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TECHNICAL
REPORT

Guidelines and Metrics for Assessing Space System Cost Estimates

Bernard Fox, Kevin Brancato, Brien Alkire

Prepared for the United States Air Force

RAND PROJECT AIR FORCE

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Preface

This report responds to the Air Force Cost Analysis Agency's (AFCAA's) need for a single reference document for reviewing cost estimates for space acquisition programs. The AFCAA reviews estimates developed by program offices and field activities for completeness, consistency, and reasonableness in support of Secretary of the Air Force acquisition and budget decisions. Since a single analyst (or, at best, a small team) must do these reviews relatively quickly, a single reference containing the following types of information was needed:

- relevant background information on space system components and their cost drivers
- guidance for conducting reviews
- historical cost ranges for various components
- brief discussion of common issues encountered in estimating space programs
- summary descriptions of estimating resources available within the AFCAA.

This handbook is intended to be a dynamic reference that will be expanded and updated as additional data become available. It can also serve as a guide for anyone charged with reviewing estimates of space programs. The majority of the research for this handbook was completed as of December 2005.

This project was sponsored by the Air Force Cost Analysis Agency under a project entitled "Cost, Risk, and Technical Assistance to the Air Force Cost Analysis Agency." It was conducted within the Resource Management Program of RAND Project AIR FORCE. This report should be of interest to government cost analysts who are developing or reviewing estimates of space acquisition programs. It should be particularly useful to junior cost analysts with limited space systems experience.

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Summary

This handbook is designed to help analysts assess cost estimates of space systems. It assumes that the reader understands common cost analysis methodologies but has limited experience with space systems. Its objective is to give the analyst tasked with reviewing an estimate information to help accomplish the following tasks:

- Plan the review.
- Identify the key programmatic, technical, and cost data needed, along with suggested sources.
- Highlight common issues to investigate.
- Provide typical cost ranges for components of relevant historical space programs.

This handbook also supplements the AFCAA's spacecraft training course by focusing on the cost analysis implications of the systems and processes covered in the course.[1] Intended to be a dynamic reference, evolving and expanding as useful material becomes available, it is organized as follows:

- Chapter One is a brief introduction to the importance of space systems for the U.S. Department of Defense (DoD) and the challenges of developing accurate estimates of their costs.
- Chapter Two provides an overview of space systems. It discusses various missions and their effects on system architecture, design, and cost. It then briefly describes the major components of typical DoD space systems, focusing on functions and common design approaches and their implications for cost. It highlights typical risk areas to give the analyst a sense of where cost and schedule problems have occurred in past programs.
- Chapter Three provides guidelines for planning and conducting a typical review, data requirements and likely sources, and common problem areas.

[1] *U.S. Air Force Cost Analysis Agency (AFCAA) Training Curriculum: Fundamentals of Design, Engineering, and Production for Spacecraft* (AFCAA, 2004) is part of the AFCAA's training curriculum and provides an introduction to space mission design, systems engineering, space vehicle subsystems, and launch and orbital operations. The course is offered periodically by AFCAA for government personnel and their supporting contractors.

- Chapter Four provides average costs and ranges for space vehicles, subsystems, and components to provide the analyst with a source of readily accessible crosschecks and to provide a resource for estimating the end points of risk distributions.
- Chapter Five describes common issues encountered in estimating the cost of space programs. These include small satellites, cost improvement in low-volume programs, use of commercial off-the-shelf (COTS) components for space applications, and the challenges of cost estimating under evolutionary acquisition.
- Chapter Six provides summary descriptions of some common cost models available to AFCAA for space programs.
- Chapter Seven presents recommendations for future additions to the handbook.
- Appendix A contains the portions of the standard Military Handbook 881B (MIL-HDBK-881B) work breakdown structure (WBS) relevant for space systems.
- Appendix B contains the Unmanned Space Vehicle Cost Model (USCM) Version 8 WBS dictionary, as the crosschecks follow its structure.
- Appendix C contains the portions of the standard MIL Handbook-881A WBS relevant for space systems. This replaces MIL-HDBK-881B for new programs.
- Appendix D contains the National Reconnaissance Office (NRO) WBS, which extends MIL-HDBK-881A to lower levels of detail.
- Appendix E is an extract of the Office of the Secretary of Defense (OSD) Cost Analysis Improvement Group (CAIG) criteria for DoD cost estimates.
- Appendix F provides a checklist for cost risk analysis.
- Appendix G contains guidance for changing the crosscheck prediction interval levels of significance.
- A bibliography provides sources of additional information on the topics covered.

Acknowledgments

The success of a project like this depends on contributions from many sources. Col Ron Phillips provided the initial impetus to develop a handbook that could be a practical resource for AFCAA analysts tasked with reviewing space system cost estimates. Lt Col Tom Mick provided early direction and access to AFCAA resources and analysts. Duncan Thomas, Jill Allen, and Maj John Dubelko provided active support and thoughtful comments, which have hopefully resulted in a document that is more useful to AFCAA, as well as other organizations in the government space community. Deidre Eberhardt of the Air Force Space and Missile Systems Center and Mike Pfeiffer of Tecolote Research provided access and insight into the data from which the crosschecks were developed.

We are particularly indebted to the reviewers of this work, James Dryden and Jerry Sollinger of RAND and Tim Anderson of the Aerospace Corporation, for their constructive comments and helpful suggestions, which greatly improved the usability of the document. We would also like to thank Nathan Tranquilli and Holly Johnson for their tireless administrative support on this project.

Abbreviations

ACE	Advanced Composition Explorer
ACS	Advanced Camera for Surveys
ADCS	attitude determination and control subsystem
AFCAA	Air Force Cost Analysis Agency
AKM	apogee kick motor
BAT	Burst Alert Telescope
BM/C3	battle management/command, control, and communications
BOL	beginning of life
C3	command, control, and communications
C&DH	command and data handling
CAIG	Cost Analysis Improvement Group
CARD	Cost Analysis Requirements Description
CCDR	Contractor Cost Data Report
CDRL	contract data requirements list
CER	cost estimating relationship
CMG	control moment gyro
COBE	Cosmic Background Explorer
COEA	cost and operational effectiveness analyses
COTS	commercial-off-the-shelf
DAB	Defense Acquisition Board
DARPA	Defense Advanced Research Projects Agency
DMSP	Defense Meteorological Satellite Program

DoD	U.S. Department of Defense
DSCS	Defense Satellite Communications System
DSP	Defense Support Program
EA	evolutionary acquisition
EEE	electrical, electronic, and electromechanical
EELV	Evolved Expendable Launch Vehicle
EGSE	electrical ground-support equipment
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EM&T	engineering management and test
EOL	end of life
EPS	electrical power subsystem
ESWBS	extended ship work breakdown structure
EUVE	Extreme Ultraviolet Explorer
FAST	Fast Auroral Snapshot
FBC	faster, better, cheaper
FLTSAT	Fleet Satellite Communications System
FPGA	field programmable gate array
FUSE	Far Ultraviolet Spectroscopic Explorer
FYDP	Future Year Defense Program
G&A	general and administrative
GEO	geosynchronous orbit
GFE	government-furnished equipment
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSE	ground-support equipment
He Si	high-efficiency silicon
HETE	High-Energy Transient Explorer

I&T	integration and test
IA&T	integration, assembly, and test
IEM	integrated electronics module
IMU	inertial measurement unit
IPS	integrated propulsion subsystem
IPT	integrated product team
JPL	Jet Propulsion Laboratory
KPP	key performance parameter
LDR	low data rate
LEO	low earth orbit
LOOS	launch and orbital operations support
MBA	multibeam antenna
MEO	medium earth orbit
MGSE	mechanical ground-support equipment
MIL-HDBK	military handbook
MNS	Mission Needs Statement
MODIS	Moderate Resolution Imaging Spectroradiometer
MUPE	minimum unbiased percentage error
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NDI	nondevelopmental item
NEAR	Near-Earth Asteroid Rendezvous
NICMOS	Near Infrared Camera and Multi-object Spectrometer
NRO	National Reconnaissance Office
O&S	operating and support
ORD	Operational Requirements Document
OSD	Office of the Secretary of Defense
P3I	preplanned product improvement

PCD	power conditioning and distribution
PCU	power control unit
PDU	power distribution unit
PEP	producibility engineering planning
PM	program management
POE	program office estimate
POL	petroleum, oil, and lubrication
QAIV	quantity as an independent variable
QML	qualified manufacturer list
QPL	qualified parts list
RCS	reaction control subsystem
R&D	research and development
RF	radio frequency
RTS	remote tracking station
SAGE	Stratospheric Aerosol and Gas Experiment
SAMPLEX	Solar Anomalous and Magnetospheric Particle Explorer
SCF	satellite control facility
SCP	spacecraft control processor
SEMP	Systems Engineering Management Plan
SE/PM	systems engineering/program management
SEi	Space Electronics Incorporated
SEIT/PM	systems engineering, integration, and test/program management
SIRTF	Space Infrared Telescope Facility
SMCE	science mission cost effectiveness
SNOE	Student Nitric Oxide Explorer
SOHO	Solar and Heliospheric Observatory
SSPA	solid state power amplifier
STAR	System Threat Assessment Report

STC	Satellite Test Center
SWAS	Submillimeter Wave Astronomy Satellite
T_1	theoretical first unit cost
TC	thermal control
TDRSS	Tracking and Data Relay Satellite System
TEMP	Test and Evaluation Master Plan
TERRIERS	Tomographic Experiment Using Radioactive Recombinative Ionosphere Extreme Ultraviolet and Radio Sources
TOPEX	The Ocean Topography Experiment
TT&C	telemetry tracking and command
TRACE	Transition Region and Coronal Explorer
TWTA	traveling wave tube amplifier
USAF	U.S. Air Force
USCM	Unmanned Space Vehicle Cost Model
USN	U.S. Navy
UV	ultraviolet
UVOT	UV Optical Telescope
VAMOSC	Visibility and Management of Operating and Support Costs
WBS	work breakdown structure
WGS	Wideband Global Satellite Communications
WIRE	Wide-Field Infrared Explorer
XRT	X-ray Telescope
XTE	X-Ray Timing Explorer

CHAPTER ONE

Introduction

Defense transformation and the global war on terror have raised the priority of space systems within the U.S. Department of Defense (DoD). The demand for near real-time intelligence, surveillance, and reconnaissance information; reliable high-volume communications between widely dispersed and highly mobile units; precise autonomous navigation in any location under all conditions; environmental information to support a wide range of missions and users; and assurance that some form of space control could be exercised if needed have led to a broad expansion of the roles spacecraft perform and the users they support. Space programs are key components of DoD's plans for transformation.

Estimating the Cost of Space Systems Poses Special Problems

Space programs have also been noteworthy for their high cost and seemingly persistent cost growth as they move from concept to orbit. Estimating the cost of space programs is in many ways similar to estimating costs of other military systems. The basic methodologies all require an understanding of the historical costs of similar programs. They involve some form of extrapolation from the historical data, adjusting for the programmatic and technical characteristics of the program being estimated. Estimates of software size or functionality must also be developed to estimate its cost. The uncertainty of the methodologies themselves, as well as in the technical and programmatic inputs, contributes to risk, which must be quantified for the decisionmaker.

But estimating the cost of space systems also involves key differences. Such systems put a premium on light weight, high reliability, long life, and autonomous operation. Operating in space requires designs that in many cases must tolerate high levels of radiation and large, repetitive temperature swings for years. The result is that specialized low-production components are knit into tightly integrated spacecraft in which a problem in one area will often cause problems in several others. In the space applications, the payoff from the successful integration of new technologies can be unusually high, as are the costs of failure. Despite attempts to standardize spacecraft to reduce nonrecurring costs and simplify production, most DoD space programs still have a high degree of customization. Taken together, these factors, along with the relatively small amount of relevant historical data, make the cost analyst's job a challenging one.

What This Handbook Contains, Who Should Use It, and How

This handbook provides an introduction to these challenges for cost analysts who have limited experience with space programs. It may also be useful for those who are not cost analysts but who are involved in the development and acquisition of space systems and thus must use cost estimates developed by others. It is not intended to be a complete description of the various principles and methodologies used in developing these estimates. A number of such references are available. Rather, the goal is to provide the reader sufficient background to evaluate the completeness, reasonableness, and consistency of space system estimates and to highlight common problem areas.

For both cost analysts and those interested in learning more about the development and acquisition of space systems, we recommend reading the main part of the document (Chapters One through Seven) in its entirety. After gaining a general knowledge of the handbook's contents, cost analysts can then refer to individual chapters for information on specific issues on an as-needed basis. The plan is to update the chapters as new data become available so that the handbook will remain a current and useful reference.

CHAPTER TWO

Space System Fundamentals

This chapter provides an overview of the characteristics of space systems, focusing on those that tend to affect cost. It describes the common types of missions for space systems and how cost analysis can help define and focus early program planning. The remainder of the chapter explains the primary elements of a space program, focusing on how they contribute to the cost of the system.

Missions

The mission of a space program defines its purpose and has a major influence on its ultimate design and, therefore, its cost. Top-level mission specifications provide program managers and developers with guidance concerning user priorities and provide the basis for derived performance specifications. Even at this early stage, rough cost estimates are often needed to support initial planning and comparisons of alternatives. This is challenging for the cost analyst, since many technical characteristics have not been determined. The central tendencies and distribution of cost provided in the crosschecks contained in Chapter Four may help in developing and validating these early estimates. The translation of the general mission objectives into specific performance expectations (called key performance parameters, or KPPs) begins to narrow the mission concepts and system architecture alternatives and therefore the range of probable system costs. The DoD requirements process attempts to carefully select and quantify the KPPs without overspecifying and possibly eliminating other cost-effective approaches. Functional requirements describe what each portion of the system will do and are derived from the mission objectives, KPPs, and constraints such as cost, schedule, weight, and available technology. Although challenging to develop, credible cost input at this early stage, before detailed technical descriptions are available, can be of critical value to decisionmakers by helping to do the following:

- Match desired performance specifications to likely funding levels.
- Ensure that the likely cost impact of additional missions or requirements is considered before they are approved.
- Assist in setting achievable performance thresholds and objectives within acceptable levels of risk.

- Provide metrics to assist stakeholders in arriving at a "best value" combination of performance and affordability.

These actions address areas that in the past have impacted space systems cost and schedule growth. Because many of the parameters that underlie these decisions must be estimated in the early stages, the system definition process is, by necessity, iterative. The thoroughness and realism of this process will strongly influence the ultimate success of the program. In fact, some experienced observers feel that requirements stability is the single most important factor in avoiding cost and schedule overruns (Griffin and French 1991, p. 8; Wertz and Larson, 1999, p. 78). Requirements stability is a particular challenge for space systems because the diversity of users tends to result in numerous, ill-defined, evolving, and sometimes conflicting requirements.

The missions that can be performed from space or supported by space-based systems have evolved with the capabilities of spacecraft and their payloads. They can be classified in various ways depending on the perspective of the user. For consistency, in this handbook, we will generally follow the mission categories used in the Unmanned Space Vehicle Cost Model (USCM), Version 8, which are

- communication
- navigation
- meteorological (including environmental)
- experimental
- scientific
- surveillance
- radar.

To better characterize certain NASA missions, we broadened "meteorological" to "environmental" to include nonweather earth-observing missions of various types. The definitions of these categories are of necessity somewhat subjective, with some satellites potentially fitting into different categories depending on their dominant mission or characteristics. Once mission requirements are specified, iterative trade-off analyses are performed to determine the optimum orbital and spacecraft characteristics. Because of the interrelationship among orbit, constellation, and spacecraft alternatives, there may be several feasible architectures that can potentially satisfy the mission requirements. Estimates of the relative costs of each alternative are key inputs to this critical decision. As alternatives are narrowed and become better defined, these decisions should be revisited to ensure that the initial conclusions remain valid. Table 2.1 gives examples of the typical orbital and spacecraft characteristics in each of the mission categories.

Table 2.1
Typical Characteristics by Mission Type

Mission Type	Orbit	Size	Power	Other
Communication	GEO MEO/LEO[a]	Large Med/Sm[a]	High Low[a]	
Navigation	Semisynchronous	Medium	Medium	
Environmental	Various	Various	Various	Observation of earth and its environment
Experimental	Various	Small	Low	Demonstrations; minimizing cost, maximizing use of proven and available components
Scientific Surveillance	Sun-synchronous Molniya GEO Interplanetary	Large	High	Large, specialized spacecraft and payloads for space and earth observation

NOTE: Orbits can be generally characterized as low earth orbit (LEO), medium earth orbit (MEO), or geosynchronous earth orbit (GEO). For equivalent coverage of the earth's surface, LEO will require more satellites, less-capable launch vehicles with the benefits of higher sensor resolution and lower-power payloads. GEO offers wide-area coverage with fewer satellites but requires higher launch-vehicle performance, higher-power payloads, and increased radiation tolerance. Specialized orbits, such as sun-synchronous and Molniya, are used when mission profiles require consistent positions with respect to the sun or improved coverage of high latitudes respectively. For additional information on orbital selection and constellation design, see Wertz and Larson (1999). From a cost perspective, it is important to remember that spacecraft with different missions may, in some cases, have similar subsystems or components. This can provide designers with the option of using proven components and cost analysts with useful analogs from previous programs.

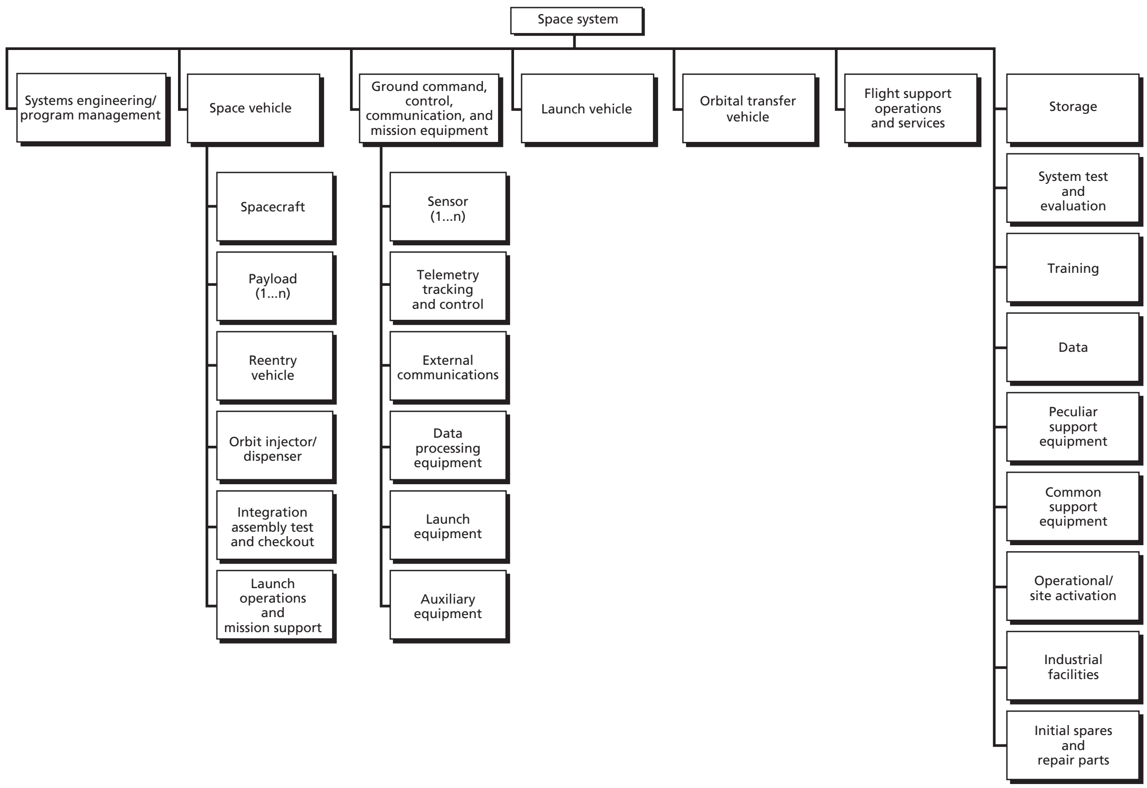
[a] If part of a constellation

Space System Elements

A space system is a carefully integrated combination of mission payload(s), spacecraft "bus," launch adapter, launch vehicle, ground segment, and various service and support equipment to enable production, testing, launch, and operation. This section provides an overview of the various components of a typical DoD space system. The intent is to provide a general orientation for analysts unfamiliar with space systems.

A comprehensive work breakdown structure (WBS) provides a good road map for understanding the components of any system and their relationship to one another. The WBS also provides a useful framework for building a cost estimate. In the DoD space arena, there are at least three common WBSs that may be encountered. Until recently, the "standard" WBS for all DoD space systems was contained in Military Handbook 881B (MIL-HDBK-881B) (Figure 2.1). The MIL-HDBK has appendixes that define WBS elements for specific types of systems and one for elements such as systems engineering/program management (SE/PM), which are common to all systems. It was intended to provide a consistent framework and is defined only to three levels. It may be extended to lower levels of detail as needed by each program. The space WBS includes launch vehicles, ground support equipment, and support costs. Appendix A provides definitions of each element. As with any standard, it must be tailored to reflect only the relevant elements for the system of interest.

Figure 2.1
MIL-HDBK-881B WBS



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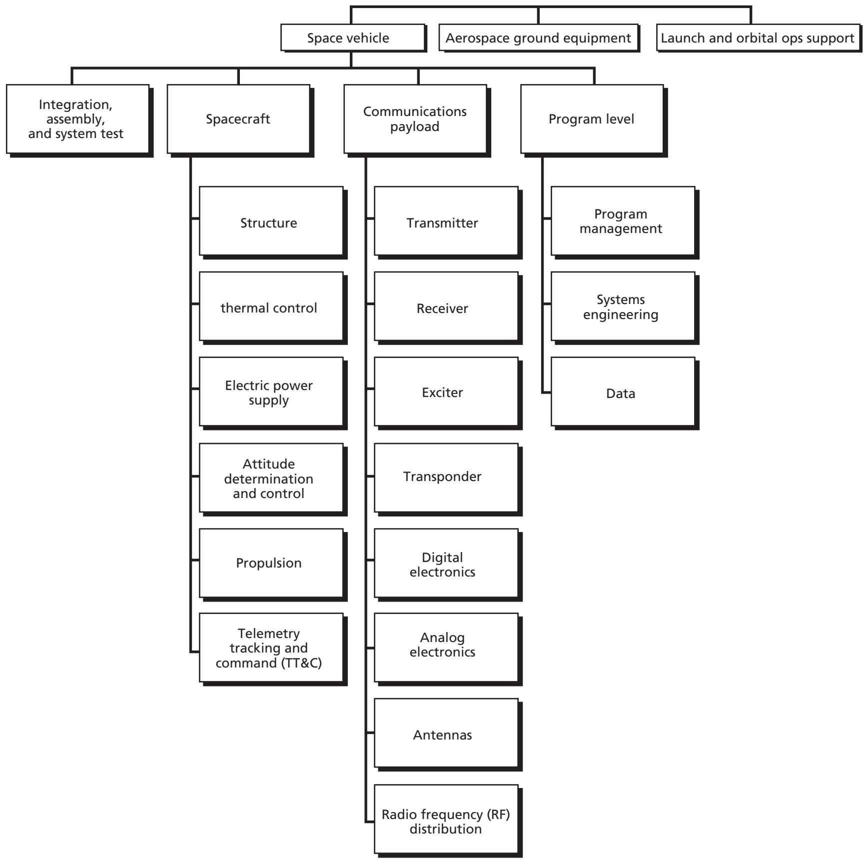
For various reasons, the WBS used for USCM differs somewhat from MIL-HDBK-881B. Its breakout reflects the structure of the USCM model and the industry data on which the model is based. Extended in some areas down to five levels, it addresses only space vehicles, aerospace ground equipment, and launch and orbital operations support. The USCM WBS is provided as Appendix B and shown in Figure 2.2.

MIL-HDBK-881B has been recently superseded, somewhat illogically, by MIL-HDBK-881A. The space portions of MIL-HDBK-881A are based on the top levels of the WBS used by the National Reconnaissance Office (NRO). The NRO WBS, specified to as many as ten levels, attempts to give visibility to support estimating and analysis at a very low level of detail. When necessary, the MIL-HDBK-881A space WBS (Figure 2.3) can be directly extended by using the lower levels of the NRO WBS. The NRO permits its contractors or program offices to use any WBS; however, it does require that contractors map their WBS into the NRO standard WBS for cost reporting. The MIL-HDBK-881A/NRO WBS addresses space vehicles, ground segment, launch, support, and other government costs. Extracts of the MIL-HDBK-881A and the NRO WBSs are contained in Appendixes C and D, respectively.

Familiarity with each of these WBSs is useful because the MIL-HDBK has been the DoD standard for historical data, the USCM WBS reflects the structure of a common cost-

Figure 2.2
USCM WBS



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estimating tool used throughout the DoD space community, and the NRO WBS potentially provides visibility down to the "box" level and is the basis for the new DoD standard. Future versions of the USCM model will follow the 881A/NRO WBS.[1] During the transition period, cost analysts may encounter any or all three, so a working knowledge of each is useful. More important is an understanding of which WBS is applicable to the data/cost model being used and the definitions of the cost elements.

For clarity, we generally follow the current USCM structure, since the crosschecks in Chapter Four are based on its definitions. In the discussion that follows, we also describe a number of elements that are part of most space systems but are not included in the USCM.

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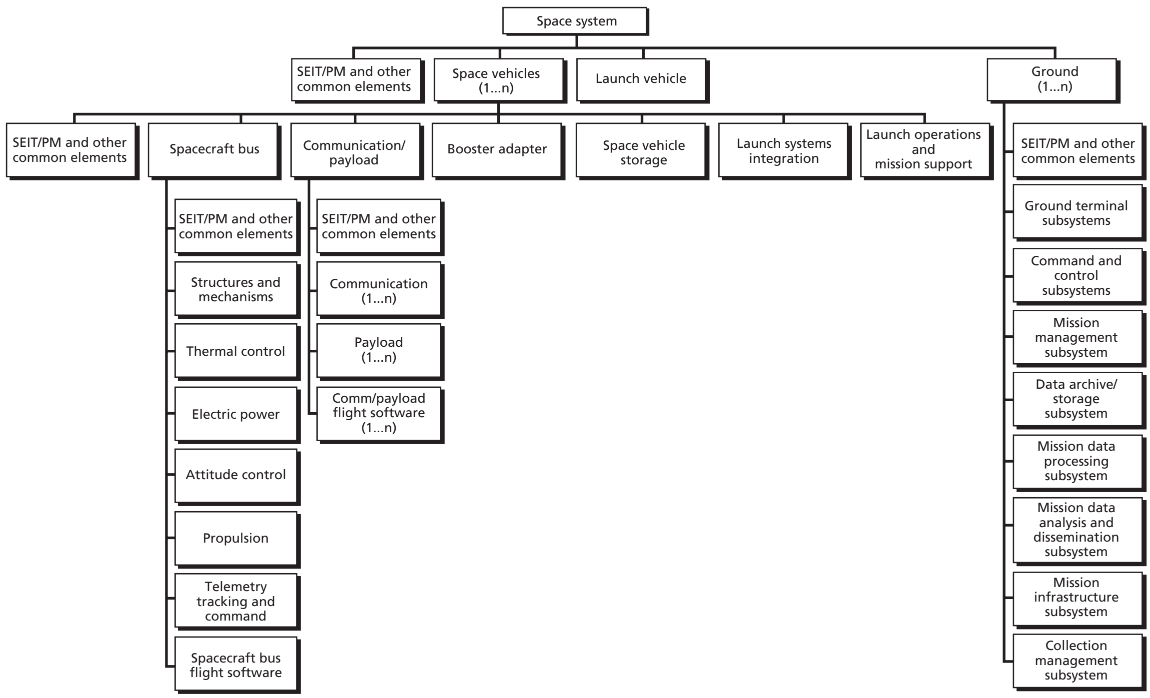
1 Recently, NASA has also adopted a standard WBS that is similar to MIK-HNBK-881A, with modifications for NASA-unique functions.

Figure 2.3
MIL-HDBK-881A WBS



NOTE: SEIT/PM = systems engineering, integration, and test/program management.
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Space Vehicle

The space vehicle consists of the following elements:

- mission, communication, and other payloads
- spacecraft
- integration, assembly, and testing
- launch vehicle adapter.

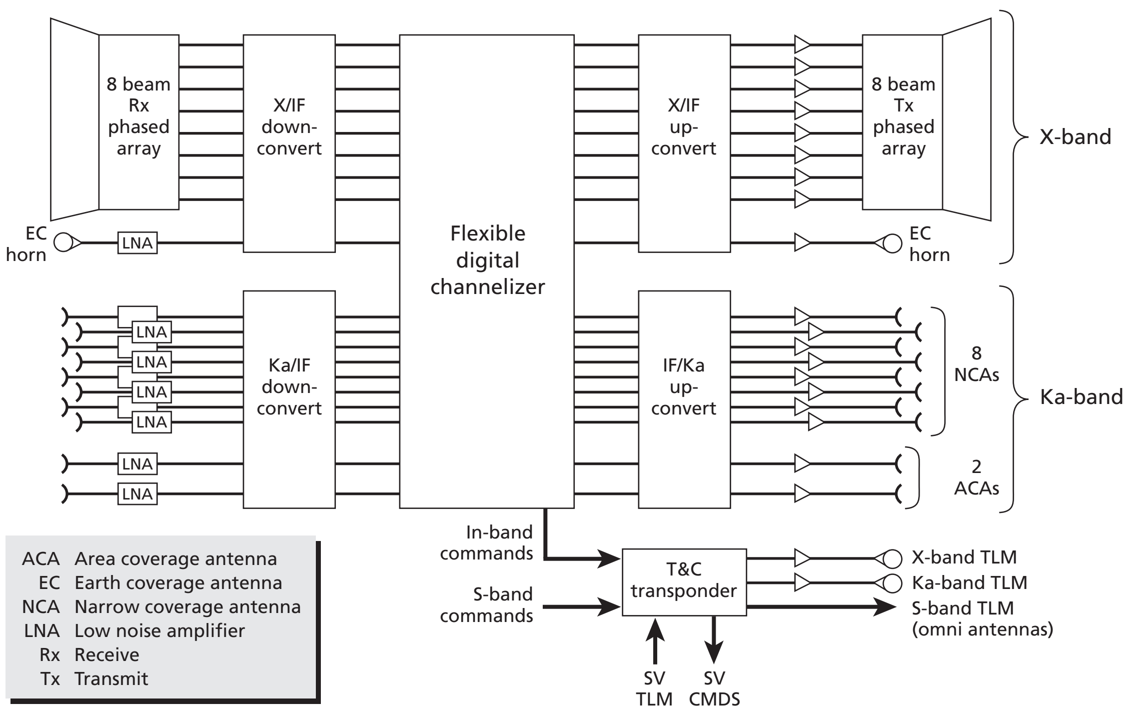
We discuss each briefly in turn.

Mission Payloads. Mission payloads are the primary element of any space system. They not only provide the functions that are the justification for the mission in the first place, but they also have a strong influence on the system operational concept, orbit selection, spacecraft and ground segment architecture, and the types of launch services required. Their design tends to be less standardized and their performance goals tend to be more challenging than those of the spacecraft bus that supports them. Payloads are often electronics intensive, which means that while the underlying technologies may be continually improving, proven space-qualified components may no longer be available because of their older technology and limited potential market.[2] Space qualification of components focuses on characteristics such as reliability and out-gassing (generating material that might contaminate other components) in the space environment. With the exception of communication payloads, which are often developed in house, specialists other than the spacecraft contractor frequently develop payloads. This means that the system prime contractor must not only integrate and test each payload with the spacecraft, but in missions flying multiple payloads, must avoid the payloads interfering with each other mechanically or electrically. This situation tends to make an already challenging system engineering task even more difficult. Payloads and their integration into the space vehicle are often the primary cost and schedule drivers of space programs.

Unfortunately, compared to spacecraft, there are relatively few broadly applicable payload cost databases or models. For all these reasons, cost analysts should generally allocate a substantial portion of their review efforts to assessing the cost, schedule, and risk of the planned payloads.

Communication Payloads. Communication payloads consist of one or more antennas, transmitters, receivers (or transceivers) and associated amplifiers, and transmission lines. An example is shown in Figure 2.4. The primary mission-level cost drivers are the amount of data

Figure 2.4
WGS Payload Block Diagram



SOURCE: Boeing. Used with permission.
RAND *TR418-2.4*

[2] It has been estimated that space electronic technology lags approximately five to ten years behind nonflight electronics (Griffin and French, 1991, p. 432).

to be transmitted per unit of time and the distance over which it must be sent. Depending on the system architecture, the communication payload can function as either a repeater (so-called "bent pipe"), which is relatively simple and reliable, or it can perform various processing functions onboard, which reduces noise and interference. Beam-forming antennas add performance and complexity.

Operating at higher frequencies can provide a number of advantages and disadvantages, as shown in Table 2.2. Because of these advantages, the general trend in satellite communication is toward ever-higher frequencies. The amount of data that can be transmitted per unit of time depends on the frequency range available to carry signals (bandwidth) and the type of modulation used. High bandwidth requires high-power or high-gain antennas. High-gain antennas provide narrow beams, which, in turn, require precise antenna pointing, increasing cost and complexity. In general, as frequency increases (or, equivalently, as wavelength decreases), the RF components get smaller, reducing both weight and volume. Unfortunately, they must be designed and built to higher standards to avoid unacceptable losses, thus increasing costs. They also generate additional heat, increasing thermal dissipation requirements.

Visible light, another form of electromagnetic energy, has a frequency even higher than the RF bands. Although there are substantial limitations in satellite to ground optical communication, the use of laser crosslinks between satellites offers the promise of very high data rates without frequency allocation problems. The very narrow beamwidth of laser transmitters provides inherently high security but requires very precise acquisition, pointing, and tracking, which increase complexity. For a given configuration, transmission power and antenna aperture are typically cost drivers. Data error checking and correction reduces data rate, as does encryption. Encryption equipment is generally provided as government-furnished equipment (GFE) to the contractor but must be integrated into the concept of operations as well as into the communication system itself.

Other Payloads. Other types of payloads include navigational and remote sensing. Navigational payloads broadcast radio signals, referenced to a very precise onboard time standard. These signals are received by user equipment, which compares signals from three or more satellites in the constellation to determine the user's precise position. Users may be on earth,

Table 2.2
Effects of Increasing Frequency in Communication Satellites

Advantages	Disadvantages
Increased bandwidth	Cost generally increases
Decreased component weight and size	Increased design complexity
Smaller antenna	Increased coaxial cable losses
Narrower beamwidth	Increased atmospheric or rain interference Increased signal shadows[a]

SOURCE: AFCAA (2004).

[a] Signal shadows are the result of interference by objects in the antenna beam. Lower frequencies can bend around objects better than higher frequencies.

airborne, or in LEO. Since navigational payloads are effectively RF beacons, their components are similar to communications payloads with similar characteristics.

Remote sensing encompasses a broad category of functions involving observing and measuring electromagnetic radiation from some distance. This includes radio frequency (radar and radiometers), infrared, visible light (cameras and telescopes), and X-ray and gamma ray radiation (telescopes). Although the designs of the payloads differ significantly, their functions are to collect, detect, and process passive or active electromagnetic emissions from the target objects.

Remote sensors generally have some form of the following components:

- antenna or telescope
- pointing mechanism
- detectors
- electronics
- thermal control
- structure.

They may also have some calibration capability. Some of these functions, such as pointing, may be partially or completely provided by the spacecraft or bus. This may save on weight and payload complexity but often complicates integration and spacecraft operations. This approach requires careful coordination between the bus and payload developers, particularly when different contractors build the spacecraft and payload or when there are multiple payloads competing for shared resources.

