Assessing the Value Proposition for Operationally Responsive Space

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Operationally Responsive Space (ORS) emphasizes meeting the needs of stakeholders in a timely and effective manner. In order to assess the value proposition of ORS, Multi-Attribute Tradespace Exploration is used to analyze alternative space system architectures using a unifying set of performance metrics. First, multi-attribute utility functions are elicited to quantitatively understand the distinction between stakeholder needs for ORS and legacy requirements. Second, candidate satellite systems are defined through a full-factorial sampling of enumerated design variables. Third, a physics-based performance model and a schedule model are constructed to calculate the cost and utility of the candidate designs. This value-centric design approach allows for the evaluation of both ORS and legacy space system preferences on the design space.

Nomenclature

J_i = attribute level
K = utility normalization constant
k_i = attribute weight
N = number of attributes
U_i = single-attribute utility function
U = multi-attribute utility function

I. Introduction

Currently, large spacecraft acquisition programs can take up to 10 to 15 years to produce an on-orbit capability. Many programs that begin to meet a specific, immediate need end up over schedule and applied to emergent mission areas. Changes in user needs during long development cycles may manifest in requirements changes, furthering driving up costs and shifting schedules to the right. To better align the pace of space system acquisitions with the rate of change in their operational environment (*e.g.*, tasking priorities, technology environmental disturbances), an initiative called Operationally Responsive Space (ORS) is emerging with the stated goal of decreasing the time required to satisfy warfighter needs. In 2007, the Office of Operational Responsive Space was established to coordinate efforts across Department of Defense (DoD) and industry. Several technologies pursued to meet ORS needs are well-understood (*e.g.*, successful TacSAT experiments, legacy national capability to launch-on-demand for strategic deterrence). However, it is unclear whether the benefits that can be delivered by ORS using current technology is aligned with stakeholder resources. Therefore, after a brief introduction to ORS and a survey of previous work, this paper will demonstrate a methodology for how the value proposition for ORS may be assessed.

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A. Operationally Responsive Space

Operationally Responsive Space has been defined broadly by the DoD as "assured space power focused on timely satisfaction of Joint Force Commanders' needs... while also maintaining the ability to address other users' needs for improving the responsiveness of space capabilities to meet national security requirements."[1] The purpose of ORS is to reduce the time constants associated with space system acquisition, design, and operation to allow the national space architecture to keep pace with changing missions, environments, and technologies. The fundamental idea is to trade off the reliability and performance achieved by satellites under the "Big Space" paradigm—the currently accepted way of conceptualizing, specifying, developing, and operating space systems—for the speed, responsiveness, and customization which may be achieved by architectures that incorporate elements such as small, modular spacecraft and low-cost, commercial launch vehicles.[2] In addition to obtaining capability on-orbit quickly, ORS attributes include tactical control and assured access. Assured access refers to the potential ability of small, tactical spacecraft to be used to partially reconstitute Air Force space mission areas (*i.e.*, Intelligence, Surveillance, and Reconnaissance; Position, Navigation, and Timing; Communications; Environmental Sensing; Missile Warning; and Space Control) should adversaries negate existing space capabilities.[3] Implicit assumptions in the ORS and "Big Space" paradigms may be traced to their respective historical contexts and original beneficiaries. Table 1 provides a first-order approximation of the distinguishing characteristics of each approach.[4]

Table 1. Distinguishing ORS from "Big Space"

Characteristic	"Big Space"	ORS
Historical Context	Cold War	acquisitions crisis; fragilities inherent in integral, long-life designs
Original Beneficiary	White House	theater combatant commander
Programmatic Drivers	performance	cost, schedule
Innovation Dynamic	capability-pull	technology-push
Payloads	customized, satisfy multiple missions	Off-the-shelf; single-mission focus
Design Life	10+ years	1+ year(s)
Risk Tolerance	risk averse	risk tolerant

B. Previous Work

Despite the purported benefits of ORS, progress on operationally responsive programs has been slow. In addition to a well-documented set of implementation hurdles,[2,5] ORS progress is stymied by an uncertain value proposition to the U.S. military. Existing analyses in the literature conflict, with advocates finding that ORS "delivers the most utility to the warfighter per dollar spent,"[6] while a former deputy director for the Tactical Exploitation of National Capabilities at Air Force Space Command declares that "tactical satellites cannot serve the effect their proponents claim to want to achieve."[7] Furthermore, because one of the core values of ORS is an enhanced ability of the U.S. space architecture to sustain value delivery in dynamic contexts—and given the limited ability of existing conceptual design methodologies to accommodate changing system configurations and operational environments—it is understandable that current evaluations of ORS are unsatisfactory.[4]

While the ORS literature is generally focused on small satellite technology, some studies have explored the policy and process aspects of ORS,[8] finding that responsiveness depends on both social and technical aspects of the design and acquisition process. For example, Ref. 8 describes several levers of responsiveness, including both technical levers such as spacecraft and launch, as well as soft levers including acquisition policies. Using these levers, engineers and decision makers might increase the responsiveness of space systems. However, many of these levers are beyond the influence of systems engineers, underscoring the criticality of policy makers on the future evolution of ORS.

