Space Communications Architecture

Application Portfolio

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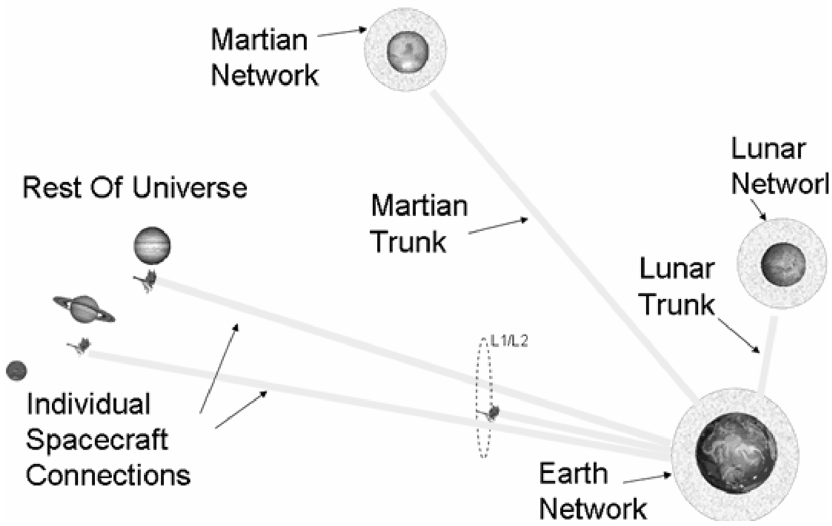

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Executive Summary

This application portfolio examines the impact of real options on NASA's Space Communications Architecture. Although this work makes a number of high-level assumptions about the scope of the problem and the nature of the uncertainties faced, it succeeds in providing an insightful exercise into how more detailed studies should proceed.

The portfolio opens with an overview of the Space Communications Architecture and NASA's vision for its implementation, including a brief discussion of some of the overarching issues and uncertainties that the designers of this system will have to face in the coming years.

The salient uncertainties include the projected lunar mission communications demand and the physical locations of the space assets. Simplistic models capturing these uncertainties are developed. For demonstration purposes, the portfolio focuses on the implications associated with the mission demand. Further studies should use the approach outlined in this portfolio to examine the impact of the uncertainty of the location of the space assets.

Two alternative architectures for the Earth-moon segment of the overall system are proposed: one fixed and the other flexible. These two alternatives are analyzed using a two-stage decision analysis to find the expected value of the costs of both systems. It turns out that the expected value of the fixed design is $27.9 million for the stated assumptions; the flexible design gives $29.8 million. Thus, given the two-stage decision analysis, if all you can do is adjusting the capacity for this system, the optimal strategy over 2 periods is the fixed design.

A lattice analysis demonstrates the impact of uncertainty on the time evolution of the projected lunar mission demand. This model is then used to analyze the impact of exercising design options over the course of the system lifetime. For simplicity, the analysis assumes the "value" of being in each node of the lattice is merely "spacecraft capacity less the demand". This number gives an indication of the necessity of acquiring a boost in capacity. If the number is large, there is a great deal of excess overcapacity. If the number is small, then the system is nearly at capacity. If the number is negative, then there is not enough capacity to support the demand requirements. The analysis further assumes that the larger the data rate "value", the better. Exercising the option to expand the link capacity by launching secondary spacecraft during period 4 appears to increase the net "value" of the system by 187 points; a significant amount. The lattice analysis used does not consider the dollar cost of exercising the option.

Overall, it appears the optimal strategy for the Space Communications Architecture is the fixed design with the option to expand capacity in period 4.

Part 1 – Defining the Topic

System of Interest

The system under consideration is the infrastructure required to support the NASA Space Communications Architecture Vision. The vision statement of the NASA SCA is "to concurrently architect the Space Communications Network to enable NASA's changing mission of Exploration." The system must be capable of providing communications and navigation capabilities as required to support the evolving exploration missions.

The system includes the individual planetary networks (e.g., Martian, Lunar, Earth, etc) as well as the wireless communication paths (below in Figure 1, "Trunk") that link each of the planetary networks and the individual spacecraft maneuvering throughout the connected regions (please see Figure 1). Also included are any necessary relay satellites that may exist at any of the Lagrange points or in any other kind of special orbit.

Each planetary network consists of any required satellites in constellations or otherwise that are necessary to link the rest of the network to the exploration resources existing on or around that planet. In the case of the Earth network, the system may include ground stations necessary to link the interplanetary internet to the existing terrestrial infrastructure. A related system that should be considered as potentially part of this system is the interplanetary supply-chain required to ensure sustained presence and development in space.

