational mission.
System Noise Temperature	340K	System noise temperature was held constant due to the need to limit the number of design variables.
Modulation	See Table 10 – Index 1, 7, 13, 16, 19, 23	Modulation parameters were chosen to present a large range of spectral efficiencies, code rates, and E_b/N_0 cutoff margins. No particular modulation or standard is endorsed here, but DVB-S2 has been chosen for simplicity, as it is well known.
Network Topology	See Table 11 – All Listed	10 different topologies have been selected, as this design variable will likely have the greatest effect on the system.

Table 10: DVB-S2 Standard & Simulation Index

Modulation	Bits/Symbol	Code Rate	Spectral Efficiency	E_b/N_0	Sim Index
QPSK	2	1/4	0.49	0.75	1
QPSK	2	1/3	0.66	0.59	2
QPSK	2	2/5	0.79	0.73	3
QPSK	2	1/2	0.99	1.05	4
QPSK	2	3/5	1.19	1.48	5
QPSK	2	2/3	1.32	1.89	6
QPSK	2	3/4	1.49	2.31	7
QPSK	2	4/5	1.59	2.67	8
QPSK	2	5/6	1.65	2.99	9
QPSK	2	8/9	1.77	3.73	10
QPSK	2	9/10	1.79	3.89	11
8PSK	3	3/5	1.80	3.00	12
8PSK	3	2/3	2.00	3.65	13
8PSK	3	3/4	2.20	4.43	14
8PSK	3	5/6	2.50	5.41	15
8PSK	3	8/9	2.60	6.46	16
8PSK	3	9/10	2.70	6.70	17
16APSK	4	2/3	2.60	4.76	18
16APSK	4	3/4	3.00	5.49	19
16APSK	4	4/5	3.20	6.03	20
16APSK	4	5/6	3.30	6.42	21
16APSK	4	8/9	3.50	7.42	22
16APSK	4	9/10	3.60	7.61	23

*Table derived from (Wertz, Everett, & Puschell, 2011)

Table 11: List of Communication Network Topologies for MATE Simulation

Simulation Index	Network Topology Orbit Type*	Network Topology Description
1	Ground	Equatorial, 3 Ground Stations
2	Ground	Continental United States, 2 Ground Stations (Bi-Coastal)
3	Ground	Continental United States, 1 Ground Station (East Coast)
4	Geostationary Earth Orbit	3 Equally Spaced Satellites
5	Geostationary Earth Orbit	1 Satellite
6	Highly-Elliptical Earth Orbit (24 Hour Tundra Orbit)	2 Equally Spaced Satellites
7	Highly-Elliptical Earth Orbit (24 Hour Tundra Orbit)	3 Equally Spaced Satellites
8	Highly-Elliptical Earth Orbit (12 Hour Molniya Orbit)	1 Satellite
9	Highly-Elliptical Earth Orbit (12 Hour Molniya Orbit)	2 Equally Spaced Satellites
10	Low Earth Orbit	16 Satellites, 4 plane Walker constellation with evenly distributed node separation

*Generic depictions of each topology are shown in Figure 5. Each network topology is shown in detail in Appendix A.

5.10 Map Design Variables to Attributes

In this step, design variables are mapped to attributes in order to enhance awareness of the tradespace. The mapping for this application is shown in Figure 7, below. It should be noted that the design variables for transmit power and regulatory difficulty based on topology map directly to their attributes. The remaining attributes are affected by almost all of the design variables. Given this complexity, the application of MATE will be highly beneficial to the effective analysis of the tradespace under consideration.

Design Variables	Data Throughput	Transmit Power	Regulatory Difficulty (Topology)	Regulatory Difficulty (Bandwidth)	Onboard Storage Required	Data Latency	Access Percent
CubeSat Orbit	x				x	x	x
Tx Power	x	x		x	x	x	x
Tx Gain	x			x	x	x	x
Tx Frequency	x			x	x	x	x
Rx Gain	x			x	x	x	x
Rx Efficiency	x			x	x	x	x
Tx Data Rate	x			x	x	x	x
System Noise Temp	x			x	x	x	x
Modulation	x			x	x	x	x
Network Topology	x		x		x	x	x

Figure 7: Map of Design Variables to Attributes

5.10.1 Cost Functions

While on the subject of mapping design variables to attributes, it is important discuss mapping design variables to cost. Here, the cost functions that have been chosen to obtain a lifecycle cost for each design vector will be presented. All of the costs presented herein are notional only. It should be stressed that the cost functions chosen are intended for use in proving out the model and providing for a first order exploration of the tradespace. As such, their values need only be correct to a rough order of magnitude. In a more detailed application, cost for each component in the design should be rigorously captured and cataloged by the analyst.

For this application, the cost has been divided into three categories: 1) the communication system onboard the CubeSat itself, 2) the cost associated with a receiver station, and 3) the cost associated with regulatory approval. Each is discussed in greater detail below.

5.10.1.1 CubeSat Onboard Communication System Cost

The cost of the onboard system is based on transmit power and transmit antenna gain, both of which are input directly as design variables. In reality, there are many more costs associated with the spacecraft transceiver and antenna, but this will suffice for our purposes. In a later iteration, a comprehensive design simulation might be done, such that individual resistors and capacitors may be chosen. However, that is left for future work. The cost functions used in this model are shown below.

$$Cost \; of \; Transmit \; Power = \left(e^{10^{\frac{Tx \; Power}{10}}} \right) * 10,000$$

$$Cost \; of \; Transmit \; Antenna \; Gain = \left(e^{2^{\frac{Tx \; Gain}{10} - 1}} \right) * 5,000$$

5.10.1.2 Receiver Station Cost

The receiver station cost function has been piecewise defined to accommodate the two network topology types used by the model: ground-based and space-based. In the ground-based receiver case, the assumption is made that there is a one-time cost of building the station. After the station has been built, it

can be used to its maximum technical capability for no additional cost. The one time cost of building the

station has been directly related to the size of the receive antenna, as shown below.

$$Ground\ Based\ Receiver\ Station\ Cost = Number\ of\ Stations * \left(e^{\frac{Receiver\ Antenna\ Diameter}{4}}\right) * 100,000$$

In the other case, that of a space-based receiver station, no fixed cost is assumed whatsoever.

Instead, only variable cost of the data ($0.01/kbit) will be considered. So, the more data the system sends,

the greater the lifecycle cost it will have to endure.

$$Space\ Based\ Receiver\ Station\ Cost = Data\ Rate * Access\ Time * \$0.01$$

5.10.1.3 Regulatory Approval Cost

Finally, the cost of regulatory approval is considered. There are many factors that play into this

cost, some political, some technical, many of them hard to predict. However, for the purposes of this

analysis, regulatory approval will be related directly to the amount of bandwidth required by the system

as shown below.

$$Regulatory\ Approval\ Cost = \left(e^{\frac{Bandwidth}{36MHz}}\right) * 100,000$$

5.11 Model the System

Using the appropriate mappings and the equations behind them, the system is modeled using a

combination of Analytical Graphics Inc., Satellite Toolkit (STK) and MATLAB.

5.11.1 Model Various Network Topologies

Each network topology is rigorously modeled in STK. These models are presented in Appendix A.

5.11.2 Calculate Line of Sight (LOS) Access

A combination of MATLAB and STK are used to calculate the raw line of sight access to each

station from the CubeSat under consideration. This data is then saved for later use.

5.11.3 Input Design Vectors

At this point, the design vectors are input as shown previously in Table 9: Design Variables for Simulation. Each design vector is created from a combination of the design variables and the design space is completely enumerated. In other words, every combination of design variables is simulated, which results in a large tradespace.

5.11.4 Calculate Link Budget

With the various parameters now in place, a critical part of the analysis may be conducted. For every LOS access time a link budget calculation is performed. A notional link budget is shown in Table 12 for reference.

