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A METHODOLOGY TO ASSESS THE UTILITY OF FUTURE SPACE SYSTEMS

THESIS

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AFIT/GSO/ENS/94D-14

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A METHODOLOGY TO ASSESS THE UTILITY OF FUTURE SPACE SYSTEMS

THESIS

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List of System Abbreviations

ASTDET - Asteroid Detection System

ASTNEG - Asteroid Negation System

GSRT - Global Surveillance, Reconnaissance and Targeting System

HEL - Space-Based High Energy Laser System

HOLPROJ - Holographic Projection

HPMW - Space-Based High Power Microwave System

IONFOR - Ionospheric Forecasting System

KEW - Kinetic Energy Weapon System

MODSYS - Space Modular System

OMV - Orbital Maneuvering Vehicle

OTV - Orbit Transfer Vehicle

PB - Space-Based Particle Beam Weapon System

SGPS - Super Global Positioning System

SMASS - Space-Based Solar Monitoring and Alert Satellite System

SOLMIR - Solar Mirror System

SPATRACS - Space Traffic Control System

TAV - Refueled Transatmospheric Vehicle

WXCON - Weather Command, Control, and Communication System

WXFOR - Weather Forecast System

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Abstract

This research identifies the assumptions and simplifications in the SPACECAST 2020 value model and assesses modifications. The model determines and prioritizes future space systems' utility toward controlling and exploiting space. This study shows that the assumption of using an additive utility function is valid. This research shows that the mission areas are mutually utility independent allowing the use of the multiplicative utility function. This research also uses the multilinear function, which requires utility independence implied in mutual utility independence. This study makes modifications to the 98 SPACECAST 2020 measure of merit scoring functions. These scoring functions all used the same scoring scale and do not allow for the determination of the overall current capability toward controlling and exploiting space. This study replaced most of these functions with either a concave, convex, linear, or "S" scoring function, which has expanded capability ranges to include current and future capabilities. The modified scoring functions and alternate utility functions do not alter the SPACECAST 2020 results but do improve upon the model. This study also presents a flexible but formalized method of space system concept identification, which explicitly considers space operational requirements.

A METHODOLOGY TO ASSESS THE UTILITY OF FUTURE SPACE SYSTEMS

I. Introduction

1.1 Problem Statement

General Merrill McPeak, Air Force Chief of Staff, commissioned the SPACECAST 2020 survey on 10 September 1993. The survey's mission was to "envision what capabilities our country needs to exploit and control space" and to "identify innovative applications of space hardware that will support national security" (16:Slide 1). The study successfully identified, assessed, and prioritized space systems and technologies that the Air Force needs to develop for and beyond the year 2020. However, the analysis model has assumptions and simplifications which could limit its usefulness as a methodology to prioritize future space systems and technologies.

1.2 Background

The SPACECAST 2020 study lasted for over ten months. However, the ranking procedure for the identified systems and technologies was completed in just over a month. The short time available severely limited the operational analysis team.

There are many techniques available to prioritize future space systems and technologies. The easiest and least formal is for a group of experts to review the systems and technologies and produce a most to least dear list. The most difficult, costly and time consuming is a cost and operational effectiveness analysis (COEA). However, such an analysis would cost thousands of dollars and take over a year to complete. Other techniques are qualitative comparisons, quantitative comparisons, analytic hierarchy process (AHP), Value-Focused Thinking (VFT), decision analysis, and Strategy-to-Task. The team selected VFT. VFT "allowed the alternatives to be evaluated at an appropriate level of detail, considering their level of definition, and could be completed within the time available for analysis" (1:S-4,5). The operational analysis team produced a value model with a hierarchy structure with "broad categories at the top level and [specified] the desired qualities in greater detail al lower levels" (1:S-5). The desired qualities were measures of merit (MOMs) relating to space operational effectiveness. This enabled the team to score the various alternatives, proposed space systems, against the measures of merit. The model gave each system a utility ranking indicating its contribution toward controlling and exploiting space, the overall objective of the model. The value model "gives a rational, traceable, objective, and quantifiable basis for ranking the . . . [proposed space systems]" (1:S-5).

1.3 Research Objectives and Scope

The objective of this thesis is to identify the key assumptions and simplifications in SPACECAST 2020 study. This thesis also makes modifications to the model addressing the identified assumptions and simplifications. Although this research uses the space systems and technologies identified in the SPACECAST 2020 survey, it provides a framework which can apply to other space systems.

This research does not address the cost and risk factors associated with future space systems. Prioritizing future systems just by their utility towards controlling and exploiting space is not sufficient. Systems with high utilization may have prohibitive costs and prove overly risky in their development.

This thesis addresses the methods of achieving the utilities toward controlling and exploiting space and assumes that the proposed system capabilities in the SPACECAST 2020 operational analysis are correct.

1.4 Use of Decision Analysis, Value-Focused Thinking, and Regression Analysis

Decision analysis is a method of analysis that provides ". . . insight about [a] situation, uncertainty, objectives, and tradeoffs, and possibly yields a recommended course of action" (2:4). The SPACECAST 2020 value model uses VFT, which is a technique of decision analysis. The value model is a value tree which shows the fundamental objective divided into objectives, sub-objectives, and quantifiable attributes. The model shows a decision maker how each element of a space system contributes to its overall objective of controlling and exploiting space.

This research uses regression analysis in order to show that results from different utility functions are nearly strategically equivalent. Strategic equivalence is defined as two value functions having the same preferential ordering of alternatives (6:81). The regression analysis shows that the preferences created by one function can be sufficiently explained by a linear transformation of another utility function's preferences.

This research uses the computer spreadsheet[1] value model created by the SPACECAST 2020 operations analysis team. It also uses a mathematical spreadsheet[2] for the modified measures of merit defined and discussed in later chapters.

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[1] Microsoft® Excel, version 5.0 (13).
[2] Mathcad® Plus 5.0 (10).

1.5 Overview of Thesis

Chapter II briefly outlines the SPACECAST 2020 model and identifies the key assumptions and simplifications. It also reviews three other methods used for measuring effectiveness and prioritization.

Chapter III presents modifications to the SPACECAST 2020 value model that address the issues presented in Chapter II.

Chapter IV discusses the results derived using the modifications to the value model. It also presents an analysis of the results.

Chapter V makes conclusions and recommendations for future research based on the results and analysis in Chapter IV.

II. Modeling the Utility of Future Space Systems and Technologies

This chapter briefly outlines the SPACECAST 2020 model and identifies the key assumptions and simplifications. For a detailed explanation of the SPACECAST model, the reader can review the Operational Analysis chapter in the SPACECAST 2020 report (1:S-1). Also, this chapter briefly reviews three other forecasting and prioritization methods.

2.1 SPACECAST 2020 Utility Model

In September 1993, General McPeak, Air Force Chief of Staff, wanted to "identify . . . those high-leverage space technologies and systems that will best support the warfighter" in the next century (11). He tasked Air University to form a study group, SPACECAST 2020.

The SPACECAST 2020 study, over the next ten months, collected ideas for future systems and technologies. The ideas came from military members, contractors, science-fiction writers, Hollywood producers, and others. In all, they collected over 400 ideas. With less than two months remaining, the SPACECAST 2020 staff called on members of the Operational Sciences department of the Air Force Institute of Technology (AFIT) to develop a model to prioritize these systems and technologies.

The operational analysis team answered the following questions (1:S-3):

1. "Which of the SPACECAST 2020 system concepts offer the greatest promise of increasing operational effectiveness?"

2. "What are the technologies that would offer the greatest leverage in making high-value system concepts into operational realities?"

The team encountered two major technical challenges. First, they had to estimate the performance of incompletely defined systems that might depend on technology that does not yet exist. Thus, the analysis depended on imprecise human judgment. Second, the they had to compare alternatives that were inherently different.

2.1.1 Methodology. The SPACECAST 2020 study uses a Value-Focused Thinking (VFT) approach. The operational analysis team considered other analysis techniques but found them less suitable for various reasons (1:S-4).

JCS PUB 3-14, *Military Space Doctrine*, is the basis for the VFT model hierarchy. At the top of the hierarchy is the goal of controlling and exploiting space from the Air Force mission statement. JCS PUB 3-14 further divides controlling and exploiting space into four mission areas:

Force Enhancement (FE):	Assisting terrestrial military forces
Force Application (FA):	Applying military force for ballistic missile defense, for defense of terrestrial forces, or directly against enemy targets
Space Control (SC):	Monitoring space activity, defending against attacks in space, and negating hostile space systems
Space Support (SS):	Launch, satellite control, and logistics operations

The JCS PUB 3-14 further divides each mission area into force capabilities and the team analyzed each capability to identify force qualities.[1] Figure 1 shows an illustration of the top levels of the value model and Appendix A gives the complete model (1:S-27). They selected force qualities that are, as far as possible, "concrete and measurable" and to do this they divided some force qualities further (1:S-6). The model contains 98 force

[1] The analysis team used the terms: mission areas, force capabilities, and force qualities. Keeney and Raiffa use the terms: fundamental objective, objectives, subobjectives, and attributes. The model's fundamental objective is to control and exploit space. The mission areas are objectives, force capabilities are subobjectives, and force qualities are attributes (6:33-34,43).

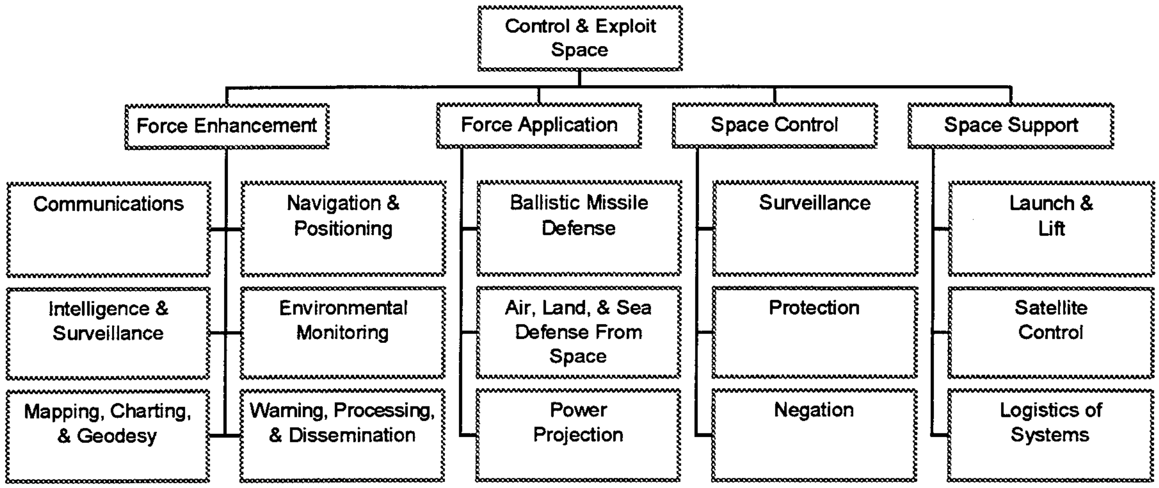

Figure 1. Upper Levels of the Value Model

qualities. For each of the 98 force qualities, the team developed one or two measures of merit (MOM) to score the systems.

2.1.2 Systems and Scoring. Once the team defined the value hierarchy, they incorporated relative weights into the model. They assigned weights, which sum to one, to the four mission areas first, and then to the force capabilities. The force capability weights sum to one under each mission area. Similarly, they set up the force quality weights for each force capability.

The team scored each system against each of the 98 MOMs. The SPACECAST 2020 study team identified 19 systems, which results in a maximum of 1862 judgments.[2] Two systems, Holographic Projection and Asteriod Negation were not scored because they did not fit into the model (1:S-12). They made these judgments using the following scale with benchmark levels of capability improvements:

[2] However, significantly fewer judgments were actually required. One system scored against only four MOMs and one system scored the most against 49 MOMs.

Improvement over current capability	Score
None (Current Capability)	0.0
Minor	0.1
Significant	0.5
Order of magnitude	0.9.

They calculated a system's utility toward controlling and exploiting space using Equation (1).

$$U(\bar{x}_i) = \sum_{m=1}^{4} k_m \sum_{c=1}^{C_m} k_c \sum_{q=1}^{Q_C} k_q \sum_{s=1}^{S_q} k_s U_{mcqs}(x_{imcqs}) \qquad (1)$$

where:

i = system, $1 \leq i \leq 19$

k's = weighting factors

m = mission area, $1 \leq m \leq 4$

c = force capability, C_m = number of force capabilities in mission area m

q = force quality, Q_c = number of force qualities in capability c

s = sub-force quality, S_q = number of sub-force qualities in force quality q

no sub-force qualities for a particular force quality $\Rightarrow k_s = 1$ and $U_{mcqs}(x_{imcqs}) = U_{mcq}(x_{imcq})$

$U_{mcqs}(x_{imcqs})$ = scoring function

The utility, which is between 0 and 1, was then scaled between 1 and 11 by mulitiplying by ten and adding one. The addition of one represented the linear transformation of current capability from zero to one.

The results show seven systems scored above the rest. The remaining systems scored very closely. To present the results, the SPACECAST 2020 technology team

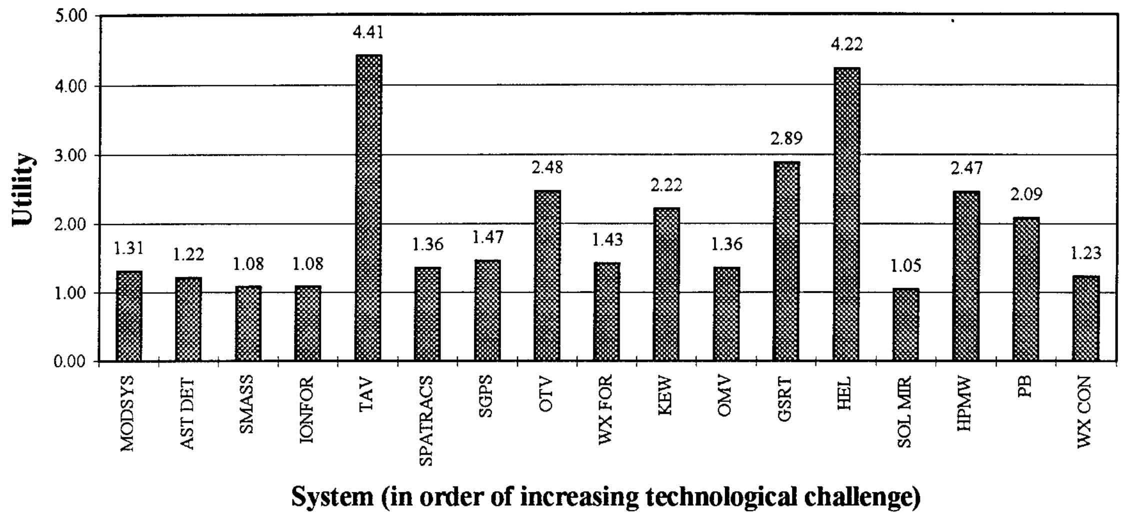

Figure 2. SPACECAST 2020 System Rankings

ordered the systems in increasing technological challenge. Figure 2 contains the key results.

2.1.3 Technology Ranking. The SPACECAST 2020 study group also identified and prioritized the high-leverage technologies that would support the warfighter. The technology team analyzed the 19 systems to determine the required technologies in each system. They used a standardized list of technologies identified in the DoD document entitled *The Militarily Critical Technologies List* (MCTL) , with one addition (virtual reality).

The technology team assigned relative weights, which summed to 100, to the technologies in each system. To get a technology's relative score, they multiplied the weights by the system utility and then summed these products across the systems. These scores identify the technology's importance to future space systems and take into account

Table 1. Technology Scores Against the Top 7 Systems (1:S-19)

Critical Technologies	System Dependence on Technologies (Percent)							Weighted Technology Score
	TAV	OTV	GSRT	HEL	HEW	HPMW	PB	
High Performance Computing	20		20	5	20	5	5	15.9
Micro-mechanical Devices	5	20	10	5	15	5	5	11.3
Materials Technology	30	5						11.0
Pulsed Power Systems						40	40	10.2
Nav., Guidance, and Vehicle Control	10			5	25	5	5	9.3
Robotics, Controllers, and End-Effectors	20	15						9.0
Lasers				25				8.1
Optics				25				8.1
High Energy Laser Systems				25				8.1
High Power Microwave Systems						45		6.6
Power Systems and Energy Conversion		20		10				6.2
Nonchem. High Specific Impulse Prop.		40						5.9
Neutral Particle Beam						45		4.9
Kinetic Energy Systems					40			4.9
Sensors			25					4.7
Data Fusion			20					3.8
Energetic Materials	10							3.4
Image Processing			15					2.8
Electromagnetic Communications			10					1.9
Vehicle Survivability	5							1.7

the relative importance of the systems in controlling and exploiting space. Table 1 shows the technology scores against the top seven systems.

2.1.4 Sensitivity Analysis. When the SPACECAST 2020 study group briefed these results, the issue of the utility's sensitivity to weight values was immediately raised. The operational analysis team performed a limited sensitivity analysis. Using five other weighting schemes for the mission areas, the team determined the system utility's sensitivity to the weights. The sensitivity analysis results show that the top seven systems remain well above the rest and in nearly the same order. The system utilities are robust to changes in the weights (1:S-14,S-18).

Armed with the system utilities and the technology scores, the SPACECAST 2020 study group reported back to General McPeak and identified high-leverage systems and technologies the military might pursue. The study group cautioned in their final report that the systems and related technologies ranked were only those which the study proposed. Also, the operational analysis team completed their model in only a few weeks and they could not address all issues.

2.2 Limitations of the SPACECAST 2020 Operational Analysis

The operational analysis team had only six weeks to complete their analysis. Therefore, they had to make some simplifying assumptions.

2.2.1 Current Capability Assessment. The SPACECAST 2020 model does not assess the current capability of the MOMs. The operational analysis team set the current capability benchmark level to zero utility.

2.2.2 Measure of Merit Scoring. The SPACECAST 2020 model scores each system against the scale outlined in Section 2.1.2. This is a major simplification that the team felt was acceptable given the scope of the study. The team did not have time to analyze each of the 98 measures of merit and determine its scoring curve. Therefore, they decided that each MOM would use a scale from 0 to 1 with benchmark levels. This simplified the ranking process and allowed model completion in the short time available. However, one cannot reasonably expect all 98 MOMs to have the same scoring curve. There are many possible scoring curves with linear, "S," concave, and convex being the most common (6:148-158;14:21).

2.2.3 Additive Utility Function. The operational analysis team, again limited by time, used an additive utility function. Additive utility functions are the simplest and best known. However, their use is restricted to value models which have additive independent attributes.[3]

[3] Keeney and Raiffa discuss additive independence in detail (6:230-232).

The value model uses the following additive utility function at the mission area level to assess each of the 19 systems:

$$U(\bar{x}_i) = \sum_{m=1}^{4} k_m U_m(x_{im})$$
$$U_m(x_{im}) = \sum_{c=1}^{C_m} k_c \sum_{q=1}^{Q_c} k_q \sum_{s=1}^{S_q} k_s U_{mcqs}(x_{imcqs}) \qquad (2)$$

where the terms are defined in Equation (1). Equation (2) is Equation (1) rewritten into two parts to show the additive utility function at the mission area level of the model. This utility function does not allow for any cross terms that account for interactions between the mission areas.

