12-10-2010

A Space Acquisition Leading Indicator Based on System Interoperation Maturity

Jason T. Shibata

A SPACE ACQUISITION LEADING INDICATOR

BASED ON SYSTEM INTEROPERATION MATURITY

THESIS

Jason T. Shibata, Major, USAF

AFIT/GSE/ENV/10-D02DL

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT/GSE/ENV/10-D02DL

A SPACE ACQUISITION LEADING INDICATOR BASED ON SYSTEM INTEROPERATION MATURITY

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Space Systems Engineering

Jason T. Shibata, BS

Major, USAF

December 2010

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT/GSE/ENV/10-D02DL

A SPACE ACQUISITION LEADING INDICATOR

BASED ON SYSTEM INTEROPERATION MATURITY

Jason T. Shibata, BS

Major, USAF

Approved:

//SIGNED//	December 2010
John M. Colombi, Ph.D. (Chairman)	Date
//SIGNED//	December 2010
David R. Jacques, Ph.D. (Member)	Date
//SIGNED//	December 2010
Joseph R. Wirthlin, Lt Col, USAF (Member)	Date

AFIT/GSE/ENV/10-D02DL

Abstract

The Department of Defense‘s space acquisition enterprise has experienced numerous challenges since the advent of space power. Space borne capabilities are needed now more than ever, but space acquisition programs frequently fail to meet cost and schedule goals. The decades of space acquisition experience form a rich history that can be used to build a leading indicator of program success and serve as an enabler toward effective program execution. First, the space acquisition areas of greatest concern were determined to be cost, schedule and requirements. These areas can be considered as systems that are composed of the people, processes and products that work together to execute the program. Their effective interoperation is vital toward achieving program success. Second, the vital interoperation characteristics, or attributes that each system must possess to be successful, can be extracted from past space acquisition lessons learned and placed into an interoperability maturity model. The maturity model can then be used to capture the relative maturity of the program‘s major systems and their ability to interoperate within the context of each critical characteristic. Third, the maturity model forms the basis for an interoperability measurement using the method developed by Dr. Thomas Ford, where higher levels of interoperability maturity will result in a higher interoperability score. Finally, this process is demonstrated with three recent space programs. This application demonstrates how the interoperability score can be used as a leading indicator with interpretive analysis provided.

Acknowledgments

I am extremely thankful and indebted to my advisor, Dr. Colombi, for his patience, thoughtful discourse, and sage guidance. I also extend my deep gratitude to Dr. Ford for his important, inaugural work, and for giving me a foundation to build upon. I must thank Col Huntley for providing ample schedule pressure, but more importantly, looking out for my best interests. I also thank Lt Col Bythewood for his invaluable leadership and mentorship during this time. Finally, to my friends and family, you keep me running.

Jason T. Shibata

Table of Contents

Page

Page

List of Figures

Page

List of Tables

Page

Page

A SPACE ACQUISITION LEADING INDICATOR

BASED ON SYSTEM INTEROPERATION MATURITY

I. Introduction

The U.S. Army is one of the largest users of space-based capabilities in DOD. As the Army transforms, its operational characteristics will, in large part, be achieved through the use and exploitation of transformational space systems. This dependency requires the Army to actively participate in defining space related capability needs that ensure necessary force structure and systems are developed and acquired to enable the land force to conduct the full range of military operations now and in the future.

—*Army Space Policy* (Headquarters, Department of the Army, 2009)

Background

There is little doubt that the tenets of network centric warfare provide military forces a decided advantage on the battlefield. Robustly networked forces share information and collaborate resulting in synchronized battlespace effects, greater speed of command, and increased lethality, survivability and responsiveness (Department of Defense, 2001). The ability to connect and interoperate between people and forces is a necessary condition toward enabling mission effectiveness in virtually any collaborative environment, including acquisition.

Interoperability has grown within the defense community from a buzzword to a mandatory system requirement. Despite its importance, the study of interoperability measurement has been disparate and remains largely unproven. Most interoperability measurement methods focus on qualitative means rather than quantitative, and no one method has been accepted as the de facto standard. In 2007, there were over 30 distinct definitions, over 60 types and at least 14 interoperability measurement models in existence (Ford, Colombi, Graham, & Jacques, 2007).

The Department of Defense‘s (DOD) approach to interoperability is manifested in the Net-Ready Key Performance Parameter (NR-KPP) and requires that joint systems adhere to compliant solution architectures, the Net-Centric Data and Services Strategy, technical standards and interfaces through the Global Information Grid (GIG) Technical Guidance, DOD Information Assurance (IA) requirements, and DOD supportability requirements (CJCSI, 2008). The NR-KPP provides a framework and data strategy to enable interoperability, but does not specify how to measure interoperability nor does it establish interoperability performance standards.

Similarly, the DOD‘s space acquisition community does not have a way to quantifiably measure the effectiveness of its acquisition programs‘ interoperations. It generally uses a series of gates and reviews that demand various levels of program maturity and rigor. These gates and reviews enforce good acquisition discipline and, in theory, provide the program with the best chance to deliver capability to the warfighter in a time confident manner. Although the term interoperability may seem foreign when viewed from within the acquisition process, the major forces that affect the outcome of an acquisition program; organizations/people, processes, information and systems, must indeed be interoperable with one another and aligned toward a common purpose.

Major Thomas Ford‘s seminal work supplied the first quantifiable method for interoperability measurement (Ford, 2008), and formed the initial links between interoperability measurement and operational mission effectiveness. He introduced the concept of ―confrontational interoperability" where interoperability is measured between two opposing systems, and where one system's ability to control the other results in a higher degree of operational mission effectiveness.

This thesis is founded on Ford's inaugural work, and extends his ideas further into the realm of collaborative interoperability within the context of space acquisition. As implied by the opening quote, there is a distinct tie between the ability to interoperate and operational mission effectiveness. This paper asserts that the same relationships exist within an acquisition program, where greater acquisition interoperability results in an increased ability to meet requirements on time and on schedule. A method to measure space acquisition interoperability is presented and provides the initial building blocks toward a quantifiable means to assess and even predict space acquisition performance.

Hypotheses/Research Objectives

The lessons learned from past space acquisition failures can be used to determine how a program's cost, schedule and requirements interoperate to produce a particular outcome. These relationships and characteristics can be extracted, placed into a maturity model, and then evaluated using Ford's interoperability measurement method to create an indicator of effective acquisition interoperation. This measurement method can then be applied to current and future acquisition programs to indicate or predict to what degree the components of a program interoperate. The measure incorporates the benefit of hindsight to determine whether or not the program is likely to achieve its requirements on time and on schedule based upon its individual components' ability to interoperate.

Methodology

The research method first examines past space acquisition failures for key factors or characters that dominated the program's eventual outcome. These failures can then be used to compose an acquisition maturity model founded upon earlier works such as the Levels of Information Systems Interoperability (LISI) model and the Organizational Interoperability Maturity Model (OIM).

Finally, a measure of acquisition effectiveness will be developed and applied using Ford's work and the aforementioned acquisition maturity model.

Assumptions/Limitations

The intent of this work is to determine the crucial acquisition characteristics that should be specifically considered when measuring acquisition interoperability. These characteristics will be developed based on past lessons learned, and will be subjective in nature. The measurement will reward a greater maturity level in a key characteristic, but cannot explain exactly how much was gained because of it. For instance, an acquisition failure may be caused by funding instability, but no quantifiable method exists to determine exactly how much the schedule, cost and performance were impacted.

Additionally, Ford's work described how the need for interoperability varies with time. A thorough examination of the time-dependencies of acquisition interoperability is not presented here but is a good candidate for future research.

Lastly, this thesis will only examine interoperability within the specific context of space acquisition. It is likely that the ideas presented in this paper are relevant to other contexts; however those aspects will not be addressed here. It is believed that these vital interoperability aspects at their core are universal and are necessary factors to enable collaborative interoperability between systems and forces. Therefore, the lessons learned from the space acquisition domain could serve as relevant factors for interoperability in any domain at their highest level of extraction.

Implications

The space acquisition maturity model and acquisition interoperability measurement supply an initial approach to quantify whether or not a space program will be effective. In other words, the measurement can help predict how likely the program will succeed in accomplishing the required level of performance within cost and schedule constraints – a leading indicator. This method could be used to evaluate a program's maturity and progress throughout its lifecycle, and potentially flag program risk areas before they are realized.

Preview

The literature review will provide background essential to understanding Ford's interoperability measurement method, interoperability maturity models, and how the models can be used to facilitate interoperability measurements. An examination of the key areas (systems) involved in and driving causes of space acquisition failures follows.

The methodology section fuses the concepts and information from the literature review to demonstrate a method to measure space acquisition interoperability. An acquisition interoperability maturity model will be built based upon the key and driving causes of space acquisition failures.

In the analysis and results chapter, the space acquisition maturity model will be used to measure the interoperability of several space programs by means of Ford's interoperability measurement method and will discuss the use of the measurements as a leading indicator of space acquisition effectiveness.

The conclusions and recommendations section will examine the results of the aforementioned interoperability measure as a leading indicator and will discuss the utility of a leading indicator with respect to ongoing and future space programs. Suggestions for future research and maturation of the leading indicator will follow.

II. Literature Review

"…a process and procedure for establishing goals for improving the efficiency and effectiveness of government agencies operations and the ability to deliver goods and services to the public using Information Technology. The goals must be measurable."

—Clinger Cohen Act, Public Law 104-106

Chapter Overview

The purpose of this chapter is to provide a summary of Ford's method, interoperability maturity models, and past space acquisition failures and their root causes. This literature review lays the foundation for the development of an acquisition effectiveness maturity model and later, a quantifiable method for measuring space acquisition interoperability. A review of leading indicators for DOD acquisition programs will also be discussed to validate the utility of the interoperability measurement.

The literature review first provides a brief summary of the foundational works that this paper relies and builds upon. The basic tenets of Ford's interoperability measurement method and the interoperability maturity models are essential knowledge to understand the concepts and applications presented in this thesis. A summary of past space acquisition failures follows. Various sources were used to identify the root causes of the space acquisition failures of the past, and these root causes will later serve as chief contributors to an acquisition interoperability maturity model in the methodology section of this paper.

Before beginning, it is critically important that a standard definition of the term ―interoperability” is provided. Ford‘s paper, the 2007 survey on interoperability measurement, LISI and OIM chose to use the DOD‘s original definition from Joint Publication 1-02 (Department of Defense, 2005) as the standard. It states that interoperability is ―the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together” (Ford, Colombi, Graham, & Jacques, 2007). This thesis will remain consistent with this definition.

Ford’s Interoperability Measurement Method

Ford created a method to measure confrontational interoperability based on and constrained by an operational scenario and the systems and processes that execute the activities contained in the scenario. Ford‘s basic process to define the interoperability measurement can be described by the figure below, taken from Ford‘s earlier work:

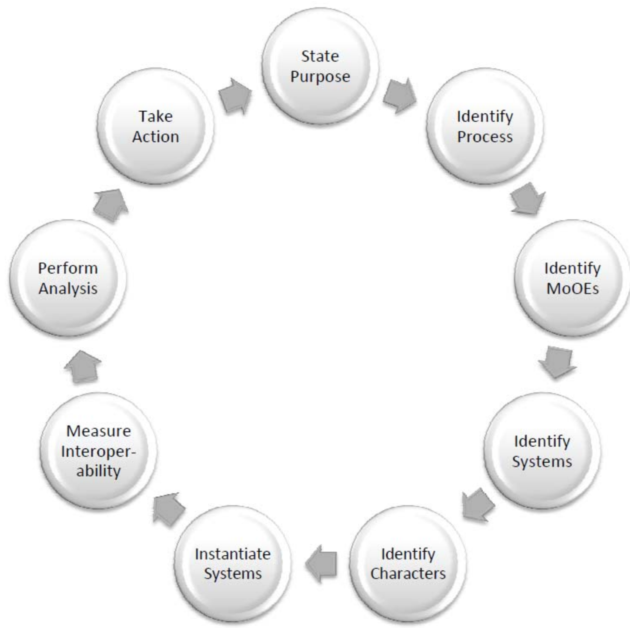


Figure 1. Interoperability Measurement Process (Ford, 2008)

The first step in Ford's interoperability measurement process is to define the purpose of the measurement. Defining the purpose is necessary to adequately scope the interoperability measurement, and serves as the anchor for the interoperability analysis. Once the purpose has been determined, the process that serves or is the subject of the purpose must be developed. In Ford's method and this paper, operational scenarios defined the process for analysis. In this paper, acquisition programs will provide the processes for analysis.

According to Defense Acquisition University, Measures of Effectiveness (MOE) are ―a measure of operational success that must be closely related to the objective of the mission or operation being evaluated. For example, the number of enemy submarines sunk or enemy tanks destroyed may be satisfactory MOEs if the objective is to destroy such weapons systems...A meaningful MOE must be quantifiable and a measure to what degree the real objective is achieved.” Ford‘s work was chiefly focused on confrontational interoperability which used MOEs based on the effectiveness of friendly, or “blue” forces compared against the effectiveness of enemy, or “red” forces (e.g. number of enemy submarines sunk). Collaborative interoperability on the other hand will use MOEs based on the effectiveness of friendly systems to operate with each other (e.g. number of successful communications messages sent and/or received).

Many definitions of the word “system” exist, but this research will maintain Ford‘s definition of a system as, “an entity comprised of related interacting elements, which act together to achieve a purpose” and is “broad enough to include a wide variety of systems including, but not limited to, technical, biological, environmental, organizational, conceptual, physical, and philosophical, among others.” (Ford, 2008). This broad view is critical to developing a flexible method to measure interoperability and can be applied to the space acquisition domain. The notation for a set of systems is $S = \{s_1, s_2 \ldots s_n\}$ where S represents the complete set of systems participating in the operational scenario, and s_n represents the individual systems.

Once the operational scenario and systems have been chosen, the interoperability characters must be defined. At a high level, characters describe salient and distinct attributes of a system (e.g. size, shape, function, etc.). The notation for characters is $X = \{x_1, x_2 \ldots x_n\}$ where X represents the set of characters used to model the systems, and x_n represents the characters used to describe the individual systems. The states of these characters (e.g. the character –size” could have a state of –25 ft”), is noted as $C = \{c_1, c_2 \ldots c_n\}$ and follows Ford‘s formal definition:

DEFINITION (System Characterization): Given a set of systems S, then X : S → C is a function which maps systems to a set of character states C and X is called the characterization of S. (Ford, 2008)

For interoperability measurement, only certain types of characters, known as interoperability characters, are used. These characters describe how the systems in the scenario interoperate, and are generally based on the actions the systems must perform to or accept from each other. These interactions, much like a conversation between two people, have two primary components. One party transmits the action, the other receives it. Ford‘s work provides a table of potential interoperability characters:

Table 1. Interoperability Characters (Ford, 2008)

Interoperability Pairs	Interoperability Type	Character
Provide ⇔ Accept	General	*Interoperate*
Transmit ⇔ Receive	Communication	*Communicate*
Attack ⇔ Attacked	Confrontational	*Attack*
Impact ⇔ Impacted	Confrontational	*Impact*
Detect ⇔ Detected	Technological	*Detect*
Publish ⇔ Subscribe	Net-Centric	*Service*
Occupy ⇔ Accommodate	Spatial	*Accommodate*
Serve ⇔ Be Served	Human	*Service*
Give ⇔ Take	Human	*Share*
Buy ⇔ Sell	Business	*Trade*
Pay ⇔ Get Paid	Financial	*Transact*
Output ⇔ Input	Traditional System	*OutputInput*
Lead ⇔ Follow	Organizational	*Dance*
Order ⇔ Obey	Human, Organizational	*Command*
Produce ⇔ Consume	Business, Human	*Economy*
Transport ⇔ Transported by	Business	*Transport*

In Ford‘s method, the states of these interoperability characters are usually denoted using absence or presence states. That is, $C = \{0,1\}$ where –zero” indicates the absence and “one” indicates the presence of a specific interoperability character. Ford‘s interoperability characters also capture the direction of the interoperation. A conversation between two people is directional in nature. One person is transmitting (speaking) a message in the direction of the other person, who is receiving (listening) the transmitted message. A conversation between two people could be described as a “bi-directional interoperation” because both parties are able to transmit and receive messages. If one person was mute or deaf, the interoperability between the conversational parties could be described as a “uni-directional interoperation” because only one party is able to transmit while the other can only receive. Ford captured these relationships graphically:

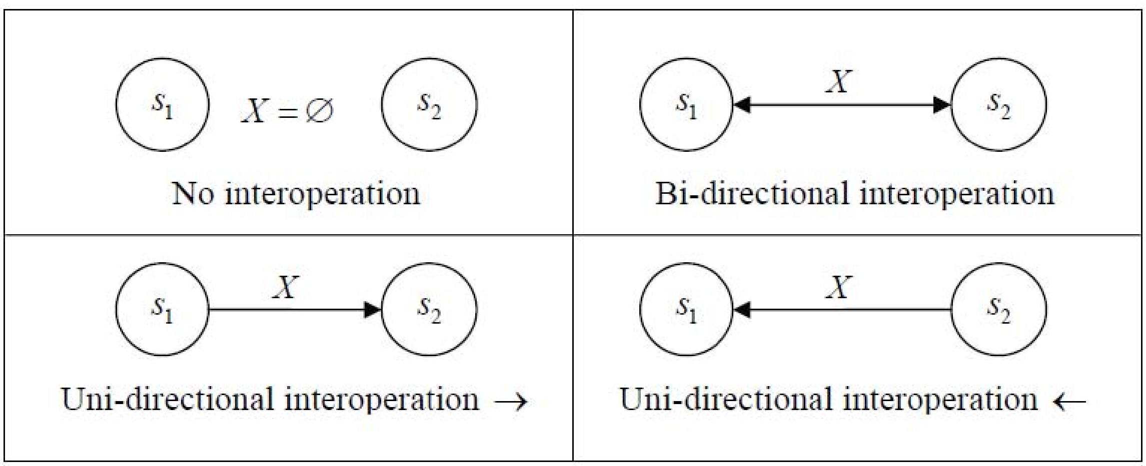


Figure 2. Directional Interoperability (Ford, 2008)

Once the systems and their characters are defined for a specific operational scenario and interoperability measurement purpose, they are “instantiated” or listed as a sequence of states for each system. For example, an aircraft could have characters of “type”, “load” and “speed”, and could be instantiated as a fighter jet with a weapons capacity of 10,000 pounds and a maximum speed of 1,200 miles per hour (σ = fighter, 10,000 pounds, 1,200 mph).

DEFINITION (System Instantiation): Given a specific s ∈ S and a set x ⊆ X of system characters descriptive of s, then $\sigma = x(s)$ *is a sequence of system character states, called the instantiation of s, which models s.* (Ford, 2008)

Ford's interoperability measurement is based on a mathematical similarity measurement. To put it simply, a similarity measurement is based upon distance. Items that are similar have less distance, and items that are disparate have more distance between them. There are various types of similarity measurements, and Ford chose to use the Minkowski similarity function to base his analysis of interoperability measurement upon. This function enables interoperability measurement between multiple systems based upon shared interoperability characters that have been instantiated and aligned. Ford captures the Sim_{Real} interoperability measurement as follows:

Equation 1. Average Character State Value (Ford, 2008)

$$\textit{Average Character State Value} = w = \frac{\sum_{i=1}^{n} \sigma'(i) + \sum_{i=1}^{n} \sigma''(i)}{2nc_{\max}}$$

DEFINITION (Sim_{Real}*): Given a pair of systems* s', s'' *instantiated as* $\sigma', \sigma'' \in \mathbb{R}^n \cap [0, c_{\max}]$*, then* $I = Sim_{Real} = w \cdot MMS$*, written out completely in [equation 2] is an interoperability function which gives a weighted, normalized measure of the similarity of systems instantiated* *with real-valued character states where w is the average character state value of a pair of system instantiations, MMS is the Modified Minkowski Similarity function, n is the number of characters used to instantiate σ', σ'', $c_{\max}$ is the maximum character state value, and r is the Minkowski parameter (usually set to $r = 2$).*

Equation 2. *Sim*

$$I = Sim_{\mathrm{Re}al} = \left[\frac{\sum_{i=1}^{n} \sigma'(i) + \sum_{i=1}^{n} \sigma''(i)}{2nc_{\max}} \right] \left[1 - \left(\frac{1}{\sqrt[r]{n}} \right) \left(\sum_{i=1}^{n} b_i \left(\frac{\sigma'(i) - \sigma''(i)}{c_{\max}} \right)^r \right)^{1/r} \right]$$

Ford's axiom further states:

AXIOM (System Similarity and Interoperability): If a pair of systems is instantiated only with system interoperability characters, then the measure of their similarity is also a measure of their interoperability. (Ford, 2008)

Levels of Information Systems Interoperability (LISI)

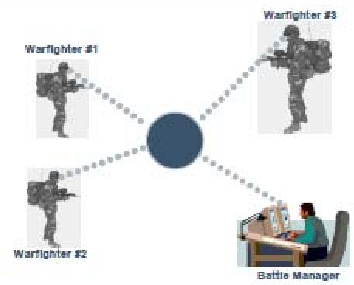
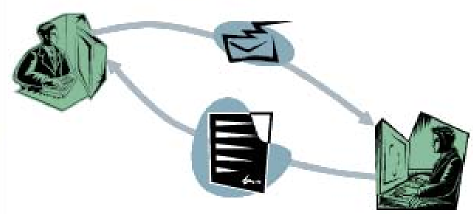
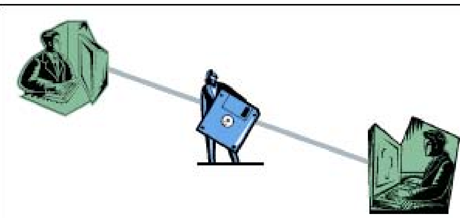
The LISI model was designed to measure information systems' interoperability by determining the degree of interoperability achieved by systems or organizations (Kasunic & Anderson, 2004). In short, it is a maturity model. The model uses four main "attributes of interoperability" (Kasunic & Anderson, 2004) to compose the framework used to measure interoperability; procedures, applications, infrastructure, and data, also known as PAID.