The system does not include the existing terrestrial network on Earth (e.g., telephone networks, internet, DirecTV, etc). The only exceptions to this rule should be those elements that were evolved from NASA's Deep Space Network, Space Network, and Ground Network.

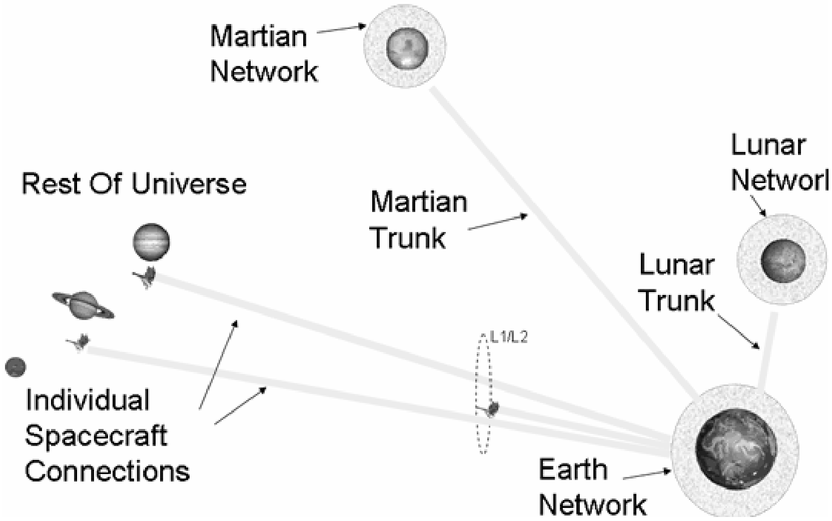

Figure 1: Top Level SCA View of the Interplanetary Internet for 2030.

Major Design Parameters and Issues

Some of the principal design variables include the network topology (e.g., where to put the communication and navigation assets as well as how many), the network protocols (e.g., how to accomplish routing in a network where the latency is so bad), the communications and navigation relay platform (single spacecraft versus distributed platform, for example), the onboard power and antenna technology (diameter, for instance), etc.

The space environment will have a huge impact on the performance of this system; space is a harsh mistress and to ensure component and mission success requires meeting the demands of the environment.

The system is highly time-variable as it is the goal of the SCA to evolve the infrastructure required from the current Deep Space Network, Space Network, and Ground Network as exploration needs change. Thus, it is important to ensure that the later elements of the architecture can leverage off of the earlier elements to enable future expansion for some reduced cost.

The long-life of the system means that many components will need to be replaced and/or replenished periodically. So, in addition to repeated capital expenditures for different stages of the infrastructure roll-out, there are significant recurring costs as well.

Major Uncertainties about the Performance of the System

A major factor that creates uncertainty about the performance of the system is the long-latency links connecting most of the network. Although delay-tolerant network strategies have been proposed, how the system will perform under these conditions is unclear. Coupled with this concern is the increasing demand of the exploration missions on the communications and navigation capabilities of the system. It is unclear how to roll out the infrastructure in such a way to be able to meet these evolving standards.

The communication delay isn't the only aspect of concern; the delay in getting parts and supplies from point A to point B is even more significant. This effect applies not only to the infrastructure components but also to the exploration missions and any sort of commercial venture allowed to develop within the SCA infrastructure.

Another major area of uncertainty is the level of government funding. It is possible that funding could disappear before the infrastructure is fully in place.

Given the time-varying nature of the orbital system of planets, reliability is a big concern in terms of quality-of-service performance, as is connectivity and robustness of the communication and navigation links.

Picture and vision statement taken from:
https://www.spacecomm.nasa.gov/spacecomm/programs/architecture.cfm

Part 2 – Defining the Salient Uncertainties

Identification of Uncertainty

The Space Communications Architecture consists of a number of space assets, the collection of which must support backbone communication services. There is a large amount of uncertainty in terms of the future demand on the architecture as a function of time. The demand drives the required capacity of the network. As time goes on, the average demand can be expected to increase, but how it will increase is definitely uncertain.

Not only is there great uncertainty in the required data rates and the time evolution of demand, but there is also great uncertainty as to the locations required to have supporting infrastructure.

Characterizing Uncertainty

The mission demand uncertainty can most likely be characterized by a trend of expected values over time with some variation from this expected trend (standard deviations, for example).

This uncertainty of asset locations can be modeled by considering the probability that a given location is chosen for a given mission as a function of time.

Uncertainty Metrics

Mission Demand:

The projected mission demand for all of the planned NASA missions to the moon have been adjusted as shown in Figure 2. The forecasted demand is an exponential curve, loosely based on some numbers provided by the NASA Space Communications Architecture Working Group for the maximum required downlink data rates. The high and low uncertainty values are a growing proportion of the forecasted values. This proportion of the mean grows from 5% to 45% over the course of the missions.