Multiplicative and multilinear utility functions are not as restrictive and allow for cross terms. However, they are more complicated and require further human judgment in assessing mission area utilities to compute the cross term weights (6:288-294). When the mission area weights sum to one, as is the case with the SPACECST 2020 value model, the cross term weights in the multiplicative and multilinear functions are all zero. The only terms left are the ones in the additive utility function.[4]

The SPACECAST 2020 value model assumes that there are no cross terms implying no interaction between the mission areas. This is a major simplifying assumption in the model. The operational analysis team assumed this lack of synergy (positive or negative) between the areas would not detract from the validity of the results.

2.2.4 System Concept Selection. The operational analysis team cautioned in its final report that the results are only for those systems and technologies identified by the

[4] Keeney and Raiffa show that the additive and multiplicative utility functions are a special cases of the multilinear utility function (6:293-294).

SPACECAST 2020 study. The SPACECAST 2020 study group sent out a general call for ideas on future system concepts and technologies. The best ideas were written up in White Papers. The study identified 19 systems and 25 technologies.

The technology team analyzed the papers and identified unique systems and their required technologies. The White Papers and the technology team did not explicitly consider *all* current or projected operational requirements. In order to have a comprehensive study, there must be a strong link between current and potential space operations and the systems and technologies entered into the value model.

2.3 Other Prioritization Methods

A review of how other organizations measure effectiveness and prioritize future systems and technologies shows that there is no widely accepted model used in the space community. This section briefly discusses three methods currently in use.

2.3.1 Air Force Space Command's Strategy-to-Task. Air Force Space Command (AFSPC) uses an approach called Strategy-to-Task to prioritize future space systems and technologies. However, this methodology is not completely formal and is ad hoc at times (18).

Headquarters AFSPC staff officers first perform a mission area assessment. They compare the National Security Strategy developed at the Presidential level and the National Military Strategy developed at the Joint Staff level with operational tasks and measures of merit. These measures of merit are at the task level and not at the system level. As an example, a measure of merit might be suppression of enemy launch rates, which is not "concrete and measurable." From this, the staff officers determine what AFSPC should be doing militarily in and from space.

They also perform a mission needs analysis. This analysis looks at AFSPC's current capabilities and systems. It also reviews systems and technologies already in research and development. They then compare this analysis to the mission area assessment and they create a list of deficiencies.

From this deficiency list, the staff officers then draft Mission Need Statements (MNS). These documents identify requirements that drive the need for future systems and technologies to eliminate the mission deficiencies. Because of limited resources, AFSPC cannot pursue all requirements equally. They then attempt to prioritize the MNSs.

They use a number of criteria in their ranking process. Two major criteria are the Research, Development, & Acquisition (RD&A) Priorities List and the Integrated Priorities List (IPL). The RD&A Priorities List rank-orders current systems and technologies in research and development. Each Unified Command creates an IPL that states its prioritization of current systems and technologies to meet mission needs. These documents in themselves do not completely prioritize the MNSs.

The staff officers then employ expert judgment in an informal group process to take all this information and develop a prioritized list of systems and technologies.

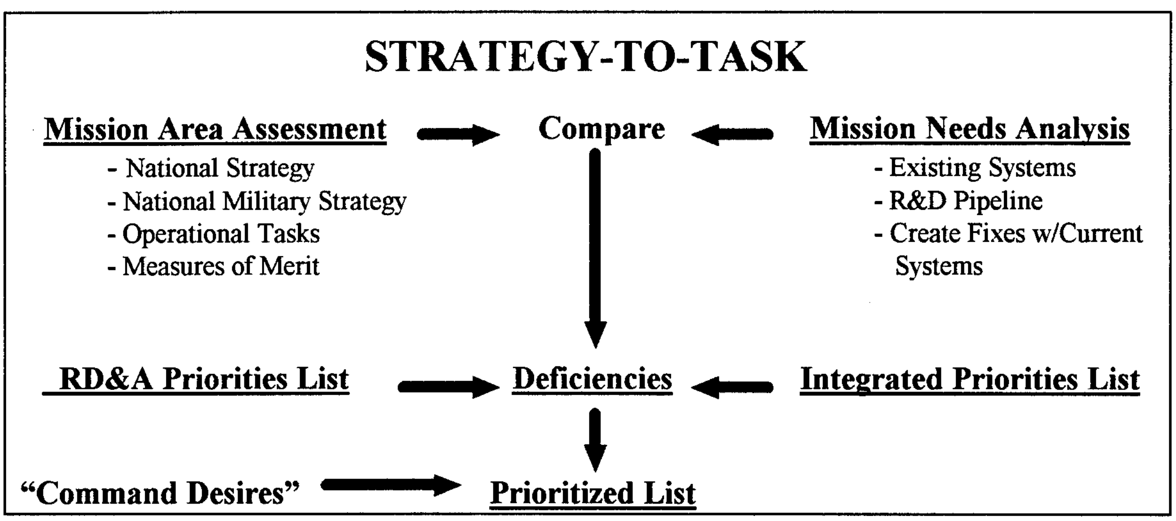

Figure 3. AFSPC's Strategy-to-Task

However, the staff officers quite often take into consideration "Command desires" (18). These desires are not always quantifiable nor concrete.

Figure 3 shows a flow diagram for AFSPC's Strategy-to-Task method. It is very good at matching current and projected mission needs with proposed systems and technologies. However, the method is not always formal and some judgments are not concrete and measurable.

2.3.2 Phillips Laboratory. Phillips Labs (PL) is closely linked with AFSPC. PL provides a large portion of the R&D for space systems and technologies. Therefore, how they prioitize projects and measure technology effectiveness is relevant to this discussion.

Phillips Labs uses three methods. First, the using command may set their priorities. As an example, AFSPC will give their prioritized list and PL will structure their projects accordingly. Second, PL has computer modeling and simulation capabilities for measuring effectiveness. This is good for known systems and technologies, however, SPACECAST 2020 is dealing with future systems and technologies about which little may

Force Capabilities	**Technologies**					
	Tech 1	Tech 2	Tech 3	Tech 4	Tech 5	Tech 6
Missile Warning Reconnaissance & Surveillance Spacelift C2 NORAD Satellite Communications Counterspace Ballistic Missile Defense C3 Nuclear Deterrence Satellite Control Conventional Deterrence Navigation Space Surveillance Environmental Sensing	1. Does the technology contribute to the mission? Yes/No 2. Score the technology: No 0 Yes 1 if useful to the mission 2 if significant to the mission 3 if critical to the mission 3. Multiply across by mission weight and sum down the technologies					
Scores	Score 1	Score 2	Score 3	Score 4	Score 5	Score 6

Figure 4. Phillips Lab Hierarchy

be known. Third, PL uses a hierarchy method similar to SPACECAST 2020 but much simpler (15). Figure 4 illustrates this hierarchy. AFSPC provided their list of force capabilities, from most to least important. Phillips Lab, in an attempt to create a prioritization method, translated this rank-ordered list into an equal interval scale of

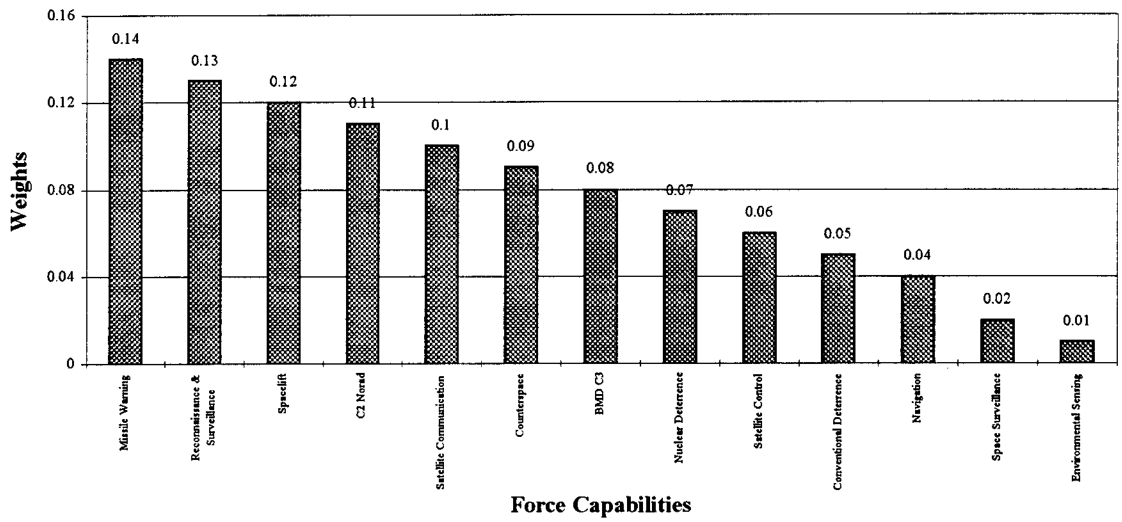

Figure 5. Phillips Lab Force Capability Weights

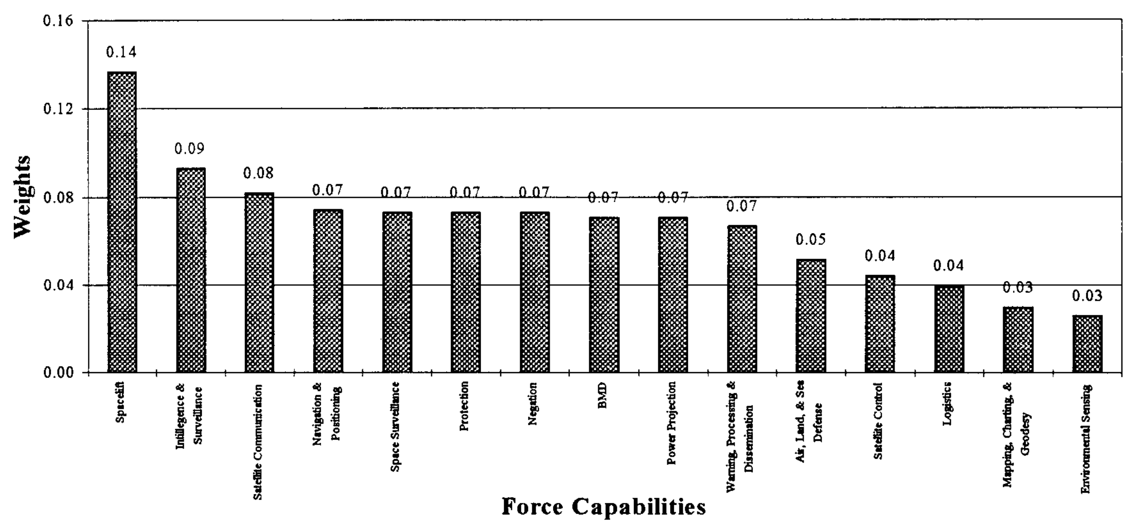

Figure 6. SPACECAST 2020 Force Capability Weights

weights. Figures 5 and 6 compare these weights with the SPACECAST 2020 force capability weights (multiplied by their corresponding mission area weights). Intuitively, the linear list of capabilities cannot reasonably represent the actual weightings. Some force capabilities may be much more or less important than the next on the list. SPACECAST 2020 weights seem more reasonable. Phillips Lab had also realized this and never used this weighting scheme as a method for technology prioritization (15). PL still uses this method, without weighting factors, as a tool to measure a technologies impact on the force capabilities.

An attractive aspect of this method is Phillips Lab's use of a formalized group session, the Delphi Method, in answering the question posed in the hierarchy (15). The Rand Corporation developed the Delphi Method in the 1950s specifically for the Air Force as a forecasting tool. It employs "an iterative questionnaire of experts . . . [to] produce a consensus and accurate forecast" (14:51). It is good at producing a consensus forecast but some raise doubt over whether or not it is accurate (14:51). Regardless, it is a traceable, formalized method.

Phillips Lab is closely linked with AFSPC on space systems and technologies. They both prioritize their systems and technologies according to their respective methods. However, neither looks outside the military for ways of forecasting systems and technologies for the future.

2.3.3 Private Sector Forecasting. When making forecasts for the future, corporations consider a multitude of issues. Overriding all these issues is the corporate strategic plan. The corporation uses the strategic plan as a "compass" to move into the future (5:114).

Corporations consider issues such as current products, competition, market size, corporate culture, cost analysis, public demand, government policy, profit projections, and many, many others. They generally have experts available to analyze each variable, employ forecasting techniques, and determine the effect on the corporate strategy. They then may move in a new "direction" as necessary to capitalize on the future. The corporation is continually allowing for unseen forces. Corporations "prepare options because [they] don't know what [they] are going to need" or have available in the future (9). Dr. Joseph Martino, a noted expert in civilian technology forecasting, uses the business situation of 1920 as an example. In 1920, nobody (or very few) could possibly imagine the advances made through 1946. In those 26 years, industry and the military developed nuclear weapons, television, radar, and jet engines. Similarly, the year 2020 is 26 years in the future. Dr. Martino cautions that any forecasting methodology must be flexible to allow for systems and technologies that we cannot image now.

2.4 Chapter Summary. The SPACECAST 2020 Study successfully identified and prioritized space systems and technologies that could support the warfighter in the future. However, in its analysis, the operational analysis team made some simplifying assumptions, due to limited time. The SPACECAST 2020 value model does not determine the current level of capability for the MOMs. The team assumed the 98 MOMs use the same scoring function and that the utility function is additive. They cautioned that the systems actually entered are not all inclusive and the White Papers did not explicity consider current and projected space operational requirements. However, they were confident that these assumptions and omissions would not reduce the completeness or validity of the results. A review of other prioritization techniques shows that there is no accepted model used by the space community. The SPACECAST 2020 model is a step foreward but more work is needed.

III. Modified SPACECAST 2020 Value Model

This Chapter presents modifications to the SPACECAST 2020 Value Model that address the issues presented in chapter two. These modifications demonstrate the validity of the SPACECAST 2020 Value Model as a tool that prioritizes future, high-leverage space systems and technologies.

3.1 Measure of Merit Scoring Functions

This research first addresses the assumption that all the scoring functions are the same as described in section 2.1.2. It identifies and reassigns scoring functions to most of the 98 measures of merit. Then it rescores each of the systems with these new functions.

3.1.1 Scoring Functions. This research uses the following four common scoring functions: linear, concave, convex, and "S." Figure 7 shows examples of these functions.

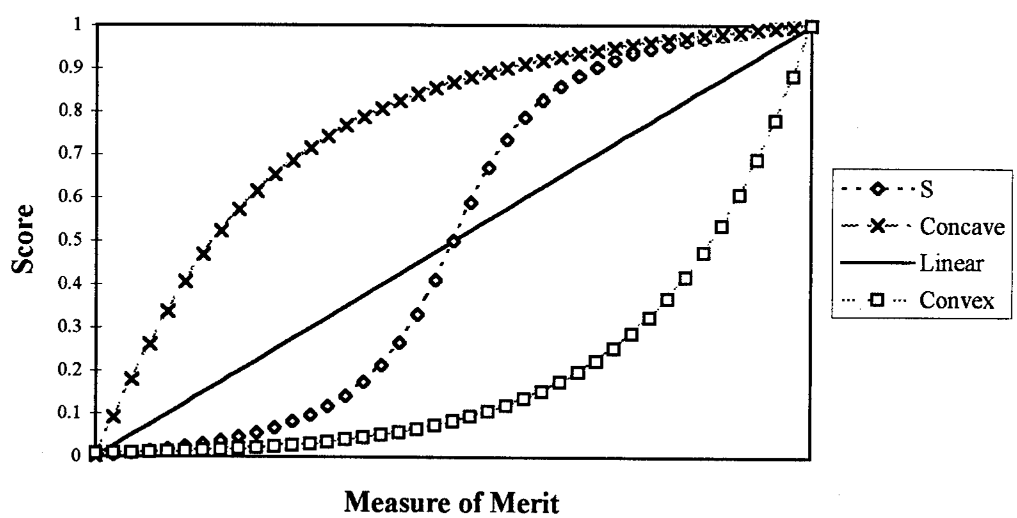

Figure 7. Example Scoring Functions

The linear, concave, and convex functions capture the three risk attitudes towards score increases for some MOM increase. The attitudes are risk-averse, risk-prone, and risk-neutral.[1]

The concave function (risk-averse) captures rapid score increases for small increases at low MOM levels with decreasing score gains at higher levels. The convex function (risk-prone) is just the opposite. It captures rapid score increases at high MOM levels. The linear function (risk-neutral) captures equivalent score increases at all capability levels.

The "S" curve is a combination of the linear, concave, and convex functions. It is convex at low capability levels, then becomes nearly linear, and then reaches a point where it is concave for high capability levels.

3.1.2 System Rescoring. In a group session, members of the SPACECAST 2020 technology team and operational analysis team reviewed the measures of merit and assigned new scoring functions to many.

Many of the original measures of merit indicate which curve provides a best fit. As an example, the second measure of merit, decompressed megabits per second (MBits/Sec), indicates a concave function. The original scoring scale with benchmark levels is:

Mbits/Sec	Score
300 (Current Capability)	0.0
600	0.1
1000	0.5
3000	0.9.

[1] Clemen gives a clear, non-technical description (2:363-368) and Keeney and Raiffa give a complete, technical discussion on risk attitudes (6:145-187).

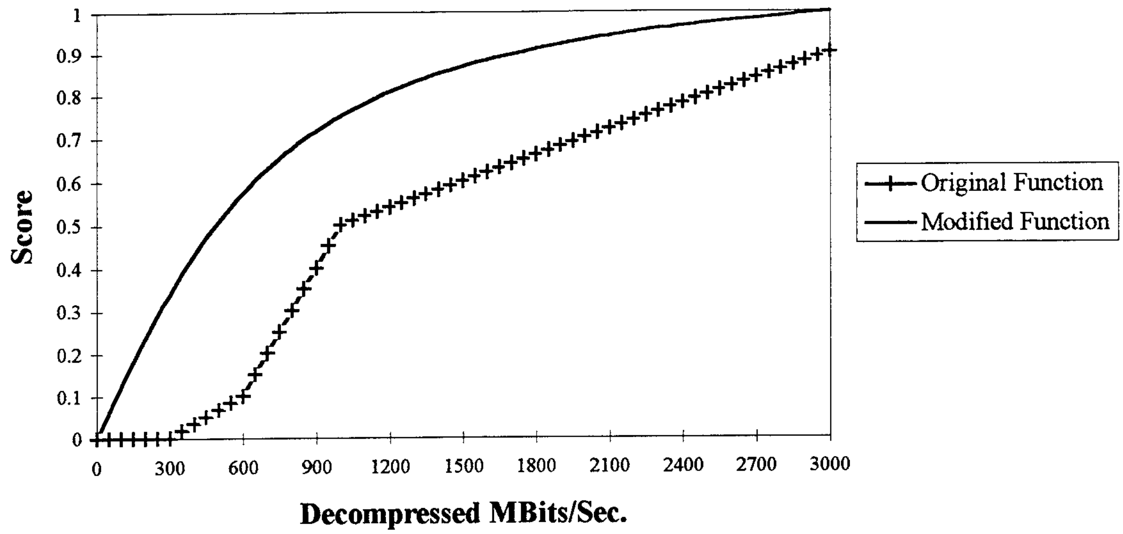

Figure 8. MOM #2, MBits/Sec, Concave Scoring Function

A plot of the number of Mbits/sec versus the score clearly shows a concave scoring function (Figure 8). This research replaces the original scale with a smooth concave curve (modified scoring function).