Cost-driving parameters for remote sensors include size, aperture, pointing accuracy, slew rate, number of detectors, operating temperature, resolution or sensitivity, and manufacturing yield. Cost drivers related to the operating concept include the degree of space segment autonomy and the number and capability of users. There is a general trend in most types of remote sensors toward onboard processing of data to reduce downlink bandwidth requirements and minimize demands on distributed or austere ground stations, which increases cost in the space segment. In USCM 8, communication of sensor output is captured in the TT&C elements of the WBS.

Spacecraft. The spacecraft provides structural support, protection, positioning, thermal control, electrical power, status monitoring, and two-way communication with the ground segment for the mission payload. These functions tend to have more commonality across missions than do payloads, so a larger pool of relevant cost and technical data is available. There are, however, many trade-offs made to optimize the spacecraft for a particular mission, so the analyst must still exercise caution in selecting analogous data for estimating purposes. In most cases, few spacecraft of a given configuration are made, so standardization is not as prevalent as with systems with large production quantities, such as aircraft or missiles. The space industry is attempting to increase standardization, generally at the subsystem level and below, to reduce both costs and development risks. Considerable savings can be realized by the use of industry-standard architectures, components, and interface specifications; however, this is often difficult in military space applications with its low-volume production and unique performance requirements. Figure 2.5 illustrates the Swift space vehicle and some of its external components.

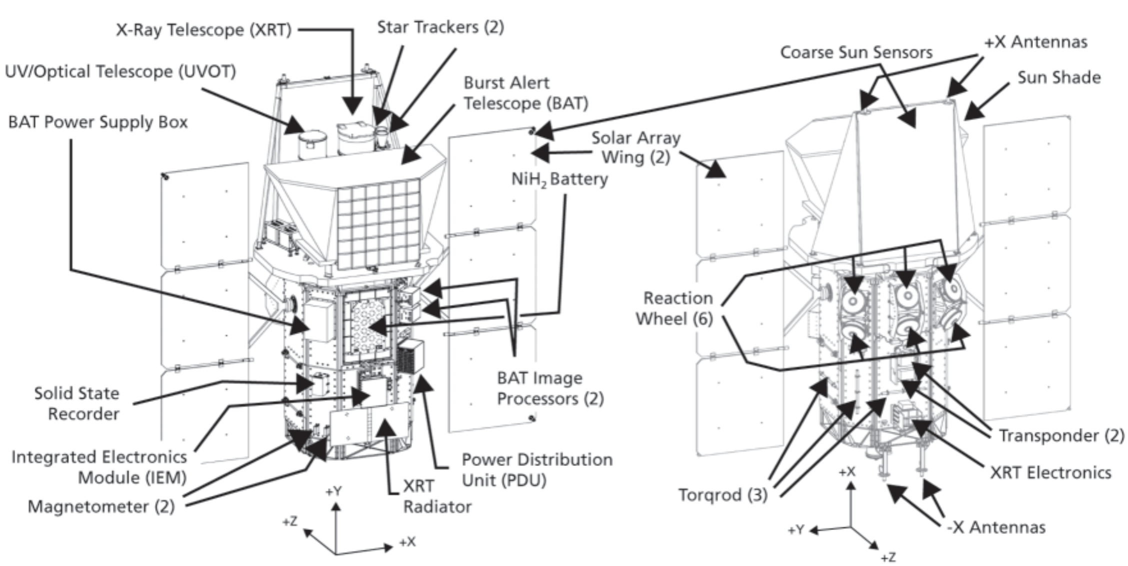
Following the USCM terminology, the generic unmanned spacecraft is composed of the following subsystems:

- structure
- thermal
- attitude determination and control
- electrical power
- propulsion
- telemetry, tracking, and command.

These are covered in detail in AFCAA (2004), Wertz and Larson (1999), and Griffin and French (1991). For the purposes of this section, we will briefly describe each subsystem's function, provide a few observations about issues relevant to estimating it, and identify common cost drivers. Additional discussion of the content of each subsystem is available in Appendix B. Table 2.3 lists common space vehicle cost drivers with arrows to indicate the approximate magnitude and direction of their effects on cost.[3]

Structure. The spacecraft structure provides the framework around which the rest of the spacecraft is built. Since all other subsystems, including payload(s), are in some fashion

Figure 2.5
Swift Space Vehicle



SOURCE: Courtesy of Spectrum Astro. Used with permission.
RAND *TR418-2.5*

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[3] Note that the arrows on this and subsequent cost-driver tables indicate the relative magnitude of cost effects within that subsystem or cost element only. They are not comparable across the entire system.

Table 2.3
Space Vehicle Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Altitude (larger launch vehicle, higher power, larger antennas and telescope apertures, orbit average downlink rate)	↑↑↑
Mass (launch vehicle)	↑↑
Size (drives structure stiffness, fairing size)	↑
Power (drives array design, spacecraft size, thermal design)	↑↑
Data rate (drives antenna size, altitude, onboard memory, necessity for relay satellites)	↑↑
Pointing accuracy (drives structure stiffness, mass, attitude determination and control system [ADCS] components required, ADCS software complexity)	↑↑
Number of telemetry points (drives harness mass, software size, testing, ease of anomaly resolution during integration and technology [I&T] and in orbit)	↑
Reliability (drives redundancy, testing complexity, mass)	↑↑
Radiation (high radiation tolerance drives redundancy, lifetime, shielding mass, more expensive hardened components)	↑
Lifetime (drives redundancy, array size, consumable mass)	↑
Number of payloads (increases number of interfaces, testing complexity)	↑↑
Number of organizations and people involved (level of oversight, documentation, potential for inefficiencies)	↑↑↑
Documentation (need appropriate amount for size of project; too little for a large project results in poor communication and rework; too much for a small project increases costs)	↑↑
Level of heritage (can increase reliability and lower costs; may increase complexity of component interfaces; costs per satellite lower for constellations)	↓
Continuity of team (high turnover creates errors and inefficiency)	↓
Maturity of design (drives number of late changes)	↓↓
Schedule (too long increases "standing army" costs; too short causes increased rework due to errors and inadequate testing)	↑↑

SOURCE: AFCAA (2004).

attached to it, its design must accommodate many, often conflicting objectives. Because of the commonality of basic functions aboard most spacecraft, industry has evolved so-called "standard" buses, which start with a relatively adaptable core that can often be configured to meet similar mission requirements. If only relatively minor changes are required, this may save considerable effort in the development phase, since previous missions have qualified the core design. Many of the other components may also be carried over, assuming that they can meet the requirements of the mission and payload(s). However, modification, or even combining proven components into new configurations, will require testing to verify that their behavior or performance is as projected. The costs of developing, fabricating, and testing these modifications are commonly overlooked or underestimated.

In designing spacecraft structure, allowing for adequate margins is critical because late changes can come from many sources. Additionally, excessively dense packaging can complicate preflight installation and testing. Cost drivers, such as strength, stiffness, and size, depend on the payload requirements and booster loads and how difficult they are to meet with conventional design and materials. While most programs will attempt to use a commercial or "standard" bus design, military payloads often require significant changes because of size, pointing accuracy, or other requirements and thus do not realize the potential cost savings associated with their use. Booster fairing size limitations require large appendages to be folded for launch operations. Structure usually includes the mechanical components used to deploy folded assemblies, such as solar arrays and antennas, once in orbit. It also includes secondary structures, such as mounting brackets. Table 2.4 summarizes structure cost drivers and the approximate relative magnitude and direction of their effects.

Thermal. The function of the thermal control subsystem is to maintain all space vehicle components within their prescribed temperature limits. The primary sources of heat are the sun, the earth, and onboard systems. In space, the lack of an atmosphere to moderate temperature changes can result in extremes of hot and cold and fluctuations between the two. Large fluctuations occur when the space vehicle goes into or out of eclipse—the shadow of the earth. The space thermal environment is a consideration in the design of nearly every component of the space vehicle.

Spacecraft thermal control approaches are generally classified as passive or active. Passive systems have no moving parts and require no external control. They are usually reliable and relatively inexpensive. Passive thermal controls include

- coatings
- insulation
- doublers (additional thermally conductive material)
- radiators
- heat pipes, which require no external power source.

Active systems usually involve some sort of thermostatic control and external power. They are used where passive approaches are insufficient to maintain required temperature ranges. Active devices include

- heaters
- louvers (rare)
- active heat pipes
- cryogenic systems.

To design the thermal control subsystem, engineers must model the entire space vehicle in all of its operating and environmental states to determine what mix of thermal controls will maintain the prescribed temperature limits. These calculations and their designs are validated

Table 2.4
Structure Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Reuse of heritage design (reduces design and analysis time, reuse tooling, models, mechanical ground-support equipment [MGSE])	↓↓↓↓
High mass margin (simplifying assumptions used to bound solution)	↓↓
Exotic materials (composites or beryllium)	↑↑↑
Full qualification test program (pre- and post-test analysis, data reduction, plans, reports)	↑↑↑
High design/mechanism complexity (increases design, analysis, testing, parts)	↑↑↑
Tight thermal stability (requires detailed modeling, often leads to exotic material)	↑↑↑↑
Complete formalized documentation	↑↑
Inadequate definition or changing requirements (numerous analysis or design cycles, mass, power changes common)	↑↑↑
Modularity of subsystems	↓↓↓
Tight pointing alignment requirement (requires tight tolerances)	↑↑

SOURCE: AFCAA (2004).

in thermal balance and thermal vacuum testing. The primary thermal control system cost drivers are the thermal requirements of the various components of the space vehicle. Costs increase with the extent of active thermal control required. Table 2.5 summarizes thermal cost drivers and the approximate relative magnitude and direction of their effects.

Attitude Determination and Control. The ADCS is one of the most complex areas of spacecraft design. As its name implies, it senses the spacecraft attitude with respect to some known references and provides corrective forces of the proper magnitude and direction to establish and maintain the desired orientation. There are many potential combinations of mechanisms used to accomplish these functions. Their selection for a particular spacecraft is a function of orbit, lifetime, orientation or pointing requirements and accuracy, weight, reliability, and cost.

Attitude determination can be accomplished by various combinations of sensors, such as

- sun sensor
- magnetometer
- star tracker
- global positioning system (GPS) receiver
- inertial measurement unit.

Table 2.5
Thermal Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Vehicle classification (Class A, B, C, or D)	
Class A space vehicle	↑↑↑
Class B space vehicle	↑↑
Class C space vehicle	↓
Class D space vehicle	↓↓
Long mission life	↑↑
Payload accommodation requirements	
Coupled payload instruments	↑↑
Isolated payloads/instruments	↓
Cryogenic application	↑↑
Orbital environment	
LEO	↓
MEO	↑
GEO	↑↑↑
MIL-STD-1540E thermal margins	
No tailoring of 11°C margin	↑↑
Reducing 11°C margin to 5°C	↓
Use of 2 phase heat pipes	
Use of capillary pumped loops	↑↑↑↑
Use of loop heat pipes	↑↑↑↑
Use of variable conductance heat pipes	↑↑
Use of constant conductance heat pipes	↑
No heat pipes	↓
Use of deployable radiators	↑↑
Development thermal vacuum testing	↑

SOURCE: AFCAA (2004).

NOTE: Space vehicle classes are a shorthand way of characterizing the reliability standards to which a space vehicle is designed and built, with A being the most stringent and D the least (NASA, 2004).

Once the spacecraft attitude is sensed, the attitude determination electronics and software determine the proper corrective forces to be applied and direct the attitude control components to place the spacecraft in the desired orientation. Most modern spacecraft employ three-axis stabilization. Table 2.6 lists some common control methods, their approximate accuracy, and primary characteristics.

Additional detail is provided in AFCAA (2004) and in Appendix B. Note that in the USCM and NRO WBSs, reaction jets and thrusters are grouped under the propulsion subsystem rather than ADCS. The crosschecks in Section 4 follow this convention. Table 2.7 sum-

Table 2.6
Attitude Control Methods

Method	Accuracy (deg.)	Characteristics
Spin stabilization	0.1	Passive, simple, inertially oriented, low cost
Gravity gradient	1–3	Passive, simple, central body oriented, low cost
Reaction jets	0.1	Quick, high authority, consumable usage, costly
Magnetic torquers	1–2	Near-earth usage, slow, lightweight, typically 3 used, low cost
Reaction wheels	0.01	Quick, high precision, typically 3, 4, or 6 used, costly
Control moment gyros	0.1	High authority, quick, heavy, costly

SOURCE: Griffin and French (1991).

Table 2.7
ADCS Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Attitude control	
Attitude (pointing) control precision	↑↑↑
Sensor selection	
Inertial reference unit	↑↑
Star tracker	↑
GPS receiver	↑↑
Mode architecture	
Increased level of autonomy	↑

SOURCE: AFCAA (2004).

marizes the ADCS cost drivers and the approximate relative magnitude and direction of their effects.

Electrical Power Subsystem. The electrical power subsystem (EPS) generates, controls, conditions, stores, and distributes electrical power to operate the payload and bus. Although various approaches are possible, including nuclear, thermodynamic, and fuel cells, the most practical system to date for earth-orbiting unmanned spacecraft uses arrays of photovoltaic cells to provide power for direct usage and for battery charging. Because of the gradual degradation of solar arrays in space, the required energy at the end of life (EOL) determines the general specifications for the EPS. Beginning of life (BOL) power is derived from it by projecting expected array degradation backward. As a result, typical EPS cost drivers are design lifetime, average power output at EOL,[4] orbit, type of solar cells, and spacecraft configuration.

Power Generation. Solar arrays are made up of grids of thousands of individual solar cells mounted on a substrate and fixed on the spacecraft body or on rigid or flexible flat panels,

[4] Peak power is generally two to three times average power (Wertz and Larson, 1999).

which are oriented to maintain maximum solar exposure. Body-mounted arrays are limited by area available, exposure time, and angle of incidence of the solar radiation. The flat panel arrays are generally stored for launch and are deployed after reaching orbit by means of mechanical joints and actuators. The complexity of these extension mechanisms can increase required testing and risk. Table 2.8 compares performance of different types of solar array cells.

Power Storage. Batteries are used to store electrical energy for periods of high demand, when the solar arrays are not illuminated, and for emergency power. Since adequate electrical power is required for spacecraft operations, and since batteries have a finite life (number of charge-discharge cycles), this characteristic is often the limiting factor of spacecraft life. Batteries can be classified as primary and secondary. Primary batteries are not rechargeable and provide either a relatively small amount of long-term power, such as for memory backup, or are used in expendables, such as launch vehicles and interceptors. They are not often used for spacecraft applications. Secondary batteries are charged by the solar arrays and provide power during eclipse and peak demand periods. Table 2.9 provides characteristics of the common space system battery types. The criteria for battery selection are energy requirement, mass, number of charging cycles, and expected depth of discharge.

Lithium-ion technology offers the designer advantages in mass, size, and charging characteristics but longevity in space applications is unproven.

Power Conditioning and Distribution. Power conditioning and distribution (PCD) provides electrical components with power of the proper type and voltage from the power generation and storage equipment. Variations in loads during spacecraft operations must not be allowed to adversely affect other equipment. The PCD components also provide fault isolation to prevent damage to other subsystems. Cabling, switches, and various conversion, regulating, and protective devices handle these functions.

Typical EPS cost drivers are complexity (number of components, interfaces, redundancy), performance relative to the state of the art, and electromagnetic interference (EMI) and electromagnetic compatibility (EMC) restrictions. Table 2.10 summarizes EPS cost drivers and the approximate relative magnitude and direction of their effects.

Propulsion. Propulsion subsystems change the motion or attitude of a spacecraft by ejecting mass. The mass may be in the form of a hot or cold gas or a stream of charged particles. The requirements for the propulsion subsystem are driven by the need to maneuver the spacecraft, adjust or change orbits, control attitude, dump momentum from mechanical reaction control systems, and de-orbit at the end of the mission. Various approaches are used to accelerate the propellant. They include chemical reactions, phase changes, simple expansion, and electrical current. Table 2.11 summarizes the advantages and disadvantages of various types of spacecraft propulsion subsystems.

Propulsion subsystems in earlier spacecraft generally consisted of a number of thrusters for spacecraft control and orbit maintenance and an upper stage or kick motor for changing orbits. The common practice today is to combine these functions into an integrated propulsion subsystem (IPS) using shared tanks, piping, and valves to save weight and cost (Wertz and Larson, 1999, p. 686). Requirements for maneuver and orbit maintenance over the life of a mission drive design and cost. Since propulsion is so critical to mission success, adequate performance margins, reliability (ideally using proven hardware), mass and volume constraints,

Table 2.8
Comparative Performance of Solar Array Cells

Performance Measure	Silicon (Si) (%)	Gallium Arsenide (GaAs) (%)	Multijunction GaAs (%)
Efficiency	15–17	18–21	22–27
Degradation/year	3.75	2.75	0.5

SOURCE: Wertz and Larson (1999); AFCAA (2004).

Table 2.9
Common Battery Types

Type	Specific Energy Density (W-hr/kg)	Status
Nickel cadmium	25–30	Space-qualified, extensive database
Nickel hydrogen	35–57	Space-qualified, good database
Lithium ion	70–110	Under development
Sodium sulfur	140–210	Under development

SOURCE: Wertz and Larson (1999).

Table 2.10
Electrical Power System Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓Cost Down
Architecture. (Redundancy, battery charging or solar array management, and power conversion can all influence the overall complexity.)	↑↑↑
Mission interfaces. (Compatibility of mission interfaces with “standard” equipment can drive costs.)	↑↑
Implementations. (Customer preferences or biases can result in a suboptimal solution.)	↑↑
Power sources. (Unusually stringent power requirements or overall mass or volume constraints requiring newer technologies will prove more costly.)	↑↑

SOURCE: AFCAA (2004).

and cost must all be balanced in designing the subsystem. Table 2.12 summarizes propulsion cost drivers and the approximate relative magnitude and direction of their effects.

TT&C. The TT&C subsystem collects mission data along with spacecraft health and status data and transmits it to the ground. It also generates spacecraft commands—or receives them from the ground segment—and interprets and distributes them to the appropriate spacecraft subsystems for execution. To perform these functions, the TT&C subsystem must interface with virtually every other active spacecraft subsystem. Some organizations separate the internal generation, translation, storage, and movement of data and commands into a command

Table 2.11
Advantages and Disadvantages of Spacecraft Propulsion Subsystems

Type	Propellant	Advantages	Disadvantages
Cold gas	N_2, N_3, freon, helium	Extremely simple Reliable Very low cost	Very low performance Heaviest of all systems for given performance level
Solid motor		Simple Reliable Relatively low cost	Limited performance Higher thrust Safety issues Performance not adjustable
Liquid			
Monopropellant	H_20_2, N_2H_4	Simple Reliable Low cost	Low performance Heavier than bipropellant
Bipropellant	0_2 and RP-1	High performance	More complicated system
	0_2 and H_2	Very high performance	Cryogenic Complicated
	N_20_4 and MMH (N_2H_4, UDMH)	Storable Good performance	Complicated
	F_2 and N_2H_4	Very high performance	Toxic Dangerous Complicated
	OF_2 and B_2H_6	Very high performance	Toxic Dangerous Complicated
	ClF_5 and N_2H_4	High performance	Toxic Dangerous
Dual mode	N_20_4 and N_2H_4	High performance	Toxic Dangerous
Water electrolysis	$H_20 \rightarrow H_2+0_2$	High performance	Complicated Not developed High power
Hybrid	0_2 and rubber	Throttleable Nonexplosive Nontoxic Restartable	Requires oxidizer fuel system Bulkier than solids
Electrothermal			
Resistojet	N_2, NH_3, N_2H_4, H_2	High performance Low power Simple feed system	More complicated interfaces More power than chemical Low thrust
Arcjet	NH_3, N_2H_4, H_2	High performance Simple feed system	High power Complicated interfaces (especially thermal)

Table 2.11—Continued

Type	Propellant	Advantages	Disadvantages
Electrostatic			
Ion	Hg, A, Xe, and Cs	Very high performance	High power required Low thrust Complicated Not well developed
Colloid	Glycerine	Moderately high performance	High development risk High power required Complicated
Hall effect thruster	Xenon	High performance Relatively high power, thrust density	High development risk High power required Complicated
Electromagnetic			
MPD	Argon	Very high performance	Very high power High development risk Expensive Complicated
Pulsed plasma	Teflon	High performance	Low thrust High power Contamination Complicated
Pulsed inductive	N_2H_4 Argon	Very high performance	High development risk Complicated Expensive Very high power

SOURCE: Wertz and Larson (1999, p. 693).

and data handling (C&DH) system, while the downlink and uplink functions are considered a communications subsystem. In the USCM WBS, these are all part of TT&C. Depending on the architecture of the spacecraft, TT&C and mission functions may share computing and communication resources. Costs are typically influenced by mission complexity, data rate, and reliability requirements. Cost drivers and the approximate relative magnitude and direction of their effects are summarized in Table 2.13.

Integration, Assembly, and Test

Integration, assembly, and test (IA&T) involves installing all space vehicle subsystems, including payloads, and performing system-level testing. The costs of IA&T include developing plans and processes and providing the resources needed to assemble, integrate, and test the complete space vehicle. Although there are corresponding activities for some of the subsystems, subsystem IA&T has historically been considered part of the subsystem costs and not separately identified. With the new 881A/NRO WBS, these costs can be identified individually down to the component or element level. As a result, the analyst using historical cost data from various

Table 2.12
Propulsion Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Delta-V requirements	
Major impulsive Delta-V requirements	↑↑
Minor impulsive Delta-V requirements	↑
Three-axis control capability	↑
New tank design or requalification required	↑↑
Having ample mass margin (not driven to high performance system nor to expensive ultra lightweight components)	↓↓
Adequate volume	↓↓
Modularity of system	↓
Design reuse/heritage	↓↓
Insufficient available power (for electrical propulsion)	↑↑
Redundancy	↑

SOURCE: AFCAA (2004).

programs may have to make adjustments to ensure the IA&T costs are handled consistently within the data being used. Because of the unique demands of the space environment, testing is generally more extensive and expensive than in other military systems.[5] Testing can be broken down into three general categories: development, qualification, and acceptance.

Development testing is nonrecurring testing performed at the part, component, or subsystem level to verify that hardware and software can meet specifications and perform as expected.

Qualification testing is undertaken to demonstrate that the specified design and manufacturing process will produce a part, component, subsystem, or system that has sufficient performance margins to meet all mission requirements. Qualification testing is usually performed to levels that exceed any expected operational environment. Subsequent articles of the same design, materials, and manufacturing process are generally considered qualified by similarity and do not have to repeat the full range of qualification tests. A *prototype* approach uses dedicated test articles, while a *protoflight* approach tests flight hardware, generally to less-stressing conditions, and refurbishes it as necessary for operational use.

Acceptance testing is conducted on to each item to verify the absence of material or manufacturing defects and that its performance is within expectations. To improve the validity of these tests, some articles must be powered up, operated, or cycled in representative environments to eliminate early-life failures or transient behavior.

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[5] See AFCAA (2004) for detailed listing of various types of tests.

Table 2.13
Telemetry Tracking and Command Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Reuse of existing hardware boards and designs as is	↓↓↓
Reuse of existing field programmable gate array (FPGA) and circuit designs	↓↓
Selection of a common processor versus distributed processors	↓↓↓
Selection of nonstandard or non-bussed systems	↑↑↑
Imposition of unique nonstandard programmatic requirements	↑↑
Use of standard payload and peripheral interfaces	↓↓
Requiring redundant C&DH subsystem implementation	↑↑↑
Requiring high-reliability piece parts	↑
Performing tasks in software for box simplicity versus in hardware for reliability and simple interface (particularly for large software.)	↓↓↓
Requiring higher-speed data paths	↑↑
Hardening for man-made nuclear or MEO radiation levels	↑↑↑↑
Larger quantity of engineering model boards required	↑
Larger quantity of flight model boards required	↑↑
Selection of a lower-performance space processor	↓
Selection of a nonspace processor	↑↑↑
Overspecifying mass data storage approach	↑↑↑↑
Overspecifying reliability requirements	↑↑↑
Requirements changes during the design cycle	↑↑↑
Shortening schedule by 33% over nominal	↑↑
Extending schedule by 50% over nominal	↑

SOURCE: AFCAA (2004).

Cost drivers for IA&T relate primarily to the complexity of the space vehicle. Metrics might include number of subsystems (especially payloads) to be integrated, number of interfaces, and degree of heritage from previous missions. Problems in IA&T often involve schedules. If hardware or software is not ready on schedule, other operations must be postponed or performed out of efficient sequence. Some testing may have to be repeated or delayed, which, in turn, increases the impact of any test failures. (In general, the earlier problems are discovered in testing, the less disruptive and expensive the recovery will be.) EMI problems often tend to be discovered in IA&T when subsystems and payloads are first tested together in all operating modes. Other cost drivers include out-of-the-ordinary requirements such as unusually stringent security, cleanliness, or other environmental requirements. Contractors can reduce costs and risks by

- using modular design approaches that facilitate early component and subassembly testing
- maximizing the use of proven parts, components, subsystems, and support equipment
- investing in test resources that facilitate early and comprehensive testing through their ability to simulate missing parts of the system.

Table 2.14 summarizes IA&T cost drivers and the approximate relative magnitude and direction of their effects.

Launch Vehicle Adapter. The launch vehicle adapter, also referred to as a *payload attach fitting*,[6] provides the structural connection between the space vehicle and any associated dispensers, or kick motors. In addition to the adapter, space vehicle electrical, data, and access requirements must be closely coordinated with the launch vehicle provider. For cost analysis purposes, the launch vehicle adapter cost, like that of the payload fairing, is generally classified as part of the launch vehicle.

Systems Engineering/Program Management/Data. *Systems engineering* can be broadly defined as "an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions that satisfy customer needs" (DAU, 2001). Major functions that generally fall under systems engineering include

- requirements definition and allocation
- system-level analysis and trade studies
- system-level specialty engineering (e.g., reliability, test, producibility)
- interface control
- system-level documentation.

Of these functions, clearly defining customer requirements, deriving corresponding system specifications, and allocating appropriate performance budgets and constraints to various parts of the system are arguably some of the most important drivers of eventual space system cost. Changes due to new, overlooked, poorly defined, or mischaracterized requirements, especially once development is well under way, can cause major delays and cost growth as analyses, designs or testing have to be redone. A space program may be particularly vulnerable to requirements growth because of the diversity of users—often with conflicting priorities—as well as the tightly integrated nature of typical space systems, in which changes in one subsystem or component may affect many others. Systems engineering typically develops and controls interface specifications. This allows each team, whether the prime contractor or a major subcontractor, to design and perform initial testing independent of each other, avoiding the delay of sequential development activities or rippling design changes.

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6 Launch vehicle contractors often refer to the spacecraft as the *payload*, whereas from the perspective of the space vehicle producer, the term generally refers to mission equipment mounted on the spacecraft.

A key feature of modern systems engineering practice is the use of integrated product teams (IPTs), normally organized along WBS lines. Because systems engineering is an integrating function, an IPT structure allows for more effective communication among subsystem developers, government acquisition personnel, end users, launch service providers, subcontractors, and vendors, as well as company and government program management. The IPT struc-

Table 2.14
Integration Assembly and Test Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Parallel integration and test flow of subsystems	↓↓↓
Modularity of subsystems	↓↓↓
Standardized electrical ground-support equipment (EGSE) (a significant cost savings in IA&T can be achieved by not having to debug new EGSE for each new program.)	↓↓↓
Subsystem redundancy (needed at the system level, but it will cost more to test in IA&T, as much as 4 times the duration over single string.)	↑↑
Too severe test levels	↑↑↑
Too little testing at system level, too little time (IA&T schedule is always reduced)	↑↑↑
Too little testing at component level	↑↑↑↑
Inadequate or changing requirements (always an issue; experienced in most programs)	↑↑↑
Well–thought-out requirements	↓
Test bed/hot bench (This will add cost initially, but saves more in the long run by early resolution of problems before system level test)	↓↓↓↓
Tailored protoqualification (MIL-STD-1540E) testing at system level	↓↓
Involving IA&T at the beginning of the program	↓↓
Accessible test points (design for testability)	↓↓
Inadequate software development prior to IA&T (time consuming and difficult to develop software for system-level test)	↑↑↑
Engineering model hardware (reduces technical and schedule risk at IA&T)	↓↓
Use of spacecraft and payload simulators for test bed/hot bench testing	↓↓↓
Design reuse/heritage	↓↓
Improper organization and designation of roles and responsibilities	↑↑
Contamination control requirements (class 100k, 10k, 1k)	↑↑
Security	↑↑

SOURCE: AFCAA (2004).

ture supports timely, constructive feedback and, hopefully, joint problem resolution without the lengthy delays typical of formal interorganization communication. Participation by all stakeholders in the development process can often reveal issues and potential conflicts early, thereby avoiding disruptive and costly changes later in development. Of particular interest to cost analysts is the ability of an IPT-based organization to facilitate trade-offs among competing system objectives in order to arrive at a balanced "best value" solution.

Systems engineering functions encompass much of the technical management of a program. Virtually all IPTs are involved in one or more systems engineering functions at various times. In the MIL-HDBK-881B and the USCM WBSs, the systems engineering element is defined as "the management of systems engineering processes or other system-level systems engineering functions that are not clearly associated with another WBS element." In effect, this focuses the systems engineering cost element on system-level functions. With the new 881A/NRO WBS, systems engineering costs can be reported at the subsystem level. While systems engineering functions are certainly performed at this lower level, this definition is inconsistent with previous practice. As a result, the analyst using historical data from various programs may have to make adjustments to ensure that systems engineering costs are handled consistently.

Program management is the planning and direction of all company and assigned subcontractor resources to achieve program objectives. The program management function is the system contractor's "face" to all external organizations (customer, subcontractor, and vendor) and the ultimate decision authority for directing labor, material, and facilities assigned to the program. Cost performance monitoring and system development network or schedule maintenance are typical program management functions. Contractors vary in the division of functions assigned to program management versus systems engineering and, as a result, the two are often combined into a single cost element (SE/PM) for cost analysis purposes.

Deliverable system data, which is often generated by the systems engineering or program management functions, is also included in the SE/PM cost element by USCM. Typical cost drivers for SE/PM include

- contractor experience with similar programs
- complexity of mission/system
  - amount of new technology
  - program class
  - stringency of performance specifications relative to state of the art
- program schedule
- complexity of organizational relationships
  - number of major subcontractors
  - number/depth of customer reviews.

Ground Segment

The ground segment of a space program encompasses the terrestrial infrastructure required to operate the space segment. The ground segment can be broken down into three functional areas:

- spacecraft operations control center
- payload operations control center
- mission control center.

The spacecraft operations control center issues all space vehicle commands and monitors health, status, and position of the spacecraft. The payload operations control center monitors status, provides commands for, and processes data from the space vehicle payload(s). The mission control center provides overall direction to the entire system including scheduling activities, processing and prioritizing user requests, monitoring ground segment operations, and interfacing with other organizations (Wertz and Larson, 1999). These functions are often combined in various ways depending on the requirements of the mission, ability of existing infrastructure to support program operations, and geographical and security considerations. Conversely, some systems will have multiple geographically dispersed facilities for reasons of spacecraft communication or redundancy.

The limitations of early spacecraft dictated that most spacecraft control and mission data processing be performed by the ground stations. Today, advances in digital electronics and increased computational power have made it practical and cost effective to move toward autonomy for routine spacecraft operations. Onboard processing of mission data is often used to reduce downlink bandwidth requirements or to allow direct downlink of time-sensitive data to dispersed users.

Most ground segment hardware is commercial off-the-shelf (COTS) or modifications of existing components developed for similar uses. In fact, most programs will use some form of existing ground control and tracking service to save the cost of developing and operating dedicated facilities. These include the Air Force Space Control Network, NASA's Tracking and Data Relay Satellite System (TDRSS), and the commercial Universal Space Network. Most terrestrial communications links are provided by leasing capacity on existing communication networks.

In general, the number of facilities, their locations, and the types of equipment installed are, in turn, influenced by spacecraft orbit, degree of coverage desired, and redundancy. For example, a single ground station could provide 100 percent coverage for a spacecraft in geostationary orbit whereas supporting a constellation in LEO will require many ground stations to achieve 100 percent coverage due to spacecraft movement along its earth track and its more limited field of view. In either case, requirements for redundancy will also increase the scope of the ground segment. Location will determine the cost of land, construction, support facilities, road extensions, primary and backup utilities, communication links, and so on.

A major equipment cost driver is the type and size of antenna(s) chosen. Although improvements in transmitter power, receiver sensitivity, and antenna efficiency have reduced its once-dominant influence on costs, antennas remain a major contributor to the cost of each ground station. Size, tracking requirements, and environmental shielding primarily determine antenna costs (Reimuller, 2005).

Much of the functionality of the ground segment is in its software. Although it is beyond the scope of this handbook to address the broader topic of software cost analysis, software is both as critical and as problematic in space programs as it is in other complex defense systems.[7] Considerable emphasis has been placed on improving software development practices over the years because of the importance of software in modern systems and the problems commonly encountered with large-scale software development. One source estimates that less than 30 percent of software projects deliver functionality within ±10 percent of planned cost and schedule (Humphrey, 2005). Unlike most hardware, with software there are diseconomies of scale, meaning that costs grow more than proportionately to the size of the effort. Much of modern software engineering practice is focused on reducing this problem by structuring the development process; automating repetitive tasks; and providing processes and tools that facilitate the definition of requirements, functions, data flows, interfaces, testing, and documentation. Incremental or spiral development attempts to break the required software functionality down to make each build-test cycle more manageable. Since the complete definition of software requirements is difficult, incremental versions can be tested and missing or misspecified requirements discovered.

Another common problem area in software cost analysis is estimating the impact of using existing programs or modules. These may be complete off-the-shelf packages (see discussion of COTS software in Chapter Five) or existing software, which requires some modification for the planned application. Using "proven" software is particularly attractive in space applications because the need for very high reliability tends to require extensive testing throughout development. However, the planned savings tend to be overstated because even off-the-shelf software must be tested in the system in which it will operate. Even "minor" modifications require additional regression testing to guard against inadvertently introducing defects.

The primary development cost drivers and risks for the ground segment involve software development and adaptation, along with the integration and testing of complex ground control and analysis functions. Distributed or mobile users requiring high bandwidth, highly processed data, or various operating modes will place greater demands on the system than will largely autonomous, repetitive spacecraft operations data sent to the control segments. Table 2.15 summarizes common cost drivers for both ground and flight software along with the approximate relative magnitude and direction of their effects.

Operations costs for a space system are, of course, determined largely by the requirements of staffing and maintaining the ground segment. The degree of spacecraft and ground-segment automation, along with mission-determined requirements for spacecraft monitoring and user interface, will influence the number of personnel and skill levels required. Operating personnel costs can be estimated relatively easily once the number of facilities to be staffed, the personnel per shift, and the number of shifts are determined. The cost of an additional cadre of engineering and support personnel who are not necessarily assigned full time to the operations facilities but who are available for troubleshooting and system maintenance must also be estimated. For additional discussion of ground-segment cost drivers, see Reimuller (2005).

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7 Useful references on software development and cost estimating include Boehm (1981), Boehm et al. (2000), and U.S. Air Force Software Technology Support Center (2003). Pfleeger, Wu, and Lewis (2005) provide a useful survey of software cost-estimating methodologies and guidelines for assessing risk in software development.