Recognizing the need for a value-centric analysis of ORS, Ref 9 enumerates a broad set of measures-of-effectiveness (MoEs).[9] These MoEs supplement traditional categories of performance, cost, schedule, and risk with responsiveness, coverage, data quality or quantity, flexibility, and goal-oriented MoEs (*e.g.*, number of lives saved). One category, responsiveness, decomposes into total response time, mean revisit time, mean response time, time late, development time, and technology insertion time. Ref 9's categories also address the disparity between traditional missions and ORS missions (*i.e.*, continuous nature of traditional satellite missions in contrast to the on-demand and customized nature of ORS missions). However, when evaluating "big space" and tactical solutions for a common stakeholder need, it is unclear what the implications are when the evaluation criteria set is not conserved across candidate designs. It is also unclear from a rational choice perspective how the MoEs are aggregated in decision making.

A rigorous approach to evaluating ORS utility is found by employing Multi-Attribute Tradespace Exploration (MATE[10]). The front-end analysis includes interviews with relevant stakeholders. Utility functions elicited from the stakeholders are used to evaluate the relative desirability of disparate designs. Since performance attributes for a given mission are used to evaluate the designs, they can be compared easily, regardless of the technology or process used to produce the solution. A Government Accountability Office report recommends that an investment plan be completed to guide ORS efforts in the near future[11], and proposes TacSAT as an example of the type of spacecraft that would allow "DoD to trade off higher reliability and performance for speed, responsiveness, convenience, and customization." A methodology, such as MATE, that can compare designs on a common basis could inform such a plan.

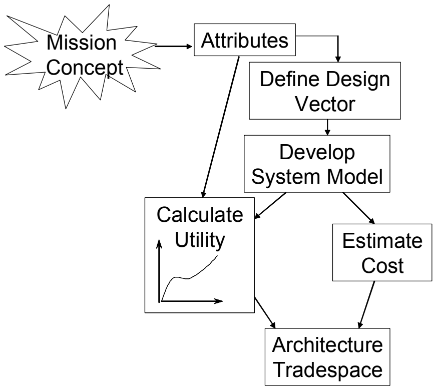

Figure 1. Multi-Attribute Tradespace Exploration

C. Structure of Paper

Having introduced the ORS paradigm and surveyed previous studies in the literature (Section I), we now turn to the value-centric design methodology employed in this research: Multi-Attribute Tradespace Exploration.

II. Methodology

Any proposed ORS mission requires detailed analysis to determine if any value will be delivered by the system. It is anticipated that in order to achieve responsiveness in terms of a reduced development to operations timeline, technical performance and reliability may need to enter the tradespace. Also, in order to determine whether the user derives the necessary responsiveness from such a system, it is necessary to model the entire development schedule: from user need identification through initial operational capability. This requires modeling not only the physical design aspects of the space system but also non-technical factors which may drive schedule.

Multi-Attribute Tradespace Exploration (Figure 1) is a conceptual design methodology well-suited for evaluating ORS. Applying decision theory to model and simulation-based design, MATE decouples the design from the need through tradespace exploration. MATE is both a solution-generating as well as a decision-making framework.[12,13]

Implementing the MATE approach to system design involves three general activities. First, evaluation criteria are defined and specified with attributes (*i.e.*, decision maker-perceived metrics that measure how well decision maker-defined objectives are met) (*e.g.*, Table 2). Single-attribute utility curves are elicited from decision makers to understand the acceptable attribute range and to capture any nonlinearity in their preference structure (*e.g.*, Appendix A). These single-attribute utility curves are aggregated using multi-attribute utility theory[14] to arrive at an aggregate utility function (*i.e.*, a dimensionless metric of user satisfaction ranging from 0, minimally acceptable, to 1, highest of expectations). Second, the attributes are inspected, and various design variables (*i.e.*, designer-controlled quantitative parameters that reflect aspects of a concept, which taken together as a set uniquely define a system architecture) are proposed (*e.g.*, Table 3). Each possible combination of design variables constitutes a unique design vector, and the set of all possible design vectors constitutes the design-space.

Table 2. EO ISR Attributes.