Next, the group set capability endpoints for the new curves. A few of the original SPACECAST 2020 current and order of magnitude capabilities became the endpoints. For most, however, the group chose entirely new endpoints in order to assign a non-zero score to current capability and to capture possible increases in capability not yet technically possible.

The modified scoring function does not return a current capability score of zero as is always the case in the original model. Again, the second measure of merit uses 300 MBits/Sec equal to zero in the original scoring function. The modified concave scoring function, where x is in Mbits/sec for system i,

$$U_{FE,Commuications,Capacity}(\bar{x}_i) = .728 Arc\tan(.00167 x_{i,FE,Communications,Capacity}) \quad (3)$$

returns a *current capability score* of .338 for 300 Mbits/sec and a *proposed capability score* unique to each system. No system scores below the current capability.

In some cases, the original MOM scoring functions are classified or cannot be represented as an equation. An example, the third MOM, common use system, uses the following scoring scale:

Commonality	Score
Little (Current Capability)	0.0
All AF Systems	0.1
All US Systems	0.5
US, Commercial, International	0.9.

The commonality levels cannot be represented as an equation unless the entire MOM is redefined. In those cases, this research uses the original scoring functions. However, this research modifies most of the non-numerical functions to assign a non-zero current capability and to capture expanded capability ranges. Appendix B contains the modified scoring functions and the current capabilities. The results are presented in Chapter IV.

This model uses three decimal precision for the MOM scores. Due to the nature of the mathematical equations, a few measures of merit return a current capability score of a few thousandths when it should be zero. This discrepancy does not alter the results. Appendix C contains the modified MOM scores and unscaled system scores.

3.2 Alternate Utility Functions

This research shows that the use of two less restrictive, but more complex, functions do not change the SPACECAST 2020 results. The two alternate utility functions are the multilinear and multiplicative utility functions.

3.2.1 Independence Assumptions. The multilinear and multiplicative utility functions require utility and mutual utility independence, respectively (6:288,293).

3.2.1.1 Preferential Independence. An attribute is preferentially independent (PI) of another attribute if the utility of the first does not depend on the level of the second. As an example,

> let Y be the time to completion of a project and X its cost. If we prefer a project time of 5 days to one of 10 days, assuming that the cost is 100 in each case, and if we also prefer a project time of 5 days to one of 10 days if the cost is 200 in both cases, then Y is preferentially independent of X . . . (2:477)

This research used a simple dialog, created by Keeney and Raiffa, to prove PI between one attribute and the others, without making any assessments (6:299-300). This approach, with four officers experienced or knowledgeable in space operations, clearly showed Space Support is PI of the others. The four officers cover a wide range of operational and staff experience. Three officers came from space operations in missile warning, space surveillance, and satellite command and control. One has recent headquarters AFSPC experience. The fourth officer is a pilot and knowledgeable in space operations. All four are members of the AFIT Graduate Space Operations degree program.

3.2.1.2 Utility Independence. Utility independence (UI) is a stronger condition than PI and more difficult to prove. UI is similar to PI but the choices are now under uncertain conditions. Extending the example above, lets assume you are indifferent between a *certain* level of Y= 8 or a 50-50 chance of getting either Y=5 or Y=10 at a fixed level of X. If your *certain* level of Y does not change when the level of X is changed then Y is UI of X. If X is UI of Y then they are mutually utility independent (2:478).

Using a very similar approach as that for PI, this research can reasonably claim that Space Support is UI of the others. The four officers gave responses that indicate SS is UI of the others. They indicated that there are some cases where SS is not completely UI by responding with *certain* levels of SS that are not equivalent to each other.

However, they always responded with "reasonably close" values, generally .01 or .02 difference, which indicate that UI is a reasonable assumption (6:266). Given Space Support is PI and UI of the others, this research shows that the mission areas are mutually independent of one another.[2]

3.2.2 Multilinear Utility Function. The multilinear utility function has the least restrictive criteria for its use. Each mission area has to be utility independent of the others, which is the case since the mission areas are mutually utility independent. The function is of the following form, with i indicating the system (6:293):

$$U(\bar{x}_i) = \sum_{m=1}^{4} k_m u_m(x_{im}) + \sum_{m=1}^{4}\sum_{j>m} k_{mj} u_m(x_{im}) u_j(x_{ij}) + \sum_{m=1}^{4}\sum_{j>m}\sum_{l>j} k_{mjl} u_m(x_{im}) u_j(x_{ij}) u_l(x_{il}) + k_{mjlp} u_m(x_{im}) u_j(x_{ij}) u_l(x_{il}) u_p(x_{ip}). \quad (4)$$

The subscripts j, l, and p also represent the mission areas. The k's are mission area weights defined below and the $u_m(x_{im})$'s are mission area utilities introduced in Equation (2). $U(x_i)$ will be between 0 and 1.

3.2.2.1 Mission Area Utilities. The value model produces the mission area utilities, $u_m(x_{im})$'s, for each system and requires no further assessments. The mission area utilities are the sum of the products of the MOM score, force quality weight(s), and force capability weight under each mission area (Appendix D).

3.2.2.2 Mission Area Weights. The mission area weights require mission area utility *assessments*. Mission area utility assessments are a decision maker's relative value, scaled from 0 to 1, of the utility of all the possible combinations of the mission areas set to maximum capability with the others at minimum capability. As an example,

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[2] Keeney and Raiffa show that mutual utility independence of the attributes is equivalent to one attribute being PI and UI of the others (6:292).

U(FE,FA,SC,SS) = U(1,0,1,0) is a decision maker's relative utility of FE and SC set to maximum capability and FA and SS set to minimum capability. Appendix E contains the defining equations, the judgments, and the subsequent weights. If the one-way weights (i.e., k_{FE}, k_{FA}, k_{SC}, and k_{SS}) sum to one, the multilinear function collapses to the additive function. Therefore, the one-way weights do not sum to one and begin with .25 for Force Enhancement and keep similar relative magnitudes to the original mission area weights (i.e., .37, .19, .22, and .22). They are also all positive because the four mission areas contribute to and do not detract from controlling and exploiting space.

3.2.3 Multiplicative Utility Function. The multiplicative utility function requires mutually utility independence between the mission areas. The multiplicative utility function is of the following form, again using the same notation as before (6:289):

$$U(\bar{x}_i) = \sum_{m=1}^{4} k_m u_m(x_{im}) + k \sum_{\substack{m=1 \\ j>m}}^{4} k_m k_j u_m(x_{im}) u_j(x_{ij}) + k^2 \sum_{\substack{m=1 \\ j>m \\ l>j}}^{4} k_m k_j k_l u_m(x_{im}) u_j(x_{ij}) u_l(x_{il}) + k^3 k_m k_j k_l k_p u_m(x_{im}) u_j(x_{ij}) u_l(x_{il}) u_p(x_{ip}). \tag{5}$$

This function uses the same one-way mission area weights and mission area utilities as the multilinear function. However, it requires one additional weight, k. This weight is the solution to the following equation (6:347-348):

$$1 + k = \prod_{m=fe,fa,sc,ss} (1 + k k_m). \tag{6}$$

Again, the k_m's are the one-way weights. Appendix E shows k = 1.88 for the given scaling constants.

3.3 SPACECAST 2020 Mission Area Weights

As Section 2.1.4 indicates, there is concern over the system score sensitivity to mission area weights. The SPACECAST 2020 study addresses this concern by using alternate weighting schemes showing the utility scores are robust to the weights. This research uses a formalized group technique to arrive at accepted weights.

3.3.1 Nominal and Delphi Group Techniques.

Delbecq and Van De Ven developed the Nominal Group Technique in the late 1960s and early 1970s (14:55).

> It has a systems engineering rigor . . . [and] is increasing in popularity as a group method, especially in technology companies. It is best used when structure is needed, such as in the following circumstances: when certain people who can be argumentative and domineering must be included in the group, when people who do not know each other are together, when people who do not like each other are together, when managers and staff analysts are mixed, when the topic is sensitive or controversial, and when corporate politics need to be managed carefully . . ." (14:55).

In the assessment of the mission area weights, the group could exhibit many or all of these characteristics. Also, many decision makers must accept the weights and this method addresses this possible controversy. However, it does not allow for an iterative process to arrive at a consensus.

The Delphi Method uses a carefully constructed questionnaire given to a group of experts not necessarily convened in one place. The moderator collects the responses, tabulates the results, and sends them back to the group members. At this time, the moderator also sends the names of the other respondents to each group member. The moderator repeats these steps until the respondants reach a consensus or until it is obvious they cannot reach one (14:51-52).

The Delphi Method and the Nominal Group Technique both contain aspects that are favorable to assigning weights to the mission areas. The Delphi Method allows for an iterative process and the Nominal Group Technique handles group dynamics very well. This research uses a mixture of these aspects to create a new, formalized technique

3.3.2 Modified Group Technique. This procedure derives the following five steps from the Delphi and Nominal Techniques:

1. The group moderator provides a detailed briefing on the topic.

2. The group members decide on their weights in private using only their knowledge and experience.

3. Each group member, in turn, gives their weights to the group and the moderator records the high and low values. The moderator places the high and low weights on a blackboard so the entire group can see them. The group members with the high and low values explain their decisions with no interruptions from the others. This forces quiet members to voice their opinions and keeps the domineering members quiet.

4. The group then discusses the weights. Here group interaction flows, within reason. This discussion distributes each individual's ideas and reasons for their decisions. It makes others aware of issues that they may not have considered.

5. The moderator repeats steps two through four until each group member is confident that they will not change their weights. The moderator collects each member's weights and performs statistical analysis to generate means, standard deviations, and confidence intervals.

3.3.3 Results. This research convened a group of ten officers with considerable knowledge and experience in space operations. To ensure unbiased weights, the members were unaware of the results of the SPACECAST 2020 study. Table 2 shows the descriptive statistics on the SPACECAST 2020 weights and the group's mean weights. The SPACECAST 2020 statistics are derived with a sample of six responses. After participating in the modified technique, this group gave weights to the mission areas

Table 2. Modified Technique Statistics

Statistic	Force Enhancement	Force Application	Space Control	Space Support
Mean:				
Group	38.1	15.1	21.2	25.6
SPACECAST	36.67	19.17	22.5	21.67
Standard Deviation	5.16	4.92	6.12	2.58
Minimum	30	10	15	20
Maximum	40	25	30	25
95% Confidence	32.54-40.80	15.24-23.10	17.60-27.40	19.60-23.74

that were almost the same as those in the SPACECAST 2020 study. However, the group's Force Application and Space Support weights are just outside the 95% confidence interval.

3.4 System Selection

AFSPC should generate new system concepts and decide which ones to enter into the value model. AFSPC should use a formalized procedure which provides a strong link to current and projected space operational requirements. The procedure must also be flexible and allow for unforeseen missions and systems in the future. This research outlines such a procedure.

3.4.1 White Paper System and Brainstorming. The SPACECAST 2020 White Paper system was good at generating new missions and system concepts. AFSPC should send out a call to other commands, researchers, colleges and universities, writers, movie producers, and any group with an interest in space to generate ideas for missions and systems in space operations. AFSPC should not limit the creativity of these groups by putting requirements on the potential ideas. Also, AFSPC should convene a group of its own "experts" for a brainstorming session to generate ideas.

3.4.2 Link to Operational Requirements. AFSPC already uses Strategy-to-Task to identify mission deficiencies. However, it does not have a formalized process of ranking the systems. The SPACECAST 2020 value model could be used. AFSPC can take the missions and systems generated through the White Paper system and its own ideas and match them to the identified deficiencies. If no system concept matches an identified deficiency, AFSPC can generate one specifically for it. The value model can then prioritize the systems for the AFSPC decision makers. Then they can compare the priorities given to those systems that meet current deficiencies, meet future missions, or provide improved capabilities. This provides the decision makers with some flexibility.

3.4.3 Flexibility. This procedure allows for flexibility in the decision making process. The decision makers may decide to spend resources pursuing a system that does not meet a current deficiency but provides a future mission or significantly improved capability. Also, by calling for White Papers and convening its own group every year or two, AFSPC ensures that they incorporate missions and capabilities not yet imaged into the decision process. As necessary, they can add and delete force capabilities, force qualities, and measures of merit and reassign the relative weights.

IV. Results and Analysis

The purpose of the model is to compute and prioritize the relative utilities of future space systems towards controlling and exploiting space. Although the magnitude of the utilities provides insight into a system's contribution, the relative ranking of the utilities is more important. The rankings tell decision makers which systems contribute the most to controlling and exploiting space.

This research uses the modified scoring functions to compute the *modified utility* rankings with the additive, multilinear, and multiplicative utility functions. It uses the SPACECAST 2020 mission area weights in the additive utility function to compare the modified results to the SPACECAST 2020 results.

This chapter shows that the additive utility function is nearly strategically equivalent (i.e., same preferential ordering) to the multilinear and multiplicative utility functions (6:81). This research validates this claim using regression analysis. The regression analysis uses the unscaled utilities.[1]

The SPACECAST 2020 study shows that the additive utility function is robust to changes in the mission area weights. This chapter shows that the multilinear and multiplicative utility functions are also robust to changes in the mission area weights and mission area utility assessments.

4.1 Additive Utility Function

4.1.1 Results. Figure 9 shows the magnitudes and the relative rankings of the modified utilities. These results are derived using the SPACECAST 2020 mission area weights, the modified scoring functions, and the additive utility function. The results show

[1] This avoids explaining in the regression analysis the different scalings used by the SPACECAST 2020 and the modified models.

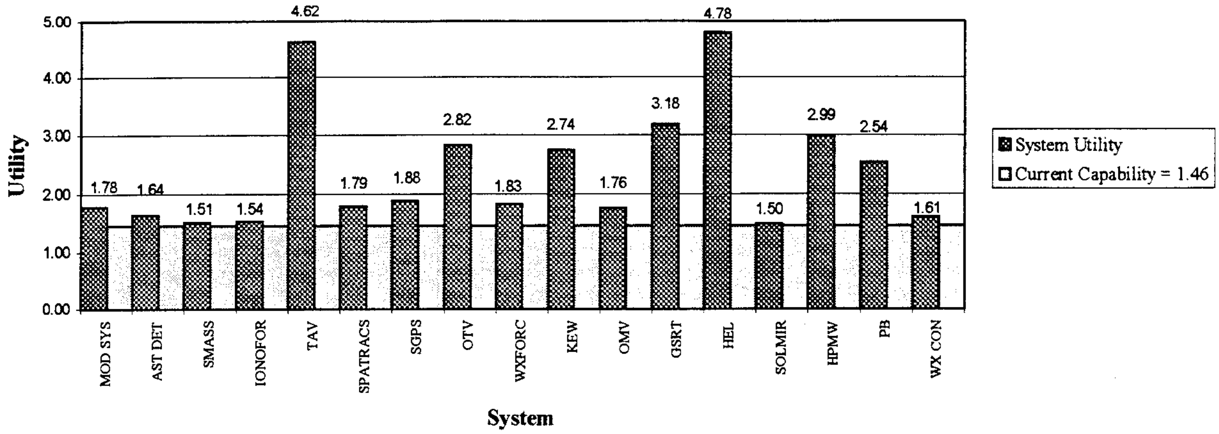


Figure 9. Additive Utility Function Results

that the same seven systems score above the others as in the SPACECAST 2020 results. There are three distinctive groupings consisting of the HEL and TAV at the top; the GSRT, HPMW, OTV, KEW, and PB in the middle; and the rest closely grouped at the bottom.

This model calculates the overall current capability. As described in Section 3.1.2, the modified scoring functions equate no capability to a zero score. The model gives current capability a non-zero score unless there is *no current capability* for a particular MOM. The overall current capability is also computed using the SPACECAST 2020 mission area weights, the modified scoring functions, and the additive utility function. The scaled current capability is 1.46 (scaled by multiplying by 10).

The model produces utility magnitudes between zero and one which are then scaled between zero and ten. Also described in Section 3.1.2, a system's utility is the weighted sums of the MOM proposed capability scores. For scaling, the system score is multiplied by 10. This is a linear transformation and produces no change in the rankings.

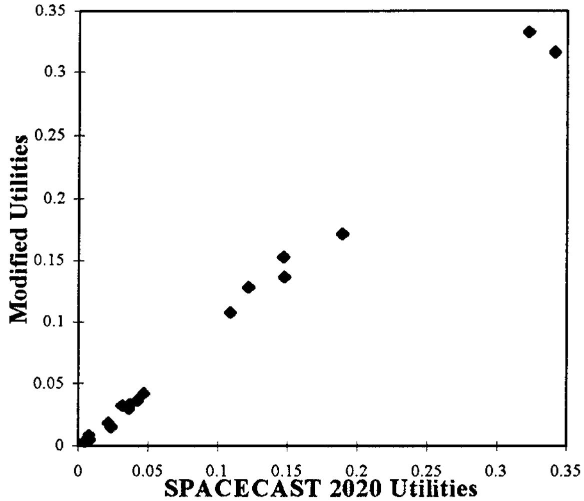


Figure 10. Comparison of the Additive Utility Function Results

4.1.2 Analysis. Figure 10 shows the SPACECAST 2020 utilities (X horizontal axis) plotted against the modified utilities (Y vertical axis). If the magnitudes and relative rankings are exactly the same, the points would lie upon a straight line through the origin with a slope of one (45 degrees). Since the utility magnitudes are not as important as the relative rankings, strategic equivalence between the utility functions is desired.

Keeney and Raiffa show that two utility functions are strategically equivalent if there exist constants B and C > 0 such that Y = C*X + B for all x_i.[2] Figure 10 shows that the utilities do not lie on a perfectly straight line because some of the system rankings changed. It also shows three distinctive groupings. They represent the groupings of systems discussed in Section 4.1.1. This pattern repeats itself in the results of the different utility functions.

Figure 10 shows some systems changed positions which indicates strict strategic equivalence does not hold. However, a regression analysis shows that a straight-line approximation is sufficient to explain the modified results and suggests using the simpler

[2] Keeney and Raiffa give a complete proof of strategic equivalence between utility functions (6:144)

model. A straight-line regression forced through the origin, Y = C*X (B = 0), produces the constant, C, required for strategic equivalence.[3] If the regression's statistical results strongly support the linear approximation, then the two utility functions are nearly stategically equivalent. Using the following hypothesis:

Null: $C \leq 0$ (i.e., the modified results are not a positive linear transformation of the SPACECAST results)
Alternate: $C > 0$ (i.e., the modified results are a positive linear transformation of the SPACECAST 2020 results),

a regression analysis produces the results in Table 3.

Table 3. Regression Analysis of the Additive Utility Functions

Coefficient	95% Confidence Interval	Students' t/P Value	R^2	Correlation
.9716	.9409-1.002	67.14/0.0000	.9965	.9982

The regression statistics strongly support the calculated value of C.[4] The students' t statistic is much greater than the rejection value of 1.746 required for a 5% significance level.[5] The rejection values are minimum values for the statistics to support a given significance level. A students' t of 67.14 has a p-value of less than 0.0000 indicating strong evidence to reject the null hypothesis. The p-value is the smallest significance value for which the null hypothesis is rejected (12:447). The R^2 statistic says that the linear equation, with C = .972, explains 99.65% of the error between the predicted and observed values based on the data obtained. The correlation value indicates that the two data sets

[3] A regression analysis not forced through the origin does not support a non-zero intercept, B, as Figure 10 indicates.
[4] Since there is only one coefficient, the F and adjusted R^2 regression statistics provide no added contribution to the argument.
[5] Rejection values for the student's t statistic are taken from tables proved by Mendenhall, et. al. (12:761,764-773). The significance level is the probability of rejecting the null hypothesis when it is true (12:430).

are 99.82% linearly correlated (4:43-44) which further supports rejecting the null hypothesis.