Table 2. LISI Attributes (Kasunic & Anderson, 2004)

P	Procedures	Policies and procedures govern a system's development through established standards and the procedures and processes which influence system integration and functional operational requirements
A	Applications	The functions a system is intended to perform. These functions reside most often in the form of user-based application programs which perform or support a specific set of processes or procedures.
I	Infrastructure	The infrastructure required to support the systems operations. Contains four sub-components which are also defined in terms of increasing levels of sophistication.
D	Data	The data and information structures used to support both the functional applications and system infrastructure.

The PAID attributes make up the columns of the LISI reference model. The rows in the model define the level of interoperability maturity and are defined by the following (in order of increasing maturity); isolated, connected, functional, domain and enterprise.

Table 3. LISI Maturity Levels (Kasunic & Anderson, 2004)

Information Exchange	Level	Computing Environment
Distributed global information and applications Simultaneous interactions with complex data Advanced collaboration, e.g. interactive COP update Event-triggered global database update	4 Enterprise Interactive manipulation; shared data and applications	
Shared databases Sophisticated collaboration, e.g., Common Operating Picture	3 Domain Shared data; "separate" applications	
Heterogeneous product exchange Basic collaboration Group collaboration, e.g., exchange of annotated imagery, maps with overlays	2 Functional Minimal common functions; separate data and applications	
Homogeneous product exchange, e.g., FM voice, tactical data links, text files, transfers, message, e-mail	1 Connected Electronic connection; separate data & applications	
Manual gateway, e.g., diskette, tape, hard copy exchange	0 Isolated Non-connected	

The combination of the interoperability attributes with the interoperability maturity levels results in the LISI reference framework:

Table 4. LISI Reference Model (Ford, 2008)

LEVEL (Environment)			Interoperabilty Attributes: P	A	I	D
Enterprise Level (Universal)	4	c	Multi-National Enterprises	Interactive (cross applications)	Multi-Dimentional Topologies	Cross-Enterprise Models
		b	Cross Government Enterprise			
		a	DoD Enterprise	Full Object Cut & Paste		Enterprise Model
Domain Level (Integrated)	3	c	Domain Service/Agency Doctrine, Procedures, Training, etc.	Shared Data (e.g., Situation Displays Direct DB Exchanges)	WAN	DBMS
		b		Group Collaboration (e.g, White Boards, VTC)		Domain Models
		a		Full Text Cut & Paste		
Functional Level (Distributed)	2	c	Common Operating Environment (e.g., DII-COE Level 5) Compliance	Web Browser	LAN	Program Models & Advanced Data Formats
		b		Basic Operations Documents Briefings Pictures & Maps Spreadsheets Databases		
		a	Program Standard Procedures, Training, etc.	Adv. Messaging Messge Parsers E-mail w/Attachments	NET	
Connected Level (Peer-to-Peer)	1	d	Standards Complaint (e.g., JTA)	Basic Messaging (e.g., Unformatted Text E-mail w/o Attachments)	Two Way	Basic Data Formats
		c		Data File Transfer		
		b	Security Profile	Simple Interaction (e.g., Telemetry, Remote Access Text Chatter, Voice, Fax)		
		a			One Way	
Isolated Level (Manual)	0	d	Media Exchange Procedures	N/A	Removable Media	Media Formats
		c	Manual Access Controls — NATO Level 3		Manual Re-entry	Private Data
		b	NATO Level 2			
		a	NATO Level 1			
		o	NO KNOWN INTEROPERABILITY			

Referencing back to Ford‘s method and the standard definition of interoperability, LISI provides a way to qualify how well systems provide and use services between one another to operate effectively. The “attributes of interoperability,” or PAID, describe key characteristics necessary for interoperability to occur. In other words, the attributes are the means by which the services are provided; they enable interoperability. The levels provide the characters' states where higher levels of maturity will result in higher levels of interoperability.

The LISI model provides a good way to measure the overall interoperability maturity of a particular system. It does not however, guarantee interoperability between systems. Two systems possessing identical maturity levels as defined by LISI will not interoperate if they use disparate technology, standards or interfaces. As Ford points out, the LISI model's strength lies in its ability to facilitate a quantifiable interoperability measurement (Ford, 2008).

Organizational Interoperability Maturity Model (OIM)

The model known as OIM was born from and uses the same basic structure as the LISI model, but instead deals with interoperability between organizations. Instead of the PAID attributes, OIM utilizes the attributes of preparedness, understanding, command style and ethos:

> **Preparedness:** This attribute describes the preparedness of the organisation to interoperate. It is made up of doctrine, experience and training.
>
> **Understanding:** The understanding attribute measures the amount of communication and sharing of knowledge and information within the organisation and how the information is used.
>
> **Command Style:** This is the attribute that describes the management and command style of the organisation – how decisions are made and how roles and responsibilities are allocated/delegated.
>
> **Ethos:** The ethos attribute is concerned with the culture and value systems of the organisation and the goals and aspiration of the organisation. The level of trust within the organisation is also included. (Clark & Jones)

The levels of organizational interoperability maturity again follow the LISI model's lead:

Level 0 - Independent - The Level 0 interoperability describes the interaction between independent organisations. These are organisations that would normally work without any interaction other than that provided by personal contact. They are likely to be organisations that do not normally share common goals or purpose but that may be required to interoperate in some scenario that has no precedent. Essentially the arrangements are unplanned and unanticipated.

Level 1 - Ad hoc - At this level of interoperability only very limited organisational frameworks are in place which could support ad hoc arrangements. There will be some guidelines to describe how interoperability will occur but essentially the specific arrangements are still unplanned. There will be some overarching shared goal but individual organisation aspirations will take precedence and the organisations remain entirely distinct.

Level 2 - Collaborative - The collaborative organisational interoperability level is where recognised frameworks are in place to support interoperability and shared goals are recognized and roles and responsibilities are allocated as part of on-going responsibilities however the organisations are still distinct. Training is likely to have taken place in some aspects of the interworking and significant communication and sharing of knowledge does occur but the home organisations' frameworks still have a significant influence.

Level 3 - Integrated - The integrated level of organisational interoperability is one where there are shared value systems and shared goals, a common understanding and a preparedness to interoperate, for example, detailed doctrine is in place and there is significant experience in using it. The frameworks are in place and practised however there are still residual attachments to a home organisation.

Level 4 - Unified - A unified organisation is one in which the organisational goals, value systems, command structure/style, and knowledge bases are shared across the system. The organisation is interoperating on continuing basis. This is really the ideal level where there is no impediment in the organisational frameworks to full and complete interoperation. It is likely to occur only in very homogeneous organisations. (Clark & Jones)

The organizational attributes and maturity levels are combined to form the OIM:

Table 5. OIM (Clark & Jones)

	Preparedness	Understanding	Command Style	Ethos
Unified	Complete - normal day-to-day working	Shared	Homogeneous	Uniform
Combined	Detailed doctrine and experience in using it	Shared comms and shared knowledge	One chain of command and interaction with home org	Shared ethos but with influence from home org
Collaborative	General doctrine in place and some experience	Shared comms and shared knowledge about specific topics	Separate reporting lines of responsibility overlaid with a single command chain	Shared purpose; goals, value system significantly influenced by home org
Ad hoc	General guidelines	Electronic comms and shared information	Separate reporting lines of responsibility	Shared purpose
Independent	No preparedness	Communication via phone etc	No interaction	Limited shared purpose

The creators of OIM note that LISI is ―strongly technological” and ―focuses on system and technical compatibility,” and that OIM was created to ―look at the layers of the model that deal with organizational issues” (Clark & Jones). They further delineate the differences between interoperability that is driven by process versus technology:

> Where interoperability has been driven by process, the focus is on the situation, the people and commander's intent.
>
> Where interoperability has been driven by technology, the focus is on assets, their properties and the levels of compatibility required.

Therefore, OIM qualitatively assesses organizational interoperability by measuring the maturity of an organization‘s processes, their situation, the people involved and the commander‘s intent. These focus areas are characterized by the attributes of preparedness, understanding, command style and ethos. Again, the attributes are the means by which the services from the definition of interoperability are provided, where increased levels of maturity in each attribute area fundamentally result in an increase in interoperability. While the attributes of preparedness, understanding, command style and ethos are highly relevant to an operational commander and their troops‘ interoperation, other attributes may be selected to properly characterize a highly collaborative, non-combat acquisition system.

Ford's Method Applied to OIM

Ford applied his interoperability measurement to the maturity model, in this case OIM, to provide a way to quantifiably measure the interoperability between coalition nations. An INTERFET coalition exercise was used to execute the measurement where the systems (*S*) were the nations, their characters (*X*) were the attributes of preparedness, understanding, command style, and ethos, and their character states (*C*) were represented by the five levels of the maturity model (Ford, 2008):

$$S = \{AUS, US, NZ, Thai, Phil, ROK\}$$

$$X = \{Preparedness, Understanding, Command\ Style, Ethos\}$$

$$C = \{0,1,2,3,4\}$$

Using maturity level assessments derived from the INTERFET exercise, the instantiation of *S, X,* and *C* yielded:

Table 6. INTERFET Instantiation (Ford, 2008)

$$\Sigma = \left[\begin{array}{c|cccc} & Preparation & Understanding & Command\ Style & Ethos \\ \hline AUS & 2 & 3 & 3 & 1 \\ US & 2 & 3 & 3 & 1 \\ NZ & 2 & 3 & 3 & 1 \\ Thai & 1 & 1 & 1 & 1 \\ Phil & 1 & 1 & 1 & 1 \\ ROK & 0 & 1 & 1 & 1 \end{array}\right]$$

Ford‘s interoperability method is then easily applied to determine the level of interoperability between the coalition nations during the INTERFET exercise:

Table 7. INTERFET Interoperability Measurement (Ford, 2008)

$M =$

	AUS	*US*	*NZ*	*Thai*	*Phil*	*ROK*
AUS	0.6	0.6	0.6	0.3	0.3	0.2
US	0.6	0.6	0.6	0.3	0.3	0.2
NZ	0.6	0.6	0.6	0.3	0.3	0.2
Thai	0.3	0.3	0.3	0.3	0.2	0.2
Phil	0.3	0.3	0.3	0.2	0.3	0.2
ROK	0.2	0.2	0.2	0.2	0.2	0.2

This method can be applied to any interoperability maturity model to determine how well a nation or system interoperates with another.

Space Acquisition Failures and Lessons Learned

The Department of Defense‘s space acquisition community has suffered through numerous failures as documented by the press, and perhaps more extensively, the Government Accountability Office (GAO). It is important to briefly define what is meant by a failed acquisition program. As defined by Merriam-Webster, failure is an ―omission of occurrence or performance; specifically, a failing to perform a duty or expected action.” In space acquisition terms, a failure can be considered a failing to meet cost, schedule or performance objectives as originally defined by the program at its inception.

A thorough review of past space acquisition failures was conducted. The majority of inputs were authored by the Government Accountability Office (GAO), who has an extensive history of evaluating space acquisition performance. The GAO reports were frequently corroborated by independent reviews and other sources, and revealed shared reasons for space acquisition failures. Perhaps the best overall summary was provided by a Defense Science Board report produced in 2003. The group was chaired by Mr. Tom Young, a former Martin Marietta Chief Executive, and included membership from many space acquisition stalwarts.

The report, simply titled ―Acquisition of National Security Space Programs", and despite its 2003 publication date, ―discerned profound insights into systemic problems in space acquisition" (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003) that still resonate within the space acquisition program offices of today. The report highlighted five deep-seated shortcomings responsible for many of the space acquisition failures of the past.

First, *"cost has replaced mission success as the primary driver in managing space development programs."* The report emphasizes the fragility of space acquisition programs, citing how ―thousands of good decisions can be undone by a single engineering flaw or workmanship error, and these flaws and errors can result in catastrophe" (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003). In basic terms, trading schedule and cost savings at the expense of mission success is a flawed approach. For space acquisitions programs, approximately 70% of the life cycle cost occurs before the system is fielded:

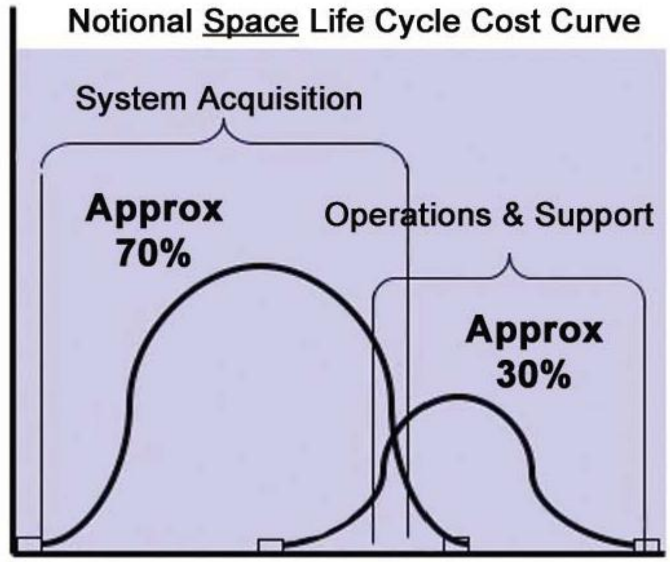


Figure 3. Space Life Cycle Cost Curve (Hamel, 2007)

There is great pressure to maintain cost and schedule during this phase, but doing so at an increased level of mission risk ultimately results in the opposite effect. The following figure characterizes a typical situation; a program manager chooses to save budget and schedule by using mission success as margin. The ultimate effect is an increased risk of mission failure, which leads to greater cost increases and schedule delays in the future.

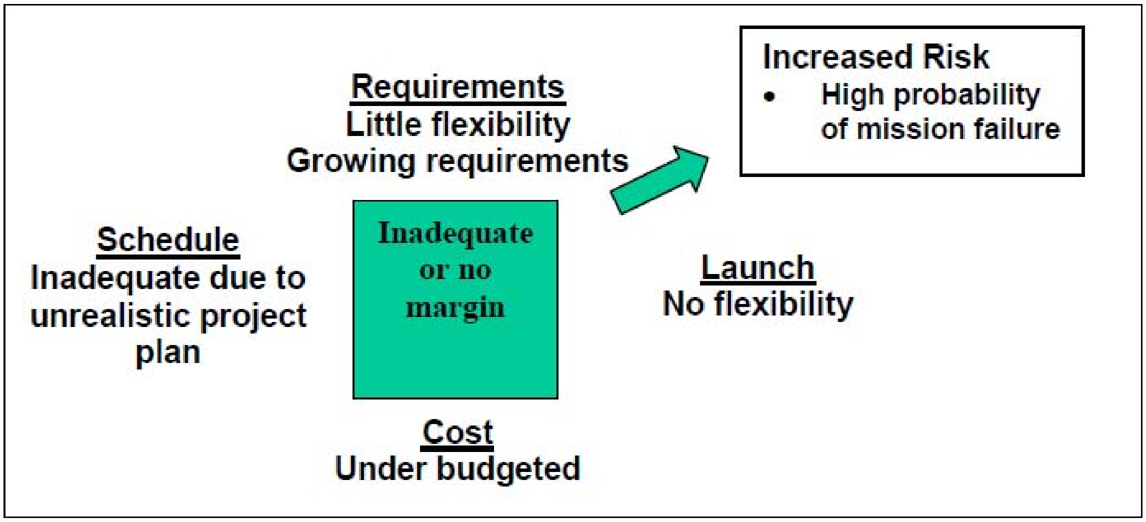


Figure 4. Space Acquisition Scenario (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003)

Second, *"unrealistic estimates lead to unrealistic budgets and unexecutable programs."* This root cause stems primarily from optimistic cost estimates provided by an incoming competitor and inadequate cost margin. The report states that ―analysis of recent space competitions found that the incumbent contractor loses more than 90 percent of the time." The incumbent contractor is ―burdened" by its very relevant and real-world legacy program experience, and will produce more realistic cost estimates for a follow-on program. The incumbent is held at a disadvantage however, to a new, less experienced contractor who may produce optimistic cost estimates to gain an edge in the competition. If the less experienced contractor wins the new contract, the program office budget is matched to the unrealistic estimate, almost guaranteeing future program delays and increased risk to mission success. The report also cites an unhealthy emphasis on program advocacy at the expense of realism as a major contributor to unrealistic estimates.

Third, *"undisciplined definition and uncontrolled growth in system requirements increase cost and schedule delays."* The inherent complexity of space systems and the ever increasing numbers of users have driven program requirements and Key Performance Parameters (KPP) to unmanageable proportions. The report adds, ―clear tradeoffs among cost, schedule, risk, and requirements are not well supported by rigorous system engineering, budget, and management processes." Programs with increased numbers of users and KPPs are more likely to suffer cost and schedule delays.

Fourth, *"government capabilities to lead and manage the space acquisition process have seriously eroded."* Inexperienced program managers tend to adopt a ―can-do" attitude in place of programmatic rigor. Additionally, the report states:

> Policies and practices inherent in acquisition reform inordinately devalued the systems acquisition engineering workforce. As a result, today's government systems engineering capabilities are not adequate to support the assessment of requirements, conduct trade studies, develop architectures, define programs, oversee contractor engineering, and assess risk. With growing emphasis on effects-based capabilities and cross-system integration, systems engineering becomes even more important and interim corrective action must be considered.

A less experienced acquisition workforce results in an inability to manage programs, and very clearly results in program failures.

Fifth and finally, *"industry has failed to implement proven practices on some programs."* The report credits industry's knowledge of and ability to utilize proven practices, but gently censures them for a lack of focus and dedication to the same.

The GAO's 2003 report, ―Military Space Operations: Common Problems and their Effects on Satellite and Related Acquisitions," provides a similarly useful summary of space acquisition failures over the last two decades. It cites four primary root causes of space acquisition failures, and corroborates many of the findings from the 2003 Defense Science Board report.

First, *"requirements for what the satellite needed to do and how well it must perform were not adequately defined at the beginning of a program or were changed significantly once the program had already begun"* (Government Accountability Office, 2003). The GAO asserts that this issue caused programs difficulty in matching requirements to their resources, and resulted in cost and schedule increases. This finding matches the third Defense Science Board finding listed above.

Second, *"investment practices were weak. For example, potentially more cost-effective approaches were not examined and cost estimates were optimistic"* (Government Accountability Office, 2003). The GAO specifically cites the lack of an overall investment strategy for DOD space as the root cause, where shifts in budget were unexpected, and money was often moved from healthier programs to pay for weaker ones. This finding corroborates the second Defense Science Board finding above.

Third, *"acquisition strategies were poorly executed. For example, competition was reduced for the sake of schedule or DOD did not adequately oversee contractors"* (Government Accountability Office, 2003). The GAO adds that the DOD took a ―schedule-driven versus a knowledge-driven approach to the acquisition process" which strongly supports the first Defense Science Board finding listed previously.