Attribute	Units	Acceptable Range
Field of Regard- area the payload can access for an image opportunity, more is better (MIB)	km^2	1,000-10,000
Global Coverage- percentage of the Earth accessible to the payload over several orbits, MIB	%	66-100
Resolution- ground sampling distance of the payload, less is better (LIB)	m	0.1-1
Revisit Rate- time between imaging opportunities, LIB	days	0.2-2
Sensitivity- range of electromagnetic spectrum payload can utilize, MIB	Sensor type	Day-Night
Availability- percentage of time the spacecraft is able to process images, MIB	%	95-99
Timeliness- time from need identification to on-orbit capability, LIB	Years	1-10

Third, a system model is developed to assess the cost and utility of the candidate designs.[15]

In Ref. 4, the first step of the MATE process was carried out and described: assessing the distinguishing attributes of ORS. In this case, the design problem is to evaluate the performance of alternative space-based intelligence, surveillance and reconnaissance (ISR) platforms across "ORS" and "big space" decision maker preference structures. The scope of the study includes a single satellite with an electro-optical imaging payload in the visible or infrared ranges. Throughout the study, an Air Force officer experienced in the acquisition career field acted as a proxy stakeholder. The elicited attributes are listed in Table 2. Next, single attribute utility functions, $U_i(J_i)$ were elicited for each attribute J_i that was described by the proxy stakeholder. These utility functions are shown in Figure 9 in Appendix A. Utility functions give the stakeholder risk preferences over the attribute ranges.

III. Development of Design Space

The second step in the MATE process is to translate attributes in the value space to tradable design variables in design, or physical space. Design variables, taken together to form the design vector, are those aspects of the design that an engineer or program manager can change. These design "knobs" require specification of name, definition, units, and sampling ranges. (The units and ranges can correspond to "user-defined" quantities, such as a choice from a menu, as would be the case if the choice were of something like propulsion system, which could be sampled from "electric", "chemical bi-propellant", or "chemical mono-propellant", for example.) The choice of design vector will also imply the types of computer models that are needed for analysis. A design vector should try to balance being exhaustive and minimal in order to drive first-order effects on attributes, while also being tractable for analysis.

	Design Variables														
	Orbit			Spacecraft						Programmatic					
Attrbutes	Orbit Altitude	Orbit Inclination	Number of Spacecraft	Slew Ability	Power Duty Cycle	Focal Length	Optics Sensitivity	Size/Mass	Software Reliability	Technology Level	Reuse of Design	Integration Complexity	Permitted Schedule	Testing	Launch
Global Coverage	9	9	9	1	3	1									
Field of Regard	9			9	1	9									
Resolution	9			3		9	9			3					
Revisit rate	9	9	9	3	1										
Sensitivity	1						9								
Availability	1	3	9		3				9					3	
Timeliness	1	1	9	3	3	9	9	9	3	3	9	9	9	9	9
Cost	1	3	9	3	3	9	9	9	3	3	9	9	9	3	9
Sum	40	25	45	22	14	37	36	18	15	9	18	18	18	15	18

Figure 2. Quality Functional Deployment to Inform Design Vector

A. Design Variable Brainstorming

As a structured process for capturing and screening design variables, a Quality Function Deployment (QFD) diagram is populated to explore relationships between attributes and potential design variables, as shown in Figure 2. First order strength of interaction between design variables and attributes is captured using a 0 (none), 1 (weak), 3 (medium), and 9 (strong) qualitative rating. Many of the brainstormed design variables characterizing the satellite system, such as orbit altitude and optics size, have strong relationships with the attribute set. Others, such as mass and reuse of design, seemed to have fewer first-order effects. Instead of including those in the design vector, they were treated as dependent variables in the model.

Table 3. EO ISR Design Variables.

Design Variable	Units	Range
Orbit Altitude	km	200-500
Orbit Inclination	degrees	20-90
Focal Length	m	0.5-2
Optics Sensitivity	day and/or night	0-2
Permitted Schedule	years	1-10

The chosen design variables, listed in Table 3, fall into three general categories. The first category is orbit design. A circular orbit was selected as the default. Orbit altitude and inclination differentiate the selected orbits. All other orbital characteristics were fixed as constants. Right ascension of the ascending node and argument of perigee were set at zero degrees, and eccentricity was set at zero. For the first model, the number of spacecraft was fixed at one. Future studies will relax this assumption.

The second category of design variables is spacecraft design. The slewing capability was set as constant. The focal length remained as a variable. The focal length is the distance from the lens where the energy is focused. It can roughly size the bus, if the type of lens is set. Optic sensitivity refers to what level of energy flux the optics requires to form a picture. The design space for this variable was coarsely sampled, giving three options. The optics sensitivity was set at day only capable, night only capable, or both. The three levels were differentiated by bus sizing requirements and costs.

The last category, referred to as programmatic design variables, contains less-technical design variables. Design reuse assumes that there is more than one spacecraft built to the same design. The architecture chosen for each design contains information on the technology readiness level and the desired timeline, as well as the process used to design and build the spacecraft. Schedule is both an attribute, known as "Timeliness" (the experienced schedule), and a design variable, known as "Permitted Schedule" (the desired schedule). In the case of ORS, decision makers are attempting to actively trade schedule, so having a knob to turn is essential to the paradigm.