Table 12: Notional Simplified CubeSat Link Budget

	Units	Worst Case	Best Case
EIRP:			
Transmitter Power	dBW	-3.00	0.00
Transmitter Line Loss	dB	0.00	0.00
Transmit Antenna Gain (net)	dBi	1.00	1.00
Equiv. Isotropic Radiated Power	dBW	-2.00	1.00
Receive Antenna Gain:			
Frequency	Ghz	2.500	2.500
Receive Antenna Diameter	m	0.75	18.30
Receive Antenna efficiency	%	50%	50%
Receive Antenna Gain	dBi	22.86	50.61
Free Space Loss:			
Propagation Path Length	km	2,380.00	427.27
Free Space Loss	dB	-167.94	-153.02
Transmission Path and Pointing Losses:			
Combined Antenna Pointing Loss	dB	-0.50	0.00
Ionospheric Loss	dB	-1.00	0.00
Atmospheric Loss (H_2O and O_2 losses)	dB	-0.34	0.00
Loss due to Rain	dB	0.00	0.00
Demodulator Loss	dB	-0.15	0.00
Splitter Loss	dB	0.00	0.00
Implementation Loss	dB	-0.50	0.00
Total Additional Losses	dB	-2.49	0.00
Data Rate:			
Data Rate	bps	500,000.00	250,000.00
Data Rate	dBbps	56.99	53.98
Boltzman's Constant:			
Boltzman's Constant	dBW/(Hz*K)	-228.60	-228.60
System Noise Temperature:			
System Noise Temperature	K	340.00	340.00
System Noise Temperature	dBK	25.31	25.31
E_b/N_o	dB	-3.28	47.89
E_b/N_o required	dB	9.60	9.60
Margin	dB	**-12.88**	**38.29**

The simulation includes all of the parameters shown in that link budget as well as a specific module written to perform atmospheric attenuation as detailed in <u>Radiowave Propagation in Satellite Communications</u> (Ippolito, 1986). As link budget analysis is a well-characterized field, it is not presented in detail here, though it is implemented within the MATE simulation. A thorough discussion of the link budget calculation methodology used can be found in <u>SME-SMAD</u> (Wertz, Everett, & Puschell, 2011) and <u>Satellite Communications Systems</u> (Maral & Bousquet, 2009).

An important result of the link budget analysis is the bit energy to noise ratio (E_b/N_0) of the communication signal. Based on the modulation scheme chosen to encode digital data onto the analog signal for transmission and forward error correction, varying levels of E_b/N_0 are required to ensure reliable communication. Conditions where E_b/N_0 required is less than E_b/N_0 actual are referred to as positive margin links and may be used for communication. This is also referred to as link closure. Referring back to Table 12, a situation in which the link closes, referred to as "Best Case," as well as a situation in which the link budget does not close, referred to as "Worst Case," are included for reference.

5.11.5 Sort Access and Choose Connection Based on Highest Link Margin

Now that the E_b/N_0 required for link closure is known as well as the E_b/N_0 that can be expected by the system to every station under consideration for all line of sight access times, the highest margin link is chosen over which to perform communication at any given time. This is important, as there may be scenarios where a link is possible to more than one receiver station at a time.

5.11.6 Iteratively Determine Data Throughput, Storage Volume, and Latency

Once the time and data rate for communication have been determined for a given design vector, a simulation of the link is performed in order to determine the actual rate at which the communication system can support the collection of mission data without loss. To be clear, this is the average rate at which data can be downlinked by the system throughout its lifetime. This simulation also yields the required storage volume and the access percent of the system. Finally, Little's Law (Little, 2011) is

applied using collection rate and storage volume to determine the latency of collected data downlinked to a receiver station.

5.11.7 Calculate System Cost

This step is accomplished by finding the total value of the cost functions for each design vector using MATLAB.

5.11.8 Calculate Additive Utility Based on System Attributes

Additive utility is calculated by assessment of the utility functions for each design vectors attribute level, as described in Section 5.8.

5.11.9 Plot Results in Utility-Cost Tradespace

Finally, each of the ~12,000 design vectors which have been assessed are plotted in the utility-cost tradespace. A tool has been written to enhance the ease of tradespace exploration, which allows the analyst to explore the attribute value and full design vector of each point in the tradespace by simply clicking on the design vector in which they are interested.

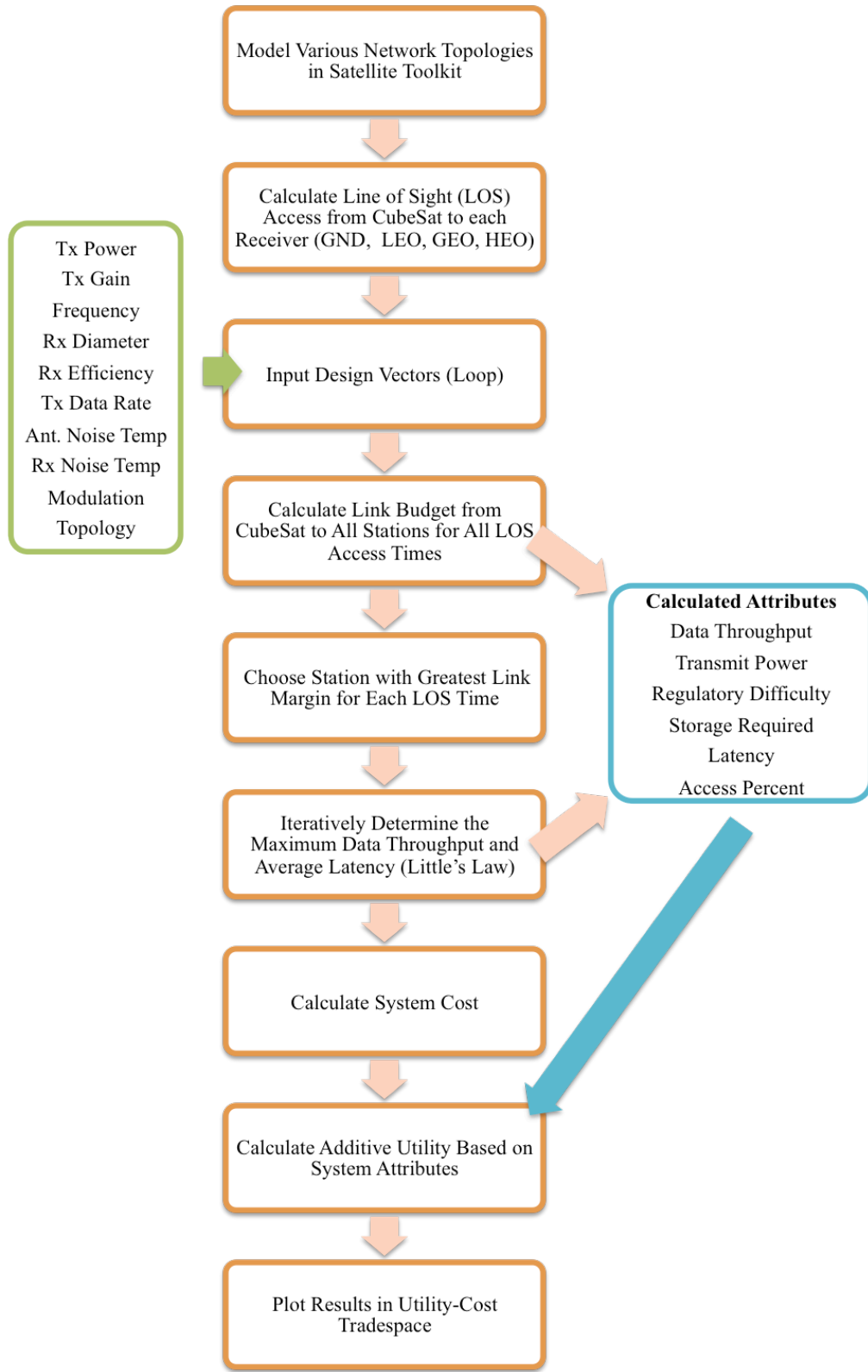**5.11.10 System Simulation Flowchart**

Figure 8: System Simulation Flowchart

5.12 Simulate the System

The simulation may be run for any number of design vectors. In this case, it was exercised with well over 12,000 unique design vectors. With this number, the simulation typically took approximately 36 hours to complete, running on a 3 GHz, quad core processor with 4GB of RAM. The output from the simulation is shown in Figure 9 on the next page. As the analyst clicks on each design vector in the utility-cost tradespace, the software displays the information shown in Table 13.