The points corresponding to the HEL and TAV have standard residuals of 2.29 and 1.84, respectively. These residuals are the largest for all the systems and lie well within the range of +/-4, which is the range of expected standard residuals (17).

Another test statistic specifically designed to test whether or not two distributions (utility functions) produce uncorrelated (and the opposite, correlated) preference rankings is Spearman's Rho (ρ) (3:243-248). It uses the following hypothesis:

Null: The distributions are uncorrelated
Alternate: There is a tendency for the functions to produce the same preferential rankings.

Given a sample of 17 values and a 5% significance level, rho must be larger than .4118 to reject the null hypothesis (3:390). Indeed, rho is .9877 for the two sets of utility values indicating that the two utility functions produce nearly the same preferential rankings. Rho is equal to one if the two functions produce the exact same preferential rankings. In this case, rho = .9877 indicates nearly identical rankings.

Although strict strategic equivalence does not hold, the regression results and the Spearman's rho test statistic indicate that the modified utilities using the modified scoring functions, additive utility function, and the SPACECAST 2020 mission area weights are sufficiently explained by the SPACECAST 2020 model.

4.2 Multilinear and Multiplicative Utility Functions

The results and analysis of the multilinear and multiplicative functions are divided into two sections. The first section deals with the results derived using the SPACECAST 2020 MOM scores. The second section deals with the results derived using the modified

MOM scoring functions. The results and analysis are similar to the ones for the additive utility function.

4.2.1 SPACECAST 2020 Data. Using the mission area utility assessments and mission area weights derived in Appendix E, the multilinear and multiplicative functions produce results which are almost exactly the same (Figure 11). Only one set of utilities is shown in Figure 11 for clarity; however, there is no loss of detail. Only one system, GSRT, has a difference in utility (.02) produced by the functions of more than .01. The two functions also produce results very similar to the SPACECAST 2020 additive function results. The multilinear and multiplicative utilities are scaled from one to eleven like the SPACECAST 2020 additive function results. The multilinear and multiplicative functions give a scaled overall current capability of one because the SPACECAST 2020 MOM scoring functions define it as such.

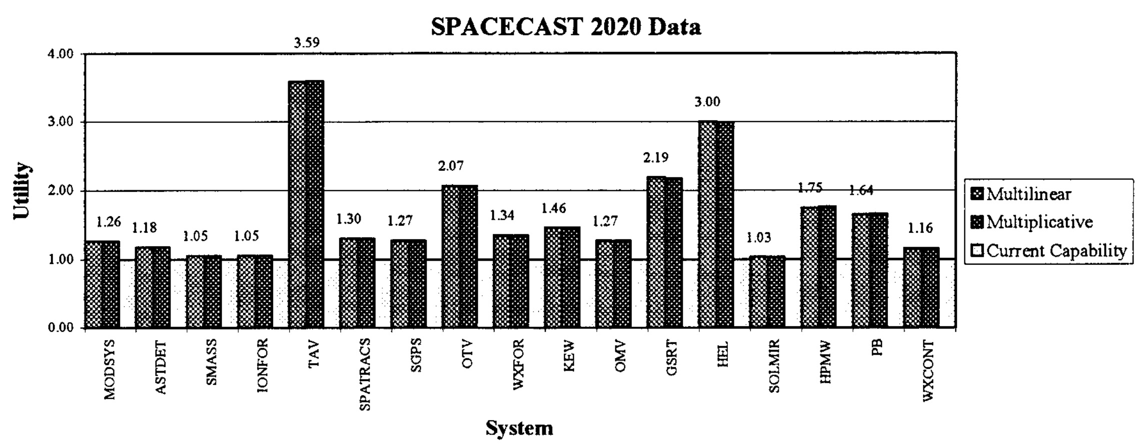


Figure 11. Results of the Multilinear and Multiplicative Utility Functions (SPACECAST 2020 Data)

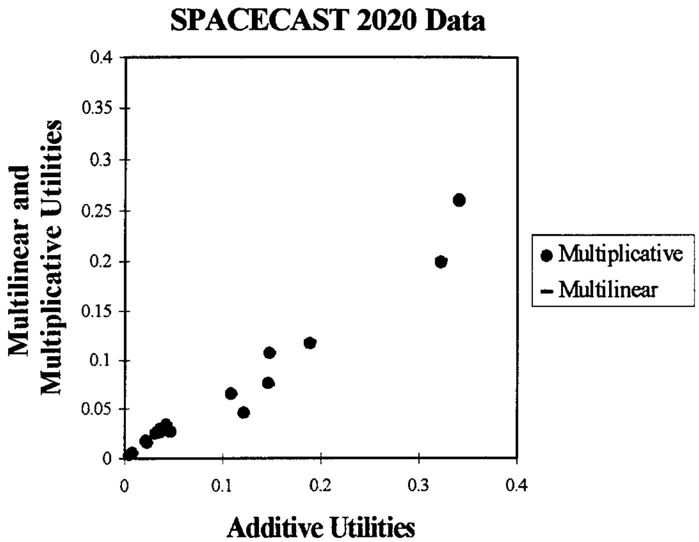


Figure 12. Comparison of the Multilinear and Multiplicative to the Additive Utility Function (SPACECAST 2020 Data)

Figure 12 plots both the multilinear and multiplicative derived utilities (Y vertical axis) against the SPACECAST 2020 utilities (X horizontal axis). The grouping pattern is the same as in Figure 10. It is difficult to see the separate points because they are in nearly the same location.

Figure 12 shows that there is more variability in the results and strict strategic equivalence does not hold; however, a regression analysis shows that the multilinear and multiplicative functions are sufficiently explained by the SPACECAST 2020 additive utility function. Table 4 gives the results of the regression analysis using the same hypothesis as Section 4.1.2. Not shown in table 4, the correlation between the multilinear and multiplicative functions is 99.99%.

Again, all of the regression statistics strongly support rejecting the null hypothesis indicating that the multilinear and multiplicative functions are sufficiently explained by the additive utility function.

Table 4. Regression Analysis of the Multilinear and Multiplicative Utility Functions Vs the Additive Function (SPACECAST 2020 Data)

Function	C	95% Confidence Interval	Students' t/ P-Value	R^2	Correlation
Multilinear	.661	.6014-.7212	23.40/0.0000	.9716	.9857
Multiplicative	.660	.6077-.7129	26.62/0.0000	.9779	.9889

The largest standard residual for the multilinear function is 2.42 (KEW) and for the multiplicative function is 2.41 (TAV). Again, both are well within the expected +/-4 standard residual range.

Spearman's rho statistics for the multilinear and multiplicative functions against the additive function are the same, .9853. This is expected because their individual results are nearly identical. Again, rho strongly supports rejecting the null hypothesis indicating that the multilinear and multiplicative functions produce nearly the same preferential rankings as the additive function. Rho for the multilinear against multiplicative function is 1, as expected.

The results of the regression analysis and Spearman's rho statistic indicate that there is strong evidence to reject the null hypothesis. The multilinear and multiplicative utility functions are sufficiently explained by and produce nearly the same rankings as the SPACECAST 2020 model. Therefore, the multilinear and multiplicative functions are nearly strategically equivalent to SPACECAST 2020 additive utility function.

4.2.2 Modified MOM Scoring Function Data. Again, the multilinear and multiplicative utility functions produce results which are almost exactly the same and are very similar to those of the additive utility function. Since the modified scoring functions are used, the current capability is computed and scaled (i.e., multiplied by 10). The multilinear and multiplicative functions both produce an overall current capability of 1.12.

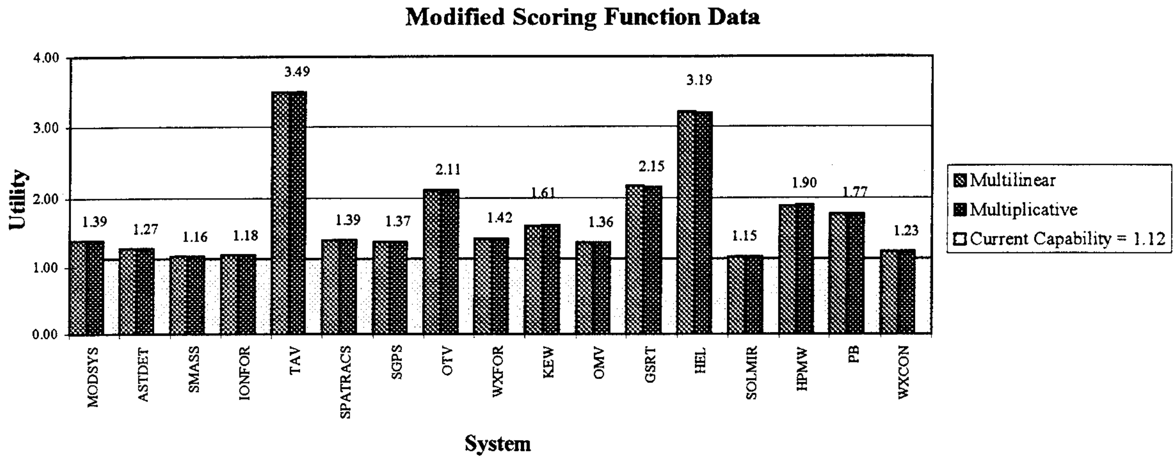


Figure 13. Results of the Multilinear and Multiplicative Utility Functions (Modified Scoring Function Data)

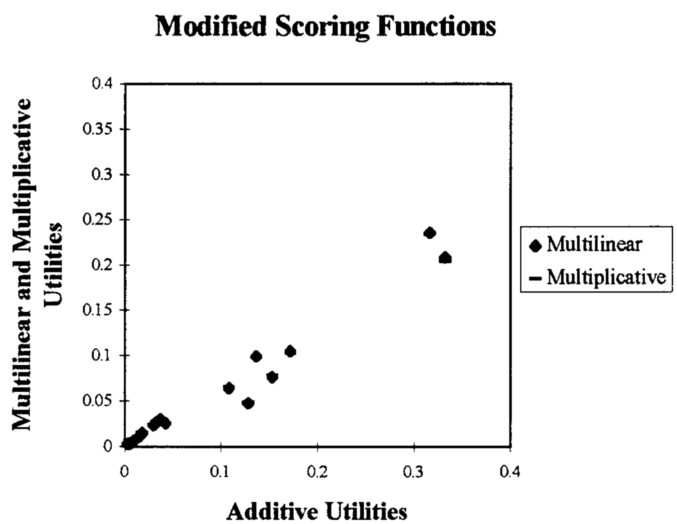


Figure 14. Comparison of the Multilinear and Multiplicative to the Additive Utility Function (Modified Scoring Function Data)

The function results are multiplied by ten and plotted in Figure 13. Figure 14 plots their unscaled utilities (Y vertical axis) against the unscaled additive utilities (X horizontal axis).

Again, Figure 13 shows only one set of utility values for clarity. Two systems, HPMW and GSRT, have the largest difference of .02. Also, Figure 14 plots both sets of utilities but it is difficult to see the individual points because they are in nearly the same location.

Again, Figure 14 shows almost the same variability and the same grouping pattern as in Figure 12. Table 5 shows the results of the regression analysis for the multilinear and multiplicative utilities as a linear function of the additive utilities. The same null and alternate hypothesis are used. The regression statistics again strongly support rejecting the null hypothesis, indicating that the multilinear and multiplicative functions are sufficiently explained by the additive utility function. The multilinear and multiplicative functions are 99.99% correlated.

Table 5. Regression Analysis of the Multilinear and Multiplicative Utility Functions Vs the Additive Function (Modified Scoring Function Data)

Function	**C**	**95% Confidence Interval**	**Students' t/P-Value**	$\mathbf{R^2}$	**Correlation**
Multilinear	.648	.5952-.7010	25.95/0.0000	.9768	.9883
Multiplicative	.647	.5953-.6995	26.35/0.0000	.9775	.9887

The largest standard residuals for both functions are 2.53 and 2.50 for the KEW. Again, these residuals are well within the expected +/-4 standard residual range.

Spearman's rho statistic is again the same, .9779, for both functions against the additive function. Again, it strongly indicates that the multilinear and multiplicative functions produce the same prefential rankings.

The results of the regression analysis and Spearman's rho statistic indicate that the results of multilinear and multiplicative functions are sufficiently explained by and produce nearly the same rankings as the additive function using the modified scoring function data. This shows that the multilinear and multiplicative utility functions are nearly strategically equivalent to the additive utility function using the modified MOM scoring functions.

4.2.3 Summary. In both cases, SPACECAST 2020 results and modified results, the multilinear and multiplicative function results are sufficiently explained by their corresponding additive utility function. Also, the modified utilities using the additive function is sufficiently explained by the SPACECAST 2020 additive model. These results indicate that there is no gain in using the more complicated, albeit, more appropriate functions. Even though additive independence between the mission areas has not been proven, there is no loss of accuracy in assuming it exists. However, before this research can assert that the additive utility function accurately calculates and prioritizes the systems' utility towards controlling and exploiting space, it must show the multilinear and multiplicative functions are robust to changes in the mission area utility assessments.

4.3 Sensitivity to Mission Area Utility Assessments

The SPACECAST 2020 study showed that the additive utility function is robust to changes in the mission area weights. This research shows that the same is true for the multilinear and multiplicative utility functions.

The mission area weights for the multilinear and multiplicative functions are functions of the mission area utility assessments. Since the mission area utility assessments are subjective but based on experience and knowledge in space operations, this research assumes that the assessments in Appendix E are baseline values. In order to show sensitivity, this research increased and decreased each of the one-way assessments (#'s 1,2,3, and 4 in Table 6, Appendix E) by 10% of their value. The same relative values for the two-way, three-way, and four-way assessments were retained. The multiplicative function weight, k, was recalculated in each case. This procedure produced eight sets of utilities for both the multilinear and multiplicative functions. Figures 15 and 16 clearly show that the multilinear and multiplicative functions (scaled utilities) are robust to changes in the mission area utility assessments. They show the same grouping pattern and near linear plotting of the utilities.

Since the multilinear and multiplicative utility functions are robust to changes in the mission area utility assessments, this research concludes that the additive utility function is sufficient to accurately calculate and prioritize the systems' utility towards controlling and exploiting space.

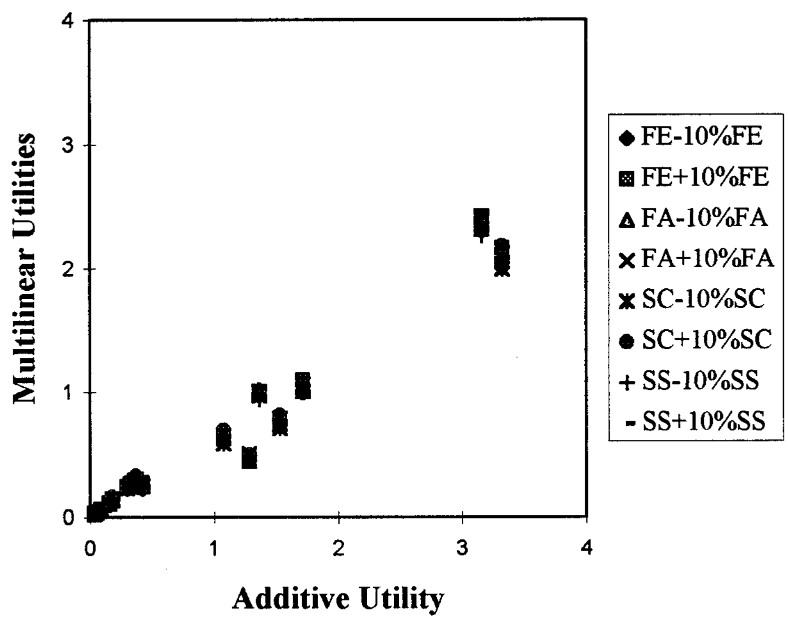


Figure 15. Multilinear Function Sensitivity

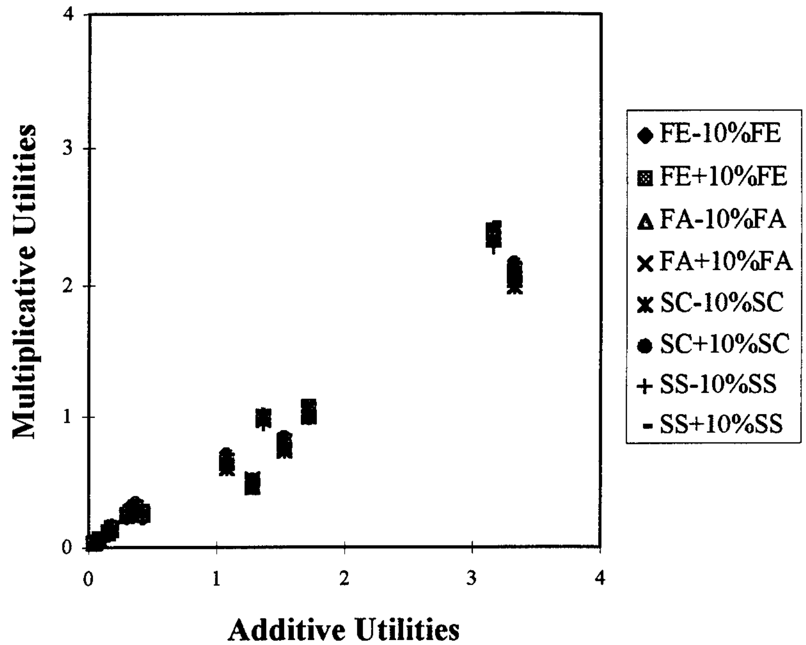


Figure 16. Multiplicative Function Sensitivity

V. Conclusions and Recommendations

This chapter discusses conclusions based upon the results of the analysis and makes recommendations for possible future research.

5.1 Conclusions

The purpose of this research was twofold: it was to identify the key assumptions and simplifications made in the SPACECAST 2020 value model and to make modifications addressing those assumptions and simplifications. This research makes the following conclusions:

1. The SPACECAST 2020 current capability is arbitrarily set to zero and a system's utility cannot be compared to it. The SPACECAST 2020 measure of merit scoring functions do not sufficiently represent the capabilities and utilities of the 98 measures of merit. The modifications made using the concave, convex, linear, and "S" utility curves more closely represent actual capabilities and utilities. They allow for the calculation of the overall current capability and for future capabilities not yet possible. A system's utility score can be directly compared to current capability and the gain in utility toward controlling and exploiting space can be determined. These modifications give the same results as the SPACECAST 2020 study.

2. The additive utility function is sufficient in calculating and prioritizing the utilities towards controlling and exploiting space. The additive utililty function requires additive independence between the mission areas; however, directly proving additive independence is difficult. This research shows that the missions areas are mutually utility independent of one another which allows for the use of the multilinear and multiplicative utility functions. The analysis of the results shows that they are nearly strategically equivalent to the additive utility function.

3. This research shows that care must be taken when selecting and evaluating systems concepts. It outlines a procedure for generating new system concepts through brainstorming and the White Paper system. It asserts that combining the model using the additive utility function and the modified scoring functions with Strategy-to-Task creates a formalized procedure for identifying mission deficiencies and prioritizing the recommended systems. Also, by using this model on a regular basis, it will allow for flexibility in the decision making process. It enables decision makers to incorporate as of yet unimaginable capabilities into the decision making process.