The forecasted demand is likely an underestimate, according to NASA. Thus, it is assumed that the probability that the actual demand is higher than the forecasted is correspondingly greater.

Location Uncertainty:

The uncertainty in the required location of assets can have a significant effect on the overall design. For example, on the moon, the missions may require end-to-end communications from the lunar poles, the lunar equator, or they may require full-lunar coverage. What a given future mission will require is highly uncertain and can have a huge impact on the infrastructure design and cost. This uncertainty is modeled in Figure 3 by considering the probability that a given location is chosen for a given mission as a function of time. For any given year, the total probability sums to 100%, even if there is not necessarily a mission planned for that year.

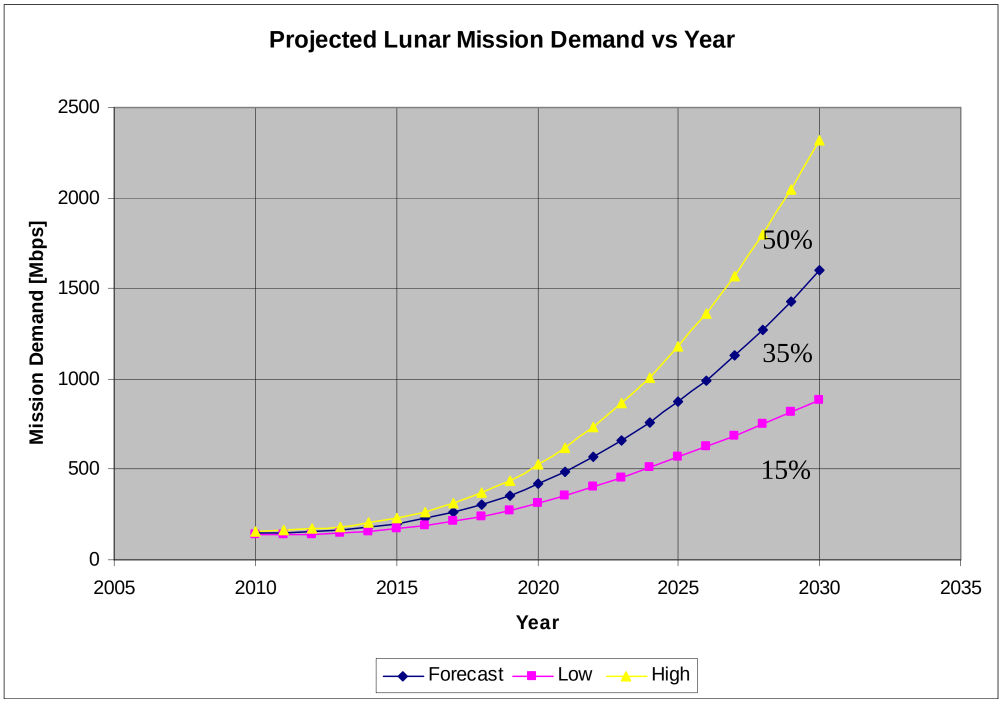

Figure 2: Uncertainty in the Lunar Mission Demand

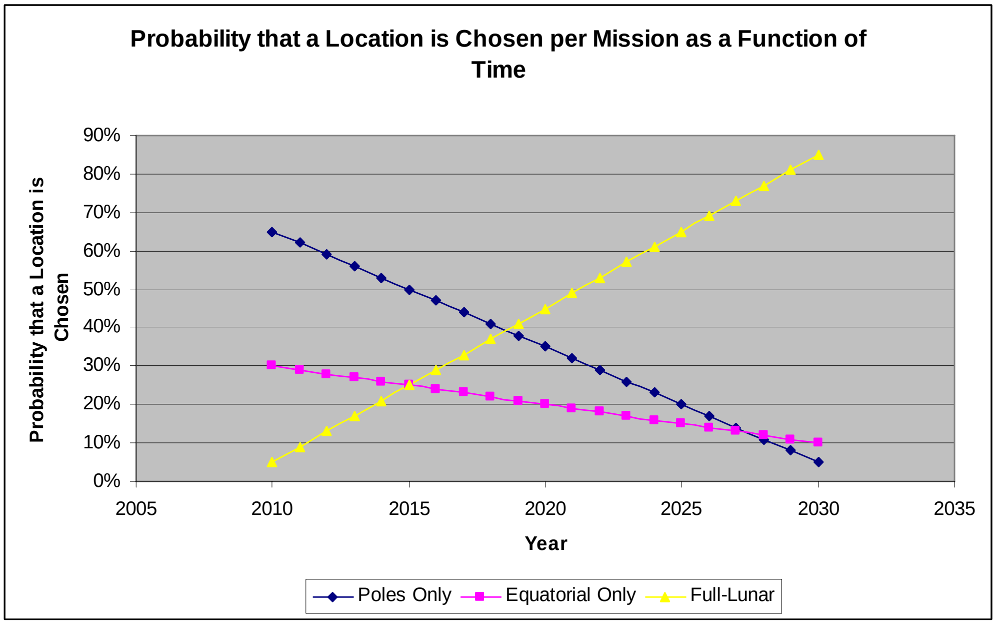

Figure 3: Uncertainty in the Mission Location

Part 3 – Defining System Designs to be Analyzed

System Geometry

The system (shown in Figure 4) is assumed to consist of a constellation of Geostationary satellites (G) that provide connectivity to the Earth-based assets and the space-based assets (these assets are assumed to be pre-existing), a potential constellation of lagrange point spacecraft (L1, L2, L4, and L5; L3 not considered here), and a potential constellation of polar satellites in lunar orbit (P1 – P6) with the capability of providing full lunar-coverage if all the satellites locations are chosen. It is assumed that L1 and L2 can see all of the lunar polar satellites at *some* time. P1 through P3 exist in a separate constellation plane than P4 through P6. It is assumed that there is no cross-plane connectivity. For simplicity, it is further assumed that the mission location on the moon is visible to all of the lunar polar satellites as well as the L1 and L2 spacecraft. This set of spacecraft locations enables flexibility in the choice of locations for the mission architecture.