5.13 Analyze the Output

Finally, the output of the model may be analyzed to draw some first-order conclusions about the tradespace shown in Figure 9. First, taking an overall look at the utility-cost tradespace, varying network topology has the greatest effect on system utility and system cost as compared to any other single design variable. For reference, the utility-cost tradespace, separated by network topology, is shown in Appendices B and C. Second, paying attention to the Pareto frontier, it appears that, at least with the current set of assumptions, space-based network topologies (marked with a "+" sign in Figure 9) dominate ground-based network topologies (marked with an "o"). Third, of the space-based network topologies, the highly elliptical and geostationary topologies produce the highest utility. Last, noting the time scale of the analysis, space-based network topologies do not greatly exceed the cost of ground-based solutions over a 180-day lifecycle.

Utility Cost Plot

GND Equ X 3
GND CONUS X 2
GND CONUS X 1
GEO X 3
GEO X 1
Tundra X 2
Tundra X 3
Molniya X 1
Molniya X 2
LEO X 16

Topology: Tundra x 2
Cost: $458k @Ind 4174
Total Utility : 0.65786 @Ind 4174
Total Utility : 0.65786 @Ind U=0.043
Throughput : 89.73kbps U=0.12
Tx Power: 0.501W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 1.501MHz U=0.12
Storage Req: 14.7MB U=0.14
Latency: 507.44s U=0.14
Access Percent: 89.3% U=0.13

1
0.9
0.8
0.7
0.6
0.5
0.4

Utility

0   200   400   600   800   1000   1200   1400

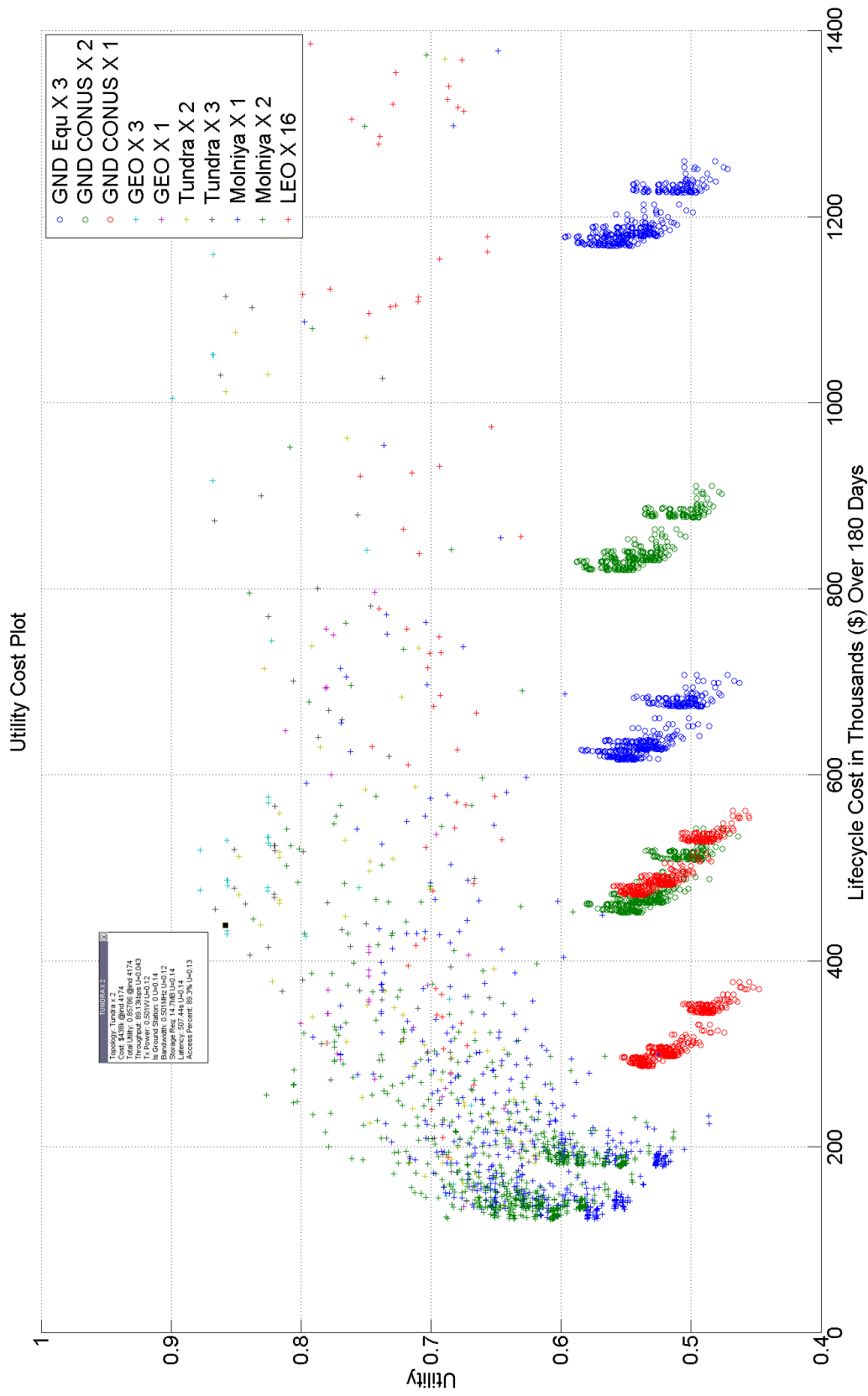Lifecycle Cost in Thousands ($) Over 180 Days

Figure 9: Utility Cost Plot - All Topologies

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Table 13: Example Simulation Output for Selected Design

Design Vector & Attributes	System Cost
Network Topology: Tundra X 2	Cost of Transmit Power: $16,506.80
CubeSat Altitude: 400km	Cost of Transmit Gain: $13,591.41
CubeSat Inclination: 45°	Cost of Data: $17,118.67
Transmit Power: -3 dBW	Cost of Bandwidth: $100,248
Transmit Power in Watts: 0.5 W	Total Life Cycle Cost for 180 days: $438,483.09
Transmitter Line Loss: 0 dB	
Transmit Antenna Gain: 10 dB	**System Utility**
Frequency: 2.4 GHz	Utility of Data Throughput: 0.0428
Receive Antenna Diameter: 5m	Utility of Transmit Power: 0.1169
Receive Antenna Efficiency: 0.4	Utility of Regulatory Difficulty (Topology): 0.1428
Tx Data Rate (Effective): 100 kbps	Utility of Regulatory Difficulty (Bandwidth): 0.1423
System Noise Temp: 340 K	Utility of Storage Required: 0.1428
Modulation: QPSK	Utility of Data Latency: 0.1425
Code Rate: ¾	Utility of Access Percent: 0.1275
Spectral Efficiency: 1.49	Total System Utility: 0.8578
E_b/N_0 required: 2.31	
Bandwidth: 0.501 MHz	
Data Throughput (Effective): 89kbps	
Access Percent: 89%	
Storage Required: 14.7 MB	
Data Latency: 507 s	

5.13.1 Tradespace Exploration

In order for a decision maker to use the results of the MATE analysis, it is necessary that he/she be able to easily explore the tradespace in order to fully understand the different design vectors in the system as well as the relationships within the tradespace. In order to enable this exploration, when the decision maker clicks on a particular design vector, a high level summary box, as shown in Figure 9, is presented to the decision maker within the tradespace itself. This box shows the design vector total cost and overall utility as well as each attribute's contribution to overall utility. Additionally, as shown in Table 13, when a design vector is selected, its detailed design variable and attributes as well as the components of overall utility and overall cost are output to the MATLAB command window. These tools

allow the decision maker to easily visualize and access pertinent information so he/she can actively explore the tradespace, increase his/her understanding of the tradespace, and ultimately make better-informed decisions.