5.2 Recommendations

This research improves upon the SPACECAST 2020 model which prioritizes future space systems. However, more research is required in the following areas:

1. The modified MOM scoring functions. They are not all easily expressed as equations. Each MOM not expressed as an equation should be redefined so as to allow for an equation. Further research should use expert judgment to more accurately identify the proper utility curve, current level of capability, and maximum capability.

2. Mission area weights. The modified group technique should be used with a statistically "large" group of experts in the space operations field to assign the mission area weights. This procedure is also appropriate for all weights in the model hierarchy.

3. System capabilities. Further research should use expert judgment to more accurately determine the system concepts' proposed capabilities.

4. As mentioned in Chapter I, this thesis does not address the cost and risk factors associated with future space systems. This model calculates and prioritizes future space systems' utility towards controlling and exploiting space. A system may score at the top of the prioritization list but its cost may be prohibitive. Likewise, a system may prove to risky to pursue its development.

APPENDIX A. SPACECAST 2020 Value Model

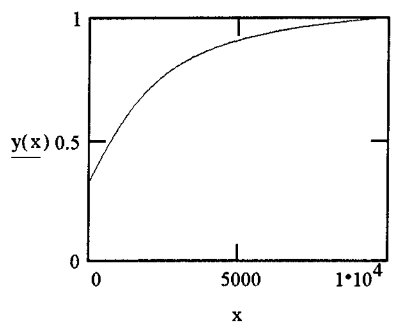
SPACECAST 2020 VALUE MODEL										
Hierarchy with weights (Spacecast 2020 "Standard World"):										
							Current	Minor	Significant	Order of
OVERALL OBJECTIVE: Control and Exploit Space					MOM		Level	Improvement	Improvement	Magnitude
					No.	Measure of Merit	(0.0)	(0.1)	(0.5)	(0.9)
		Crisis availability	0.35		1	Initial # links in theater	about 10	25	100	1000's
	Communications	Capacity	0.35		2	Decompressed MB/sec	300 Mbits/sec/link	600	1000	3000
	0.22	Interoperability	0.20		3	Common-use systems	Little	All AF systems	All US systems	US, commercial, intl.
		Security	0.10		4	Level of secure links	Corps	Division	Battalion	Platoon
		Availability	0.10		5	Crisis Availability	Very good	100%	--	--
	Navigation &	Data availability	0.25		6	Receiver size/cost	Handheld/$1000	Handheld/$100	Wristwatch/$50	On one chip
Force	Positioning	Accuracy	0.25		7	Location precision	10 m	1 m	1 cm	--
Enhance-	0.20	Robustness	0.40		8	Resistance to CM	None (common user)	Antijam	Antijam, antispoof	AJ, AS, antivirus
ment		Processing Speed	0.36		9	Auto image processing	Some change det.	Search, recognition	Humans for review only	Full auto report to user
	Intelligence &				10	(not used)				
0.37	Surveillance	ID Capability	0.21		11	Image interpretability	(classified)	(classified)	(classified)	(classified)
	0.25	Coverage	0.14		12	Area per unit time	(classified)	(classified)	(classified)	(classified)
		Day-night, All Weather	0.29		13	% time data available	(classified)	(classified)	(classified)	(classified)
					14	(not used)				
	Environmental	Spectral Bands	0.20		15	Multispectral bands	5	10	100's	1000's
	Monitoring and	Weather Prediction	0.20		16	Prediction	24 hrs	3 day	1 week	1 month
	Control	Multispectral Coverage	0.20		17	Multispectral revisit time	7 days	5 days	1 day	Hours
		Weather Detail	0.20		18	Instant WX info	Cloud cover	Clouds+precipitation	Clds+precip+winds	--
	0.07	Weather Control	0.20		19	Amount of control	--	Clear fog	Modify patterns	Weather on demand
	Mapping,				20	(not used)	0%			
	Charting, &	Surface Characterizatn	0.31		21	Amount of detail	Surface terrain	Trafficability	All structures	Full resource characteriztn
	Geodesy	Mensuration	0.31		22	Geodetic precision	(classified)	(classified)	(classified)	(classified)
	0.08	Data availability	0.38		23	Time to get new map	Months	1 month	1 week	1 day
		Coverage	0.20		24	Coverage	Ltd global ICBM	Ltd global MRBM	Global MRBM	Global SRBM/cruise
	Warning,	ID Capability	0.30		25	What and where	(classified)	(classified)	(classified)	Missile type and target
	Processing, &	Timeliness	0.40		26	Time to tactical warning	10 min	5-10 min	1 min	Seconds
	Dissemination	Security	0.10		27	Resistance to CM	None	Antijam	Antijam, antispoof	AJ, AS, antivirus
	0.18									
		Acquisition & Tracking	Coverage	0.33	28	Covered area	--	Most of Eurasia	Half of globe	World
		0.25	Accuracy	0.33	29	Track accuracy	--	3 m in atmos.	3 m everywhere	1 m everywhere
			Discrimin	0.33	30	ID/Discrimination	--	Warning of RV/decoy	Limited discrimination	Mid-course discrimination
	Ballistic	Survivability	0.13		31	Qualitative judgment	--	No 1-point	Some capacity	Full capacity
	Missile							failures	concerted attack	major power attack
	Defense	Kill lethality	0.23		32	Pk	--	0.7 endoatmospheric	0.7 endo & boost	> 0.7 all phases
		Timeliness	0.14		33	Required warning time	--	10 days	Hours	Seconds
Force		Coverage	0.14		34	Defended area	--	--	Regional	Global
Application	0.37	Capacity	0.12		35	RVs handled at a time	--	A few	100	Entire enemy force
0.19		Acquisition & Tracking	Coverage	0.33	36	Covered area	--	Most of Eurasia	Half of globe	World
		0.20	Accuracy	0.33	37	Accuracy	--	3 m, unmoving tgt	3 m, large moving tgt	1 m, ground or air tgt
	Air, Land, & Sea		Discrimin	0.33	38	ID/Discrimination	--	ID ground targets	Discr. mobile ground	Discr. ground/air decoys
	Defense from	Survivability	0.17		39	Qualitative judgment	--	No 1-point	Some capacity	Full capacity
	Space							failures	concerted attack	major power attack
		Kill lethality	0.13		40	Pk	--	0.9, fixed targets	0.5, armored vehicles	0.9, ground/air tgts
	0.27	Timeliness	0.23		41	Required warning time	--	Weeks	Days	Minutes
		Coverage	0.27		42	Covered area	--	--	Regional	Global
		Acquisition & Tracking	Coverage	0.33	43	Covered area	--	Most of Eurasia	Half of globe	World
		0.30	Accuracy	0.33	44	Accuracy	--	3 m, unmoving tgt	3 m, large moving tgt	1 m, ground or air tgt
	Power		Discrimin	0.33	45	ID/Discrimination	--	ID ground targets	Discr. mobile ground	Discr. ground/air decoys
	Projection	Survivability	0.13		46	Qualitative judgment	--	No 1-point	Some capacity	Full capacity
								failures	concerted attack	major power attack
	0.37	Kill lethality	0.17		47	Pk	--	0.9, fixed targets	0.5, armored vehicles	0.9, ground/air tgts
		Timeliness	0.22		48	Required warning time	--	10 days	Hours	Seconds
		Coverage	0.18		49	Covered area	--	--	Regional	Global

APPENDIX A. SPACECAST 2020 Value Model

SPACECAST 2020 VALUE MODEL (Part 2)							Current	Minor	Significant	Order of
					MOM		Level	Improvement	Improvement	Magnitude
					No.	Measure of Merit	(0.0)	(0.1)	(0.5)	(0.9)
	Surveillance	Availability	Coverage	0.20	50	Percent of space	90% Earth orbits	All Earth orbits	Cislunar space	Heliocentric orbits
		0.33	Revisit Tim	0.80	51	Time to view	10s of hrs	1-6 hrs	10-60 min	< 1 min
		Robustness	Survivabilit	0.50	52	Qualitative judgment	Single-point	No 1-point	Some capacity	Full capacity
							failures	failures	concerted attack	major power attack
	0.33	0.33	Maintainab	0.50	53	Time to restore	Months +	Days	Hours	Seconds
		Accuracy	Resolution	0.25	54	Target sample distance	(classified)	1 m	10 cm	1cm
Space		0.33	Identificatio	0.25	55	Percent objects ID'd	(classified)	(classified)	85%	100%
Control			Track/Pred	0.50	56	Avg # objects lost	500	100	10	0
0.22	Protection	Active	Maneuver	0.30	57	Response time	Hours	1 hour	Minutes	Seconds
						Delta Velocity	m/sec	10 m/sec	100 m/sec	km/sec
		0.40	Jamming	0.30	58	Spectral range	Selected bands	Double # bands	All major bands	All RFs
			Decoys	0.30	59	Avg decoys / S/C	0	0.5	1	10
						Range of effectiveness	--	VIS	VIS+IR	VIS+IR+Radar
	0.33		Defensive I	0.10	60	Pk	--	0.1	0.2	0.7
		Passive	Redundanc	0.30	61	Qualitative judgment	Single-point	No 1-point	Some capacity	Full capacity
							failures	failures	concerted attack	major power attack
		0.60	CC&D	0.30	62	Pd	1	0.8	0.5	0.2
			Hardening	0.30	63	Sure safe W on target	1 W	10 W	100 W	1 MW
			Crypto Sec	0.10	64	Percent S/C with crypto	90%	100%	--	--
	Negation	Target Acq			65	Time to produce state	Hours-days	2 hours	90 min	Minutes
		0.20				vector after launch				
		Destructive	Coverage	0.40	66	Percent of S/C	--	10%	20%	70%
	0.33	ASAT	Weapon C	0.30	67	Avg # shots / target	--	0.1	1	10
		0.20	Effectivene	0.30	68	Pk / shot	--	0.1	0.2	0.7
		Incapacitating	Coverage	0.60	69	Percent of systems	--	10%	20%	70%
		Systems	Effectivene	0.40	70	Pr(incapacitate)	--	0.1	0.2	0.7
		0.60								
		Cost	Recurring	0.50	71	Cost/lb to orbit	$6,500	$5,000	$2,000/lb	$200/lb
	Launch/Lift	0.25	Non-recurr	0.50	72	Develop/procure cost	$10B	$5B	$2B	$300M
	0.62	Responsiveness	Timeliness	0.17	73	Required warning time	Months	Weeks	Days	Hours
		0.20	Orbit range	0.17	74	Inclinations achievable	30%	40%	70%	90%
			Surge capa	0.17	75	Increase in rate	1 x	2 x	5 x	10 x
			Mission ra	0.17	76	Missions supported	1	2	Several	All current
			Non-destru	0.17	77	Pr(soft abort\abort)	0	0.1	0.5	0.9
Space			Post-abort	0.17	78	Time to restart ops	Years	Months	Weeks	Days
Support		Reliability	0.15		79	Pr(destructive abort)	5%	2-3%	1%	1%
0.22		Operability	Locations	0.20	80	# locations/orbit plane	1	2	5	10
		0.15	Fuel	0.20	81	Ease of handling	Cryogenic/toxic	Part noncryo, nontoxic	All non-cryo, non-toxic	Nontoxic solids
			Ease of ha	0.20	82	Percent blue-suit	0%	10%	50%	90%
			Launch ra	0.20	83	Number and location	One coastal site	--	Many coastal sites	All CONUS
			Cmd & Co	0.20	84	Similarity to air ops	Current launch ops	Like Pegasus/Taurus	Further simplification	Like current air ops
		Environmental impacts	0.10		85	Toxicity and waste	High and much	Mostly dirty	Mostly clean	Clean, low waste
		Survivability	0.10		86	Type bases	Fixed/soft	Dispersed	Mobile/very dispersed	V. many/hardened/mobile
		Payload	0.05		87	Pounds to orbit	50K	100K	200K	--
	Satellite	Communications	0.33		88	Link reliability	99.999%	--	99.9999%	99.99999%
	Control	Diagnosis	0.33		89	Avg time to diagnose	Hours	90 min	20 min	2 min
	0.20	Survivability	0.33		90	Type ground stations	Soft, worldwide	US territory	Mobile backups	Mainly mobile
		Sustainability	S/C--adapt	0.13	91	HW failure recovery	Redundancy only	Ltd. reconfigurability	Major reconfigurability	Only minor mission losses
	Logistics of	0.40	S/C--upgra	0.13	92	Design provisions	None	Limited	Major	Mission changes via S/W
	System		Grd--maint	0.13	93	Level of repairs rqd	Component	Board	LRU	S/W only
	0.18		Grd--maint	0.13	94	Frequency of actions	Daily	Monthly	Many months	Years
			Grd--maint	0.13	95	Type of personnel	Contract specialist	Mix contract	High-skilled military	5-level
			Grd--parts	0.13	96	Type of piece parts rqd	Specialized	Mostly MIL-SPEC	MIL-SPEC	Off the shelf
			Grd--repair	0.13	97	% work value on site	100%	75%	50%	10%
			Grd--reliab	0.13	98	MTBF, critical parts	100% of system life	125% of system life	150% of system life	200% of system life
		Commonality	0.20		99	S/C commonality	System-specific	Modular subsystems	Reconfigure designs	Assemble at launch site
		Interoperability	0.20		100	S/C Interchangeability	None	Alternates available	Standard interface	S/C on any launcher
		Depots/Infrastructure	0.20		101	Dual-use technology	Ltd use, components	Expand use	Some dual-use designs	All systems dual-use

APPENDIX B. Modified Scoring Functions

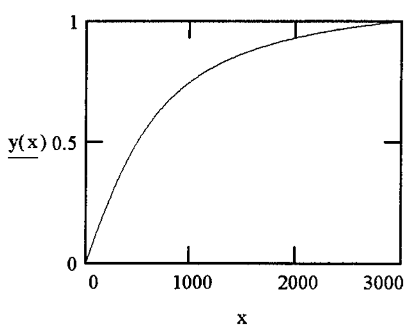
MOM #1 # Links in theater $x := 1, 20 .. 10000$ Links $y(x) := .488 \cdot atan(.0005 \cdot x) + .33$



Current capability

$y(10) = 0.332$

MOM #2 Decompressed MB/sec $x := 0, 10 .. 3000$ MB/sec $y(x) := .728 \cdot atan(.00167 \cdot x)$



Current capability

$y(300) = 0.338$

MOM #3 Common use systems

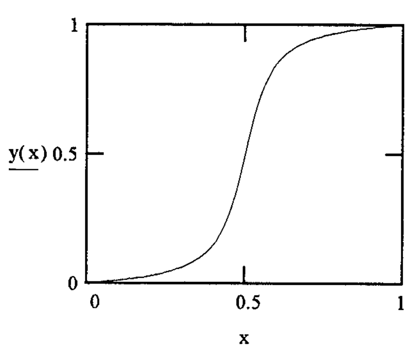
None = 0.0
Little = 0.25 (current)
All AF systems = 0.5
All US systems = 0.75
US, commercial, International = 1

MOM #4 Level of secure links

None = 0.0
Corps = 0.1 (current)
Division = .25
Battalion = .5
Platoon = .75
Soldier = 1.0

Maximum capability reassessed to be at the soldier level.

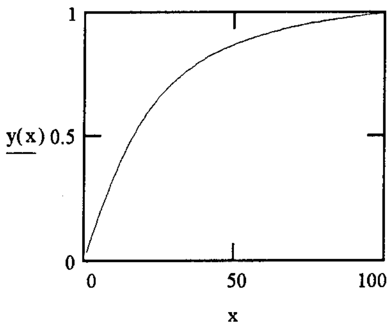
MOM #5 Crisis availability $x := 0, .01 .. 1$ Probability $y(x) := .34565 \cdot atan(15.916 \cdot x - 8) + .5$



Current capability
"Very good" assessed to be .95

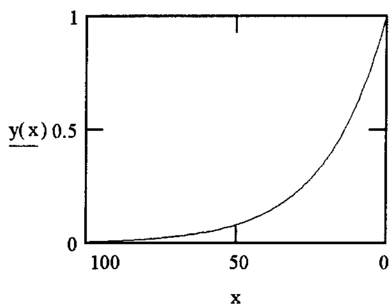
$y(.95) = 0.995$

MOM #6 Receiver size/cost $x := 1, 2 .. 100$ Unitless $y(x) := .728 \cdot \text{atan}(.05 \cdot x)$



Handheld/$1000 (current) $y(25) = 0.652$
Handheld/$100 $y(50) = 0.867$
Wristwatch/$50 $y(75) = 0.954$
One chip $y(100) = 1$

MOM #7 Location precision $x := 100, 99 .. 0$ Meters $y(x) := \left(e^{-.05 \cdot x}\right)$



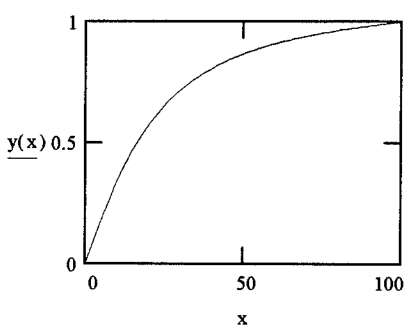
Current capability

$y(10) = 0.607$

MOM #8 Resistance to CM

None = 0.0 (current)
Antijam = 0.1
Antijam/antispoof = 0.5
AJ/AS/antivirus = 0.9

MOM #9 Auto image processing $x := 0, 1 .. 100$ Unitless $y(x) := .728 \cdot \text{atan}(.05 \cdot x)$



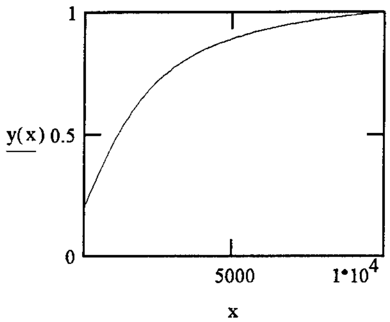
Some change Det (current) $y(25) = 0.652$
Search, recognition $y(50) = 0.867$
Human review only $y(75) = 0.954$
Full auto report to user $y(100) = 1$

MOM #10 Not used

MOM #11 Image interpretability; #12 Area per unit time; #13 % time data available - Classified: Use SPACECAST 2020 Weights

MOM # 14 Not used

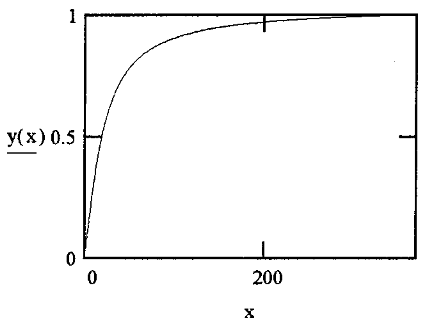
MOM #15 Multispectral Bands $x := 1, 100 .. 10000$ Bands $y(x) := .582 \cdot atan(.0005 \cdot x) - .2$



Current capability

$y(5) = 0.201$

MOM #16 Prediction $x := 0, 1 .. 365$ Days $y(x) := .6599 \cdot atan(.05 \cdot x)$



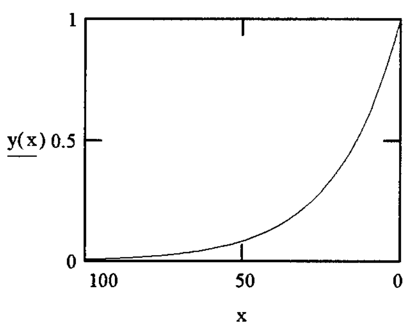
Current capability

$y(1) = 0.033$

This curve is steeper than the other concave functions to capture most of the utility in the first few months.

