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Multi-Attribute Tradespace Exploration for Survivability

Adam M. Ross,[*] David B. Stein,[†] and Daniel E. Hastings[‡]
Massachusetts Institute of Technology, Cambridge, MA 02139

Multi-Attribute Tradespace Exploration for Survivability is a system design and analysis methodology that incorporates survivability considerations into the tradespace exploration process (*i.e.*, a solution-generating and decision-making framework that applies decision theory to model-based design). During the concept generation phase of tradespace exploration, the methodology applies seventeen empirically validated survivability design principles spanning susceptibility reduction, vulnerability reduction, and resilience enhancement. During subsequent concept evaluation, the methodology adds value-based survivability metrics to traditional architectural evaluation criteria of mission utility and lifecycle cost. Applied to a satellite radar mission, the methodology allowed operational survivability to be statistically evaluated across representative distributions of naturally occurring disturbances in the space environment and for survivability to be incorporated as a decision factor earlier in the design process. Constellations in the illustrative example are shown to be the most survivable, mitigating disturbances architecturally, rather than through additive features.

Nomenclature

A_T	=	threshold availability, %
ΔV	=	change in velocity, m/s
k_i	=	multi-attribute utility scaling factor for attribute i
P_t	=	transmit power, w
P	=	peak power, w
R	=	distance to target, m

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[*] Research Scientist, Systems Engineering Advancement Research Initiative. Senior Member AIAA.
[†] Undergraduate Research Assistant, Systems Engineering Advancement Research Initiative.
[‡] Professor of Aeronautics and Astronautics and Engineering Systems,. Fellow AIAA.

σ	=	radar cross section, m^2
λ	=	wavelength, m
T_{dl}	=	time of design life, years
U_e	=	emergency utility threshold (zero by definition), utilities are dimensionless
$U_i(x_i)$	=	single-attribute utility function over attribute x_i
$\bar{U}_L$	=	time-weighted average utility loss from design utility, U_0
$\bar{U}_t$	=	time-weighted average utility
$U(t)$	=	utility delivery over time; multi-attribute utility trajectory
$U(\underline{x})$	=	multi-attribute utility function over attributes $\underline{x}$ at a point in time
U_x	=	required utility threshold

I. Introduction

Complex space systems have always demanded high levels of reliability due both of the high costs of launch and the difficulty in reaching and repairing a system if it malfunctions in any kind of orbit. Discussion in recent years has started to focus on the need for complex space systems to have other outcomes associated with them. These outcomes are associated with the "illities" and include properties such as adaptability, flexibility, changeability and survivability. Explicit attention to the existence of these outcomes is the way to design these systems for the inevitable uncertainty[1] they will experience in their (long) operational lives. This paper focuses on one of these "illities" namely, survivability.

Survivability engineering is critical to minimizing the impact of disturbances (*e.g.*, orbital debris, signal attenuation) to the operation of space systems,[2] and its importance is underscored by growing survivability concerns.[3,4] In this paper, Multi-Attribute Tradespace Exploration (MATE) for Survivability is introduced as a general methodology for the generation and assessment of alternative system architectures that must operate across disturbance environments. While the focus for this paper is on naturally occurring disturbances in the space environment, the methodology can inform survivability against disturbances more generally in concept generation and system evaluation activities during conceptual design. To improve the generation of survivable design alternatives, MATE for Survivability consults seventeen survivability design principles spanning susceptibility reduction, vulnerability reduction, and resilience enhancement techniques. Empirically derived from highly survivable military and commercial aerospace systems,[5,6] the design principles enable consideration of survivability

strategies that prevent system value losses across the entire lifecycle of a disturbance (*i.e.*, before, during, and after such losses are realized). To improve the evaluation of survivability, MATE for Survivability utilizes value-based metrics that assess survivability as a dynamic, continuous, and path-dependent system property. While beneficial for expanding the scope of survivability-enhancing solutions, a value-based approach has the drawback of formulating survivability as a "meta" objective (i.e. an objective on objectives) and therefore cannot be simply included as part of the value at the system performance level.[7]

In this paper, survivability is a dynamic system property comprised of three types, and is achieved by delivering value above an emergency value threshold and returning to delivering value above a required nominal value threshold within a permitted recovery time. The three types of survivability are susceptibility (*i.e.*, the likelihood or magnitude of a disturbance occurring within a system boundary), vulnerability (*i.e.*, the sensitivity of system value delivery to disturbance-induced losses), and resilience (*i.e.*, the ability of a system to recover from disturbance-induced value losses within a permitted recovery time), illustrated in Figure 1 below.
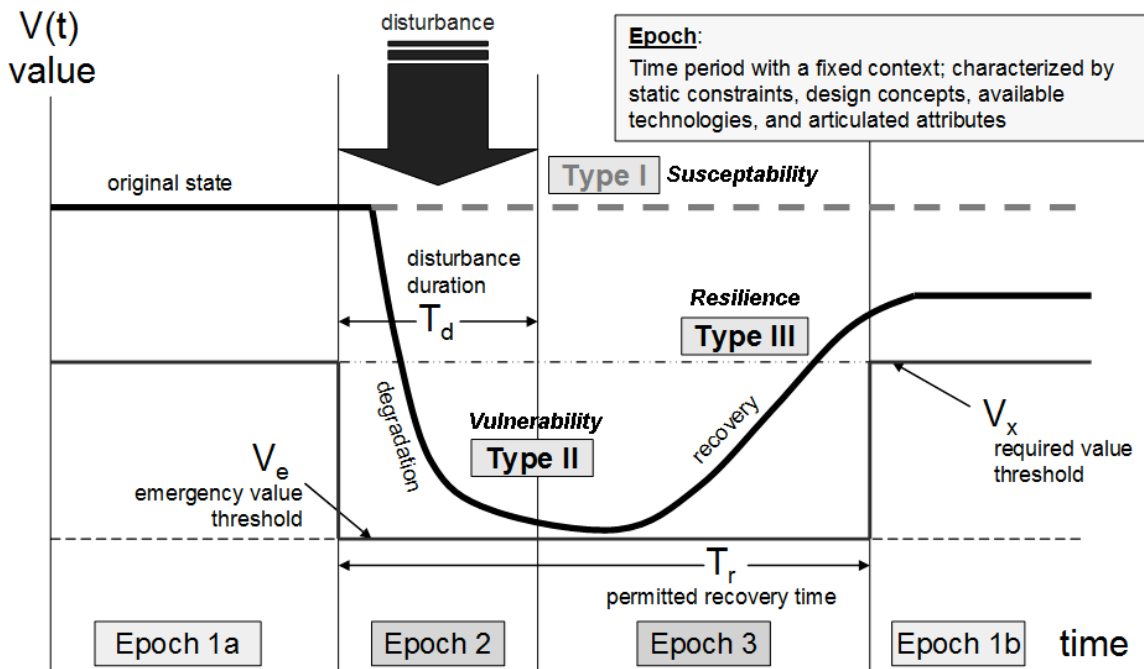

Figure 1. Survivability as a dynamic, value-centric system property in three types: susceptibility, vulnerability, and resilience (based on Fig. 1 from Ref 7).

This article complements prior work on survivability metrics[7] but is distinct in that it focuses on concept generation (rather than only on concept evaluation) through the introduction and application of survivability design principles to tradespace exploration. While the survivability metrics have previously demonstrated the ability to rapidly filter thousands of individual satellite alternatives, the seventeen design principles have not previously been introduced, applied to concept generation of space systems, or integrated with the survivability metrics into a generalized methodology for both design and analysis. Furthermore, the value-based survivability metrics have not previously been applied to systems at an architecture-level unit-of-analysis (*e.g.*, alternative satellite constellations). Incorporating survivability considerations into the definition of the system architecture contrasts to traditional survivability methodologies, which examine the cost-effectiveness of survivability features, added to a baseline design.[8] By incorporating survivability considerations into the definition of the baseline system concept, MATE for Survivability allows survivability to be incorporated earlier into a system development.

Following this introductory section, Section II formulates the need for an enhanced tradespace exploration methodology for designing for survivability to allow active trading of survivability beyond that which can be done using current survivability engineering and system analysis methodologies. Next, Section III provides a general overview of MATE for Survivability.

Section IV applies the methodology to the analysis of satellite radar alternatives operating in the presence of disturbances from the natural space environment. First, a notional value proposition for satellite radar is elicited through multi-attribute utility interviews from a proxy decision maker. (While the notional utility interviews limit the implications of the results for satellite radar, the purpose of the case application is to demonstrate the methodology and illustrate the emergent survivability insights that may be derived from its application.) Second, concepts are proposed to meet the elicited decision maker attributes and promising alternatives are formulated as design options through a parametric design vector. Third, disturbances in the operating environment (*e.g.*, orbital debris, signal attenuation) are enumerated and concept-neutral models of disturbance frequency and magnitude are developed. Fourth, the seventeen survivability design principles are consulted to incorporate susceptibility reduction, vulnerability reduction, and resilience enhancement strategies into the design vector (*e.g.*, shielding, relay downlink option, satellite sparing). Fifth, having formulated the design problem, the performance of alternative satellite radar constellations are simulated using a physics-based simulation. Deterministic performance parameters of lifecycle cost and design utility are calculated and utilized to identify Pareto-efficient satellite radar constellations

operating in nominal operating environments. Sixth, the performance of the constellations across a sample of disturbance encounters is simulated to examine survivability and to gain an understanding of how decision maker needs are met in perturbed environments. Seventh, the survivability metrics developed in Ref. 7, time-weighted average utility loss and threshold availability, are applied to each design alternative as summary statistics of constellation degradation. Eighth, integrated cost, performance, and survivability trades are performed across the design space to identify promising alternatives for more detailed analysis.

Section V discusses the implications of the case application for the design problem and for the underlying survivability design and analysis methodology. The tradespace results show that while most design alternatives in the design problem are survivable to the natural disturbances under consideration, the rank-order preferences of the decision-maker on alternatives are subject to change when disturbances are taken into account. Section VI concludes the paper with a summary of the key findings.

II. Problem Formulation

In addition to meeting requirements in a static context, the performance of engineering systems is increasingly defined by an ability to deliver value to stakeholders in the presence of changing operational environments, economic markets, and technological developments.[9,10] As temporal system properties that reflect the degree to which systems are able to maintain or even improve function in the presence of change, the "-ilities" (*e.g.*, flexibility) constitute a rich area of research for improving value delivery over the lifecycle of systems.[11] Applicable across engineering domains, the "-ilities" are particularly critical to space systems which are characterized by high cost, long design lives, high complexity, interdependencies with other systems, and dynamic operational contexts.[12]

Although survivability is an emergent system property that arises from interactions among system components and between a system and its environment, conventional approaches to survivability engineering are often reductionist, focusing only on selected properties of subsystems or modules in isolation, and fail to accommodate dynamic threat environments.[8] (One notable exception demonstrated for combat aircraft is the Probabilistic System of Systems Effectiveness Methodology, POSSEM, which links engineering-level changes to campaign-level measures of effectiveness.[13,14]). Additionally, current methods fail to facilitate stakeholder communication for performing integrated trades among system lifecycle cost, performance, and survivability.

Given the limitations of existing survivability design methods for aerospace systems discussed in prior work[15] (*i.e.*, treatment of survivability as a constraint on design, static system threat assessment reports, assumption of

independent disturbance encounters, limited scope, and focus on physical integrity), there is a need for a design method that (1) incorporates survivability as an active trade in the design process, (2) captures the dynamics of operational environments over the entire lifecycle of systems, (3) captures path dependencies of system survivability to disturbances, (4) extends in scope to architecture-level survivability assessments, and (5) takes a value-centric perspective to allow alternative value-delivery mechanisms in the tradespace. Recent research on how decision-makers can recognize and evaluate dynamically relevant designs, including Multi-Attribute Tradespace Exploration[16] and Epoch-Era Analysis,[17] offers a theoretical foundation for the development of an improved design methodology for survivability.