5.13.2 The Pareto Frontier

Traditionally, analyzing MATE results begins with exploring the design vectors that exist on the Pareto frontier. We can see in Figure 9 that design vectors from the highly elliptical and geostationary orbit-based network topologies populate that frontier. In particular, the single-satellite Molniya orbit network topology yields the lowest cost Pareto efficient solution and the three-satellite geostationary orbit network topology yields the highest utility Pareto efficient solution. The remainder of the frontier is made up of design vectors from the two-satellite Molniya and three-satellite tundra obit network topologies.

Assuming a perfect model, the decision maker should logically choose one of the results on the frontier. However, in a complex system, it is not unlikely that unaccounted for variables, unanticipated interactions, or inaccurately captured utility functions could place a feasible, or even desirable, solution away from the frontier. So it is important to consider dominated solutions, those not on the Pareto frontier, as well. In the result shown above, these dominated solutions consist of the LEO, one-satellite GEO, and two-satellite tundra orbits as well as all of the ground-based network topologies. In the following analysis, we will explore this result, suggest where the greatest sensitivities can be found, and characterize the overall limitations of the model.

5.13.3 Varying Network Topology

The most obvious characteristic of the tradespace above is that varying network topology has the greatest overall effect in regards to both utility and cost. This is most easily seen when examining Figure 9 with respect to different ground station network topologies. Within this set of topologies, there is a significant cost increase associated with each additional ground station. For example, one CONUS ground station (red circle) is less costly than two CONUS ground stations of equal size (green circle) with only a

65

relatively small reduction in utility. It can also be seen in Figure 9, and in greater detail in Appendices B and C, that an increase in receiver antenna size within a particular network topology significantly increases cost while only slightly increasing utility to the decision-maker.

As the utility functions are currently defined, the model indicates that there is only a marginal benefit to the decision maker to use either multiple ground stations or larger receiver antennas. However, that result could be somewhat misleading as it is highly dependent on the preferences of the decision-maker and the assumption that the ground stations must be built from scratch. To explore this further, let us say that the decision maker placed a higher utility on overall data throughput (X_1) relative to any other attribute. In that case, adding ground stations would clearly increase the overall utility to the decision maker. Further, if a satellite program could avoid incurring the cost of building a new ground station through buying time on commercial ground stations, utilizing a cooperative network, or re-tasking/updating a legacy ground station, then the cost of using such a network topology could be drastically reduced. Overall, either of these changes to the model would move the ground-based topologies toward the Pareto frontier.

5.13.4 Space-Based vs. Ground-Based Network Topologies

Shown earlier in Figure 9, the Pareto frontier is entirely populated with space-based topologies. This is due to a greater utility contribution from increased access percent (X_7), decreased data latency (X_6), lower onboard data storage required (X_5), and reduced regulatory difficulty (X_3) relative to the ground-based cases. It is also a result of how cost is calculated in space-based topologies. Instead of incurring a one-time cost as in the ground-based topology case, the CubeSat operator in this model is charged based on the amount of data that is sent through the space-based topology in dollars per bit.

As a result of these characteristics and the equal weighting of the attributes, cross-linked communications represent a dominant solution. However, since space-based network topologies generally perform with lower data throughput (X_1) than ground-based topologies and cost is directly related to

throughput, the model shows them having a much lower cost at the Pareto frontier relative to a ground-based topology of similar utility. If the preferences of the decision maker change such that data throughput utility (X_1) is weighted higher relative to other attributes, then an alternate tradespace where ground-based topologies represent the dominant solution could result.

A further limitation of the space-based portion of the model relating to cost is the assumption that the technology to perform cross-linked communication from a CubeSat exists and could be fielded with no cost beyond what could be acquired from a commercial vendor today. In reality, this is not the case and some amount of technology advancement would be required to make such a system functional. Specifically, this means accounting for the cost of development activity for CubeSat transceivers and bus systems that support high-pointing accuracy, high-gain antennas, increased transmit power, and/or significant forward error correction. In order to reliably include such information in this analysis, a concurrent design effort would be required. While that is not included here, this model does provide an indication that the development of such systems would be of great utility to a decision maker once fielded.

5.13.5 Summary of Model Limitations

Generally, the equal weighting of the attributes relative to one another in this first-order application of the model does not necessarily represent the true preference space of a decision maker. In reality, a decision-maker might place far more weight on a single attribute and that could drastically change the results of this model. In a future application of this model, a decision maker's true preference space should be rigorously captured through structured interviews.

Additionally, this model does not capture the loss of utility and increased cost to a decision maker that is associated with conducting the development of advanced CubeSat communication technology for crosslink. As such, the result shown here represents a state of the world in which that technology already exists and should be taken as a positive indication that a market would exist for such technology were it

commercially available. However, without high Technology Readiness Level (TRL) commercially available CubeSat communication systems that can perform cross-link, ground based-terminals are likely to remain the dominant choice of decision makers.

5.13.6 Use of First Order Results

While this first-order analysis of the data obviously yields more questions, it can be used to motivate further research in a direction that will maximize decision maker utility. In this case, that research should be conducted in the area of space-based network topologies. As the current industry standard is to use ground-based topologies, it could be argued that without the application of a value-centric framework (such as MATE) the pursuit of such a novel solution, rather than sticking with the status quo, would not be as easy to motivate. Though it is tempting to perform further analysis on this tradespace, the use of notional utility and cost functions would make doing so a somewhat limited endeavor. As such, it is more appropriate to enhance the model and perform more detailed analysis with data from a subsequent iteration. The recommended steps to do so are detailed in the next section.

5.14 Next Steps

The next step in this analysis is to exercise the model with real cost functions and decision maker-derived utility functions. Following this model update, the next steps should be to conduct a sensitivity analysis over each design variable and then select a reduced solution space for further investigation. At that point it is also appropriate to re-engage with decision makers to refine their preference space. Finally, once a design vector has been selected, it can be passed on to an engineering team for detailed design and feasibility analysis. This design can then be benchmarked using the MATE simulation and further iteration can occur to obtain a maximum utility design.

6   Conclusion

MATE is a powerful framework that has been well designed to handle a broad range of considerations for value-centric design. In this work, it was shown that it can be an appropriate framework for use in a time-constrained application process with imperfect information. Through thoughtfully created utility functions and design vectors, the tradespace can be explored, which leads to greater understanding of the tradespace relationships. That knowledge can then be applied to drive future analysis and system design.

While an abbreviated application is no substitute for rigorous application of the full MATE framework, it is certainly a utility-enhancing endeavor. Further, it is decidedly more desirable than the alternative, where decisions are often made in the absence of information. That is to say, picking a solution space without understanding the complete utility-cost tradespace in which that solution space might exist. Decision makers are aided by the information output by this abbreviated methodology and can thus better direct their resources to maximize utility and overall stakeholder value. At the very least, they could be spurred into further researching the direction in which a system design should go before deciding on a solution.