Table 2.15
Space Software Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Technical complexity (numerous data streams to fuse, complex algorithms, hard real-time, new technologies)	↑↑
Overaggressive schedule (overtaxed critical path causes broken schedules, does not match hardware delivery, shortened design phase, incomplete testing)	↑↑↑
Immature or changing requirements (invalid cost estimates and invalid schedule estimates cause delayed start and rework; architectural incompatibility causes late fixes and workarounds, replanning, redesign, and repeat testing)	↑↑↑
Software engineering environment changes	↑
High reuse of architecture, design, tools, code, test scripts, and commercial real-time operating systems	↓↓
Simplified life cycle (incremental buildup in conjunction with hardware design and development)	↓↓↓
Simplified development standards (limited customer deliverables, i.e., not 2167A)	↓↓
Hardware and software developed and tested concurrently in hot bench environment (all hardware and software interfaces integrated and tested prior to spacecraft I&T with actual engineering models of hardware and flight-like software)	↓↓↓
Small, experienced teams	↓↓↓
Better integrated development environments (better tools cost more up front but pay for themselves in increased productivity)	↓↓

SOURCE: AFCAA (2004), modified.

Launch Services

Launch vehicles provide the means to place space vehicles into initial orbit. Launch vehicles may be single or multiple stage and may include strap-on units for additional thrust in the initial stage of flight. The launch vehicle also includes the fairing that encapsulates the space vehicle(s) and provides protection for the portion of the flight within the atmosphere. It may also provide an orbit injector, dispenser, and/or adapter to attach the space vehicle to the launch vehicle. In addition to the launch vehicle itself, an additional propulsion system may be used to raise the space vehicle to a higher orbit. These upper stages are typically designed for compatibility with particular launch vehicles. An alternative is an integrated propulsion system that is designed as part of the space vehicle and provides positioning as well as orbit changing using common tankage and plumbing.

With the advent of the evolved expendable launch vehicle (EELV), the Air Force is attempting to reduce the cost and increase the flexibility of access to space. The philosophy behind the EELV was to have competing providers of launch services who were bidding on both government and commercial launch opportunities. A minimum number of assured government launches would preserve competition in the market. Boeing and Lockheed Martin both developed EELV systems using corporate funding with supplementary funding from

DoD. The EELV concept was to design launch vehicles that were more cost effective to build, configure, support, and launch, with the objective of reducing launch costs by a minimum of 25 percent. This was to be accomplished using modular designs; simplified manufacturing processes; standardization of interfaces, environmental, and performance requirements; and streamlined launch processing.

The near-term prospects for commercial launch volume deteriorated considerably after the collapse of many planned commercial wideband satellite ventures, and DoD is reevaluating its approach to launch services. For additional information on EELV, space launch policy considerations, and the economics of current launch services see McCartney et al. (2006).

From the perspective of the space vehicle program, costs can be reduced by controlling weight and minimizing unique integration, environmental, and performance requirements. Designing for compatibility with alternative launch vehicles can increase flexibility and avoid the risk of a prolonged launch delay due to problems with a particular launch vehicle.

Launch and Orbital Operations Support

Launch and orbital operations support (LOOS) encompasses the activities related to planning and preparation for spacecraft launch, on-orbit checkout, and turnover to the user. Prelaunch activities include planning, developing, and documenting operational procedures, training, and control center display formats. Operational simulations are also developed and used to conduct rehearsals. The launch phase generally involves preparing the space vehicle for shipment, shipment to the launch site, fueling and battery installation, integration and test with the launch vehicle, and supporting the launch. Postlaunch activities usually involve initializing the spacecraft, on-orbit testing, and initial operation prior to turnover to the user for routine operations. (Note that the USCM classifies all LOOS as recurring.)

Primary cost drivers for the launch phase are the length and complexity of the operations at the launch site, especially if major integration and checkout will be done at the launch site. Cost drivers for the prelaunch and postlaunch phases are the complexity of the mission, degree of hardware and software heritage, team experience with similar previous missions, and staffing plan. Table 2.16 summarizes cost launch and orbital operations cost drivers and the approximate relative magnitude and direction of their effects.

Other costs depend on the nature of the particular program being estimated. These include the following:

- aerospace ground equipment
- storage
- operational site activation
- industrial facilities
- initial spares and repair parts.

Aerospace ground equipment or ground-support equipment (GSE) is the test equipment, fixtures, and containers used for development, production, test, and transport of the space vehicle. It is normally considered a nonrecurring cost. Cost drivers are typically space vehicle complexity and degree of heritage. EGSE consists primarily of standard types of test equip-

Table 2.16
Launch and Orbital Operations Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
Air transportation	↑↑
Major integration at launch site (integration of solar array, antenna or payload increases complexity and duration of launch campaign)	↑↑↑↑
Special launch site facility requirements (contamination)	↑↑↑
Use of GFE launch site facilities	↓↓
Spacecraft single string versus redundant hardware	↑↑
Multiple payloads with differing operating scenarios	↑↑
Space vehicle ground automation—development	↑↑
Space vehicle ground automation—operations support	↓↓
Plans and procedure reuse from a common design	↓↓
Too little training and spacecraft/space vehicle exposure for the operations team	↑↑↑
Well–thought-out operational requirements	↓↓↓
Operations team access to hot bench assets during development and test	↓↓
Higher spacecraft to ground data rates (includes ground communication costs)	↑↑
Operations and I&T flight procedure reuse	↓↓
Comprehensive simulation and rehearsal program	↓↓
Experienced operations staff	↓↓
Operations involvement with I&T	↓
Early operational involvement in the design and requirements phase	↓↓

SOURCE: AFCAA (2004), modified.

ment, configured and driven by tailored software to generate signals that simulate the full range of space vehicle operations. The responses of the components or systems under test are analyzed to ensure proper operation. Because modern test equipment can mimic all necessary interfaces and signals, components can be tested early in development, reducing the chances of discovering problems in system test. Cost drivers for EGSE are space vehicle complexity and uniqueness. MGSE includes fixtures used for assembly and testing, and containers used for shipping. Drivers are space vehicle size and the precision required in assembly and transport.

Table 2.17 summarizes GSE cost drivers along with the approximate relative magnitude and direction of their effects.

Table 2.17
Ground Support Equipment Cost Drivers

Cost Driver	Rating ↑ Cost Up ↓ Cost Down
High-speed downlink data interfaces (>50 Mbs)	↑↑
Unusual interfaces (require additional development)	↑↑
Standardized modular EGSE	↓↓↓
Subsystem redundancy (higher material cost but greater resources for card test)	↑
Involving EGSE at the beginning of the program	↓↓
Well-defined early requirements	↓↓↓
Deviations from standard interfaces (require additional development)	↑
Inadequate or changing requirements	↑↑↑
Number of subsystem boards (C&DH and EPS) supported	↑
Reuse of heritage design (reduces design and analysis time, may eliminate design, fabrication tasks)	↓↓↓↓
Simplified tolerances (cable mockup dimensions typical held to approximately 0.25 inches)	↓↓
Use of simplified material (no exotic material)	↓↓
Simplified analysis (use of high factor of safety, conservative assumptions)	↓↓↓
Tight pointing alignment requirement (requires tight tolerances in tooling)	↑↑
Tight thermal stability requirement (requires tight tolerances in tooling)	↑↑
Welding (increases MGSE analysis time, critical welds require nondestructive testing)	↑↑
Mechanism complexity (increases MGSE design, analysis)	↑↑↑
Inadequate or changing requirements (large mass increases will require reanalysis and retest; may require redesign)	↑↑↑

SOURCE: AFCAA (2004).

Other Costs

Storage costs obviously depend on the duration and type of storage environment, as well as monitoring and security requirements. Operational site activation and industrial facilities costs are driven by new or unique requirements of the program that cannot be met by existing infrastructure. Initial spares and repair parts may be required for ground segment support. These costs usually vary considerably from program to program, depending on the characteristics of the mission and operating concept. The reviewer's task is to verify that all appropriate costs are identified and that their magnitude is reasonable.

CHAPTER THREE

Reviewing a Cost Estimate

Large U.S. government space programs commonly have their estimates reviewed by organizations separate from that of the developers of the original estimate. Most often, a command- or headquarters-level organization reviews estimates developed by a system program office for program reviews or as part of their budget submission.[1] These reviews verify that the estimate is complete, consistent, and reasonable, and document their findings for the acquisition decisionmakers and the system program director or manager. This chapter details the steps involved in a typical review.

Setting a Review Schedule

Generally, one, or at most, a small team of cost analysts perform estimate reviews. As with any cost estimate, it is important for the reviewer to understand clearly the nature of the program, the expectations for the review, and any areas of special interest so that time and effort can be allocated accordingly. With the required completion date set by the initial tasking, the reviewer can develop a more detailed working schedule. Some contact with the developers of the estimate should be made as soon as possible to discuss supporting documentation needed to do a thorough review. A tentative schedule of meetings with the program office or contractor can also be discussed at this time. The analyst should determine the availability of other documentation that may be useful in conducting the review. It is a good idea to follow up discussions with a confirming email documenting any action items. This facilitates follow-up for both parties and minimizes potential misunderstandings. As soon as the initial data have been reviewed, a working schedule can be developed. Typical events or actions include meetings with the program office or contractors, anticipated receipt of key documentation not yet provided, completion of draft review results, clarification or reconciliation meetings if expected, and completion of final documentation.

1 DoD space major defense acquisition program decision reviews require a complete independent cost estimate (or independent cost analysis for Key Decision Point A) (DoD, 2004).

Assembling Program Information

Obviously, to properly review an estimate, the estimate itself with supporting information, along with background information on the program, must be made available in a timely manner. At this point, a current Cost Analysis Requirements Description (CARD) along with complete (or draft) estimate documentation should be available. It is important to procure these documents quickly because they will assist the reviewer in assessing the status of the program and estimate and in identifying those areas that will require the most attention in the review. Late availability of key information can compromise the quality of the review, so it is important that the request for data be made as early as possible, clearly identifying the information required. The reviewer should also recognize the limitations of the program office in responding to data requests and questions while simultaneously preparing for a major program review. As a result, the reviewer should provide the program office with a clear list of the specific information required to perform the sufficiency review, suggest meetings as appropriate, and be flexible in combining requirements with other related activities that may be taking place in parallel with the sufficiency review. If the information flow is insufficient or late, the reviewer should make this clear to the program office and possibly suggest some workarounds. If the problem continues, then the reviewer may have to get management involved to help expedite the required information or, possibly, delay the review completion date.

For major programs, the most useful source of relevant program information is an up-to-date CARD. The CARD is the official program description to be used in developing cost estimates. All estimates for a key decision point review should be based on it. (That is *not* to imply that all plans, projections, and assumptions contained in the CARD must be accepted without question; rather, it simply provides a common baseline for all estimates. The reviewer should critically assess all key assumptions or projections included within the CARD.) A draft CARD must be submitted to the Office of the Secretary of Defense (OSD) 180 days prior to a defense space acquisition board meeting. The required contents of the CARD are

- system overview with hardware and software characteristics including comparisons with the key characteristics of predecessor or similar systems
- program manager's assessment of risk areas and plans for risk management
- operational concept
- system quantities by year
- personnel requirements
- planned system operational rates
- program schedule by phase with significant events
- acquisition plan or strategy
- system development plan including developmental and operational testing
- contractor and government facilities requirements
- track to prior CARD
- approved (or proposed) Contractor Cost Data Report (CCDR) plan (DoD, 1992).

In addition to the CARD, the reviewer should obtain copies of the current (and prior, if available) program estimate. This includes the estimate documentation, as well as the underlying spreadsheets, cost models, and backup for any externally provided "pass-through" values.

The most current Cost Performance Report, the risk management plan, previous cost estimates, recent program briefings, and/or the latest Integrated Program Summary can also give the reviewer useful insight into the program.

Reviewing the Estimate

After assessing the information collected, the reviewer should be able to identify the high-cost and high-risk areas of the program. While all parts of the estimate should be examined, the high-cost and -risk areas are where the bulk of the review effort should be spent. Table 3.1. is an AFCAA checklist of common areas to examine when reviewing any cost estimate.

To further assist the reviewer, approximately 150 space vehicle cost crosschecks are provided in Chapter Four of this handbook. These can be used to make an initial determination of whether various components of the estimate are within historical ranges as well as a cross-check on other estimating methodologies. They can also be used to assist in developing end points of cost probability distributions for risk analysis. However, for the high-cost and high-risk portions of the estimate, additional analysis will be needed to assess the reasonableness

Table 3.1
Cost Estimate Review Checklist

Completeness and consistency	Are all pertinent costs included in the estimate?
	Have the latest available actual costs been used to develop or check the estimate?
	Is the scope of the cost estimate clearly defined and consistent with the directed program?
	Is the estimate consistent with the latest schedule estimate?
	Has the estimate been summarized by appropriation and fiscal year?
	Are the OSD inflation indexes applied properly?
Reasonableness	Are the methods used to estimate each cost element appropriate?
	Does the estimate provide a coherent, organized, and systematic presentation of methodologies?
	Is the estimate developed from proper historical costs using accepted methods or a logical approach?
	Are the assumptions, engineering judgment rationale, and estimating relationships (including cost improvement slopes, production rates, usage rates, and so on) clearly stated and reasonable?
Documentation	Is the documentation clear and complete?
	Are the latest actual data values and sources clearly shown in the documentation?
	Can the methods used to develop the estimate be easily followed and replicated?

of the costs presented. The specific approaches will vary depending on the technique used to develop the original estimate, the phase of the program, and availability of appropriate cost models or analogous data from similar programs. The OSD Cost Analysis Improvement Group (CAIG) criteria for cost estimates is another useful guide for evaluating estimates (DoD, 1992). Although some of the procedures and documents described in it have been superseded, the discussion of issues to be examined in a review remain relevant. This information is provided as Appendix E.

In addition to these general guidelines, some common problem areas for space estimating in particular include the following:

- Are the system requirements and capabilities well understood and stable?
- If the program involves significant development, has there been an independent technical review? Did any findings affect the cost estimate?
- Are unproven technologies part of the system design? Are there realistic alternatives in case of development problems?
- If the program involves integration of many components, payloads, or user equipment from other sources, has this effort and schedule been realistically estimated?
- If COTS or "heritage" components or software will be used, will modifications and/or testing be required? Are sufficient time and resources included for selection, integration, testing, and documentation? Is vendor support likely to be available for the expected service life of the component? Can the system design easily accommodate vendor updates?
- Have all government costs (including GFE) been included? Were they estimated or approved by the organization providing the components or services?
- How does the schedule compare with similar historical programs? Are the assumptions underlying the planned schedule realistic?
- How has risk been incorporated into the estimate? Are the cost probability distributions reasonable given the amount of development and integration involved? Were correlations between program elements included?[2]

By definition, every estimate of future costs has some degree of uncertainty. An assessment of this uncertainty, particularly the probability that the final cost will exceed some value, is of vital concern to decisionmakers. This probability of an adverse outcome is referred to as *risk*. A credible analysis of risk should be a part of every cost estimate. There are a variety of ways to perform a cost risk analysis, depending on the time, resources, and information available. A recent RAND study (Arena et al., 2006) examined various approaches to cost risk analysis and provided recommendations for improving their quality and usefulness. Table 3.2 lists common risk analysis methodologies along with their advantages and disadvantages.

The common sources of cost risk in space systems can be broadly classified as shown in Table 3.3, using the taxonomy from Arena et al. (2006):

Despite advances in the calculation and presentation of risk, determining realistic risk distributions remains challenging. The true ranges of cost probability distributions are often

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2 For additional information, see Arena et al. (2006) and Smith et al. (2007).

underestimated, even by objective analysts who have no intent to understate costs. Common problem areas include the following:

- Elicitation of risk ranges from subject matter experts is subject to well-documented biases.[3] Questions should be posed in contexts with which the expert is familiar and should be phrased carefully to avoid "leading" the subject. Using multiple experts can also help by determining whether a degree of consensus exists or whether additional work is needed to examine areas of disagreement.
- Capturing the interrelationships (correlation) of cost behavior among the various parts of a program is also difficult. Correlation can increase risk ranges substantially, but establishing correlation values among the many activities on a typical program requires far more data than are likely to be available. A partial solution is to use functionally correlated cost estimating relationships (CERs), in which the output of one CER provides the input for another, thus linking related cost elements.

Although the presentation of a program cost probability curve (*s curve*) is deceptively simple, demonstrating its validity is not. Without additional information, the decisionmaker is, in effect, asked to accept the curve on faith. Garvey (2000) proposed one possible solution to this dilemma: Present estimates of one or more specific scenarios to show the effect on cost of varying key assumptions. This gives the evaluator insight into the behavior of the estimate, allowing comparison with previous experience. Arena et al. (2006) suggest using the scenarios as an overlay to the standard cost probability distribution, hopefully increasing confidence in

Table 3.2
Methodologies for Cost Risk Analysis

Methodology	Detail Provided	Time	Data	Personnel	Communication
Historical	Little	Little	Little	Few	Easy
Growth factor	Little	Little	Little	Few	Easy
Sensitivity analysis	Moderate	Moderate	Moderate	Moderate	Easy
Propagation of errors[a]	Extensive	Moderate	Moderate	Few	Moderate
Expert judgment	Moderate	Much	Little	Many	Hard
Error of estimating equations	Moderate to extensive	Moderate to much	Moderate to much	Moderate	Hard
Method of moments[a]	Moderate	Moderate	Moderate	Moderate	Hard
Monte Carlo	Extensive	Much	Extensive	Moderate	Hard

SOURCE: Arena et al. (2006).
[a] Uncommon in cost risk analysis.

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[3] A useful discussion of these biases can be found in Arena et al. (2006, Appendix D) and in Morgan and Henrion (1990).

Table 3.3
Common Sources of Risk

Estimating	How well do the database, analogies, or expert judgements that underlie the estimate reflect the characteristics of the system being estimated?
	What are the key assumptions implied by the estimating methodologies and what are the effects if they are wrong?
	Are the correlations among the elements of the estimate adequately accounted for?
	Are the cost probability distributions reasonable, given the amount of development and integration involved?
Economic or business-related	Are the inflation, labor rate, and quantity assumptions used in normalizing the underlying data and developing the estimate realistic?
	How experienced is the development team in successfully executing similar space programs?
	Is the program funded to include a realistic management reserve?
	What is the health of the supplier base for critical components? Are there alternatives?
Technical	Are the system requirements stable and well understood by the contractor?
	Have the key components been demonstrated in flight, or only in prototype or conceptual design?
	Are alternatives to high risk technologies or approaches available?
	Are the cost drivers for parametric relationships appropriate and logically related to the cost behavior of the system and its technology?
	Will COTS or nondevelopmental components have to be modified? Will they be available and supported by the vendor for their expected period of use?
Schedule	Is the schedule realistic given the program goals and content? How does it compare to similar historical programs?
	Do modular design approaches allow components and subsystems to be designed, built, and tested on their own, or are key development activities highly interdependent?

SOURCE: Arena et al. (2006).

the cost probability curve as well as demonstrating the sensitivity of the estimate to changes in particular risks.

Since an in-depth discussion of risk analysis is beyond our scope here, sources of additional information on risk analysis are listed in the bibliography.[4] A detailed checklist for cost risk analysis extracted from Arena et al. (2006) is provided as Appendix F.

Documenting Findings

The results of a review are normally documented in an annotated briefing or memorandum. The briefing or memo should summarize the tasking, participants, schedule, documents reviewed, findings, and key issues, and back them up with supporting detail.

[4] See Arena et al. (2006), Garvey (2000), and Smith et al. (2007).

In presenting the findings, the most significant issues should be identified clearly for the decisionmaker. The positions and underlying rationale for *both* program manager and reviewer should be documented so that the decisionmaker can make an informed judgment.

CHAPTER FOUR

Space Vehicle Cost Crosschecks

In reviewing cost estimates of space programs, particularly in situations in which time is limited, the analyst should focus first on the high-cost and high-risk portions of the estimate. To identify these areas and assess their reasonableness, some general ranges or rules can be useful. The crosschecks in this chapter provide a set of metrics by which the estimated recurring cost of the proposed system can be compared to the range of actual costs of previous systems, thus highlighting cost elements meriting further investigation. Since these reviews may involve immature or alternative designs about which limited information is available to the analyst, the data were stratified using parameters that should be known or easily estimated, even in the early stages of system definition. An additional purpose is to assist in setting uncertainty ranges for risk analysis at the subsystem and component levels.

Crosscheck Development

The crosschecks that follow were developed from data that were collected to support development of the Air Force's USCM 8.[1] The programs selected from that database are shown in Table 4.1. For consistency with the normalization of the original data, the USCM8 WBS was retained. A WBS dictionary is provided as Appendix B.

All cost data are presented in thousands of constant FY 2000 dollars escalated using OSD-approved indexes. Costs shown are contractor costs through general and administrative (G&A) and do not include prime contractor fee. The database provides theoretical first unit costs (T_1) calculated using an assumed 95 percent cumulative average cost improvement curve. Costs given for spacecraft using a "standard" bus are average unit costs over the quantity procured since prior quantities could not be determined. The nine commercial communication satellites are not further identified because of proprietary data concerns. Additional information on the database and normalization is available in the USCM user documentation (U.S. Air Force Space and Missile Systems Center, 2002).

Data were not available for every WBS element either because the WBS element did not apply to the program or it did not appear in the original records from which the database was developed. Crosschecks were not developed for nonrecurring cost because of the varying degrees of development represented by the programs in the database and the lack of sufficient

1 USCM 8 database, May 2004, with corrections provided by Tecolote Research, Inc.

Table 4.1
Programs Included in Analysis

Satellite Program	Procurer	Contract Start Date	Contractor	Number of Satellites	Dry Weight (lb)	Stabilization Type	Design Life (months)	BOL Power (watts)
Communication								
Advanced Communication Technology Satellite	NASA	1984	Lockheed Martin	1	2,799	Three-axis	48	1,770
Defense Satellite Communications System (DSCS) IIIA (1&2)	USAF	1977	GE (Martin)	4	1,920	Three-axis	120	1,240
DSCS IIIB (4–7)	USAF	1982	GE (Martin)	4	1,920	Three-axis	120	1,240
DSCS IIIB (8–14)	USAF	1987	GE (Martin)	7	1,881	Three-axis	120	1,240
Fleet Satellite Communications System (FLTSAT) (1–5)	USAF/USN	1972	TRW	5	1,951	Three-axis	60	1,640
FLTSAT (6–8)	USAF/USN	1983	TRW	3	1,992	Three-axis	60	2,192
TDRSS (1–6)	NASA	1976	TRW	6	3,401	Three-axis	120	2,400
Low data rate (LDR) I F2 (MILSTAR payload)	USAF	1983	TRW	1	2,500	N/A	120	N/A
LDR II F4 (MILSTAR payload)	USAF	1992	TRW	1	2,380	N/A	120	N/A
LDR II F5&6 (MILSTAR payload)	USAF	1992	TRW	2	2,158	N/A	120	N/A

Table 4.1—Continued

Satellite Program	Procurer	Contract Start Date	Contractor	Number of Satellites	Dry Weight (lb)	Stabilization Type	Design Life (months)	BOL Power (watts)
Medium data rate (MILSTAR payload)	USAF	1992	Hughes	4	1,112	N/A	120	N/A
XLINKS (MILSTAR payload)	USAF	1991	Hughes	4	736	N/A	120	N/A
UHF Follow-On F6[a]	USN	1990	Hughes (Boeing)	1	3,000	Three-axis	120	3,628
9 Communication satellites[a]	Commercial	>1990	N/A	9	>2,750	Three-axis	>120	>6,500
Navigation								
GPS (9–11)	USAF	1979	Rockwell	3	1,116	Three-axis	60	520
GPS II/IIA (13–40)	USAF	1983	Rockwell	28	1,758	Three-axis	90	980
GPS IIR (41–61)	USAF	1989	Lockheed Martin	21	2,292	Three-axis	120	1,720
Environmental								
AQUA bus	NASA	1997	TRW	1	3,970	Three-axis	72	4,860
Defense Meteorological Satellite Program (DMSP) 5D-1	USAF	1973	RCA (Martin)	3	634	Three-axis	18	1,153
DMSP 5D-2	USAF	1979	RCA (Martin)	3	1,035	Three-axis	36	1,266
DMSP 5D-3	USAF	1989	Lockheed Martin	5	1,742	Three-axis	60	2,077
Geostationary Operational Environmental Satellite (GOES) I-M	NASA/NOAA	1985	Space Systems/ Loral	5	2,184	Three-axis	60	1,304[b]
RADARSAT 1	Canada	1989	Ball Aerospace	1	3,139	Three-axis	84	N/A

Table 4.1—Continued

Satellite Program	Procurer	Contract Start Date	Contractor	Number of Satellites	Dry Weight (lb)	Stabilization Type	Design Life (months)	BOL Power (watts)
Synchronous Meteorological Satellite (SMS) 1–3	NASA	1970	Philco-Ford	3	1,284 (wet)	Spin	60	173
The Ocean Topography Experiment (TOPEX)	NASA/CNES	1987	Fairchild	1	4,726	Three-axis	60	3,380
Experimental								
Atmospheric Explorer	NASA	1971	RCA (Martin)	3	1,109	Three-axis	12	170
Combined Release and Effects Satellite	USAF	1983	Ball Aero	1	5,687	Spin	12	450
Orbiting Satellite Observatory–1	NASA	1971	Ball Aero	1	1,456	Spin	12	460
S3	USAF	1972	Boeing	3	340	Spin	6	100
P72-2	USAF	1972	Rockwell (Boeing)	1	1,689	Three-axis	6	260
P78-1	USAF	1976	Ball Brothers	1	1,020	Spin	12	330
P78-2	USAF	1976	Martin Marietta	1	1,015	Spin	12	310
Scientific								
Advanced X-ray Astrophysics Facility	NASA	1988	TRW	1	10,189	Three-axis	60	2,280
Gamma Ray Observatory	NASA	1978	TRW	1	29,770	Three-axis	28	4,610

Table 4.1—Continued

Satellite Program	Procurer	Contract Start Date	Contractor	Number of Satellites	Dry Weight (lb)	Stabilization Type	Design Life (months)	BOL Power (watts)
Space Infrared Telescope Facility (SIRTF) bus	NASA	1996	Lockheed Martin	1	786	Three-axis	30	N/A
Support System Module	NASA	1978	Lockheed Martin	1	23,667	Three-axis	180 (with servicing)	5,000
Surveillance								
Defense Support Program (DSP) 18–22	USAF	1987	TRW	5	2,899	Three-axis	60	1,550
Passive sensors								
DSP Sensor	Air Force	1987	Aerojet	5	N/A	N/A	36	N/A
Enhanced Thematic Mapper +	NASA	1992	Raytheon SBRS	1	N/A	N/A	60	N/A
Moderate Resolution Imaging Spectro-Radiometer (MODIS)	NASA	1991	Raytheon SBRS	2	N/A	N/A	60	N/A
SIRTF cryogenic telescope assembly	NASA	1997	Lockheed Martin	1	N/A	N/A	30	N/A
ACS	NASA	1995	Ball Aerospace	1	837	N/A	60	N/A
Space Telescope Imaging Spectrograph	NASA	1985	Ball Aerospace	1	781	N/A	N/A	N/A

Table 4.1—Continued

Satellite Program	Procurer	Contract Start Date	Contractor	Number of Satellites	Dry Weight (lb)	Stabilization Type	Design Life (months)	BOL Power (watts)
Near infrared Camera and Multi-Object Spectrometer (NICMOS)	NASA		Ball Aerospace	1	598	N/A	60	N/A
Thermal infrared Array Camera	NASA	1992	Ball ATC	1	40	N/A	N/A	N/A
Stratospheric Aerosol and Gas Experiment (SAGE) III	NASA	1995	Ball Aerospace	3	69	N/A	60	N/A

SOURCE: USCM 8 database documentation.

[a] Standard bus.

[b] End-of-life power.

information to characterize the scope of each development program. An additional limitation was the lack of data for complete space vehicles for other than communication programs. To begin addressing this limitation, the Air Force has collected passive sensor payload data on programs other than those in the current version of USCM for use in the next update of the model. This data was included in the crosschecks under *passive sensors*. Because of the proprietary nature of the data, no identification of costs for individual programs is included. In those few cases in which data from only one or two programs were available for a cost element, it is not shown.

The programs listed in Table 4.2 were excluded from the analysis based on their characteristics or quality of data. The Combined Release and Radiation Effects Satellite was reclassified from *scientific* to *experimental* based on its characteristics.

To develop the crosschecks, the remaining data were stratified in various ways in an attempt to create more homogeneous data subsets. At the spacecraft level, the most satisfactory classification scheme was based on primary mission, as shown in Table 4.3. Missions with similar characteristics or components and small numbers were further combined to increase the population of each resulting category. For completeness, we analyzed costs at the spacecraft, subsystem, and component levels as the data allowed.

Crosschecks

The 140 crosschecks presented in this section were selected based on likely cost drivers and their variability (as measured by the coefficient of variation) or, in a few cases, on areas in which they illustrated the character of the overall data set or provided more complete coverage of a WBS element of interest. In many cases, we provide alternative crosschecks to give the analyst the flexibility to choose the one most appropriate to the situation. Mindful of the dual objectives of characterizing a representative cross-section of system, subsystem, and component costs, while at the same time minimizing unexplained variation in the data, we analyzed data by the

Table 4.2
Programs Excluded from Analysis

Program	Reason
Galileo	Non-earth orbit; nuclear power
MILSTAR payloads	Incomplete system; included only with communication payloads
TDRSS-7	Large unexplained cost variance
GPS 1-8	Large unexplained cost variance
Hyperion	Incomplete costs
Submillimeter Wave Astronomy Satellite (SWAS)	Incomplete costs
Two-axis gimble mirror	Incomplete costs

Table 4.3
Spacecraft Primary Missions

Mission	Characteristics
Communication	Provide communication services worldwide; GEO; high heritage; long life
Navigation	Broadcast precision navigation signals; large constellation in LEO; series production
Environmental	Remote sensing of earth; long life
Experimental	Testbeds for technology demonstrations; small; high heritage in other than demonstration hardware; short life
Scientific	Scientific observation; large; multiple payloads; low heritage; long life
Surveillance	Detection, location of missile launches or nuclear detonations; constellation; secure or survivable; long life

characteristics available, which included mission, weight, power, area, number of channels, and relationship to other costs.

To get a sense of the relative size of the various costs in the typical spacecraft program, Figures 4.1 through 4.31 show the average percent share of total spacecraft cost by subsystem or program-level cost and mission type. Table 4.4 provides the standard deviations for each. (For consistency, payload costs are not included in these calculations.)

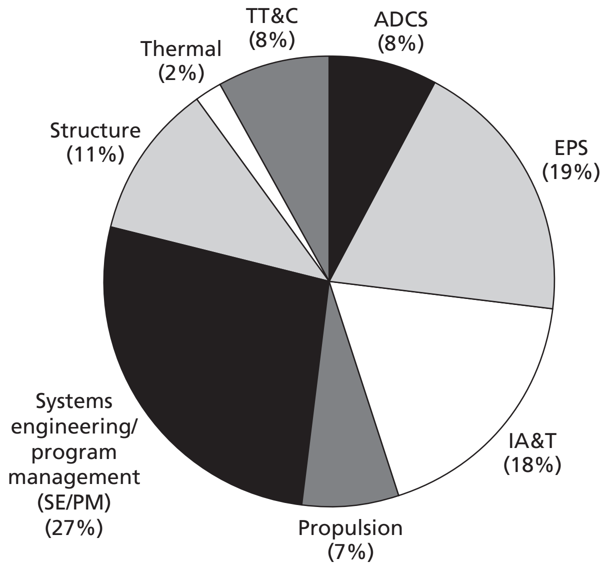
The crosschecks give the mean, standard deviation, and coefficient of variation (standard deviation divided by the mean). The number of observations reflects the number of data points with sufficient information available in the database. Lower and upper prediction limits are calculated, assuming a log-normal distribution, to give the analyst a ready reference for the range of likely values for the item of interest without presenting specific details.[2] These ranges can also be useful for setting the end points of risk distributions for Monte Carlo simulations. Histograms are also shown to give a sense of the distribution of the data across its range.[3] Where physical or technical characteristics are part of the crosscheck, their ranges are also given.

When using these prediction limits, the analyst should note that we are assuming that all system, subsystem, and component costs follow a log-normal distribution with the mean and standard deviation shown. In most cases, the histograms show that this is a reasonable assumption. But if the data do not fit well—either because there are simply too few data points or because the data points are not actually distributed log-normally—then the use of a log-normal distribution's prediction interval will not provide a useful guide to future costs and is likely to cause confusion. In those cases, the analyst should simply look at the actual distribution of costs in the crosscheck histograms.

[2] Given the distribution of costs of similar components, a prediction interval estimates the range of dollar values in which the cost of a future component will lie to a specified degree of confidence. This degree of confidence is specified by a confidence level, which is a number between 0 percent and 100 percent chosen by the analyst, with greater numbers indicating higher confidence that the interval will include a future article's cost and yielding wider (and perhaps less helpful) intervals. These confidence levels commonly range from 70 percent to 95 percent. Appendix G describes the process and provides the values needed to compute crosscheck confidence limits for values other than 90 percent.

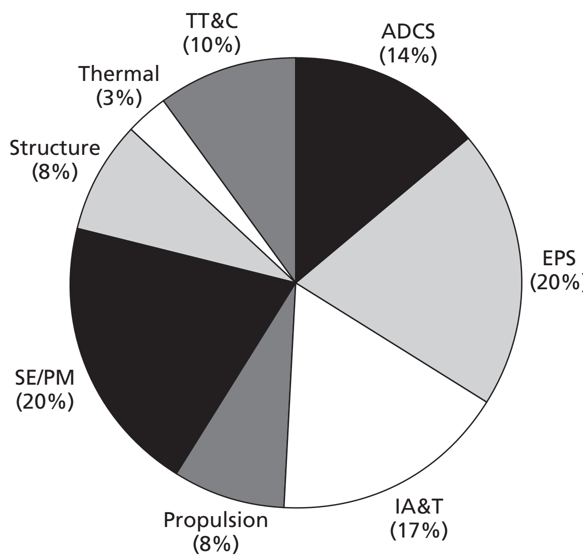
[3] These ranges have been broadened somewhat to protect any underlying proprietary data.