Fourth, and finally, *"technologies were not mature enough to be included in product development"* (Government Accountability Office, 2003). Although not specifically stated, this cause is tied to the Defense Science Board's fourth finding above. It can be inferred that a lack of program management and systems engineering rigor allowed immature technologies to be used, ultimately resulting in increased program risk.

In 2006, a Defense Acquisition Performance Assessment (DAPA) panel was commissioned by the Deputy Secretary of Defense to evaluate the overall defense acquisition enterprise. The panel's major findings place significant emphasis on the ability of acquisition's major elements to interoperate effectively:

> The evidence we discovered was persistent in recognizing that an effective Acquisition System requires stability and continuity that only can be provided through successful integration of the major elements upon which it depends. When we began this task, we presumed the Department's Acquisition System to be an efficient integration of the acquisition, requirements and budget processes. However, in the course of our review we found that the System is a highly complex mechanism that is fragmented in its operation. (Defense Acquisition Performance Assessment Project, 2006)

The report breaks defense acquisition into six major elements; organization, workforce, budget, requirements, acquisition [process], and industry, and provides an assessment of each element. Although not specific to space acquisition, the DAPA review generally upholds the findings from the 2003 Defense Science Board report.

The panel found that *"the current decision making process is flawed"* in the organization element introducing uncertainty and instability in program execution. The panel cites several root causes including disconnects between the acquisition, budget and requirements processes. This finding is captured at a high-level, and can be attributed to many of the findings from the 2003 Defense Science Board's report.

For the workforce element, the panel noted that *"a successful program requires a professional workforce with subject matter expertise."* The panel alludes to poor integration of budget and requirements personnel into the acquisition workforce, as well as a significant lack of experience and training as primary workforce problem areas. This corresponds to the fourth Defense Science Board finding above. The panel also states:

> Experience and expertise in all functional areas has been de-valued and contributes to a ―Conspiracy of Hope" in which we understate cost, risk and technical readiness and, as a result, embark on programs that are not executable within initial estimates. (Defense Acquisition Performance Assessment Project, 2006)

The ―Conspiracy of Hope" strongly supports the first and second Defense Science Board findings listed previously.

For the budget element, the panel emphasizes that, *"successful Research, Development, Test and Evaluation and Procurement programs require stable budgets and accurate planning"* and that this stability simply does not exist. The panel also determined that budget shortfalls were often met by ―stretching programs" whereby the DOD ―accepts long-term cost increases and delays in acquisition programs to achieve short-term savings and budget flexibility." These findings directly support the Defense Science Board‘s first finding above. The panel also cites a problematic use of optimistic budget estimates on acquisition programs, further supporting the Defense Science Board‘s second finding.

The panel continues by listing a *"lengthy and insufficiently advised requirement development process"* often based upon *"immature technologies and overly optimistic estimates of future resource needs and availability"* as well as requirements instability as major problem areas in the requirements element. These findings validate the second and third findings from the Defense Science Board report.

The acquisition element, when viewed from a process perspective, is characterized by the panel as being part of the ―Conspiracy of Hope" where *"industry is encouraged to propose unrealistic cost, optimistic performance and understate technical risk estimates during the acquisition solicitation process and the Department is encouraged to accept these proposals as the foundation for program baselines,"* reinforcing the Defense Science Board's second finding.

The panel found that the final element, industry, is extremely fragile, where *"consolidation of the industrial base, caused by unstable defense demand, has reduced the benefits of competition, introduced industrial organizational conflict of interest issues, and made every defense contract a "must win" situation for the prime contractors."* This description does not directly relate to a specific Defense Science Board finding, but can be cited as a contributing factor.

To summarize, the DAPA findings provide a more recent overview of acquisition lessons learned that validate the earlier Defense Science Board findings from 2003.

Leading Indicators

The ―Systems Engineering Leading Indicators Guide" serves as the primary reference for leading indicators in this thesis. It states that ―a leading indicator is a measure for evaluating the effectiveness of how a specific activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance objectives" and is useful to ―support the effective management of systems engineering by providing visibility into expected project performance and potential future states" (Massachusetts Institute of Technology, INCOSE, and PSM, 2010)[1]. Leading indicators often use historical data and trends to provide this predictive measure of performance and are ―composed of characteristics, a condition and a predicted behavior":

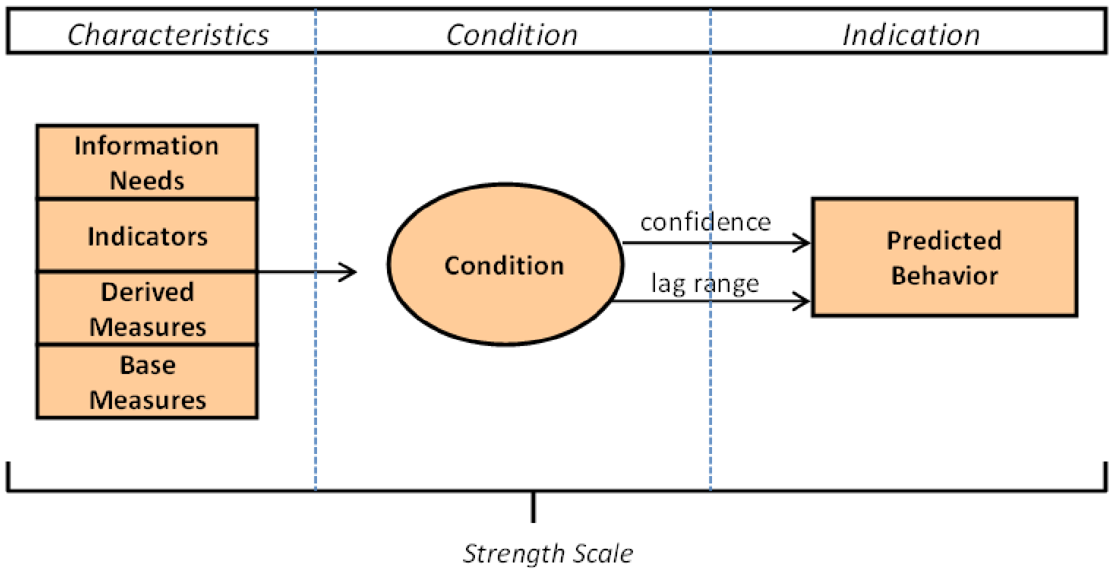


Figure 5. Depiction of a Leading Indicator (Massachusetts Institute of Technology, INCOSE, and PSM, 2010)

The characteristics are the data, the condition supplies the context in which to evaluate the data, and when combined, they provide an indication or predicted behavior. The strength scale captures the relative importance of the indicator based upon past experience.

The guide recommends that leading indicators supplement a program's existing set of measures, and urges them to properly set planned targets and thresholds using

[1] *General Use: Permission to reproduce, use this document or parts thereof, and to prepare derivative works from this document is granted, with attribution to LAI, INCOSE, PSM, and SEAri, and the original author(s), provided this copyright notice is included with all reproductions and derivative works.*

empirical data. If data is not available, expert opinion may be used to set targets. The preferred method however is to utilize “a good historical base of information” where “organizations…build the collection of the historical measurement data into…collection practices” (Massachusetts Institute of Technology, INCOSE, and PSM, 2010).

These targets are based upon the phases of the acquisition cycle as defined by DOD Instruction 5000.02, and help programs understand readiness with respect to program milestones. The applicability of the indicator also varies with program phase. As illustrated by the following figure, the indicator “Requirements Trends” provides insight in all acquisition phases, while “System Definition Change Backlog Trend” is only applicable to three of the five phases.

Table 8. Systems Engineering Leading Indicators Overview (truncated)

(Massachusetts Institute of Technology, INCOSE, and PSM, 2010)

Leading Indicator	Insight Provided	Phases / Stages									
		P 1	P 2	P 3	P 4	P 5	S 1	S 2	S 3	S 4	S 5
Requirements Trends	Rate of maturity of the system definition against the plan. Additionally, characterizes the stability and completeness of the system requirements that could potentially impact design, production, operational utility, or support.	●	●	●	●	●	●	●	●	●	●
System Definition Change Backlog Trend	Change request backlog which, when excessive, could have adverse impact on the technical, cost and schedule baselines.			●	●	●		●	●	●	
Interface Trends	Interface specification closure against plan. Lack of timely closure could pose adverse impact to system architecture, design, implementation and/or V&V any of which could pose technical, cost and schedule impact.	●	●	●	●	●	●	●	●	●	
Requirements Validation Trends	Progress against plan in assuring that the customer requirements are valid and properly understood. Adverse trends would pose impacts to system design activity with corresponding impacts to technical, cost & schedule baselines and customer satisfaction.	●	●	●	●	●	●	●	●	●	

The guide provides 18 major leading indicators with example graphs and detailed specifications for use on acquisition programs. The ―Requirement Trends” display below demonstrates how a leading indicator might be used on an acquisition program:

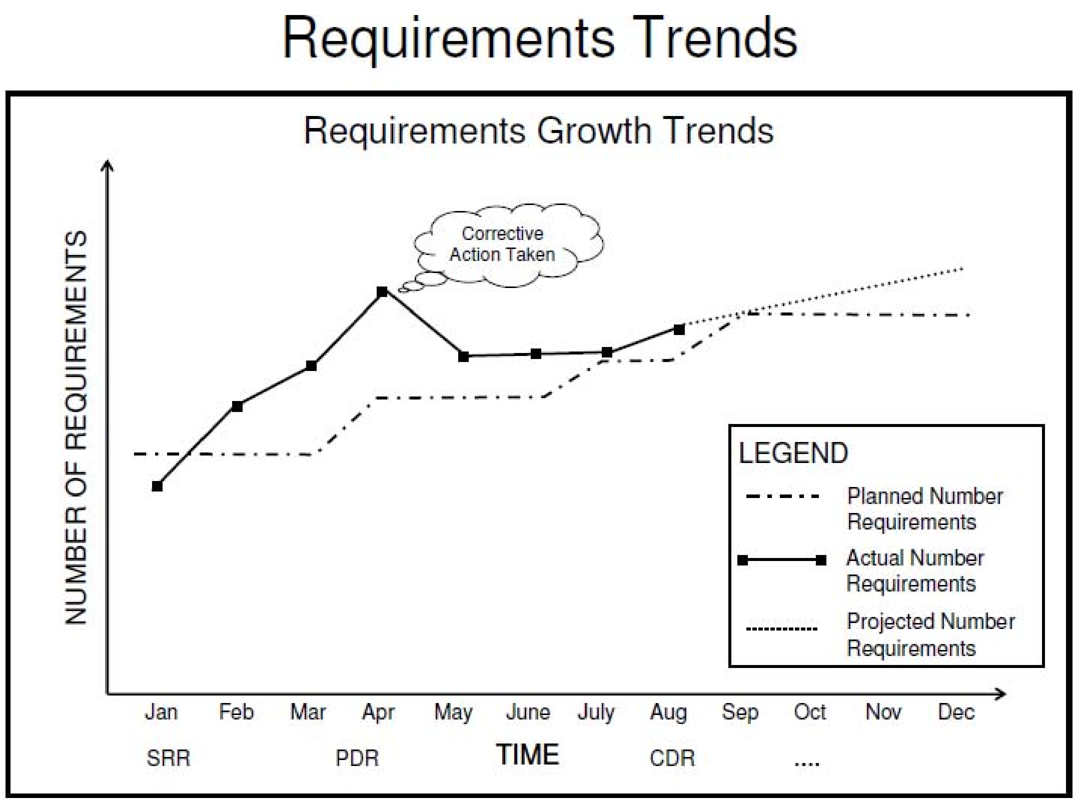


Figure 6. Requirements Trends Example (Massachusetts Institute of Technology, INCOSE, and PSM, 2010)

In this example, the leading indicator shows a problem with requirements growth which drives the program to take action in April. Later that summer, the program was able to evaluate the effectiveness of their actions as the growth in requirements was stemmed. The ―Requirements Trends” leading indicator can be directly attributed to the 2003 Defense Science Board‘s finding ―*undisciplined definition and uncontrolled growth* *in system requirements increase cost and schedule delays"* (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003), and provides a way to measure how well a program is or is not protecting itself from the causes of the acquisition failures of the past.

It is important to recognize that lessons learned represent a source of historical empirical data that can be used to develop a leading indicator. In this case, the Defense Science Board, GAO and DAPA reports provide the characteristics and conditions in which to formulate and evaluate a leading indicator of space acquisition program success.

Summary

The 2003 Defense Science Board and GAO reports provide a concise and comprehensive review of the space acquisition failures of the past. Each report supports the other's findings, and presents a strong case identifying the primary space acquisition characteristics that drive success or failure. These characteristics can serve as attributes or characters for the basis of an interoperability measurement and a leading indicator of program performance.

III. Methodology

Furthermore, if systems implement a confrontational operational process and are identified and modeled in the context of a measure of operational effectiveness tied to that process, then another fundamental result mathematically relates the change in interoperability of the systems with a change in the measure of operational effectiveness.

—Thomas C. Ford (Ford, 2008)

Chapter Overview

The purpose of this chapter is to develop a method to measure acquisition interoperability using key, driving acquisition characters derived from past acquisition experience. This method will use Ford‘s inaugural work on confrontational interoperability measurement to create a new collaborative, acquisition interoperability measurement, and will be applied to several space acquisition programs for demonstration in the ―Analysis and Results” chapter. These scenarios will also emphasize the utility of the new method for assessing the effectiveness of acquisition processes that must interact to accomplish a specific goal.

Space Acquisition Interoperability

Within an acquisition program, there is little doubt that cost, schedule and requirements are intrinsically linked. The numerical values of cost in dollars, schedule in years, and requirements in number of KPPs can be approximated using basic mathematical relationships, e.g. more KPPs will result in an increase in cost and schedule. Acquisition systems on the other hand drive the ability of a program to manage and control these values. The people, processes and products that determine a program‘s cost, schedule and requirements can be described as systems. The following figure from the Defense Science Board report supplies a depiction of the major space acquisition systems found on a typical space program (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003):

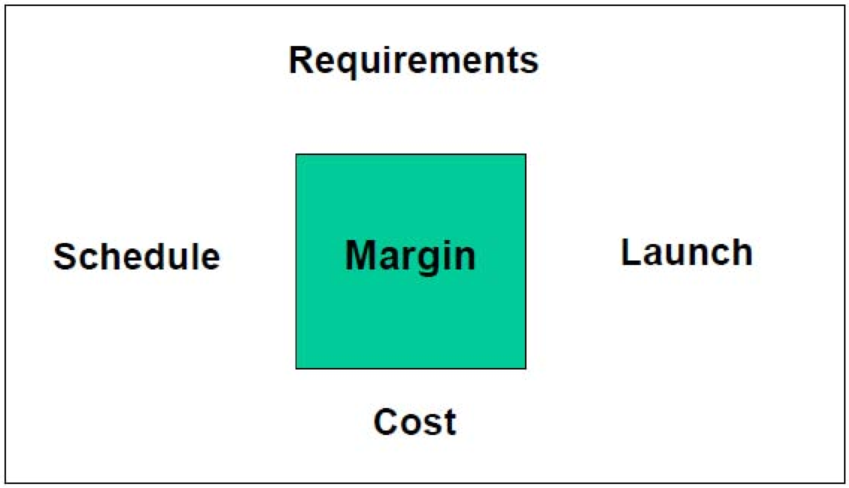


Figure 7. Space Acquisition Systems (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003)

Note: In this case, the term "margin" is not a system in and of itself. It is better described as a program characteristic. Additionally, the report included the term "launch" to illustrate specific launch constraints placed upon a program, e.g. the satellite's size and weight. Although launch is an important aspect of any program, it was not explicitly cited as a prime cause of space acquisition failures and was omitted as a result.

These acquisition systems must work together to create a program that is executable in order to deliver mission performance on time and budget. More specifically, the cost, schedule and requirements systems must provide and accept services from one another in order to operate effectively. Therefore, using Ford's nomenclature, the space acquisition systems are captured as: $S = \{cost, schedule, requirements\}$. Each system represents the people, processes and products that determine and control the cost, schedule and requirements for a given program.

The interoperations that occur between these space acquisitions systems are profuse and complex. Using the lessons learned from past space acquisition failures, the quintessential interoperations can be extracted and applied to a maturity model. In order to compose the model, the individual interoperations between systems must be examined.

Requirements-to-Schedule Interoperability

The requirements-to-schedule interoperation is most simply described in terms of requirements stability, scope and complexity. As the 2003 Defense Science Board report states, more Key Performance Parameters (KPP) as well as ―undisciplined definition and uncontrolled growth" in requirements will result in increased schedule (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003). More complex requirements may drive a program to pursue less mature technologies, which will also result in increased schedule. The schedule system cannot effectively operate if the requirements system is unstable or attempts to take major leaps in capability.

Schedule-to-Requirements Interoperability

This interoperation is focused on the program‘s intent and priority when performing trades or utilizing margin. A program‘s requirements become less executable when schedule is traded at the expense of mission assurance. Therefore, this relationship is defined by the way the systems utilize shared margin, and how that use impacts the program‘s overall executability. If the schedule system dominates trade decisions, the requirements system will be compromised.

Requirements-to-Cost Interoperability

The requirements-to-cost interoperation is analogous to the requirements-to-schedule interoperation. More KPPs drive program complexity and decrease the ability of the cost system to accurately predict and control program costs. Again, the requirements drive the selection of technology. That is, a demand for cutting edge performance will likely drive a state-of-the-art technology choice, which decreases cost confidence. Additionally, the requirements influence the level of experience that exists within industry. If the requirements system chooses to baseline a program that has no legacy or comparable system, then the availability of experience will shrink, ultimately decreasing cost confidence.

Cost-to-Requirements Interoperability

Unrealistic cost estimates have been a mainstay of space acquisition criticism and are the driving factor in this interoperation. More realistic cost estimates will deliver a program that is more executable. The ability of the cost system to justify and secure the appropriate funding will also influence the requirements system's ability to achieve the intended performance.

Schedule-to-Cost Interoperability

The schedule-to-cost interoperation again deals with realistic estimates and how margin is utilized by the acquisition systems. In this case, a poor schedule estimate or overly aggressive plan will result in a poor cost estimate. When schedule is traded at the expense of mission assurance, the cost system will suffer because it is forced to accept more risk.

Cost-to-Schedule Interoperability

This interoperation is simply the reverse of the schedule-to-cost interoperation. Therefore the schedule-to-cost or cost-to-schedule relationship is considered to be bi-directional.

Space Acquisition Interoperability Characters

The National Security Space Acquisition Policy Interim Guidance provides a good starting point for character development. Paragraph 4, titled “DOD SPACE MDA GUIDING PRINCIPLES” states, “Over the first fifty years of the history of space acquisition, several enduring principles have emerged. The following principles should be considered by all NSS members to set the tone and guide decision making in the acquisition of NSS systems” (Department of Defense, 2009). When merged with the key system interoperations based upon past acquisition failures, the vital interoperability characteristics that must be present and mature to enable mission success are revealed. As captured in the interim guidance, the principles of “mission success”, “stable”, “disciplined” and “cost realism” best match the findings from the 2003 Defense Science Board report:

Mission Success: The overarching principle behind all National Security Space programs is mission success. When acquiring space systems, mission success must be the first consideration when assessing the risks and trades among cost, schedule, and performance. Risk management, test planning, system engineering, and funding profiles must be driven by this objective.

Stable: Within a given acquisition increment, stable budgets, stable requirements, stable direction, and low personnel turnover are necessary for successful program acquisition. Decisions made by the acquisition execution chain must be durable.

Disciplined: All parties to this space acquisition policy must exercise the discipline necessary to achieve its goals without allowing its procedures to become unnecessarily burdensome and/or time consuming.

Cost Realism: The goal is to develop and grow a world-class national security space cost estimating capability. Cost estimates must be independent and accomplished in a timely, realistic, and complete manner. Cost will be controlled by estimating accurately and focusing on quality to reduce rework and achieve mission success. All members of the NSS acquisition execution chain must insist on, and protect, a realistic management reserve.

These NSS principles are then tailored for the purpose of measuring acquisition interoperability based upon the cardinal lessons learned. The following four acquisition interoperability characters and definitions are produced:

Mission Focus: When acquiring space systems, mission success must be the first consideration when assessing the risks and trades among cost, schedule, and performance. Risk management, test planning, system engineering, and funding profiles must be driven by this objective.