The maximum capability reassessed to be 365 days.

MOM #17 Multispectral revisit time $x := 100, 99 .. 0$Days $y(x) := e^{-.05 \cdot x}$



Current capability

$y(7) = 0.705$

"Hours" set to .2 days

MOM #18 Instant WX information

None = 0.0
Cloud cover = 0.1 (current)
Cloud/precipitation = 0.5
Cloud/precipitation/winds = 0.9

MOM #19 Amount of control

None = 0.0
Clear fog = 0.1 (current)
Modify patterns = 0.5
WX on demand = 0.9

Current capability reassessed to be clearing fog.

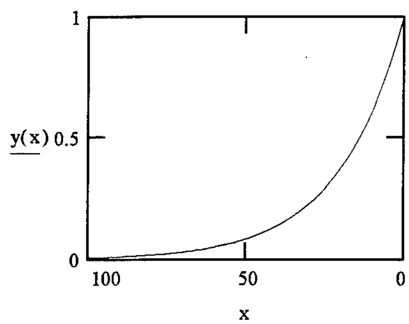
MOM #20 Not Used

MOM #21 Amount of detail

None = 0.0
Surface terrain = 0.25 (current)
Trafficability = 0.5
All structures = 0.75
Full resource characterization = 1

MOM #22 Geodetic precision - Classified: Use SPACECAST 2020 Weights

MOM #23 Time to get new map $x := 100, 99 .. 0$ Days $y(x) := e^{-.05 \cdot x}$



Current capability

$y(60) = 0.05$

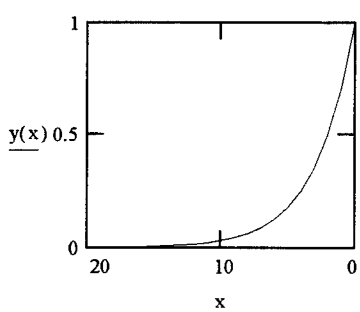
"Months" set to 60 days.

MOM #24 coverage

None = 0.0
Limited global ICBM = 0.25 (current)
Limited global MRBM = 0.5
Global MRBM = 0.75
Global SRBM/cruise = 1

MOM #25 What and Where - Classified: Use SPACECAST 2020 weights

MOM #26 Time to tactical warning $x := 20, 19 .. 0$ Minutes $y(x) := e^{-.35 \cdot x}$



Current capability

$y(10) = 0.03$

MOM #27 Resistance to CM

None = 0.0 (current)
Antijam = 0.1
Antijam/antispoof = 0.5
AJ/AS/antivirus = 0.9

MOM #28 Covered area

None = 0.0 (current)
Most of Eurasia = 0.1
Half of Globe = 0.5
World = 0.9

MOM #29 Track accuracy

None = 0.0 (current)
3 m in atmosphere = 0.1
3 m everywhere = 0.5
1 m everywhere = 0.9

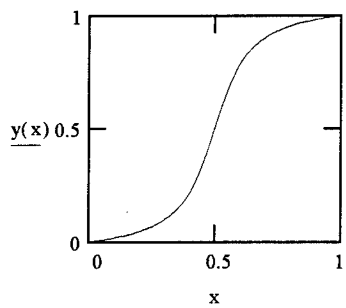
MOM #30 ID/Discrimination

None = 0.0 (current)
Warning of RV/decoy = 0.1
Limited discrimination = 0.5
Mid-course discrimination = 0.9

MOM #31 Qualitative judgment

None = 0.0 (current)
No 1-point failures = 0.1
Some capacity concerted attack = 0.5
Full capacity major power attack = 0.9

MOM #32 PK $x := 0, .01 .. 1$ Probability $y(x) := .364 \cdot \text{atan}(10 \cdot x - 5) + .5$



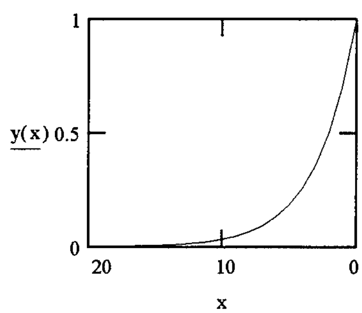
Current capability

$y(0) = 8.212 \cdot 10^{-5}$

Rounded to 0.0

Note: All PK functions are set to "S" curves because the original SPACECAST 2020 data exhibits a slight "S" shape.

MOM #33 Required warning time $x := 20, 19 .. 0$ days $y(x) := e^{-.34 \cdot x}$



Current capability

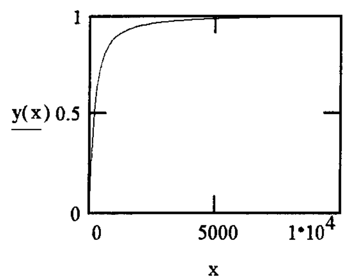
$y(20) = 0.001$

SPACECAST 2020 current capability set at no capability. Modified scale has utility starting at 20 days.

MOE #34 Defended area

None = 0.0 (current)
City = 0.1
Regional = 0.5
Global = 0.9

MOM #35 Rvs handled at a time $x := 0, 100 .. 10000$ RVs $y(x) := .645 \cdot atan(.005 \cdot x)$



Current capability
$y(0) = 0$

This curve is steeper than the other concave curves to capture the utility expressed in the SPACECAST 2020 scale.

Maximum, "entire enemy force," set to 10000 RVs and "a few" set to 10.

MOM #36 Covered area

None = 0.0 (current)
Most of Eurasia = 0.1
Half of Globe = 0.5
World = 0.9

MOM #37 Track accuracy

None = 0.0 (current)
3 m unmoving target = 0.1
3 m large moving target = 0.5
1 m ground or air targets = 0.9

MOM #38 ID/Discrimination

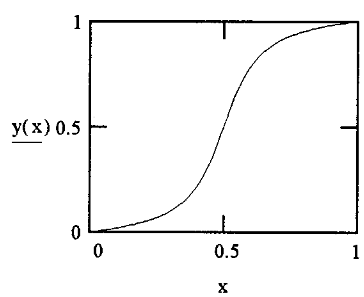
None = 0.0 (current)
ID ground targets = 0.25
Discrimination mobile ground = 0.5
Discrimination ground/air targets = 0.75
People = 1

MOM #39 Qualitative judgement

None = 0.0 (current)
No 1-point = 0.1
Some capacity = 0.5
Full capacity = 0.9

Maximum reassessed to be "people."

MOM #40 PK $x := 0, .01 .. 1$ Probability $y(x) := .364 \cdot atan(10 \cdot x - 5) + .5$

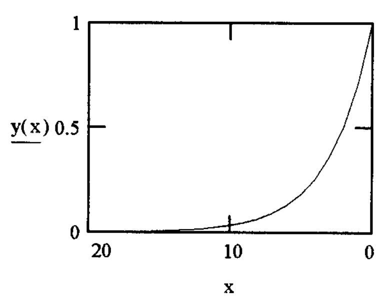


Current capability

$y(0) = 8.212 \cdot 10^{-5}$

Rounded to 0.0

MOM #41 Required warning time $x := 20, 19 .. 0$ days $y(x) := e^{-.34 \cdot x}$



Current capability

$y(20) = 0.001$

MOM #42 Covered area

None = 0.0 (current)
City = 0.1
Regional = 0.5
Global = 0.9

MOM #43 Covered area

None = 0.0 (current)
Most of Eurasia = 0.1
Half of globe = 0.5
World = 0.9

MOM #44 Track accuracy

None = 0.0 (current)
3 m unmoving target = 0.1
3 m large moving target = 0.5
1 m ground or air targets = 0.9

MOM #45 ID/Discrimination

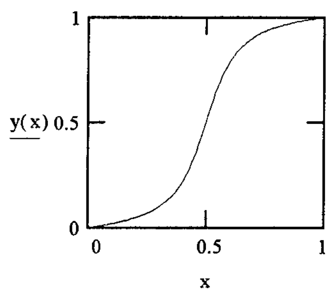
None = 0.0 (current)
ID ground targets = 0.1
Discrimination mobile ground = 0.5
Discrimination ground/air targets = 0.9
People = 1

MOM #46 Qualitative judgement

None = 0.0 (current)
No 1-point failure = 0.1
Some capacity concerted attack = 0.5
Full capacity major power attach = 0.9

Maximum set to the "people" level.

MOM #47 PK $x := 0, .01 .. 1$ Probability $y(x) := .364 \cdot \text{atan}(10 \cdot x - 5) + .5$

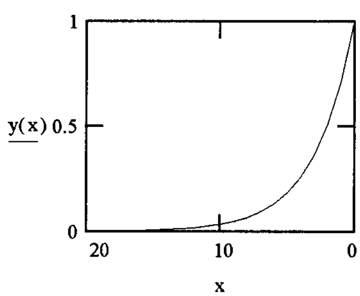


Current capability

$y(0) = 8.212 \cdot 10^{-5}$

Rounded to 0.0

MOM #48 Required warning time $x := 20, 19 .. 0$ days $y(x) := e^{-.34 \cdot x}$



Current capability

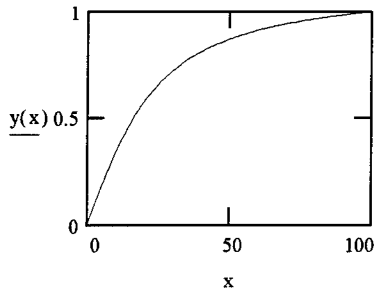
$y(20) = 0.001$

See notes on MOM #33

MOM #49 Covered area

None = 0.0 (current)
City = 0.1
Regional = 0.5
Global = 0.9

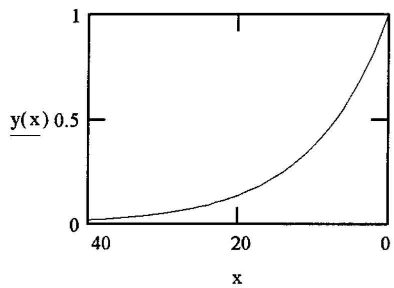
MOM #50 Percent of Space $x := 0, 1 .. 100$ Percent $y(x) := .728 \cdot \text{atan}(.05 \cdot x)$



90% of Earth orbit (current) $y(30) = 0.715$
All Earth orbits $y(50) = 0.867$
Cislunar orbits $y(80) = 0.965$
Heliocentric orbits $y(100) = 1$

Concave chosen because most utility is in Earth/Lunar orbits.

MOM #51 Time to view $x := 40, 39 .. 0$ Hours $y(x) := e^{-.1 \cdot x}$



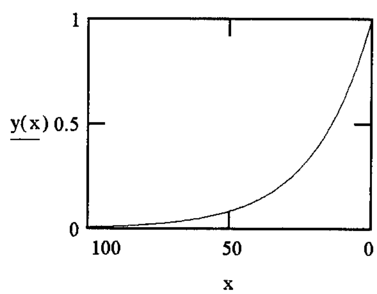
"Tens of hours" (current) $y(20) = 0.135$
"1-6 hours" $y(6) = 0.549$
"10-60 hours" $y(1) = 0.905$

"<1 minute" $y\left(\frac{1}{60}\right) = 0.998$

MOM #52 Qualitative judgment

Single point failures = 0.0 (current)
No 1-point failures = 0.1
Some capacity against concerted attack = 0.5
Full capacity against major power attack = 0.9

MOM #53 Time to restore $x := 100, 99 .. 0$Days $y(x) := e^{-.05 \cdot x}$

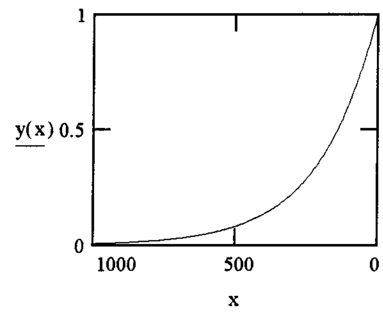


Current capability

$y(60) = 0.05$

MOM #54 Target sample distance; #55 Percent of objects ID'd - Classified: Use SPACECAST 2020 Weights

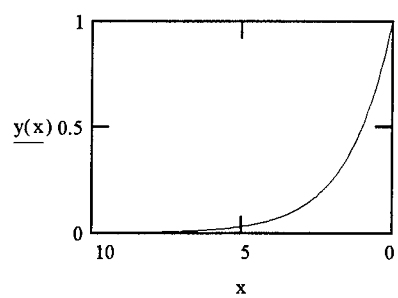
MOE #56 Avg # objects lost $x := 1000, 995 .. 0$ Objects $y(x) := e^{-.005 \cdot x}$



Current capability

$y(500) = 0.082$

MOM #57 Response time $x := 10, 9.9 .. 0$ Hours $y(x) := e^{-.7 \cdot x}$



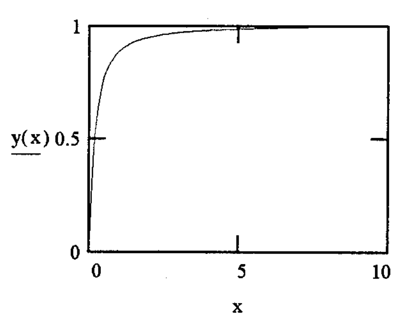
Current capability

$y(5) = 0.03$

MOM #58 Spectral Range

None = 0.0
Selected bands = 0.25 (current)
Double # bands = 0.5
All major bands = 0.75
All radio frequencies = 1

MOM #59 Average decoys per spacecraft $x := 0, .1 .. 10$ Decoys $y(x) := .645 \cdot \operatorname{atan}(5 \cdot x)$

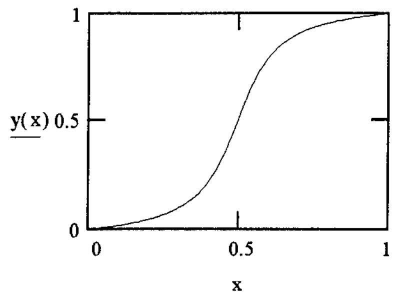


Current capability

$y(0) = 0$

Steeper concave function used to capture the SPACECAST 2020 utility.

MOM #60 PK $x := 0, .01 .. 1$ Probability $y(x) := .364 \cdot \text{atan}(10 \cdot x - 5) + .5$



Current capability

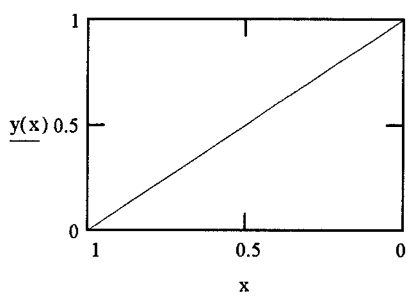
$y(0) = 8.212 \cdot 10^{-5}$

Rounded to 0.0

MOM #61 Qualitative judgment

Single point failures = 0.0 (current)
No 1-point failures = 0.1
Some capacity against concerted attack = 0.5
Full capacity against major power attack = 0.9

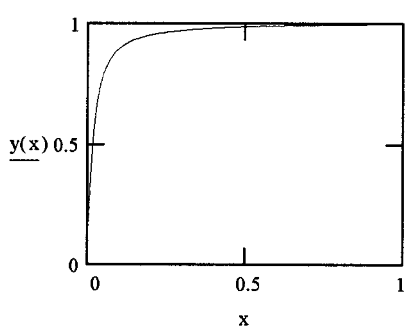
MOM #62 Probability of detection $x := 1, .9 .. 0$ Probability $y(x) := 1 - x$



Current capability

$y(1) = 0$

MOM #63 Sure safe watts on target $x := 0, .01 .. 1$ Megawatts $y(x) := .5805 \cdot \text{atan}(50 \cdot x) + .1$

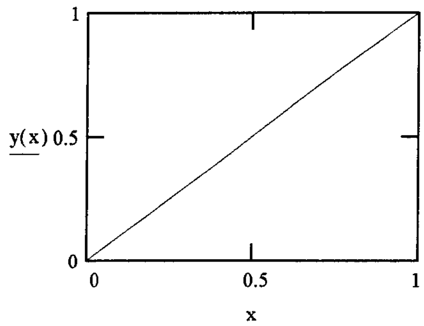


Current capability

$y(1 \cdot 10^{-6}) = 0.1$

This curve is steeper than other concave curves to capture the the utility expressed in the SPACECAST 2020 scale.

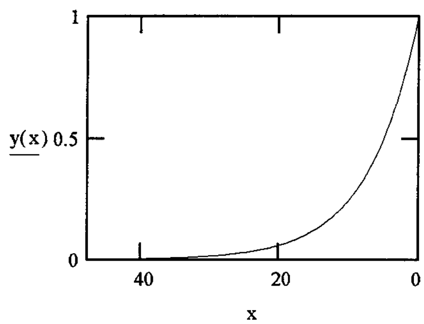
MOM #64 Percent S/C with crypto $x := 0, .1 .. 1$ Probability $y(x) := x$



Current capability

$y(.9) = 0.9$

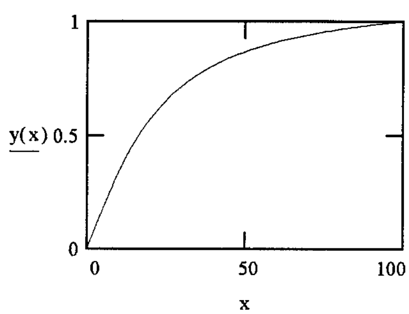
MOM #65 Time to produce state vector after launch $x := 48, 47.5 .. 0$ hours $y(x) := e^{-.14 \cdot x}$



Current capability

$y(24) = 0.035$

MOM #66 Percent of S/C $x := 0, 1 .. 100$ Percent $y(x) := .728 \cdot \mathrm{atan}(.05 \cdot x)$

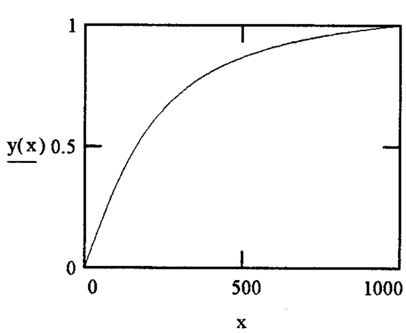


Current capability

$y(0) = 0$

The SPACECAST 2020 data shows a slight "S" curve but it was felt that a concave function captures this utility best.

MOM #67 Average number of shots per target $x := 0, 1 .. 1000$Shots/target $y(x) := .728 \cdot \mathrm{atan}(.005 \cdot x)$

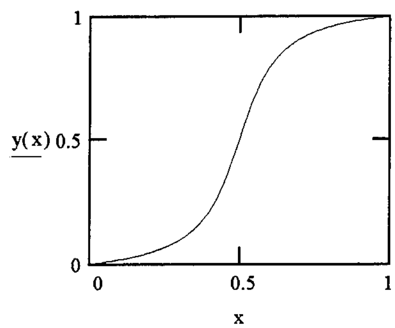


Current capability

$y(0) = 0$

Maximum set at 1000

MOM #68 Pk/shot $x := 0, .01 .. 1$ Probability $y(x) := .364 \cdot \text{atan}(10 \cdot x - 5) + .5$

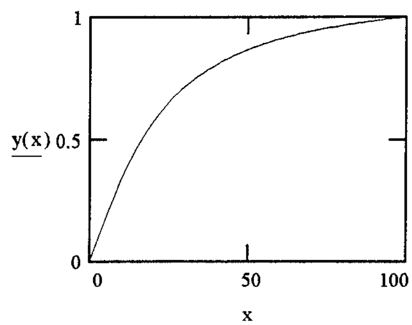


Current capability

$y(0) = 8.212 \cdot 10^{-5}$

Rounded to 0.0

MOM #69 Percent of hostile systems which can be targeted $x := 0, 1 .. 100$ Probability $y(x) := .728 \cdot \text{atan}(.05 \cdot x)$

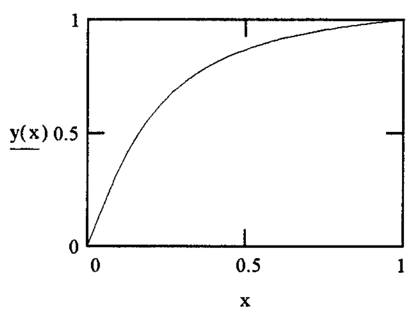


Current capability

$y(0) = 0$

See note on MOM #66.