To provide the ability to increment capacity at each location over time, it is assumed that it is possible to set up distributed platforms in each of these locations. Thus, as demand increases, it is possible to launch secondary spacecraft to these locations to complement the existing assets to provide the full required capacity.

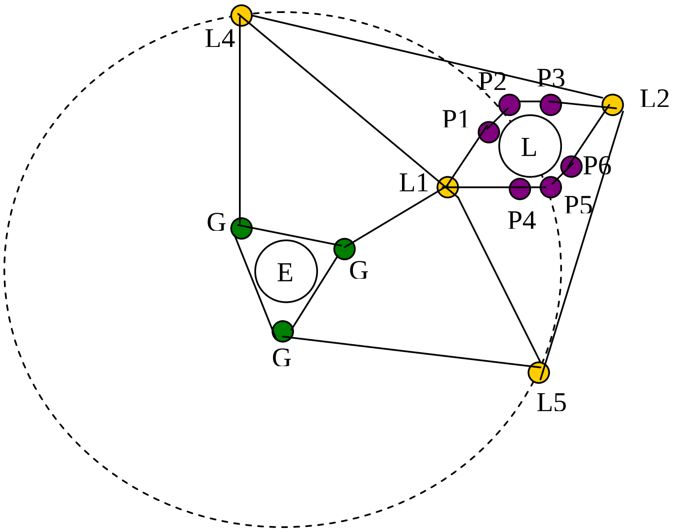

Figure 4: Simplified System Geometry

Fixed Design

The fixed design for the Space Communications Architecture is similar to the garage development case. The best architecture is chosen a priori and the infrastructure is in place before operations begin. For the purposes of this project, the fixed design is assumed to be the architecture shown in Figure 5 in which all of the assets are capable of providing the maximum forecasted demand and full-lunar coverage with the minimum number of assets (based on the preliminary architecture chosen by the NASA Space Communication Architecture Working Group).

Flexible Design

The flexible design for the Space Communications Architecture allows both the location of space assets and the capacity of those space assets to vary over time. To limit the work required for this portfolio demonstration, varying the capacity of the space assets over time is the only aspect considered.

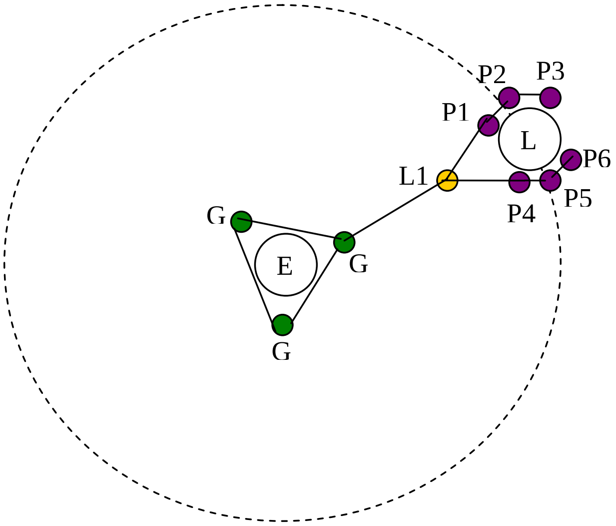

Figure 5: Fixed Design Architecture

Part 4 – Two-stage Decision Analysis of Alternate Designs

For now, assume that the only uncertainty is the demand and that the flexibility in the design only exists in expanding the capacity. The NPV values are for the discounted costs of the system based on the required antenna diameter sizes to provide the required communication capacity. This assumption simplifies the analysis but ignores many significant factors that contribute to the cost of the system.