IV. Development of System Model

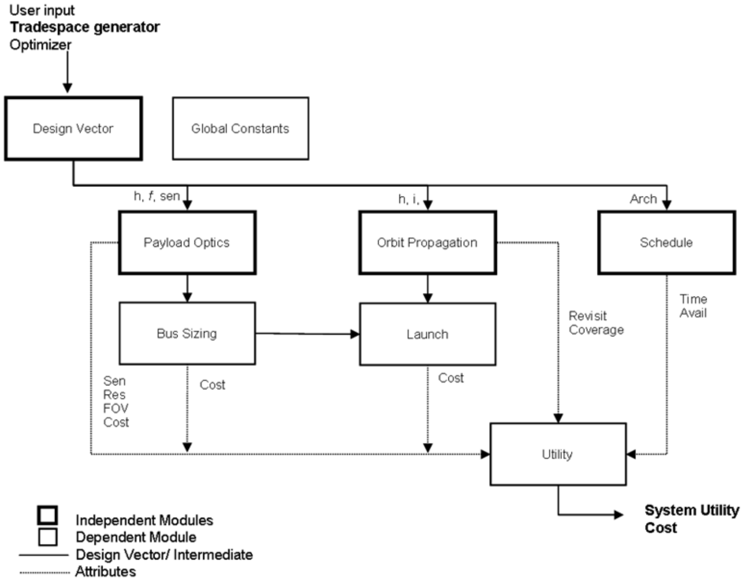

Figure 3. Model Block Diagram

Mathworks™ MATLAB® was chosen as the modeling environment. The system model was informed by the three categories of design variables. The computer model consists of several modules, or self-contained functions, which take in a given design vector and compute the attribute levels. The model currently runs the modules sequentially. Figure 3 shows a block diagram of the modules, with simplified inputs and outputs. User input is captured in the design vector module, which is also where an optimizer can be wrapped around the code. The constants module contains values that are used by more than one module, like the radius of the Earth, as well as parameters that might be changed in later iterations. Modules in Figure 3 with bold borders take inputs from the design vector, while the others are dependent sub-modules. Iterations exist within the modules themselves, but no feedback between modules is allowed, as that slows the runtime of the code. The optics and bus sizing module runs first. Since the most important orbit design variable, altitude, is an input to the system, the optics can be sized before the orbit module is run. The bus sizing module also estimates cost of the system.

Directly after the optics sizing, the orbit selection module runs. The orbits selected are circular orbits. The module propagates the satellite, assuming a simple drag model and J2 effects. The orbit module also calculates a revisit rate over a point on the globe. An arbitrary point was chosen to illustrate the coverage statistics between different orbit designs.

The launch module takes input from the optics and orbits module, and selects a launch vehicle to boost the payload to the selected orbit. The launch module outputs the launcher chosen and the approximate cost of the launch. All the costs are aggregated across modules, and the attributes are fed into the utility calculation module.

The schedule module is described in detail in Ref. 4. It accepts as input the design vector and associated permitted schedule and derives a nominal schedule—the time period required for risks from Technical Readiness Level (TRL) and Process Readiness Level (PRL) to be reduced to a negligible level. If the permitted schedule is less than the nominal schedule, the risk from TRL and PRL is estimated and recorded, which then induces potential performance risk for the design, resulting in more uncertainty on the utility for the design with a "risky" schedule.

V. Tradespace Results

Once the models are created, the next step is to enumerate various levels of the design variables to generate the design space for analysis. This design space is run through the model to determine the attribute performance as well as the cost and utilities of each design alternative. For this problem, attribute weights were elicited from a proxy stakeholder. The weights are not required to add to one because a multiplicative form of utility aggregation is used:[13]

$$KU(J) + 1 = \prod_{i=1}^{N} [Kk_i U_i (J_i) + 1] \tag{1}$$

where U_i is the single attribute utility function at attribute level J_i (shown in Figure 9 in Appendix A), N is the number of attributes, and k_i is the weighting factor associated with each of the attributes. An additional term, the *K,* normalizes the multi-attribute utility from 0 to 1. MATE tradespaces are typically displayed as system utility vs lifecycle cost. As seen in Figure 4 below, the tradespace is populated with 2500 designs. The number of designs is a result of the sampling levels of the design variables.

A. Initial Tradespace

Several trends emerge from observing Figure 4. Those designs with higher utility tend to cost more. The utopia point, representing the the best possible design lies in the upper left corner (*i.e.,* a design with utility one at zero cost). Designs may be infeasible by exceeding the capabilities of any launch vehicle or technology limits.