Figure 4.1
Communication Spacecraft Cost Composition



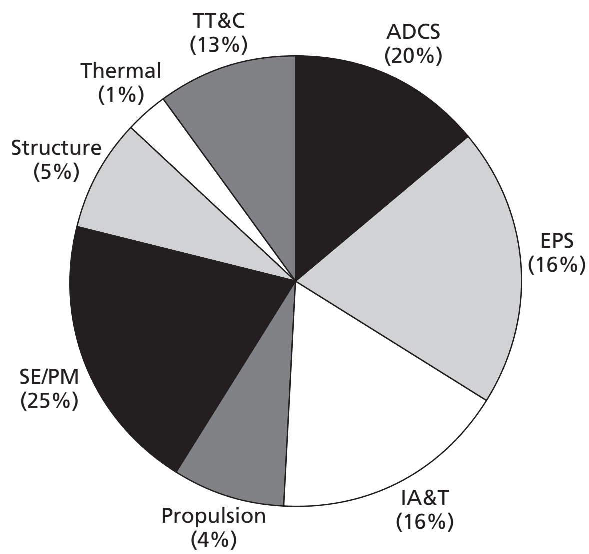
RAND *TR418-4.1*

Figure 4.2
Navigation Spacecraft Cost Composition



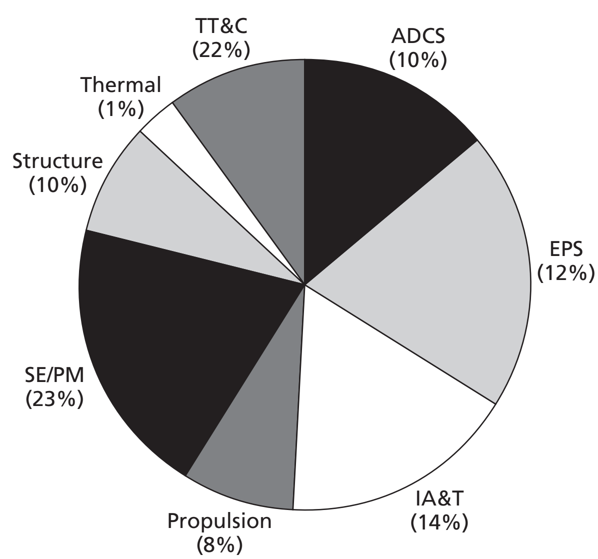
RAND *TR418-4.2*

Figure 4.3
Environmental Spacecraft Cost Composition



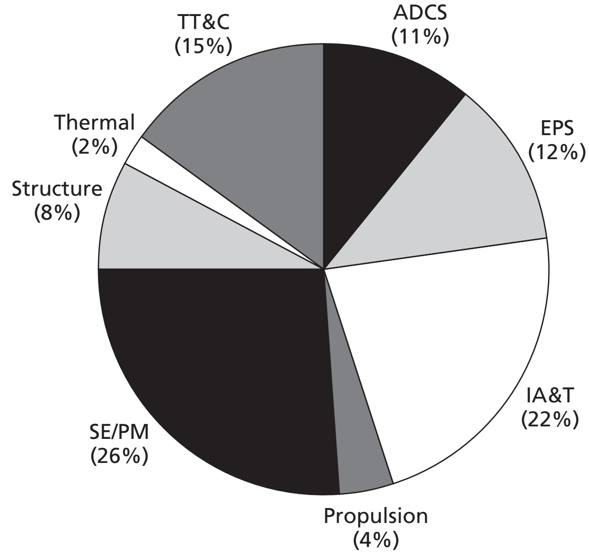
RAND *TR418-4.3*

Figure 4.4
Experimental Spacecraft Cost Composition



RAND *TR418-4.4*

Figure 4.5
Scientific and Surveillance Spacecraft Cost Composition



RAND *TR418-4.5*

Table 4.4
Spacecraft Cost Composition: Averages and Standard Deviations

	Average (%) (standard deviation)							
Cost	**ADCS**	**EPS**	**IA&T**	**Prop**	**SE/PM**	**Structural**	**Thermal**	**TT&C**
Communication	8.0 (2.2)	19.1 (7.9)	18.0 (8.6)	6.6 (3.3)	26.8 (9.2)	11.2 (6.7)	2.3 (1.4)	8.0 (3.5)
Environmental	19.8 (6.1)	15.6 (4.2)	15.6 (9.0)	4.1 (1.9)	24.9 (6.8)	5.4 (2.4)	1.4 (0.7)	13.2 (4.3)
Navigation	13.6 (2.4)	21.0 (3.2)	16.9 (4.2)	7.7 (1.5)	20.0 (7.9)	7.6 (5.4)	3.1 (0.3)	10.1 (3.6)
Scientific/survey	11.4 (1.4)	12.3 (7.8)	22.2 (13.0)	3.6 (4.5)	25.0 (8.8)	8.2 (3.7)	1.9 (0.9)	15.4 (18.2)
Experimental	9.6 (4.8)	12.0 (2.2)	13.9 (4.6)	8.0 (9.3)	23.3 (7.3)	10.0 (5.5)	1.4 (2.6)	22.0 (4.5)
Communication/ navigation/ environmental	12.0 (6.4)	18.3 (6.8)	17.2 (8.2)	6.0 (3.0)	25.5 (8.5)	9.2 (6.1)	2.1 (1.2)	9.8 (4.3)

Spacecraft

The system-level crosschecks were developed from 40 selected space programs. As expected, the variability is high when all programs are grouped together. Classifying the spacecraft by mission reduces this variability significantly. Interestingly, there was less variation among T_1 costs by mission than with average cost per pound.

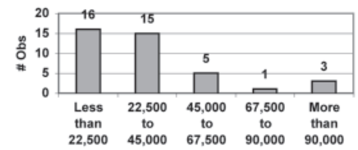
Subsystem

Average T_1 cost by subsystem across all missions shows considerable dispersion, which is marginally reduced when cost per pound is used. In both cases, these average values are clearly too variable to use for cost analysis purposes and are provided for completeness only.

Figure 4.6
Spacecraft Crosschecks

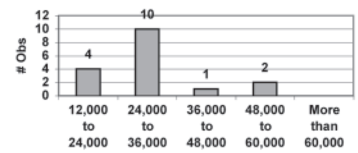
Spacecraft T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
All	40	34,187.01	24,590.38
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	71.9	8,630.52	87,833.45

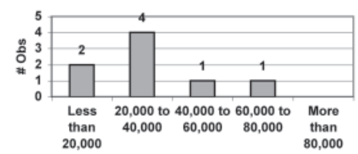


Spacecraft T1 by Mission ($K)

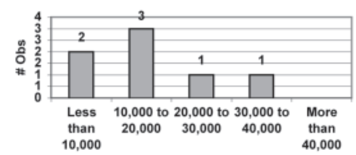
Mission	# Obs	Mean	Std Dev
Communications	17	31,214.76	9,587.34
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	30.7	17,875.95	50,273.65



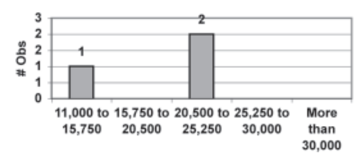
Mission	# Obs	Mean	Std Dev
Environmental	8	30,852.49	21,617.98
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	70.1	6,762.14	95,726.01



Mission	# Obs	Mean	Std Dev
Experimental	7	15,763.33	9,031.75
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	57.3	2,975.42	58,037.34



Mission	# Obs	Mean	Std Dev
Navigation	3	20,296.19	4,412.12
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	21.7	9,162.88	43,447.34



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	83,755.51	26,613.83
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	31.8	34,941.30	182,821.71

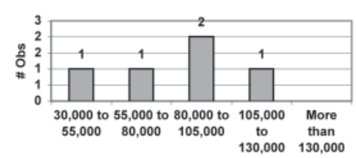
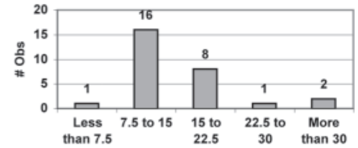


Figure 4.6—Continued

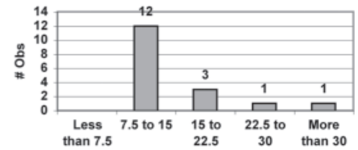
SC T1 Cost per Pound ($K/lb.)
(Dry Weight)

Mission	N Obs	Mean	Std Dev
ComNavEnv	28	15.75	6.61
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	42.0	7.77	27.75



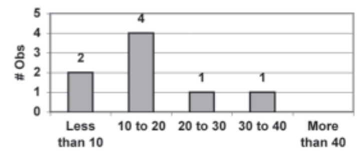
Mission	# Obs	Mean	Std Dev
Communications	17	15.56	6.63
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	42.6	8.05	26.61

Communications SC weigh between 1200.7 and 3857.3 lbs



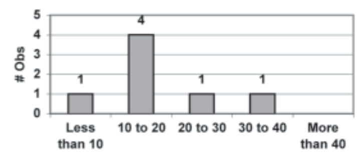
Mission	# Obs	Mean	Std Dev
Environmental	8	16.15	8.16
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	50.6	5.21	40.13

Environmental SC weigh between 633.9 and 3969.7 lbs



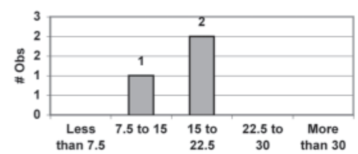
Mission	# Obs	Mean	Std Dev
Experimental	7	14.86	8.73
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	58.7	3.81	43.56

Experimental SC weigh between 340.4 and 3219.4 lbs



Mission	# Obs	Mean	Std Dev
Navigation	3	15.76	2.27
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	14.4	9.51	25.75

Navigation SC weigh between 862.3 and 1615.7 lbs



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	27.57	29.64
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	107.5	1.89	179.44

Sci/Surv SC weigh between 786.0 and 11278.6 lbs

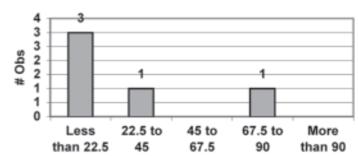
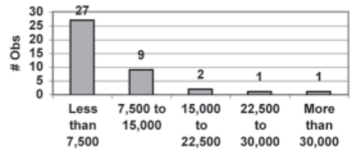


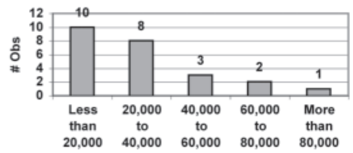
Figure 4.7
Subsystem Crosschecks

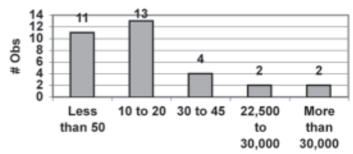
T1 Cost ($K) by Subsystem

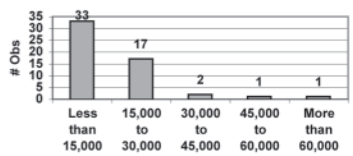
Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
ADCS	40	7,022.85	6,552.72	93.3	1,159.52	21,689.70
Communications	24	30,951.42	23,953.40	77.4	5,461.81	98,633.98
EPS	40	10,130.37	8,872.56	87.6	1,565.57	32,619.23
IA&T	40	12,822.78	19,437.29	151.6	1,357.71	39,869.87
LOOS*	34	6,093.21	6,563.21	107.7	416.92	29,175.82
Other*	35	17,687.05	53,562.54	302.8	29.29	229,257.61

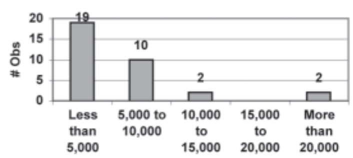
*Cost elements not included in analysis











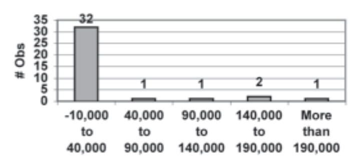
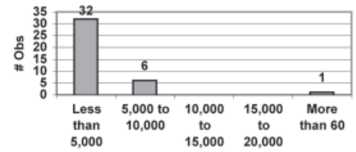
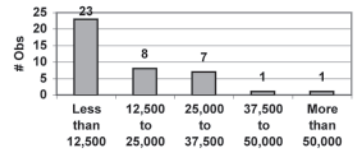


Figure 4.7—Continued

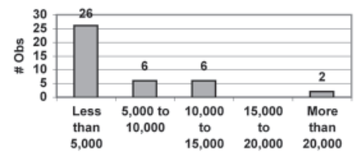
Mission	# Obs	Mean	Std Dev
Propulsion	39	3,293.84	3,696.97
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	112.2	348.82	13,056.73



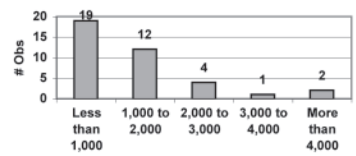
Mission	# Obs	Mean	Std Dev
SEPM	40	16,040.92	13,312.04
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	83.0	2,620.29	50,953.30



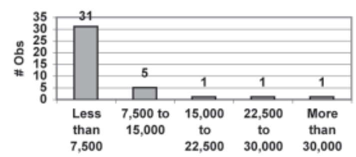
Mission	# Obs	Mean	Std Dev
Structure	40	5,670.82	5,681.82
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	100.2	739.51	19,150.47



Mission	# Obs	Mean	Std Dev
Thermal	38	1,241.36	1,145.21
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	92.3	113.31	5,291.26



Mission	# Obs	Mean	Std Dev
TT&C	39	7,082.64	7,715.46
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	108.9	1,711.88	16,754.20



Mission	# Obs	Mean	Std Dev
TT&C	38	50.29	30.10
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	59.9	16.60	112.14

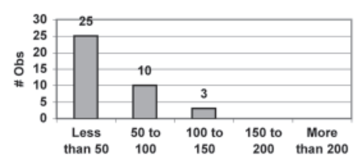
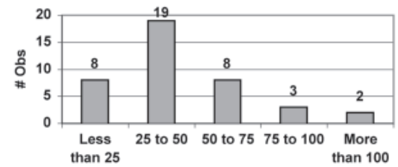


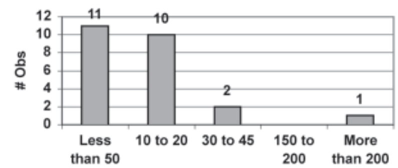
Figure 4.7—Continued

Subsystem T1 Cost per Pound ($K/lb.)

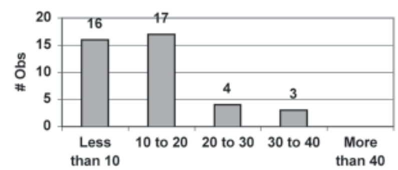
Mission	# Obs	Mean	Std Dev
ADCS	40	44.06	24.59
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	55.8	14.02	101.77



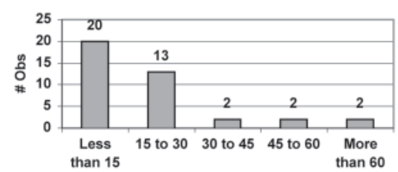
Mission	# Obs	Mean	Std Dev
Communications	24	65.39	47.73
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	73.0	21.35	143.98



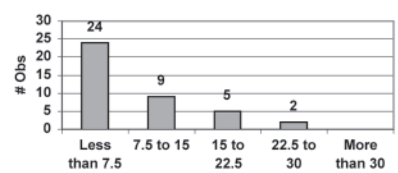
Mission	# Obs	Mean	Std Dev
EPS	40	13.81	8.63
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	62.5	4.61	30.30



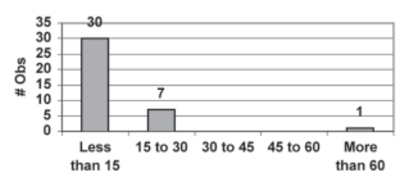
Mission	# Obs	Mean	Std Dev
Propulsion	39	19.51	17.56
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	90.0	2.23	75.81



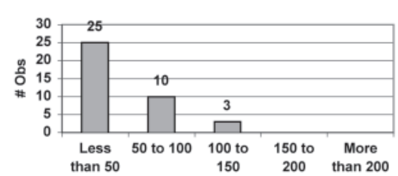
Mission	# Obs	Mean	Std Dev
Structure	40	8.32	5.93
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	71.3	1.96	22.13



Mission	# Obs	Mean	Std Dev
Thermal	38	13.33	20.78
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	156.0	2.39	33.97



Mission	# Obs	Mean	Std Dev
TT&C	38	50.29	30.10
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	59.9	16.60	112.14



Attitude Determination and Control Subsystem

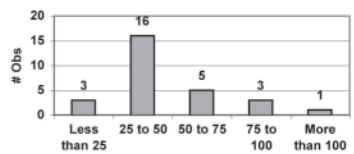
Looking at subsystem and component costs, stratified by mission type, as appropriate, gave predictably improved results. For attitude determination and control, categorization by mission provided only marginal improvement. Combining the communication, navigation, and environmental into a single category based on similarities in size and function helped, as did analysis of component-level cost. This is probably due to the variety of subsystem configurations that can perform the ADCS functions. Unfortunately, as we look at lower levels of the WBS, the number of programs with cost data for items of interest is reduced, sometimes dramatically.

Figure 4.8
Attitude Determination and Control Subsystem Crosschecks

ADCS by Mission
T1 Cost per Pound ($K/lb.)

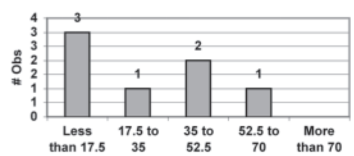
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	46.07	23.19
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	50.3	17.93	94.46

ComNavEnv ADCS weigh between 64.1 and 315.5 lbs



Mission	# Obs	Mean	Std Dev
Experimental	7	29.70	19.41
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	65.3	4.91	115.35

Experimental ADCS weigh between 22.5 and 202 lbs



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	52.94	34.84
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	65.8	9.96	200.50

Sci/Surv ADCS weigh between 61.0 and 1152.2 lbs

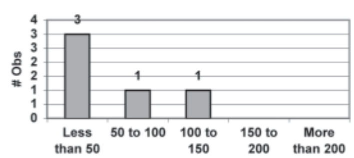
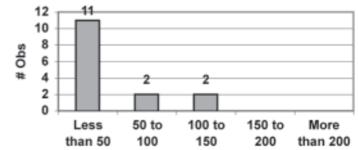


Figure 4.8—Continued

ADCS/Attitude Determination/Digital Electronics by Mission
T1 Cost per Pound ($K/lb.)

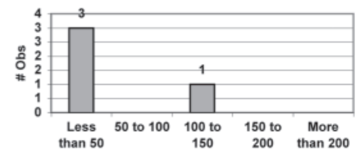
Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
ComNavEnv	16	51.08	40.80	79.9	7.70	177.35

ComNavEnv ADCS/AD weigh between 14 and 86.5 lbs



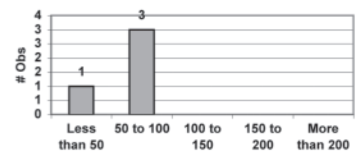
Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
Experimental	4	36.15	46.34	128.2	1.38	596.02

Experimental ADCS/AD weigh between 20.5 and 44.6 lbs



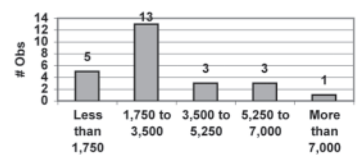
Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
Sci/Surv	3	62.43	31.41	50.3	0.92	1,310.39

Sci/Surv ADCS/AD weigh between 3.8 and 85.5 lbs

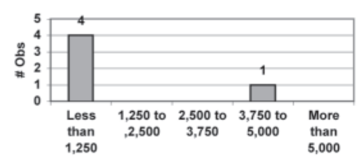


ADCS/Attitude Determination/Sensor by Mission
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
ComNavEnv	26	3,210.10	1,801.11	56.1	1,019.86	8,839.40



Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
Experimental	5	1,278.92	1,557.63	121.8	21.14	21,265.81



Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
Sci/Surv	5	9,538.82	6,334.63	66.4	318.36	54,638.67

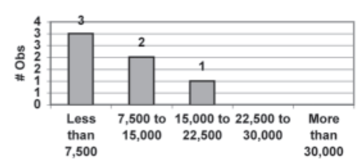
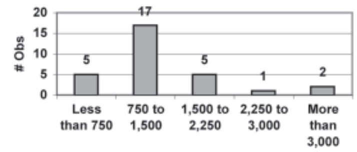


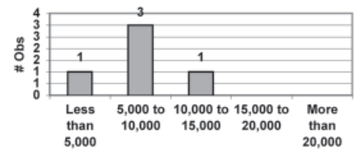
Figure 4.8—Continued

ADCS/Mechanical RCS by Mission
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
ComNavEnvExp	30	1,304.09	826.66
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	63.4	418.44	2,954.84

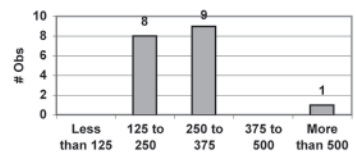


Mission	# Obs	Mean	Std Dev
Sci/Surv	5	6,933.50	3,916.45
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	56.5	183.21	114,760.06

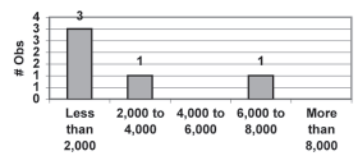


ADCS/Mechanical RCS/Reaction Wheel Assembly By Mission
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
ComNavEnvExp	18	281.67	97.18
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	34.5	147.55	484.55

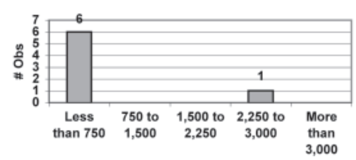


Mission	# Obs	Mean	Std Dev
Sci/Surv	5	2,680.53	2,471.18
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	92.2	162.08	20,887.70



ADCS/Mechanical RCS/Momentum Wheel Assembly
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
ComNavEnvExp	7	722.30	894.66
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	123.9	95.72	2,583.08



Communication Subsystem

Since data on communication payloads were available in the USCM database, we analyzed them as a standalone subsystem, but they were not included in any cross-program analyses at the subsystem level or higher to maintain compatibility among the data. Also note that the various MILSTAR communication payloads were used only for communication subsystem crosschecks because no other MILSTAR costs were available. Various metrics were tried to minimize the unexplained variability in the averages; the best are presented in Figures 4.13 and 4.14. Cost per channel provides a useful basis for comparing costs across a wide range of communication subsystem implementations, clearly reflecting the economies of scale enjoyed by large geosynchronous communication satellites. Note that metrics are given both with and without the MILSTAR payloads to enable selection of the most appropriate value for specific estimating situations.[4]

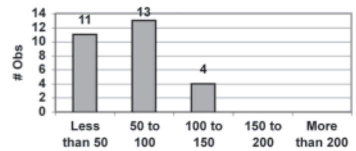
[4] Where the inclusion of MILSTAR made little difference, those values are the only ones shown.

Figure 4.9
Communication Subsystem Crosschecks

Communications (with Milstar)
T1 Cost per Pound ($K/lb.)

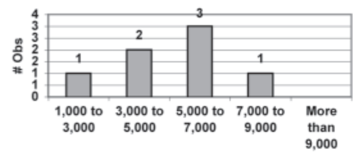
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	62.17	29.02
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	46.7	25.37	124.53

ComNavEnv payloads weigh from 30.4 to 2042.4 lbs

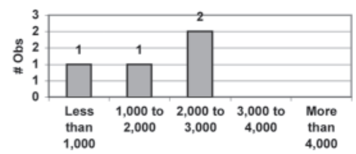


Communications
T1 Cost per Channel ($K/Ch.)

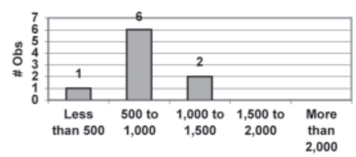
Mission	# Obs	Mean	Std Dev
1<Channels<=10	7	4,665.07	1,717.04
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	36.8	1,633.55	11,378.16



Mission	# Obs	Mean	Std Dev
10<Channels<=25	4	1,824.62	663.96
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	36.4	558.41	5,274.38

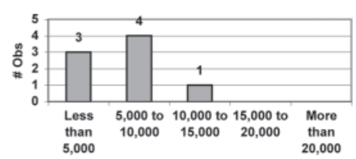


Mission	# Obs	Mean	Std Dev
25<Channels	9	842.36	234.67
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	27.9	451.61	1,457.69



Communications (with Milstar)
T1 Cost per Channel ($K/Ch.)

Mission	# Obs	Mean	Std Dev
1<Channels<=10	8	5,442.33	2,712.94
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	49.8	1,627.30	14,397.06



Mission	# Obs	Mean	Std Dev
10<Channels<=25	4	1,824.62	663.96
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	36.4	558.41	5,274.38

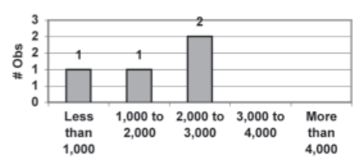
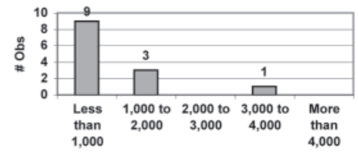


Figure 4.9—Continued

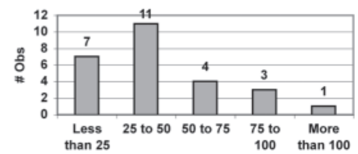
Mission	# Obs	Mean	Std Dev
25<Channels	13	1,010.65	1,010.65
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	100.0	371.83	2,129.18



Communications/Antenna (with Milstar)
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	26	44.44	25.84
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	58.1	11.55	117.38

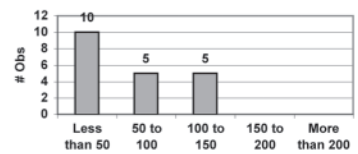
Antennae weigh from 4.4 to 838.8 lbs



Communications/Transmitter
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	20	60.58	38.23
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	63.1	11.18	198.97

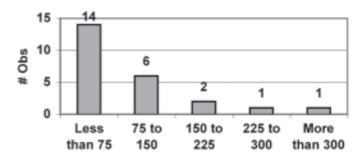
ComNavEnv transmitter weights from 10.1 to 704.9 lbs



Communications/Transmitter (with Milstar)
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	24	87.57	76.31
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	87.1	11.64	315.49

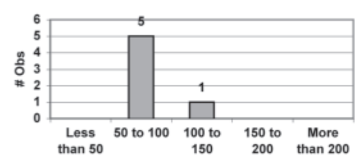
ComNavEnv transmitter weights from 10.1 to 704.9 lbs



Communications/Transponder (with Milstar)
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	6	68.67	25.79
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	37.6	33.12	129.77

ComNavEnv transponder weights from 13.8 to 109.4 lbs



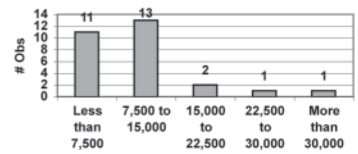
Electrical Power Subsystem

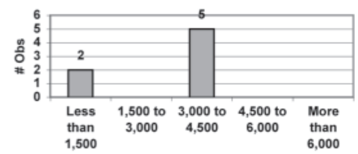
At the EPS level, various metrics are shown to give maximum flexibility in selecting one or several crosschecks for use on a range of spacecraft types. Cost per watt is relatively consistent except for the communication/navigation/environmental spacecraft. The stratification by range of BOL power rather than mission further reduced the dispersion and gave three relatively equal groups. Solar power generation includes panels composed of silicon, high-efficiency silicon, or gallium arsenide solar cells; array drives; and associated electronics. Averages are given for each type of solar cell; unfortunately, there are few data points for the more advanced types of arrays (gallium arsenide and high-efficiency silicon).

Figure 4.10
Electric Power Subsystem Crosschecks

EPS
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
ComNavEnv	28	10,037.60	6,756.23	67.3	2,416.48	27,166.83
Experimental	7	2,865.02	1,317.90	46.0	624.41	9,798.17
Sci/Surv	5	20,821.33	14,883.45	71.5	1,637.27	149,059.55





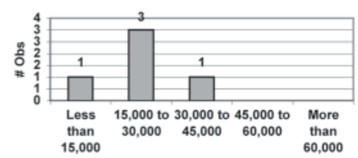
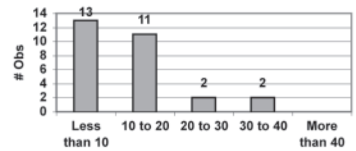


Figure 4.10—Continued

EPS
T1 Cost per Pound ($K/lb.)

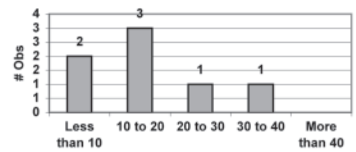
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	13.32	8.64
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	64.9	4.24	30.24

ComNavEnv EPS weigh between 104.3 and 1921.1 lbs



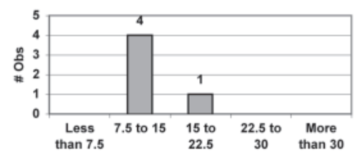
Mission	# Obs	Mean	Std Dev
Experimental	7	16.12	11.09
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	68.8	3.53	51.14

Experimental EPS weigh between 68.3 and 494.5 lbs



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	13.34	5.17
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	38.8	5.45	29.29

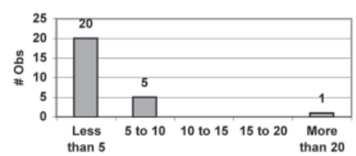
Sci/Surv EPS weigh between 286.5 and 3253 lbs



EPS
T1 Cost per BOL Watt ($K/W)

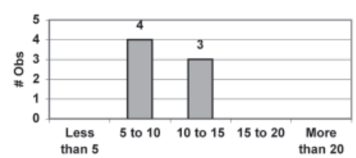
Mission	# Obs	Mean	Std Dev
ComNavEnv	26	4.46	4.73
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	106.1	0.71	13.19

ComNavEnv power is between 173 and 13090 Watts.



Mission	# Obs	Mean	Std Dev
Experimental	7	9.53	2.27
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	23.8	5.73	15.13

Experimental power is between 100 and 460 Watts.



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	8.12	2.60
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	32.0	2.96	19.85

Sci/Surv power is between 430 and 5000 Watts.

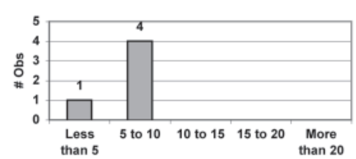
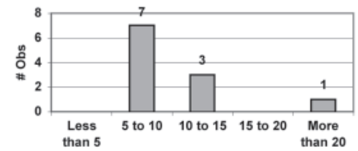


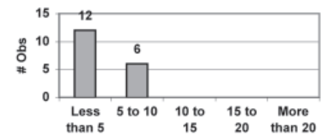
Figure 4.10—Continued

EPS
T1 Cost per BOL Watt ($K/W)

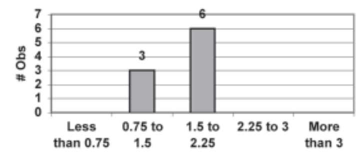
Mission	# Obs	Mean	Std Dev
1<W<=1000	11	10.36	4.48
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	43.2	5.12	18.54



Mission	# Obs	Mean	Std Dev
1000<W<=5000	18	5.31	3.35
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	63.2	1.17	15.52



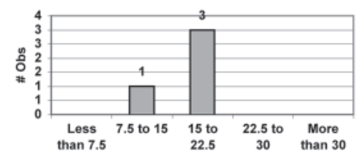
Mission	# Obs	Mean	Std Dev
5000<W<13090	9	1.54	0.28
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	18.3	1.02	2.23



EPS/(GaAs) Generation
AUC Cost per Area ($K/sq.ft.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	4	16.87	2.93
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	17.4	8.48	41.37

ComNavEnv (GaAs) arrays are between 30.1 and 227 sq. ft.



EPS/(GaAs) Generation
AUC Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	5	25.67	4.07
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	15.8	17.50	36.90

ComNavEnv (GaAs) generation weigh between 38.8 and 502.6 lbs

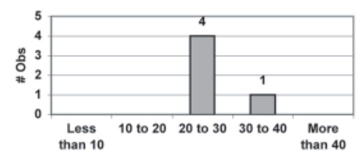
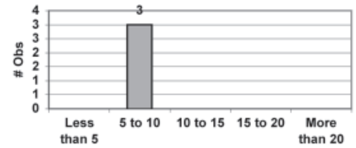


Figure 4.10—Continued

EPS/(He Si) Generation
AUC Cost per Area ($K/sq.ft.)

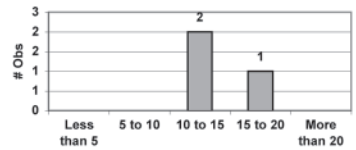
Mission	# Obs	Mean	Std Dev
ComNavEnv	3	7.61	1.71
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	22.5	3.59	15.62



ComNavEnv (HeSi) arrays are between 351.6 and 531.8 sq. ft.

EPS/(He Si) Generation
AUC Cost per Pound ($K/lb.)

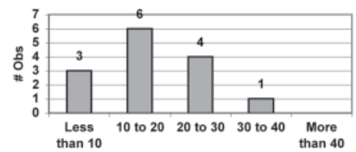
Mission	# Obs	Mean	Std Dev
ComNavEnv	3	14.18	2.48
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	17.5	7.82	25.17



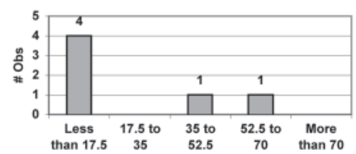
ComNavEnv (HE Si) generation weigh between 200.8 and 278.3 lbs

EPS/(Si) Generation
T1 Cost per Area ($K/sq.ft.)

Mission	# Obs	Mean	Std Dev
24 < Area < 200	14	19.04	8.57
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	45.0	7.35	40.66



Mission	# Obs	Mean	Std Dev
200 <= Area < 400	6	23.38	21.15
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	90.5	2.86	104.08



Mission	# Obs	Mean	Std Dev
400 <= Area < 832	6	7.04	1.56
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	22.2	4.10	11.54

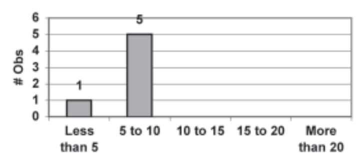
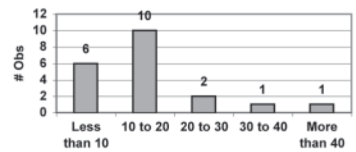


Figure 4.10—Continued

EPS/(Si) Generation
T1 Cost Per Pound ($K/lb.)

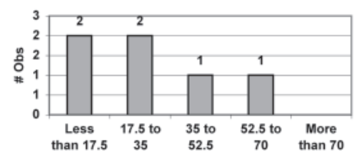
Mission	# Obs	Mean	Std Dev
ComNavEnv	20	15.96	10.52
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	65.9	5.08	36.41

ComNavEnv Si arrays weigh between 42.3 and 621.1 lbs



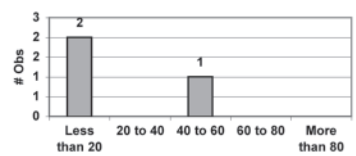
Mission	# Obs	Mean	Std Dev
Experimental	6	27.89	19.20
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	68.8	6.25	88.74

Experimental Si arrays weigh between 10.9 and 154 lbs



Mission	# Obs	Mean	Std Dev
Sci/Surv	3	28.72	23.26
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	81.0	1.69	320.05

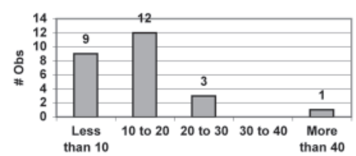
Sci/Surv Si arrays weigh between 184.2 and 1298.1 lbs



EPS/Power Conditioning & Distribution
T1 Cost Per Pound ($K/lb.)

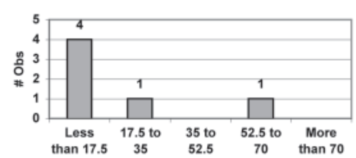
Mission	# Obs	Mean	Std Dev
ComNavEnv	25	14.17	9.64
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	68.0	4.30	33.16

ComNavEnv PCD weigh between 86.9 and 783.3 lbs



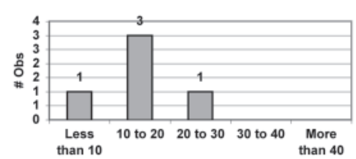
Mission	# Obs	Mean	Std Dev
Experimental	6	18.07	25.81
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	142.9	0.71	119.72

Experimental PCD weigh between 9.1 and 345.2 lbs



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	13.98	8.34
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	59.7	1.78	73.54

Sci/Surv Si arrays weigh between 124.5 and 1242.3 lbs



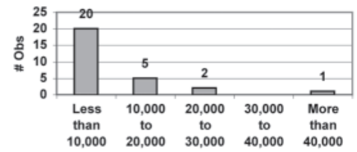
Integration Assembly and Test

IA&T varies considerably across and within mission categories and is best estimated as a percentage of spacecraft T_1. In the case of communication satellites for which payload data were also available, we also provide IA&T as a percentage of spacecraft plus payload T_1.