Stage 1 is defined as the missions from 2010 to 2020 while stage 2 is defined as the missions from 2020 to 2030.

The decision graph is broken into two pieces, one reflecting the fixed design and one reflecting the flexible design. The flexible design has the space assets in the same locations as in the fixed design, but the capacity can be expanded over time, as needed.

Fixed Design

Since the fixed design can't be changed at the second stage, the decision graph for the fixed design can be generated as in Figure 6. It should be clear from the figure that the expected value of the cost of the fixed design is $27.9 million for the stated assumptions.

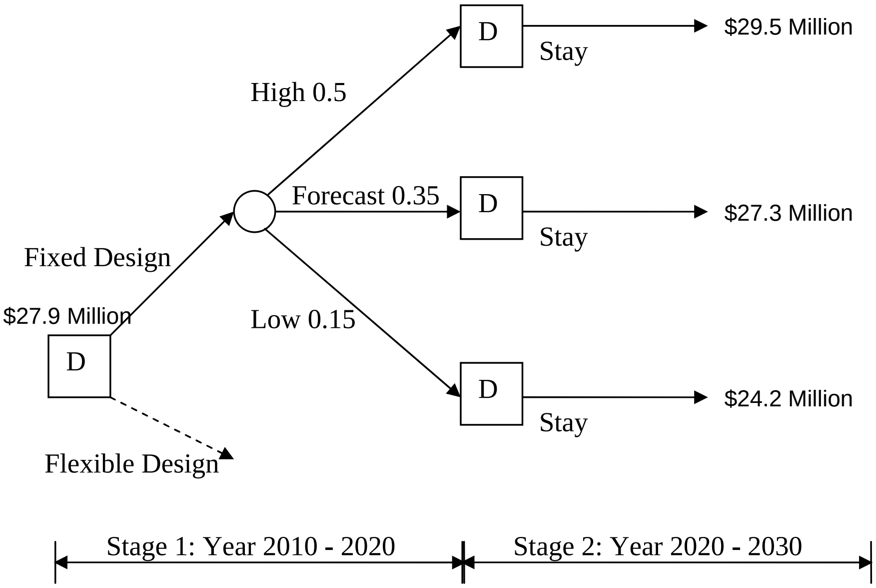

Figure 6: Decision Graph for the Fixed Design Segment of the Analysis

Flexible Design

The flexible design focuses on expanding the capacity of the network by adding assets to given locations with the aim of bringing every location up to capacity. Thus, the second-stage decision boils down to adding a satellite at each location such that this secondary satellite provides the remaining capacity to achieve the target capacity at the end of life (2030).

Thus, as can be seen in Figure 7, the expected value of the costs of the flexible design is $29.8 million for the stated assumptions.

The optimal strategy over 2 periods is the fixed design if all you can do is adjusting the capacity for this system.

A similar calculation can be done assuming a fixed capacity (at forecast levels) and variable mission location.