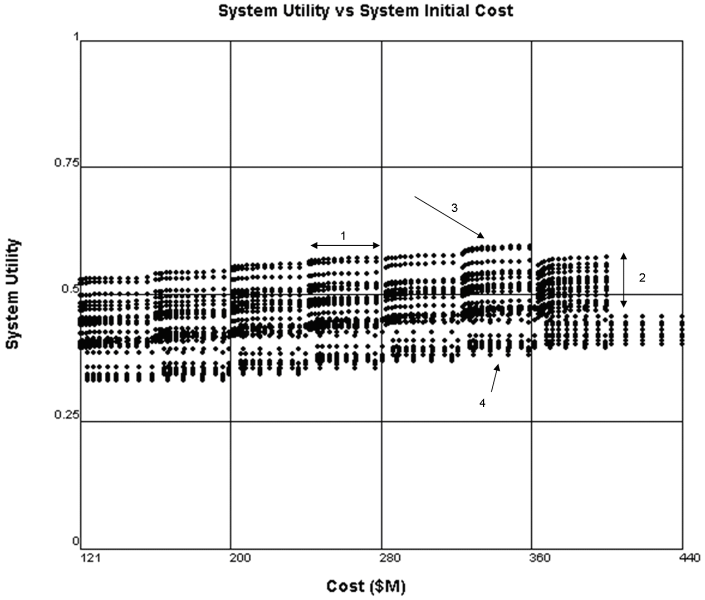

Figure 4. System Tradespace. *A trend of increasing cost as system utility increases. 1) horizontal banding 2) column 3) vertical strip 4) bottom cluster*

Several bands are observed in the tradespace. The horizontal banding illustrated as 1) in Figure 4 is a modeling artifact of altitude discretization. As the orbital altitude increases, the launch vehicle needs more delta velocity (fuel) to achieve the desired orbit, and therefore costs more. However, a higher altitude results in a larger field of view, also increasing the utility of those designs at higher altitudes. The column 2) is caused by inclination, which doesn't increase cost significanlty in the model, but does increase utility. The vertical strips 3) are caused by focal length discretization. As focal length increases, the utility of the design increases. The two cluster of designs, top and bottom 4) are caused by payload sensitivity, and the bottom cluster contains the design with infrared optics.

Examining the design variables and system utility, the model discretization is immediately apparent. Designs variables were sampled at their extremes and then at several intermediate points. The range of utility for each column is similar, but for altitude and inclination, they are not uniform. Focal length is uniform across each column. That means that focal length is coupled with one or two attributes, and the effect of focal length is uniform across the rest of the attributes. Altitude and inclination are related to the system utility in a more complicated way.

A closer look at some of the attributes reveals interesting design spaces. System utility vs. resolution (Figure 5) has two clusters- one for infrared designs on the right and a tightly packed cluster to the left for visible wavelengths.

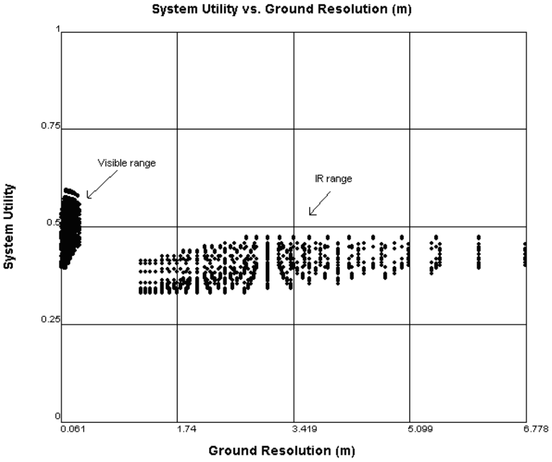

Figure 5. Utility vs. Ground Resolution. *Clusters exist for the types of sensors.*

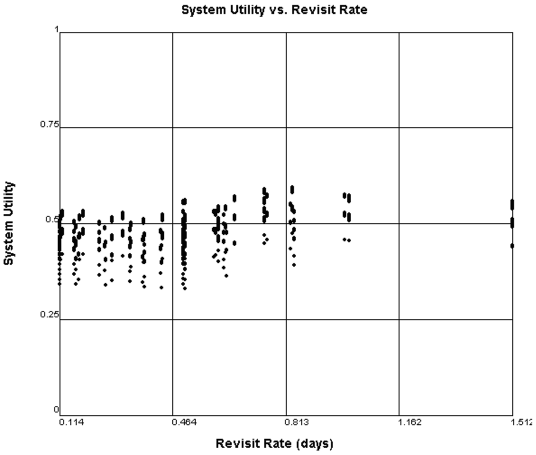

Figure 6. Utility vs. Revisit Rate. *Bands are caused by design variable sampling.*

The single attribute utility curve for resolution is fairly linear, with utility decreasing as ground sampling distance increases. Figure 6, which shows utility and revisit rate, indicates a complicated relationship between altitude and inclination. The designs are clustered by both these design variables. The points in the columns are differentiated based on focal length and architecture. Those designs with a low revisit rate tend to have lower system utility. For instance, the anchor points on the system utility vs. cost plot are two extremes of the design space. The design point lying in the upper left of the cluster has a low altitude and small focal length, both of which tend to have lower cost. The design point at the upper right has a higher altitude and longer focal length, both of which increase cost, but also have an increase in utility over designs to the left.