MOM #70 Probability that one shot will incapacitate a target $x := 0, .01 .. 1$ Probability $y(x) := .728 \cdot \text{atan}(5 \cdot x)$

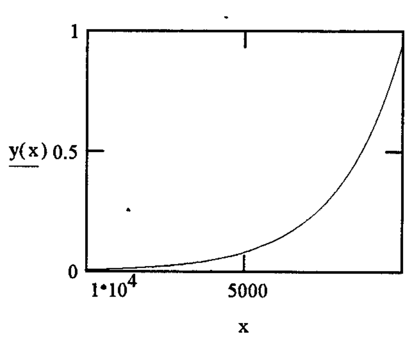


Current capability

$y(0) = 0$

See note on MOM #66.

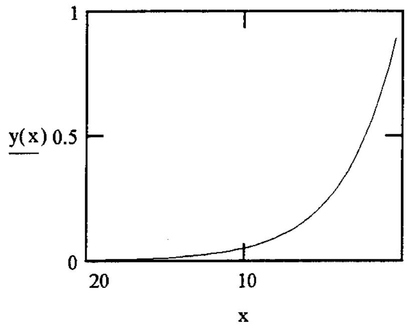
MOM #71 Cost/lb to orbit $x := 10000, 9900 .. 100$ \$/lb $y(x) := e^{-.0005 \cdot x}$



Current capability

$y(6500) = 0.039$

MOM #72 Development & procurement cost $x := 20, 19.5 .. 1$ Billions of \$ $y(x) := \frac{e^{-.3 \cdot x}}{.97}$

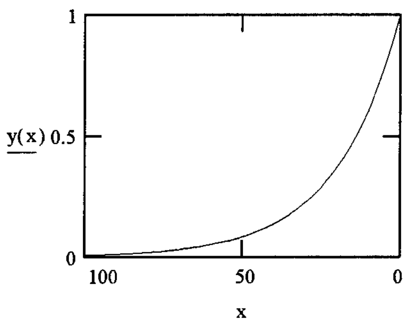


Current capability

$y(10) = 0.051$

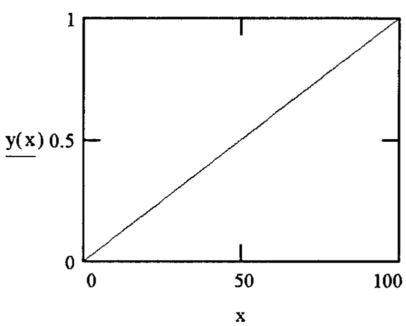
Maximum capability set at \$100 billion and no capability set at \$20,000 billion.

MOM #73 Required warning time $x := 100, 99 .. 0$ Days $y(x) := e^{-.05 \cdot x}$



"Months" (current)	$y(60) = 0.05$
"weeks"	$y(14) = 0.497$
"days"	$y(7) = 0.705$
"hours"	$y(.5) = 0.975$

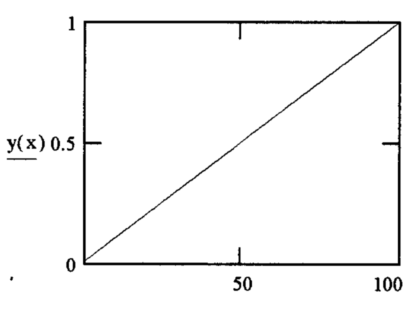
MOM #74 Inclinations achievable $x := 0, 1 .. 100$ Percent $y(x) := \frac{x}{100}$



Current capability

$y(.3) = 0.003$

MOM #75 Increase in launch rate during crisis $x := 0, 1 .. 100$ Factor increase $y(x) := \frac{x}{100}$



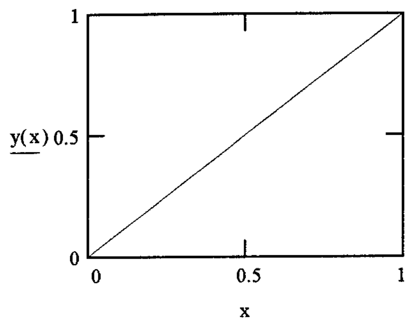
Current capability

$y(0) = 0$

MOM #76 Missions supported

None = 0.0
One mission = 0.1 (current)
Two missions = 0.25
Half of all missions = 0.5
All current missions = 0.9

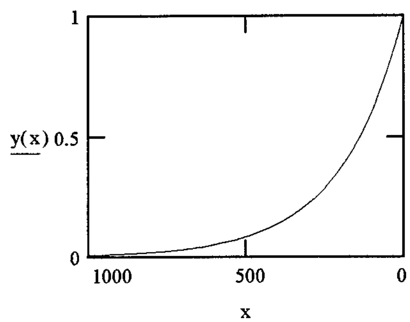
MOM #77 P(soft abort/abort) $x := 0, .1 .. 1$ Probability $y(x) := x$



Current capability

$y(0) = 0$

MOM #78 Time to restart Operations $x := 1000, 990 .. 0$ Days $y(x) := e^{-.005 \cdot x}$

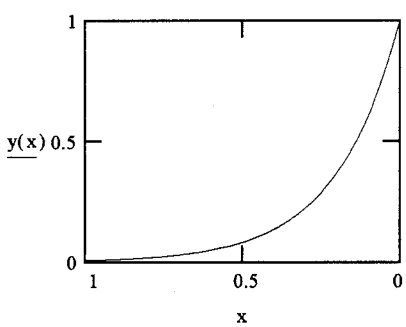


Current Capability (2 Years)

$y(730) = 0.026$

"Years" set to 1000 days
"Months" set to 60 days
"Weeks" set to 14 days

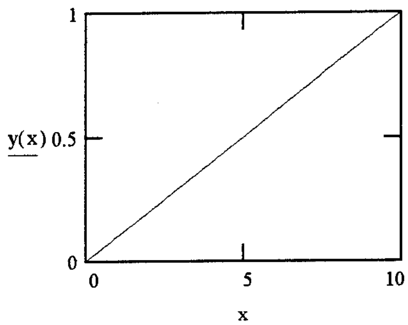
MOM #79 P(destructive abort) $x := 1, .99 .. 0$ Probability $y(x) := e^{-5 \cdot x}$



Current capability

$y(.05) = 0.779$

MOM #80 # of launch locations/orbit plane $x := 0,.1..10$ # Locations $y(x) := \frac{x}{10}$



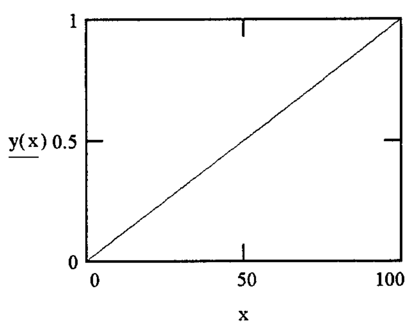
Current capability

$y(1) = 0.1$

MOM #81 Ease of handling

Cryogenic/toxic = 0.0 (current)
Part non-toxic = 0.1
Mostly non-cryo/toxic = 0.5
All non-cryo/toxic = 0.9

MOM #82 Percent blue suit $x := 0, 1..100$ Percent $y(x) := \frac{x}{100}$



Current capability

$y(0) = 0$

MOM #83 Number and location

None = 0.0
One coastal site = 0.1 (current)
Many coastal sites = 0.5
All CONUS = 0.9

MOM #84 Similarity of air operations

Current launch operations = 0.1 (current)
Like Pegasus/Taurus = 0.33
Further simplification = 0.66
Like current air ops = 0.9

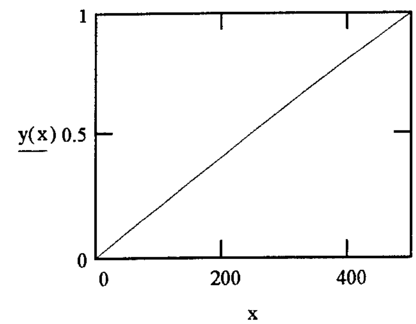
MOM #85 Toxicity and waste

High and much = 0.0 (current)
Mostly dirty = 0.1
Mostly clean = 0.5
Clean, low waste = 0.9

MOM #86 Type of bases

Fixed/soft = 0.0 (current)
Dispersed = 0.1
Mobile/very dispersed 0.5
Very many/mobile/hardened = 0.9

MOM #87 Maximum lift/launch $x := 0, 50 .. 500$ x1000 Kg $y(x) := \frac{x}{500}$

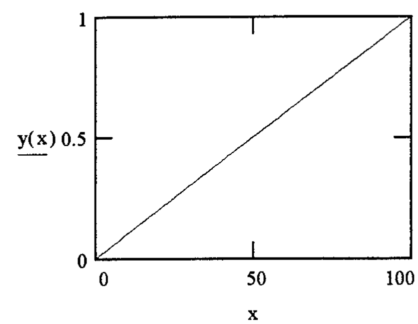


Current capability

$y(50) = 0.1$

The maximum was increased to 500,000 kg to account for a significant improvement over the past performance of the Saturn V booster. The Saturn V could put up a maximum payload of 127,000 kg to LEO. (12:731)

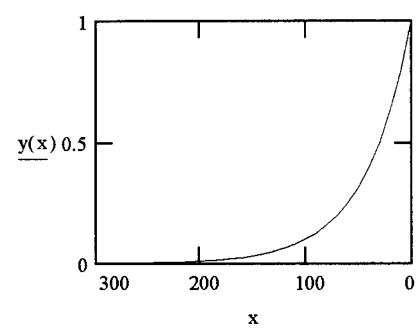
MOM #88 Link reliability $x := 0, 1 .. 100$ Percent $y(x) := \frac{x}{100}$



Current capability

$y(99.999) = 1$

MOM #89 Average time to diagnose and correct a failure $x := 300, 290 .. 0$ Minutes $y(x) := e^{-.023 \cdot x}$



Current capability

$y(300) = 0.001$

MOM #90 Type of ground stations

Soft, worldwide = 0.1 (current)
US territory = 0.25
Mobile backups = 0.5
Mainly mobile = 0.9

MOM #91 HW failure recovery

Redundancy only = 0.1 (current)
Ltd. reconfigurability = 0.25
Major reconfigurability = 0.5
Only minor mission losses = 0.9

MOM #92 Design provisions

- None = 0.0 (current)
- Limited = 0.1
- Major = 0.5
- Mission changes via S/W = 0.9

MOM #93 Level of repairs required

- Component = 0.1 (current)
- Board = 0.25
- LRU = 0.5
- S/W only = 0.9

MOM #94 Frequency of actions

- Daily = 0.1 (current)
- Monthly = 0.25
- Many months = 0.5
- Years = 0.9

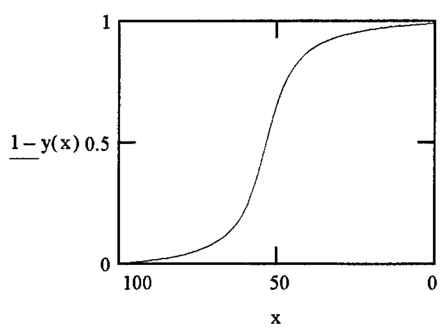
MOM # 95 Type of personnel

- Contract specialists = 0.1 (current)
- Mix contract = 0.25
- High-skilled military = 0.5
- 5-level = 0.9

MOM #96 Type of piece parts required

- Specialized = 0.1 (current)
- Mostly MIL-SPEC = 0.25
- MIL-SPEC = 0.5
- Off the shelf = 0.9

MOM #97 Percent work value on site $x := 100, 99..0$ Percent $y(x) := .3442 \cdot \text{atan}(.15 \cdot x - 8) + .50817$

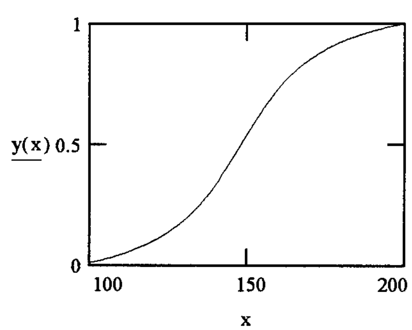


Current capability

$1 - y(100) = 2.871 \cdot 10^{-6}$

Rounded to 0.0

MOM #98 MTBF, critical part $x := 100, 101..200$ Percent of system life $y(x) := .407 \cdot \text{atan}(.054 \cdot x - 8) + .5$



Current capability

$y(100) = 0.01$

MOM #99 S/C commonality

System-specific = 0.0 (current)
Modular subsystems = 0.1
Reconfigure designs = 0.5
Assemble at launch site = 0.9

MOM #100 S/C interchangeability

None = 0.0 (current)
Alternates available = 0.1
Standard interface = 0.5
S/C on any launcher = 0.9

MOM #101 Dual-use technology

Limited use, components = 0.1 (current)
Expanded use = 0.25
Some dual use designs = 0.5
All systems dual-use = 0.9

APPENDIX C. System and MOM Scores

System scores and MOM capabilities listed here are the improvements above current capability, which is added back into the system score, scaled, and plotted in the applicable figures.

Additive Utility Function w/Modified Scoring Function Data (Scores are unscaled)

	TAV (#1)		OTV (#2)		OMV (#3)		MODSYS (#4)		GSRT (#5)		SGPS (#6)		SPATRACS (#7)		WX FOR (#8)		SMASS (#9)	
	Sys Score:	0.31600	Sys Score:	0.13668	Sys Score:	0.02998	Sys Score:	0.03241	Sys Score:	0.17202	Sys Score:	0.04257	Sys Score:	0.03333	Sys Score:	0.03722	Sys Score:	0.00538
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score
1	0.645	0.01838	0.017	0.00048	0.012	0.00034											0.004	0.00011
2																		
3																		
4																		
5	0.005	0.00004	0.003	0.00002	0.005	0.00004					0.005	0.00004						
6																		
7											0.393	0.00727						
8											0.500	0.01480						
9									0.348	0.01150								
10																		
11									0.900	0.01784	0.500	0.00991						
12	0.900	0.01189	0.400	0.00529					0.900	0.01189								
13	0.900	0.02379	0.400	0.01057	0.300	0.00793			0.900	0.02379								
14																		
15															0.001	0.00001		
16															0.065	0.00034	0.616	0.00319
17	0.246	0.00127	0.074	0.00038											0.285	0.00148		
18															0.400	0.00207	0.400	0.00207
19																		
20																		
21																		
22											0.100	0.00093						
23	0.901	0.01000																
24	0.550	0.00733	0.450	0.00599	0.350	0.00466												
25																		
26																		
27																		
	TAV (#1)		OTV (#2)		OMV (#3)		MODSYS (#4)		GSRT (#5)		SGPS (#6)		SPATRACS (#7)		WX FOR (#8)		SMASS (#9)	
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score
28	0.900	0.00522	0.400	0.00232					0.900	0.00522								
29									0.900	0.00522								
30									0.900	0.00522								
31	0.900	0.00815	0.100	0.00091														
32																		
33																		
34	0.900	0.00846	0.400	0.00376														
35	0.299	0.00250																
36	0.900	0.00304	0.400	0.00135														
37											0.900	0.00304						
38																		
39	0.900	0.00775	0.100	0.00086														
40											0.017	0.00011						
41																		
42	0.900	0.01231	0.400	0.00547														
43	0.900	0.00627	0.900	0.00627					0.900	0.00627								
44									0.900	0.00627	0.900	0.00627						
45									0.900	0.00627								
46	0.900	0.00815	0.100	0.00091														
47											0.017	0.00020						
48									0.999	0.01508								
49	0.900	0.01149	0.400	0.00511					0.900	0.01149								

APPENDIX C. System and MOM Scores

System scores and MOM capabilities listed here are the improvements above current capability, which is added back into the system score, scaled, and plotted in the applicable figures.

	ION FOR (#10)		HEL (#12)		KEW (#13)		HPMW (#14)		PB (#15)		WX CON (#16)		SOL MIR (#17)		AST DET (#18)		Current Capability
-	Sys Score:	0.00856	Sys Score:	0.33234	Sys Score:	0.12836	Sys Score:	0.15306	Sys Score:	0.10793	Sys Score:	0.01547	Sys Score:	0.00385	Sys Score:	0.01813	Overall Score: 0.145908
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Current Capability
1	0.004	0.00011															0.332
2	0.234	0.00667															0.338
3																	0.250
4																	0.100
5																	0.995
6																	0.652
7																	0.607
8																	
9																	0.652
10																	
11			0.900	0.01784													
12			0.900	0.01189													
13			0.900	0.02379													
14																	
15											0.141	0.00073					0.201
16											0.616	0.00319					0.033
17											0.285	0.00148					0.705
18											0.800	0.00414					0.100
19											0.800	0.00414	0.400	0.00207			0.100
20																	
21																	0.250
22																	
23																	0.050
24			0.500	0.00666													0.250
25			0.500	0.00999													
26			0.674	0.01796													0.030
27																	
	ION FOR (#10)		HEL (#12)		KEW (#13)		HPMW (#14)		PB (#15)		WX CON (#16)		SOL MIR (#17)		AST DET (#18)		
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Current Capability
28			0.900	0.00522	0.900	0.00522			0.900	0.00522							
29			0.900	0.00522	0.900	0.00522			0.500	0.00290							
30			0.900	0.00522	0.900	0.00522			0.500	0.00290							
31			0.900	0.00815	0.500	0.00453			0.500	0.00453							
32			0.983	0.01575	0.500	0.00801			0.500	0.00801							
33			0.992	0.00933	0.971	0.00913			0.999	0.00940							0.001
34			0.900	0.00846	0.500	0.00470			0.900	0.00846							
35			0.299	0.00250	0.299	0.00250			0.299	0.00250							
36			0.900	0.00304	0.900	0.00304	0.900	0.00304									
37			0.500	0.00169	0.500	0.00169	0.100	0.00034									
38																	
39			0.500	0.00431	0.500	0.00431	0.500	0.00431									
40			0.500	0.00329	0.017	0.00011	0.903	0.00595									
41			0.992	0.01156	0.711	0.00829	0.992	0.01156									0.001
42			0.400	0.00547	0.500	0.00684	0.900	0.01231									
43			0.900	0.00627	0.900	0.00627	0.900	0.00627									
44			0.700	0.00488	0.100	0.00070	0.500	0.00348									
45																	
46			0.900	0.00815	0.500	0.00453	0.500	0.00453									
47			0.214	0.00253	0.017	0.00020	0.903	0.01069									
48			0.999	0.01508	0.944	0.01425	0.999	0.01508									0.001
49			0.500	0.00639	0.700	0.00894	0.900	0.01149									

APPENDIX C. System and MOM Scores

System scores and MOM capabilities listed here are the improvements above current capability, which is added back into the system score, scaled, and plotted in the applicable figures.