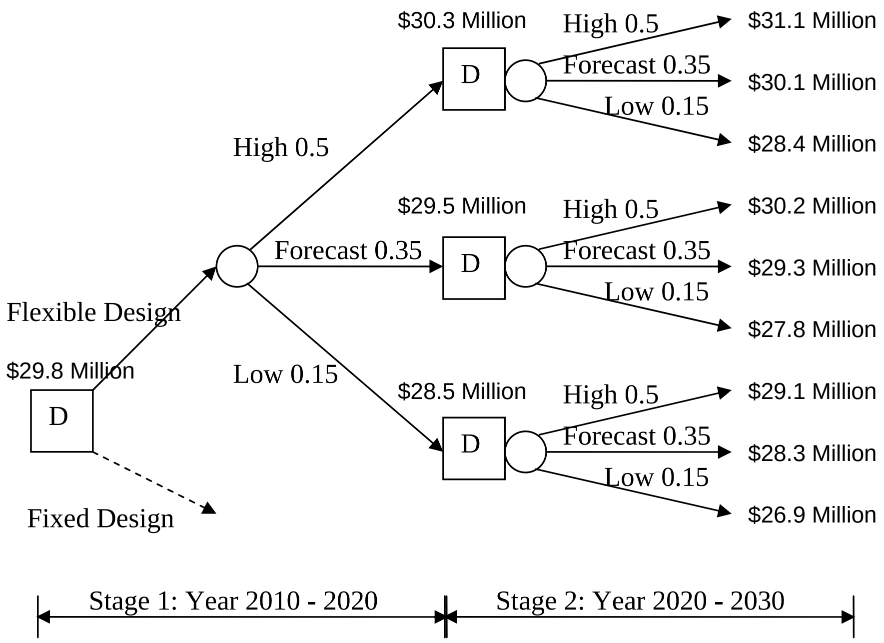

Figure 7: Decision Graph for the Flexible Design Segment of the Analysis

Part 5 – Lattice Analysis of Evolution of a Major Uncertainty

For the purposes of this exercise, it was assumed that the major uncertainty under study was the lunar mission demand in terms of the required data throughput. Figure 8 shows the forecasted mission demand as a function of time as well as the exponential regression trendline.

From Figure 8, the modal forecast can be assumed to be: $y = 102.22e^{0.1311t}$. It was assumed that the volatility was 25% (found by taking the average standard deviation of the mission demand from the last application portfolio). Given this information, the parameters for the lattice analysis can be found using:

- ⇨ S = 102.22
- ⇨ r = 13.11%
- ⇨ σ = 25%
- ⇨ Δt =1 year

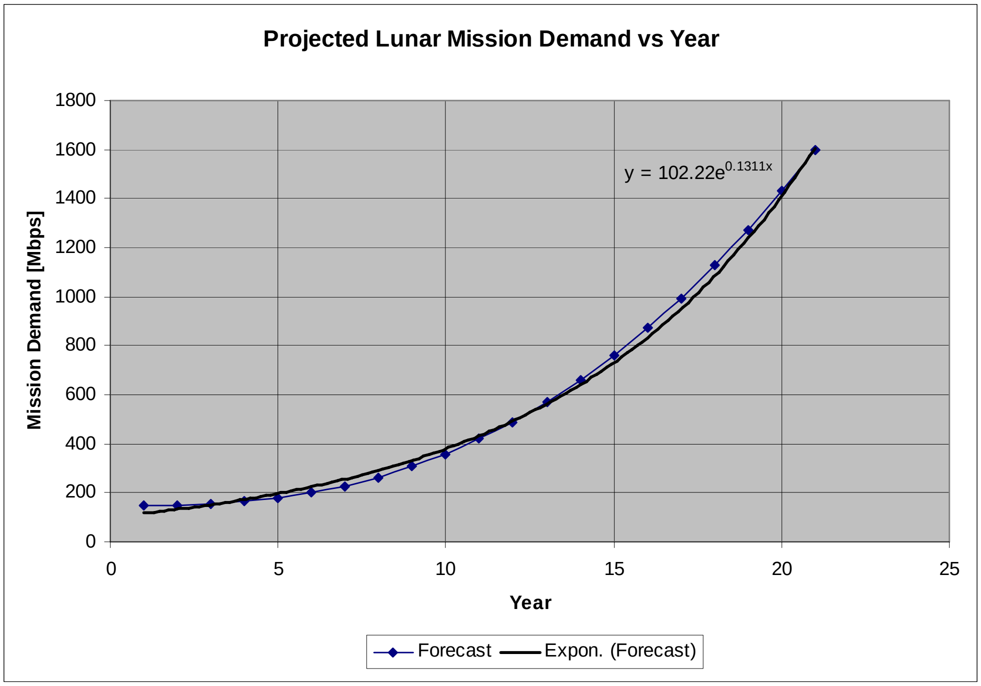

Figure 8: Projected Lunar Mission Demand versus Time with Trendline

To find, u, d, and p for the lattice analysis:

$u = \exp(\sigma\sqrt{\Delta t}) = \exp(0.25) = 1.2840$

$d = \exp(-\sigma\sqrt{\Delta t}) = \exp(-0.25) = 0.7788$

$p = 0.5 + 0.5(r/\sigma)\sqrt{\Delta t} = 0.5 + 0.5(0.1311/0.25) = 0.7622$

Plugging these values into “binomial lattice.xls” provides the outcome lattice shown in Table 1, and the corresponding probability lattice given in Table 2. The PDF for the lattice and the PDF for the log of the relative outcomes are shown in Figures 9 and 10, respectively. Note that these analyses assume a 6 year operational period rather than the 20 years of the models to cut down on clutter.

Table 1: Projected Lunar Mission Demand Outcome Lattice.