Competing attributes add to designs not achieving utility one. The objectives are a mix of supporting and opposing. There are more opposing objectives than supporting objectives. Some objectives are opposing or supporting simply on the basis of physics and orbital mechanics. Global coverage is opposed to revisit rate, as seen in Figure 7, because both are affected in the first order by the design variable inclination. A higher inclination will increase global coverage, but increase revisit rate (not desirable), as long as the target is not at the poles. Field of regard is opposed to resolution and revisit rate, because of the effect of orbit altitude. As altitude increases, revisit rate increases (not desirable) because the orbital period is greater, but of course a higher orbit will allow more of the Earth to fall into the total field of view. Revisit rate and resolution are, however, supporting, in that a lower orbit will lead to both a lower period (and thus a higher revisit rate) and a smaller distance from the orbital asset to the ground (allowing a better resolution from the same sensor).

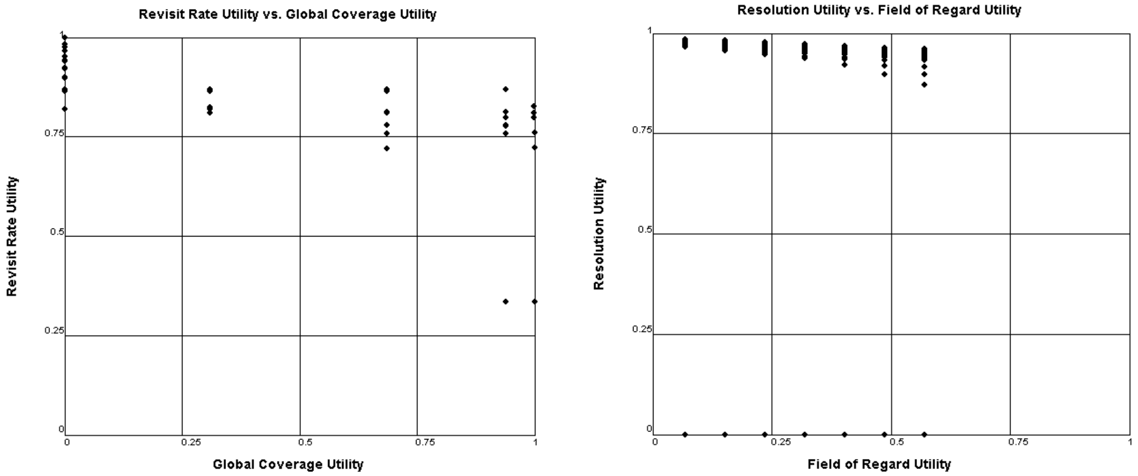

Figure 7. Competing Attributes. *Neither tradespace achieves utility one*

Certain other objectives are decoupled, such as field of regard and global coverage. Global coverage is largely related to the orbital inclination, while field of regard is related to the orbital altitude. The two parameters can be independently selected or varied within any family of orbits. It is not likely that field of regard will have to be traded against global coverage in order to find an optimum.

B. Pareto Efficient Designs

The Pareto Front is a theoretical set of designs where any changes that result in improvement in one objective must decrease performance in another objective. This Pareto Front shows that for an increase in utility along the front, there is a general increase in cost. Off the front, one can increase utility without increasing cost; however these designs are considered “dominated” in that at the same cost, a higher utility design exists, or at the same utility, a lower cost design exists. Designs on the Pareto Front tend to be highly integrated, reaching the boundaries of several constraints, such as technology limits. While these designs offer higher utility for a static context, they may not be value robust under changing contexts. For instance, if in the future the user’s needs change, and quick deployment is valued more than high performance, the designs on this Pareto Front may not be as valuable to the user. In this perspective, value is delivered over time, and designs need to be evaluated under different contexts to determine the time-dependant value. By moving off the Pareto Front, designs are less optimized for a given context, but may contain latent value that can be tapped under different contexts. When this latent value requires user input to activate, it is called flexibility.

Table 4. EO ISR Attribute Weights.

Attribute	Weight 1 "Big Space"	Weight 2 "ORS"
Field of Regard	0.7	0.35
Global Coverage	0.4	0.2
Resolution	0.8	0.4
Revisit Rate	0.45	0.25
Sensitivity	0.4	0.2
Availability	0.98	0.5
Timeliness	0.7	0.8

Of important note is that just because the designs don't achieve utility of one, doesn't imply they are bad designs. As there are competing user attributes that must be traded, no technically feasible designs exist that can achieve the best level of all of the user defined attribute ranges. For the most part this limitation is due to physics (*e.g.,* orbit mechanics) and technology limits.