In the application to CubeSat communications, though no explicit answer for a design was obvious, it has been shown that network topologies with space-based receiver stations should be carefully considered for use in CubeSat missions. These network topologies enable high utility design vectors at relatively low cost. Further, they dominate the ground-based solutions currently in use today from a utility-cost tradespace point of view. While this could be attributed to un-captured utility and cost considerations, the difference is large enough to motivate further consideration of space-based network topologies for use with CubeSats as they move toward becoming operational assets.

6.1   Future Research

With regard to the application of MATE as a first-order analysis tool, the next step in this research is to exercise the simulation in a real-world scenario, under real time constraints, with real decision makers. While the model has been shown to work in an academic setting, more stressing conditions would serve to expose any flaws and enhance its effectiveness.

As for the problem of selecting a CubeSat communications system, the next step in the research is to rigorously capture actual component cost and technical performance information that is available on the market today. This information would better inform a decision maker of what options exist in the tradespace. Additionally, structured utility interviews with relevant decision makers who are actually facing the problem of selecting a CubeSat communication system would greatly enhance the effectiveness of the simulation and lend further credence to its results.

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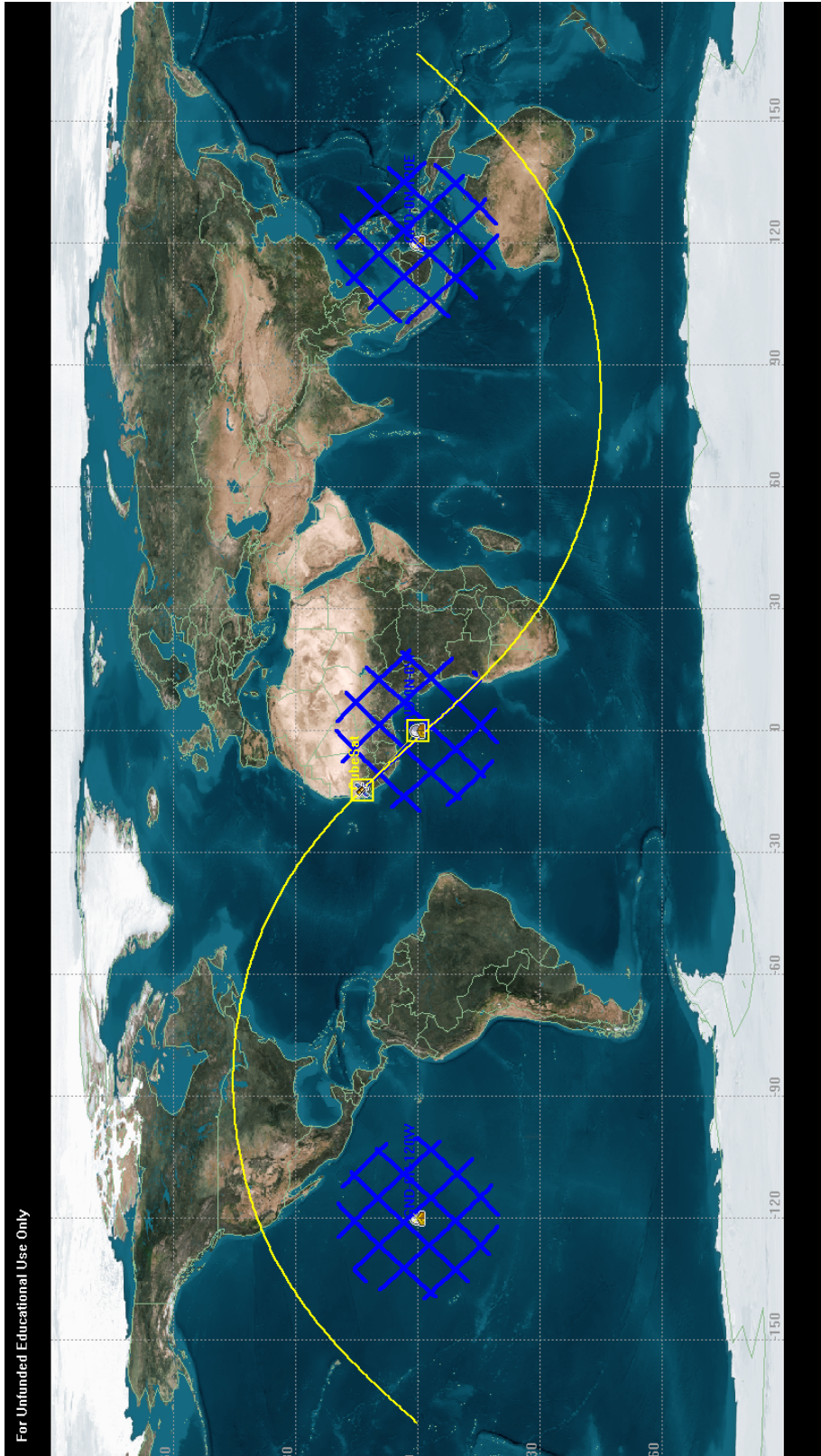
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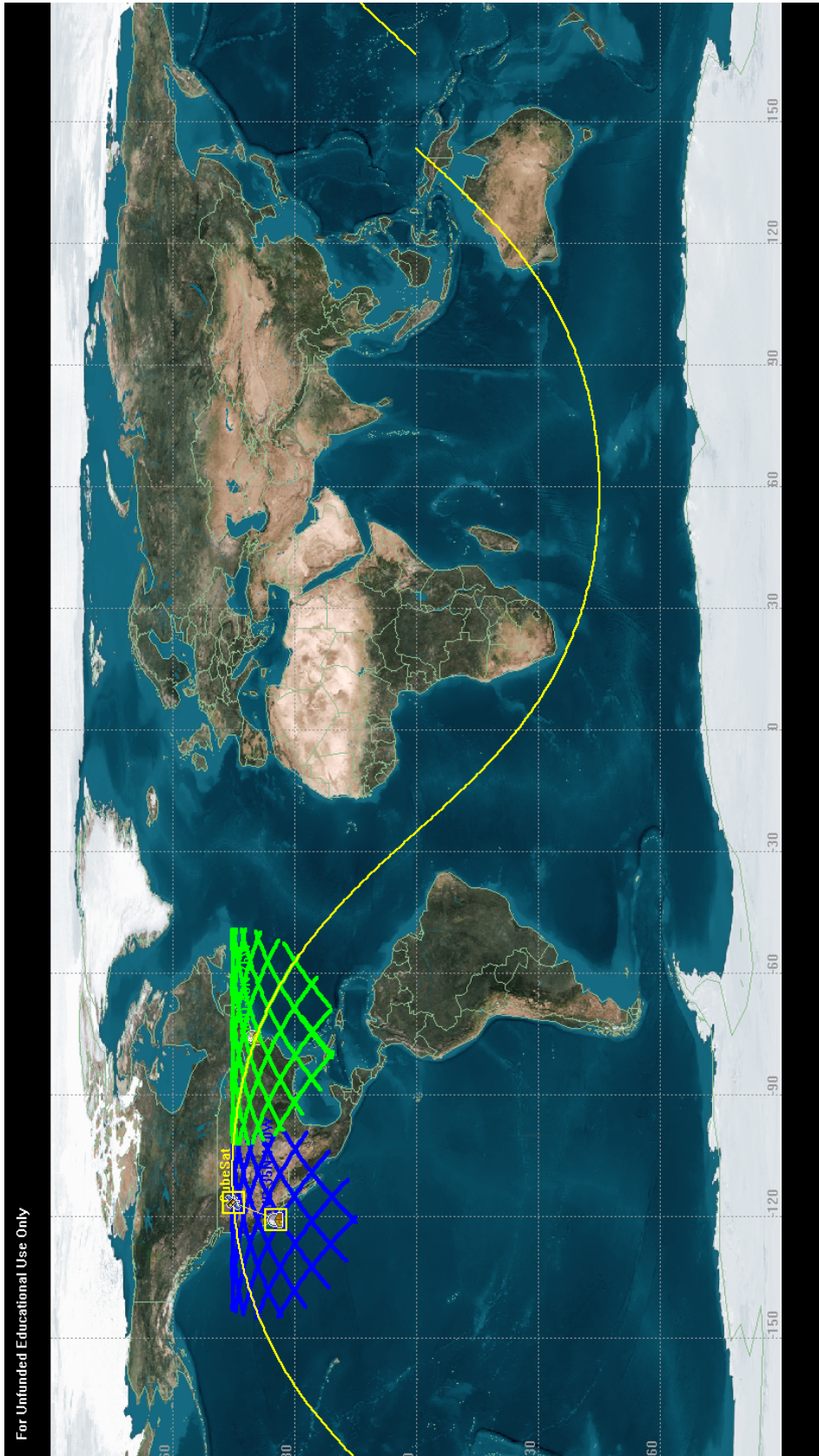
1 - Equatorial Ground Station Network, 3 Stations