OUTCOME LATTICE

102.22	131.25	168.53	216.39	277.84	356.75	458.06
	79.61	102.22	131.25	168.52	216.38	277.83
		62.00	79.61	102.22	131.25	168.52
			48.29	62.00	79.61	102.21
				37.60	48.28	62.00
					29.29	37.60
						22.81

=102.22*d*d

Table 2: Corresponding Probability Lattice for the Projected Lunar Mission Demand.

PROBABILITY LATTICE

1.00	0.76	0.58	0.44	0.34	0.26	0.20
	0.24	0.36	0.41	0.42	0.40	0.37
		0.06	0.13	0.20	0.25	0.29
			0.01	0.04	0.08	0.12
				0.00	0.01	0.03
					0.00	0.00
						0.00

=(1-p)*(1-p)

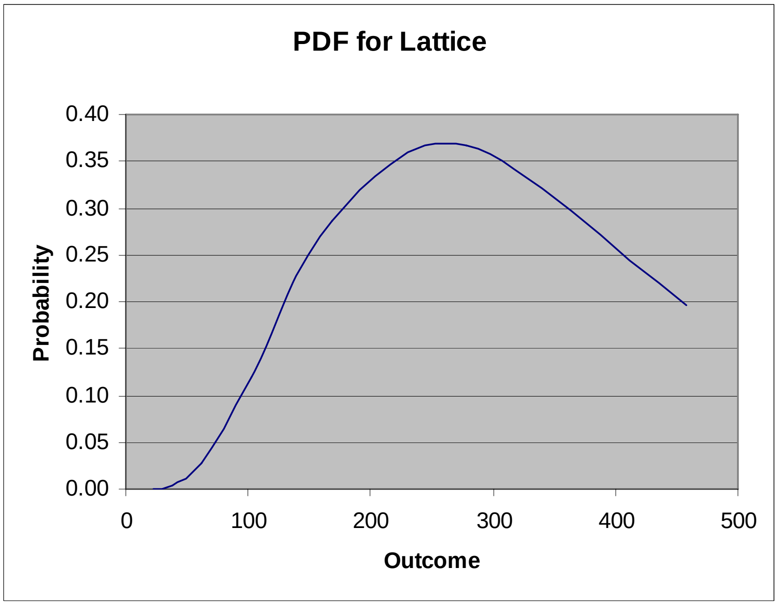

Figure 9: PDF for the Outcome Lattice of Mission Demand

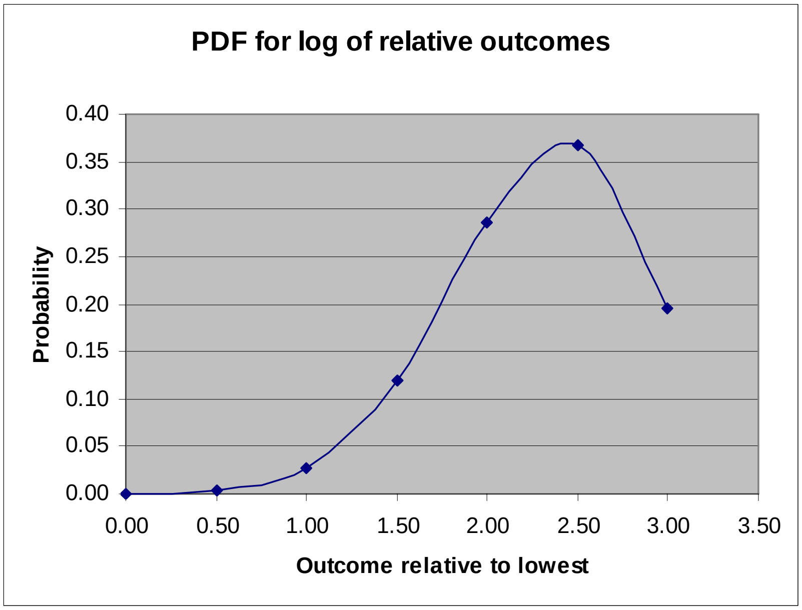

Figure 10: PDF for the log of Relative Outcomes of Mission Demand

Part 6 – Decision Analysis using Lattice

Option to Exercise

Suppose we can design, build, and launch spacecraft with the capability to support 250 Mbps each. Thus, the option is to launch a secondary spacecraft in each orbital slot to boost the link capacity if needed.

Although it would be nice to incorporate the dollar cost models illustrated in Part 4 into the lattice evaluation, doing so would not be particularly meaningful in this situation. There is no clear net "revenue" associated with a particular level of data rate and no easy way of generating an option to make use of the dollar costs since the option to "close" is a policy decision and not a design decision. Likewise, the option to launch secondary spacecraft to boost capacity will likely provide no economic benefit, only performance benefit. Thus, for the purposes of this exercise, a demand cost function is created to transform the performance of "sufficient capacity to meet demand needs" into something that can be applied to the lattice valuations.