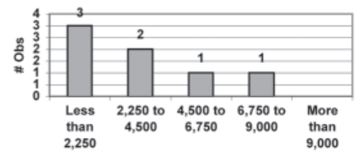
Figure 4.11
Integration Assembly and Test Crosschecks

IA&T
T1 Cost ($K)

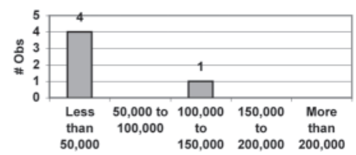
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	9,883.20	10,368.88
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	104.9	1,990.99	26,645.70



Mission	# Obs	Mean	Std Dev
Experimental	7	3,485.17	2,603.81
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	74.7	609.34	12,703.75

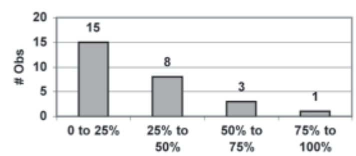


Mission	# Obs	Mean	Std Dev
Sci/Surv	5	42,357.05	40,550.32
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	95.7	3,664.88	251,730.96

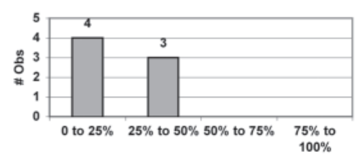


IA&T
IA&T T1 Percentage of SC T1

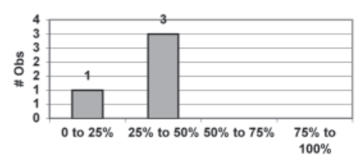
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	33%	24%
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	72.3	9%	79%



Mission	# Obs	Mean	Std Dev
Experimental	7	23%	9%
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	38.7	9%	48%

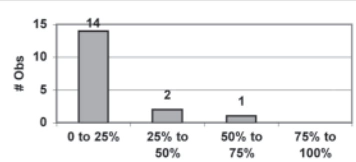


Mission	# Obs	Mean	Std Dev
Sci/Surv	5	46%	34%
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	74.6	8%	100%



IA&T
IA&T T1 Percentage of SC+Comm Payload T1

Mission	# Obs	Mean	Std Dev
Comm	17	17%	13%
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	75.0	4%	45%



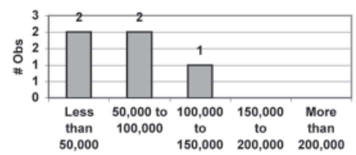
Passive Sensor

The passive sensor data was recently added to the database. In general, these sensors are not associated with the spacecraft in the database. The SE/PM and IA&T values are the costs incurred by the sensor contractor. Because of the variety of sensors and components and the limited technical data available, these results should be considered preliminary.

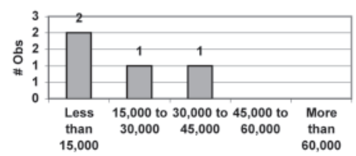
Figure 4.12
Passive Sensor Crosschecks

Passive Sensor
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
Cryogenic	5	56,457.68	32,334.62
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	57.3	10,045.35	229,973.10



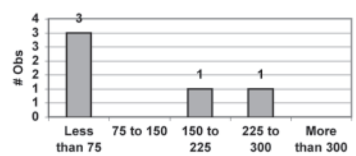
Mission	# Obs	Mean	Std Dev
Non-Cryogenic	4	19,592.79	15,519.23
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	79.2	2,755.82	94,886.09



Passive Sensor
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
All	5	104.77	93.03
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	88.8	6.59	785.71

Passive sensor weigh between 32 and 836.6 lbs



Passive Sensor Components
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
Calibration	5	1,005.79	1,649.09
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	164.0	8.79	13,762.09

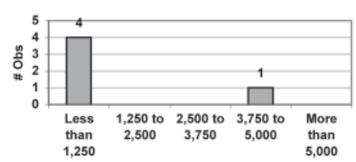
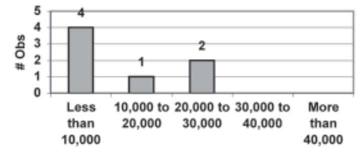
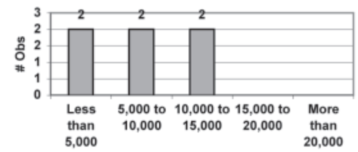


Figure 4.12—Continued

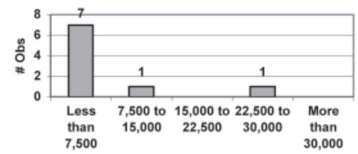
Mission	# Obs	Mean	Std Dev
Electronics	7	11,666.12	11,470.16
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	98.3	374.95	105,135.69



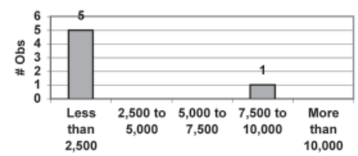
Mission	# Obs	Mean	Std Dev
Focal Plane Array	6	6,733.23	4,181.00
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	62.1	685.55	39,145.52



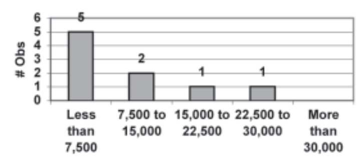
Mission	# Obs	Mean	Std Dev
IA&T	9	7,887.25	8,327.58
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	105.6	812.36	33,742.62



Mission	# Obs	Mean	Std Dev
Pointing Systems	6	3,072.57	3,293.20
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	107.2	442.67	11,617.93



Mission	# Obs	Mean	Std Dev
SEPM	9	9,427.37	7,187.37
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	76.2	1,657.73	32,257.33



Mission	# Obs	Mean	Std Dev
Structure	8	1,407.17	1,196.65
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	85.0	105.12	8,016.31

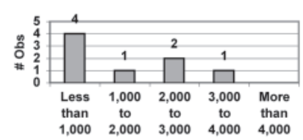
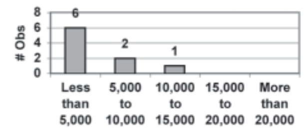
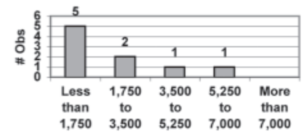


Figure 4.12—Continued

Mission	# Obs	Mean	Std Dev
Telescope	9	4,562.07	3,463.34
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	75.9	336.85	27,265.23

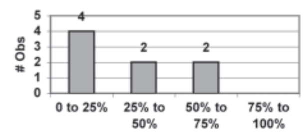


Mission	# Obs	Mean	Std Dev
Thermal	9	1,957.73	2,210.04
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	112.9	2.02	80,540.01



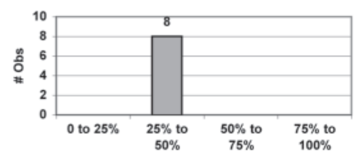
Passive Sensor/IA&T
IA&T T1 Percentage of Passive Sensor T1 less IA&T and SEPM

Mission	# Obs	Mean	Std Dev
All	8	33%	21%
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	62.8	7%	100%



Passive Sensor/SEPM
SEPM T1 Percentage of Passive Sensor T1 less SEPM

Mission	# Obs	Mean	Std Dev
All	8	30%	3%
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	9.4	5%	100%



Propulsion

Spacecraft propulsion subsystems were segregated into those with separate reaction control systems and apogee kick motors, and those with an integral propulsion subsystem using shared tankage, piping, and controls to maintain orbit and attitude as well as make orbital changes and deorbit.

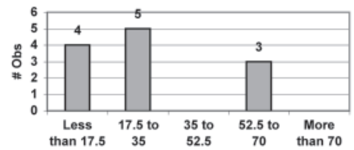
Figure 4.13
Propulsion Crosschecks

Propulsion/IPS vs. Propellant RCS + AKM
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv: RCS	12	29.49	17.03

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
57.8	9.47	69.70

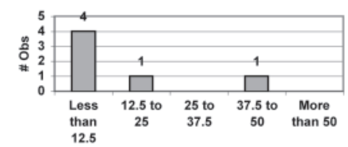
ComNavEnv RCS weigh between 38.4 and 190.8 lbs



Mission	# Obs	Mean	Std Dev
Experimental: RCS	6	16.02	14.98

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
93.5	1.86	72.78

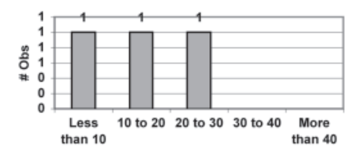
Experimental RCS weigh between 4.3 and 120.3 lbs



Mission	# Obs	Mean	Std Dev
Sci/Surv: RCS	3	17.58	8.74

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
49.7	2.59	99.21

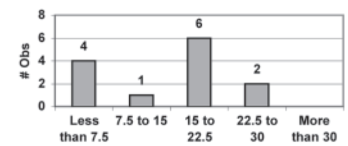
Sci/Surv RCS weigh between 42.8 and 608.9 lbs



Mission	# Obs	Mean	Std Dev
ComNavEnv: IPS	13	14.91	6.60

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
44.3	5.01	35.31

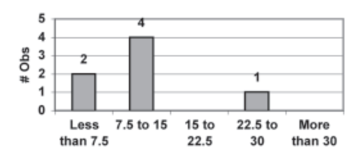
ComNavEnv IPS weigh between 98.3 and 343.5 lbs



Mission	# Obs	Mean	Std Dev
ComNavEnv: AKM	7	9.13	8.13

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
89.0	0.11	168.63

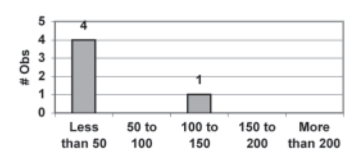
ComNavEnv AKM weigh between 60 and 701.7 lbs



Mission	# Obs	Mean	Std Dev
Experimental: AKM	5	27.82	55.45

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
199.3	0.01	978.83

Experimental AKM weigh between 53 and 614.7 lbs



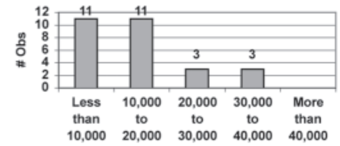
Systems Engineering/Program Management

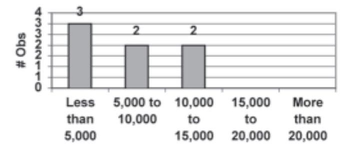
As with IA&T, calculating SE/PM as a percentage of spacecraft plus IA&T T_1 reduced dispersion of the SE/PM T_1 values. For communication satellites for which payload information was available, SE/PM was also calculated as a percentage of spacecraft, payload, and IA&T T_1.

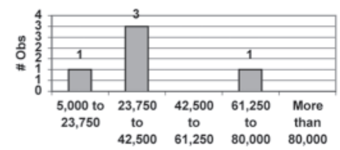
Figure 4.14
SE/PM Crosschecks

SEPM
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
ComNavEnv	28	14,467.84	9,305.46	64.3	3,642.92	38,169.48
Experimental	7	6,050.31	4,106.19	67.9	820.50	27,082.27
Sci/Surv	5	38,837.00	16,626.71	42.8	13,541.16	96,677.74

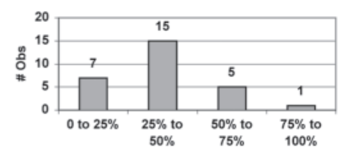


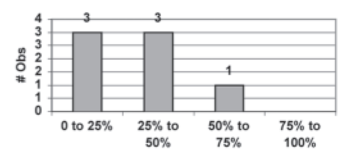


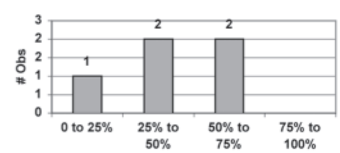


SEPM
SEPM T1 Percentage of (SC + IA&T) T1

Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
ComNavEnv	28	36%	17%	46.6	15%	72%
Experimental	7	31%	14%	44.5	13%	66%
Sci/Surv	5	35%	16%	45.3	10%	100%

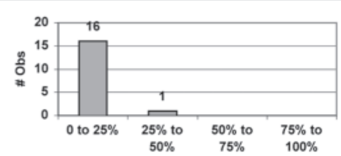






SEPM
SEPM T1 Percentage of (SC + Payload + IA&T) T1

Mission	# Obs	Mean	Std Dev	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
Comm	17	19%	6%	33.8	10%	32%



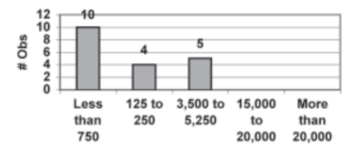
Structure

The costs of structure and mechanisms vary across the range of systems included in the database. When the data are stratified by weight, the category averages become more consistent and the expected economies of scale for larger structures become apparent.

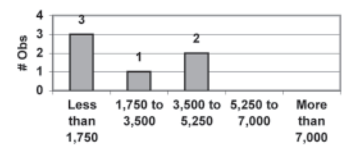
Figure 4.15
Structure Crosschecks

Structure
T1 Cost ($K)

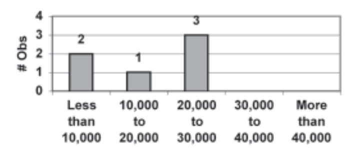
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	4,888.97	3,514.89
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	71.9	966.22	14,468.02



Mission	# Obs	Mean	Std Dev
Experimental	7	2,451.18	1,816.31
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	74.1	214.25	13,961.14

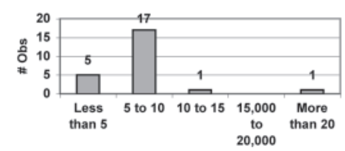


Mission	# Obs	Mean	Std Dev
Sci/Surv	5	14,556.69	10,261.64
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	70.5	1,893.94	70,915.18



Structure
T1 Cost per Pound ($K/lb.)

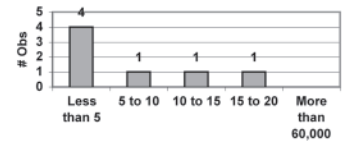
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	8.60	5.20
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	60.5	2.49	21.17



ComNavEnv structure weigh between 119.2 and 1761.5 lbs

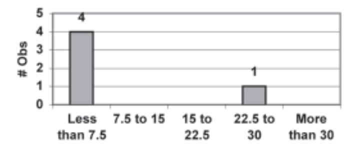
Figure 4.15—Continued

Mission	# Obs	Mean	Std Dev
Experimental	7	6.78	6.60
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	97.4	0.69	31.44



Experimental structure weigh between 141.3 and 1850.7 lbs

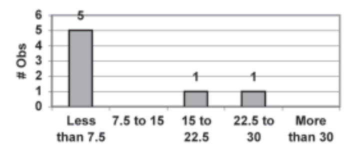
Mission	# Obs	Mean	Std Dev
Sci/Surv	5	8.92	9.48
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	106.2	0.78	50.03



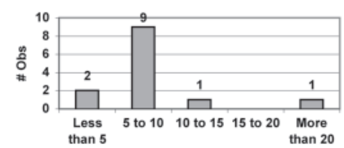
Sci/Surv structure weigh between 184.6 and 10729 lbs

Structure
T1 Cost per Pound ($K/lb.)

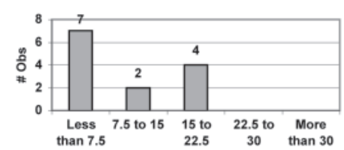
Mission	# Obs	Mean	Std Dev
100<=Lbs<=250	7	9.75	8.92
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	91.5	1.24	40.34



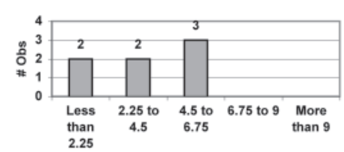
Mission	# Obs	Mean	Std Dev
250<Lbs<=500	13	8.94	5.37
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	60.0	2.63	22.66



Mission	# Obs	Mean	Std Dev
500<Lbs<=1,000	13	9.23	5.48
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	59.4	2.17	26.91



Mission	# Obs	Mean	Std Dev
1,000<Lbs	7	4.05	2.20
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	54.2	0.95	12.68



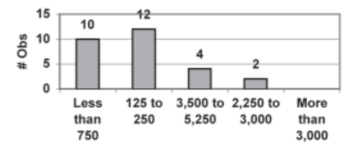
Thermal

The thermal control subsystem was best represented by average T_1 costs by mission type.

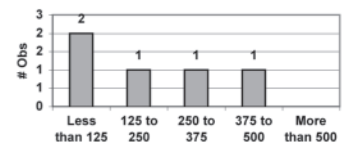
Figure 4.16
Thermal Crosschecks

Thermal
T1 Cost ($K)

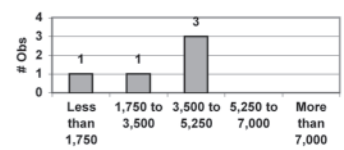
Mission	# Obs	Mean	Std Dev
ComNavEnv	28	1,074.29	668.63
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	62.2	237.93	3,072.01



Mission	# Obs	Mean	Std Dev
Experimental	5	196.51	151.14
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	76.9	8.17	2,112.96



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	3,221.78	1,621.18
	Coeff of Variation	**Lower 90% Pred. Limit**	**Upper 90% Pred. Limit**
	50.3	349.38	19,662.24



Telemetry Tracking and Command

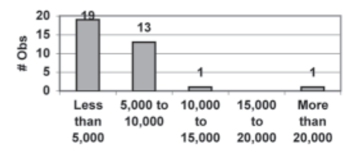
TT&C subsystem costs were classified by mission, number of channels, and weight. We were able to analyze selected major components with generally acceptable results.

Figure 4.17
Telemetry Tracking and Command Crosschecks

TT&C
T1 Cost ($K)

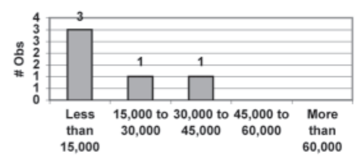
Mission	# Obs	Mean	Std Dev
ComNavEnvExp	34	5,259.67	3,498.62

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
66.5	1,964.78	10,817.91



Mission	# Obs	Mean	Std Dev
Sci/Surv	5	19,478.88	15,627.08

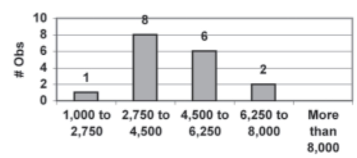
Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
80.2	2,059.13	106,869.18



TT&C
T1 Cost per Channel

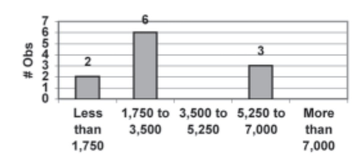
Mission	# Obs	Mean	Std Dev
One	17	4,421.61	1,599.24

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
36.2	1,811.76	9,204.37



Mission	# Obs	Mean	Std Dev
Two	11	3,065.85	1,704.72

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
55.6	998.44	7,261.05



TT&C
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
All	38	50.29	30.10

Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
59.9	16.60	112.14

TT&C weigh between 27.8 and 606 lbs

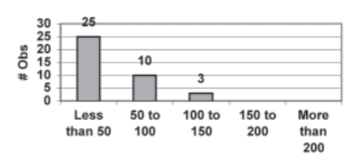
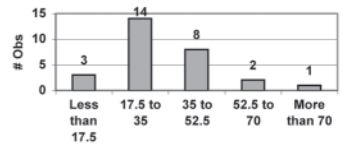


Figure 4.17—Continued

TT&C/Digital Electronics
T1 Cost per Pound ($K/lb.)

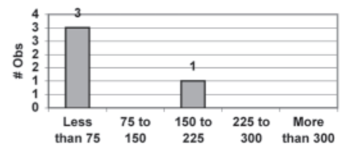
Mission	# Obs	Mean	Std Dev
ComNavEnvExp	28	33.19	15.59
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	47.0	11.47	75.26

ComNavEnvExp TT&C/digital electronics weigh between 21.1 and 149 lbs



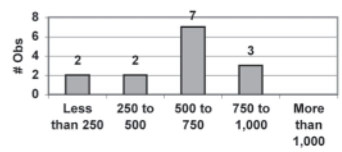
Mission	# Obs	Mean	Std Dev
Sci/Surv	4	68.80	73.70
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	107.1	0.18	4,777.70

Sci/Surv TT&C/digital electronics weigh between 48.4 and 397.5 lbs

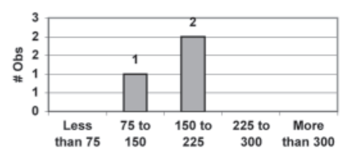


TT&C/Receiver
T1 Cost ($K)

Mission	# Obs	Mean	Std Dev
ComNavEnv	14	545.84	209.54
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	38.4	172.12	1,382.44



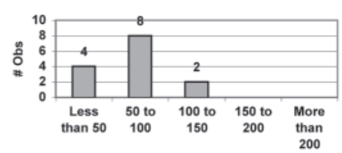
Mission	# Obs	Mean	Std Dev
Experimental	3	164.87	52.62
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	31.9	53.35	475.38



TT&C/Receiver
T1 Cost per Pound ($K/lb.)

Mission	# Obs	Mean	Std Dev
ComNavEnv	14	67.49	33.23
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	49.2	21.29	164.89

ComNavEnv TT&C/receivers weigh between 5 and 21.2 lbs



Mission	# Obs	Mean	Std Dev
Experimental	3	52.40	10.05
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	19.2	27.90	96.15

Experimental TT&C/receivers weigh between 2.5 and 4.7 lbs

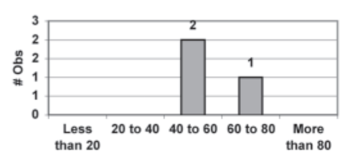
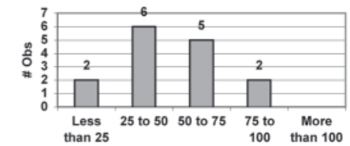


Figure 4.17—Continued

TT&C/Transmitter
T1 Cost per Pound ($K/lb.)

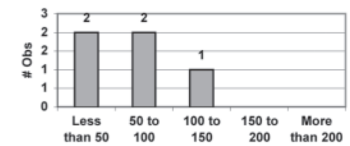
Mission	# Obs	Mean	Std Dev
ComNavEnv	15	49.32	23.73
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	48.1	11.13	153.19

ComNavEnv TT&C/transmitters weigh between 5.4 and 20.9 lbs



Mission	# Obs	Mean	Std Dev
Experimental	5	60.03	40.67
	Coeff of Variation	Lower 90% Pred. Limit	Upper 90% Pred. Limit
	67.7	12.40	211.84

Experimental TT&C/transmitters weigh between 2.3 and 13.9 lbs



Using the Crosschecks

The crosschecks presented in this section were developed to fill the need of government analysts for general rules to assist in evaluating the reasonableness of space program cost estimates. While a variety of parametric models are available to develop estimates, they require both time and program characteristic data. These crosschecks may be used in the following ways:

- a quick determination of which portions of a cost estimate are consistent with historical cost ranges and which may need additional justification or analysis.
- an objective basis for setting endpoints of cost risk distributions for estimates of spacecraft components.

Obviously, if time and input data are available, statistically derived CERs are preferred for developing estimates, since they should have not only a lower standard error, they are sensitive to a wider variety of cost-driving parameters. Setting valid end points for cost risk distributions can be difficult without a fairly extensive historical database. A frequent criticism of cost risk analyses is that the range of possible outcomes is too narrow. There are a number of probable causes for this, including ignoring or incorrectly modeling interelement correlations. However, another contributor is likely to be the understating of the ranges of possible costs of the component cost distributions used in Monte Carlo simulations to determine the cost probability distribution for the overall estimate. These ranges are often set by the judgment of either a technical expert or the estimator. Unfortunately, even knowledgeable technical experts are subject to well-known biases that tend to understate the actual uncertainty.[5] In cases in which time or access to technically knowledgeable personnel is limited, cost analysts must often fall back on

5 See Arena et al. (2006, p. 76).

crude rules or simple factors applied to the point estimate value to generate the high and low values. Neither of these can be supported with much confidence.

Obviously, these crosschecks are limited by the data from which they were derived, as well as the need to protect the proprietary nature of individual data points. However, they do provide a means for setting ranges for component costs that are based on actual experience rather than subjective judgment or analytical convenience. To illustrate how these crosschecks might be used, let's suppose a cost analyst is attempting to assess a cost estimate for a proposed communication satellite program with characteristics as shown in Table 4.5. Focusing on the electrical power subsystem, the average EPS recurring cost and prediction limits for communication/navigation/environmental spacecraft can be read directly from the crosschecks. The other subsystem crosschecks can be calculated by multiplying the EPS cost per pound and cost per BOL watt crosscheck values by the appropriate weight and power characteristics for the spacecraft being estimated. This results in the four sets of values for EPS subsystem costs, which range from $10.038 million to $18.585 million. Of these relationships, the cost per pound and cost per BOL watt by power class have the smallest coefficients of variation. However, the EPS cost per pound for communication/navigation/environmental is based on 28 data points compared with the 18 that fall in the relevant power class for the cost per watt crosscheck and, at 800 pounds, is close to the middle of the weight range for communication/navigation/environmental EPS data points. Thus, it is the most relevant crosscheck at the subsystem level.

Table 4.5
Example Using Crosschecks

Spacecraft Characteristics	
Mission	**Communications**
Electrical power system	
Type	Si solar panels
Total weight (lbs.)	800
Beginning of life power (W)	3,500
Solar array area (sq. ft.)	300
Solar array weight (lbs.)	200
Power conditioning and distribution weight (lbs.)	250

Applying crosschecks	Recurring Cost (FY 2000$ millions)		
Mission	Average	Low	High
Electrical power system			
Average cost (CommNavEnv)	10.038	2.417	27.167
$/lb (CommNavEnv)	10.656	3.392	24.192
$/W (CommNavEnv)	15.610	2.285	48.650
$/W (1,000–5,000 W)	18.585	4.095	54.320
EPS/(Si) generation			
$/sq ft (200–400 sq. ft.)	7.014	0.858	31.224
$/lb (CommNavEnv)	3.192	1.016	7.282
Power conditioning and distribution			
$/lb (CommNavEnv)	3.543	1.075	8.290

If the cost ranges of the major EPS components are required, the same procedure is used to calculate the values shown for power generation and power conditioning and distribution. In the case of power generation, the cost-per-pound crosscheck is preferred because of its lower cost variance and larger number of data points. PCD has only a single crosscheck form.[6]

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[6] The only EPS component for which a crosscheck is not available is power storage (batteries), which could be estimated using a supplier quote or by other means. The sum of the EPS component average costs could then be compared with the subsystem-level EPS costs as an additional check.

CHAPTER FIVE

Common Issues in Estimating Space Programs

In this chapter, we discuss a number of issues that are commonly encountered in estimating the cost of space programs. These are not intended to be comprehensive guides but rather are to acquaint the analyst who may be new to space estimating with the issues and some potential approaches to dealing with them, along with reference citations for more in-depth information. The following topics are addressed:

- small spacecraft
- cost improvement in space systems
- cost considerations of COTS components
- evolutionary acquisition.

Small Spacecraft

During the 1980s, the primary sources of funding for small spacecraft were the Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force Space Test Program. Spacecraft procured during this time were smaller and made maximum use of existing hardware. Their primary purpose was to demonstrate a particular technology before developing a full-capability spacecraft. Time lines were typically 24 to 48 months from approval to launch. The costs associated with technology development and flight certification were minimized by using the most mature hardware and software available.

In the 1990s, the level of functionality possible in small spacecraft increased dramatically due to the availability of space-compatible computational power. The trend toward cost reduction in small spacecraft enabled a change in philosophy, which had a greater tolerance for risk, as evident in programs such as Clementine and the NASA Small Satellite Technology Initiative's Lewis and Clark (Bearden, 2001). In response to budget pressures and the loss or damage of billion-dollar missions, NASA administrator Daniel Goldin, promoted the notion of the faster, better, cheaper (FBC) approach for NASA. Programs would be faster by constraining the development schedule and cheaper by imposing a firm funding cap. To what extent these programs represent "better" remains open to question.[1] Suggested benefits have included a larger number of simpler, more focused missions, providing opportunities for a broader range

[1] In recent years, NASA has moved away from the faster, better, cheaper approach.

of scientists and suppliers to participate. Also, compressed development schedules presumably allow the incorporation of components and technologies nearer the state of the art than large traditional programs with long development and test cycles. These constraints fueled more than a decade of controversy over FBC.

The FBC approach is not inherently limited to small spacecraft. However, NASA has shifted from a reliance on large, multibillion-dollar spacecraft to the almost exclusive development of small spacecraft, and hence FBC has become synonymous with small spacecraft (Sarsfield, 2000, pp. 5–6). For these reasons, much of the discussion that follows focuses on the experiences of NASA and particularly on spacecraft designed under the FBC approach.

There are many ways of defining small spacecraft. For example, they could be defined in terms of their development, management, and operation costs. The most common way of defining a small spacecraft is in terms of mass. Mosher et al. (1999) observe that the typical "wet" mass of space vehicles has decreased by approximately 85 to 95 percent since NASA adopted the FBC paradigm (Mosher et al., 1999). For example, Table 5.1 shows that the average mass for traditional missions is 3013 kg, while the average mass for FBC missions is 400 kg. Sarsfield (2000) defines small spacecraft[2] as those whose space vehicle has a dry mass of less than approximately 500 kg and notes that this definition does a good job of focusing attention on programs that have pursued low-cost options. We will adopt this definition for the remainder of the discussion.

The use of small spacecraft is driven principally by the potential for lower life-cycle costs. Other factors driving small spacecraft include shorter development cycles, miniature enabling technologies, and the ability to spread mission risks across multiple small spacecraft rather than one large spacecraft. We will discuss the implications of small versus large spacecraft in terms of cost, schedule, and quality in the following sections.

Mission Implications

Small spacecraft do not necessarily replace their large counterparts. For example, Mosher et al. (1999) note that the mission objectives of the great space observatories such as Hubble Space Telescope and Chandra cannot be achieved by a small package. As noted by Sarsfield, a 1996 National Research Council Workshop on Reducing Mission Cost questioned the assumption that a small orbiter-and-lander mission for the 2001 NASA Mars exploration plan was preferable to applying funds to a larger spacecraft with a later launch date (Sarsfield, 1998). Larger

Table 5.1
Space Vehicle Wet Masses (as of 1999)

Mission Class	Average (kg)	Median (kg)
Traditional	3,013	2,787
FBC	400	295

SOURCE: Mosher et al. (1999).

[2] Sarsfield uses the term *spacecraft* to describe what we refer to as the *space vehicle*.

satellites have the advantage of being able to collect simultaneously from multiple instruments. Simultaneous observations can also be made using multiple small satellites, but this requires careful phasing of missions so that particular instruments are in orbit at the same time for coordinated viewing (Sarsfield, 1998).

The missions performed by small spacecraft often serve as precursors to missions performed by larger spacecraft. In some cases, they exploit opportunities for small spacecraft that were identified in previous missions with larger spacecraft or perform focused investigations.

Schedule Implications

Sarsfield evaluated 32 spacecraft developed between 1989 and 1999 and categorized them as either FBC or non-FBC spacecraft. The results are shown in Table 5.2.

Sarsfield estimated that the average development time for non-FBC missions was six years, while the development time for FBC missions was 3.5 years. That is, small spacecraft had shorter development cycles—about 41 percent shorter than traditional missions. However, the average dry mass of non-FBC spacecraft was estimated to be 2,787 kg, while the average dry mass of FBC spacecraft was estimated at 295 kg. That is, there was a reduction in mass of 89 percent, but a reduction in development time of only 41 percent. Sarsfield suggests that one reason development cycles have not been reduced further is that small spacecraft tend to be more complex than their larger counterparts.

Mosher et al. (1999) also report a 40 to 50 percent reduction in development time. They note, however, that often more risk is accepted in small spacecraft development. We turn to this topic next.

Reliability Implications

One advantage of small spacecraft is that risk can be spread among several small spacecraft rather than one large spacecraft. However, failure rates are significantly higher for small spacecraft than for larger, traditional spacecraft. Mosher et al. (1999) report a 10 percent catastrophic failure rate for traditional spacecraft and a 28 percent catastrophic failure rate for small spacecraft. They report a 30 percent total (partial and catastrophic) failure rate for traditional spacecraft and a 44 percent total failure rate for small spacecraft. These statistics are summarized in Table 5.3.

Sarsfield (2000, p. 29) reports a 6.7 percent spacecraft failure rate for traditional spacecraft built in the 1990s, and a 35.3 percent spacecraft failure rate for FBC spacecraft built in the 1990s. It should be noted, however, that launch rates were found to be higher for small spacecraft (Sarsfield, 2000).

In the past, NASA categorized spacecraft into one of four classes, referring to the standards and controls used in its construction. The classes reflect the level of accepted risk. Class A referred mainly to human-rated spacecraft. At the other end of the spectrum is Class D, which can be built using commercial-grade components with relaxed inspection and test standards. While this classification system is no longer used, the majority of small spacecraft are built to a Class C standard. Traditional spacecraft tended to be built to a higher-class standard. For example, Chandra and Cassini are built to a Class A standard (Sarsfield, 2000).

Table 5.2
FBC and Non-FBC Missions, 1989 to 1999

Year	Name	FBC?
1999	Chandra X-Ray Center	No
1999	Far Ultraviolet Spectroscopic Explorer (FUSE)	No
1999	Tomographic Experiment Using Radioactive Recombinative Ionosphere Extreme Ultraviolet and Radio Sources (TERRIERS)	Yes
1999	Wide-Field Infrared Explorer (WIRE)	Yes
1999	Stardust	Yes
1999	DS-2 Microprobe	Yes
1999	Mars Polar Lander	Yes
1998	Mars Climate Orbiter	Yes
1998	SWAS	Yes
1998	Deep Space 1	Yes
1998	Transition Region and Coronal Explorer (TRACE)	Yes
1998	Student Nitric Oxide Explorer (SNOE)	Yes
1998	Lunar Prospector	Yes
1997	Cassini+Huygens	No
1997	Advanced Composition Explorer (ACE)	No
1996	Mars Pathfinder	Yes
1996	Mars Global Surveyor	Yes
1996	High-Energy Transient Explorer (HETE)	Yes
1996	Fast Auroral Snapshot (FAST)	Yes
1996	Near-Earth Asteroid Rendezvous (NEAR)	Yes
1995	X-Ray Timing Explorer (XTE)	No
1995	Solar and Heliospheric Observatory (SOHO)	No
1994	Wind	No
1994	Clementine	Yes
1992	Mars Observer	No
1992	Solar Anomalous and Magnetospheric Particle Explorer (SAMPLEX)	No
1992	Extreme Ultraviolet Explorer (EUVE)	No
1991	Gamma ray observatory	No
1990	Hubble Space Telescope	No
1989	Cosmic Background Explorer (COBE)	No
1989	Galileo	No
1989	Magellan	No

SOURCE: Sarsfield (2000).

Table 5.3
Spacecraft Failure Rates

Mission Class	Catastrophic Failure Rate (%)	Total Failure Rate (%)
Traditional	10	30
FBC	28	44

SOURCE: Mosher et al. (1999).

Mosher et al. (1999) indicate that hardware problems in particular proved to be the largest contributing factor in design related failures. Sarsfield's findings suggest that new technology has traditionally not been the source of mission failure.

A workshop titled "Best Practice and FBC Workshop," jointly chaired by the RAND Corporation and NASA, was held in Pasadena, California, in December of 1999. Among the recommendations made at the conclusion of the workshop was that NASA should focus on better, recognizing that faster developments and cheaper life-cycle costs will invariably result, and noting that price and value are not equivalent (Sarsfield, 2000). This was also a recommendation of the Young Panel on space systems acquisition (DoD, 2003a).

Cost Implications

Potential cost reduction areas for small space vehicles include the following:

- shortening development time, reducing labor costs, and encouraging the use of standard designs and components
- smaller teams, enabling more efficient communication and coordination
- lower absolute launch costs by using either smaller launch vehicles or multiple manifesting on a single launch vehicle.