The infeasible region is a result of two sets of competing attributes, resolution against field of regard, and global coverage against revisit rate. The design variable orbit altitude affects both resolution and field of regard. They are inversely related to changes in altitude. As altitude decreases, resolution improves but field of regard decreases. One way to improve both resolution and field of regard is to increase the focal length, or improve the optical payload. The design vector limits the optics achievable in the tradespace, thus creating an infeasible region near utility one. Global coverage and revisit rate are affected by inclination. As the inclination increases, global coverage increases, but revisit rate in general tends to decrease. Again there is an infeasible region at utility one, this time because of orbital mechanics and the chosen orbit designs.

C. Tradespace with ORS k Values

The weights of several attributes were changed, increasing the relative importance of timeliness and decreasing that of the performance attributes. For the plots illustrated above in Figure 4, 5, and 6, the weights were Weight 1 as shown in Table 4. In this initial preference set, where timeliness has a lower weighting than the performance attributes, the value proposition is equivalent to that which has resulted in the "Big Space" paradigm, where performance was desired above timeliness. At the end of the design process under the "Big Space" value proposition, designs tended toward larger satellites, shown in the tradespace as designs with longer focal lengths.

When the weights are set as Weight 2 in Table 4, where the value proposition shifts to be equivalent to "ORS" priorities with timeliness slightly more important than before, but much more important than the performance attributes, the tradespace shifts and is shown in Figure 8. Note that the top layer of the tradespace along the Pareto Front contains those designs with the shortest development times. They are differentiated from the designs with a longer development schedule, and clustered at the top of the tradespace. The initial tradespace in Figure 4 showed designs with shortest development times mixed in with other designs along the front. When the weights are shifted to reflect ORS decision makers' needs, there is a clear delineation in utility space between the designs with shortest development times and those with larger satellite designs. The higher performance of the shorter development time designs is partly an artifact of the model; for this particular analysis, the increased performance risk due to the shortened schedule was not used to determine an expected utility loss. The schedule model will output the increased uncertainty for the performance attributes due to compressed schedule, which implies that over a large number of samples, some of these designs will perform worse than expected. Future work will conduct a Monte Carlo analysis over these design alternatives to generate the expected system utility, as opposed to the deterministic system utility illustrated in Figure 8. It is expected that once the nondeterministic performance utility is assessed, the riskier designs will not dominate the other designs as clearly.

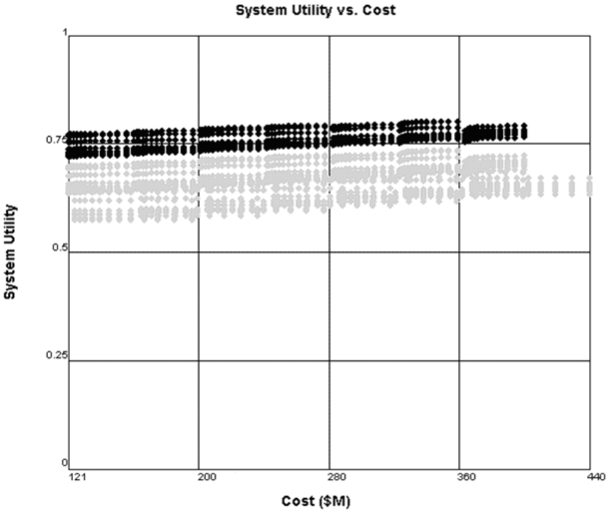

Figure 8. System Utility vs. Cost with Attribute Weight 2. *Designs with the shortest development time (in black) are grouped at the top of the tradespace, indicating a higher utility than large satellite designs.*

VI. Conclusion

A. Discussion

ORS requires designs that are timely. As the plan developed by the DoD[1] indicates, the desired design development cycles are on the order of months to years. Until that is available in a practical program, designs that trade performance for timeliness won't deliver maximum utility. Further study of the design space is required to determine where in the continuum it is desirable to pursue a balance between traditional measures of spacecraft effectives and ORS demands for timeliness.

The tradespace method allows a decision maker to very easily compare tradeoffs between designs. For instance, the decision maker can see the trade between increasing focal length and cost, or how changing orbit inclination affects utility.

B. Future Work

While this particular study did not include drastically different design concepts, it would be simple to imagine a few concepts that creatively handle competing attributes. For instance, a design could have two physically separate systems in different orbit altitudes. One at higher altitude would achieve a high utility in field of view, while the system at lower altitude would achieve high utility resolution.

The next step is to examine constellations of designs, in which many smaller, short development time spacecraft may produce enough utility to out-perform fewer, larger satellite designs. In this case it is important to reconsider the attribute set, as most of the attributes are calculated for a single spacecraft. Aggregating across a constellation must be carefully done so that advantages and disadvantages are captured accurately in the metrics.