Demand Cost Function

For simplicity, assume the "value" of being in each node of the lattice is merely "spacecraft capacity less the demand". This number gives an indication of the necessity of acquiring a boost in capacity. If the number is large, there is a great deal of excess overcapacity. If the number is small, then the system is nearly at capacity. If the number is negative, then there is not enough capacity to support the demand requirements. Thus, the larger the data rate "value", the better.

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Further assume that the "value" of being in each node of the lattice is not subject to a discount rate since it is not a dollar cost.

The results of the demand cost function lattice are given in Table 3.

Table 3: Demand (in terms of data rate) Cost Function Lattice

0	1	2	3	4	5	6
DATA RATE COST FUNCTION LATTICE						
147.78	118.75	81.47	33.61	(27.84)	(106.75)	(208.06)
	170.39	147.78	118.75	81.48	33.62	(27.83)
		188.00	170.39	147.78	118.75	81.48
			201.71	188.00	170.39	147.79
				212.40	201.72	188.00
					220.71	212.40
						227.19

=Capacity – Value in Table 1 = 250 - 62

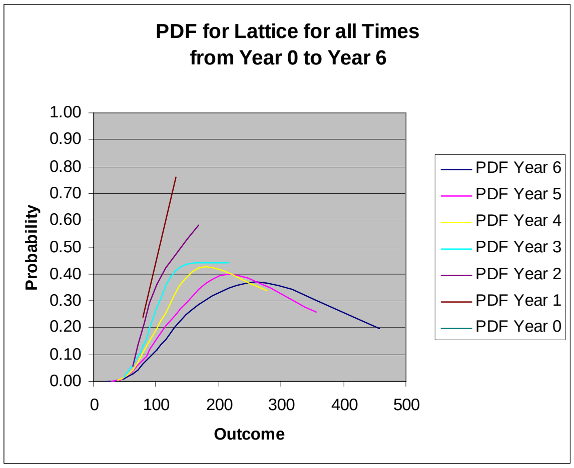

Figure 11: PDF for the Demand Cost Function Lattice from Year 0 to Year 6

Modeling the Uncertainty

Parts 3 and 5 of this application portfolio outline the modeling of the uncertainty for the mission data rate demand for this system.

The PDF of the lattice can be found for all times from Year 0 to Year 6, and is shown in Figure 11.

Analysis Recognizing Uncertainty

The "value" of the system on the assumption that no capacity is added regardless of the evolution of the mission data rate demand is shown in Table 4. The expected value of the system value is found to be 442.

Table 4: Expected Value of the System Value Recognizing Uncertainty using the Probability Weighted Net Value

	0	**1**	**2**	**3**	**4**	**5**	**6**
	0	91	47	15	9	27	41
		41	54	49	34	13	10
			11	22	29	30	23
				3	8	13	18
					1	2	5
						0	1
							0
E [Value]	0	132	114	92	66	37	2
							442

= Cost Function(x) * Probability(x) = 188.00*0.06

Valuation of Option to Add Capacity

Exercising the option during period 4 appears to increase the net “value” of the system by a significant amount, as demonstrated by Tables 5 and 6. The option is valued at 187 points, roughly 30% of the expected value of the system with the option exercised and about 42% of the expected value of the system without the option.

Table 5: Expected Value of the System with Option Exercised

WITH OPTIONS	**0**	**1**	**2**	**3**	**4**	**5**
(check next year)	629	556	370	230	149	143
		863	653	478	349	284
			820	594	390	216
				754	532	328
					618	396
						437

=594*p+754*(1-p)
+ Cost Function(x)

Table 6: Value of the Option to Boost Capacity

Value of option =	629
-	442
	187

Conclusions

In the context of the Space Communications Architecture study, it will likely turn out that applying a flexible approach to the location of the space assets will be more valuable than considering capacity expansion. However, to confirm this assessment will require the development of some fairly sophisticated models first. The lattice valuation approach seems like it may have some strong applicability to further studies of the Space Communications Architecture. At the very least, it should provide a high-level view of the impact of uncertainties on the design space without having to deal with an exorbitant number of combinations.

I feel that I have learned a useful and potentially very powerful methodology for designing systems faced with a great deal of uncertainty, such as the Space Communications Architecture. Although I wasn’t able to delve into many of the specifics of the SCA in this exercise, I think I have learned enough to be able to apply the concepts to any future models I may develop.