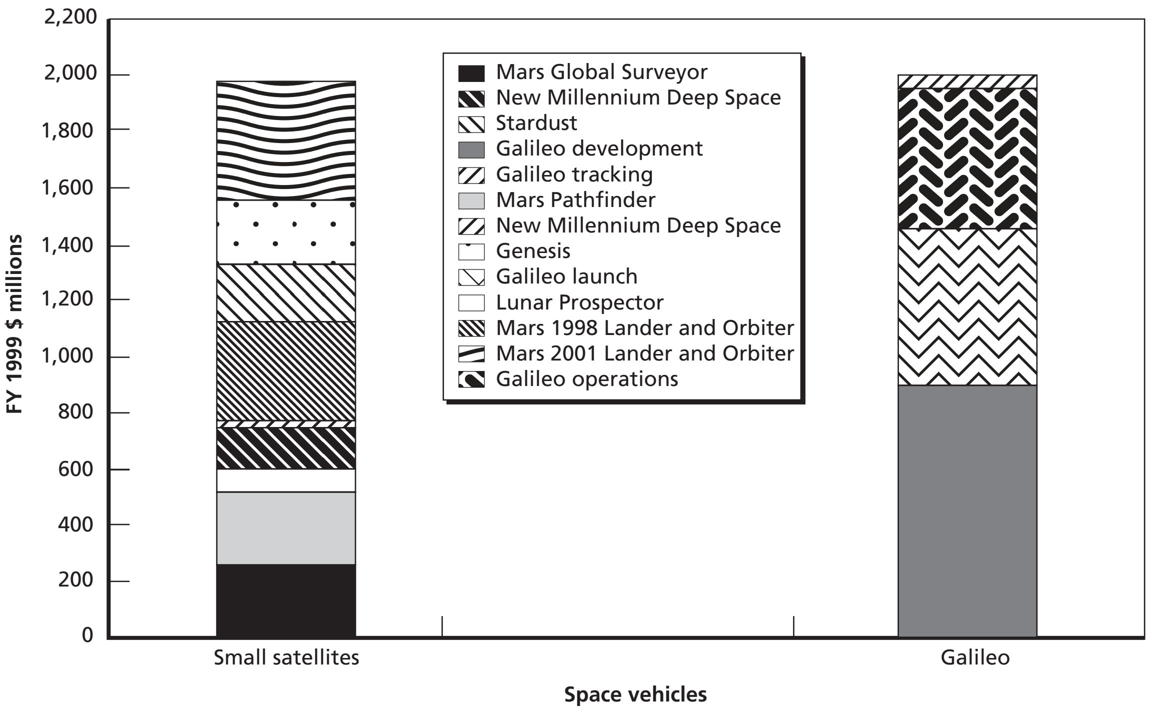
Potential drivers of increased cost for small space vehicles include the following:

- higher complexity if mission objectives are not scaled back
- lost economies of scale—higher cost per kg to launch
- greater risk tolerated with small satellites with higher potential for failure.

Figure 5.1 shows the total life-cycle cost for nine small space vehicle programs is approximately $2 billion (FY 1999 dollars). By comparison, Galileo, a large and traditional space vehicle, is about the same cost. This comparison makes clear the magnitude of the cost difference between small and large spacecraft. (It is possible that some observed cost reductions may be due to other factors not directly related to size. For example, over time, the role of design inheritance and improved technology may drive down costs, regardless of the size of the spacecraft.)

Although a variety of metrics can be used to compare "faster" and "cheaper" dimensions of space programs, assessing the "better" is both the most important and the most difficult. Ultimately, the success of the FBC approach must be judged by its cost effectiveness, but effectiveness measures tend to be more complex and less precise than cost. However, during

Figure 5.1
Life-Cycle Costs of Nine Small Space Vehicles Versus Galileo



SOURCE: Mosher et al. (1999).
RAND *TR418-5.1*

project execution, the often-aggressive schedule and cost targets tend to be closely monitored, whereas the more diffuse indicators of design margins and performance risk unintentionally may become secondary considerations.

Bearden (2001) proposes an approach to discern the risk of FBC mission failure by relating cost, schedule, and a mission complexity metric based on 21 system characteristics. Although the analysis of these parameters and their interrelationships was suggested as a topic for future research, this approach has the advantage of avoiding subjective complexity characterizations. His preliminary results show that partial or full mission failure or significant cost or schedule growth is associated with programs having high relative complexity. With additional analysis, this approach could be used to determine cost, schedule, and complexity thresholds beyond which the risk of failure is high.

Sarsfield evaluated total mission cost per unit mass for FBC and non-FBC missions and demonstrated that cost does not scale linearly with mass. As spacecraft become smaller, the retained complexity becomes a more important determinant of cost than size. In other words, if the spacecraft mass is reduced by aggressive miniaturization but retains similar functionality, cost will not decrease proportionately with size.

It is not surprising that small spacecraft tend to cost less than their larger counterparts. We have already seen that small spacecraft do not necessarily perform the same missions as larger spacecraft, and we have also seen that small spacecraft have been less reliable. Hence, the more important issue is whether small spacecraft are more cost effective than their larger counterparts.

Quality of Science and Cost Effectiveness

One approach to evaluating cost effectiveness is to estimate the amount of science return provided for the mission costs. Mosher et al. (1999) define the instrument-months of science return as the product of the number of instruments onboard the spacecraft with the duration of time (in months) that the instruments collect data at their final destination. The cost effectiveness metric they propose, called *science mission cost effectiveness* (SMCE), is the instrument-months divided by the total mission cost. They evaluated the SMCE for traditional missions as 0.52 and for FBC missions as 0.82. That is, FBC missions were 57 percent more cost effective according to this metric.

Conclusions

Small spacecraft are typically an order of magnitude smaller by mass than their larger counterparts. They do not necessarily perform the same missions as their larger counterparts. For example, small spacecraft could not perform the missions of the Hubble Space Telescope or Chandra. Large spacecraft have the advantage of being able to collect data from multiple instruments simultaneously. Development schedules for small spacecraft are typically 40 to 50 percent shorter. Smaller spacecraft have been less reliable than their larger counterparts. Possible contributing factors include the high relative complexity of small spacecraft, constrained development environment, and a tolerance for higher risk by NASA. Life-cycle costs are much lower for small spacecraft than for large spacecraft. However, it is not clear whether they are more cost effective. Sarsfield suggests that as size decreases, complexity rather than size becomes the dominant factor in cost. Studies by Mosher et al. (1999) suggest that NASA's small spacecraft have been more cost effective when considering the instrument return per total mission cost.

Several space system cost models are available for estimating small spacecraft costs, including the NASA/Air Force Cost Model (NAFCOM).

Cost Improvement

The goal of a space system cost estimate is to predict the actual costs of a future space system. Cost improvement theory, often referred to as *cost progress*, *experience*, or *learning* curves quantifies the idea that producing more than one unit of a complex product should result in more efficient use of labor, improved processes, and solved problems such that later units are cheaper to produce than are earlier ones.

For the most part, cost improvement is assumed to occur in space vehicle production; it has actually been quantified in only a relative handful of higher-quantity programs. Although cost improvement is routinely found in a wide range of high-output manufacturing programs—from aircraft to microchip manufacturing (see Dutton and Thomas, 1984)—it has not been empirically validated in low-output settings, as frequently occur in satellite production.

Still, cost improvement theory is a standard component of estimating space systems. This section provides the analyst some perspective on its application to the peculiarities of space system production.

Cost Improvement Theory

Cost improvement theory posits that when producing a sequence of identical products, improvements in labor productivity, process management, and technology application reduce the cost of each additional unit. Specifically, the theory postulates that with every doubling of quantity produced, the cost is reduced by a constant factor. The theory can be used to allocate total production lot costs to specific units. The standard mathematical procedure involves fitting a curve through the lot costs and projecting lot costs backward to determine T_1. This fitted curve can then be used to apportion the costs to any chosen unit.

The basic formula is

$$C(Q) = T_1 * Q^b,$$

where $C(Q) =$ cost of the Qth unit *or* average cost of the first Q units, depending on learning theory assumed; $T_1 =$ theoretical first unit cost; and $b = \ln(\text{decimal slope})/\ln(2)$.

Applying Cost Improvement to Space Systems

In general, cost data come from the contractor as total expenditures for all units in a given production lot. To apply cost improvement theory, the analyst must first separate these into one-time costs relating to the entire program (nonrecurring) and costs related to the production of individual units (recurring). Cost improvement applies to recurring costs only. The effects of inflation must then be removed by converting all costs to equivalent constant dollars.

Cost improvement modeling techniques were originally developed for production of a large number of nearly identical products in multiple sequential lots. In these applications fitting a slope and theoretical cost at some specified unit (T_1, T_{100}, and so on) that best characterizes the actual lot data is relatively straightforward.[3] Unfortunately, this is rarely the case in satellite production. Table 5.4 contains data from the USCM 8 database. For the 60 lots from 52 programs, over half the programs contain one lot with a single unit. Obviously, for these programs, cost improvement does not apply. Cost improvement should apply, however, for the other programs, and it becomes increasingly important as the total number of spacecraft produced increases.

A further complication is that a sequence of small lots of spacecraft often has modifications from one lot to the next. Even follow-on production lots frequently have additional nonrecurring costs because parts become obsolete. Instead of mass production, the data suggest that it may be more appropriate to think of satellite production as "build to order."

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[3] Book and Burgess have shown that the high rate of change of costs over early units introduces a high degree of uncertainty in databases or models that use the first unit (T_1) normalized cost value (Book and Burgess, 1996). Using T_{100}, or even T_{10}, will reduce the potential errors in fitting multiple programs to a common cost improvement rate. Unfortunately, most space programs do not have sufficient production quantities to support this.

Table 5.4
Lot Sizes in the USCM 8

Total Number of Spacecraft in Lot	Number of Lots
1	33
2	6
3	6
4–8	13
> 20	2

While built-to-order programs can certainly exhibit cost improvement, the incentives and environment for low-quantity production will probably result in a flatter-than-average rate of cost improvement.

Other factors, such as production breaks, changes in design or suppliers, and personnel turnover, can all affect cost improvement negatively, so that the cost of units later in production may not decrease as much as in other commodities.

Estimating Cost Improvement in Space Systems

Cost improvement will typically be different from program to program and subsystem to subsystem. In developing space cost estimates, many analysts assume a cost improvement curve of 95 percent, since this is the slope used to develop T_1 data in USCM and therefore, the CERs themselves. (Cost improvement slope and T_1 are paired values; changing one will change the other.) However, a review of the literature provides some insight into other approaches to determining an appropriate slope.

One approach is to select a slope depending on total program quantity. Apgar, Bearden, and Wong (1999) repeat the guidelines for cost improvement slope (Meisl and Morales, 1994, Appendix C), shown in Table 5.5.

Since only three of 52 programs in the USCM database had more than 10 satellites (GPS II/IIA and IIR and DSCS IIB), the 95 percent rule appears at first to be a reasonable default value; however, this value is based more on expert judgment than on empirical data.

In general, application of cost improvement theory to large programs is well supported. Even then, widely varying estimates of cost improvement curve slopes do not give the analyst a

Table 5.5
Cost Improvement Slope for Various Production Quantities

Total Program Quantity	Cost Improvement Slope (%)
1–10	95
11–50	90
> 50	85

clear indication that any general rule or specific slope is appropriate for estimating. Meisl and Morales (1994) find a range of cumulative cost improvement slopes—from 79.57 percent to 93.94 percent at the spacecraft level (for DMSP with 16 units and DSCS with 11 satellites). With a program that underwent design changes from one lot to the next (GPS with 31 units), the fitted cost improvement curve slope was 118 percent, indicating that the effects of design changes overshadowed any savings due to cost improvement.

Table 5.6 shows that although both Meisl and Morales (1994) and Whitehair (1992) examine the GPS Block II and DSCS Block III satellite production runs, they come to very different conclusions about the slopes.

These two programs were chosen for comparison because they were the only two present in both studies. Some of the discrepancy between them can be deduced from the different methodological approaches and specific data. It should be noted that at the subsystem level, slopes vary considerably from one subsystem to another. Table 5.7 reproduces Exhibit V-2 from Miesl and Morales (1994).

The varying rates for subsystems reflect the nature of the production operations and content of each, as well as the incentives for contractors to use standardized designs to the maximum extent possible. ("Standard" components or even entire spacecraft appear to exhibit flatter cost improvement because they actually have higher prior quantities than would be indicated from the program being estimated.)

Examining cost improvement curves within and across organizations, Dutton and Thomas (1984, p. 237) conclude that

> in general, the empirical findings caution against simplistic uses of either industry experience curves or a firm's own progress curves. Predicting future progress rates from past historical patterns has proved unreliable.

Even with both an excellent fit to historical data (as measured by metrics like R^2), and meeting almost all of the theoretical requirements of cost improvement, there is no guarantee of accurate prediction of future costs.

One would expect that, under optimal conditions, an improvement slope estimate of direct labor hours would be reasonably accurate. After all, the original learning theory was derived from the observed reduction of hours needed to produce later units. However, even projections based on producing an almost identical product over all lots, in a single facility, with large lot sizes, and no production break or design changes, do not necessarily yield reliable forecasts of labor hours. Out-of-sample forecasting using early lots to predict later lots has shown that, even under optimal conditions, labor improvement curve analyses have error rates of about ±25 percent.

These problems can be significant, particularly as production quantities increase. The direct effect of an incorrectly specified cost improvement slope of 95 percent on total cost can be seen in Table 5.8.

As the table shows, if the total quantity to be produced is two, and the "true" value of the cost improvement slope is 85 percent, costs will be overestimated by 12 percent. With a program size of five satellites, the error is 29 percent.

Table 5.6
Differing Estimates of Cumulative Average Cost Improvement on Two Programs

Program	Meisl and Morales (1994)	Whitehair (1992)[a]
DSCS Block III	79.6%	95%
GPS Block II	$118.2 million (98.5%)[b]	93%

[a] The cost improvement curve data published in Whitehair (1992) are no longer included in Sidor (2000).

[b] Accounting for technological change, the GPS cost improvement slope estimate is 98.5 percent.

Table 5.7
Spacecraft Subsystem Cost Improvement Slopes

Spacecraft Subsystem	DMSP (%)	DSCS (%)
Structure	96.62	95.34
ACS	79.30	82.71
Thermal control	168.68	79.80
EPS	99.02	87.95
TT&C	85.73	136.66
Propulsion	N/A	N/A
IA&T	56.08	78.36
Other	N/A	74.85
Program level	117.56	69.90

Table 5.8
Effect on Total Cost Due to Misspecifying a 95-Percent Cost Improvement Slope

"True" Cost Improvement (%)	Total Quantity						
	2 (%)	3 (%)	4 (%)	5 (%)	10 (%)	15 (%)	20 (%)
85	12	19	25	29	45	54	62
90	6	9	11	13	20	24	26
95	0	0	0	0	0	0	0
100	–5	–8	–10	–11	–16	–18	–20
105	–10	–15	–18	–21	–28	–32	–35

Alternative Approaches for Modeling Cost Improvement

Attempting to overcome or avoid the difficulties presented by the conventional approach to estimating and applying cost improvement, various authors have proposed alternative methods.

Killingsworth (2002) proposes a modification of the conventional approach by focusing on the environmental factors that influence learning, independent of product type. These factors are design stability, system complexity, and scale. He proposes developing "cost improvement relationships" from a mixed data set of avionics, missiles, and spacecraft. In a feasibility study, he found that the most significant driver was product instability during the production run. Unfortunately, the instability metric was somewhat subjective, so he substituted production rate, weight, and cost per pound as objective and easily available metrics. Using his test data set, the results were promising.

Book and Burgess (2003) have suggested another alternative approach. It is referred to as *quantity as an independent variable*, in which historical lot average unit cost is regressed on technical or physical parameters, total quantity produced, and/or prior quantity in program. In mathematical terms:

$$AUC_L = a + bW^x N^y Q^Z,$$

where $AUC_L =$ the average unit cost of lot L; $W =$ weight (or other technical parameter); $N =$ lot size; $Q =$ prior quantity produced; and a, b, x, y, and z are parameters to be estimated from *actual* cost data (not adjusted for quantity).

Total program cost is then calculated by summing over all lots of a program the product of a lot's size, N, and its estimated average unit cost:

$$TC = N_1 * AUC_1 + N_2 * AUC_2 + \ldots N_n * AUC_n.$$

This technique attempts to capture the effect of lot sizes and production quantity in an explicit way, with the significant advantage of requiring no assumptions about cost improvement. A recent study compared CERs derived using quantity as an independent variable (QAIV) with conventional CERs derived by minimum unbiased percentage error (MUPE) regression (Hu, Fong, and Enser, 2006). Using the USCM 8 data set and cost-driving parameters, the standard error, adjusted R2, mean absolute deviation, and Pearson's correlation squared of CERs developed using QAIV were found to be roughly equivalent to those of the conventional CERs. Interestingly, the imputed cost improvement slopes for the QAIV CERs generally fell in the 90 to 100 percent range. Although this test is not conclusive, it does demonstrate the practical application of QAIV as an alternative approach to CER development, which avoids the difficulties of assumed cost improvement rates.

Cost Considerations of COTS Components in Space Systems

Lower procurement costs, greater availability, and state-of-the-art performance make the use of COTS parts attractive alternatives for custom-built or military- and space-grade components in space systems. (In this discussion we use the term *COTS components* to describe articles ranging from piece parts to complete subsystems.) Market forces drive the development of COTS components for non–space-related applications. When are COTS components suitable for use in space applications, and what cost, schedule, and performance trade-offs should be considered?

In addressing these questions, we begin with a discussion of the advantages and disadvantages of COTS components. We then give some examples of COTS use in space applications, and provide a set of recommendations for evaluating the cost implications of COTS components in DoD space systems.

Advantages of COTS

One of the principal perceived advantages of COTS is that it minimizes design-related cost and schedule risks because the components have already been developed and presumably proven in the marketplace in similar applications.

The combination of competitive pressures and quantity production tends to drive down the price of COTS components, reducing procurement costs relative to military grade or custom alternatives. These pressures also tend to advance the state of the art in functionality and performance to compete effectively in the commercial marketplace.

COTS suppliers are able to amortize development costs over a large number of units. On the production side, commercial volumes will often justify investment in production process improvements. This has led to increasing automation, a major contributor to the increased quality levels seen in modern electronics. For example, the quality and reliability of commercial electronic components have greatly improved since the early days of the space program when highly screened parts were necessary to assure reliability. Today, some commercial electronic components are achieving levels of quality and reliability equivalent to fully screened "Class S" parts (Sarsfield, 1998).[4] As quality has improved, costs have decreased dramatically.

As in the case of hardware, software for space or ground-segment applications is also available as COTS. Standardized, well-documented COTS software is available for functions that are common across a variety of space systems, such as navigation, simulation, displays, and so on. COTS software, if appropriate for the intended application, can be five to 10 times cheaper than custom software (Wertz and Larson, 1999, p. 65).

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[4] Since some space system components are not available in the commercial market or will be used in applications for which commercially available components are not suitable, the demand for space-qualified parts remains. The process for qualifying parts and systems for use in space applications is complex and often costly and its specifics vary depending on the part and system types. The qualified manufacturer list (QML) and the qualified parts list (QPL) are U.S. government endorsements of electrical, electronic, and electromechanical (EEE) parts for space and military programs. The QPL endorses specific device types. The QPL is described in MIL-M-38510. In contrast, the QML qualifies the manufacturer's entire fabrication process rather than specific devices. The QML is described in MIL-I-38535 (see Wall and MacDonald, 1993, Appendix 2). The government grants two levels of certification: Class B is for parts used in tactical military systems and low criticality space systems. The certification must be achieved within one year of qualification. Class S is for strategic military systems and high-criticality space systems. The certification must be achieved within two years of qualification.

Disadvantages of COTS

Superficial cost and performance comparisons of relevant COTS hardware and software frequently highlight its advantages over custom or military- or space-quality components. However, the functionality and performance needs in the space environment can differ significantly from those of typical commercial applications.[5]

Because DoD represents a relatively small portion of the total market for most COTS products, it has limited ability to influence the design and vendor testing of the products. For example, the commercial market may favor software functionality that often comes at the expense of reliability or security. DoD lacks sufficient market leverage to influence COTS software developers to deliver products with the reliability and security needed for many space and military applications. Figure 5.2 shows a $62 billion international market for COTS operating systems in 1998. The U.S. market accounted for $31 billion, or about half of the total international market. However, DoD expenditures for COTS operating systems totaled $250 million, which is less than 1 percent of the U.S. market and less than 0.5 percent of the international market.

The situation is similar in the case of semiconductors. Figure 5.3 shows the size of the international commercial market for semiconductors in FY 1999. Semiconductors for U.S. military applications accounted for less than 2 percent of this total, with semiconductors for military applications in space accounting for less than 0.2 percent.

While EEE components and systems, including semiconductors, represent only around 5 to 10 percent of total spacecraft and satellite costs at present, they are expected to represent a much higher percentage of costs in the future.[6]

Decreased availability of radiation-hardened parts produced on qualified processing lines is a continual concern. Figure 5.4 shows the number of radiation-tolerant microelectronics manufacturers in 1985, 1993, and 1995. This decline increases the pressure to use COTS EEE components in space applications, requiring careful consideration of the trade-offs involved.

In many cases, products designed for commercial applications may not meet the requirements for DoD space systems. Commercial competitiveness to reduce cost and improve performance relative to commercial applications can jeopardize reliability, security, or system longevity. Because of rapid commercial product cycles, parts obsolescence is often a problem. It is not uncommon to find that planned-for components are no longer available in their original configuration, requiring costly redesign, reevaluation, and testing to ensure equivalent performance and compatibility. Solutions can involve bulk buys of critical items; finding, testing,

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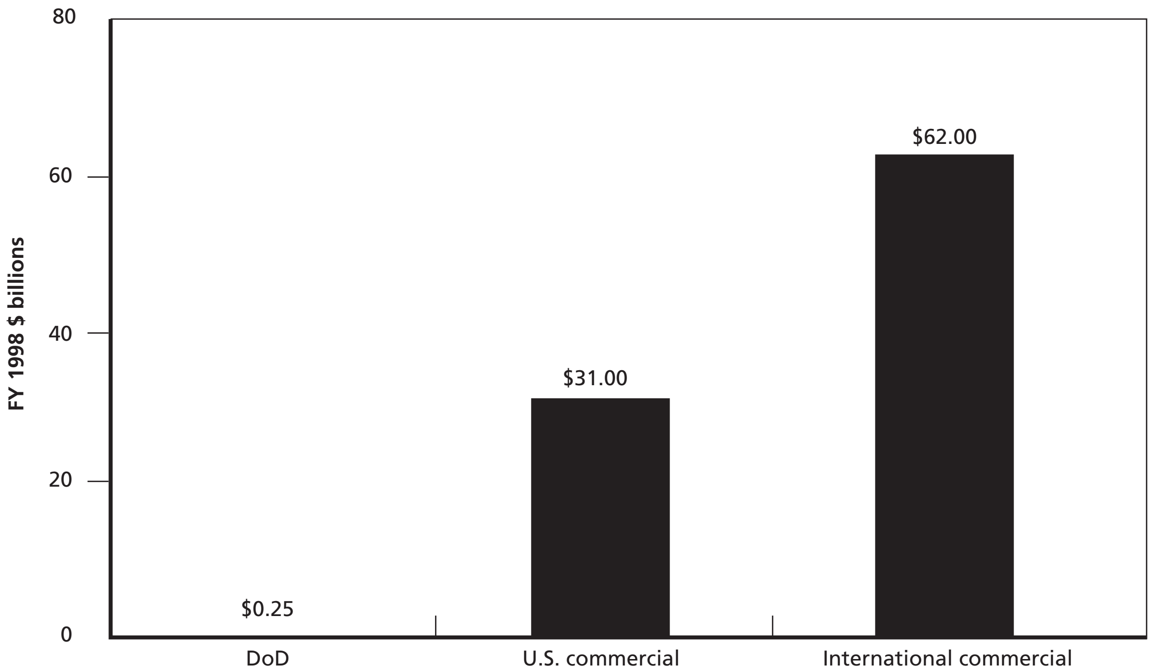
[5] A good example of an area in which COTS components may not meet the requirements for space applications is EMC. The objective of EMC is to eliminate EMI with the proper operation of the space system. EMI occurs when unintended transfer of electromagnetic energy degrades the performance of a component, subsystem, or system. Electromagnetic energy can be conducted or radiated and its source may be external or from another part of the system. A common example is the interference from nearby electrical equipment heard on an AM radio. In spacecraft, EMI is particularly challenging because of the density of electronic components, high power levels, and sensitive receivers. EMC is a design criterion but must be verified by testing at the component, subsystem, and system levels (including external support equipment) since the arrangement or packaging of components may introduce EMI even though it may not have occurred in previous applications of the same components.

[6] See Barnes and Johnston (1999).

Figure 5.2
Expenditures for COTS Operating Systems for DoD Versus Commercial Customers in 1998



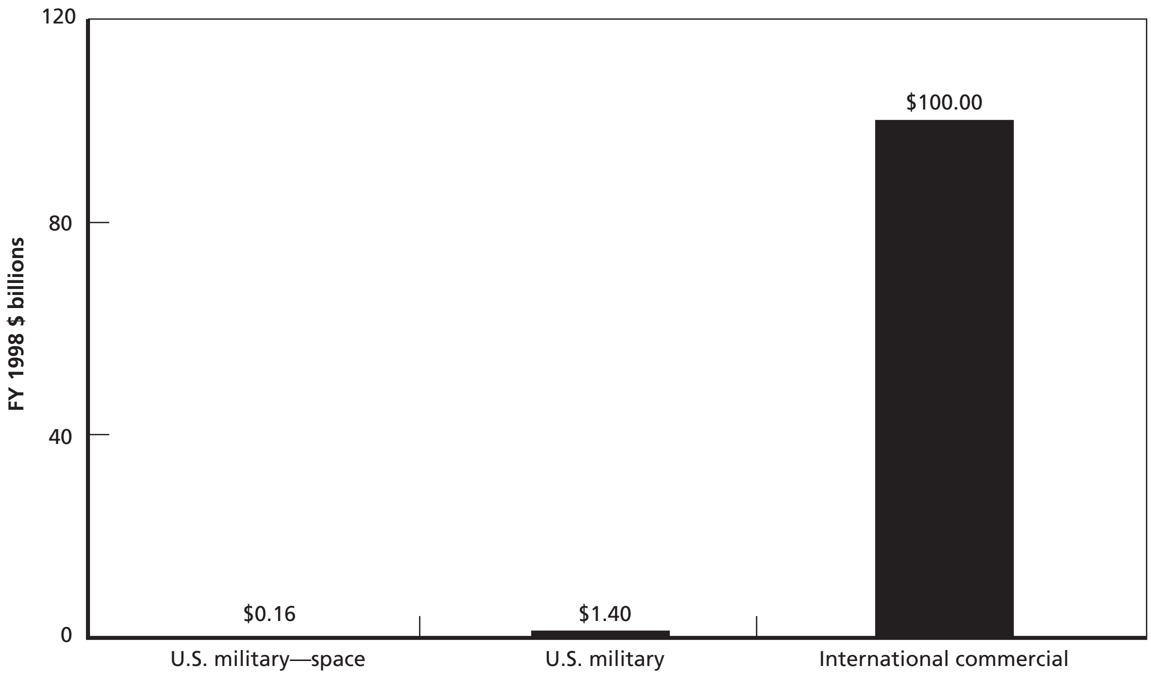
SOURCE: Anderson and Hundley (1998).
RAND *TR418-5.2*

and qualifying alternative COTS components; or developing custom-built replacements that emulate the original. This risk is obviously an important consideration in total life-cycle costs.

Perhaps the most obvious disadvantage of using COTS EEE parts and components is that they are typically not qualified for use in space applications. Radiation-hardness assurance issues are of particular concern, especially with devices such as analog-to-digital converters. Other considerations include temperature range, outgassing, and vulnerability to corrosion.

COTS components can be tested and qualified for use in space applications, but often with negative effects on cost and schedule. The magnitude of cost and schedule effect varies depending on the component or system type and other particulars. Typical accommodations include additional testing, shielding, and redundant design. A common application of the COTS approach is software, particularly in the ground segment. Although it is unusual for large portions of the software to be completely COTS, numerous COTS components are frequently used. It is also common in the early stages of program planning and estimating for these components to be treated as if they are “drop-ins.” This is rarely the case. Adams and Eslinger (2001) document a useful series of lessons learned from using COTS software in the ground segments of space systems. Their key findings are as follows:

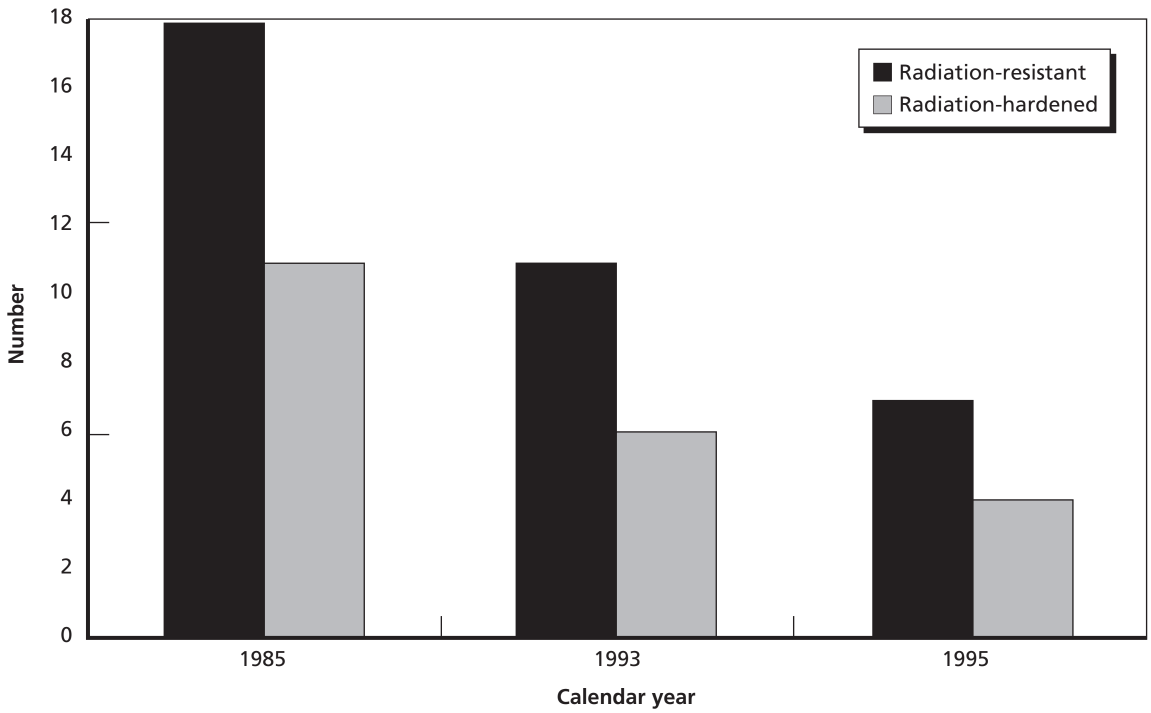
Figure 5.3
Military and Commercial Semiconductor Markets in 1999



SOURCE: Barnes and Johnston (1997).
RAND *TR418-5.3*

- While commercial software features and vendor practices are driven by the market, DoD applications often have unique requirements that vendors may or may not be willing to address. Problems may include
  - limited testing by the vendor
  - little influence over the content and schedule of software updates
  - compatibility issues with target hardware, especially if the DoD platform represents a small portion of commercial market
  - functionality driven by commercial market
  - lack of assured long-term support
  - inappropriate fee structure for site or individual user licenses.
- COTS eliminates only software development for those functions performed by the application. Systems and software engineering activities are still required, as are the other system-level tasks. In fact, more frequent releases/upgrades often mean more modifications, testing, and training.
- COTS requires a close relationship with the vendor to maintain communication, support, and flexibility.
- COTS products evolve continually, typically with a 12- to 18-month release cycle (versus a DoD development cycle of 36 to 48 months or more). Versions must be kept up to date to maintain vendor support.

Figure 5.4
Number of Radiation-Tolerant Microelectronics Manufacturers in 1985, 1993, and 1995



SOURCE: Barnes and Johnston (1997).
RAND *TR418-5.4*

- For all these reasons, COTS cost and schedule savings projections are nearly always overstated. Activities such as prototyping, testing at the component and system levels, training, documentation, vendor support, and license fees are often underestimated or overlooked since few estimating models account for them without user intervention. Additionally, unanticipated functionality or interface problems with COTS are not uncommon.

Their conclusion was that "[COTS-based system] cost and schedule estimates almost never contain enough margin to handle the COTS software problems encountered" (Adams and Eslinger, 2001, p. 7).

In some cases, COTS suppliers can offset testing requirements by providing their own test data. However, often the requirements for testing for the space environment are much more stringent than are those for typical commercial applications, or the required reliability data are unknown or unavailable because of proprietary considerations.

Although COTS components have wide application in the ground segments of space systems, component or system reliability and long-term product support issues may still be a concern. Continual hardware and software revision to follow commercial product cycles may add millions of dollars to the total ownership cost of the system. One general rule is to plan for approximately 15 percent of the purchase price of software each year for maintenance and upgrades (Wertz and Larson, 1999, p. 66.). (It should be noted that increased functionality and reliability might be a desirable by-product of these shorter upgrade cycles.) The current preference for open system architectures is an attempt to reduce dependence on original sources. Specifying industry-standard architectures and components is another approach to reducing the difficulty and expense of supporting systems over their service lives.

Examples of COTS Usage in Space Systems

COTS Analog-to-Digital Converter in Mars Pathfinder. A COTS hybrid analog-to-digital converter from a nongovernment certified supplier was used in Mars Pathfinder because of cost and schedule constraints. The converters were ordered to a military temperature range; however, the Jet Propulsion Laboratory (JPL) had to work diligently with the vendor to obtain parts that met specifications. JPL later obtained additional quantities of the same part from the same vendor for subsequent projects and found that the corrective actions required for Mars Pathfinder did not persist. Eleven of 13 samples from different lots were rejected. It reported eight operational failures in hardware, and the extensive effort required to solve the problems proved very expensive. (See Sandor and Agarwal, 1998.)

Radiation-Hardened Field Programmable Gate Array. Strobel, Czajkowski, and Shanken (1999) report that the Actel 1280A COTS FPGA has low sensitivity to single event latch-up, a desirable attribute for space application. However, they note that the part is vulnerable to total ionizing dose failures. Space Electronics Incorporated (SEi) and Actel signed an agreement to shield the FPGA using SEi's RAD-PAK technology. The result is an affordable, radiation-tolerant FPGA for space application. The part was in production with flight heritage as of 1999. (See Strobel, Czajkowski, and Shanken, 1999).

COTS Real-Time Operating System for Mars Pathfinder. The Mars Pathfinder rovers used a COTS real-time operating system. The rover exhibited a failure where the primary computer would continually reset itself after a time-out period. The problem was that a high-priority task in the operating system required a resource that was being held by a lower-priority task. The high-priority task could never gain access to the resource. After a time-out period, the operating system would reset itself. Analysis revealed that there was no bug in the operating system itself, but obscure aspects of the way the operating system worked caused the problem. It required mission engineers to have an extraordinary knowledge of the details of the COTS operating system to cope with the situation. (See Goodwins, 2000.)

Recommendations

We offer the following recommendations when considering the cost, schedule, and performance implications of using COTS components and systems for space applications:

- Consider life-cycle costs, including the cost of integration, testing, and potential failures, not simply the procurement costs. This is of particular concern with the first use of a COTS component in a particular application or environment. The full costs of COTS software are often understated. In addition to the costs of initial licensing, along with integration and testing, the costs of purchasing/licensing, reintegrating, and retesting new software releases every one to two years should be included. For similar reasons, overestimating the degree of software reuse is very common.

- Maximum use of industry standards supported by multiple vendors can improve the availability and affordability of COTS components.
- For EEE COTS parts, determine what data the vendor can supply and whether it is sufficient to support the design requirements. This may save significant costs in testing.
- Radiation-hardened parts are generally required for core systems, such as flight computers.
- Ensure that there are sufficient design margins to account for damage from radiation and other degradation.
- Consider using hardware and software risk mitigation techniques when employing COTS.