III. Methodology Overview: Multi-Attribute Tradespace Exploration for Survivability

Multi-Attribute Tradespace Exploration (MATE) for survivability provides system analysts a structured approach for determining how a system can maintain value delivery across operational environments characterized by disturbances. The intent of the process is to couple the benefits of Multi-Attribute Tradespace Exploration in conceptual design with the benefits offered by the survivability design principles and the survivability metrics. In particular, MATE for Survivability is a value-driven process in which the designs under consideration are directly traced to the value proposition[18], and the measures-of-effectiveness reflect the preferences of the decision-maker during nominal and perturbed environmental states. By following a parametric modeling approach, broad exploration of the tradespace is enabled in which the decision-maker gains an understanding of how their value proposition maps onto a large number of alternative system concepts. By emphasizing breadth, larger promising areas of the tradespace may be selected with confidence for further analysis, and sensitivities between survivability design variables and disturbance outcomes may be explored.

A. Legacy Methodology: Multi-Attribute Tradespace Exploration

MATE for Survivability builds on the legacy conceptual design methodology of Multi-Attribute Tradespace Exploration (MATE). MATE applies decision theory to model and simulation-based design. Decoupling the design from the need through tradespace exploration, MATE is both a solution generating as well as a decision-making framework. (Many "value-centric design methods"[19] exist for evaluating, and sometimes motivating the generation of, design alternatives[20], such as Robust Concept Exploration Method (RCEM)[21]. These methods often combine techniques from multiple disciplines, such as robust design for generating and framing alternatives, multi-disciplinary optimization for evaluating alternatives[22,23], and decision theory for ranking alternatives. Evaluation

and ranking techniques such as Analytic Hierarchy Process[24], Multi-Attribute Utility Analysis[30], and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)[25] each vary in their approach, and are incorporated to varying degrees in published conceptual design and evaluation methods. MATE couples both the solution generating and evaluating and ranking techniques, distinguishing it from traditional decision analyses techniques that often focus on the evaluation and ranking step. Techniques such as cost-benefit analysis[26], or real options analysis, fall short in generating alternatives for evaluation[27,28].) The survivability enhancement to MATE described in this paper could be similarly applied to other conceptual design generation and evaluation methods. Because MATE displayed the desired properties of being value-focused, and general in applicability, it was selected as the legacy method for survivability enhancement. Descended from the Generalized Information Network Analysis (GINA) methodology that applies metrics from information theory to the quantitative evaluation of communications spacecraft,[29] MATE draws on multi-attribute utility theory[30] to expand the analysis to systems that cannot be modeled as information networks. To date, MATE has been applied to over a dozen (mostly aerospace) systems and utilized in research examining requirements generation,[31] policy uncertainty,[32] space system architecting and design,[33,34] concurrent engineering,[35] spiral development,[36] evolutionary acquisition,[37,38] modularity,[39] orbital transfer vehicle design,[40] and value robustness.[41]

Ref. 33 provides a detailed description of an example set of 48 steps that could comprise a full MATE study. At a high level, the process consists of three general phases: mission definition, concept generation, and design evaluation. In the first phase, the mission needs and preferences of a decision-maker are defined and specified with attributes (*i.e.*, decision-maker-perceived metrics that measure how well decision-maker-defined objectives are met). Attributes and their associated utility curves and multiplicative weighting factors are elicited through formal utility interviews with decision-makers. Single-attribute utility curves are typically aggregated using a multiplicative utility function (*i.e.*, a dimensionless metric of user satisfaction ranging from 0, minimally acceptable, to 1, highest of expectations).

In the second phase, the attributes are inspected and various design variables are proposed that drive performance in the attributes. (Design variables are designer-controlled quantitative parameters that reflect aspects of a concept, which, taken together as a set, uniquely define a system architecture.) The actual performance will be evaluated in phase three using physics-based models. Each possible combination of design variable enumeration choices constitutes a unique design vector, and the set of all possible design vectors constitutes the design-space. This

solution-generating phase—using the decision-maker-derived attributes to propose design variables to include in the trade study—explicitly links the value and technical domains of a system.

In the third phase, physics-based models are developed to evaluate the lifecycle cost and utility of the designs under consideration. To assess the full-factorial sampling of the design space, parametric computer models are used to transform each design vector into attribute values against which utility functions can be applied. Following a MATE analysis, a limited number of Pareto-efficient designs may then be matured in a concurrent engineering environment. The broad, front-end evaluation of thousands of design alternatives on a common, quantitative basis provides decision-makers a prescriptive framework for selecting designs to carry forward for more detailed analysis.

B. Incorporating Survivability Considerations into Multi-Attribute Tradespace Exploration

Multi-Attribute Tradespace Exploration for Survivability extends the existing MATE approach by incorporating survivability considerations into each phase of the MATE process. In addition to eliciting attributes from decision-makers (*i.e.*, stakeholders with control over system development resources and/or driving needs) to specify the system value proposition, the mission definition phase includes the enumeration of disturbances, by leveraging expert knowledge and historical data, to characterize the operational environment of the system under analysis. The concept generation phase is extended by applying the survivability design principles to the design vector.[42] This application ensures that a broad portfolio of behavioral and structural survivability strategies is considered for inclusion in the subsequent tradespace exploration. In the design evaluation phase, the static MATE analysis of estimating the lifecycle cost and multi-attribute utility of each design alternative is supplemented by a dynamic, lifecycle analysis to model the performance of design alternatives over distributions of representative disturbances from a Monte Carlo analysis. The utility trajectory outputs from the dynamic analysis (*i.e.*, distributions of multi-attribute utility over time) may be then evaluated using the survivability metrics as summary statistics.[7] This formulation, as compared to treating survivability as an attribute, is described in Ref 7. Integrating the deterministic assessment of lifecycle cost and mission utility (at beginning of life) with the stochastic survivability metrics allows decision-makers to navigate an integrated tradespace of lifecycle cost, beginning of life mission utility, and operational survivability. Figure 2 provides a flow chart of MATE for Survivability and identifies relationships with the legacy MATE process (*i.e.*, either unchanged from MATE, evolved from MATE, or new to MATE).
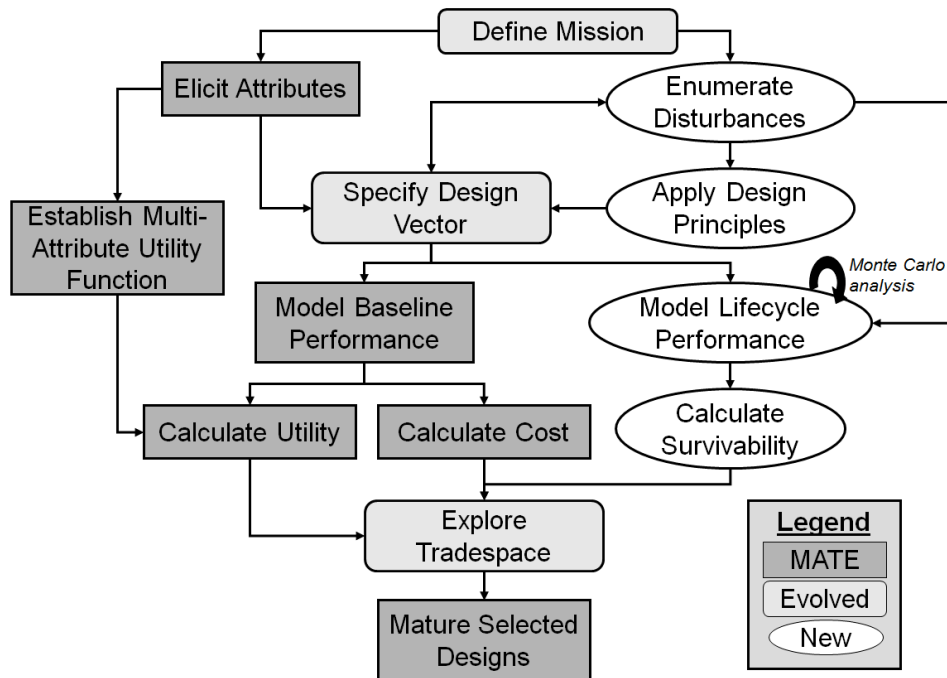
Figure 2. Multi-Attribute Tradespace Exploration (MATE) for Survivability

Given the extensions to the legacy MATE process, MATE for Survivability is implemented over eight general phases:

1. **Elicit value proposition** – Identify mission statement and quantify decision-maker needs during nominal and emergency states.

2. **Generate concepts** – Formulate system concepts that address decision-maker needs.

3. **Characterize disturbance environment** – Identify potential disturbances and develop models, which are relevant across multiple concepts, of these disturbances in operational environment of proposed systems.

4. **Apply survivability principles** – Motivated by the list of potential disturbances, incorporate susceptibility reduction, vulnerability reduction, and resilience enhancement strategies into design alternatives.

5. **Model baseline system performance** – Develop physics-based performance models of design alternatives to gain an understanding of how decision-maker attributes are met in a nominal operational environment. Develop parametric cost models to estimate lifecycle cost.

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6. **Model impact of disturbances on lifecycle performance** – Model and simulate performance of design alternatives across a representative sample of disturbance encounters to gain an understanding of how decision-maker needs are met in perturbed environments.

7. **Apply survivability metrics** – Compute time-weighted average utility loss and threshold availability for each design alternative as summary statistics for system performance across representative operational lives. (See Ref. 7 for justification of these metrics.)

8. **Explore tradespace** – Perform integrated cost, performance, and survivability trades across design space to identify promising alternatives for more detailed analysis.

The following section illustrates the methodology through an application to satellite radar.

IV. Case Application: Satellite Radar

This section applies MATE for Survivability to an analysis of alternative satellite radar constellations. Radar systems provide unique all-weather reconnaissance and surveillance capabilities.[43,44] Transitioning radar sensors from airborne to space platforms is challenging, particularly the range requirements and strict size, weight, power, and reliability requirements imposed by satellites.[45] Given the repeated attempts over the past decade by the U.S. military to acquire a satellite radar capability (*e.g.*, Discover II,[46] Space-Based Radar [SBR],[47] Space Radar[48]) and the taxpayer dollars at stake, satellite radar offers a promising subject both to test the proposed survivability design and analysis methodology and to gather prescriptive insights to inform future trade studies.

Past analyses of satellite radar alternatives have focused on the synthetic aperture radar (SAR) imaging and ground moving target identification (GMTI) missions because they are considered the highest priority, driving missions.[46,49,50] in applying MATE for Survivability to satellite radar, a simplifying assumption is made to focus on GMTI. Therefore, operational utility is assessed in terms of the GMTI mission for a single decision-maker rather than introducing multi-stakeholder tensions across users of SAR and GMTI. (Ref. 41 provides one approach for incorporating multi-stakeholder considerations into MATE, and Ref. 50 provides a specific application of the methodology to competing stakeholders in satellite radar.)

A. Phase 1: Elicit Value Proposition

In the first phase of MATE for Survivability, attributes are elicited from a decision-maker as quantifiable parameters for measuring how well decision-maker-defined objectives are met. Six key attributes for the GMTI mission were derived from interviews (described in Ref. 49): (1) number of target boxes, (2) minimum detectable target velocity, (3) minimum detectable radar cross-section, (4) target acquisition time, (5) track life, and (6) tracking latency.[49,50] These attributes provide quantitative performance metrics that can be used to define mission utility for a tactical military user. While the former three attributes are satellite-level properties that characterize the performance of the radar sensor, the latter three attributes, for the purposes of this case study, are used to evaluate constellation performance.