6 - Highly Elliptical (Tundra) Earth Orbiting Satellite Network Topology, 2 Satellites

1 - Tradespace for Equatorial Ground Station Network, 3 Stations

Utility Cost Plot - GND Equ X 3

Topology : GND Equ X 3
Cost : $627r @lnd 302
Total Utility : 0.58427 @lnd 302
Throughput : 72.753kbps U=0.036
Tx Power : 0.501kW U=0.12
Is Ground Station : 1 U=0
Bandwidth : 0.501MHz U=0.12
Storage Req : 117MB U=0.14
Latency : 5656.9s U=0.14
Access Percent : 7.29% U=0.01

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

Utility Cost Plot - GND CONUS X 2

Topology: GND CONUS x 2
Cost: 84616 @gnd 303
Total Utility: 0.58061 @gnd 303
Throughput: 78.823kbps U=0.039
Tx Power: 0.50W U=0.12
Is Ground Station: 1 U=0
Bandwidth: 0.50MHz U=0.12
Storage Req: 463MB U=0.14
Latency: 21823s U=0.13
Access Percent: 8.01% U=0.011

Utility Cost Plot - GND CONUS X 1

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

Topology: GND CONUS x 1
Cost: $483K @gnd 320
Total Utility: 0.55936 @gnd48
Throughput: 45.705kbps U=0.024
Tx Power: 0.501W U=0.12
Is Ground Station: 1 U=0
Bandwidth: 0.501MHz U=0.12
Storage Req: 319MB U=0.14
Latency: 25946s U=0.13
Access Percent: 4.81% U=0.0069

Topology: GND CONUS x 1
Cost: $298k @gnd 303
Total Utility: 0.55321 @gnd 303
Throughput: 38.827kbps U=0.021
Tx Power: 0.501W U=0.12
Is Ground Station: 1 U=0
Bandwidth: 0.501MHz U=0.12
Storage Req: 28MB U=0.14
Latency: 29528s U=0.13
Access Percent: 4.02% U=0.0057

Utility Cost Plot - GEO X 3

Topology: GEO x 3
Cost: $1005k @rnd 27
Total Utility: 0.89902 @rnd 27
Throughput: 243.96kbps U=0.09
Tx Power: 1W U=0.096
Is Ground Station: 0 U=0.14
Bandwidth: 1MHz U=0.096
Storage Req: 0MB U=0.14
Latency: 0s U=0.14
Access Percent: 100% U=0.14

Topology: GEO x 3
Cost: $147k @rnd 4
Total Utility: 0.68824 @rnd 4
Throughput: 4.82kbps U=0.0027
Tx Power: 0.501W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.501MHz U=0.12
Storage Req: 21.6MB U=0.14
Latency: 1663s U=0.13
Access Percent: 4.85% U=0.0069

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

5 - Tradespace for Geostationary Earth Orbiting Satellite Network Topology, 1 Satellite

Utility Cost Plot - GEO X 1

Topology: GEO X 3
Cost: $647k @lev 27
Total Utility: 0.81188 @lev 27
Throughput: 145.897kbps U=0.063
Tx Power: 1W U=0.096
Is Ground Station: 0 U=0.14
Bandwidth: 1MHz U=0.096
Storage Req: 53.9MB U=0.14
Latency: 1302.2s U=0.14
Access Percent: 58.6% U=0.084

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

Utility Cost Plot - Tundra X 2

Utility Cost Plot - Tundra X 3

Topology: Tundra x 2
Cost: $406 @md 73
Total Utility: 0.83904 @md 73
Throughput: 90.91kbps U=0.044
Tx Power: 1W U=0.096
Is Ground Station: 0 U=0.14
Bandwidth: 1MHz U=0.096
Storage Req: 48.6MB U=0.14
Latency: 2109.4s U=0.14
Access Percent: 90.9% U=0.13

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

8 - Tradespace for Highly Elliptical (Molniya) Earth Orbiting Satellite Network Topology, 2 Satellites

Utility Cost Plot - Molniya X 1

Topology: Molniya x 1
Cost: $318k @jnd 417
Total Utility: 0.79067 @jnd 417
Throughput: 54.447kbps U=0.028
Tx Power: 0.501W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.501MHz U=0.12
Storage Req: 77.4MB U=0.14
Latency: 5179.8s U=0.14
Access Percent: 54.6% U=0.078

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

Utility Cost Plot - Molniya X 2

Topology: Molniya x 2
Cost: $256k @tnd 646
Total Utility: 0.52687 @tnd 646
Throughput: 7.24kbps U=0.036
Tx Power: 0.501W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.501MHz U=0.14
Storage Req: 43.2MB U=0.12
Latency: 1960.8s U=0.14
Access Percent: 72.9% U=0.1

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

Utility Cost Plot - LEO X 16

SCATTERSGROUP
Topology: LEO x 16
Cost: $1117k @tnd 39
Total Utility: 0.79877 @tnd 39
Throughput: 57.417kbps U=0.029
Tx Power: 0.501W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.501MHz U=0.12
Storage Req: 20MB U=0.14
Latency: 1175s U=0.14
Access Percent: 57.4% U=0.082