Stability: Within a given acquisition increment, stable budgets, stable requirements, stable direction, and low personnel turnover are necessary for successful program acquisition. Decisions made by the acquisition execution chain must be durable. Technology is sufficiently mature and stable.

Discipline: The program must exercise the discipline necessary to achieve its goals using an experienced acquisition team adhering to proven programmatic and system engineering processes.

Realism: Program estimates must be independently verified and accomplished in a timely, realistic, and complete manner. Technology, schedule and cost will be controlled by estimating accurately and focusing on quality to reduce rework and achieve mission success. All members of the NSS acquisition execution chain must insist on, and protect, a realistic management reserve.

These four characters, *X = {mission focus, stability, discipline, realism},* capture the chief causes of space acquisition failures as described above at a high level. It is recognized that lower levels of detail will discover additional, more specific characters that could lend themselves to a more detailed measure of acquisition interoperability. As Ford noted with OIM, ―Although the final version of the OIM model remained limited to a 4-attribute, 5-level model, at least 35 sub-attributes were further defined” however, ―by not addressing them as individual attributes, fidelity is lost from the model, and their contribution is effectively averaged out” (Ford, 2008). Therefore it is important to only select the key and driving characters as evidenced by past experience to avoid watering down the results with less relevant characters.

Incorporating Interoperability Lessons Learned Into a Maturity Model

The 2003 GAO and Defense Science Board reports on the space acquisition enterprise provide the foundation for development of a space acquisitions maturity model based upon the systems and characters described above. The levels of the maturity model can be built by examining the recommended solutions from the 2003 Defense Science Board report (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003) discussed earlier.

Maturity Model Levels

As illustrated earlier, the LISI and OIM models utilized a five-level scale to define and measure the maturity of a system in a specific character. The acquisition model will follow a similar five-level construct and is guided by the definitions provided by OIM. Using Ford‘s nomenclature, the maturity levels represent character states; that is, $C = \{0, 1, 2, 3, 4\}$.

Level 0 – Separated: The system operates independently of others. The system‘s goals are not congruent with others, and little evidence exists to guide decision-making. The people, processes and products of the system are inexperienced and unproven.

Level 1 – Aligned: The system recognizes the impact it has on others and considers space acquisition best practices and lessons learned when making decisions, but continues to value its own goals over others. The people, processes and products possess experience in the domain, but remain unproven for the task at hand.

Level 2 – Structured: The system is aware of the impact it has on others and utilizes space acquisition best practices and lessons learned when making decisions. The system‘s decisions are made with a shared goal in mind. The people, processes and products have experience executing a similar task.

Level 3 – Associated: The system understands its impact on others and has incorporated space acquisitions best practices and lessons learned into its overall baseline, as well as its decision making process. Decisions are made in a structured environment with other systems using shared goals. The system will forgo its own interests for the betterment of the whole. The people, processes and products have executed similar tasks on many occasions.

Level 4 – Accordant: The system‘s decision-making process is integrated with others. Space acquisition best practices and lessons learned are unified across all systems and guide decision making. Knowledge is shared and understood across systems. The system does not maintain its own interests; all efforts are integrated toward a shared goal. The people, processes and products have successfully executed nearly identical tasks on many occasions.

The Space Acquisition Interoperability Maturity Model (SAIMM)

The SAIMM fuses the space acquisition interoperability characters and maturity levels into a format that readily facilitates an acquisition interoperability measurement based upon space acquisition history. The character states capture the key and driving aspects of each character, and reflect the significant drivers of the cost, schedule and requirements systems‘ interoperation success.

Table 9. SAIMM

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve

Note: The stability character also captures the legal requirement contained in Title 10 United States Code (U.S.C.) Section 2366b that "the technology in the program has been demonstrated in a relevant environment [commonly accepted as technology readiness level (TRL) 6]*, as determined by the Milestone Decision Authority on the basis of an independent review and assessment by the Director of Defense Research and Engineering"*

Summary

The SAIMM may be used to characterize the interoperability maturity of any space acquisition program by providing a framework informed by the acquisition failures of the past.

IV. Analysis and Results

Recent operations have once again illustrated the degree to which U.S. national security depends on space capabilities. We believe this dependence will continue to grow, and as it does, the systemic problems we identify in our report will become only more pressing and severe.

— *Mr. A. Thomas Young* (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003)

Chapter Overview

Using the OIM construct and INTERFET exercise, Ford's interoperability measurement provided insight into coalition nation interoperability. The SAIMM construct delivers a mechanism to do the equivalent for the space acquisition world. Space acquisition systems, *S = {cost, schedule, requirements},* can be characterized using the characters, *X = {mission focus, stability, discipline, realism},* and character states, *X = {0, 1, 2, 3, 4},* from SAIMM, which facilitates an interoperability measurement using Ford's method. In this chapter, several space acquisition programs will be evaluated for their acquisition systems' interoperability using SAIMM. A review of each evaluation will be used to explain the utility of the acquisition interoperability measurement.

It is important to note that some subjectivity was required when evaluating the programs in the following examples using SAIMM. Each SAIMM level includes multiple factors for evaluating a program's maturity. For example, the SAIMM Level 3 in the *stability* character requires that ―budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature." A program could have mature technology but suffer from requirements that frequently changed. The resulting SAIMM score in this character could fall somewhere between 1 and 3. In this and the following examples, the worst case score was generally chosen. Scoring was further influenced by the historical result and impact that the action or condition had on the program.

Advanced Extremely High Frequency (AEHF) System

The AEHF system, the replacement for the aging MILSTAR constellation of communications satellites, recently launched the first of four satellites into orbit. The prime contractor for the system is Lockheed Martin Space Systems Company (Sunnyvale California) and the payload provider is Northrup Grumman Aerospace Systems (Redondo Beach California). Lockheed Martin Space Systems Company was also the prime contractor on the legacy MILSTAR system.

AEHF was challenged by multiple launch slips and a Nunn-McCurdy breach in September 2008. At program inception, five satellites were to be delivered at an estimated cost of $5.4 billion. In 2003 the program scope had diminished to three satellites, but the total program cost remained at $4.8 billion (Government Accountability Office, 2003). This represents a growth in average per satellite cost by $570 million. The GAO cites several factors in the requirements, schedule and cost systems that led to AEHF‘s inability to meet its goals. The Department of Defense frequently altered requirements, pursued an overly aggressive, unrealistic schedule, and did not have the required funding to support the activities and manpower to design and build the satellites faster (Government Accountability Office, 2003).

Based on this evidence, it is clear that the major failures were primarily caused by poor interoperability in the *stability* and *realism* characters. Frequent requirement and design changes resulted in cost growth and schedule delays. Although the program utilized an experienced (incumbent) contractor with strong technical maturity, they pursued an incredibly aggressive schedule with inadequate funding. This unrealistic schedule and cost effectively severely compromised the overall system's ability to accomplish the requirements. The program's *mission focus* was also skewed in favor of schedule and cost. Therefore, the AEHF SAIMM is scored as follows:

Table 10. AEHF SAIMM, 2003

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve
	COST			
	SCHEDULE			
	REQUIREMENTS			

This SAIMM score results in the following instantiation of AEHF:

Table 11. AEHF Instantiation, 2003

AEHF (2003)	Mission Focus	Stability	Discipline	Realism
Cost	0	2	1	0
Schedule	0	2	1	1
Requirements	1	0	4	3

Recall that c_{max} represents the range of possible character states, n signifies the number of characters used to instantiate the systems, and r is ordinarily set to 2. Using Ford's Sim_{real} function where $r = 2$, $c_{max} = 4$, and $n = 4$, and assuming no self-interoperability, the interoperability measurement yields:

Table 12. AEHF Interoperability Measurement, 2003

AEHF (2003) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.191	0.138
Schedule	0.191	0.000	0.176
Requirements	0.138	0.176	0.000

The AEHF program was again, albeit briefly reviewed by the GAO roughly five months before the program's first launch in August of 2010. The report provided several morsels of new evidence that can be used to update the program's interoperability measurement from 2003. The program made significant progress since the 2003 GAO report, but it came at the expense of hundreds of millions of dollars in cost growth and multiple launch slips representing approximately four years of delay. The program achieved strong *stability* and *discipline* in the requirements system, and maintained solid maturity across the remaining systems and characters. The SAIMM for AEHF at this point is as follows:

Table 13. AEHF SAIMM, 2010

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve
	COST			
	SCHEDULE			
	REQUIREMENTS			
	COST, SCHEDULE & REQUIREMENTS			

Which results in the following interoperability instantiation:

Table 14. AEHF Instantiation, 2010

AEHF (2010)	Mission Focus	Stability	Discipline	Realism
Cost	3	3	3	3
Schedule	3	3	3	3
Requirements	3	4	4	3

Using Ford's Sim_{real} function where $r = 2$, $c_{max} = 4$, and $n = 4$, and assuming no self-interoperability, the interoperability measurement yields:

Table 15. AEHF Interoperability Measurement, 2010

AEHF (2010) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.750	0.669
Schedule	0.750	0.000	0.669
Requirements	0.669	0.669	0.000

National Polar-Orbiting Operational Environmental Satellite (NPOESS)

NPOESS was a tri-agency program (Department of Commerce, National Air and Space Administration, and the Department of Defense) that suffered through numerous setbacks. Originally scheduled to launch in 2006, the program was restructured in 2007 due to a Nunn-McCurdy breach, and its first satellite, known as the NPOESS Prepatory Project, is now scheduled to launch in late 2011 (Government Accountability Office, 2010). Earlier this year the program was cancelled and split into separate Department of Commerce and Department of Defense programs. The prime contractor for NPOESS was Northrop Grumman Aerospace Systems (Los Angeles, California) who also had significant experience building the DOD‘s legacy weather satellite, the Defense Meteorological Satellite Program.

In 2009, an independent review team was commissioned by the NPOESS Executive Committee to review the program‘s management approach and to determine key issues and risks. The review team was chaired by Mr. Tom Young, who was also the chair of the 2003 Defense Science Board review team, and based on their findings (NPOESS Independent Review Team, 2009), the NPOESS program demonstrated significant issues across all of the major acquisition systems as manifested heavily in the *mission focus* and *stability* characters. Cost and schedule took priority over mission success, budgets were inadequate, the management team lacked experience, and the program's requirements were in conflict due to the tri-agency management structure. The resulting SAIMM score:

Table 16. NPOESS SAIMM, 2009

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve
	COST			
	SCHEDULE			
	REQUIREMENTS			

Which yields the following NPOESS instantiation:

Table 17. NPOESS Instantiation, 2009

NPOESS	Mission Focus	Stability	Discipline	Realism
Cost	0	2	1	2
Schedule	1	2	1	1
Requirements	1	0	2	1

Using Ford's Sim_{real} function where $r = 2$, $c_{max} = 4$, and $n = 4$, and assuming no self-interoperability, the interoperability measurement yields:

Table 18. NPOESS Interoperability Measurement, 2009

NPOESS - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.257	0.188
Schedule	0.257	0.000	0.203
Requirements	0.188	0.203	0.000

Space-Based Infrared System (SBIRS) High

In the early 1990s, the DOD embraced a Total System Performance Responsibility (TSPR) approach for system acquisitions. In theory, TSPR allowed the government to leverage existing contractor management and commercial practices with minimal oversight by turning government-led functions over to the contractor. In 1996, the SBIRS program was initiated and Lockheed Martin was selected as the prime contractor with Northrup Grumman as their major subcontractor. Northrup Grumman was both the prime contractor and sensor developer for the legacy Defense Support Program. Despite this legacy experience, the program generated expansive cost and schedule failures. By the fall of 2001, SBIRS had an estimated cost growth in excess of $2 billion (Government Accountability Office, 2003). After three Nunn-McCurdy violations, problems on the SBIRS program have persisted to the present day as manifested by a 200% change in total program cost and a unit cost growth of nearly $2.5 billion (Government Accountability Office, 2010).

The program instituted several independent reviews while the GAO continued to monitor the program‘s progress against cost, schedule and performance goals. Three reports were issued in 2003, 2005 and 2008 that capture various findings from independent reviews, the GAO and others. The causes for the program‘s cost growth, schedule delays and performance issues are often attributed to the TSPR-model, but a deeper examination is required to root out the specific causes of a ―troubled program that could be considered a case study for how not to execute a space program" (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003).

The 2003 GAO report was issued after the program restructured in 2002. The GAO determined that significant cost and schedule risk remained despite the restructuring. From an acquisition system interoperability perspective, the SBIRS High program had fatal flaws across all of the interoperability characters in each system. At this point in time, the program moved ahead despite numerous best practice violations in all characters. Requirements were not well understood and the overall complexity of the program was underestimated. The management team was unable to deal with this untenable situation, which resulted in ―the Program Office and contractor having to spend 25 of the first 60 months of the contract on replanning activities" (Government Accountability Office, 2003). The 2003 Defense Science Board summarized the core issue, ―In short, SBIRS High illustrates that while government and industry understand how to manage challenging space programs, they abandoned fundamentals and replaced them with unproven approaches that promised significant savings. In so doing, they accepted unjustified risk" (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003). The following SAIMM results:

Table 19. SBIRS SAIMM, 2003

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve
	COST			
	SCHEDULE			
	REQUIREMENTS			

Which yields the interoperability instantiation of:

Table 20. SBIRS Instantiation, 2003

SBIRS (2003)	Mission Focus	Stability	Discipline	Realism
Cost	1	1	1	0
Schedule	0	1	1	1
Requirements	1	0	0	0

Using Ford's Sim_{real} function where $r = 2$, $c_{max} = 4$, and $n = 4$, and assuming no self-interoperability, the interoperability measurement yields:

Table 21. SBIRS Interoperability Measurement, 2003

SBIRS (2003) - Sim_{Real}	Cost	Schedule	Requirements
Cost	0.000	0.154	0.103
Schedule	0.154	0.000	0.094
Requirements	0.103	0.094	0.000

In 2005, many of the GAO‘s concerns were realized as the program continued to experience difficulties. During this period, the Secretary of Defense was directed by Congress to provide a report ―on the cause of the most recent SBIRS cost increases, schedule delays, and technical problems; the most recent Defense Support Program gap analysis and any effect that further delays will have on U.S. early warning, technical intelligence, and missile defense capabilities; steps taken to address the most recent SBIRS technical difficulties; any adjustments in management and contract arrangements with the contractor to reflect the most recent program challenges; remaining risk areas; and an assessment of the confidence level in the SBIRS schedule and cost estimates current as of October 1, 2004" (Office of the Secretary of Defense, 2005). The subsequent report cited a lack of ―sound system engineering processes and procedures…insufficient schedule and budget…process escapes" and ―an inadequate architecture design and a flawed flight software development plan" (Office of the Secretary of Defense, 2005). The report also cites several program initiatives designed to ―better focus resources on key program issues," and to ―formally adopt an ‗event-driven‘ approach, replacing the ‗schedule-driven‘ mentality of the past…ensures the program no longer enters an activity unless the probability for success is high" (Office of the Secretary of Defense, 2005). Adjustments to the program‘s business rhythm, testing activities, and contract were also noted. These findings do not represent a major improvement in the SBIRS program however as the findings from 2003 were either realized or persisted. As such, there is not enough evidence presented in the 2005 report to significantly alter the interoperability measurement from 2003.

Fast forward to 2008; SBIRS has just experienced a major setback with its flight software and the GAO once again warns against an ―ambitious,” even ―optimistic” plan to resolve the problems. The 2008 GAO report found that the issues largely stemmed from the program‘s test and evaluation area, however it is more important to examine the GAO‘s assessment of the program‘s plan going forward. With respect to the flight software issue, significant interoperability issues remained in the *mission focus, discipline* and *realism* characters. Cost and schedule estimates were overly optimistic, and there was little to no margin to react to more problems if they occurred. The program also requested waivers to forgo ―disciplined processes,” which marginalized mission assurance (Government Accountability Office, 2008).

Just prior to the GAO report, in 2007, another independent review team was commissioned to review the program‘s status. The following chart summarizes the program‘s progress against this independent review team‘s findings and recommendations:

Table 22. Independent Program Assessment (Government Accountability Office, 2008)

Table 2: IPA Findings, Recommendations, and Status of Implementation

Finding	Recommendation	Implemented? (as of April 2008)
1. Lockheed Martin's program process discipline is poor	• Engage Lockheed Martin functional areas and ensure that processes are being followed	Yes
2. Air Force has limited management control over SBIRS	• Amend contract to provide necessary management control	Yes
3. Adversarial relationships exist between Air Force and Lockheed Martin	• Fix responsibility, accountability, and authority disconnects	Yes
4. Government organizational structure is flawed because cost and schedule responsibilities are separated.	• Combine in a single office the review of contractor cost and schedule data	Yes
5. Focal point for FSS completion is needed	• Designate a program manager within flight software system • Establish giver/receiver relationships	Yes

Source: Aerospace Corporation (data) and U.S. Air Force (data); GAO (analysis and presentation).

This table indicates the program has improved interoperability between the cost and schedule systems, as well as between the government and contractor team. Based on the 2007 independent review team‘s findings and the 2008 GAO report, there is sufficient evidence to update the program‘s SAIMM and interoperability measurements.

Table 23. SBIRS SAIMM, 2008

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve
	COST			
	SCHEDULE			
	REQUIREMENTS			

Which yields the following instantiation:

Table 24. SBIRS Instantiation, 2008

SBIRS (2008)	Mission Focus	Stability	Discipline	Realism
Cost	1	2	3	2
Schedule	0	2	3	2
Requirements	1	3	2	1

Using Ford's Sim_{real} function where $r = 2$, $c_{max} = 4$, and $n = 4$, and assuming no self-interoperability, the interoperability measurement yields:

Table 25. SBIRS Interoperability Measurement, 2008

SBIRS (2008) - Sim $_{Real}$	**Cost**	**Schedule**	**Requirements**
Cost	0.000	0.410	0.367
Schedule	0.410	0.000	0.328
Requirements	0.367	0.328	0.000

The GAO provided a brief assessment of the SBIRS High program again in 2010 and noted that ―all three critical technologies…are now mature” and ―99 percent of the…expected design drawings are now releasable,” but also cited ―design-related problems” and an assessment of cost and schedule as ―high risk” (Government Accountability Office, 2010). This update delivers an adequate amount of new information to update the program‘s SAIMM. The program has matured significantly in the *mission focus* character, but continues to suffer from a lack of *realism*. *Stability* has improved to a lesser degree as the maturity of the design and requirements is high, but *discipline* remains unchanged due to continued problems and unknowns with the flight software, and an apparent inability to control and plan the remaining work required. The 2010 GAO assessment yields the following SAIMM:

Table 26. SBIRS SAIMM, 2010

	MISSION FOCUS	STABILITY	DISCIPLINE	REALISM
Level 4 - Accordant	Mission success is weighted significantly higher than cost and schedule; its priority is reflected in risk management, test planning, system engineering, and funding profiles	Stable budgets, stable requirements, stable direction, and low personnel turnover are maintained across the board; program decisions are constant; technology is mature (TRL 7 or higher)	The acquisition team is experienced (previous experience on the legacy program as a prime contractor) and maintains strict adherence to proven programmatic and system engineering processes	Program estimates are independently verified and accomplished in a timely, realistic, and complete manner; minimal rework is required; program funding and management reserve is realistic (80/20 cost confidence with 25% management reserve)
Level 3 - Associated	Mission success is weighted higher than cost and schedule	Budgets, requirements, direction and personnel turnover rarely change and remain stable in critical areas; program decisions rarely change; technology is sufficiently mature (TRL 6)	The acquisition team is experienced (previous experience on the legacy program as a major subcontractor) and maintains adherence to proven programmatic and system engineering processes	Program estimates are independently verified; rework is rarely required; program funding is unrealistic (between 80/20 and 50/50 cost confidence) with realistic management reserve (20% or greater)
Level 2 - Structured	Mission success is weighted equally to cost and schedule	Budgets, requirements, direction or personnel turnover change occasionally in a few minor areas; program decisions change occasionally; technology requires maturation (TRL 5)	The acquisition team has some experience (previous experience on a similar program as a subcontractor) and utilizes proven processes in most areas	Program estimates are independently verified but unrealistic in a few minor areas; rework is occasionally required; program funding is unrealistic (50/50 cost confidence) with realistic management reserve (20% or greater)
Level 1 - Aligned	Cost and schedule are weighted higher than mission success	Budgets, requirements, direction or personnel turnover change frequently in several critical areas; program decisions change frequently; technology requires significant maturation (TRL 4)	The acquisition team has limited experience (previous experience on a portion of a similar program) and has knowledge of proven processes but does not use them consistently	Program estimates are unrealistic in several critical areas; rework is frequently required; program funding is unrealistic with inadequate (less than 20%) management reserve
Level 0 - Separated	Cost and schedule are weighted significantly higher than mission success	Budgets, requirements, direction and personnel turnover continually change in many critical areas; program decisions continually change; technology is not mature (TRL 3)	The acquisition team has no experience (first-ever program) and does not have access to proven processes (they do not exist)	Program estimates are unrealistic and focused on program advocacy; rework is continually required; program funding is unrealistic with little or no management reserve
	COST			
	SCHEDULE			
	REQUIREMENTS			
	COST, SCHEDULE & REQUIREMENTS			

Resulting in the following interoperability instantiation:

Table 27. SBIRS Instantiation, 2010

SBIRS (2010)	Mission Focus	Stability	Discipline	Realism
Cost	3	3	3	1
Schedule	3	3	3	1
Requirements	3	4	2	1

Using Ford's Sim_{real} function where $r = 2$, $c_{max} = 4$, and $n = 4$, and assuming no self-interoperability, the interoperability measurement yields:

Table 28. SBIRS Interoperability Measurement, 2010

SBIRS (2010) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.625	0.515
Schedule	0.625	0.000	0.515
Requirements	0.515	0.515	0.000

Interpreting the Results

The interoperability measurements for AEHF, NPOESS and SBIRS High demonstrate how the SAIMM can be used to measure a space acquisition program‘s interoperability maturity, and then measure interoperability between its major systems. The measurements also show how the interoperability can change over time and with respect to program phases. A specific tie between the interoperability measurement and actual cost, schedule and requirements performance has not been directly established, but is indirectly captured by using the examples of the past. Therefore, it is reasonable to assume that a measurement of a failed program‘s interoperability can provide a baseline from which to compare other programs‘ interoperability and chance of success or failure.