Table 1. Satellite Radar Attributes (GMTI)

Attribute	Definition	Acceptable Range
number of target boxes	number of 200x200 km target boxes (consisting of targets with a given velocity and radar cross section) that can be imaged by a single satellite during a single pass	1 → 6
minimum detectable velocity (m/s)	lowest possible velocity of a target that can be detected from the backdrop of its surroundings	5 ← 50
minimum detectable radar cross section (m²)	minimal target area capable of reflecting a signal detectable by the radar's receiver in response to a radar pulse	0.01 ← 1000
target acquisition time (min)	95th percentile longest duration until a randomly assigned target can be tracked	0 ← 300
track life (min)	95th percentile shortest duration of continuous target monitoring	1 → 60
tracking latency (min)	95th percentile longest duration until Moving Target Identification data is received by warfighter	1 ← 240

Table 1 defines the six attributes and describes ranges of acceptability, as expressed in the interviews. Each attribute delivers zero utility when it is at the "worst" value that is still acceptable to the stakeholders. A utility of one is reached when the stakeholders are fully satisfied. Increasing utility (from 0 to 1) is indicated in Table 1 by the direction of the arrows. As illustrated in Figure 3, the attributes that range over many orders of magnitude are assumed to map logarithmically to the attributes, while attributes with narrower ranges have a near-linear mapping. These particular single attribute utility curves are based on informal interviews with experts providing sketches of utility for various levels of attributes. The weights were derived from an attribute importance ranking provided in the interviews. Sensitivity analysis on utility function "shapes" as well as ranges, weights, and attribute set definition can be performed in terms of enumerating various "preference epochs" to understand the impact of varying

preferences on the evaluation of alternative designs.[50,51] Alternatives that are less sensitive to preference assumptions can be identified through such analyses. In this paper this type of sensitivity analysis was not performed for the sake of clarity to focus on survivability.

The attributes are used to compute the utility using multi-attribute utility methods. For the illustrative purpose of this published study, the attribute ranges and utility functions are based on approximate data. While conducting formal utility interviews are preferred for mapping the attributes to utility, since they are derived from expressed desires, these proxy values are still more likely to correspond to stakeholder expectations than assuming an analyst-proposed objective function. The attribute set maps closely to the attribute set used in a 2002 study of SBR alternatives: tracking area, minimum detectable speed, SAR resolution, SAR area, geolocation accuracy, gap time, and center of gravity area.[38]
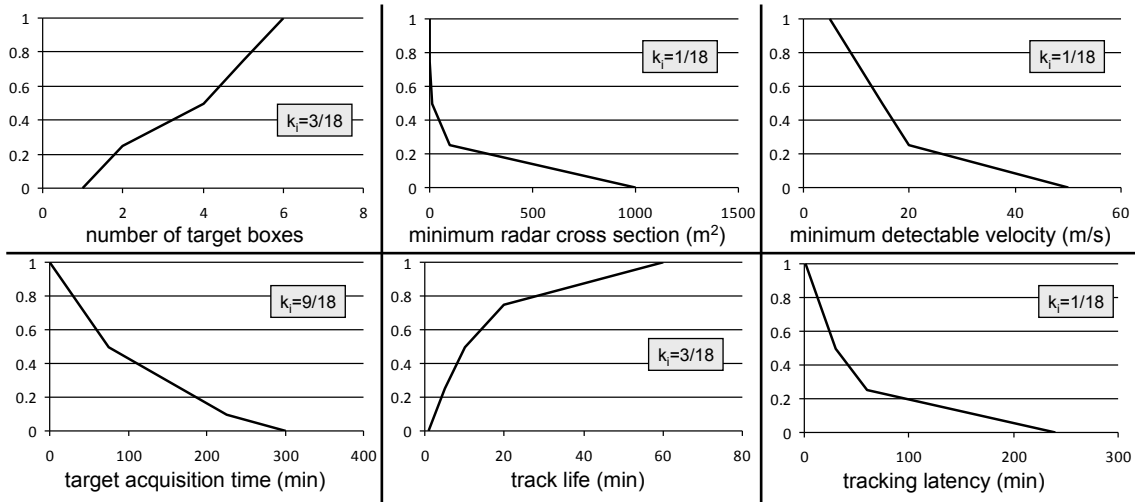
Figure 3. Single-Attribute Utility Functions for GMTI

Since the purpose of this case study is to illustrate the survivability method described in this paper, and not make particular recommendations for a satellite radar tracking mission, some simplifications to the analysis were made for clarity. To determine the multi-attribute utility for the GMTI mission, for simplicity a simple linear-weighted sum is used in which the single-attribute utilities are multiplied by their respective k_i weighting factors:

$$U(\underline{X}) = \sum_{i=1}^{6} k_i \cdot U(X_i) \tag{1}$$

To incorporate survivability considerations into the value elicitation phase, it is necessary to consider whether stakeholder expectations change during and immediately after disturbance events. For the case of a constellation of military radar satellites, it is assumed that tactical user expectations for GMTI are not reduced as a function of space environmental disturbances given an emphasis on assured capability.

B.   Phase 2: Generate Concepts

Following elicitation of decision-maker attributes, alternative design concepts for the satellite radar tradespace are generated in Phase 2 (Generate Concepts). The concepts focus on conventional designs and are informed by existing analyses of military satellite radar.[52] Current or near-future satellite radar technology documented in the literature constrain the design space.[53,54] It is assumed that the satellites interact with existing or near-future space communication and ground communication infrastructure to disseminate GMTI data. Consideration is also given to the possibility of direct, in-theater tasking and downlink.

In Phase 2 (Generate Concepts), the attributes are inspected and various design variables and associated ranges and enumerations are proposed. (Design variables are designer-controlled quantitative parameters that reflect aspects of a concept, which taken together as a set uniquely define a system architecture.) Possible combinations of design variable enumeration levels constitute an architecture alternative, and the set of all possible alternatives constitutes the design-space. This solution-generating phase—inspecting the decision maker-derived attributes to determine which design variables to include in the trade study, along with appropriate enumeration ranges for the design variables—ensures that design activities in the technical domain are explicitly linked to the stakeholder needs elicitation in the value domain.

Table 2. Value Mapping Matrix for Satellite Radar

		ATTRIBUTES															
		Mission											Programmatics				
		Tracking						Imaging					Cost		Schedule		
Variable Name	Definition Range	Minimum Target RCS	Min. Discernable Velocity	Number of Target Boxes	Target ID Time	Target Track Life	Tracking Latency	Resolution (Proxy)	Targets per Pass	Field of Regard	Revisit Frequency	Imaging Latency	Baseline Cost	Actual Costs (Era)	Baseline Schedule	Actual Schedule (Era)	Total Impact
Peak Transmit Power	1.5 10 20 [KW]	9	9	9	3	1	1	9	9	9	0	1	9	9	9	9	**96**
Radar Bandwidth	.5 1 2 [GHz]	9	9	3	3	1	1	9	9	9	0	1	3	3	3	3	**66**
Physical Antenna Area	10 40 100 200 [m^2]	9	9	9	3	1	1	9	9	9	1	1	9	9	9	9	**97**
Antenna Type	Mechanical vs. AESA	9	9	9	3	3	1	9	9	9	1	1	9	9	9	9	**99**
Satellite Altitude	800 1200 1500 [km]	9	9	3	9	9	3	9	9	9	9	3	1	1	1	1	**85**
Constellation Type	8 Walker IDs	0	0	1	9	9	3	0	0	3	9	3	9	9	9	9	**73**
Comm. Downlink	Relay vs. Downlink	0	0	0	0	0	9	0	0	0	0	9	9	9	3	9	**48**
Tactical Downlink	Yes vs. No	0	0	0	0	3	9	0	0	0	0	9	9	9	3	9	**51**
Maneuver Package	1x, 2x, 4x	1	1	1	1	1	0	1	1	1	1	0	9	3	3	3	**27**
Constellation Option	none, long-lead, spare	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9	**36**
Total		46	46	35	31	28	28	46	46	49	21	28	76	70	58	70	

In Table 2, the columns consist of attributes elicited from decision makers and the rows consist of potential design variables for incorporation in the trade study. The intersecting cells—indicating the interaction between a design parameter and an attribute—are scored on a "no impact," "low impact," "medium impact," and "high impact" scale using expert judgment (i.e., 0, 1, 3, and 9, respectively). An aggregate sum is computed for each design variable row as an indicator of the importance of its inclusion in the design-space. This matrix exercise is a mapping of the perceived relationship between choices in the design space and "performance" in the value space and is equivalent to a very low fidelity model. Rather than being used to actually evaluate alternatives, this matrix has been used to help prioritize experience-based predicted design drivers. After evaluation models are constructed, the actual complex relationship between the design space and value space can be compared to this low fidelity initial assessment. The size of the tradespace grows geometrically as design variables are added, requiring the pre-screening of design variables if limited computing resources are available. Various techniques exist for either pre-screening, or intelligently sampling the design space in order to reduce the problem to lower dimensionality for computationally constrained modeling efforts. The particular choice of technique does not affect the overall method described herein. In addition to informing selection of design variables for subsequent modeling and simulation (high row sums), the design value mapping matrix may also be used to check whether the selected design variables adequately drive value delivery across all of the stakeholder-derived attributes (high column sums).

The preliminary set of design variables in Table 2 includes elements of the radar sensor deployed, orbital properties of the satellite platforms, communications systems, and other satellite capabilities. Selecting a value for each particular design variable involves making a host of trade-offs. For example, as discussed in Ref. 46, two major options exist for radar antennae: active electronically-scanned arrays (AESA) or conventional reflectors. This particular table illustrates the larger satellite radar study, which included both the GMTI and SAR missions, as well as considerations for programmatics. The full matrix is included here to illustrate the inclusion of particular design variable choices based on their anticipated link to attributes of interest (i.e. sufficient row and column sums indicating a set of design variables that cover the desired attributes).

C. Phase 3: Characterize Disturbance Environment

Once the baseline design vector is established, the next step in a traditional MATE study is to model the performance of the design alternatives to estimate lifecycle cost and utility. In MATE for Survivability, this step is preceded by two phases: characterizing the disturbance environment (Phase 3) and applying the survivability principles to the design vector (Phase 4).

Having selected a general system concept for the satellite radar system, environmental disturbances are enumerated and characterized. Table 3 shows the disturbances for an Earth-observing satellite operating at 800-1500 km and a 53° inclination. Since all disturbances are not of equal concern, an importance score for each disturbance is assigned based on the magnitude of impact and likelihood of occurrence. (The importance score provides a relative ranking of disturbances in the space environment on mission impact. The score is a first order estimate of magnitude of impact of a disturbance on mission value. The scores may range from 0 [*i.e.*, effects produced can be ignored] to 10 [*i.e.*, effects produced will negate mission].) The importance estimates for the first four disturbances in Table 3 are based on Ref. 55 and the subsequent estimates are based on engineering judgment. For example, aerodynamic drag forces from the upper atmosphere may degrade orbits and chemically erode surfaces.[56] However, given that the circular orbits in the design vector begin at 800 km, this disturbance is of low importance to the design vector. In contrast, micrometeorites and debris are of concern to Earth-observing constellations at this altitude.