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

Appendix C: Tradespaces for Various Network Topologies Plotted to Fit Data

1 - Tradespace for Equatorial Ground Station Network, 3 Stations
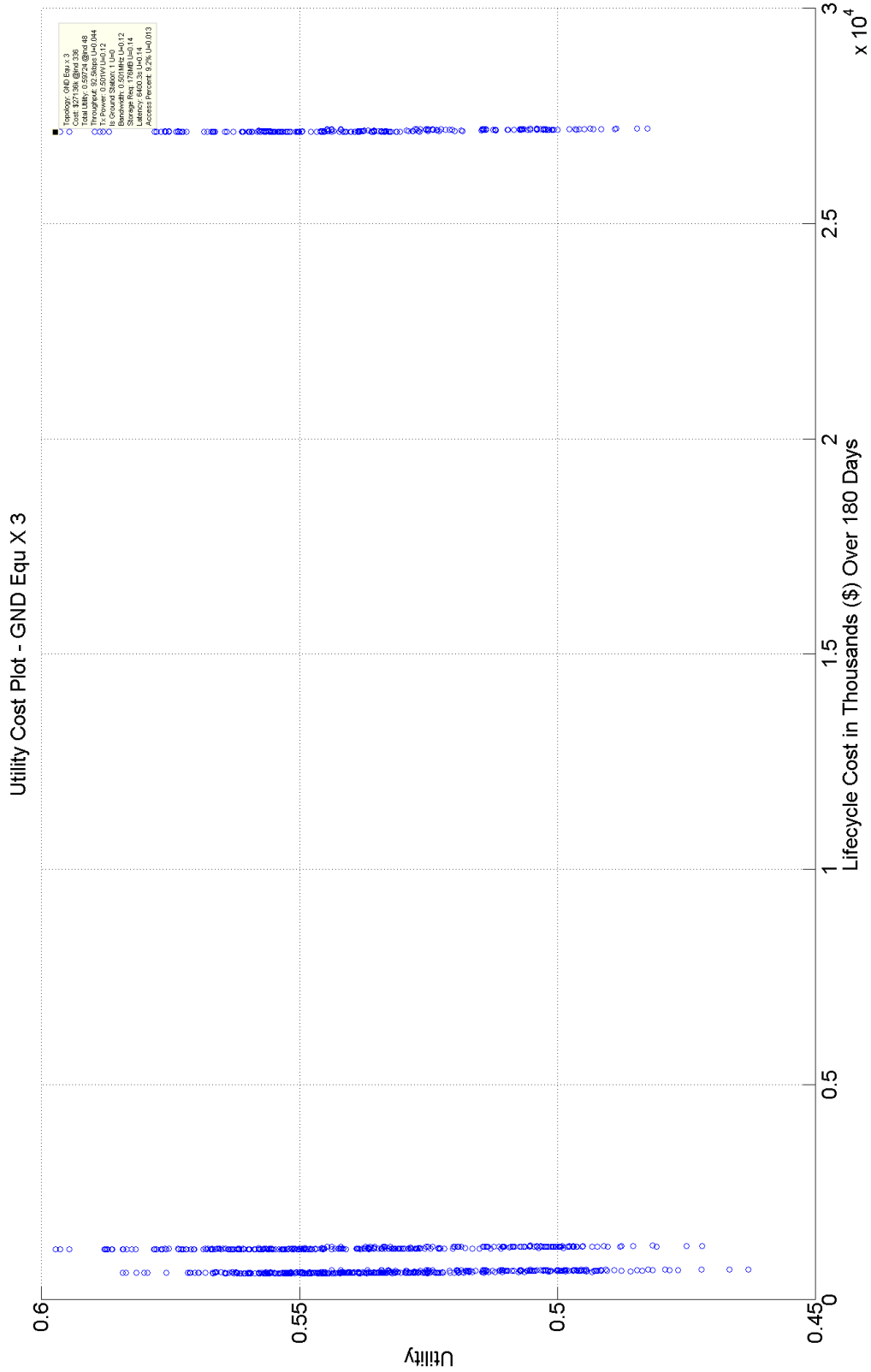
2 - Tradespace for Continental United States Ground Station Network, 2 Stations

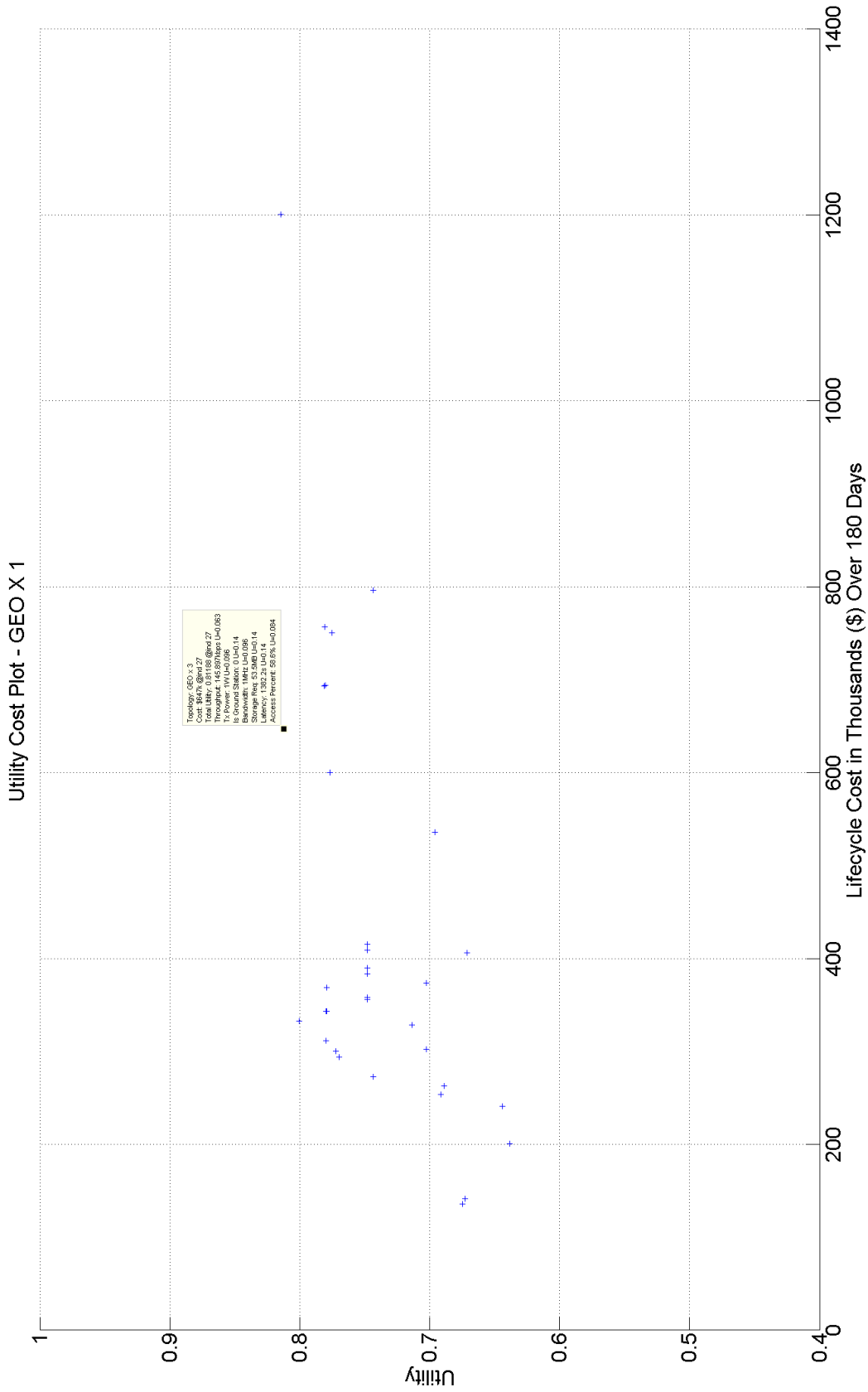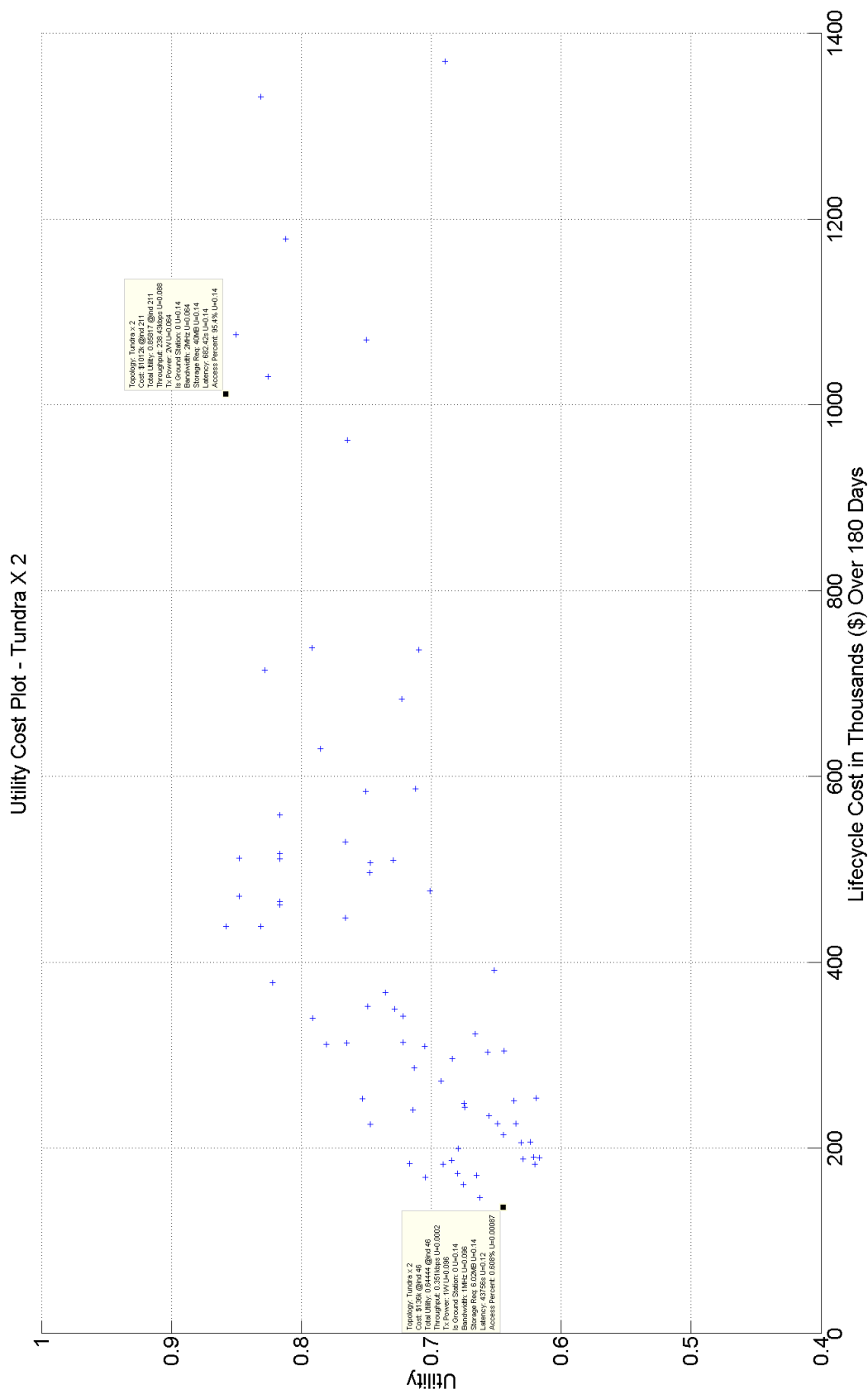Utility Cost Plot - GND CONUS X 2