For AEHF, interoperability measurements were provided in 2003 and 2010. According to GAO reports, during that time the program‘s overall cost nearly doubled from 4.8 to 10.4 billion dollars and the predicted launch date slipped approximately four years. The interoperability measurements also exhibit dramatic differences:

Table 29. AEHF Interoperability Measurement, 2003

AEHF (2003) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.191	0.138
Schedule	0.191	0.000	0.176
Requirements	0.138	0.176	0.000

Table 30. AEHF Interoperability Measurement, 2010

AEHF (2010) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.750	0.669
Schedule	0.750	0.000	0.669
Requirements	0.669	0.669	0.000

The program launched shortly after the 2010 interoperability measurement was taken. It is expected that a program's interoperability measurement will converge to 1 as it approaches a launch since most of the mandatory reviews and maturity gates for the program will have been passed. Accordingly, an increase in the program's measure of interoperability indicates an increase the program's mission readiness.

The NPOESS program experienced extreme difficulties and was eventually cancelled as a result. According to GAO records, the program cost estimate was 6.1 billion dollars in 2003, but ballooned to 13.1 billion dollars in 2010. During this same period, the predicted launch date moved from 2009 to 2014. The 2003 NPOESS interoperability scores are reasonably close to the 2003 AEHF scores, and point toward significant program issues and a severely hampered ability to achieve cost, schedule and performance goals.

Table 31. NPOESS Interoperability Measurement, 2009

NPOESS - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.257	0.188
Schedule	0.257	0.000	0.203
Requirements	0.188	0.203	0.000

The SBIRS High program is a notorious example of inability to meet cost, schedule and performance goals. Between 2003 and 2010, the program's cost grew by

5.1 billion dollars and the launch date slipped approximately four years. Unit cost grew by almost two billion dollars. The program's interoperability scores were lower than both the AEHF and NPOESS scores in 2003 due to severe problems across all interoperability characters:

Table 32. SBIRS Interoperability Measurement, 2003

SBIRS (2003) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.154	0.103
Schedule	0.154	0.000	0.094
Requirements	0.103	0.094	0.000

In 2008, the program improved in three out of four areas, but continued to place mission success at risk due to cost and schedule goals and constraints. The program was readying for launch, but the interoperability scores did not exhibit a level of interoperability maturity comparable to AEHF just prior to its launch in 2010:

Table 33. SBIRS Interoperability Measurement, 2008

SBIRS (2008) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.410	0.367
Schedule	0.410	0.000	0.328
Requirements	0.367	0.328	0.000

This difference in interoperability maturity reflects the substantial risks and issues remaining on the program. In 2010, the program continued to experience problems due to flight software issues. The GAO and other independent estimates stressed a lack of realism in the program's ability and plan to resolve the problem. Despite a marked increase in the *mission focus, stability* and *discipline* characters, the program remained less interoperable in the *realism* character. The interoperability scores again indicated improvement, but did not reach the same level as AEHF just prior to their launch:

Table 34. SBIRS Interoperability Measurement, 2010

SBIRS (2010) - Sim $_{Real}$	Cost	Schedule	Requirements
Cost	0.000	0.625	0.515
Schedule	0.625	0.000	0.515
Requirements	0.515	0.515	0.000

The SBIRS High program now projects a launch date in early 2011.

These high-level correlations between a program's interoperability score and its resulting performance reveal the interoperability measurement's ability to serve as a leading indicator for space acquisition success or failure. The measurement also provides insight into where interoperability can be improved to increase chances of program success.

Summary

A method to measure space acquisition interoperation, using system interoperability, was developed based upon Ford's interoperability measurement work. The measurement was facilitated by a maturity model that was built using the lessons learned and best practices from space acquisition failures of the past. The method measured interoperability between space acquisition systems, *S = {cost, schedule, requirements}*, using key and driving acquisition characters, *X = {mission focus, stability, discipline, realism}* based on five character state levels, *C = {separated, aligned, structured, associated, accordant}*, and applied to three specific acquisition programs. The resulting measurements were then compared to demonstrate how the method can be used as a leading indicator of the program's ability to execute the required level of performance on time and within budget.

V. Conclusions and Recommendations

...a host of problems not previously viewed as interoperability related can now be looked at as such. This means that many old problems can be solved in a new way, possibly lending insight or providing a means of reporting progress not previously available.

—Thomas C. Ford (Ford, 2008)

This is a logical and progressive evolution in warfare, yet its tenets remain undemonstrated and unproven…The network-centric warfare objective needs further investigation and technological exploitation for it to be…a workable system.

—Lt. Col. Edmund C. Blash, USAR (Blash, 2003)

Conclusions of Research

Ford's interoperability measurement using a maturity model is indeed a powerful tool that can be used to measure the quality of acquisition system interactions. As Ford notes, ―Sim_{Real} has the capability of yielding very precise similarity measures of system instantiations limited only by the number of characters and the precision of those characters' states" (Ford, 2008). In this case, the maturity model dictates the number and precision of characters. The SAIMM was built upon experts' analysis of past space acquisition failures and their recommendations for improvement. In other words, the SAIMM captures the specific system attributes that must be present and mature in order for a program to avoid the mistakes of past space acquisition programs. These attributes are universal and may be applied to any major space acquisition program, but the model's precision suffers as a result. As such, a SAIMM facilitated interoperability measurement is best used on a macro level to gage a program's health and status.

The SAIMM is principally based upon the lessons learned from space acquisition program failures, and does not consider expert analysis of programs that were deemed successful. Finding examples of program successes is extremely difficult due to the extent and complexity of space acquisition programs, and little, if any expert analyses exist in the publically available literature. The SAIMM is valuable because it is based on the cause and effect of real-world events, but it is important to note that SAIMM is rooted in lessons learned almost exclusively from programs that failed to meet their goals. Future versions of the SAIMM or similar models must strive to capture and incorporate evidence from program successes to improve the robustness and richness of the model.

In conclusion, the concept of acquisition interoperability was described and linked to program success or failure by utilizing a maturity model based upon past space acquisition experience. The method was demonstrated by measuring the interoperability between the cost, schedule and requirement systems in three major space programs during various acquisition phases. The results were compared to validate the utility of the method as a potential leading indicator of space acquisition success or failure. LTC Blash's caveat must be heeded however; "further investigation" is indeed required to mature the model and understand the relationship between interoperability and program performance before it can be used as an effective space acquisition metric.

Recommendations for Future Research

Ford states that "The flexibility of the method supports the instantiation of systems at any level of abstraction, with resultant interoperability measurements at any desired level of precision." The SAIMM and resulting interoperability measurements are captured at a very high level of abstraction and should only be used at the macro level. Future research is needed to increase the depth and breadth of the SAIMM in order to enable a more precise measurement. As alluded to earlier, the bulk of the publically available knowledge on space acquisition focuses on programs that have or are currently not meeting their cost, schedule and performance targets. Very few analyses of ―successful" space acquisition programs have been conducted, and the addition of lessons learned based on successful programs will improve the SAIMM's ability to properly characterize a space program's acquisition interoperability. Additionally, the bulk of the information used to build the SAIMM was supplied by the GAO and independent review teams led by Mr. Tom Young. Although extremely valuable, there are other sources of data that can be used to improve the SAIMM's precision. This may limit the ability of the material to be publically released, but would still provide benefit to most government entities.

Further research must also consider the fundamental building blocks of SAIMM and the interoperability measurements used in this thesis. Additional systems and characters, to include the way they are captured in the model itself, can mature the SAIMM for both generic and specific purposes. Further decomposition of the cost, schedule and requirements systems could improve the precision of the SAIMM. For example, the requirements system could be broken into the requirements (user-centric) and design (program office-centric) systems. The purpose and context of the measurement, as well as increased knowledge of lessons learned will reveal new and important characters for consideration. The interoperation between the cost, schedule and requirement's systems *processes*, *methods* and *tools* should be considered, as well as the influence of the systems' interoperation in the *flexibility* and *transparency* characters.

It is also recommended that future research further leverage the benefit of hindsight to solidify and better quantify the relationship between acquisition system interoperability and a program's cost, schedule and performance. One possible way to do this would be to build a baseline of interoperability measurements across many space acquisition programs during various acquisition phases. This baseline of interoperability measurements could then be compared to the actual cost, schedule and mission performance of the programs to infer a cost per unit of interoperability metric. A simple example might consider how much a program's interoperability improved or declined between systems, and how much cost, schedule or performance was impacted as a result. This effort would likely require extensive analysis and a more precise SAIMM in order to produce meaningful results.

An analysis of how the program's acquisition phase and context affects the interoperability measurement and program performance would also serve as a valuable contribution to this area of research. Ford states (Ford, 2008):

> Interoperability is generally time variant. For example, atmospheric effects due to the changes from night to day will degrade the optical interoperability of reconnaissance satellites and ground targets. Similarly, the directional interoperability of an attacker and his target may increase as the attacker has ingressed long enough to come in range of the target. Finally, end-to-end computer interoperability may improve or diminish with changes in network congestion tied to worker shift changes, lunchtime usage, etc.

Within the context of space acquisitions, it is important to consider how the interoperability characters vary in time based on the program's acquisition phase. For instance, the character *stability* may prove to be more valuable later in a program's life than earlier. It should also be recognized that the characters selected for the SAIMM may not adequately capture the interoperability needs across the program's acquisition lifecycle. Additional characters may need to be developed to fully portray the key and driving interoperability factors during each phase of the acquisition program.

The concept above could be expanded to include statistical predictions based upon the baseline of past space acquisition experience. Distribution models or Monte Carlo analysis could be used to correlate interoperability measurements against actual program performance. A series of probability curves or other tools could then link a measurement of a current program's acquisition system interoperability to a probability of success or failure, i.e. program x's interoperability score of y between the cost and schedule systems indicates the program has a 65% chance of exceeding its current budget.

Finally, it is recommended that prospective research consider how the acquisition interoperability measurement be incorporated into a larger framework of metrics, most likely driven by the "Systems Engineering Leading Indicators Guide" referred to earlier.

Summary

This research combines the power of Ford's interoperability measurement with the lessons harvested from decades of space acquisition experience, and as such, is inherently tied to overall acquisition effectiveness. It provides a way to characterize a program's health by measuring its ability to interoperate between the cost, schedule and requirements systems. The measurement can be used as a leading indicator of program performance, a guide to locate and solve issues, and can be tailored for use in many different contexts and situations.

There appears to be great utility and power in this measurement, but much work remains to be done in order to operationalize it. The institutions responsible for space program execution, and more importantly, delivering capability to the warfighter and our nation, must continue to foster and invest in ways to measure and improve programmatic and system engineering rigor.

Appendix A – Independent Assessments of AEHF, NPOESS and SBIRS High

In 2003, the GAO assessed the AEHF program's status as follows (Government Accountability Office, 2003):

> 2003 GAO reported in the early phases of the program, DOD substantially and frequently altered its requirements; the system design changed. While considered necessary, some changes increased costs by hundred of millions of dollars and caused scheduling delays.
>
> 2003 GAO reported that once DOD decided to accelerate its plans to build the satellites, the contractors proposed and DOD agreed to support a high-risk schedule that turned out to be overly optimistic and highly compressed—leaving little room for error and depending on a chain of events taking place at certain times. Substantial delays occurred when some events, such as the award of the contract or the availability of equipment, did not occur on time. In commenting on the AEHF report, DOD noted the decision to accelerate the program was based on a satellite constellation gap caused by the loss of a Milstar satellite. DOD also stated many in DOD expressed concern about the risks, but believed the risk was acceptable based on information known at the time.
>
> 2003 GAO reported that at the time DOD decided to accelerate the program, it did not have the funding needed to support the activities and manpower needed to design and build the satellites quicker. The lack of funding also contributed to schedule delays, which in turn, caused more cost increases.
>
> 2003 GAO reported that the program demonstrated most technology knowledge at development with 11 of 12 critical technologies having reached maturity according to best practice standards. However, the program office did not project achieving maturity on the remaining technology—the phased array antenna— by the design review in June 2004 and did not have a backup capability. Program officials assessed the software development for the mission control system as moderate risk and have developed a risk mitigation strategy. However, until these mitigation actions are completed, software may be at risk for unplanned cost and schedule growth.
>
> 2003 GAO reported that significant design changes affected cost and delayed the AEHF schedule. For example, software growth occurred as more requirements were added and as the design of the system stabilized. These increases in software requirements for both the satellite and the mission control segments increased the software cost estimate by over 77 percent or about $223 million.

The GAO provided a brief synopsis of the AEHF program's status just prior to the launch of AEHF-1 in August of 2010 (Government Accountability Office, 2010):

> According to the program office, all 14 AEHF critical technologies are mature, with all either flight- qualified through test and demonstration or flight- proven through successful mission operations. System-level environmental testing for the first satellite was completed in July 2009. The AEHF's design appears stable with all of its expected design drawings released.
>
> …during initial system level environmental testing for the first and second satellites, several flight boxes experienced failures due to defective components that required removal, repair, and reinstallation. Because of the number of components that had to be removed and reinstalled, the first satellite had to undergo an additional round of system-level environmental tests. These actions delayed the first launch almost 2 years and increased program cost. According to the program office, the additional testing was successfully completed in July 2009. The second satellite also completed system level environmental testing in 2009, and no new problems or issues were discovered.

An independent review team, led by Mr. Tom Young, assessed the NPOESS program in 2009 (NPOESS Independent Review Team, 2009):

> The priorities of NOAA, NASA and DOD/USAF are not aligned: The DOD has stated that while the program should continue to pursue the current NPOESS requirements, the DOD is willing to accept legacy performance (DMSP and POES) to maintain continuity, cost and schedule goals and is not willing to provide additional funding to pursue requirements beyond legacy. NOAA states that legacy performance would be a step back in today's performance because of their current operational use of NASA research satellites that are well beyond their design life
>
> NPOESS is being managed with cost as the most important parameter: One observation of this cost priority is reflected in the award fee structure and its emphasis on cost control. Successful space acquisition requires mission success to be the top priority not cost as the overarching factor
>
> The PEO and IPO do not have sufficient space systems acquisition expertise and processes: The NPOESS program is not part of a supporting space systems acquisition center, such as the AF Space and Missile Systems Center (SMC) or the NASA Goddard Space Flight Center (GSFC). These types of established space acquisition organizations can provide institutional knowledge, robust infrastructure support, and a cadre of seasoned space systems acquisition experts

Funding shortfalls are causing the IPO to make short-sighted decisions to cover VIIRS cost growth and stay within allocated budget at a significant increase to outyear costs and program risks: While the IPO has no choice but to make these decisions, risk is being deliberately built into the program to stay within allocated budget.

The current budget is inadequate: Budgeting to a 50-50 cost estimate leads to insufficient funding. It lacks sufficient management reserve, and as noted in Finding #6, this leads to programs using risk as its management reserve. The current budget is not at the 50/50 level. The most probable cost is at the 80/20 level including reserves

The SBIRS program has been reviewed numerous times by the GAO and other entities. The 2003 GAO report lists the following findings (Government Accountability Office, 2003):

History of moving forward without sufficient knowledge to ensure that the product design is stable and meets performance requirements and that adequate resources are available

The program passed its critical design review with only 50 percent of its design drawings completed, compared to 90 percent as recommended by best practices. Consequently, several design modifications were necessary, including 39 to the first of two infrared sensors to reduce excessive noise created by electromagnetic interference—a threat to the host satellite's functionality—delaying delivery of the sensor by 10 months or more

The program was too immature to enter the system design and development phase. Program activation was based on faulty and overly optimistic assumptions about software reuse and productivity levels, the benefits of commercial practices, management stability, and the level of understanding of requirements.

The complexity of developing engineering solutions to meet system requirements was not well understood by program and contracting officials. The systems integration effort was significantly underestimated in terms of complexity and the associated impacts. In addition, the requirements refinement process was ad hoc, creating uncertainty on the status of program priorities and affecting cost and schedule.

Breakdown in execution and management. Overly optimistic assumptions and unclear requirements eventually overwhelmed government and contractor management. The 2-year delay of the GEO satellite launches, which occurred in 1998, contributed to management instability and was a factor in the Program Office and the contractor having to spend 25 of the first 60 months of the contract on replanning activities.

The Department of Defense was tasked by Congress to provide a report on the SBIRS High program's status in 2005 (Office of the Secretary of Defense, 2005) which listed the following findings:

> Latent defects, resulting from insufficient product assurance activity in earlier design and production activities…lack of sound system engineering processes and procedures
>
> Insufficient schedule and budget to ensure robust GEO first article integration/ test…insufficient time scheduled for GEO system integration and test; SPO concluded the ground software productivity levels were optimistic; the flight software architecture was not sufficiently defined to allow software coding; and inadequate on-orbit checkout time was planned. Finally, the resources and tools for simulations, analysis, and troubleshooting were inadequate and required more effort
>
> Process escapes due to human error/insufficient training/fragile processes…improper or inadequate processes, insufficient training, questionable inspection practices, and/or human error as causal factors. Recent events include excess debris or contamination in delivered hardware, improper use of soldering materials, improper installation of thermal blankets, and missing test procedure documentation
>
> A poor design and build implementation to comply with the EMI specifications of the HEO P/L…flawed design approach
>
> Faulty hardware and software design of the HEO/GEO flight computers, i.e., the single board computer _halt' anomalies…hardware design problem with a control signal on an Application-Specific Integrated Circuit (ASIC)
>
> An inadequate architecture design and a flawed flight software development plan for the GEO satellite's Signal Processing Assembly (SPA)…state of the software architecture, a very aggressive contractor schedule, and inadequate planning

The GAO again assessed the SBIRS High program in 2008 following a setback with the program's flight software (Government Accountability Office, 2008):

> While DOD has estimated that the SBIRS program will be delayed by 15 months and cost $414 million to resolve the software problems, those estimates appear too optimistic, given the cost and schedule risks involved. For example, SBIRS contractors' report low confidence that software can be produced in time to meet the December 2009 satellite launch goal. Further, DOD and the contractor face significant challenges and risks that could result in more time and money being required to meet program goals, to include the bypassing of some disciplined software practices that add risk to cost and schedule. Finally, as of August 2008, DOD reported that SBIRS was already behind schedule on some software development efforts, and thousands of activities remain that must be integrated and tested across various systems, with cost and schedule implications, if problems or unintended consequences occur.