Table 3. Environmental Disturbances to Satellite Radar

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Disturbance	Importance (1-10)
Atmospheric drag fluctuations	1
Arc discharging	3
High-flux radiation	4
Micrometeorites/debris	7
Signal attenuation	5
Change in target definition	4
Failure of relay backbone	6
Loss of ground node	2

Having enumerated disturbances types, the disturbances are checked for non-additive interactions. For example, an intelligent pairing of certain disturbances may lead to non-linear losses in value delivery. Given an intelligent pairing, it would be necessary to include such combinations of disturbances as additional rows in Table 3. Such intelligent pairing was not identified in this study; for the analysis of satellite radar in this paper, the focus is on naturally occurring disturbances in the space environment that are assumed to be randomly distributed. Therefore, while it remains necessary to model the impact of extreme combinations of disturbances in Phase 6 (Model Impact of Disturbances on Lifecycle Performance), such interactions do not dominate the general characterization of the disturbance environment in Phase 3 (Characterize Disturbance Environment).

D. Phase 4: Apply Survivability Principles

After the baseline set of design variables is established and the disturbance environment is characterized, the survivability design principles are applied to the tradespace. Applying the design principles supplements the concept generation activities in Phase 2 (Generate Concepts) by incorporating survivability strategies that mitigate the disturbances identified in Phase 3 (Characterize Disturbance Environment). This phase consists of five steps: (1) enumerate survivable concepts from design principles, (2) parameterize survivable concepts with design variables, (3) assess ability of design variables to mitigate disturbances, (4) filter survivability design variables, and (5) finalize design vector.

First, seventeen empirically validated survivability design principles[5,6] are consulted to inform the generation of system concepts that mitigate the impact of each disturbance. Each design principle provides a concept-neutral architectural strategy for achieving survivability. Given the baseline set of design variables and environmental disturbances, a variety of concept enhancements may be brainstormed for the satellite radar mission. This brainstorming is done through the art of design. To aid in the activity, the design principles have been grouped by which type of survivability they enhance: susceptibility reduction (Type I), vulnerability reduction (Type II), or resilience enhancement (Type III). The first two columns of the Survivability Design Variable Mapping Matrix

(Table 4) illustrate the mapping from principle to concept enhancements. For example, the design principle of margin is applied to the satellite constellation as well as to four different spacecraft subsystems (*i.e.*, power generation, communications, propulsion, and data storage). The design principle of redundancy is also applied to different elements of the system architecture, including the satellite-level, constellation level, and ground segment. In all, 24 concepts are generated from 13 of the survivability design principles. (Given the focus on natural disturbances, the Type I survivability design principles that modify the observations, decision-making, and actions of hostile actors are not applicable. These not applicable design principles are mobility, concealment, deterrence, and preemption).

Table 4. Survivability Design Variable Mapping Matrix

	design principles	concept enhancements	design variables (units)	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target definition	failure of relay backbone	loss of ground node
				disturbances							
Type I	prevention	reduce exposed surface area	antenna area (m^2)	9	0	3	9	0	0	0	0
Type I	mobility										
Type I	concealment										
Type I	deterrence										
Type I	preemption										
Type I	avoidance	maneuvering	ΔV (m/s)	9	0	3	1	0	0	0	0
Type I	avoidance	maneuvering	servicing interface	9	0	1	1	0	0	0	0
Type I	avoidance	ground receiver maneuverability	mobile receiver	0	0	0	0	3	0	0	3
Type II	hardness	radiation-hardened electronics	hardening (cal/cm^2)	0	3	9	1	0	0	0	0
Type II	hardness	bumper shielding	shield thickness (mm)	0	0	0	9	0	0	0	0
Type II	redundancy	duplicate critical functions	bus redundancy	0	1	9	3	0	0	0	0
Type II	redundancy	on-orbit satellite spares	extra vehicle per orbital plane	0	1	3	3	0	3	0	0
Type II	redundancy	multiple ground receivers	ground infrastructure level	0	0	0	0	3	0	0	9
Type II	margin	over-design power generation	peak transmit power (kW)	0	0	0	3	9	9	0	0
Type II	margin	over-design link budget	assumed signal loss (dB)	0	0	0	0	9	0	0	0
Type II	margin	over-design propulsion system	ΔV (m/s)	3	0	3	0	3	9	0	0
Type II	margin	excess on-board data storage	data capacity (gbits)	0	0	0	0	0	0	3	3
Type II	margin	excess constellation capacity	number of satellites	0	1	3	9	0	0	0	0
Type II	heterogeneity	interface with airborne assets	tactical downlink	3	3	3	3	3	3	3	3
Type II	heterogeneity	multiple communication paths	communications downlink	0	0	1	1	9	0	9	3
Type II	heterogeneity	multiple communication paths	tactical downlink	0	0	1	1	9	0	9	3
Type II	distribution	spatial separation of spacecraft	orbital altitude (km)	1	1	3	3	0	9	0	0
Type II	distribution	spatial separation of orbits	number of planes	0	0	3	9	0	1	0	1
Type II	failure mode reduction	reduce complexity	bus redundancy	0	0	9	0	0	0	0	0
Type II	fail-safe	autonomous operations	autonomous control	0	0	0	0	3	0	3	3
Type II	evolution	flexible sensing operations	antenna type	0	0	0	0	3	9	0	0
Type II	evolution	flexible sensing operations	radar bandwidth (MHz)	0	0	0	0	9	3	0	0
Type II	evolution	retraction of appendages	reconfigurable	0	0	9	3	0	0	0	0
Type II	containment	fault monitoring and response	autonomous control	0	1	3	1	0	0	0	0
Type III	replacement	rapid reconstitution	constellation spares	0	1	3	9	0	0	0	0
Type III	repair	on-orbit-servicing	servicing interface	9	1	3	3	0	3	0	0

The second step of applying the survivability principles is to parameterize the survivable concepts by specifying design variables. The third column of Table 4 illustrates this mapping. While concepts are qualitative descriptions of system strategies (*e.g.*, bumper shielding), design variables are quantitative parameters that represent an aspect of a concept that can be controlled by a designer (*e.g.*, shield thickness). To reduce the total number of design variables considered, the baseline set of design variables (developed in Table 2) is consulted, utilizing existing design variables where possible in the process of survivable concept parameterization.

The third step in Phase 4 (Apply Survivability Principles) is to assess the degree of impact of each survivability design variable on each disturbance type. As illustrated in the fourth set of columns in Table 4, this mapping

consists of a qualitative assessment in which a modified Quality Function Deployment[57] process is followed. Having drawn a matrix of design principles (rows) against disturbances (columns), estimates regarding the strength of the relationship between the disturbances and mitigating survivability design variables are made in the intersecting cells using engineering judgment. Typically, a non-linear scale is used: 0 (no impact), 1 (low impact), 3 (medium impact), and 9 (strong impact). For example, the design variable of assumed signal loss in the link budget will reduce the impact of signal attenuation but will not directly mitigate any of the other disturbances. The qualitative assessments may be revisited after survivability models are developed in Phase 6 (Model Impact of Disturbances on Lifecycle Performance).

The fourth step is to filter the enumerated survivability design principles based on the importance of their inclusion in subsequent phases of concept evaluation. Table 5 illustrates how the redundant design variables are consolidated and ordered to inform selection of a final set of design variables for the satellite radar system. This step is similar to what was done in Phase 2 (Generate Concepts). While most survivability enhancement concepts are specified by a unique design variable or set of design variables, a few design variables may serve to parameterize more than one principle and concept. For example, providing the satellite with a servicing interface (*i.e.*, docking port) may enable utilization of an orbital transfer vehicle for enhanced maneuverability as well as a robotic servicing vehicle for on-orbit repair of damaged components. This mapping of design variable to applicable survivability design principle is indicated by an 'X' in the table and design variables with more than one 'X' are consolidated "duplicates." In consolidating duplicate design variable rows from the survivability design matrix (Table 4), the maximum mitigating impact score for each disturbance is kept.

Table 5. Selection of Survivability Enhancement Features for Inclusion in Design Space

design variables (units)	prevention	mobility	concealment	deterrence	preemption	avoidance	hardness	redundancy	margin	heterogeneity	distribution	failure mode reduction	fail-safe	evolution	containment	replacement	repair	atmospheric drag fluctuations	arc discharging	high-flux radiation	micrometeorites / debris	signal attenuation	change in target definition	loss of relay backbone	loss of ground node	type	impact
	Type I						Type II									Type III											
tactical downlink										X								3	3	3	3	9	3	9	3	baseline	**162**
communications downlink										X								0	0	1	1	9	0	9	3	baseline	**116**
peak transmit power (kW)									X									0	0	0	3	9	9	0	0	baseline	**102**
antenna area (m^2)	X																	9	0	3	9	0	0	0	0	baseline	**84**
number of planes										X								0	0	3	9	0	1	0	1	baseline	**81**
ΔV (m/s)						X		X										9	0	3	1	3	9	0	0	baseline	**79**
constellation spares																X		0	1	3	9	0	0	0	0		**78**
number of satellites								X										0	1	3	9	0	0	0	0	baseline	**78**
orbital altitude (km)										X								1	1	3	3	0	9	0	0	baseline	**73**
shield thickness (cm)							X											0	0	0	9	0	0	0	0		**63**
autonomous control														X	X			0	1	3	1	3	0	3	3		**61**
bus redundancy								X										0	1	9	3	0	0	0	0		**60**
servicing interface						X											X	9	1	3	3	0	3	0	0		**57**
radar bandwidth (MHz)													X					0	0	0	0	9	3	0	0	baseline	**57**
reconfigurable													X					0	0	9	3	0	0	0	0		**57**
hardening							X											0	3	9	1	0	0	0	0		**52**
antenna type													X					0	0	0	0	3	9	0	0		**51**
extra vehicle per orbital plane								X										0	1	3	3	0	3	0	0		**48**
assumed signal loss (dB)									X									0	0	0	0	9	0	0	0		**45**
telemetry												X						0	0	9	0	0	0	0	0		**36**
ground infrastructure level								X										0	0	0	0	3	0	0	9		**33**
data capacity (gbits)									X									0	0	0	0	0	0	3	3		**24**
mobile receiver						X												0	0	0	0	3	0	0	3		**21**
weight																		1	3	4	7	5	4	6	2		

The fifth step of applying the survivability principles is to finalize the design vector by selecting a small number for inclusion in the tradespace. Four considerations may be incorporated into the process of determining which dedicated survivability design variables to include: coverage of design principles, mitigating impact on disturbances, modeling difficulty, and leveraging "baseline" design variables proposed in Phase 2 (Generate Concepts). Using these considerations, two "additional" survivability-enhancing design variables of constellation spares, and shield thickness were selected for inclusion in the study in this paper. The considerations are now described in more detail.

First, the coverage of the consolidated set of design variables across the seventeen design principles may be visually inspected (Table 5). In some cases, potential conflicts may exist between susceptibility reduction and vulnerability reduction features, so a designer should inspect the consolidated list to identify such potential conflicts. In spite of this, if the operational environment of the system being designed is highly uncertain, it may be wise to ensure representation of Type I, Type II, and Type III survivability trades in the design-space. Second, the mitigating impact of each consolidated design variable across the set of disturbances may be estimated by using a linear-weighted sum (in which weights are based on disturbance impact) (Table 3). In Table 5, the survivability design variables are ordered by this estimate of mitigating impact. Third, it is important to consider downstream

constraints associated with the modeling effort and computing resources when expanding the design-space. While it may be theoretically possible to parameterize all of the design principles and selectively sample the design-space using multi-disciplinary design optimization techniques (*e.g.*, genetic algorithms), such an implementation would require orders-of-magnitude increases in the modeling effort. While the geometric growth of the tradespace (as design variables are added) may be addressed by selectively sampling the tradespace, accelerating models through low-dimensional projections (such as through Response Surface Modeling), or by scaling to appropriate levels of computing resources, developing a stochastic, physics-based performance model for every disturbance and mitigating design variable will at some point become intractable in terms of time, effort, and complexity to model.[58] Therefore, unless the system analyst has access to an extensive team of engineers, there is a limit to how many survivability design variables may be incorporated into the final design vector. Fourth, engineering judgment and knowledge gained from previous iterations of the MATE model may inform whether a particular survivability enhancement feature should be permanently turned "on". (Design variables analyzed using previous iterations of the MATE model are labeled "baseline".) Given these four considerations, two dedicated survivability design variables were selected for inclusion in the satellite radar tradespace: constellation spares and shielding thickness.