Evolutionary Acquisition

Evolutionary acquisition (EA) is a strategy that has been adopted across DoD in an attempt to address certain problems with the conventional acquisition process. These problems include

- long development cycles resulting in long delays getting new capabilities to users
- overly optimistic program plans for maturing and integrating multiple new technologies, which resulted in slipped schedules and cost overruns
- operational requirements generated based on how existing systems could be improved and extended rather than focusing on the user's current and future needs.

While evolutionary acquisition has been mandated in DoD Directive 5000.1 and DoD Instruction 5000.2 (DoD, 2000, 2003b), there remain a variety of interpretations of how it applies to existing and future acquisition programs. A recent RAND examination of evolutionary acquisition (Lorell, Lowell, and Younossi, 2004) found that many of the implementation issues and approaches had yet to be resolved.

A good first step is to define the relevant terms. EA is the preferred DoD strategy for rapid acquisition of mature technology. An evolutionary approach delivers capability in increments, recognizing, up front, the need for future capability improvements. The objective is to balance needs and available capability with resources and to put capability into the hands of the user quickly. The success of the strategy depends on consistent and continuous definition of requirements and the maturation of technologies that lead to disciplined development and production of systems that provide increasing capability toward a materiel concept (DoD, 2003b). *EA* is the general term for approaches that explicitly plan for introducing capabilities in a series of time-phased "blocks" or increments, with each fielded increment adding useful capability to the user.

DoD recognizes two processes that implement evolutionary acquisition: incremental and spiral development:

> **Spiral Development.** In this process, a desired capability is identified, but the end-state requirements are not known at program initiation. Those requirements are refined through demonstration and risk management; there is continuous user feedback; and each incre-

ment provides the user the best possible capability. The requirements for future increments depend on feedback from users and technology maturation.

Incremental Development. In this process, a desired capability is identified, an end-state requirement is known, and that requirement is met over time by developing several increments, each dependent on available mature technology. (DoD, 2003b)

To clarify these definitions, it is important to understand how EA differs from similar previous approaches such as preplanned product improvement (P3I). In P3I, both the final capabilities and system requirements are specified at the beginning of the program. The number of increments and their content were also specified as part of the program approval process. In EA, and particularly with spiral development, program plans evolve with user needs, the actual performance of previous increments, and the maturing of relevant technologies, all of which are difficult to forecast at program initiation.

Advocates of evolutionary acquisition feel that it will improve the acquisition process for, users, buyers, and developers. Lorell, Lowell, and Younossi (2004) summarize claimed EA benefits as

- fielding operationally useful capability much faster than the old "single step" to full capability approach
- resulting in system capabilities that are much more responsive to the war fighter's real operational needs
- leading to rapid and continuing insertion of the latest technologies into the system, thus avoiding obsolescence and the problem of diminishing manufacturing sources
- reducing the likelihood of major research and development (R&D) schedule delays and cost overruns by focusing on realistic expectations based on mature technology.

Under an EA approach, a program plan might look similar to Figure 5.5.

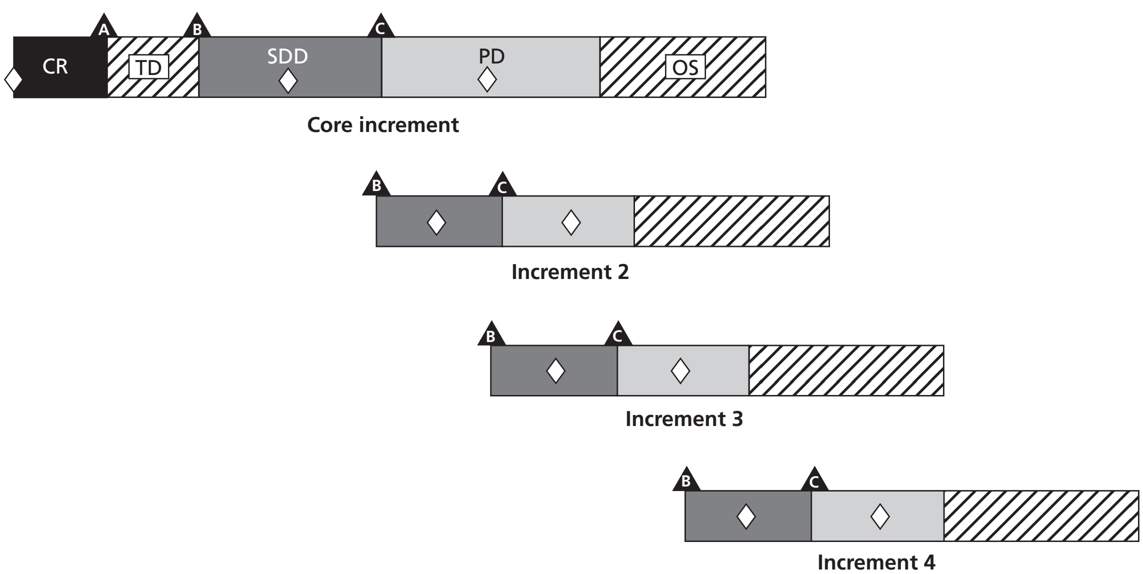
Implications for Cost Analysis

Obviously, EA presents new challenges for cost analysts. Meaningful cost estimates are generally based on a specific scope and configuration. Even early conceptual estimates, made with a minimum amount of information, implicitly assume that the estimated program has characteristics similar to those on which the estimating methodologies are based. If an EA strategy is followed consistently, the initial increment or spiral should involve a shorter and lower risk development effort since the introduction of immature technologies would be delayed to later increments. Presumably the production quantities of each increment will be lower, since additional capability is promised with each succeeding increment. Managing multiple simultaneous increments in various phases will be challenging, since cross-utilization of key personnel and infrastructure will be needed for cost and continuity reasons. The planning and execution of retrofit programs to update high cost or high inventory units from previous increments is another consideration inherent in EA.

Since these characteristics differ from prevailing acquisition practices, it would be prudent for the cost analyst to attempt to bound their possible effects and to document the results and corresponding assumptions for decisionmakers. Until several programs implementing EA complete an acquisition phase, determining how EA will actually be implemented and its effects on cost and schedule will require the analyst to make informed projections. The following are examples of the issues that should be considered in arriving at these projections.

- Controlling requirements creep (particularly in space programs) has been the objective of various recent initiatives. Will requirements based on more interactive user feedback be even more variable than past programs and introduce late changes to agreed-upon specifications? Is the systems engineering capability in place to effectively implement and preserve a flexible system design and to evaluate and trade-off user requests versus available resources?
- Are assessments of technical maturity realistic or will schedules have to be slipped or design approaches changed due to understated technological risks? (This is particularly important since many of the projected benefits of EA depend on reducing technical risk by using mature technologies.)
- Are the scope and schedule planned for the development efforts realistic? Is the scope of work stable and understood by the contractor? Is the contract structured to incentivize the contractor to submit a realistic proposal and execute the program within those limits, or will scope flexibility or government commitment to the program encourage overly aggressive bids?
- How will the increased use of heritage and COTS components affect areas such as development effort, testing, cost improvement, contractor resource allocation (make versus buy), and so on?

Figure 5.5
Overlapping Increments of Evolutionary Acquisition



RAND *TR418-5.5*

- What are the implications of fielding multiple configurations on technical and software support, spares, maintenance, training, and retrofit?
- Are the increased complexities of program and technical management resulting from multiple, simultaneous system versions accounted for in cost and schedule estimates?

In the case of spiral development, estimating the cost of future, undefined spirals is virtually impossible. This can result in a “design-to-budget” approach. The classic application of spiral development is in software, in which a set of core functions is coded and tested, and, based on user feedback, additional functions are added in subsequent spirals. This results in system functionality that is built up one layer at a time, with many of the layers being nondeliverable code. Translating this process to apply to a large space program is obviously challenging.

Of the programs reviewed by Lorell, Lowell, and Younossi (2004) most were evolving toward an incremental (versus spiral) development approach to better control growth in requirements and justify commitments of future funding. Their findings concerning the effects of EA in acquisition management can be summarized as follows:

- Currently, EA terminology and application varies considerably, even within a single acquisition organization.
- Nearly all programs are struggling with defining threshold and objective capabilities or requirements for each increment and total program.
- True spiral development is a very difficult strategy for major programs because of pressure for clear program definition from the political, requirements, and cost analysis communities.

They also identified cost management findings:

- Cost analysis generally focuses on the first increment.
- EA requires extensive and ongoing involvement of the cost community.
- There is concern about committing the Air Force to a large program before full cost implications are understood.
- Accurate assessments of the total life-cycle cost implications of EA are difficult at this early stage.
- Budgets must reflect the higher cost uncertainty caused by limited program definition.
- Some of the traditional program management uncertainties such as requirements creep and technological maturity may be more pronounced under an EA strategy.

CHAPTER SIX

Resources for Space System Cost Estimation

This chapter provides brief summaries of space vehicle estimating resources available to the AFCAA.

USCM 8

Set of CERs for unmanned earth orbiting space vehicles. Expanded and modified since first edition was published in 1969. Version 8 adds 25 programs and drops five from previous version. Also modified WBS to add visibility for modeling various configurations and expanded estimating guidance. Development costs classified as either full or partial; programs judged as partial development efforts were excluded from CER development. Costs normalized to T_1 using 95 percent assumed cost improvement slope; average unit cost is used for standard bus programs. CERs derived using minimum unbiased percentage error technique.

Phases Estimated

Development, production (contractor costs only)

System Types

Military (24), NASA (12), Commercial (9). Mission types—communications (23), weather (6), navigation, (4) scientific (4), experimental (7), surveillance (1).

Currently, only communication payloads are modeled. Development start dates range from 1970 through 1990s. Standard buses are included for all commercial programs, GOES I-M, TOPEX, and UHF follow-on.

Level of Cost Detail

Nonrecurring, recurring by system, subsystem, and selected components. Contractor costs only. Costs through G&A.

Version

Eight; June 2002

Developer

Tecolote Research, Inc.
3601 Aviation Blvd., Suite 1600
Manhattan Beach, CA 90266
http://www.tecolote.com

Sponsor

U.S. Air Force Space and Missile Systems Center

NAFCOM

Automated integrated model based on NASA and Air Force space programs. The user can select normalization (escalation) using either NASA or OSD inflation indexes. All programs are modeled using a prototype development approach by adjusting protoflight programs by a factor. Program résumés summarizing key programmatic and technical characteristics of each system are provided. Users can develop estimates using either conventional CERs or complexity generators. Complexity generators use new design content, technology, and management factors, in addition to weight, to develop complexity factors to better characterize the program being estimated and its relation to past programs. The CER approach uses parameters of "first pound cost," weight, and slope with the same functional form as a conventional learning curve calculation to estimate the first flight article. The first pound cost for each subsystem is derived from the database, the estimated subsystem weight is a user input, and the slope is an average parameter derived from various external Marshall Space Flight Center CERs and verified using the NAFCOM database. System-level costs are calculated similarly. First pound costs or complexity factors can be derived from either the entire database or from user-selected programs. NAFCOM can estimate either by a product WBS or a labor, material, and overhead functional breakdown structure. Wizards assist the user in structuring a WBS appropriate for the system being estimated. NAFCOM has an integrated risk analysis capability, which includes modeling correlation between cost elements. Program schedule and time phasing of funding are also estimated. Both unrestricted and government-only versions of NAFCOM are available.

Phases Estimated

Development and production (contractor costs only); NASA operations (using Space Operations Cost Model)

System Types

122 NASA and Air Force unmanned earth-orbiting and planetary spacecraft, launch vehicles, engines, scientific instruments, manned space vehicles

Level of Cost Detail

System, subsystem, selected components

Version

2004

Developer

Science Applications International Corporation
675 Discovery Drive
Suite 300
Huntsville, AL 35806
http://www.saic.com

Sponsor

NASA Marshall Spaceflight Center

Small Satellite Cost Model

An automated model for estimating costs of satellites weighing less than 1,000 kg, it was first developed in 1991 to better reflect the differences in design philosophy and program oversight of small spacecraft when compared to large traditional space programs. The CERs are based on data from 35 post-1990 small satellite programs. The CERs, developed using a generalized error regression model, are hosted in Microsoft® Excel® with Visual Basic® modules. Risk is modeled using the statistics generated from CER development and user-specified triangular distributions for technical uncertainty. System-level confidence percentiles are calculated using the FRISK methodology. It can spread funding across fiscal years.

Phases Estimated

Development and production

System Types

Earth-orbiting and interplanetary spacecraft weighing less than 1,000 kg.

Level of Cost Detail

System (spacecraft without payload), subsystems

Version

2005

Developer

The Aerospace Corporation
Space Architecture Department
P.O. Box 92957, M4/939
Los Angeles, California 90009-2957
http://www.aero.org

Sponsor

Various

Costs of Space, Launch, and Ground Systems ("The Whitehair Study")

A compendium of general data, guidelines, comparisons, and high-level trends relevant to space systems in annotated briefing format. It has historical data on cost, schedules, and personnel for various space systems and activities. The topics covered include

- national space-related budgets (historical data on budgets and trends)
- launch systems
- satellites (DSP, GPS, DSCS, DMSP, Navy communication satellites, small satellites)
- International Space Station
- Stratospheric Observatory for Infrared Astronomy
- ground systems
- software
- R&D
- cost estimating (level-of-effort work, risk, Teal Ruby case study, cost improvement, earned value)

Distribution limited to government- and federally funded R&D centers only.

Phases Estimated
Various data from development, production, and operating and support

System Types
Launch vehicles, satellites (see above), manned NASA programs, some ground segment, some software

Level of Cost Detail
Generally trends and high-level comparisons; some subsystem percentages

Version
Eighth edition, September 2000

Developer
The Aerospace Corporation

Sponsor
The Aerospace Corporation
http://www.aero.org

Cost Estimating Relationships for Space-Based Systems: IDA Paper P-2513

The model was developed for Defense Communication Agency to identify and quantify the effects of performance and mission requirements on the cost of future space-based communications systems. Space program cost and technical data were taken from the Unmanned Space Vehicle Cost Model Version 6 (USCM 6). Data from the Jet Propulsion Laboratory and MIT Research and Engineering (MITRE) were used for software analysis and modeling. The authors hypothesize that, when performance is held constant, much of the cost reduction in modern space vehicles is due to advances in the "cross-cutting" technologies of digital electronics and software and that these components are best modeled separately from their associated systems. (Since the USCM 6 data has software costs included with the subsystems, the software relationships cannot be used directly with the hardware CERs.) Software CERs for ground, avionics, and space applications are provided in alternative forms using size-only and size-adjusted by the COCOMO effort adjustment factors as inputs. Estimating relationships are also provided for subsystem weights.

Distribution limited to U.S. government agencies only.

Phases Estimated

Development and production

System Types

Military (10), NASA (4) and commercial (3) communication and experimental spacecraft, communication payloads, crosslinks

Level of Cost Detail

Spacecraft subsystem; communication payload and crosslink transponders, transmitter, and antennas; digital electronics; ground, avionics, and space software

Version

April 1991

Developer

Institute for Defense Analyses
Cost Analysis and Research Division
4850 Mark Center Drive
Alexandria, VA 22311
http://www.ida.org

Sponsor

Defense Communications Agency

Spacecraft Functional Cost Estimating Relationships

Briefing contains CERs for engineering and manufacturing functions by subsystem. Programmatic, technical, and weight cost drivers are modeled. CERs estimate nonrecurring engineering, nonrecurring manufacturing, recurring (sustaining) engineering, and recurring manufacturing (T_1) costs (not hours). Subsystems addressed are structure; thermal; electrical power; attitude control; reaction control; telemetry, tracking, and command; communications; and apogee kick motor. Program level costs are recurring engineering, integration and assembly, program management and data, system test and evaluation, systems engineering, aerospace ground equipment, and launch operations and support.

Phases Estimated

Development and production

System Types

DoD (16), NASA (6), and commercial (1) spacecraft

Level of Cost Detail

Subsystem and program-level costs

Version

August 1993

Developer

Institute for Defense Analyses
Cost Analysis and Research Division
4850 Mark Center Drive
Alexandria, VA 22311
http://www.ida.org

Sponsor

N/A

Passive Sensor Cost Model (PSCM)

CERS for development and production of space passive sensor subsystems. Incorporates data from predecessor models (Aerospace Sensor Model, MCR Sensor Model, and previous versions of PSCM.) Volume II (Data) available for analogy estimates; distribution authorized to U.S. government agencies only. Normalized contractor costs through G&A. T_1 costs developed for recurring elements by assuming a 95 percent cost improvement slope for development (prototype) and 90 percent for production. Where CERs were not developed, means and standard deviations with parameter ranges are provided. Program-level costs, other than IA&T for the sensor, are not included.

Phases Estimated
Development and production

System Types
Passive sensors for space applications

Level of Cost Details
Passive sensor subsystems; recurring and nonrecurring costs identified where possible. CERs or means/standard deviations included for focal plane arrays

- optical telescope assemblies
- cryocoolers (Stirling, Brayton, and pulse tube)
- gimbals
- control electronics
- power supplies
- IA&T (at sensor level)
- star sensors.

Version
Phase V, April 7, 1997

Developer
EER Systems, Inc.
2250 E. Imperial Highway, Suite 750
El Segundo, CA 90245

Sponsor
Space and Missile Systems Center
Directorate of Cost
Los Angeles AFB, CA 90245

Satellite and Laser Communications Cost Model

Study to develop methodologies for estimating laser and EHF satellite crosslinks. At the time of the study no such systems had completed development so Technomics was forced to extrapolate historical cost data for satellite-to-ground and satellite-to-satellite communications systems (from UHF through SHF) to develop CERs for extremely high-frequency crosslinks. For laser crosslinks, Technomics used analogies based on estimates at completion from two ongoing laser crosslink development programs. CERs were developed for

- transponders (17 data points)
- transmitters (6 data points)
- parabolic antennas (6 data points)
- phased array antennas (4 data points).

Phases Estimated

First unit manufacturing cost

System Types

Satellite-to-ground and satellite-to-satellite communication links

Level of Cost Detail

CERs for transponders, transmitters, parabolic antennas, phased array antennas

Version

April 1990

Developer

Technomics, Inc.
5290 Overpass Rd.
Santa Barbara, CA 93111
http:// www.technomics.net

Sponsor

Defense Communication Agency/Institute for Defense Analyses

CHAPTER SEVEN

Recommendations

The AFCAA's objective in sponsoring this document was to create a resource for cost analysts who had worked in other areas but had limited experience with space programs. The agency also needed a ready reference with information useful for any analyst conducting reviews of program cost estimates. Although useful information was available, it was scattered in a variety of studies, engineering texts, cost model documentation, briefing slides, and analysts' files. Frequently, published references were only partially relevant to cost analysis. These resources were scattered and often unknown to new analysts, so this document was conceived as a vehicle to begin assembling information useful to cost analysts, making it accessible to all.

While we hope that the topics contained in this current volume will be immediately useful, there are at least as many other subjects that have not been included for reasons of data availability, changing policies, emerging technologies, or oversight. Some of these are readily apparent, and others will become clear as analysts use the document. The following areas are also important and, for various reasons, could not be included in the first edition of the document.

- **Payloads.** There were very limited data available to us on noncommunication payloads. Because of their cost and risk, payload crosschecks at some level would be very useful.
- **Nonrecurring Costs.** We could not develop crosschecks for nonrecurring costs because of limited insight into the development program scope and other key information for the data available at AFCAA.
- **Ground Segment.** AFCAA currently has limited data on ground segment costs. This is another area where focused collection of cost, technical, and programmatic information would be highly beneficial.
- **Recent Programs.** Most of the DoD space programs in the current USCM database were placed on contract in the 1970s and 1980s. Collection of data from more recent programs and incorporating it into USCM (and the crosschecks) should be a priority.
- **New Mapping.** There is an ongoing effort to remap the USCM database into the new MIL-HDBK 881A/NRO WBS in preparation for the development of the next version of the USCM model. Additional data is also being added. Once this is available, the crosschecks should be updated.

APPENDIX A

MIL-HDBK-881B Space Systems WBS

The material in this appendix is excerpted directly from the handbook.

(Extract from *Department of Defense Handbook 881: Work Breakdown Structure,* Appendices F and H, January 2, 1998.)

Space Systems

Work Breakdown Structure And Definitions

F.1 SCOPE

This appendix provides the space system work breakdown structure. Definitions for the launch vehicle; the orbital transfer vehicle; the space vehicle; and for ground command, control, communications and mission equipment; flight support operations and services; and storage are provided in this appendix. Definitions for WBS elements common to the space system and all other defense materiel items are in Appendix H: Work Breakdown Structure Definitions, Common Elements.

F.2 WORK BREAKDOWN STRUCTURE LEVELS

Level 1	Level 2	Level 3
Space System		
	Launch Vehicle	
		Propulsion (Single Stage Only)
		Stage I
		Stage II . . . n (As Required)
		Strap-On Units (As Required)
		Shroud (Payload Fairing)
		Guidance and Control
		Integration, Assembly, Test and Checkout
	Orbital Transfer Vehicle	
		Propulsion (Single Stage Only)
		Stage I
		Stage II . . . n (As Required)

		Strap-On Units (As Required)	
		Guidance and Control	
		Integration, Assembly, Test and Checkout	
	Space Vehicle		
		Spacecraft	
		Payload I . . . n (As Required)	
		Reentry Vehicle	
		Orbit Injector/Dispenser	
		Integration, Assembly, Test and Checkout	
	Ground Command, Control, Communications and Mission Equipment		
		Sensor I . . . n (As Required)	
		Telemetry, Tracking and Control	
		External Communications	
		Data Processing Equipment	
		Launch Equipment	
		Auxiliary Equipment	
	Flight Support Operations and Services		
		Mate/Checkout/Launch	
		Mission Control	
		Tracking and C	
		Recovery Operations and Services	
		Launch Site Maintenance/Refurbishment	
	Storage		
		Planning and Preparation	
		Storage	
		Transfer and Transportation	
	Systems Engineering/Program Management		
	System Test and Evaluation		
		Development Test and Evaluation	
		Operational Test and Evaluation	
		Mock-ups	
		Test and Evaluation Support	
	Training		
		Equipment	

		Services		
		Facilities		
	Data			
		Technical Publications		
		Engineering Data		
		Management Data		
		Support Data		
		Data Depository		
	Peculiar Support Equipment			
		Test and Measurement Equipment		
		Support and Handling Equipment		
	Common Support Equipment			
		Test and Measurement Equipment		
		Support and Handling Equipment		
	Operational/Site Activation			
		System Assembly, Installation and Checkout on Site		
		Contractor Technical Support		
		Site Construction		
		Site/Ship/Vehicle Conversion		
	Industrial Facilities			
		Construction/Conversion/Expansion		
		Equipment Acquisition or Modernization		
		Maintenance (Industrial Facilities)		
	Initial Spares and Repair Parts			

F.3 DEFINITIONS

F.3.1 Space System

The complex of equipment (hardware/software), data, services, and facilities required to attain and/or maintain an operational capability in space. This operational capability requires the ability to develop, deliver, and maintain mission payload(s) in specific orbit, which further requires the ability to place, operate, and recover manned and unmanned space systems.

Includes:

- launch vehicles, orbital transfer vehicles, shrouds, space vehicles, communications, command and control facilities and equipment, and any mission equipment or other items necessary to provide an operational capability in space.

F.3.2 Launch Vehicle

The primary means for providing initial thrust to place a space vehicle into its operational environment. The launch vehicle is the prime propulsion portion of the complete flyaway (not to include the orbital transfer vehicle and space vehicle). The launch vehicle may be single-stage or multiple-stage configuration.

Includes:

- the structure, propulsion, guidance and control, and all other installed equipment integral to the launch vehicle as an entity within itself
- the design, development, and production of complete units (i.e., the prototype or operationally configured units which satisfy the requirements of their applicable specification, regardless of end use)
- Sub-elements to the launch vehicle (F.3.2.1—F.3.2.7)

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.2.1 Propulsion (Single Stage Only)

The means for generating the launch vehicle into its operational orbit or its intended path.

Includes, for example:

- engine, structure, propellant and fuel, distribution and control of propellant and fuel, starting means, safety devices, and internal environmental control grouped as a functional entity
- design, development, production, and assembly efforts to provide the propulsion subassembly

F.3.2.2 Stage I

The launch vehicle stage which provides initial lift-off propulsion for the complete launch vehicle (flyaway) and cargo.

Includes, for example:

- structure, propulsion, controls, instrumentation, and all other installed subsystem equipment integral to Stage 1 as an entity

- design, development, production, and assembly efforts to provide Stage I as an entity

Excludes:

- strap-on units

> **NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.**

F.3.2.3 Stage II . . . n (As Required)

The second and subsequent launch vehicle stages (if applicable) used to place a space vehicle into its operational environment.

Includes, for example:

- propulsion following separation of the first stage and subsequent stages (if applicable)
- structure, propulsion, controls, instrumentation, separation subsystems, and all other installed subsystem equipment integral to the stage as an entity
- design, development, production, and assembly efforts to provide each individual stage as an entity

Excludes:

- strap-on units

> **NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.**

F.3.2.4 Strap-On Units (As Required)

Solid or liquid propulsion assemblies that provide additional thrust or propellant to assist the launch vehicle in placing a spacecraft into its operational orbit if strap-on units are employed.

Includes, for example:

- complete set of strap-on units-case, nozzle, igniter, tanks, mounting structure, cordage, etc.
- design, development, production, and assembly efforts to provide the strap-on units as an entity

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.2.5 Shroud (Payload Fairing)

The protective covering and equipment mated to the launch vehicle that protects the cargo (i.e., orbital transfer vehicle or space vehicle/orbital transfer vehicle combination) prior to and during the launch vehicle ascent phase.

Includes, for example:

- structure-the shroud structure, mechanisms and hinges
- instrumentation-the hardware and software required to measure the environment and loads being experienced by the shroud during the ascent phase until shroud separation and deployment
- separation subsystem-the sequencers, ordnance, and other necessary mechanisms to assure a successful shroud separation from the launch vehicle and cargo
- power system-the necessary generation, storage, and distribution of electrical power and signals, hydraulic power, and any other power required by the shroud
- thermal control systems-thermal paint, insulation, heat shield tiles, or any other active or passive means necessary to maintain appropriate temperature of the shroud and mission equipment within it
- integration, assembly, test and checkout

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.2.6 Guidance and Control

The means (hardware/software) for generating or receiving guidance intelligence, conditioning the intelligence to produce control signals, and generating appropriate control forces.

Controllers may interface with the structure by actuating moveable aero surfaces or with the propulsion system to produce control reaction forces or may independently produce reaction forces for control.

If the design is such that electronics are packaged into a single rack or housing as an assembly, this rack or housing will be considered part of the guidance and control system.

Includes, for example:

- guidance intelligence system, computer, sensing elements, etc.

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.2.7 Integration, Assembly, Test, and Checkout.

The integration, assembly, test, and checkout element includes all efforts as identified in Appendix H: Work Breakdown Structure Definitions, Common Elements, to provide a complete launch vehicle.

F.3.3 Orbital Transfer Vehicle

Any transportation system utilized for placing spacecraft in an operational environment following launch vehicle separation or deployment. Orbital transfer vehicle includes, for example, "upper-stages" and orbital maneuvering vehicles. The orbital transfer vehicle may be single-stage or multiple-stage configuration.

Includes:

- structure, propulsion, guidance and control; all other installed equipment; and all software integral to the vehicle
- design development, and production of complete units (i.e., prototype or operationally configured units which satisfy the requirements of their applicable specifications, regardless of end use)
- Sub-elements to the orbital transfer vehicle-Propulsion, Stage I, Stage II . . . n, Strap-On Units, Guidance and Control, Integration, Assembly, Test and Checkout (Sections F.3.3.1 through F.3.3.4)

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.3.1 Propulsion (Single Stage Only).

The means for generating the orbital transfer vehicle into its operational orbit.

Includes, for example:

- engine, structure, propellant and fuel, distribution and control of propellant and fuel, starting means, safety devices, and internal environmental control grouped as a functional entity
- design, development, production, and assembly efforts to provide the propulsion structure as an entity

F.3.3.2 Stage I

The orbital transfer vehicle stage which provides initial propulsion for the orbital transfer vehicle following separation or deployment from the launch vehicle.

Includes, for example:

- structure, propulsion, controls, instrumentation, separation, and all other installed subsystem equipment integral to Stage 1 as an entity
- design, development, production, and assembly efforts to provide Stage I as an entity

Excludes:

- strap-on units

F.3.3.3 Stage II . . . n (As Required)

The second orbital transfer vehicle stage and subsequent stages (as required) used to place a space vehicle into its operational environment. This stage provides propulsion following separation of the first stage.

Includes, for example:

- structure, propulsion, controls, instrumentation, separation subsystems, and all other installed subsystem equipment integral to the stage as an entity
- design, development, production, and assembly efforts to provide each stage as an entity

Excludes:

- strap-on units

F.3.3.4 Strap-On Units (As Required)

The solid or liquid propulsion assemblies that provide additional thrust or propellant to assist the orbital transfer vehicle in placing a space vehicle into its operational orbit if strap-on units are employed.

Includes, for example:

- complete set of strap-on units-the case, nozzle, igniter, tanks, mounting structure, cordage, etc.
- design, development, production, and assembly efforts to provide the strap-on units as an entity

F.3.3.5 Guidance and Control

The means (hardware/software) for generating or receiving guidance intelligence, conditioning the intelligence to produce control signals, and generating appropriate control forces.

Controllers may interface with the structure by actuating moveable aero surfaces or with the propulsion system to produce control reaction forces or may independently produce reaction forces for control.

If the design is such that electronics are packaged into a single rack or housing as an assembly, this rack or housing will be considered part of the guidance and control element.

Includes, for example:

- guidance intelligence system, computer, sensing elements, etc.

F.3.3.6 Integration, Assembly, Test, and Checkout

The integration, assembly, test, and checkout element includes all efforts as identified in Appendix H: Work Breakdown Structure Definitions, Common Elements, to provide a complete orbital transfer vehicle.

F.3.4 Space Vehicle

The complete vehicle, or group of vehicles placed into space (operational orbit environment).

Includes:

- spacecraft, payload, reentry vehicle and orbit injection/dispenser, and integration, assembly, test, and checkout
- design, development, and production of complete units-(i.e., prototype or operationally configured units which satisfy the requirements of their applicable specifications, regardless of end use)
- sub-elements to the space vehicle-Spacecraft, Payload I . . . n, Reentry Vehicle, Orbit Injector/Dispenser, Integration, Assembly, Test and Control (F.3.4.1—F.3.4.5)

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.4.1 Spacecraft

The principal operating space vehicle which serves as a housing or platform for carrying a payload and other mission-oriented equipments in space.

Includes, for example:

- structure, power, attitude determination and control, and other equipments characteristic of spacecraft
- all design, development, production, and assembly efforts to provide the spacecraft as an entity

F.3.4.2 Payload

The equipment provided for special purposes in addition to the normal equipment integral to the spacecraft or reentry vehicle.

Includes, for example:

- experimental equipment placed on board the vehicle and flight crew equipment (space suits, life support, and safety equipment)
- communications, displays and instrumentation, telemetry equipment and other equipments specifically to collect data for future planning and projection purposes

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.4.3 Reentry Vehicle

The principal operating vehicle specifically designed to safely reenter the atmosphere in order to land a payload (experimental equipment or crew).

Includes, for example:

- navigation and guidance, power supply, command and control, attitude control, environmental control, propulsion, and other equipments homogeneous to the reentry vehicle
- all design, development, production, and assembly efforts to provide the reentry vehicle as an entity

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.4.4 Orbit Injector/Dispenser

The function of placing orbiting objects in the planned orbital path.

Includes, for example:

- structure, propulsion, instrumentation and stage interface, separation subsystem, and other equipment necessary for integration with other level 3 elements

NOTE: All effort directly associated with the remaining level 3 WBS elements and the integration, assembly, test, and checkout of these elements into the launch vehicle is excluded.

F.3.4.5 Integration, Assembly, Test, and Checkout

The integration, assembly, test, and checkout element includes all efforts as identified in Appendix H: Work Breakdown Structure Definitions, Common Elements, to provide a complete space vehicle.

F.3.5 Ground Command, Control, Communications, and Mission Equipment

The ground hardware/software equipment used for communicating between control and tracking facilities, monitoring the health and status of space vehicles, commanding the space vehicle's hardware, and adjusting the space vehicle's orbit as required for space vehicle health or mission purpose.

Two configurations for the ground command, control, communications and mission equipment are the parabolic dish-based antenna system and the phased array-based antenna system.

If a ground site has multiple antenna configurations, each will have its own separate command and control equipment, communications equipment, data processing equipment and test equipment.

Includes:

- the design, development, and production of complete units-(i.e., prototype or operationally configured units which satisfy the requirements of their applicable specifications, regardless of end use)
- sub-elements to the ground command, control, communications, and mission equipment (F.3.5.1—F.3.5.6)

F.3.5.1 Sensor I . . . n (As Required)

Those hardware and software elements/components which comprise the sensor system.

Includes, for example:

- antenna, platform/pedestal, radome, transmission equipment, reception equipment, and other sensor subsystems
- design, development, production, and assembly efforts to provide each sensor as an entity

F.3.5.2 Telemetry, Tracking and Control

The hardware/software elements that facilitate launch decisions and command and control of the aerospace vehicle.

Includes, for example:

- supplementary means for guidance of those aerospace vehicles not having completely self-contained guidance and control and means to command destruct
- control and check-out consoles, data displays, and mission records

F.3.5.3 External Communications

The hardware and software components that allow the ground station to communicate with any external data link or source like telephone (analog) lines, digital data lines, nonsatellite radio receivers. While the terrestrial data lines may connect to radio of other satellite communications stations, the external communications subsystem ends where these links physically connect to the secure communications, modulation/demodulation (modem) or coder/decoder equipment.

F.3.5.4 Data Processing Equipment

The hardware and software components that provide the activities and means to condition data generated at the launch site or aboard the space vehicle, or data received from associated systems to accommodate the needs of command and control or mission data processing.

Includes, for example:

- central processing unit (computer), peripheral equipment, and the software required to operate the data processing equipment.

F.3.5.5 Launch Equipment

The means to launch the aerospace vehicle from stationary sites.

Includes, for example:

- storage facilities and checkout stations for readiness verification when these are integral to the launcher
- safety and protective elements when these are not integral to the launch platform or facilities

F.3.5.6 Auxiliary Equipment

The general purpose/multi-usage ground equipment utilized to support the various operational capabilities of the command and launch equipments.

Includes, for example:

- power generators, power distribution systems, environmental control, cabling, malfunction detection, fire prevention, security systems, and other common-usage items not applicable to specific elements of the ground based equipment

F.3.6 Flight Support Operations and Services

Mate/checkout/launch; mission control; tracking; and command, control and communications (C^3); recovery operations and services; and launch site maintenance/refurbishment. This element supports the launch vehicle, orbital transfer vehicle, and/or space vehicle during an operational mission.

Sub-elements to the flight operations and services (F.3.6.1—F.3.6.5).

F.3.6.1 Mate/Checkout/Launch

The preflight operations and services subsequent to production and/or storage, and the actual launch of the complete system and payload.

Includes, for example:

- materials to conduct equipment receiving and checkout at launch site, preflight assembly and checkout, pre/post flight data reduction and analysis, and any prelaunch flight control/mission control planning

F.3.6.2 Mission Control

The personnel and materiel required to operate individual mission control centers and to perform ground command and control with the space vehicles.

Includes, for example:

- mission control centers such as Constellation Command Center, Battle Management/Command Control Center (BM/C^3), Space Asset Support System Control Center, and Space Transportation Control Center

Excludes:

- tracking and communications centers (these are included in WBS element F.3.6.3)

F.3.6.3 Tracking and C^3

The personnel and materiel required to perform the functions of telemetry, tracking, controlling, and data retrieval for the mission control systems.