The GAO's annual assessment of selected programs revealed a higher level of technical maturity for SBIRS High, but still maintained concerns about the ability of the program to adhere to its cost and schedule (Government Accountability Office, 2010):

> The SBIRS High program began system development in 1996 with none of its three critical technologies mature. All three critical technologies—the infrared sensor, thermal management, and on-board processing—are now mature and have been demonstrated in at least a relevant environment. Furthermore, according to the program office, the HEO sensor's on-orbit performance instills confidence that the GEO infrared scanning sensor will work as intended.
>
> According to program officials, 99 percent of the SBIRS High expected design drawings are now releasable. However, the program continues to experience design-related problems, and more could emerge. For example, flight software design problems have plagued the program for several years, causing cost increases and schedule delays, and the program may still be underestimating the amount of work that remains to resolve the issues.
>
> According to the Defense Contract Management Agency (DCMA), unplanned work continues to be a challenge for the software development effort and its cost and schedule have been assessed as high risk.
>
> The SBIRS High program remains at high risk for cost and schedule growth. DCMA is currently projecting over $245 million in cost overrun from the current baseline at contract completion. This amount has more than doubled in the past year and continues to steadily grow.
>
> Additional contractor cost increases and schedule delays are expected due in part to hardware rework on the first satellite, continued difficulty with the flight

software development, and delays in integration and test activities. The program‘s management reserve— funds set aside to address unanticipated problems— will likely be depleted before the first GEO satellite launches, and additional funding could be required if future problems occur. Additional schedule delays could also occur since meeting current launch estimates depends on the results of system-level integration tests.

According to the program office, the first GEO integrated payload and spacecraft successfully completed thermal vacuum (TVAC) testing in November 2009. Program officials say these testing results give them high confidence that the GEO satellite will perform similarly to the successful HEO sensors, noting that HEO TVAC test performance differed only slightly from its on-orbit performance.

Program officials say that although technical issues discovered during testing have increased program cost, parallel activities have actually minimized program cost and schedule growth. They further stressed that mission assurance remains their top priority.

Appendix B – Space Acquisition Cost and Schedule Challenges

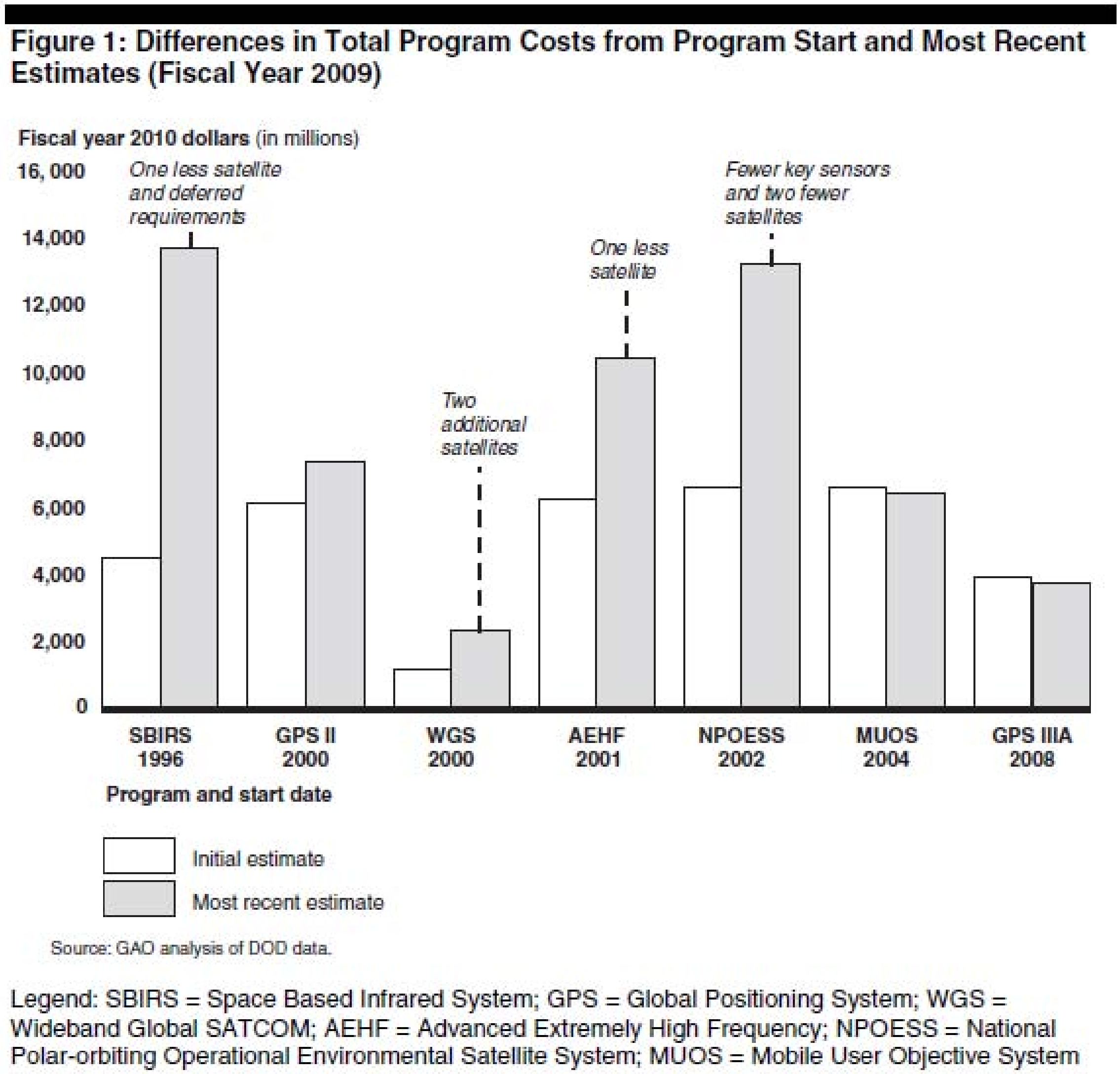
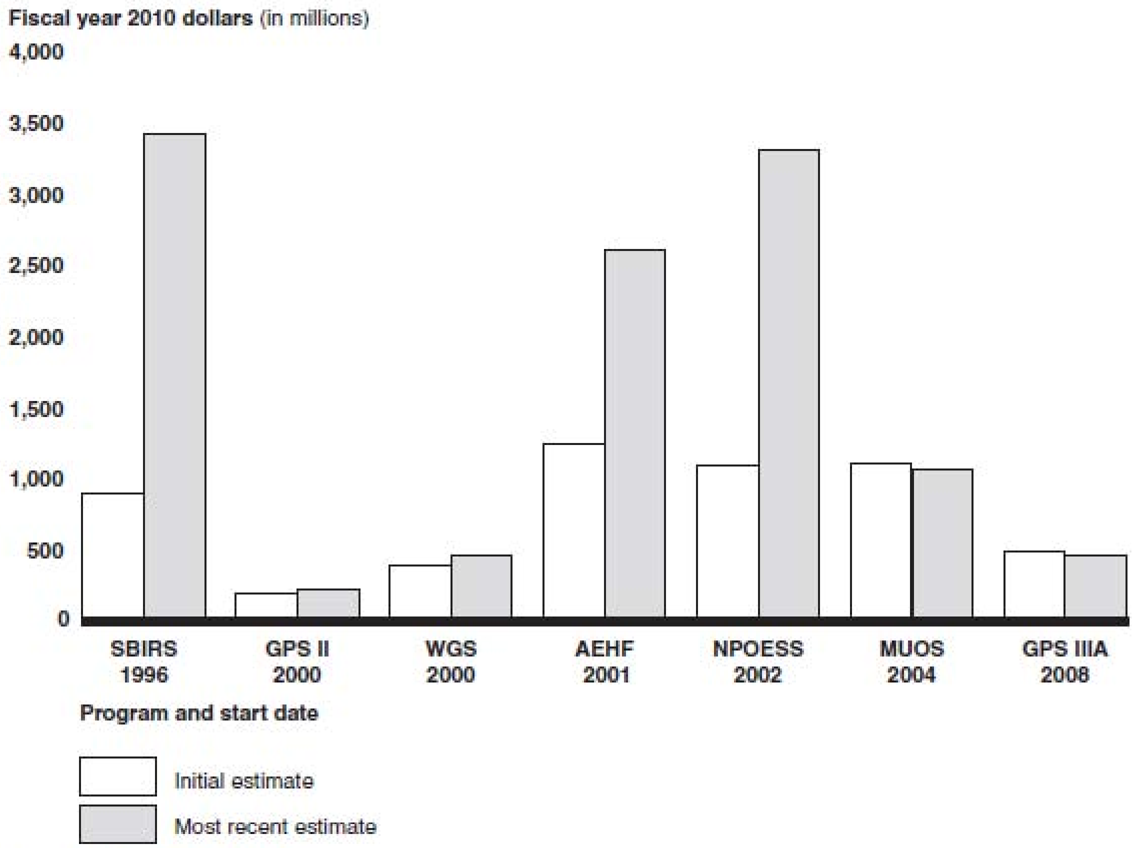


Figure 8. Space Program Cost Growth (Government Accountability Office, 2010)

Figure 2: Differences in Unit Costs from Program Start to Most Recent Estimates (Fiscal Year 2009)

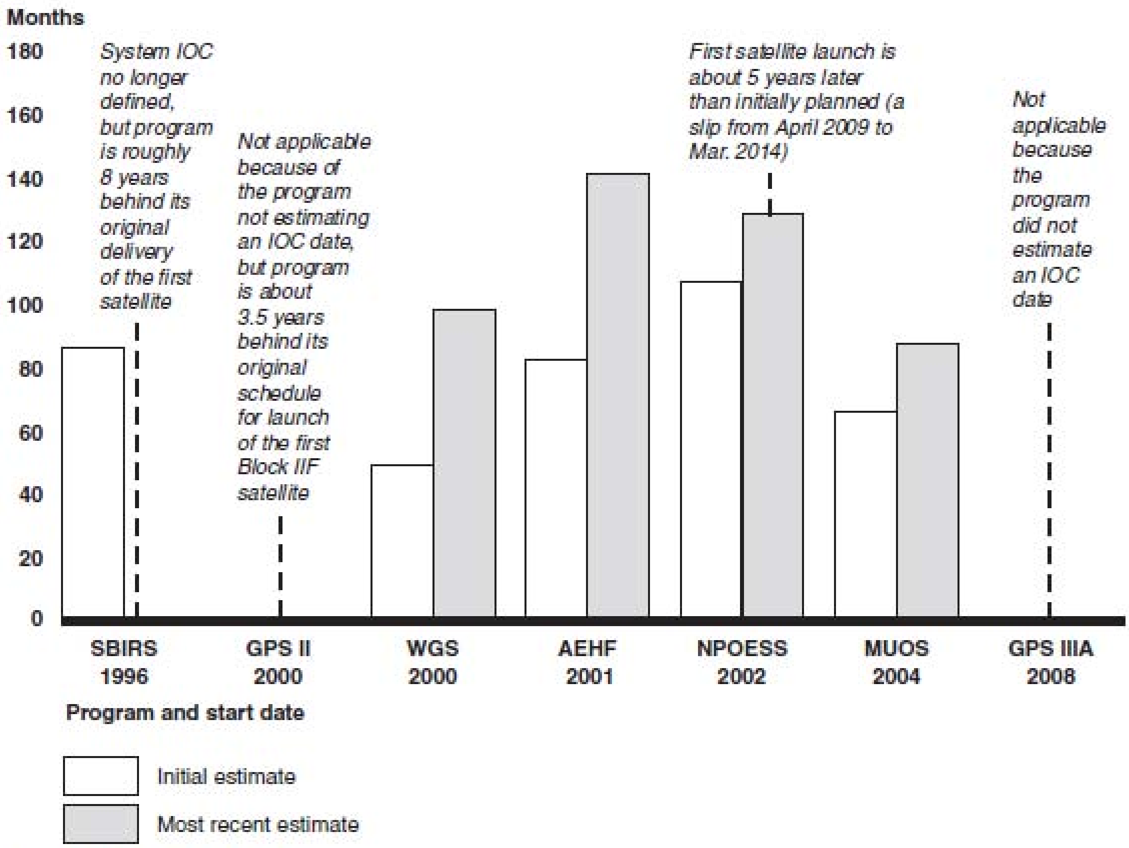


Source: GAO analysis of DOD data.

Legend: SBIRS = Space Based Infrared System; GPS = Global Positioning System; WGS = Wideband Global SATCOM; AEHF = Advanced Extremely High Frequency; NPOESS = National Polar-orbiting Operational Environmental Satellite System; MUOS = Mobile User Objective System

Figure 9. Space Program Unit Cost Growth (Government Accountability Office, 2010)

Figure 3: Differences in Total Number of Months to IOC from Program Start and Most Recent Estimates



Source: GAO analysis of DOD data.

Legend: SBIRS = Space Based Infrared System; GPS = Global Positioning System; WGS = Wideband Global SATCOM; AEHF = Advanced Extremely High Frequency; NPOESS = National Polar-orbiting Operational Environmental Satellite System; MUOS = Mobile User Objective System.

Figure 10. Space Program Schedule Delays (Government Accountability Office, 2010)

Appendix C – A Summary of Space Acquisition Findings and Root Causes

Table 35. Space Acquisition Lessons Learned

System or Subject	Failure // Root Cause	Year	Source
AEHF	early phases of the AEHF program, DOD substantially and frequently altered requirements; DOD decided to accelerate its plans to build the AEHF satellites, high risk schedule that turned out to be overly optimistic and highly compressed-leaving little room for error; did not have the funding needed to support the activities and the manpower needed to design and build the satellites quicker	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions
Distributed Common Ground-Surface System (DCGS)	DOD has been slow to plan for this initiative and it has not addressed important questions such as how and when systems will be pared down and modified as well as how the initiative will be funded. Moreover, DOD is fielding new systems and new versions of old systems without following its own certification process	2003	GAO - Steps Needed to Ensure Interoperability of Systems That Process Intelligence Data
Distributed Common Ground-Surface System (DCGS)	incompatible data formats, process for testing and certifying that systems will be interoperable is not working effectively // lack of an overarching test plan	2003	GAO - Steps Needed to Ensure Interoperability of Systems That Process Intelligence Data
GOES, lessons learned incorporation	establish realistic cost and schedule estimates	2006	GAO - Steps Remain in Incorporating Lessons Learned from Other Satellite Programs
GOES, lessons learned incorporation	ensure sufficient technical readiness of the system's components prior to key decisions // GOES I-M series, NOAA and NASA did not require engineering analyses prior to awarding the development contracts in order to accelerate the schedule and launch the first satellite. The lack of these studies resulted in unexpected technical issues in later acquisition phases—including the inability of the original instrument designs to withstand the temperature variations in the geostationary orbit	2006	GAO - Steps Remain in Incorporating Lessons Learned from Other Satellite Programs

GOES, lessons learned incorporation	provide sufficient management at government and contractor levels // The key drivers of poor management included inadequate systems engineering and earned value management capabilities, unsuitable allocation of contract award fees, inadequate levels of management reserve, and inefficient decision-making and reporting structure within the program office	2006	GAO - Steps Remain in Incorporating Lessons Learned from Other Satellite Programs
GOES, lessons learned incorporation	perform adequate senior executive oversight to ensure mission success // lack of timely decisions and regular involvement of senior executive management was a critical factor in the program‘s rapid cost and schedule growth	2006	GAO - Steps Remain in Incorporating Lessons Learned from Other Satellite Programs
GOES-R risks	hardware that is to be used for the ground segment is mature, key components have not previously been integrated. Consequently, if the components do not work together, the program might have to procure separate antennas, which would impact the program‘s cost and schedule	2009	GAO - Acquisition Is Under Way, but Improvements Needed in Management and Oversight
GOES-R risks	Advanced Baseline Imager estimates that the instrument is over 50 percent complete and reports that it has experienced technical issues, including problems with the quality of components in the focal plane module, mirrors, and telescope. none has yet been demonstrated in a lab or test environment, the risk remains that the technologies are not sufficiently mature	2009	GAO - Acquisition Is Under Way, but Improvements Needed in Management and Oversight
Incentives & Pressures	lack of an overall investment strategy; tendency to set start dates for programs before a sound business case for them has been established; DOD starts more programs than it can afford and rarely prioritizes them for funding purposes; Such an approach has cascading effects—from creating negative behaviors associated with competing for funds, to increasing technology challenges, to creating unanticipated and disruptive funding shifts, to stretching out schedules in order to accommodate the whole portfolio of space programs	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• DOD starts more programs than it can afford over the long run, forcing programs to underestimate costs and overpromise capability. This was attributed to both the Office of the Secretary of Defense and the Air Force. The September 11, 2001, terror attacks on the United States spurred DOD to attempt to pursue even more satellite programs, believing that there was now a greater need for persistent surveillance and more robust communication and networking capabilities.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions

Incentives & Pressures	• When faced with a lower budget, senior executives within Office of the Secretary of Defense and the Air Force would rather make across-the board cuts to all space programs than hard decisions as to which ones to keep and which ones to cancel or cut back.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Because programs are funded annually and priorities have not been established, competition for funding continues over time, forcing programs to view success as the ability to secure the next installment rather than the end goal of delivering capabilities when and as promised.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• More often than not, DOD seeks substantial leaps in capability versus incremental leaps. While this approach helps a program to gain support, it substantially increases the technical challenge and the level of unknowns about a program at the time it is started.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Having to continually ―sell" a program also creates incentives to suppress bad news about the program's status and avoid activities that uncover bad news.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Launching demonstrators in space is a good way to reduce risks and learn about technologies before starting a new acquisition program. But because of the high cost of testing technologies in space and the overall competition for funding, programs are incentivized not to pursue this approach. At the same time, resources outside acquisition programs devoted to testing in an operational environment are declining.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• DOD faces resource shortages beyond funding because it starts more programs than it can afford. Principally, it does not have a sufficient workforce to support space acquisitions or experienced program managers to guide them.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	diverse array of officials and organizations involved with the acquisition process, tensions between the S&T and acquisition communities as to who is better suited to translate technology concepts into reality	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions

Incentives & Pressures	• The lengthy development period required for space systems puts pressure on program managers to continually develop technologies. There is a fear that if these technologies do not reach maturity during this time frame, they will be outdated by the time the satellites are ready to be launched.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Once a program has formally begun, it is easier to secure current and future years' funding.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Satellites tend to last longer than expected, and they cannot be retrieved for upgrades, putting more pressure on programs to push for attaining as much technological capability as possible within the acquisition program.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• The acquisition community does not believe that labs in charge of developing space technologies adequately understand its needs—in terms of capabilities and time frames—and would rather pursue its own goals.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Program managers also believe that they would have more control over technology development if it was conducted by contractors who answered to them rather than to DOD labs.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• DOD has not had an effective strategy for steering activities within the S&T community to ensure that they will eventually fit in with acquisition needs. (Note: DOD has recently developed a space S&T strategy. We reported on this effort in January 2005.)	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	pressures resulting from short tenures among staff critical to achieving acquisition success, and difficulties in overseeing contractors	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions

Incentives & Pressures	• Nonincumbent contractors are often able to submit a lower price than the incumbent because they can be optimistic without being challenged by DOD. These optimistic estimates enable them to win new contracts. At the same time, however, nonincumbents are not necessarily the best organizations to carry out the development program, particularly because they do not have the technical and management experience associated with the legacy system being replaced.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Industry has been consolidated to a point where there may be only one company that can develop a needed component for a satellite system. This has enabled contractors to hold some programs hostage.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Program managers are often not equipped to understand what is behind a contractor's proposal, particularly because contractors are not likely to disclose technical risks and highlight other negative aspects.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Industry puts pressure on programs to have contractors develop critical technologies within an acquisition environment versus having the labs do it. When labs build technologies, the government allows the contractors that work on the system that would ultimately use the technologies to scrap them in favor of employing their own methods and expertise.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Program managers are not always experienced enough to stand up to contractors when development is being mismanaged. Program managers also may not understand the best ways to incentivize contractors and gain insight into their performance.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
Incentives & Pressures	• Contractors are facing workforce pressures similar to those experienced by the government, that is, not enough technical expertise to develop highly complex space systems. (Our recent report on space S&T echoed this concern as well, pointing out that several studies have found that both industry and the U.S. government face substantial shortages of scientists and engineers and that recruitment of new personnel is difficult because the space industry is one of many sectors competing for the limited number of trained scientists and engineers.)	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions

Incentives & Pressures	• Some space programs are facing pressures related to funding and technology development because of an expectation widely held in the 1990s that the commercial space market would experience a boom. At the time, DOD decreased funding for some capabilities, principally space launch, assuming the market could pay for a portion of research and development and that economies of scale would result. It also relied on the commercial sector to develop knowledge about production of satellites that eventually were purchased as part of the Wideband Gapfiller Satellite program. However, when anticipated commercial orders using the same technologies did not pan out, the government experienced unanticipated schedule delays.	2005	GAO - Defense Acquisitions: Incentives and Pressures That Drive Problems Affecting Satellite and Related Acquisitions
NPOESS	requirements setting problems attributable to the broad base of internal customers each agency has and the diversity of requirements that needed to be met	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions
NPOESS	NPOESS is being managed with cost as the most important parameter: One observation of this cost priority is reflected in the award fee structure and its emphasis on cost control. Successful space acquisition requires mission success to be the top priority not cost as the overarching factor	2009	NPOESS Independent Review Team
NPOESS	The EXCOM process is ineffective: The EXCOM is intended to be a decision body to provide streamlined direction to the PEO. The current DOD EXCOM representative has not been delegated the proper authority from the Defense Acquisition Executive (DAE), who is also the NPOESS Milestone Decision Authority (MDA), and decisions require an additional meeting and coordination to be finalized	2009	NPOESS Independent Review Team
NPOESS	The PEO and IPO do not have sufficient space systems acquisition expertise and processes: The NPOESS program is not part of a supporting space systems acquisition center, such as the AF Space and Missile Systems Center (SMC) or the NASA Goddard Space Flight Center (GSFC). These types of established space acquisition organizations can provide institutional knowledge, robust infrastructure support, and a cadre of seasoned space systems acquisition experts	2009	NPOESS Independent Review Team
NPOESS	Funding shortfalls are causing the IPO to make short-sighted decisions to cover VIIRS cost growth and stay within allocated budget at a significant increase to outyear costs and program risks: While the IPO has no choice but to make these decisions, risk is being deliberately built into the program to stay within allocated budget.	2009	NPOESS Independent Review Team

NPOESS	The priorities of NOAA, NASA and DOD/USAF are not aligned: The DOD has stated that while the program should continue to pursue the current NPOESS requirements, the DOD is willing to accept legacy performance (DMSP and POES) to maintain continuity, cost and schedule goals and is not willing to provide additional funding to pursue requirements beyond legacy. NOAA states that legacy performance would be a step back in today's performance because of their current operational use of NASA research satellites that are well beyond their design life	2009	NPOESS Independent Review Team
NPOESS	The current budget is inadequate: Budgeting to a 50-50 cost estimate leads to insufficient funding. It lacks sufficient management reserve, and as noted in Finding #6, this leads to programs using risk as its management reserve. The current budget is not at the 50/50 level. The most probable cost is at the 80/20 level including reserves	2009	NPOESS Independent Review Team
NPOESS	Committee lacks the membership and leadership needed to effectively and efficiently oversee and direct the program. Specifically, the DOD Committee member with acquisition authority does not attend Executive Committee meetings—and sometimes contradicts the Committee's decisions, the Committee does not track its action items to closure, and many of the Committee's decisions do not achieve desired outcomes // DOD's acquisition authority has never attended an Executive Committee meeting. This individual delegated the responsibility for attending the meetings—but not the authority to make acquisition decisions—to the Under Secretary of the Air Force // agreements between committee members have been overturned by the acquisition authority, leading to significant delays // NPOESS Executive Committee generally took immediate action to mitigate the risks that were brought before them; however, a majority of these actions were not effective—that is, they did not fully resolve the underlying issues or result in a successful outcome // interagency disagreements and differing priorities	2009	GAO - With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making
NPOESS	Specifically, ongoing challenges with VIIRS development, design, and workmanship have led to additional cost overruns and delayed the instrument's delivery to NPP	2009	GAO - With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making

NPOESS	problems discovered during environmental testing on CrIS led the contractor to further delay its delivery to NPP and added further unanticipated costs to the program	2009	GAO - With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making
NPOESS risks	Progress Has Been Made in Establishing an Effective NPOESS Management Structure, but Executive Turnover Increases Risks and Staffing Problems Remain	2007	GAO - ENVIRONMENTAL SATELLITE ACQUISITIONS Progress and Challenges
NPOESS risks	Space Segment—Progress Made, but Key Sensors Continue to Face Major Risks // VIIRS - completed environmental tests of VIIRS‘s engineering design unit (a prototype) (1) band-to-band co-registration, an issue in which band registration shifts with different temperatures; (2) cross-talk, which involves information from sensor cells leaking into other cells; and (3) line-spread function issues, in which the instrument‘s focus changes with changes in temperature, CrIS - Development of CrIS was put on hold in October 2006 when the flight unit designated to go on NPP experienced a major structural failure during its vibration test	2007	GAO - ENVIRONMENTAL SATELLITE ACQUISITIONS Progress and Challenges
SBIRS	program‘s history of moving forward without sufficient knowledge to ensure that the product design is stable and meets performance requirements and that adequate resources are available	2003	GAO - Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns
SBIRS	program passed its critical design review with only 50 percent of its design drawings completed, compared to 90 percent as recommended by best practices. Consequently, several design modifications were necessary, including 39 to the first of two infrared sensors to reduce excessive noise created by electromagnetic interference—a threat to the host satellite‘s functionality—delaying delivery of the sensor by 10 months or more	2003	GAO - Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns
SBIRS	testing of the first infrared sensor revealed several deficiencies in the flight software involving the sensor‘s ability to maintain earth coverage and track missiles while orbiting the earth (flight software still major program risk)	2003	GAO - Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns
SBIRS	The program was too immature to enter the system design and development phase. Program activation was based on faulty and overly optimistic assumptions about software reuse and productivity levels, the benefits of commercial practices, management stability, and the level of understanding	2003	GAO - Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns

	of requirements.		
SBIRS	The complexity of developing engineering solutions to meet system requirements was not well understood by program and contracting officials. The systems integration effort was significantly underestimated in terms of complexity and the associated impacts. In addition, the requirements refinement process was ad hoc, creating uncertainty on the status of program priorities and affecting cost and schedule.	2003	GAO - Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns
SBIRS	Breakdown in execution and management. Overly optimistic assumptions and unclear requirements eventually overwhelmed government and contractor management. The 2-year delay of the GEO satellite launches, which occurred in 1998, contributed to management instability and was a factor in the Program Office and the contractor having to spend 25 of the first 60 months of the contract on replanning activities.	2003	GAO - Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns
SBIRS	latent defects, resulting from insufficient product assurance activity in earlier design and production activities // lack of sound system engineering processes and procedures	2005	DOD - Status of the Space Based Infrared System Program, Report to the Defense and Intelligence Committees
SBIRS	insufficient schedule and budget to ensure robust GEO first article integration / test // insufficient time scheduled for GEO system integration and test; SPO concluded the ground software productivity levels were optimistic; the flight software architecture was not sufficiently defined to allow software coding; and inadequate on-orbit checkout time was planned. Finally, the resources and tools for simulations, analysis, and troubleshooting were inadequate and required more effort	2005	DOD - Status of the Space Based Infrared System Program, Report to the Defense and Intelligence Committees
SBIRS	process escapes due to human error / insufficient training / fragile processes // improper or inadequate processes, insufficient training, questionable inspection practices, and/or human error as causal factors. Recent events include excess debris or contamination in delivered hardware, improper use of soldering materials, improper installation of thermal blankets, and missing test procedure documentation	2005	DOD - Status of the Space Based Infrared System Program, Report to the Defense and Intelligence Committees

SBIRS	A poor design and build implementation to comply with the EMI specifications of the HEO P/L // flawed design approach	2005	DOD - Status of the Space Based Infrared System Program, Report to the Defense and Intelligence Committees
SBIRS	Faulty hardware and software design of the HEO/GEO flight computers, i.e., the single board computer ‗halt' anomalies // hardware design problem with a control signal on an Application-Specific Integrated Circuit (ASIC)	2005	DOD - Status of the Space Based Infrared System Program, Report to the Defense and Intelligence Committees
SBIRS	An inadequate architecture design and a flawed flight software development plan for the GEO satellite's Signal Processing Assembly (SPA) // state of the software architecture, a very aggressive contractor schedule, and inadequate planning	2005	DOD - Status of the Space Based Infrared System Program, Report to the Defense and Intelligence Committees
SBIRS	flight software for the first satellite underwent testing and failed; timing of stored programs // test beds that had matured in parallel with the flight software and hardware, making it difficult to distinguish between test bed and software issues; oversubscription of test beds and lack of simulation resources that precluded them from checking out high-risk areas (timing, and stored programs); insufficient modeling of timing, and analysis of stored program implementation, which might have shed light earlier on lack of robustness	2008	GAO - DOD's Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	flight software for the first satellite underwent testing and failed; distribution of control between processors // test beds that had matured in parallel with the flight software and hardware, making it difficult to distinguish between test bed and software issues; oversubscription of test beds and lack of simulation resources that precluded them from checking out high-risk areas (timing, and stored programs); insufficient modeling of timing, and analysis of stored program implementation, which might have shed light earlier on lack of robustness	2008	GAO - DOD's Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	flight software for the first satellite underwent testing and failed; failure at the hardware interface level // // test beds that had matured in parallel with the flight software and hardware, making it difficult to distinguish between test bed and software issues; oversubscription of test beds and lack of simulation resources that precluded them from checking out high-risk areas (timing, and stored programs); insufficient modeling of timing, and analysis of stored program implementation, which might have shed light earlier on lack of robustness	2008	GAO - DOD's Goals for Resolving Space Based Infrared System Software Problems Are Ambitious

SBIRS	weaknesses in management responsibility, accountability and organizational structure; Air Force has limited management control over SBIRS	2008	GAO - DOD‘s Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	Lockheed Martin‘s program process discipline is poor	2008	GAO - DOD‘s Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	Adversarial relationships exist between Air Force and Lockheed Martin	2008	GAO - DOD‘s Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	Government organizational structure is flawed because cost and schedule responsibilities are separated	2008	GAO - DOD‘s Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	Focal point for FSS completion is needed	2008	GAO - DOD‘s Goals for Resolving Space Based Infrared System Software Problems Are Ambitious
SBIRS	reasons for the delay include poor government oversight of the contractor, technical complexities, and rework. The program continues to struggle with flight software development, and during testing last year, officials discovered hardware defects on the first GEO satellite, though the program reports that they have been resolved	2010	GAO - DOD Poised to Enhance Space Capabilities, but Persistent Challenges Remain in Developing Space Systems
SBIRS-High	• Cost-driven, • Underfunded, • Optimistic contractor proposal, • Uncontrolled requirements, • Limited program manager authority and capability, • Funding instability (four replans), • Program manager instability (four government and four industry program managers), and • Failure to implement ―best practices.”	2003	Defense Science Board - Acquisition of National Security Space Programs

SBIRS-High	independent review team chartered by DOD to examine the reasons behind cost and scheduling problems in the SBIRS-High program reported that a key root cause was that system requirements were not well-understood when the program began and as it evolved; requirements setting process was often adhoc with many decisions being deferred to the contractor. The review team also found that the program was too immature to enter system design and development. Further, there was too much instability on the program after the contract award	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions
Space Radar	• Knowledge point 1: A match must be made between the customer's requirements and the developer's available resources before product development starts. As noted earlier, DOD plans to start SBR product development in 2006. • Knowledge point 2: The product's design must be stable and must meet performance requirements before initial manufacturing begins. • Knowledge point 3: The product must be producible within cost, schedule, and quality targets and demonstrated to be reliable before production begins.	2004	GAO - DEFENSE ACQUISITIONS Space-Based Radar Effort Needs Additional Knowledge before Starting Development
Space Radar	A defined requirements approval process helps decision makers resolve disagreements that may occur and ensure they will remain committed to their decisions after formal approval. Based on our past reports on uncovering problems and our best practice work, we believe that the steps in a formal approval process include: • explaining how decision makers' requirements and comments are obtained and addressed; • identifying the officials and/or the organizations responsible for taking specific approval action; • establishing a mechanism and time frame for providing approval or disapproval; • establishing a system for addressing unresolved issues as they relate to key program documentation; and • assessing changes to approved requirements based on their effect on the program's cost and schedule.	2004	GAO - DEFENSE ACQUISITIONS Space-Based Radar Effort Needs Additional Knowledge before Starting Development

Space Radar	it is expected that some critical SBR technologies will not be mature when product development starts, that is, not tested in a relevant or operational environment. Typical outcomes of this lack of knowledge are significant cost and schedule increases because of the need to fix problems later in development. Furthermore, TCA, a new, more robust communications infrastructure that could transmit SBR's imagery data much more quickly than the current infrastructure, is facing uncertainties. Specifically, one of TCA's primary components, the Transformational Satellite, may not be ready in time to support SBR. However, if DOD begins product development with less than mature technologies and without knowing the availability of TCA, accurate cost estimates for SBR will be much more difficult to prepare	2004	GAO - DEFENSE ACQUISITIONS Space-Based Radar Effort Needs Additional Knowledge before Starting Development
Space, Common Problems	requirements definition and control issues	2003	Defense Science Board - Acquisition of National Security Space Programs
Space, Common Problems	Cost has replaced mission success as the primary driver in managing acquisition processes, resulting in excessive technical and schedule risk	2003	Defense Science Board - Acquisition of National Security Space Programs
Space, Common Problems	overall underappreciation of the importance of appropriately staffed and trained system engineering staffs to manage the technologically demanding and unique aspects of space programs; Government capabilities to lead and manage the acquisition process have seriously eroded	2003	Defense Science Board - Acquisition of National Security Space Programs
Space, Common Problems	The space acquisition system is strongly biased to produce unrealistically low cost estimates throughout the acquisition process. These estimates lead to unrealistic budgets and unexecutable programs; widespread lack of budget reserves required to implement high risk programs on schedule; unhealthy cost bias in proposal evaluation // government typically has invested significantly in capital and intellectual resources for the incumbent. When the incumbent loses, both capital resources and the mature engineering and management capability are lost. A similar investment must be made in the new contractor team. The government pays for purchase and installation of specialized equipment, as well as fit-out of manufacturing and assembly spaces that are tailored to meet the needs of the program	2003	Defense Science Board - Acquisition of National Security Space Programs
Space, Common Problems	While the space industrial base is adequate to support current programs, long-term concerns exist; Industry has failed to implement proven practices on some programs	2003	Defense Science Board - Acquisition of National Security Space Programs

Space, Common Problems	requirements for what the satellite needed to do and how well it must perform were not adequately defined at the beginning of a program or were changed significantly once the program had already begun. This made it more difficult for programs to ensure that they could match their requirements to their resources (in terms of money, time, and technology). The more requirements were added or changed, the more that cost and schedule increased • Program did not adequately define requirements • Unresolved conflicts among users on requirements • Frequent changes made to requirements after product development began // schedule-driven versus a knowledge-driven approach; diverse array of organizations with competing interests involved in overall satellite development, no high-level official within the Office of the Secretary of Defense dedicated to developing and implementing an overall investment strategy for space; attempted to satisfy all requirements in a single step, regardless of the design challenge or the maturity of technologies to achieve the full capability	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions
Space, Common Problems	investment practices were weak. At times, programs did not explore potentially more cost-effective investment approaches. Once they settled on an approach, programs often did not develop realistic cost estimates. From a broader perspective, investments in programs were not made in accordance with an overall space investment strategy for DOD. Funds were sometimes shifted from healthier programs to pay for weaker ones. Further, according to DOD officials, decisions external to the program office were sometimes imposed that resulted in unexpected funding cuts • Program did not adequately analyze investment alternatives • Cost and/or schedule estimates were optimistic • Funding was unstable // schedule-driven versus a knowledge-driven approach; diverse array of organizations with competing interests involved in overall satellite development, no high-level official within the Office of the Secretary of Defense dedicated to developing and implementing an overall investment strategy for space	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions

Space, Common Problems	acquisition strategies were poorly executed. For example, competition was reduced for the sake of schedule or DOD did not adequately oversee contractors. At times, contract type was not suitable for the work being done • Level of competition was reduced or eliminated • Contract type was not suitable for work being done • Poor oversight over contractors // schedule-driven versus a knowledge-driven approach	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions
Space, Common Problems	programs did not always ensure that technologies were mature before making heavy investments in the program. This often caused cost and schedule increases due to the need to fix problems later in development. A continuing problem is that software needs are poorly understood at the beginning of a program • Technology not sufficiently mature at program start • Software needs poorly understood • Testing compressed, skipped, or done concurrently with production // schedule-driven versus a knowledge-driven approach; attempted to satisfy all requirements in a single step, regardless of the design challenge or the maturity of technologies to achieve the full capability	2003	GAO - Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions
Space, Common Problems	There are insufficient numbers of technically competent and experienced space acquisition personnel to execute the responsibilities of the Space and Missile Systems Center (SMC) and the National Reconnaissance Office (NRO) // The reduced availability of government personnel with the necessary technical competence has sharply reduced the government's capability to acquire space systems and is believed by many experts to be a major cause of acquisition program failures	2008	Institute for Defense Analyses - Leadership, Management, and Organization for National Security Space
Space, Common Problems	Lax requirements discipline, technical performance problems, cost growth, and schedule delays have plagued U.S. space programs // existing leadership and management practices have failed to define, fund, and execute new satellite programs. Strong management is needed to implement proven acquisition practices	2008	Institute for Defense Analyses - Leadership, Management, and Organization for National Security Space

Space, Common Problems	leadership for National Security Space is currently fragmented and unfocused. Authorities and responsibilities are spread across numerous organizations, including many within the Office of the Secretary of Defense (OSD) [Under Secretary of Defense (USD)/Intelligence; USD/Acquisition, Technology, and Logistics; USD/Policy; and the Assistant Secretary of Defense (ASD)/Networks & Information Integration], USAF, USN, USA, USMC, DARPA, MDA, and NRO. Although the Secretary of the Air Force is the DOD Executive Agent for Space, its authorities have been diminished from those envisioned by the 2001 Space Commission. Moreover, as perceived by many, its stewardship of Space does not enjoy the same priority as other traditional Air Force missions. The customers who use Space capabilities observe that there is no responsible official who looks across all the available resources and capabilities to seek the best solution, whether from the military, intelligence, civilian, or commercial sector. This represents a critical need	2008	Institute for Defense Analyses - Leadership, Management, and Organization for National Security Space
TSAT	When DOD established initial goals for the TSAT program, it lacked sufficient knowledge about key critical technologies. Our past work has shown that a knowledge-based model leads to better acquisition outcomes. This model can be broken down into three cumulative knowledge points for technology maturity, design maturity, and production maturity. At the first knowledge point, a match is made between a customer‘s requirements and the product developer‘s available resources in terms of technical knowledge, time, money, and capacity. We have also reported that starting a complex program like TSAT with immature technologies can lead to poor program performance and outcomes.	2006	GAO - SPACE ACQUISITIONS DOD Needs Additional Knowledge as it Embarks on a New Approach for Transformational Satellite

The table above contains text from the following sources: (Government Accountability Office, 2010) (Government Accountability Office, 2003) (Government Accountability Office, 2004) (Government Accountability Office, 2003) (Government Accountability Office, 2005) (Government Accountability Office, 2007) (Government Accountability Office, 2009) (Government Accountability Office, 2006) (Government Accountability Office, 2003) (Government Accountability Office, 2009) (Government Accountability Office, 2006) (Government Accountability Office, 2008) (Institute for Defense Analyses, 2008) (NPOESS Independent Review Team, 2009) (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003)

Appendix D – Recommendations for Space Acquisition Improvement

The 2003 Defense Science Board report laid out a number of steps necessary to correct the space acquisition deficiencies previously discussed. The combination of space acquisition lessons learned and recommendations for improvement were used to compose the maturity model. The report cited the following steps (Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, 2003):

> 1. The Under Secretary of the Air Force/Director National Reconnaissance Office (USecAF/DNRO) should establish *mission success* as the guiding principle in all space systems acquisition. This requires incorporation of the principle in policy statements, leadership actions, and contractual provisions and incentives.
>
> 2. The SecDef should establish the same authority for the USecAF for DOD space programs as the DNRO has for implementing the National Reconnaissance Program (NRP) budget.
>
> 3. To ensure realistic budgets and cost estimates, the USecAF/DNRO should
>
> > • Direct that space acquisition programs be budgeted to a most probable (80/20) cost, with a 20-25 percent management reserve for development programs included within this cost; also direct that reserves are not to be used for new requirements;
> >
> > • Direct that source selections evaluate contractor cost credibility and use the estimate as a measure of their technical understanding;
> >
> > • Conduct more effective independent cost estimates and program assessments and incorporate the results into the program budget and plan;
> >
> > • Implement independent senior advisory reviews at critical acquisition milestones with experienced, respected outsiders.
>
> 4. The USecAF/DNRO should compete space system acquisitions only when *clearly* in the best interest of the government (e.g., new mission capability, major new technology, or poor incumbent performance). When a competition occurs and a nonincumbent is the winner, the loss of investment in the losing incumbent must be reflected in the program budget and plan. In addition, provisions must be made to assure continuity between the legacy system and the new system.