Table 6. Finalized Satellite Radar Design Vector (n=3888)

n=3888　　　　　　　　　**survivability variables**

Orbit Altitude (km)	Walker ID	Antenna Area (m^2)	Constellation Spares
800	5/5/1	10	0
1500	9/3/2	40	1
	27/3/1	100	2
	66/6/5		

Peak Transmit Power (kW)	Radar Bandwidth (MHz)	Comm. Architecture	Shield Thickness (mm)
1.5	500	Direct Downlink Only	1
10	1000	Relay Backbone	5
20	2000		10

Table 6 provides the final design vector for satellite radar. As the independent variables for subsequent tradespace exploration, sampling these parameters is intended to define concepts that offer trades among lifecycle cost, design utility, and survivability. Given a full-factorial sampling of the eight design variables, 3888 unique alternatives are defined. (Prior to selection of these 3888 alternatives to demonstrate the methodology, over 50,000 designs had been examined in a baseline MATE analysis. With the addition of 500 Monte Carlo simulations for

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each alternative in this survivability analysis, the total number of system lifecycles modeled in each run of the model is nearly 2 million.)

Although two dedicated survivability design variables have been added to the final design vector, it is important to note that several of the baseline design variables (*i.e.*, design variables enumerated during concept generation before considering survivability) also serve to parameterize survivability design principles. This overlap indicates latent survivability in the baseline design vector.

E.   Phase 5: Model Baseline System Performance

In Phase 5, the lifecycle cost and design utility (*i.e.*, utility at beginning-of-life) of each design alternative is computed by evaluating the design vectors in a physics-based, parametric model. To enable concurrent and collaborative model development, the satellite radar system was decomposed into several MATLAB modules to determine attribute values and intermediate variables given a design. The attribute outputs are then used to compute lifecycle cost and design utility.

Table 7 shows the N^2 mapping for the evaluation model for the satellite radar case. The model translates designs from the design vector and computes the corresponding costs, attributes, and utilities. In particular, each design of interest is enumerated, and then run through the modules sequentially by a main loop, which stores the computed values for each design for subsequent exploration and analysis.[2] As evidenced by the lack of above-diagonal dependencies, the modules are carefully structured such that they can be executed sequentially without iteration or optimization loops. Eliminating feedback among modules is critical for achieving reasonable runtimes (of a few minutes for one potential system lifecycle of one architectural alternative) on current desktop computers.

Table 7. N² Diagram of Satellite Radar Evaluation Model

	Design Enumerator	Constants	Design Space Selector	Target	Orbit	Radar	Constellation	On-Board Processor	Communications	Ground Processor	Satellite Bus	Attributes	Cost	Utility	Survivability
Design Enumerator	■														
Constants		■													
Design Space Selector	X		■												
Target		X		■											
Orbit		X	X		■										
Radar		X	X	X	X	■									
Constellation		X	X	X	X	X	■								
On-Board Processor		X			X	X		■							
Communications		X	X		X	X	X	X	■						
Ground Processor		X								■					
Satellite Bus		X	X		X			X	X		■				
Attributes		X	X			X	X	X	X	X	X	■			
Cost		X	X			X		X	X	X	X		■		
Utility												X		■	
Survivability		X	X				X				X	X		X	■

The following paragraphs briefly describe the key computations performed by the individual modules. Given finite project resources, modules are written at an intermediate level of fidelity. Direct physics-based models are used where possible, and simplifying assumptions and heuristics are applied for less sensitive parts of the analysis.

Design Enumerator. Given the design variables (Table 6), the design enumerator creates a list of candidate designs through a series of nested "for" loops. Each design is numbered sequentially and stored.

Constants. The constants module returns a data structure containing fixed values regarding technology availability (*e.g.*, specific performance of solar array), modeling assumptions (*e.g.*, diameter of tactical downlink dish), and parametric cost estimating relationships. These constants span the payload, processing, communications, and bus subsystems. The nominal context is based on the availability of technology with technology readiness level (TRL) 9, current generation launch vehicles, and a communications infrastructure based on DoD's Wideband Global SATCOM System (WGS)[59] and the Air Force Satellite Control Network (AFSCN)[60].

Design Space Selector. The design space selector takes a sample of enumerated designs. In this case application, a full-factorial sample is selected, including all 3,888 possible combinations of the eight design variables.

Target. The target module selects a target set from the list of targets elicited from subject matter experts. The target is characterized by a constant array of structures, each containing target location, radar cross section (RCS), velocity, and terrain type. Terrain type is operationalized as minimum elevation angle. For the baseline system

performance, the target set is based on an operations plan that distributes large moving targets in East Asia and small moving targets in the Middle East.

Orbit. The orbit module computes basic orbital properties that are required inputs to the radar module. Given an orbital altitude and Walker formation, orbit radius, satellite velocity, maximum eclipse length, and orbit period are computed using basic geometry. A circular orbit and a spherical earth are assumed, as well as constant satellite altitude and velocity.

Radar. The radar module computes the performance attributes of the radar specified by the design variables as a function of the calculated orbit and given target deck. Computation of the radar attributes must account for the ability of the attributes to be traded against one another. To decouple these computations, a major assumption of the CONOPS is that evaluation of particular attribute occurs when the radar is operating in such a way as to optimize that attribute. (By nature, AESA radars are flexible systems open to a wide variety of CONOPS. Rather than modeling the optimal CONOPS at all times in the simulation [outside of the study's scope] or including different CONOPS in the design vector [computationally prohibitive], this assumption makes the performance modeling tractable.)

For example, the minimum detectable RCS, σ, can be computed using the radar range equation and the dwell time equation[61]:

$$P_t = \frac{(4\pi R)^2}{P_r G_t A_r \sigma F^4} \tag{2}$$

$$T = \left(\frac{P}{180\deg}\right)\cos^{-1}\left(\frac{\cos\lambda_{max}}{\cos\lambda}\right) \tag{3}$$

$$dwelltime_{max} = \frac{T}{t\arg etboxes} \tag{4}$$

$$dwelltime = \frac{cnr(4\pi)^\partial R^4 k_\beta noise}{PG_t^2 v^2 \sigma W_p} \tag{5}$$

When computing the minimum radar cross section, we assume we have only one target and set dwell time during the time an average point is in view given the orbit in our design vector (T). When computing the maximum number of targets that the system can have, we fix the value of σ to the maximum acceptable value and work backwards to

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find the minimum dwell time. Similar tradeoffs exist between duty cycle, dwell time, and field of regard, each of which are fixed based on the current epoch while the others are computed.

Constellation. The constellation module inputs the calculated radar performance attributes and orbit values and outputs coverage statistics and communications availability. Coverage statics are also pre-computed for cases involving the random loss of one or more satellites. The constellation module uses the time and altitude data from the orbit module to simulate satellite movement on a minute-by-minute basis, projecting the surface area that each satellite can cover in each minute using the swath information from the radar module. An iterative simulation tracks the relative position and motion of targets, satellites, communications systems, and warfighter users of the GMTI data.

On-Board Processor. Taking inputs from the constants, orbit, and radar modules, the on-board processor module estimates the latency increment as well as the raw sensor data rate of the payload. Processor mass, cost, and power requirements are also computed.

Communications. The communications module estimates the data latency and the data throughput attributes as well as the mass, power, and cost of the spacecraft communications architecture. With inputs from the constants, design space selector, orbit, radar, constellation, and on-board processor modules, communications requirements and performance are determined using a link budget.[62]

Ground Processor. The ground processor module sets the latency associated with processing the data received from the constellation before it is received by the warfighter. As with other subsystem modules, recurring and non-recurring engineering costs are estimated.

Satellite Bus. The satellite bus module determines the spacecraft and launch vehicle characteristics necessary to support the radar payload and communications system. First-order models of satellite structure, power, and propulsion subsystems are applied as well as heuristic measures for the attitude control and thermal control subsystems.[63] The satellite bus module outputs the mass and cost of each satellite in the constellation.

Attributes. The attributes module takes the attributes calculated by the subsystem modules and wraps them in a single structure. It also computes attributes that are simple functions of intermediate variables from separate modules (*e.g.*, adding processing and communications latencies for tracking latency).

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Cost. The cost module collects the non-recurring and recurring engineering cost estimates from the satellite subsystem modules to calculate the cost of an individual satellite and to estimate a baseline program lifecycle cost.[63] Finally, an overall program lifecycle cost is computed based on the constellation sparing strategy.

Utility. Given outputs from the attribute module and the utility functions elicited from the decision-maker in Phase 1 (Elicit Value Proposition), the utility module calculates the single-attribute utilities and the multi-attribute utility for each design alternative.

Survivability. Once the costs and benefits of design alternatives in a static context have been determined by calculating overall lifecycle cost and multi-attribute utility, the survivability module examines the performance of design alternatives in dynamic operational environments. The survivability module and its associated outputs are the subject of Phase 6 (Model Impact of Disturbances on Lifecycle Performance).
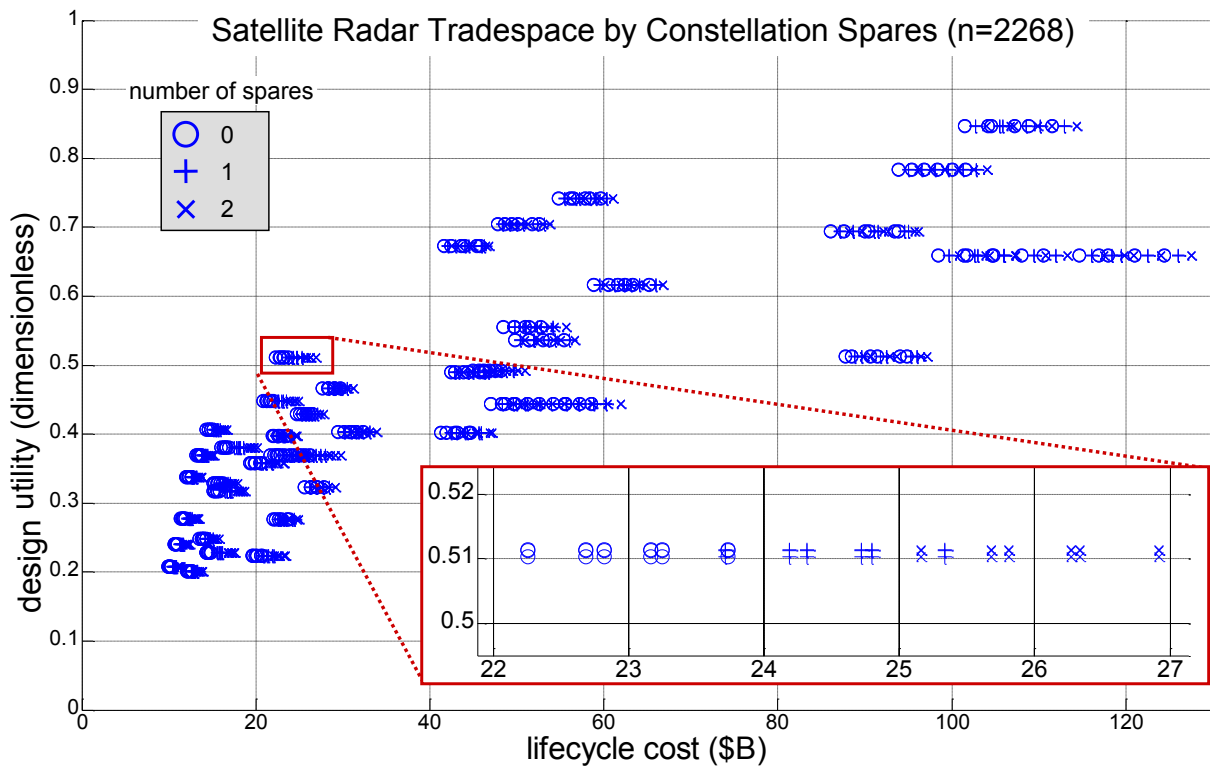
Figure 4. Baseline Satellite Radar Tradespace

Figure 4 shows the baseline Satellite Radar tradespace which evaluates each design alternative in a static, nominal environment. Each point represents a unique system architecture and is plotted in terms of a twenty-year lifecycle cost (in billions of dollars) and multi-attribute utility (Equation 1). While 3888 design alternatives are

generated from a full-factorial sampling of the design variables (Table 6), only 2268 are plotted in Figure 4 for consideration. This 42% reduction of the tradespace occurs because many of the designs fail to perform above the minimum acceptable level in one or more attributes (defined in Table 1). For example, the constellations composed of satellites with an antenna area of 10 m^2 are filtered from the tradespace.