Topology: GND CONUS x 2
Cost: $181129k @gnd 48
Total Utility: 0.5692 @gnd 48
Throughput: 89.8kbps U=0.043
Tx Power: 0.50kW U=0.12
Is Ground Station: 1 U=0
Bandwidth: 0.501MHz U=0.12
Storage Req: 510MB U=0.14
Latency: 2061ksi U=0.13
Access Percent: 9.2% U=0.013

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

x 10⁴

Utility Cost Plot - GND CONUS X 1

Topology: GND CONUS x 1
Cost: $91746 @gnd 46
Total Utility : 0.55989 @gnd 46
Throughput: 45.705kbps U=0.024
Tx Power: 0.501kW U=0.12
Is Ground Station: 1 U=0
Bandwidth: 0.501MHz U=0.12
Storage Req: 319MB U=0.14
Latency: 25948s U=0.13
Access Percent: 4.81% U=0.0089

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

Utility Cost Plot - GEO X 3

Topology: GEO x 3
Cost: $1917k @Ind 94
Total Utility: 0.99948 @Ind 94
Throughput: 498.99kbps U=0.12
Tx Power: 2W U=0.064
Is Ground Station: 0 U=0.14
Bandwidth: 2MHz U=0.064
Storage Req: 0MB U=0.14
Latency: 0s U=0.14
Access Percent: 100% U=0.14

Utility

Lifecycle Cost in Thousands ($) Over 180 Days

Utility Cost Plot - GEO X 1

Topology: GEO x 3
Cost: $1,200k @md 94
Total Utility: 0.81436 @md 94
Throughput: 291.793kbps U=0.098
Tx Power: 2W U=0.064
Is Ground Station: 0 U=0.14
Bandwidth: 2MHz U=0.064
Storage Res: 107MB U=0.064
Latency: 1382.2s U=0.14
Access Percent: 59.6% U=0.084

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

Utility Cost Plot - Tundra X 2

Topology: Tundra x 2
Cost: $101.2k @2nd 211
Total Utility: 0.85817 @2nd 211
Throughput: 238.43kbps U=0.088
Tx Power: 2W U=0.064
Is Ground Station: 0 U=0.14
Bandwidth: 2MHz U=0.064
Storage Req: 40MB U=0.14
Latency: 682.42s U=0.14
Access Percent: 85.4% U=0.14

Topology: Tundra x 2
Cost: $79k @2nd 76
Total Utility: 0.70569 @2nd 76
Throughput: 54.25kbps U=0.028
Tx Power: 1W U=0.096
Is Ground Station: 0 U=0.14
Bandwidth: 1MHz U=0.096
Storage Req: 180MB U=0.14
Latency: 1122?s U=0.14
Access Percent: 22.8% U=0.033

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

Utility Cost Plot - Tundra X 3

Topology: Tundra x 2
Cost: $2323k @lvl 210
Total Utility: 0.8189 @lvl 210
Throughput: 205.98kbps U=0.08
Tx Power: 2W U=0.084
Is Ground Station: 0 U=0.14
Bandwidth: 2MHz U=0.064
Storage Req: 231MB U=0.14
Latency: 4217.3s U=0.14
Access Percent: 82.2% U=0.12

Topology: Tundra x 2
Cost: $272k @lvl 8
Total Utility: 0.7708 @lvl 8
Throughput: 48.04kbps U=0.025
Tx Power: 0.50W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.501MHz U=0.12
Storage Req: 1.29MB U=0.14
Latency: 9558.1s U=0.14
Access Percent: 48.7% U=0.07

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

Utility Cost Plot - Molniya X 1

SCATTERGROUP

Topology: Molniya X 1
Cost: $305k @ind 419
Total Utility: 0.73008 @ind 419
Throughput: 25.793kbps U=0.014
Tx Power: 0.50W U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.501MHz U=0.12
Storage Req: 10MMB U=0.14
Latency: 154.5s U=0.13
Access Percent: 25.8% U=0.037

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

Utility Cost Plot - Molniya X 2

Topology: Molniya x 2
Cost: $795k @2nd 2015
Total Utility: 0.639678 @2nd 2015
Throughput: 348.86kbps U=0.11
Tx Power: 2W U=0.064
Is Ground Station: 0 U=0.14
Bandwidth: 2MHz U=0.064
Storage Req: 241MB U=0.064
Latency: 2185.2s U=0.14
Access Percent: 70.3% U=0.1

Lifecycle Cost in Thousands ($) Over 180 Days

Utility

10 - Tradespace for Low Earth Orbiting Satellite Network Topology, 16 Satellites

Utility Cost Plot - LEO X 16

Topology: LEO x 16
Cost: $5883k @lvl 203
Total Utility : 0.91775 @lvl 203
Throughput : 246.95kbps U=0.09
Tx Power: 0.50kW U=0.12
Is Ground Station: 0 U=0.14
Bandwidth: 0.50 MHz U=0.12
Storage Req: 6.0 kMB/ U=0.14
Latency: 75.23 fs U=0.14
Access Percent: 98.6% U=0.14

Lifecycle Cost in Thousands ($) Over 180 Days

Utility