5. SecDef and the Director of Central Intelligence (DCI) should designate senior leaders in the DOD and intelligence community with authority to lead their respective requirements processes for national security space systems. The senior leaders must have the support necessary to assess—technically and fiscally—proposed requirements and the authority to couple requirements with funding.

6. The USecAF/DNRO should authorize the program manager to control requirements within the approved baseline. The program manager should continuously trade and challenge requirements throughout the program life cycle. Significant requirements changes should require the approval of the senior leaders for requirements.

7. The Commander, Air Force Space Command, should complete the ongoing effort to establish a dedicated career field for space operations and acquisition personnel.

8. The USecAF/DNRO should require that key program management tours be a minimum of 4 years.

9. The USecAF/DNRO should, through policy and leadership action, clearly define the responsibility, authority, and accountability for program managers, recognizing the criticality of program managers to the success of their programs. In selecting managers, acquisition experience must be a prerequisite.

10. USecAF/DNRO should develop a robust systems engineering capability to support program initiation and development. Specifically, USecAF/DNRO should

- Reestablish organic government systems engineering capability by selecting appropriate people from within government, hiring to acquire needed capabilities, and implementing training programs; and

- In the near term, ensure full utilization of the combined capabilities of government, Federally Funded Research and Development Center (FFRDC), and systems engineering and technical assistance (SETA) system engineering resources.

11. The USecAF/DNRO should require program managers to identify and report potential problems early.

- Program managers should establish early warning metrics and report problems up the management chain for timely corrective action.

- Severe and prominent penalties should follow any attempt to suppress problem reporting.

12. The USecAF/DNRO should demand that national security space contractors

- Account for the quality of their program implementation and for mission success,

- Identify proven management and engineering practices and ensure they are being utilized, and

- Account for the early identification and open discussion of problems in their program.

13. Program managers should align contract and fee structure to focus industry attention on proven management and engineering practices and mission success.

Appendix E – Excerpts from the Systems Engineering Leading Indicators Guide

Table 36. Systems Engineering Leading Indicators Overview (Massachusetts Institute of Technology, INCOSE, and PSM, 2010)

Leading Indicator	Insight Provided	Phases / Stages									
		P 1	P 2	P 3	P 4	P 5	S 1	S 2	S 3	S 4	S 5
Requirements Trends	Rate of maturity of the system definition against the plan. Additionally, characterizes the stability and completeness of the system requirements that could potentially impact design, production, operational utility, or support.	•	•	•	•	•	•	•	•	•	•
System Definition Change Backlog Trend	Change request backlog which, when excessive, could have adverse impact on the technical, cost and schedule baselines.			•	•	•		•	•	•	
Interface Trends	Interface specification closure against plan. Lack of timely closure could pose adverse impact to system architecture, design, implementation and/or V&V any of which could pose technical, cost and schedule impact.	•	•	•	•	•	•	•	•	•	
Requirements Validation Trends	Progress against plan in assuring that the customer requirements are valid and properly understood. Adverse trends would pose impacts to system design activity with corresponding impacts to technical, cost & schedule baselines and customer satisfaction.	•	•	•	•	•	•	•	•	•	
Requirements Verification Trends	Progress against plan in verifying that the design meets the specified requirements. Adverse trends would indicate inadequate design and rework that could impact technical, cost and schedule baselines. Also, potential adverse operational effectiveness of the system.	•	•	•	•	•	•	•	•	•	•
Work Product Approval Trends	Adequacy of internal processes for the work being performed and also the adequacy of the document review process, both internal and external to the organization. High reject count would suggest poor quality work or a poor document review process each of which could have adverse cost, schedule and customer satisfaction impact.	•	•	•	•	•	•	•	•	•	
Review Action Closure Trends	Responsiveness of the organization in closing post-review actions. Adverse trends could forecast potential technical, cost and schedule baseline issues.	•	•	•	•	•	•	•	•	•	•
Risk Exposure Trends	Effectiveness of risk management process in managing / mitigating technical, cost & schedule risks. An effective risk handing process will lower risk exposure trends.	•	•	•	•	•	•	•	•	•	•
Risk Treatment Trends	Effectiveness of the SE organization in implementing risk mitigation activities. If the SE organization is not retiring risk in a timely manner, additional resources can be allocated before additional problems are created.	•	•	•	•	•	•	•	•	•	•
Technology Maturity Trends	Risk associated with incorporation of new technology or failure to refresh dated technology. Adoption of immature technology could introduce significant risk during development while failure to refresh dates technology could have operational effectiveness/customer satisfaction impact.		•	•	•	•		•	•	•	
Technical Measurement Trends	Progress towards meeting the Measures of Effectiveness (MOEs) / Performance (MOPs) / Key Performance Parameters (KPPs) and Technical Performance Measures (TPMs). Lack of timely closure is an indicator of performance deficiencies in the product design and/or project team's performance.			•				•			
Systems Engineering Staffing & Skills Trends	Quantity and quality of SE personnel assigned, the skill and seniority mix, and the time phasing of their application throughout the project lifecycle.	•	•	•	•	•	•	•	•	•	•

Leading Indicator	Insight Provided	Phases / Stages									
		P 1	P 2	P 3	P 4	P 5	S 1	S 2	S 3	S 4	S 5
Process Compliance Trends	Quality and consistency of the project defined SE process as documented in SEP/SEMP. Poor/inconsistent SE processes and/or failure to adhere to SEP/SEMP, increase project risk.	●	●	●	●	●	●	●	●	●	●
Facility and Equipment Availability Trends	Availability of non-personnel resources (infrastructure, capital assets, etc.) needed throughout the project lifecycle.	●	●	●	●	●	●	●	●	●	●
Defect/Error Trends	Progress towards the creation of a product or the delivery of a service that meets the quality expectations of its recipient. Understanding the proportion of defects being found and opportunities for finding defects at each stage of the development process of a product or the execution of a service.	●	●	●	●	●	●	●	●	●	●
System Affordability Trends	Progress towards a system that is affordable for the stakeholders. Understanding the balance between performance, cost, and schedule and the associated confidence or risk.	●	●	●	●	●	●	●	●	●	●
Architecture Trends	Maturity of an organization with regards to implementation and deployment of an architecture process that is based on an accept set of industry standards and guidelines.	●	●	●			●	●			
Schedule and Cost Pressure	Impact of schedule and cost challenges on carrying out a project	●	●	●	●	●	●	●	●	●	●

Table 37. Leading Indicator Specification Example (Massachusetts Institute of Technology, INCOSE, and PSM, 2010)

3.1.1 Requirements Trend Specification

Requirements Trends	
Information Need Description	
Information Need	• Evaluate the stability and adequacy of the requirements to understand the risks to other activities towards providing required capability, on-time and within budget. • Understand the growth, change, completeness and correctness of the definition of the system requirements.
Information Category	1. Product size and stability – Functional Size and Stability 2. Also may relate to Product Quality and Process Performance (relative to effectiveness and efficiency of validation)
Measurable Concept and Leading Insight	
Measurable Concept	Is the SE effort driving towards stability in the System definition and size?
Leading Insight Provided	• Indicates whether the system definition is maturing as expected. • Indicates risks of change to and quality of architecture, design, implementation, verification, and validation. • Indicates schedule and cost risks. • Greater requirements growth, changes, or impacts than planned or lower closure rate of TBDs/TBRs than planned indicate these risks. • May indicate future need for different level or type of resources/skills. • Indicates potential lack of understanding of stakeholder requirements that may lead to operational or supportability deficiencies.
Base Measure Specification	
Base Measures	1. Requirements 2. Requirement TBDs/TBRs 3. Requirement Defects 4. Requirement Changes 5. Requirement Change Impact
Measurement Methods	1. Count the number of Requirements (record associated attributes of interest; e.g., Process Phases, Disposition Action, Maturity States, Priority Levels, Cause, Impact Level, Classification Type, and Dates & Times) 2. Count the number of Requirement TBDs/TBRs (record associated attributes of interest; e.g., Process Phases, Disposition Action, Maturity States, Priority Levels, Cause, Impact Level, Classification Type, and Dates & Times) 3. Count the number of Requirement Defects (record associated attributes of interest; e.g., Process Phases, Disposition Action, Maturity States, Priority Levels, Cause, Impact Level, Classification Type, and Dates & Times) 4. Count the number of Requirement Changes (record associated attributes of interest; e.g., Process Phases, Disposition Action, Maturity States, Priority Levels, Cause, Impact Level, Classification Type, and Dates & Times) 5. Estimate the impact of a Requirement Change

Requirements Trends	
Unit of Measurement	1. Requirements 2. Requirement TBDs/TBRs per associated attributes 3. Requirement Defects per associated attributes 4. Requirement Changes per associated attributes 5. Effort Hours per Requirement Change (effort hours or range of effort hours expected for each change)
Entities and Attributes	
Relevant Entities	• Requirements
Attributes	• Requirement TBDs/TBRs • Requirement Defects • Requirement Changes • Additional attributes including but not limited to the Process Phases, Disposition Action, Maturity States, Priority Levels, Cause, Impact Level, Classification Type, and Dates & Times coupled with the associated events
Derived Measure Specification	
Derived Measure	1. % Requirements Approved 2. % Requirements Growth 3. % TBDs/TBRs Closure Variance per Plan 4. % Requirements Modified 5. Estimated Impact of Requirements Changes for a given time interval (in Effort Hours) 6. Requirement Defect Profile 7. Requirement Defect Density 8. Requirement Defect Leakage (or Escapes) 9. Cycle time for Requirement Changes (each and average)
Measurement Function *	1. (Requirements Approved / Requirements identified and defined)*100 for a given time interval 2. ((Requirements in current baseline - Requirements in previous baseline) / (Requirements in previous baseline) * 100 3. ((TBDs/TBRs planned for closure – TBDs/TBRs closed) / TBDs/TBRs planned for closure) * 100 4. (Requirements Modified / Total Requirements) * 100 for a given time interval 5. Sum of estimated impacts of Requirement Changes during a given time interval 6. Requirement Defects for each defect category 7. Requirement Defects / Requirements as a function of time 8. Subset of Requirement Defects found in a phase subsequent to its insertion 9. Elapsed time (difference between start and stop times) or total effort hours for each Requirements Change

Requirements Trends	
Indicator Specification	
Indicator Description and Sample	Line or bar graphs that show trends of requirements growth and TBD/TBR closure per plan. Stacked bar graph that shows types, causes, and impact/severity of changes. Show thresholds of expected values based on experiential data. Show key events along the time axis of the graphs. 1. Line or bar graphs that show growth of Requirements over time 2. Line or bar graphs that show % Requirements Approved over time 3. Line or bar graphs that show % TBDs/TBRs not closed per plan 4. Line or bar graphs that show % Requirements Change 5. Line or bar graphs that show Estimated Impact of Requirements Change for a given time interval (in effort hours) 6. Line or bar graphs that show Defect Profile (by types, causes, severity, etc.) 7. Line or bar graphs that show Defect Density 8. Stacked bar graph that shows types, causes, and impact/severity of Requirements Changes
Thresholds and Outliers	Organization dependent.
Decision Criteria	Investigate, and potentially, take corrective action when the requirements growth, requirements change impact, or defect density/distribution exceeds established thresholds <fill in organization specific threshold> or a trend is observed per established guidelines <fill in organizational specific>.

Indicator Interpretation	• Used to understand the maturity of the system definition
	• Used to understand impact on system definition and impact on production.
	• Analyze this indicator for process performance and other relationships that may provide more "leading perspective".
	• Ops Concept quality may be a significant leading indicator of the requirements stability (may be able to use number of review comments; stakeholder coverage in defining the Ops Concept).
	• Care should be taken that the organization does not create incentives driving perceptions that all requirements change is undesirable. Note: Requirements changes may be necessary to accommodate new functionality.
	• Review of this indicator can help determine the adequacy of:
	    o Quantity and quality of Systems Engineers
	    o Infrastructure
	    o Process maturity (acquirer and supplier)
	    o Interface design capability
	    o Stakeholder collaboration across life cycle
	• Funding by customer; financial challenge by the program management

Requirements Trends	
Additional Information	
Related Processes	Stakeholder Requirements, Requirements Analysis, Architectural Design
Assumptions	• Requirements Database, Change Control records, defect records are maintained & current. • TBDs and TBRs are recorded and tracked.
Additional Analysis Guidance	• May also be helpful to track trends based on severity/priority of changes • Defect leakage - identify the phases in which defect was inserted and found for each defect recorded.
Implementation Considerations	• Requirements that are not at least at the point of a draft baseline should not be counted. • Usage is driven by the correctness and stability of requirements definition. ○ Lower stability means higher risk of impact to other activities and other phases, thus requiring more frequent review. ○ Applies throughout the life cycle, based on risk. ○ Track this information per baseline version to track the maturity of the baseline as the system definition evolves.
User of Information	• Program/Project Manager • Chief Systems Engineer • Product Managers • Designers
Data Collection Procedure	• See Appendix F
Data Analysis Procedure	• See Appendix F

Appendix F – SAIMM Interoperability Measurement Checklist

Step 1 – Determine Program Interoperation Maturity

Assess the subject program's interoperation maturity for the cost, schedule and requirements areas using the SAIMM matrix provided in Chapter III (SAIMM link). The program may tailor the matrix based upon their historical precedent and lessons learned.

Step 2 – Instantiate the Program Character States

Place the respective SAIMM scores for each area and attribute into a spreadsheet or similar tool. The following format was used to perform the calculations in this thesis:

Table 38. Instantiation Example Format

Program X	Mission Focus	Stability	Discipline	Realism
Cost	1	1	1	1
Schedule	1	1	1	1
Requirements	1	1	1	1

Step 3 – Perform the Interoperability Measurement

Apply the Sim_{Real} function to the instantiation matrix to perform the interoperability measurement. Set r to 2, and n and c_{max} to 4.

Step 4 – Evaluate the Results

Examine the resulting interoperability scores. The program may use the AEHF, NPOESS and SBIRS examples in this thesis for comparison. The program may also perform the measurement during various phases in the program to evaluate progress.

Bibliography

Blash, L. C. (2003). Network-Centric Warfare Requires A Closer Look. *SIGNAL Online*.

CJCSI. (2008, December 15). Interoperability and Supportability of Information Technology and National Security Systems. *Chairman of the Joint Chiefs of Staff Instruction*.

Clark, T., & Jones, R. (n.d.). *Organisational Interoperability Maturity Model for C2.*

Defense Acquisition Performance Assessment Project. (2006). *Defense Acquisition Performance Assessment Report.* Washington DC: Department of Defense.

Department of Defense. (2001). *Network Centric Warfare, Department of Defense Report to Congress.*

Department of Defense. (2005). Department of Defense Dictionary of Military and Associated Terms. *Joint Publication 1-02*. Washington DC: Department of Defense.

Department of Defense. (2009, March). National Security Space Acquisition Policy Interim Guidance.

Ford, T. C. (2008). *Interoperability Measurement.* Air Force Institute of Technology.

Ford, T. C., Colombi, J. M., Graham, S. R., & Jacques, D. R. (2007). *A Survey on Interoperability Measurement.* Wright Patterson AFB OH: Air Force Institute of Technology.

Government Accountability Office. (2003). *Defense Acquisitions, Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns.* Government Accountability Office.

Government Accountability Office. (2003). *Defense Acquisitions, Steps Needed to Ensure Interoperability of Systems That Process Intelligence Data.* Government Accountability Office.

Government Accountability Office. (2003). *Military Space Operations: Common Problems and Their Effects on Satellite and Related Acquisitions.* Washington DC: Government Accountability Office.

Government Accountability Office. (2004). *Defense Acquisitions, Space-Based Radar Effort Needs Additional Knowledge before Starting Development.* Government Accountability Office.

Government Accountability Office. (2005). *Defense Acquisitions: Incentives and Pressures that Drive Problems Affecting Satellite and Related Acquisitions.* Government Accountability Office.

Government Accountability Office. (2006). *Geostationary Operational Environmental Satellites, Steps Remain in Incorporating Lessons Learned from Other Satellite Programs.* Government Accountability Office.

Government Accountability Office. (2006). *Space Acquisitions, DOD Needs Additional Knowledge as it Embarks on a New Approach for Transformational Satellite.* Government Accountability Office.

Government Accountability Office. (2007). *Environmental Satellite Acquisitions, Progress and Challenges.* Government Accountability Office.

Government Accountability Office. (2008). *Space Acquisitions, DoD's Goals for Resolving Space Based Infrared System Software Problems are Ambitious.* Government Accountability Office.

Government Accountability Office. (2009). *Geostationary Operational Environmental Satellites, Acquisition Is Under Way, but Improvements Needed in Management and Oversight.* Government Accountability Office.

Government Accountability Office. (2009). *Polar-Orbiting Environmental Satellites, With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Government Accountability Office.

Government Accountability Office. (2010). *Defense Acquisitions, Assessments of Selected Acquisition Programs.* Washington DC: Government Accountability Office.

Government Accountability Office. (2010). *DOD Poised to Enhance Space Capabilitites, but Persistent Challenges Remain in Developing Space Systems.* Government Accountability Office.

Hamel, M. L. (2007). *Space Test and Evaluation.* Los Angeles: Space and Missile Systems Center.

Headquarters, Department of the Army. (2009). *Army Regulation 900-1, Department of the Army Space Policy.* Washington DC.

Institute for Defense Analyses. (2008). *Leadership, Management, and Organization for National Security Space.* Alexandria VA: Institute for Defense Analyses.

Kasunic, M., & Anderson, W. (2004). *Measuring Systems Interoperability: Challenges and Opportunities.* Carnegie Mellon University.

Massachusetts Institute of Technology, INCOSE, and PSM. (2010). *Systems Engineering Leading Indicators Guide, Version 2.0.* Lean Advancement Initiative, Systems Engineering Advancement Research Initiative, International Council on Systems Engineering, PSM.

NPOESS Independent Review Team. (2009). *Final Report.*

Office of the Secretary of Defense. (2005). *Report to the Defense and Intelligence Committees of the Congress of the United States on the Status of the Space Based Infrared System Program.* Washington DC.

Office of the Undersecretary of Defense for Acquisition, Technology and Logistics. (2003). *Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs.* Washington DC: Office of the Undersecretary of Defense for Acquisition, Technology and Logistics.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
December 2010	Master‘s Thesis	Jan 2009 – Dec 2010

4. TITLE AND SUBTITLE	
A Space Acquisition Leading Indicator Based On System Interoperation Maturity	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Shibata, Jason T., Major, USAF	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865	AFIT/GSE/ENV/10-D02DL
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Jay McClain, SMC/DPSI 483 North Aviation Blvd El Segundo CA 90245-2808 DSN: 633-6274, COM: 310-653-6274, jaye.mcclain@losangeles.af.mil	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Department of Defense‘s space acquisition enterprise has experienced numerous challenges since the advent of space power. Space borne capabilities are needed more than ever, but space acquisition frequently fails to meet its goals. The decades of space acquisition experience form a rich history that can be used to build a leading indicator of success to enable effective program execution. First, the space acquisition areas of greatest concern were determined to be cost, schedule and requirements. These areas are considered as systems composed of the people, processes and products that execute the program. Second, the vital interoperation characteristics, or attributes that each system must possess to be successful, can be extracted from past space acquisition lessons learned and placed into an interoperability maturity model. The maturity model can then be used to capture the relative maturity of the program‘s major systems and their ability to interoperate within the context of each critical characteristic. Third, the maturity model forms the basis for an interoperability measurement using the method developed by Dr. Thomas Ford, where higher levels of interoperability maturity will result in a higher interoperability score. The process is demonstrated with three recent space programs with interpretive analysis provided.

15. SUBJECT TERMS

SPACE SYSTEMS, ACQUISITION, INTEROPERABILITY, MEASUREMENT

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			John M. Colombi, Ph.D.
U	U	U	UU	125	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3355, x3347 (john.colombi@afit.edu)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18