The baseline tradespace includes 198 cost-utility Pareto-optimal designs (*i.e.*, designs of highest utility at a given cost). Within this set, the baseline tradespace reveals interesting trade-offs among Walker constellation type, antenna area, peak transmit power, and cost. Several different satellite radar constellations occupy different regions of the Pareto front, including sparse constellations with low power-aperture products, and dense constellations with greater transmit powers and antenna areas. In a static MATE analysis, promising designs identified in the baseline tradespace (*e.g.*, designs on the "knee" of the Pareto front) might be selected for further evaluation.

A critical limitation of the baseline tradespace is that only the costs of survivability (rather than the costs and benefits) are internalized. For example, Figure 4 shows the effect of the number of constellation spares on the tradespace based upon shape. Interestingly, every design comprising the 198-count Pareto set incorporates the minimum number of constellation spares of 0. However, the mass penalty of purchasing constellation spares adds lifecycle cost. As a result, all designs with increased shielding are in the interior region of the tradespace. The subsequent section describes how the static tradespace analysis of satellite radar is extended to incorporate both the costs and benefits of survivability.

F. Phase 6: Model Impact of Disturbances on Lifecycle Performance

Phase 6 involves modeling and simulating the performance of design alternatives across a representative sample of disturbance encounters to gain an understanding of how decision-maker needs are met in perturbed environments. While the previous phase is focused on assessing deterministic measures of system effectiveness (*i.e.*, lifecycle cost, design utility), this phase focuses on dynamically characterizing system performance. The occurrence of uncertain future disturbance events from the natural space environment is modeled in a stochastic simulation, and a Monte Carlo analysis is conducted to extract representative distributions of utility trajectories. Two disturbances are incorporated into the analysis: micrometeorites/debris impacts and signal attenuation. This paper did not look at synergistic interactions between disturbances. More comprehensive analysis could include this consideration.

As an extension of the baseline MATE analysis, the survivability module is the final element of the Satellite Radar (SR) software architecture. As shown in Table 7, the module receives inputs from the constants vector (*e.g.*,

bumper shielding materials), design space selector (*e.g.*, shield thickness), constellation module (*e.g.*, pre-computed coverage statistics for degraded constellations), satellite bus module (*e.g.*, exposed cross-sectional area), and attributes and utility modules. These inputs are then used to model the susceptibility, vulnerability, and resilience of design alternatives. The output of an individual run of the model is a dynamic characterization of the system performance in the attributes. This dynamic characterization is translated to a multi-attribute utility trajectory for ten years of operational life. Since the simulation outputs are probabilistic, 500 Monte Carlo trials are conducted for each satellite radar constellation in the design vector.
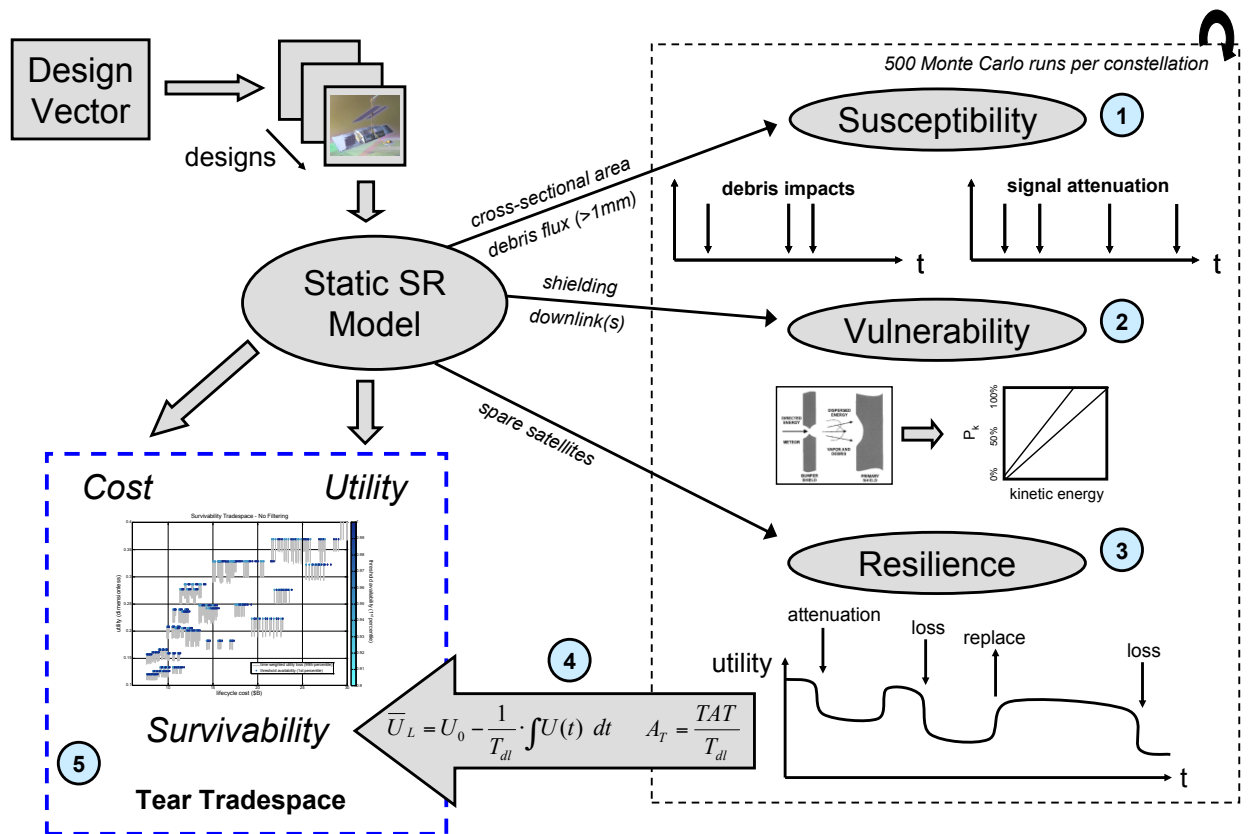
Figure 5. Incorporation of Survivability Considerations into Satellite Radar Tradespace

Figure 5 provides a flow-chart representation of how survivability considerations are incorporated into the satellite radar tradespace. Treating the baseline MATE model as a black-box, implementation of the survivability analysis involves five general steps. In the first step, susceptibility to debris impacts is modeled as a function of the exposed cross-sectional area of alternative constellations and a typical debris flux for Earth-observation satellites. Debris event times, defined as an impact by an object >1 mm, are randomly generated according to a Poisson process (with the Poisson parameter set to the average inter-arrival time of historical debris flux).[64] Given a debris

event, the type of impact is determined by probabilistically sampling the distribution of debris sizes and assuming a fixed relative velocity of 7.5 km/s. Susceptibility to global signal attenuation is also modeled in the third step using Poisson arrivals (and assuming an average inter-arrival time of five years). Whereas susceptibility to debris varies by satellite design and constellation type, susceptibility to global signal attenuation is assumed uniform. The duration of attenuation events, assumed to average six months, is also modeled using the Poisson distribution.

In the second step, the vulnerability of the designs to the generated disturbances is assessed. In the case of debris events, the ability of the satellite shielding to block the debris is determined based on the shield thickness and the momentum of the impacting debris. If a debris impact can be repelled by the shield, no losses occur and the simulation exits the vulnerability model. If the shield is not thick enough to repel the debris, satellite vulnerability is assessed probabilistically using conservative assumptions from a binary loss model based on the kinetic energy of the debris.[64] If satellite failure occurs, the impact on constellation performance is determined by re-computing multi-attribute utility. In particular, the values of target acquisition time and track life for the degraded constellation are found using pre-computed coverage statistics from the constellation module. These attribute levels are used to recalculate the single-attribute utilities and overall multi-attribute utilities at the time of the debris impact. In the case of signal attenuation, vulnerability is based simply on the availability of a relay backbone for downlink communications. Attenuation is assumed to have no impact if such a backbone exists. If no backbone is available, a total loss of mission utility is assumed for the duration of the attenuation event.

In the third step, the resilience of each design is assessed. If the output of the vulnerability model is a satellite loss, the design vector is checked for the availability of spare satellites. If a spare is available, a replacement satellite is launched. (Once launched, ground spares are not replaced.) The time of launch is assumed to be six months plus a random delay (according to a Poisson process with an expected value of six months). At the time of satellite replacement, the attribute levels and utilities are recomputed for the constellation. By continuously monitoring constellation performance in the attributes, multi-attribute utility may be assessed over the entire lifecycle. This dynamic characterization of overall system health is termed a utility trajectory. Figure 6 shows a sample utility trajectory, showing the impact of satellite loss, satellite replacement, and signal attenuation (in the absence of a relay backbone) on constellation performance. As discussed in Phase 1 (Elicit Value Proposition), the required utility threshold of the decision-maker is equivalent to the emergency utility threshold (*i.e.*, $U_x = U_e = 0$).
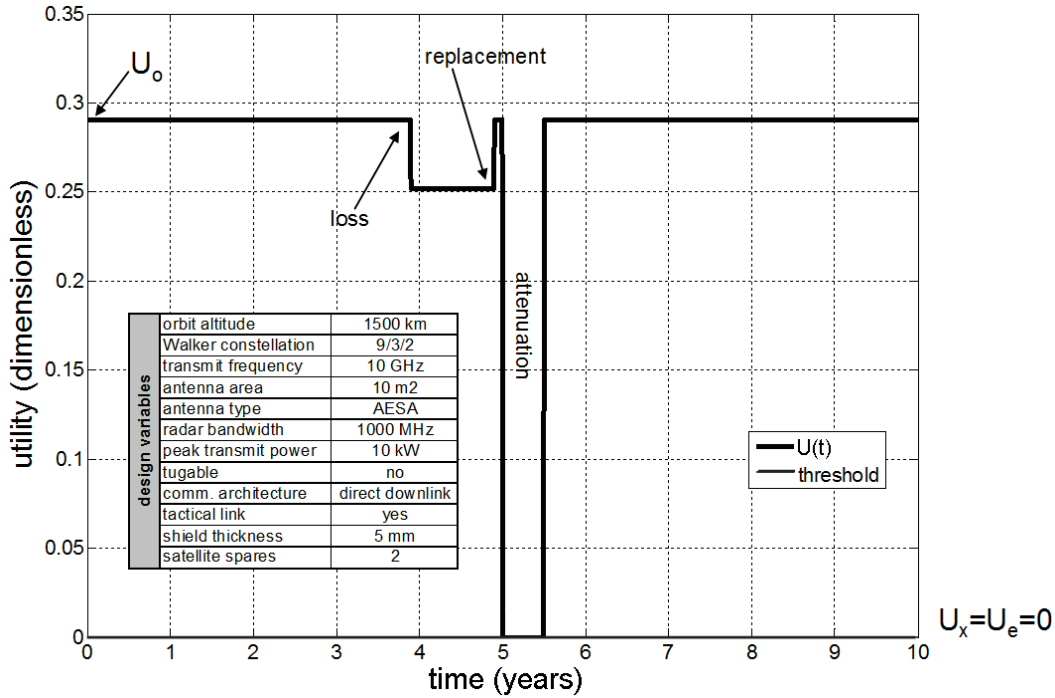
The design variables table within the figure:

design variables		
orbit altitude	1500 km
Walker constellation	9/3/2
transmit frequency	10 GHz
antenna area	10 m2
antenna type	AESA
radar bandwidth	1000 MHz
peak transmit power	10 kW
tugable	no
comm. architecture	direct downlink
tactical link	yes
shield thickness	5 mm
satellite spares	2