Demonstrating a schedule model within the MATE static tradespace opens up the application of the method. The tradespace shows a snapshot of the system at the beginning of life. Dynamic tradespace methods that include phases of development are in early stages and could potentially inform the entire development process. Future work on this branch of research includes refinement of the schedule model to include the impact of iterative design work, as well as the impact of schedule changes on system performance. In particular, application of a Monte Carlo analysis to determine the expected performance impact due to increased risk from compressed schedules will highlight the utility loss that might be expected over time from pursuing aggressively shortened schedules.

This study examined the effects of changing preferences on an electro-optical payload design. "Big Space" preferences tended to reward systems with large payloads, while "ORS" preferences tended to reward designs with shorter development schedules. This result is expected and follows directly from the stated ORS goals; however, more work need to be done to model the effects of shortening development schedule.

Appendix A- Utility Functions for Proxy Stakeholder for the Air Force ISR Mission

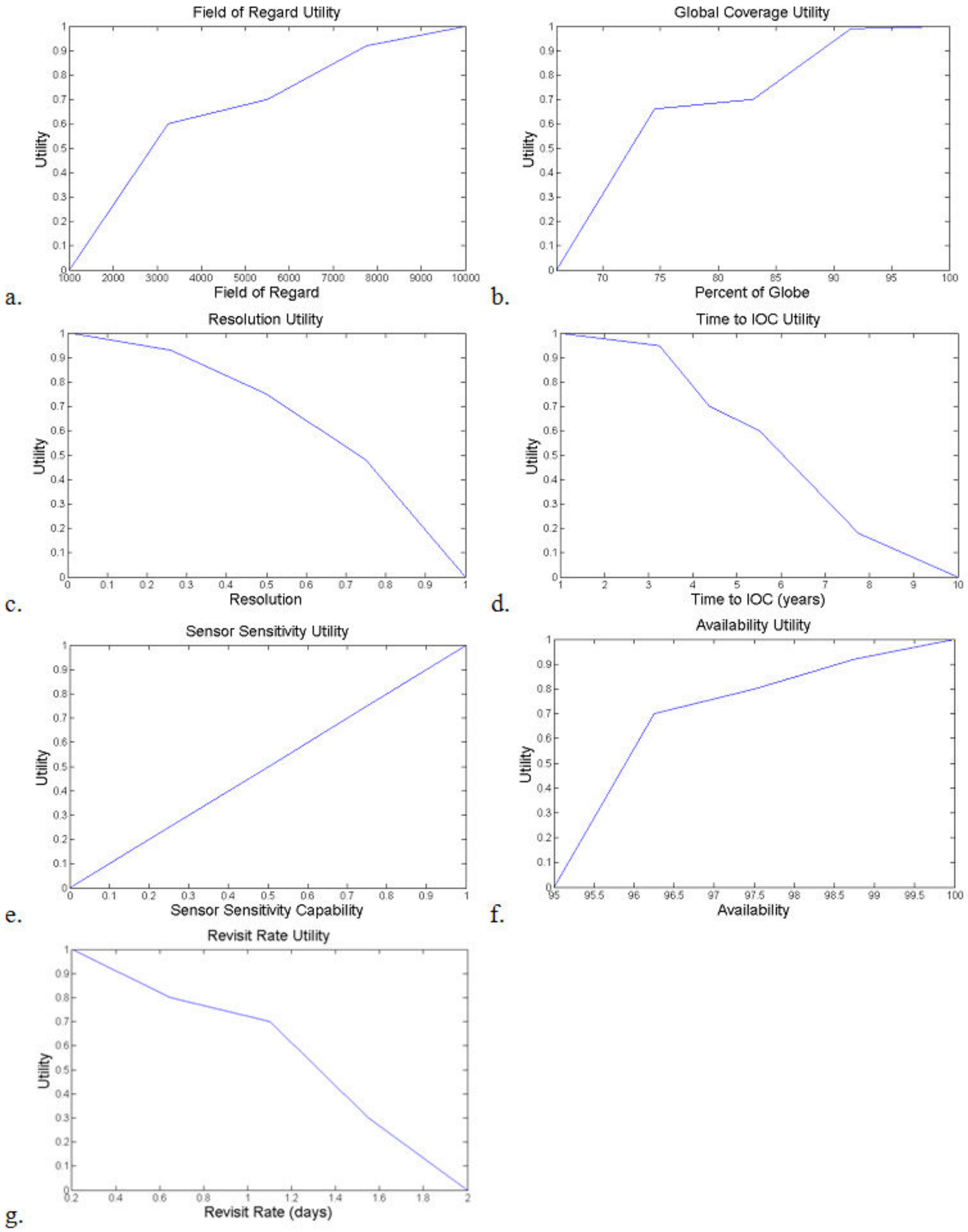

Figure 9. Single Attribute Utility Functions. *a.) Field of Regard b.) Global Coverage c.) Resolution d.) Time to IOC e.) Sensitivity f.) Availability g.) Revisit Rate*

Acknowledgments

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