	TAV (#1)		OTV (#2)		OMV (#3)		MODSYS (#4)		GSRT (#5)		SGPS (#6)		SPATRACS (#7)		WX FOR (#8)		SMASS (#9)	
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score
50	0.285	0.00139	0.225	0.00110					0.151	0.00074			0.151	0.00074	0.151	0.00074		
51									0.863	0.01688			0.863	0.01688	0.863	0.01688		
52	0.500	0.00611	0.100	0.00122					0.500	0.00611			0.500	0.00611	0.500	0.00611		
53	0.938	0.01146	0.447	0.00546														
54									0.900	0.00550			0.300	0.00183	0.300	0.00183		
55									0.900	0.00550			0.700	0.00428	0.700	0.00428		
56									0.918	0.01122			0.286	0.00350	0.286	0.00350		
57					0.561	0.00494												
58																		
59																		
60																		
61	0.500	0.00660	0.100	0.00132														
62																		
63																		
64																		
65																		
66	0.941	0.00552	0.513	0.00301														
67	0.036	0.00016	0.004	0.00002														
68																		
69	0.941	0.02484	0.513	0.01354														
70																		

	TAV (#1)		OTV (#2)		OMV (#3)		MODSYS (#4)		GSRT (#5)		SGPS (#6)		SPATRACS (#7)		WX FOR (#8)		SMASS (#9)	
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score
71	0.866	0.01477	0.329	0.00561														
72	0.712	0.01214	0.514	0.00876														
73	0.925	0.00421	0.655	0.00298														
74	0.200	0.00091	0.200	0.00091														
75	1.000	0.00455																
76	0.600	0.00273	0.600	0.00273														
77	0.900	0.00409	0.600	0.00273														
78	0.906	0.00412	0.773	0.00351														
79	0.197	0.00403	0.140	0.00286														
80	0.900	0.00368	0.250	0.00102														
81	0.700	0.00286	0.100	0.00041														
82	0.900	0.00368	0.900	0.00368														
83	0.900	0.00368																
84	0.800	0.00327	0.560	0.00229														
85	0.800	0.01091	0.500	0.00682														
86	0.500	0.00682	0.500	0.00682														
87			0.300	0.00205														
88																		
89							0.630	0.00924										
90																		
91	0.400	0.00079	0.400	0.00079	0.400	0.00079	0.400	0.00079										
92	0.500	0.00099	0.500	0.00099	0.500	0.00099	0.900	0.00178										
93	0.400	0.00079																
94																		
95	0.600	0.00119																
96	0.600	0.00119																
97	0.937	0.00186																
98																		
99	0.900	0.00713					0.900	0.00713										
100	0.900	0.00713			0.500	0.00396	0.900	0.00713										
101	0.800	0.00634	0.800	0.00634	0.800	0.00634	0.800	0.00634										

APPENDIX C. System and MOM Scores

System scores and MOM capabilities listed here are the improvements above current capability, which is added back into the system score, scaled, and plotted in the applicable figures.

	ION FOR (#10)		HEL (#12)		KEW (#13)		HPMW (#14)		PB (#15)		WX CON (#16)		SOL MIR (#17)		AST DET (#18)		
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Current Capability
50			0.250	0.00122											0.285	0.00139	0.715
51			0.793	0.01551													0.135
52			0.700	0.00856													
53																	0.050
54			0.500	0.00306											0.100	0.00061	
55			0.800	0.00489											0.900	0.00550	
56			0.697	0.00852											0.869	0.01062	0.082
57																	0.030
58																	0.250
59																	
60			0.983	0.00288	0.500	0.00147	0.983	0.00288	0.983	0.00288							
61							0.500	0.00660	0.500	0.00660							
62																	
63																	0.100
64																	0.900
65			0.855	0.01254	0.855	0.01254											0.035
66			0.941	0.00552	0.747	0.00438	0.941	0.00552	0.941	0.00552							
67			0.338	0.00149	0.036	0.00016	0.338	0.00149	0.338	0.00149							
68			0.983	0.00433	0.983	0.00433	0.983	0.00433	0.983	0.00433							
69			0.941	0.02484			0.941	0.02484	0.941	0.02484							
70			0.941	0.01656			0.941	0.01656	0.941	0.01656							
	ION FOR (#10)		HEL (#12)		KEW (#13)		HPMW (#14)		PB (#15)		WX CON (#16)		SOL MIR (#17)		AST DET (#18)		
MOM No.	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Capability	MOM Score	MOM Current Capability
71																	0.039
72																	0.051
73																	0.050
74																	0.300
75																	
76																	0.100
77																	0.300
78																	0.260
79																	0.779
80																	0.100
81																	
82																	
83																	0.100
84																	0.100
85																	
86																	
87																	0.100
88																	1.000
89																	0.001
90																	0.100
91	0.400	0.00079	0.400	0.00079	0.400	0.00079	0.400	0.00079	0.400	0.00079	0.400	0.00079	0.400	0.00079			0.100
92	0.500	0.00099	0.500	0.00099	0.500	0.00099	0.500	0.00099	0.500	0.00099	0.500	0.00099	0.500	0.00099			
93																	0.100
94																	0.100
95																	0.100
96																	0.100
97																	
98																	0.010
99																	
100																	
101																	0.100

APPENDIX C. System and MOM Scores

System scores and MOM capabilities listed here are the improvements above current capability, which is added back into the system score, scaled, and plotted in the applicable figures.

SPACECAST 2020 Data

Multilinear Utility Function

System	Mission Area Utilities U(FE)	U(FA)	U(SC)	U(SS)	System Score	Scaled (1-11) System Score
MODSYS				0.14313	0.025763	1.25763
ASTDET			0.09778		0.0176	1.17600
SMASS	0.0217				0.005425	1.05425
IONFOR	0.0154			0.009	0.00548	1.05480
TAV	0.22283	0.39495	0.24756	0.58685	0.259106	3.59106
SPATRACS			0.16556		0.029801	1.29801
SGPS	0.09629	0.0587			0.02746	1.27460
OTV	0.09046	0.14189	0.08667	0.30945	0.107087	2.07087
WXFOR	0.0168		0.16556		0.034195	1.34195
KEW		0.51518	0.1	0.009	0.045541	1.45541
OMV	0.05733		0.008	0.0594	0.026779	1.26779
GSRT	0.225	0.3135	0.21		0.118735	2.18735
HEL	0.22564	0.68795	0.48256	0.009	0.200486	3.00486
SOLMIR	0.007			0.009	0.003374	1.03374
HPMW		0.43551	0.282	0.009	0.074549	1.74549
PB		0.23516	0.282	0.009	0.064417	1.64417
WXCONT	0.0574			0.009	0.016006	1.16006
Current Capability						1.00000

Multiplicative Utility Function

System	Mission Area Utilities U(FE)	U(FA)	U(SC)	U(SS)	System Score	Scaled (1-11) System Score
MODSYS				0.14313	0.025763	1.25763
ASTDET			0.09778		0.0176	1.17600
SMASS	0.0217				0.005425	1.05425
IONFOR	0.0154			0.009	0.005482	1.05482
TAV	0.22283	0.39495	0.24756	0.58685	0.259746	3.59746
SPATRACS			0.16556		0.029801	1.29801
SGPS	0.09629	0.0587			0.02714	1.27140
OTV	0.09046	0.14189	0.08667	0.30945	0.107061	2.07061
WXFOR	0.0168		0.16556		0.034236	1.34236
KEW		0.51518	0.1	0.009	0.046387	1.46387
OMV	0.05733		0.008	0.0594	0.026821	1.26821
GSRT	0.225	0.3135	0.21		0.116612	2.16612
HEL	0.22564	0.68795	0.48256	0.009	0.19896	2.98960
SOLMIR	0.007			0.009	0.003375	1.03375
HPMW		0.43551	0.282	0.009	0.076461	1.76461
PB		0.23516	0.282	0.009	0.065454	1.65454
WXCONT	0.0574			0.009	0.016014	1.16014
Current Capability						1.00000

Modified Scoring Function Data

Multilinear Utility Function

System	Mission Area Utilities U(FE)	U(FA)	U(SC)	U(SS)	System Score	Scaled (0-10) System Score
MODSYS				0.1473	0.026514	1.38836
ASTDET			0.08239		0.01483	1.27153
SMASS	0.01453				0.003633	1.15955
IONFOR	0.01833			0.0081	0.006051	1.18373
TAV	0.19647	0.38611	0.25496	0.51751	0.236408	3.48730
SPATRACS			0.15151		0.027272	1.39594
SGPS	0.08904	0.05065			0.025153	1.37476
OTV	0.06146	0.14189	0.11671	0.27941	0.09922	2.11542
WXFOR	0.01051		0.15151		0.030011	1.42333
KEW		0.54583	0.10397	0.0081	0.047634	1.59956
OMV	0.03505		0.02244	0.0594	0.023817	1.36140
GSRT	0.17571	0.32136	0.20884		0.104735	2.17057
HEL	0.23817	0.69752	0.49959	0.0081	0.208585	3.20908
SOLMIR	0.0056			0.0081	0.002861	1.15184
HPMW		0.46871	0.28282	0.0081	0.076197	1.88519
PB		0.23121	0.28282	0.0081	0.064181	1.76504
WXCONT	0.03699			0.0081	0.010726	1.23049
Current Capability	0.241146	0.000195	0.071679	0.1855	0.112322	1.12322

Multiplicative Utility Function

System	Mission Area Utilities U(FE)	U(FA)	U(SC)	U(SS)	System Score	Scaled (0-10) System Score
MODSYS				0.1473	0.026514	1.39253
ASTDET			0.08239		0.01483	1.27569
SMASS	0.01453				0.003633	1.16371
IONFOR	0.01833			0.0081	0.006053	1.18792
TAV	0.19647	0.38611	0.25496	0.51751	0.2367	3.49439
SPATRACS			0.15151		0.027272	1.40011
SGPS	0.08904	0.05065			0.024898	1.37637
OTV	0.06146	0.14189	0.11671	0.27941	0.099075	2.11814
WXFOR	0.01051		0.15151		0.030034	1.42773
KEW		0.54583	0.10397	0.0081	0.048553	1.61292
OMV	0.03505		0.02244	0.0594	0.023819	1.36558
GSRT	0.17571	0.32136	0.20884		0.103247	2.15986
HEL	0.23817	0.69752	0.49959	0.0081	0.206891	3.19630
SOLMIR	0.0056			0.0081	0.002862	1.15601
HPMW		0.46871	0.28282	0.0081	0.078254	1.90993
PB		0.23121	0.28282	0.0081	0.065207	1.77946
WXCONT	0.03699			0.0081	0.010731	1.23470
Current Capability	0.241146	0.000195	0.071679	0.1855	0.112739	1.12739

APPENDIX D. Mission Area Utilities

Table 6. Original SPACECAST 2020 Data

System	U(FE)	U(FA)	U(SC)	U(SS)
TAV	.22283	.39495	.24756	.58685
OTV	.09046	.14189	.08667	.30945
OMV	.05733	0	.008	.0594
MOD SYS	0	0	0	.14313
GSRT	.225	.3135	.21	0
SGPS	.09629	.0587	0	0
SPATRACS	0	0	.16556	0
WX FOR	.0168	0	.16556	0
SMASS	.0217	0	0	0
ION FOR	.0154	0	0	.009
HEL	.22564	.68795	.48256	.009
KEW	0	.51518	.1	.009
HPMW	0	.43551	.282	.009
PB	0	.23516	.282	.009
WX CON	.0574	0	0	.009
SOL MIR	.007	0	0	.009
AST DET	0	0	.09778	0

Table 7. Modified Scoring Functions Data

System	U(FE)	U(FA)	U(SC)	U(SS)
TAV	.19647	.38611	.25496	.51751
OTV	.06146	.14189	.11671	.27941
OMV	.03505	0	.02244	.0594
MOD SYS	0	0	0	.1473
GSRT	.17571	.32136	.20884	0
SGPS	.08904	.05065	0	0
SPATRACS	0	0	.15151	0
WX FOR	.01051	0	.15151	0
SMASS	.01453	0	0	0
ION FOR	.01833	0	0	.0081
HEL	.23817	.69752	.49959	.0081
KEW	0	.54583	.10397	.0081
HPMW	0	.46871	.28282	.0081
PB	0	.23121	.28282	.0081
WX CON	.03699	0	0	.0081
SOL MIR	.0056	0	0	.0081
AST DET	0	0	.08239	0

APPENDIX E. Mission Area Utility Assessments and Weights

E.1 Table 8. Mission Area Utility Assessments:

Mission Area (FE,FA,SC,SS)	Utility	Reason
1. (1,0,0,0)	.25	Subjective point such that the four do not sum to 1
2. (0,1,0,0)	.05	Subjective but taking the original data into account
3. (0,0,1,0)	.18	Same as above
4. (0,0,0,1)	.18	Same as above
5. (1,1,0,0)	.38	Sum of 1 and 2 but synergy increases their combined value
6. (1,0,1,0)	.50	Sum of 1 and 3 but synergy increases their combined value
7. (1,0,0,1)	.50	Sum of 1 and 4 , synergy
8. (0,1,1,0)	.30	Sum of 2 and 3 and synergy
9. (0,1,0,1)	.30	Sum of 2 and 4, synergy
10. (0,0,1,1)	.45	Sum of 3 and 4, synergy, and FE+SC>SC+SS>FE+FA
11. (1,1,1,0)	.70	Sum of 1,2, and 3 and synergy greater than any two-way
12. (1,1,0,1)	.70	Sum of 1,2, and 4, synergy, and compare w/11 SS=SC
13. (1,0,1,1)	.9	Sum of 1,3, and 4, synergy, SC>FA, best three-way
14. (0,1,1,1)	.65	Sum of 2,3, and, 4, synergy, compare w/11 FE>SS, and greater than any two-way
15. (1,1,1,1)	1.0	Perfect satellite which does everything perfectly

E.2 Table 9. Mission Area Weights:

Constant	Formula	Value
k1 Note: 1 = FE	U(1,0,0,0)	.25
k2 Note: 2 = FA	U(0,1,0,0)	.05
k3 Note: 3 = SC	U(0,0,1,0)	.18
k4 Note: 4 = SS	U(0,0,0,1)	.18
k12	U(1,1,0,0)-k1-k2	.08
k13	U(1,0,1,0)-k1-k3	.07
k14	U(1,0,0,1)-k1-k4	.07
k23	U(0,1,1,0)-k2-k3	.07
k24	U(0,1,0,1)-k2-k4	.07
k34	U(0,0,1,1)-k3-k4	.09
k123	U(1,1,1,))-k1-k2-k3-k12-k13-k23	0.0
k124	U(1,1,0,1)-k1-k2-k4-k12-k14-k24	0.0
k134	U(1,0,1,1)-k1-k3-k4-k13-k14-k34	.06
k234	U(0,1,1,1)-k2-k3-k4-k23-k24-k34	.01
k1234	U(1,1,1,1)-k123-k124-k134-k234-k12-k13-k14-k23-k24-k34-k1-k2-k3-k4	-.18

E.3 Multiplicative Utility Function k value derivation:

1. The sum of the one-way k_i's is .66, therefore k>0[1]. Zero is always a solution to the equation. However, the zero root represents the case where the one-way k_i's sum to one which causes the multiplicative function to collapse to the additive function.

2. K is the positive root to the following equation:

$$(1+.25*k)*(1+.05*k)*(1+.18*k)(1+.18*k)-k-1=0$$

3. Exact solution (to 2 decimal places):

k=1.88

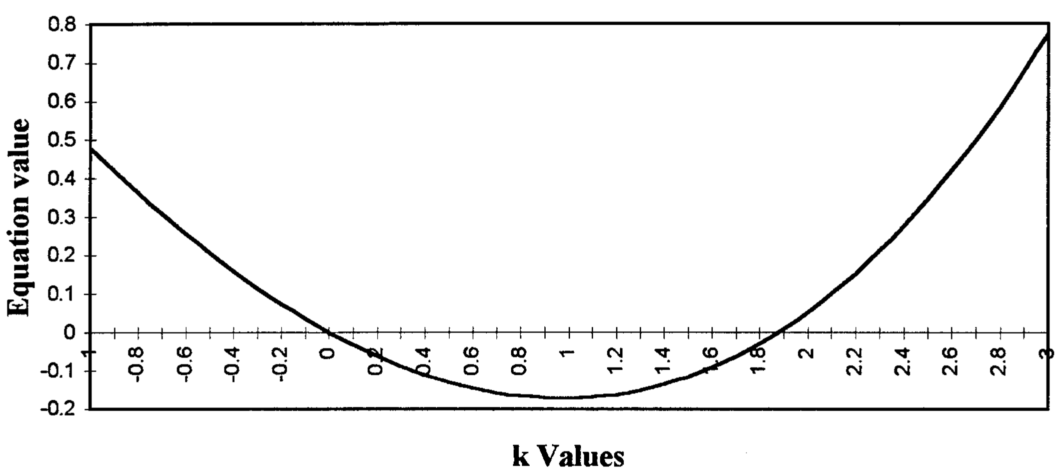


Figure 17. Root Equation Value Vs k Values

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[1] The proof of this is in Appendix 6B of Keeney and Raiffa's book (6:347-348).

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Vita

Captain Bruce Rayno was born in 1965 in Middletown, CT. His family moved to Meredith, NH in 1970 where he spent the rest of his childhood. He graduated from Inter-Lakes Regional High School and accepted an Air Force ROTC scholarship to Syracuse University in 1984. He graduated from Syracuse University in 1988 with a B.S. degree in Mathematics and as a Distinguished Graduate from AFROTC. He accepted a commission in the Air Force and attended Undergraduate Space Training at Lowry AFB in Denver, CO. His first assignment was to the 4th Satellite Communications Squadron, Holloman AFB, NM as a Missile Warning Crew Commander. He later became qualified as a Field Commander. As a Field Commander he was responsible for all aspects of deployments of a road-mobile, Defense Support Program ground station. He also spent a year on the Operational, Test and Evaluation staff, which was responsible for all hardware and software upgrades to the mission equipment. His next assignment, in 1992, was to the 16th Space Surveillance Squadron, Shemya AFB, AK as a Space Surveillance Crew Commander. There he commanded a crew in the daily operations of space surveillance, missile warning, and radar intelligence gathering on Russian ballistic missile tests. Upon his return from this remote assignment in 1993, he attended Squadron Officer's School before entering the Graduate School of Engineering, Air Force Institute of Technology.

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Abstract

This research identifies the assumptions and simplifications in the SPACECAST 2020 value model and assesses modifications. The model determines and prioritizes future space systems' utility toward controlling and exploiting space. This study shows that the assumption of using an additive utility function is valid. This research shows that the mission areas are mutually utility independent allowing the use of the multiplicative utility function. This research also uses the multilinear function, which requires utility independence implied in mutual utility independence. This study makes modifications to the 98 SPACECAST 2020 measure of merit scoring functions. These scoring functions all used the same scoring scale and they do not allow for the determination of the overall current capability toward controlling and exploiting space. Most of these functions are replaced with either a concave, convex, linear, or "S" scoring function, which has an expanded capability range to include current and future capabilities. The modified scoring functions and alternate utility functions do not alter the SPACECAST 2020 results but do improve upon the model. This study also presents a flexible but formalized method of space system concept identification, which explicitly considers space operational requirements.

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