Figure 6. Sample Utility Trajectory Output from a Single Run of the Simulation

In the fourth step, time-weighted average utility and threshold availability are calculated at the end of each ten-year simulation as summary statistics for the utility trajectory output. As each run of the simulation is stochastic, a 500-run Monte Carlo analysis is performed for each design to obtain a significant sample of utility trajectories. (Following a convergence study on the number of Monte Carlo runs, 500 trials were found to achieve a good balance between accuracy and computing time.) In the seventh step, the probabilistic survivability metrics are integrated with the deterministic metrics of lifecycle cost and design utility for integrated tradespace exploration. These final two steps, application of the survivability metrics and tradespace exploration, are described in detail in the following two subsections.

G. Phase 7: Apply Survivability Metrics

Having generated utility trajectories over the distribution of possible degradation and recovery sequences for each design vector, the survivability metrics are applied to the utility trajectories as summary statistics of lifecycle survivability. Applying the survivability metrics requires establishing a percentile reporting level for the distribution of each metric.[7]

Previous work introduced a dynamic, continuous, and path-dependent characterization of survivability as the ability of a system to minimize value losses while meeting critical value thresholds before, during, and after

environmental disturbances.[7]   This dynamic characterization of survivability was then operationalized using two metrics: *time-weighted average utility loss* and *threshold availability*.[7]   Time-weighted average utility loss assesses the difference between the design utility (at beginning-of-life), U_o, and the time-weighted average utility achieved over the system design life, T_{dl}:

$$\overline{U}_L = U_0 - \frac{1}{T_{dl}} \cdot \int U(t) \ dt \tag{6}$$

Time-weighted average utility loss addresses the limitations of traditional binary survivability metrics in assessing favorable system behaviors such as graceful degradation by internalizing the timing, magnitude, and rate of failures.

Threshold availability assesses the ability of a system to meet critical value thresholds. Specifically, it is defined as the ratio of the time that $U(t)$ is above operable (required or emergency) utility thresholds (*i.e.*, time above thresholds [TAT]) to the total design life:

$$A_T = \frac{TAT}{T_{dl}} \tag{7}$$

In applying the survivability metrics to the satellite radar utility trajectories, the time-weighted average utility distributions are characterized by highly-skewed and long-tailed distributions while the distributions of threshold availability are limited in range.[2]   To reflect the risk aversion associated with failing to meet emergency utility thresholds due to disturbances from the natural space environment, the reporting percentile for threshold availability is set at the 1st percentile (*i.e.*, 99% of the runs perform above the reported availability level). Given that utility losses within permissible thresholds are less severe, the reporting percentile for time-weighted average utility loss is set at the 95th percentile (*i.e.*, 95% of the runs experiences utility losses below the reported level). Other percentile thresholds could be chosen as appropriate. (Sensitivity of the results to the percentile reporting level may be performed during Phase 8 (Explore Tradespace) by producing a survivability tear[drop] tradespace for multiple reporting percentiles and analyzing variance across the sets of Pareto-efficient designs. Table 8 illustrates an example showing both 95th and 99th percentiles for utility loss of five satellite radar alternatives.)

Figure 7 shows how the probabilistic survivability metrics may be integrated with deterministic performance metrics of cost and utility in a survivability "tear(drop)" tradespace. Decision-makers may navigate the tradespace

by examining designs near the top-left (high utility, low cost) with high availability (darker) and minimal utility loss (shorter tail). The histogram provides an example of one of the distributions of time-weighted average utility values underlying the reported time-weighted utility losses (*i.e.*, the difference between the design utility and 95th percentile utility loss in the histogram is equal to the length of the utility loss tail in the called-out region of the tradespace, and is shown by the length of the horizontal arrow in the histogram).
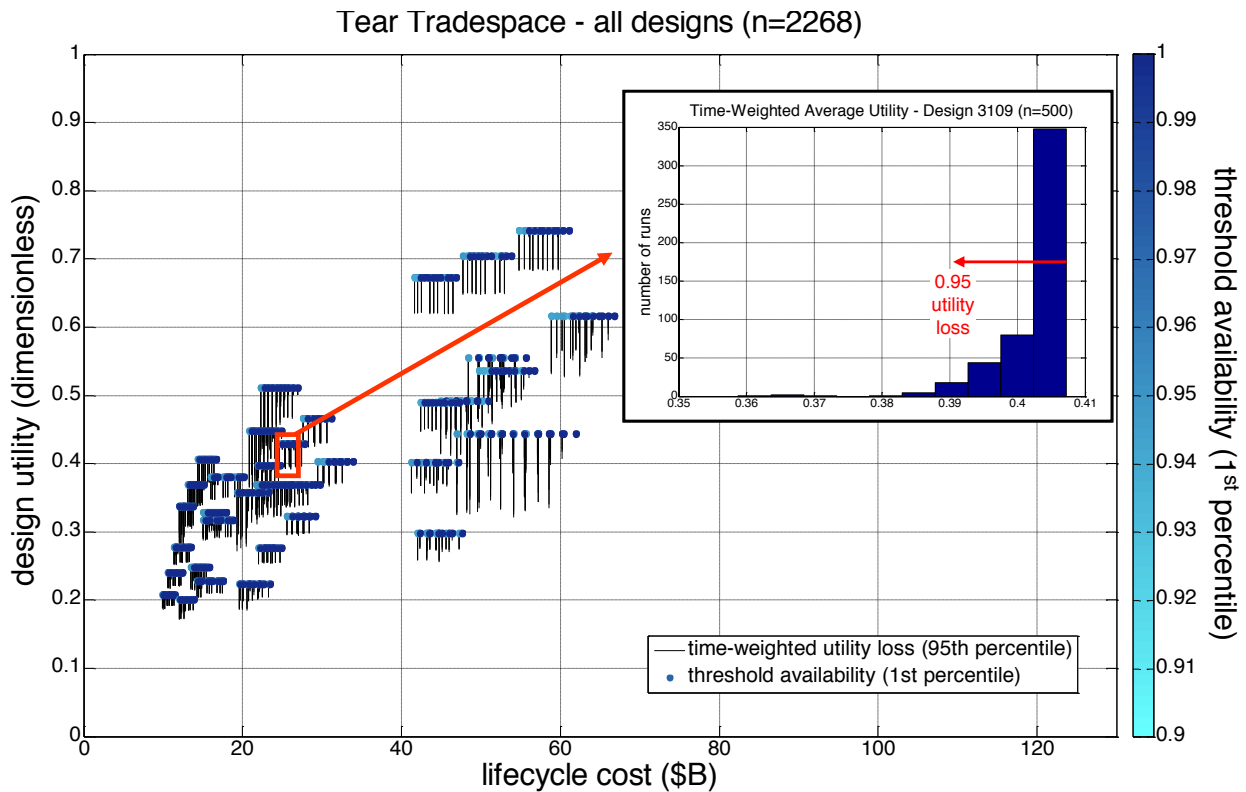
Figure 7. Survivability Tear Tradespace – Satellite Radar

A close inspection of Figure 7 yields several insights. Because the value of the communications relay architecture, bumper shielding, and constellation spares is only manifested in the tradespace through additional cost and survivability, the clusters of points that form horizontal lines may be inferred to constitute the same baseline satellite radar architecture. While baseline utility remains fixed as the cost of these survivability enhancements are added to a given constellation, performance in time-weighted utility loss and threshold availability varies. As design options progress towards the interior region of the tradespace (*i.e.*, to the right, away from the Pareto front of cost and utility), survivability performance generally improves. The effect is not uniform, however, with several constellation clusters in the lower-end of the Pareto front unable to eliminate utility losses even with all survivability

design variables at the highest setting. Most importantly, the tear tradespace shows that the time-weighted average utility of alternative satellite radar constellations (realized in operation) is different from the baseline utility achieved by the designs before disturbances are considered. Therefore, depending on the importance of survivability *vis-à-vis* cost and utility, the rank order preferences of the decision-maker on the static design space (*e.g.*, baseline tradespace in Figure 4) are subject to change.

H. Phase 8: Explore Tradespace

Having evaluated the cost, utility, time-weighted average utility loss, and threshold availability of each design alternative, integrated trades are made among the satellite radar constellations. Designs in the Pareto-efficient region are examined for prescriptive insights, and interesting designs are flagged as candidates for more detailed design.

The tear tradespace presents four dimensions of data across thousands of design alternatives. To mitigate the complexity associated with visualizing the variation in cost, utility, and survivability performance, the design space may be selectively filtered to reduce the number of designs under consideration. For example, if designs located off the Pareto front of cost and design utility are eliminated from the tear tradespace, only 198 "non-dominated" designs (of the 2268) remain in Figure 7. (These designs located in the interior of the tradespace are "dominated" in the baseline cost and utility analysis since alternative designs are available with greater utility at the same cost). However, filtering based only on cost and design utility is undesirable given that the remaining designs are frequently the least survivable.
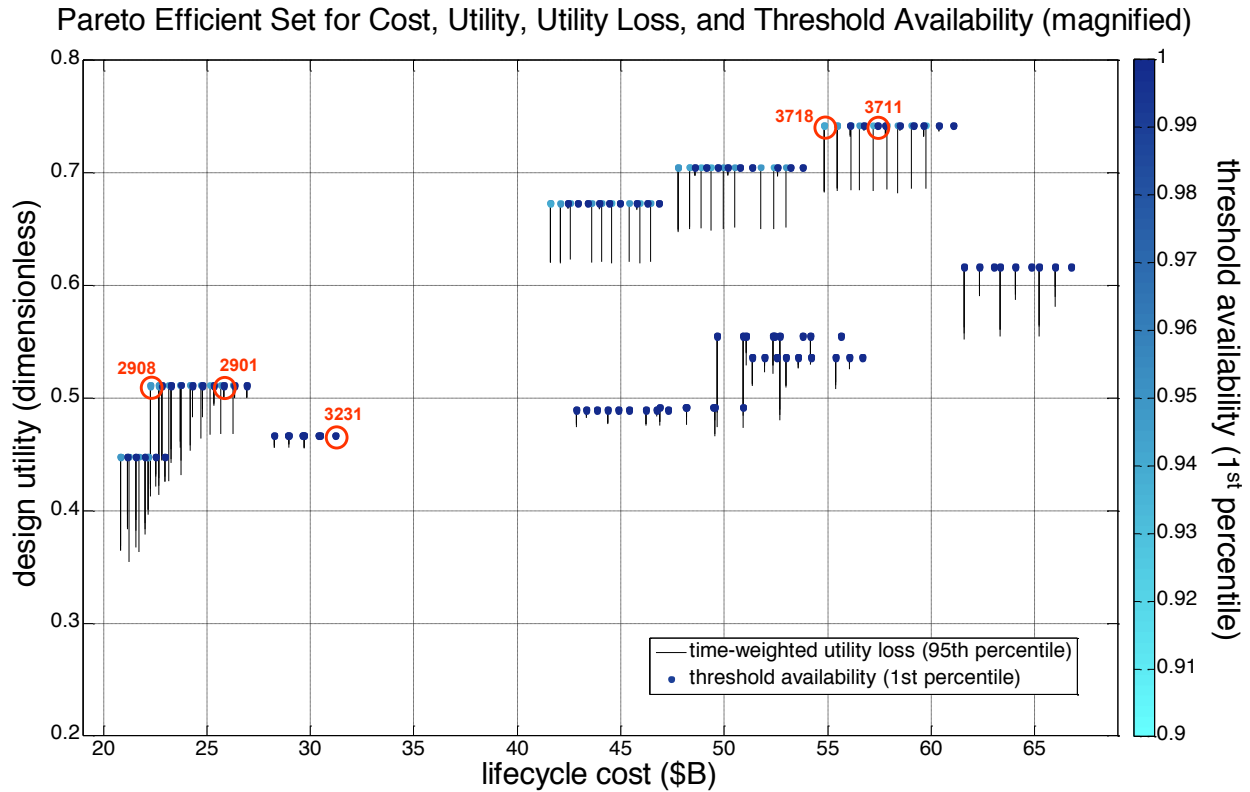
Figure 8. Magnified and Filtered Survivability Tear Tradespace

Figure 8 applies a four-dimensional filter to a magnified region of the tear tradespace (*i.e.*, high-utility designs between $20B and $65B). The filter was formed by looking at the tradeoffs of the four metrics of interest. In particular, only designs belonging to the four-dimensional Pareto-efficient set of lifecycle cost, design utility, utility loss, and threshold availability are plotted. While the filtering has greatly reduced the number of designs under consideration, dozens of "optimal" design remain within this central region of the tradespace. Five designs of particular interest are circled and labeled in Figure 8 for further investigation. Two of the designs, DV(2908) and DV(3718), are selected given their location in the traditional Pareto front. The other three designs are selected given their strong performance in the traditional metrics of cost and utility while also achieving high survivability. To complement the examination of DV(2908) and DV(3718), DV(2901) and DV(3711) are selected as alternatives within the same constellation cluster that exhibit better survivability performance. In addition, DV(3231) is selected as a highly survivable alternative located in the interior region because it has a shorter tail (*i.e.*, very small time-weighted utility loss). Dialogue with decision makers is important to determine tradeoff priorities to help in this downselect to designs of particular interest.

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Table 8. Properties of Circled Design Vectors in Figure 8

Design Vector ID	2908	2901	3231	3718	3711
orbit altitude (km)	1500			1500	
Walker constellation	9/3/2	9/3/2	27/3/1	66/6/5	66/6/5
transmit frequency (GHz)	10			10	
antenna area (m^2)	100	100	40	40	
antenna type	AESA			AESA	
radar bandwidth (MHz)	2000			2000	
peak transmit power (kW)	20			20	
tugable	no			no	
comm. architecture	direct	relay	relay	direct	relay
tactical link	yes			yes	
shield thickness (mm)	1	1	10	1	
satellite spares	0	2	2	0	2
lifecycle cost ($B)	22.3	25.8	31.2	54.8	57.4
utility	0.51	0.51	0.47	0.74	0.74
utility loss (95th)	0.09	0.01	0.00	0.06	0.00
utility loss (99th)	0.12	0.02	0.00	0.07	0.01
threshold availability (1st)	0.95	1.00	1.00	0.95	1.00

Table 8 shows the design variable inputs and decision metric outputs of the satellite radar model for the five designs of interest. The designs are divided into two groups, with DV(2908), DV(2901), and DV(3231) located in the lower-left of the Pareto region, and DV(3718) and DV(3711) located in the upper-right region. Comparing columns allows explicit trades to be made between cost and survivability. For example, selecting DV(2901) in lieu of DV(2908) increases cost by $3.5B (through the addition of a relay communications system and the purchase of two satellite spares) but reduces utility loss to 0.01 and increases threshold availability to 1.00. Similarly, the additional $3.6B cost of DV(3711) reduces utility loss to effectively zero and increases threshold availability to 1.00.

Rather than improving the survivability of a Pareto front design (*i.e.*, optimal in terms of lifecycle cost and design utility) exclusively through survivability enhancements, substituting DV(3231) for DV(2908) also improves survivability through the benefits afforded by a different system architecture. Although located close to the cost and utility values of DV(2908), DV(3231) has a different constellation structure consisting of more numerous, less-capable satellites. In particular, the Walker constellation is increased from 9/3/2 to 27/3/1, and the antenna area of each satellite is decreased from 100 to 40 m^2. The more distributed constellation structure combined with the investments in shielding and satellite spares yields a design that is highly survivable even at the 99th reporting percentile.

V. Discussion

Having applied MATE for Survivability to an analysis of military satellite radar, this section offers general insights for the design problem and for the methodology itself.

A. Design Problem Insights

From the baseline performance modeling, the satellite radar case application revealed an extremely broad tradespace, with alternative designs varying in cost by an order-of-magnitude. Performance in the six GMTI attributes varied tremendously as a function of Walker constellation, power-aperture product of the radar sensor, and downlink options.

Given the results from the dynamic tradespace model, the satellite radar alternatives are survivable to the space environment (of orbital debris and signal attenuation). The survivability metrics applied to the utility trajectory outputs indicate that the enumerated constellations are able to meet the acceptability criteria for GMTI as specified in the utility functions. While time-weighted average utility is reduced following satellite losses in small and medium sized constellations, the reductions are small and the distributions of threshold availabilities remain above 90% at even the 1st percentile. However, when applied to sparse constellations, this finding is sensitive to changes in the decision-maker's acceptability ranges for target acquisition time and track life (*i.e.*, if more stringent acceptability ranges were established for target acquisition time and track life in the modeled disturbance environment, threshold availability would dip below 90% for the sparse constellations).

Although the satellite radar constellations are found to be survivable, the tear tradespace analysis shows that the rank-order preferences of the decision-maker on alternatives are subject to change when environmental disturbances are taken into account. By adding time-weighted average utility and threshold utility as additional decision metrics, designs in the interior region of the tradespace join the Pareto front designs in the "optimal" set. Resolution of these integrated cost, utility, and survivability trades requires dialogue with the decision-maker.

The tradespace model yielded several insights regarding the cost and survivability implications of the design variables. Maximizing survivability design variable levels (and hence constellation cost) does not necessarily equate to the most survivable satellite radar system. For example, shielding is found to have a very limited impact on time-weighted average utility. In contrast, supplementing direct downlink communications with a relay option is important in the model for mitigating signal attenuation. Investments in satellite spares have a variable impact, with

sparse constellations benefitting the most from the option to rapidly reconstitute. There are diminishing returns, however, when purchasing additional spares.

Most interestingly, the most survivable designs mitigate disturbances architecturally. The tear tradespace identified constellations that are co-located in the baseline tradespace (of cost and utility) with variable survivability performance. In particular, by sacrificing individual satellite performance and accepting moderate growth in lifecycle cost through selecting a more distributed constellation of less-capable satellites, it is possible to achieve higher levels of survivability.

B. Methodological Insights

MATE for Survivability was applied to a satellite radar system to enhance the front-end generation of survivable concepts and the back-end discrimination of alternatives. Building on a static MATE analysis, the methodology allowed survivability considerations to be incorporated into concept generation and tradespace evaluation. In concept generation, the designs principles revealed latent survivability trades in the initial design space and informed definition of a new design vector incorporating explicit survivability enhancements. In tradespace evaluation, the survivability metrics were applied to probabilistic utility trajectory outputs from a dynamic state model, enabling discrimination of thousands of design alternatives in terms of survivability.

Many recommended practices for implementing MATE for Survivability emerged from the satellite radar case application. First, given that the survivability metrics are dependent on the percentile reporting levels, it is important to examine the sensitivity of the results to the selected percentile of the distribution with the decision maker (*e.g.*, stability of set of designs on four-dimensional Pareto surface when reporting time-weighted average utility loss at the 95th and 99th percentiles). Second, the broad insights that may be derived from the design variable impact tradespaces, tear tradespaces, and response surfaces, should be complemented by querying individual point designs. Close inspection of individual designs (including design variables, intermediate variables, calculated attributes, and performance metrics) allows the analyst to gain a deeper understanding of the causal relationships in the performance model as well as to verify model accuracy. Third, producing the filtered tear tradespace should not mark the end of the survivability analysis but rather mark a departure point for navigating the tradespace with the decision-maker. Although the 760 designs that arise along the four-dimensional Pareto surface in the satellite radar tear tradespace are less than the 2268 in the unfiltered tradespace, they are significantly more than the 198 designs along the traditional Pareto front of cost and utility.[2] Therefore, having identified the region of optimal trade-offs

among cost, utility, and survivability, it is particularly important to engage with the decision-maker in the process of selecting a small number of alternatives for more detailed design.

The application of MATE for Survivability also shows the benefits of the methodology for making better design decisions. By extracting information from decision-makers during needs elicitation regarding their risk preferences, the analyst is able to explore additional trades with the performance data. In particular, the qualitative QFD assessment of survivability enhancement techniques may be augmented with the tear tradespaces that allow the analyst to identify filtered candidate designs that are architecturally insensitive to modeled disturbances and elicited decision-maker preferences.

The analysis shows that that using tradespace exploration solely to identify designs on the traditional Pareto front of cost and utility excludes the most survivable designs. Furthermore, the methodology allows system-level and architecture-level survivability trades to be made in concert rather than delaying survivability considerations until after selection of a baseline system concept. Incorporating survivability considerations into the definition of the system concept is important if the dedicated survivability design variables (*e.g.*, shielding) are less critical to achieving survivability than the fundamental system architecture (*e.g.*, constellation type). By applying the concept-neutral criteria of lifecycle cost, multi-attribute utility, and the survivability metrics, the tear tradespaces may be used to identify promising design alternatives among thousands of technically-diverse systems.

VI. Conclusions

Multi-Attribute Tradespace Exploration for Survivability is introduced as general methodology for the assessment of alternative system architectures that must operate in disturbed environments. In particular, the tradespace exploration process is extended to leverage the survivability design principles and metrics in concept generation and concept evaluation, respectively. The methodology consists of eight phases: first, elicit value proposition, second, generate concepts, third, characterize disturbance environment, fourth, apply survivability principles, fifth, model baseline system performance, sixth, model impact of disturbances on lifecycle performance, seventh, apply survivability metrics, and eighth, explore tradespace.

Two recurring trends in applying Multi-Attribute Tradespace Exploration for Survivability underscore the importance of incorporating survivability considerations into conceptual design. First, the designs located along the traditional Pareto front of lifecycle cost and mission utility lack survivability. Second, there is tremendous variation in the survivability of the baseline system concepts before the addition of survivability design variables to the design

vector. The first trend suggests that traditional implementations of tradespace exploration (which focus on selecting a small number of technically diverse systems located along the Pareto front for more-detailed design activities) will exclude survivable alternatives from subsequent analysis. The second trend suggests that survivability may be incorporated more effectively at the architecture-level rather than as an additive feature to a baseline system concept. Taken together, these trends indicate that delaying survivability analysis until detailed design may lead to globally suboptimal trades for decision-makers among cost, utility, and survivability. Conversely, the survivability tear tradespaces may be used to conduct integrated trade-offs along the Pareto efficient surface of cost, utility, and survivability.

Acknowledgments

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