Includes, for example:

- mission control systems, on the ground or in space, including Satellite Control Facility; Remote Tracking Station; Tracking, Data, Relay Satellite System; and other ground/space tracking systems

Excludes:

- initial acquisition of tracking and C^3 (acquisition of these systems is included in WBS element F.3.6.4)

F.3.6.4 Recovery Operations and Services

The contractor effort and materiel necessary to effect recovery of the space vehicle or other mission equipment.

Includes:

- the launch site recovery forces, reentry site recovery forces, logistics support to recovery forces, logistics support to the recovery operations, communications, and transportation of recovered equipment to assigned facilities

F.3.6.5 Launch Site Maintenance/Refurbishment

The organization, maintenance, and management of launch vehicle facilities and mission equipment, and support at the launch base.

Includes, for example:

- requirements to clean up and refurbish each launch site after each launch

F.3.7 Storage

Those costs of holding portions of the space system while awaiting use of the system being stored, prepared for storage, or recovered from storage. Periods of holding result from schedule changes and/or technological problems exogenous to the portion of the space system.

Includes:

- Sub-elements to storage (F.3.7.1—F.3.7.3)

F.3.7.1 Planning and Preparation

The planning and preparation costs for storage of all systems/subsystems associated with the launch vehicle, orbital transfer vehicle, and space vehicle equipment.

Includes, for example:

- generation of any storage or maintenance instructions and documents necessary for repairable systems or subsystems

F.3.7.2 Storage

The cost incurred while the systems or subsystems of the launch vehicle, orbital transfer vehicle, and space vehicle equipment are in storage.

F.3.7.3 Transfer and Transportation

The transfer and storage costs incurred when the systems/subsystems of the launch vehicle, orbital transfer vehicle, and space vehicle equipment are moved from one location to another.

Includes, for example:

- costs of relocation necessitated by mission requirements

F.3.8 WBS Common Elements

Definitions for common WBS elements applicable to the space system and all other defense materiel items are in Appendix H: Work Breakdown Structure Definitions, Common Elements.

Common Elements

Work Breakdown Structure And Definitions

H.1 SCOPE

This appendix provides the WBS elements common to all types of systems. Applicable government and non-government documents are listed. Definitions for the common WBS elements are provided in this appendix.

H.3 DEFINITIONS

H.3.1 Integration, Assembly, Test, and Checkout

In those instances in which an integration, assembly, test, and checkout element is used (Appendices A through G), this element includes all effort of technical and functional activities associated with the design, development, and production of mating surfaces, structures, equipment, parts, materials, and software required to assemble the level 3 equipment (hardware/software) elements into a level 2 mission equipment (hardware/ software) as a whole and not directly part of any other individual level 3 element.

Includes:

- the development of engineering layouts, determination of overall design characteristics, and determination of requirements of design review
- the set up, conduct, and review of testing assembled components or subsystems prior to installation
- the detailed production design, producibility engineering planning (PEP), and manufacturing process capability, including the process design development and demonstration effort to achieve compatibility with engineering requirements and the ability to produce economically and consistent quality
- inspection activities related to receiving, factory and vendor liaison
- design maintenance effort
- quality planning and control
- tooling (initial production facilities, factory support equipment) including planning, design, and fabrication
- administrative engineering
- the joining or mating and final assembly of level 3 equipment elements to form a complete prime mission equipment when the effort is performed at the manufacturing facility
- integration of software (including loading and verification of firmware)
- conduct of production acceptance testing

Excludes:

- all systems engineering/program management and system test and evaluation which are associated with the overall system

NOTE: When an integration, assembly, test, and checkout element is utilized at lower levels of the contract work breakdown structure, it will be summarized into the next higher level equipment (hardware/software) work breakdown structure element and should never be summarized directly into a level 3 integration, assembly, test, and checkout element.

H.3.2 Systems Engineering/Program Management

The systems engineering and technical control as well as the business management of particular systems and programs. Systems engineering/ program management elements to be reported and their levels will be specified by the requiring activity.

Includes:

- the overall planning, directing, and controlling of the definition, development, and production of a system or program including supportability and acquisition logistics, e.g., maintenance support, facilities, personnel, training, testing, and activation of a system

Excludes:

- systems engineering/program management effort that can be associated specifically with the equipment (hardware/software) element

Systems Engineering

The technical and management efforts of directing and controlling a totally integrated engineering effort of a system or program.

Includes but not limited to:

- effort to define the system and the integrated planning and control of the technical program efforts of design engineering, specialty engineering, production engineering, and integrated test planning
- effort to transform an operational need or statement of deficiency into a description of system requirements and a preferred system configuration
- technical planning and control effort for planning, monitoring, measuring, evaluating, directing, and replanning the management of the technical program

- (all programs, where applicable) value engineering, configuration management, human factors, maintainability, reliability, survivability/ vulnerability, system safety, environmental protection, standardization, system analysis, logistic support analysis, etc.
- (for ships) the extended Ship Work Breakdown Structure (ESWBS), Configuration Management (811), Human Factors (892), Standardization (893), Value Engineering (894), and Reliability and Maintainability (895) elements

Excludes:

- actual design engineering and the production engineering directly related to the WBS element with which it is associated

Examples of systems engineering efforts are:

1) System definition, overall system design, design integrity analysis, system optimization, system/cost effectiveness analysis, and intra-system and inter-system compatibility assurance, etc.; the integration and balancing of reliability, maintainability, producibility, safety, human health, environmental protection, and survivability; security requirements, configuration management and configuration control; quality assurance program, value engineering, preparation of equipment and component performance specifications, design of test and demonstration plans; determination of software development or software test facility/ environment requirements.

2) Preparation of the Systems Engineering Management Plan (SEMP), specification tree, program risk analysis, system planning, decision control process, technical performance measurement, technical reviews, subcontractor and vendor reviews, work authorization, and technical documentation control.

3) Reliability engineering-the engineering process and series of tasks required to examine the probability of a device or system performing its mission adequately for the period of time intended under the operating conditions expected to be encountered.

4) Maintainability engineering-the engineering process and series of tasks required to measure the ability of an item or system to be retained in or restored to a specified condition of readiness, skill levels, etc., using prescribed procedures and resources at specific levels of maintenance and repair.

5) Human factors engineering-the engineering process and the series of tasks required to define, as a comprehensive technical and engineering effort, the integration of doctrine, manpower, and personnel integration, materiel development, operational effectiveness, human characteristics, skill capabilities, training, manning implication, and other related elements into a comprehensive effort.

6) Supportability analyses-an integral part of the systems engineering process beginning at program initiation and continuing throughout program development.

Supportability analyses form the basis for related design requirements included in the system specification and for subsequent decisions concerning how to most cost effectively support the system over its entire life cycle. Programs allow contractors the maximum flexibility in proposing the most appropriate supportability analyses.

Program Management

The business and administrative planning, organizing, directing, coordinating, controlling, and approval actions designated to accomplish overall program objectives which are not associated with specific hardware elements and are not included in systems engineering.

Includes for example:

- cost, schedule, performance measurement management, warranty administration, contract management, data management, vendor liaison, subcontract management, etc.
- support element management, defined as the logistics tasks management effort and technical control, and the business management of the support elements. The logistics management function encompasses the support evaluation and supportability assurance required to produce an affordable and supportable defense materiel system
- planning and management of all the functions of logistics. Examples are:
    - maintenance support planning and support facilities planning; other support requirements determination; support equipment; supply support; packaging, handling, storage, and transportation; provisioning requirements determination and planning; training system requirements determination; computer resource determination; organizational, intermediate, and depot maintenance determination management; and data management
- (for ships) the Extended Ship Work Breakdown Structure (ESWBS), Project Management (897); Data Management (896); and Supply Support (853) elements.

H.3.3 System Test and Evaluation

The use of prototype, production, or specifically fabricated hardware/ software to obtain or validate engineering data on the performance of the system during the development phase (normally funded from RDT&E) of the program.

Includes:

- detailed planning, conduct, support, data reduction and reports (excluding the Contract Data Requirements List data) from such testing, and all hardware/software items which are consumed or planned to be consumed in the conduct of such testing

- all effort associated with the design and production of models, specimens, fixtures, and instrumentation in support of the system level test program

NOTE: Test articles which are complete units (i.e., functionally configured as required by specifications) are excluded from this work breakdown structure element.

Excludes:

- all formal and informal testing up through the subsystem level which can be associated with the hardware/software element
- acceptance testing

NOTE: These excluded efforts are to be included with the appropriate hardware or software elements.

H.3.3.1 Development Test and Evaluation

This effort is planned, conducted and monitored by the developing agency of the DoD component. It includes test and evaluation conducted to:

- demonstrate that the engineering design and development process is complete.
- demonstrate that the design risks have been minimized.
- demonstrate that the system will meet specifications.
- estimate the system's military utility when introduced.
- determine whether the engineering design is supportable (practical, maintainable, safe, etc.) for operational use.
- provide test data with which to examine and evaluate trade-offs against specification requirements, life cycle cost, and schedule.
- perform the logistics testing efforts to evaluate the achievement of supportability goals, the adequacy of the support package for the system, (e.g., deliverable maintenance tools, test equipment, technical publications, maintenance instructions, and personnel skills and training requirements, etc.).

Includes, for example:

- all contractor in-house effort
- (all programs, where applicable) models, tests and associated simulations such as wind tunnel, static, drop, and fatigue; integration ground tests; test bed aircraft and associated support; qualification test and evaluation, development flight test, test instrumentation, environmental tests, ballistics, radiological, range and accuracy demonstrations, test facility operations, test equipment (including its support equipment), chase and calibrated pacer aircraft and support thereto, and logistics testing
- (for aircraft) avionics integration test composed of the following:

- test bench/laboratory, including design, acquisition, and installation of basic computers and test equipments which will provide an ability to simulate in the laboratory the operational environment of the avionics system/subsystem
- air vehicle equipment, consisting of the avionics and/or other air vehicle subsystem modules which are required by the bench/lab or flying test bed in order to provide a compatible airframe avionics system/subsystem for evaluation purposes
- flying test bed, including requirements analysis, design of modifications, lease or purchase of test bed aircraft, modification of aircraft, installation of avionics equipment and instrumentation, and checkout of an existing aircraft used essentially as a flying avionics laboratory
- avionics test program, consisting of the effort required to develop test plans/procedures, conduct tests, and analyze hardware and software test results to verify the avionics equipments' operational capability and compatibility as an integrated air vehicle subsystem
- software, referring to the effort required to design, code, de-bug, and document software programs necessary to direct the avionics integration test

- (for engines) engine military qualification tests and engine preliminary flight rating tests
- (for ships) model basin, hydrostatic, fatigue, shock, special sea tests and trials, etc., including the Extended Ship Work Breakdown Structure (ESWBS), Trials Agenda Preparation, Data Collection & Analysis (842); Dock and Sea Trials (9823); and Hull Vibration Survey (9825) elements

H.3.3.2 Operational Test and Evaluation

The test and evaluation conducted by agencies other than the developing command to assess the prospective system's military utility, operational effectiveness, operational suitability, logistics supportability (including compatibility, inter-operability, reliability, maintainability, logistic requirements, etc.), cost of ownership, and need for any modifications.

Includes, for example:

- Initial operational test and evaluation conducted during the development of a weapon system
- such tests as system demonstration, flight tests, sea trials, mobility demonstrations, on-orbit tests, spin demonstration, stability tests, qualification operational test and evaluation , etc., and support thereto, required to prove the operational capability of the deliverable system
- contractor support (e.g., technical assistance, maintenance, labor, material, etc.) consumed during this phase of testing
- logistics testing efforts to evaluate the achievement of supportability goals and the adequacy of the support for the system (e.g., deliverable maintenance tools, test

equipment, technical publications, maintenance instructions, personnel skills and training requirements, and software support facility/environment elements)

H.3.3.3 Mock-ups

The design engineering and production of system or subsystem mock-ups which have special contractual or engineering significance, or which are not required solely for the conduct of one of the above elements of testing.

H.3.3.4 Test and Evaluation Support

The support elements necessary to operate and maintain, during test and evaluation, systems and subsystems which are not consumed during the testing phase and are not allocated to a specific phase of testing.

Includes, for example:

- repairable spares, repair of reparables, repair parts, warehousing and distribution of spares and repair parts, test and support equipment, test bed vehicles, drones, surveillance aircraft, tracking vessels, contractor technical support, etc.

Excludes:

- operational and maintenance personnel, consumables, special fixtures, special instrumentation, etc., which are utilized and/or consumed in a single element of testing and which should be included under that element of testing

H.3.3.5 Test Facilities

The special test facilities required for performance of the various developmental tests necessary to prove the design and reliability of the system or subsystem.

Includes, for example:

- test tank test fixtures, propulsion test fixtures, white rooms, test chambers, etc.

Excludes:

- brick and mortar-type facilities identified as industrial facilities

H.3.4 Training

Deliverable training services, devices, accessories, aids, equipment, and parts used to facilitate instruction through which personnel will learn to operate and maintain the system with maximum efficiency.

Includes:

- all effort associated with the design, development, and production of deliverable training equipment as well as the execution of training services

Excludes:

- overall planning, management, and task analysis function inherent in the WBS element Systems Engineering/Program Management

H.3.4.1 Equipment

Distinctive deliverable end items of training equipment, assigned by either a contractor or military service, required to meet specific training objectives.

Includes, for example:

- operational trainers, maintenance trainers, and other items such as cutaways, mock-ups, and models

H.3.4.2 Services

Deliverable services, accessories, and aids necessary to accomplish the objectives of training.

Includes:

- training course materials; contractor-conducted training (in-plant and service training); and the materials and curriculum required to design, execute, and produce a contractor developed training program
- materiel, courses, and associated documentation (primarily the computer software, courses and training aids)

Excludes:

- deliverable training data associated with the WBS element Support Data

H.3.4.3 Facilities

The special construction necessary to accomplish training objectives.

Includes, for example:

- modification or rehabilitation of existing facilities used to accomplish training objectives

Excludes:

- installed equipment used to acquaint the trainee with the system or establish trainee proficiency
- the brick and mortar-type facilities identified as industrial facilities

H.3.5 Data

The deliverable data required to be listed on a Contract Data Requirements List, DD Form 1423.

Includes:

- only such effort that can be reduced or avoided if the data item is eliminated
- (government-peculiar data) acquiring, writing, assembling, reproducing, packaging and shipping the data
- transforming into government format, reproducing and shipping data identical to that used by the contractor but in a different format

H.3.5.1 Technical Publications

Technical data, providing instructions for installation, operation, maintenance, training, and support, formatted into a technical manual. Data may be presented in any form (regardless of the form or method of recording). Technical orders that meet the criteria of this definition may also be classified as technical manuals.

Includes, for example:

- operation and maintenance instructions, parts lists or parts breakdown, and related technical information or procedures exclusive of administrative procedures
- data item descriptions set forth in categories selected from the Acquisition Management Systems and Data Requirements Control List (DoD 5010.12-L)
- (for ships) Extended Ship Work Breakdown Structure (ESWBS), Technical Manuals and Other Data (856) element

H.3.5.2 Engineering Data

Recorded scientific or technical information (regardless of the form or method of recording) including computer software documentation. Engineering data defines and documents an engineering design or product configuration (sufficient to allow duplication of the original items) and is used to support production, engineering and logistics activities.

Includes, for example:

- all final plans, procedures, reports, and documentation pertaining to systems, subsystems, computer and computer resource programs, component engineering, operational testing, human factors, reliability, availability, and maintainability, and other engineering analysis, etc.
- Technical data package (reprocurement package) which includes all engineering drawings, associated lists, process descriptions, and other documents defining physical geometry, material composition, and performance procedures
- (for ships) Extended Ship Work Breakdown Structure (ESWBS), Design Support, Ship's Selected Records (8302); Design Support, Services, Reproduction (8303); and Engineering Drawings and Specifications (855) elements

Excludes:

- computer software or financial, administrative, cost or pricing, or management data or other information incidental to contract administration

H.3.5.3 Management Data

The data items necessary for configuration management, cost, schedule, contractual data management, program management, etc., required by the government in accordance with functional categories selected from the DODISS and DoD 5010.12-L.

Includes, for example:

- contractor cost reports, cost performance reports, contract funds status reports, schedules, milestones, networks, integrated support plans, etc.
- (for ships) Extended Ship Work Breakdown Structure (ESWBS), Contract Data Requirements (988) element

H.3.5.4 Support Data

The data items designed to document support planning in accordance with functional categories selected from DoD 5010.12-L.

Includes, for example:

- supply; general maintenance plans and reports; training data; transportation, handling, storage, and packaging information; facilities data; data to support the provisioning process and all other support data; and software supportability planning and software support transition planning documents.

H.3.5.5 Data Depository

The facility designated to act as custodian to maintain a master engineering specification and establish a drawing depository service for government approved documents that are the property of the U.S. Government. As custodian for the government, the depository, authorized by approved change orders, maintains these master documents at the latest approved revision level. This facility is a distinct entity.

Includes, for example:

- all drafting and clerical effort necessary to maintain documents

Excludes:

- all similar effort for facility's specification and drawing control system, in support of its engineering and production activities.

> **NOTE: When documentation is called for on a given item of data retained in the depository, the charges (if charged as direct) will be to the appropriate data element.**

H.3.6 Peculiar Support Equipment

The design, development, and production of those deliverable items and associated software required to support and maintain the system or portions of the system while the system is not directly engaged in the performance of its mission, and which are not common support equipment (See H.3.7 below).

Includes:

- vehicles, equipment, tools, etc., used to fuel, service, transport, hoist, repair, overhaul, assemble, disassemble, test, inspect, or otherwise maintain mission equipment
- any production of duplicate or modified factory test or tooling equipment delivered to the government for use in maintaining the system. (Factory test and tooling equipment initially used by the contractor in the production process but subsequently delivered to the government will be included as cost of the item produced.)
- any additional equipment or software required to maintain or modify the software portions of the system

Excludes:

- overall planning, management and task analysis functions inherent in the work breakdown structure element, Systems Engineering/Program Management
- common support equipment, presently in the DoD inventory or commercially available, bought by the using command, not by the acquiring command

H.3.6.1 Test and Measurement Equipment

The peculiar or unique testing and measurement equipment which allows an operator or maintenance function to evaluate operational conditions of a system or equipment by performing specific diagnostics, screening or quality assurance effort at an organizational, intermediate, or depot level of equipment support.

Includes, for example:

- test measurement and diagnostic equipment, precision measuring equipment, automatic test equipment, manual test equipment, automatic test systems, test program sets, appropriate interconnect devices, automated load modules, taps, and related software, firmware and support hardware (power supply equipment, etc.) used at all levels of maintenance
- packages which enable line or shop replaceable units, printed circuit boards, or similar items to be diagnosed using automatic test equipment

H.3.6.2 Support and Handling Equipment

The deliverable tools and handling equipment used for support of the mission system.

Includes, for example:

- ground support equipment, vehicular support equipment, powered support equipment, nonpowered support equipment, munitions material handling equipment, materiel handling equipment, and software support equipment (hardware and software)

H.3.7 Common Support Equipment

The items required to support and maintain the system or portions of the system while not directly engaged in the performance of its mission, and which are presently in the DoD inventory for support of other systems.

Includes:

- acquisition of additional quantities of this equipment needed to support the item
- all efforts required to assure the availability of this equipment to support the item

H.3.7.1 Test and Measurement Equipment

The common testing and measurement equipment which allows an operator or maintenance function to evaluate operational conditions of a system or equipment by performing specific diagnostics, screening or quality assurance effort at an organizational, intermediate, or depot level of equipment support.

Includes, for example:

- test measurement and diagnostic equipment, precision measuring equipment, automatic test equipment, manual test equipment, automatic test systems, test program sets, appropriate interconnect devices, automated load modules, taps, and related software, firmware and support hardware (power supply equipment, etc.) used at all levels of maintenance
- packages which enable line or shop replaceable units, printed circuit boards, or similar items to be diagnosed using automatic test equipment

H.3.7.2 Support and Handling Equipment

The deliverable tools and handling equipment used for support of the mission system.

Includes, for example:

- ground support equipment, vehicular support equipment, powered support equipment, nonpowered support equipment, munitions material handling equipment, materiel handling equipment, and software support equipment (hardware/software)

H.3.8 Operational/Site Activation

The real estate, construction, conversion, utilities, and equipment to provide all facilities required to house, service, and launch prime mission equipment at the organizational and intermediate level.

Includes:

- conversion of site, ship, or vehicle
- system assembly, checkout, and installation (of mission and support equipment) into site facility or ship to achieve operational status
- contractor support in relation to operational/site activation

H.3.8.1 System Assembly, Installation, and Checkout on Site

The materials and services involved in the assembly of mission equipment at the site.

Includes, for example:

- installation of mission and support equipment in the operations or support facilities and complete system checkout or shakedown to ensure operational status. (Where appropriate, specify by site, ship or vehicle.)

H.3.8.2 Contractor Technical Support

The materials and services provided by the contractor related to activation.

Includes, for example:

- repair of reparables, standby services, final turnover, etc.

H.3.8.3 Site Construction

Real estate, site planning and preparation, construction, and other special-purpose facilities necessary to achieve system operational status.

Includes, for example:

- construction of utilities, roads, and interconnecting cabling

H.3.8.4 Site/Ship/Vehicle Conversion

The materials and services required to convert existing sites, ships, or vehicles to accommodate the mission equipment and selected support equipment directly related to the specific system.

Includes, for example:

- operations, support, and other special purpose (e.g., launch) facilities conversion necessary to achieve system operational status. (Where appropriate, specify by site, ship or vehicle.)

H.3.9 Industrial Facilities

The construction, conversion, or expansion of industrial facilities for production, inventory, and contractor depot maintenance required when that service is for the specific system.

Includes:

- equipment acquisition or modernization, where applicable
- maintenance of these facilities or equipment
- industrial facilities for hazardous waste management to satisfy environmental standards

H.3.9.1 Construction/Conversion/Expansion

The real estate and preparation of system peculiar industrial facilities for production, inventory, depot maintenance, and other related activities.

H.3.9.2 Equipment Acquisition or Modernization

The production equipment acquisition, modernization, or transferal of equipment for the particular system. (Pertains to government owned and leased equipment under facilities contract.)

H.3.9.3 Maintenance (Industrial Facilities)

The maintenance, preservation, and repair of industrial facilities and equipment.

H.3.10 Initial Spares and Repair Parts

The deliverable spare components, assemblies and subassemblies used for initial replacement purposes in the materiel system equipment end item.

Includes:

- repairable spares and repair parts required as initial stockage to support and maintain newly fielded systems or subsystems during the initial phase of service, including pipeline and war reserve quantities, at all levels of maintenance and support

Excludes:

- development test spares and spares provided specifically for use during installation, assembly, and checkout on site. Lower level WBS breakouts should be by subsystem.

APPENDIX B

USCM WBS

The material in this appendix is excerpted from USCM WBS user documentation.

(Extract from Unmanned Space Vehicle Cost Model User Documentation)

B.3 USCM Work Breakdown Structure

The WBS, shown in Figure 2, further expands the space vehicle tiering to show the lowest level at which contractor costs were consolidated and normalized in the database.

A brief discussion of each item in the WBS follows. The intent of the discussion is twofold: (1) to define the USCM WBS subsystem and component content for modeling purposes, and (2) to provide trained cost analysts and estimators, who have little or no space acquisition experience, with a general overview of space vehicle subsystem and component functions.

B.3.1 Space Vehicle

The space vehicle consists of the spacecraft integrated with the payload and the interstage/dispenser. All program-level costs are also included in the space vehicle.

Figure 2. USCM8 WBS

SPACE VEHICLE
- INTEGRATION, ASSEMBLY, AND SYSTEM TEST (IA&T)
- SPACECRAFT
  - Structure
  - Thermal Control
  - Attitude Determination Control System (ADCS)
    - Attitude Determination (AD)
      - Sensors
      - Digital Electronics
    - Mechanical Reaction Control System (RCS)
  - Electrical Power Supply (EPS)
    - (Si, He Si, or GaAs) Generation
    - Storage
    - Power Conditioning and Distribution (PCD)
  - Telemetry, Tracking, and Command (TT&C)
    - Transmitter
    - Receiver
    - Exciter

Transponder
Digital Electronics (Signal/Data Processor)
Analog Electronics
Antennas
RF Distribution
Propulsion
Integral Propulsion System (IPS)
Propellant RCS
Apogee Kick Motor (AKM)
COMMUNICATIONS PAYLOAD
Transmitter
Receiver
Exciter
Transponder
Digital Electronics (Signal/Data Processor)
Analog Electronics
Antennas
RF Distribution
PROGRAM LEVEL
Program Management
Systems Engineering
Data

AEROSPACE GROUND EQUIPMENT (AGE)

LAUNCH AND ORBITAL OPERATIONS SUPPORT (LOOS)

B.3.1.1 Integration, Assembly, and System Test-Space Vehicle Level

Although not a satellite subsystem, IA&T contributes to the total cost of a space vehicle. For a component-level estimating model, such as USCM8, there are two distinct groupings of IA&T. The costs for each grouping are accounted for separately. The first grouping, called subsystem IA&T, addresses the cost of integrating and assembling individual components into a subsystem. In USCM8, subsystem IA&T costs are embedded in the subsystem- and component-level (and component part-level) CER values. The second grouping, called space vehicle IA&T, addresses the cost of integrating and assembling all space vehicle subsystems into an operable space vehicle. These costs are carried under a separate CER in USCM8, called Space Vehicle IA&T. Both groupings of IA&T include the cost for all testing effort required to develop the system and accomplish planned test objectives, including collecting test data. In addition to costs for the space vehicle level IA&T discussed above, those space vehicle level costs that cannot be related to any specific space vehicle subsystem are included in the USCM definition of space vehicle IA&T costs. These IA&T costs cover the IA&T of the spacecraft and payload into a space vehicle. They do not include IA&T of the space vehicle to the launch vehicle.

B.3.1.2 Spacecraft (Platform/Bus)

The spacecraft, often called the bus or platform, consists of structure; thermal; attitude determination control (ADCS); electrical power supply (EPS); telemetry, tracking, and command (TT&C); and propulsion subsystems.

B.3.1.2.1 Structure

The space vehicle structure carries, supports, and protects the spacecraft and payload from the initial stresses endured during launch and from the hazards of space during the spacecraft's lifetime. The structure subsystem consists of a primary and secondary structure. The primary structure, or Satellite Structure in USCM8, is usually a single, cylindrical, conical, or box-shaped equipment bay with externally attached bays. It serves as the central frame of the space vehicle, providing support and mounting surfaces for all equipment, and bearing the major space vehicle stress loads. The secondary structure, or Mechanism in USCM8, deploys spacecraft and payload components after achieving final orbit and provides support for those components. USCM8 only provides a subsystem relationship for Structure since the primary and secondary structures are often indiscernible from one another during data collections.

In addition to costs for the primary satellite structure described above, the costs associated with pyrotechnic devices, deployment mechanisms, the solar array boom supporting the paddle-mounted solar array, struts, antenna supports, experimental booms, and mechanical design equipment, as well as any non-hardware accounts for effort directly associated with the structure system, are included in the USCM definition of space vehicle structure costs.

B.3.1.2.2 Thermal Control

Thermal control maintains the temperature of the spacecraft and mission equipment by modifying the heat transfer to and from each space vehicle element so that its temperature will remain within allowable ranges during the entire life of its mission. The AFSC Space Handbook emphasizes the importance of thermal control: "Temperature stability and temperature gradients are also primary concerns in the design of the subsystem, with the onboard thermal environment being determined by the magnitude and distribution of radiation inputs from the sun, planets, and internal sources such as rockets and electrical operations."[10]

Thermal control systems for spacecraft can be grouped into two generic categories: passive thermal control and active thermal control. Passive thermal control uses material coatings such as blankets and paints to control temperature. Active thermal control techniques include closed liquid loops, expendable heat sinks, and mechanical cooling. USCM8 groups patch heaters and heat pipes along with the active components, although they are often thought of as passive thermal control because of their high reliability and lack of apparent moving parts.

Passive thermal control techniques (and the locations where they are employed) include (1) special paints, second surface mirrors, silvered teflon sheets, and tapes (component surfaces, platform surfaces, internal array surfaces, and end closures); (2) insulation (propellant lines and tanks, and end closures); (3) thermal isolators (thruster supports, propellant tank supports, diagonal and vertical trusses) and reflective tunnels for enhancing solar energy absorption and radiation coupling (axial and radial thrusters).[11] Within the first category, paint is extremely light and reliable. For example, white paint helps the space vehicle's external skin surface achieve a combination of low solar absorption in the solar wavelengths and high emittance in the long infrared wavelengths. According to the Space Handbook, the second category, thermal insulation, is designed "to reduce the rate of heat flow per unit area between two boundary surfaces at specified temperatures. It can be a single, homogeneous material such as low thermal-conductivity foam, or an evacuated, multi-layered insulation, often called a blanket, in which the layers act as a low emittance radiation shield and are separated by spacers."[12] The third grouping encompasses radiators, a term which actually describes surface material properties. Because space vehicle surfaces are exposed to external energy sources, their material properties greatly impact thermal control. Therefore, their material makeup is based on radiative properties that will achieve the desired balance between internally generated heat, external heat, and heat rejected to space. Designs for passive temperature control systems are integral to the satellite structure, adding between one and four percent to the total system weight.[13] The Satellite Control Facility's (SCF) "Spacecraft Systems Familiarization Course" states that "[The] system can be designed to hold temperatures of equipment to within +/-3 deg F of any selected temperature within a range of approximately 0–130 degrees."[14]

Active thermal control techniques include heat pipes, louvers, and heaters. Heat pipes are simple, contained devices that conduct both external and internal heat away from sensitive equipment by closed, fluid flow loops, which transfer heat to radiators or expendable heat sinks. The inner walls of the heat pipes "are lined with a wicking material saturated with a working fluid. Heat is conducted from a source, such as electronics, through the heat pipe walls and into the working fluid. The additional heat causes the evaporation of the working fluid, which then travels, by the induced pressure gradient, to a colder portion of the pipe. At that point, heat is conducted through the wall to a heat rejection system. The condensed fluid is then pumped back to the hot end by the capillary action of the wicking material, therein completing the closed loop cycle."[15] Louvers offer a simple and reliable method of temperature control. The most common configuration consists of a series of polished aluminum blades arranged like venetian blinds over a high emittance radiator. By varying their degree of openness, the louvers can alter the effective emittance of the radiator. Thermostats, which are also very common, usually are part of a closed-loop system that includes a temperature-sensing element and an electronic temperature controller. Thermostats coupled with electrical heaters are perhaps the most common active control device.

Cryogenic thermal control maintains the temperature through a cryogenic heat sink, using the capacity of a fixed amount of cryogen in an insulated vessel or by using a mechanical refrigerator. In addition to costs for the hardware described above, any non-hardware accounts for effort directly associated with the thermal system are included in the USCM definition of space vehicle thermal costs.

B.3.1.2.3 Attitude Determination and Control Subsystem

The ADCS is the spacecraft subsystem that stabilizes the satellite to some pre-determined set of stabilization requirements. The ADCS performs the following two functions: determines spacecraft attitude using onboard sensors, and controls the spacecraft attitude using passive or active devices or a combination of passive/active devices. The ADCS contains only mechanical components (e.g., reaction wheels), whereas the propellant elements (i.e., thrusters) are identified as part of the Propulsion subsystem. There are several techniques that can be employed for attitude determination and control. Some of these techniques use a combination of propellant and mechanical components to perform attitude control. Attitude determination components and reaction control techniques are summarized in Figure 3.

Figure 3. ADCS Sensors and Techniques

Attitude Determination and Control Subsystem

ATTITUDE DETERMINATION SENSORS	REACTION CONTROL TECHNIQUES
Inertial Measurement Devices	Gravity Gradient
Gyros	Gravity Gradient and Momentum Wheel
Accelerometers	Passive Magnetic
Sun Sensors	Spin Stabilization
Star Sensors	Pure Spin Stabilization
Horizon Sensors	Dual Spin Stabilization
Magnetometers	Three-Axis Control
	Bias Momentum
	Zero Momentum

Attitude Determination. Attitude determination is classified into two categories: sensors and digital electronics. The digital electronics represent the processors and components that regulate the housekeeping functions of the bus, such as maintaining satellite stability and monitoring satellite health. Some of the sensors used for attitude determination are described below.

Inertial Measurement Devices (Gyroscopes and Accelerometers). Inertial measurement units (IMU) can use gyroscopes (gyros) and/or accelerometers, depending on satellite requirements. Gyros measure angular motion and accelerometers measure translational motion. Accelerometers are used if a measurement of velocity is required. Gyros and accelerometers are often mounted on a gimballed platform that maintains a given inertial position in space. There are other IMU design approaches, including strapdown units and fiber-optic and hemispherical resonating gyros. Strapdown systems have no gimbals; rather they use high-resolution software to resolve the output of the body-referenced sensors into an inertial reference frame. The accuracy of a strapdown system is comparable to a gimballed system and it is more reliable. IMUs are subject to gyro drift error and bias errors. For IMU use over more than a few hours, information updates must be provided from external reference sensors. Gyroscope drift rate range is 0.0003 degrees/hour to 1 degree/hour. Accelerometer linearity is 1 to 5 * 10^-6 g/g^2 over a range of 20 to 60 g. These devices are usually in the range of 6.6 to 55 pounds, while the power consumption ranges from approximately 10 to 200 watts.

Sun Sensors. Sun sensors are detection devices that operate in the visible spectrum and use the sun as the reference source. They are accurate and reliable. Sun sensor accuracy can be better than 0.01 degrees, or about 173 microradians. These devices weigh in the 1.1- to 4.4-pound range and their power consumption is typically less than 3 watts.

Star Sensors. There are several types of star sensors: scanning star sensors (scanners), tracking star sensors (trackers), and mapping star sensors (mappers). Star sensors can operate in any part of the electromagnetic spectrum. Generally, they are designed to operate in the visible and infrared spectrum. Star sensors are designed to look for and recognize particular stars to determine attitude and/or location.

Scanning star sensors mechanically scan a relatively small, predetermined area. (It is described as having a narrow field-of-view.) The mechanical scanning motion accomplished with one or more gimbal(s) causes the reference sources (stars) to pass through a narrow slit or slits onto a detector located in the star sensor. The resultant electrical signal provides the means of deriving the vehicle's attitude.

Star trackers and mappers are used in three-axis-stabilized spacecraft. The star tracker is fixed mechanically to the spacecraft and views a relatively large area. (It is described as having a large field-of-view.) The tracker scans the sky electronically until it detects and then tracks a known star.

A star mapper operates similarly to the tracker, except that it is capable of handling more than one star in its field-of-view.

Star sensor attitude measurement accuracies are achievable over a range of 0.0003 degrees to 0.01 degrees (5 microradians to 173 microradians).

Horizon Sensor. Horizon sensors are infrared devices that detect the contrast between the cold of deep space and the heat of the earth's atmosphere. Simple narrow field-of-view fixed-head types (called pippers or horizon-crossing indicators) are used on spinning spacecraft to measure specified parameters to determine earth nadir. Scanning horizon sensors use a rotating mirror or lens to replace or augment the spinning spacecraft. They are often used in pairs for improved performance and redundancy. Horizon sensors provide earth-relative information directly for earth-pointing spacecraft, which may simplify onboard processing. Typical accuracies for attitude determination are 0.1 degree to 1 degree for low earth orbit (LEO) but may be as accurate as 0.1 degree to 0.25 degree. Scanner/pippers weigh in the range of 4.4 to 11 pounds and consume in the range of 5 to 10 watts. Fixed-head (static) sensors weigh approximately 5.5 to 7.7 pounds and consume 0.3 to 5 watts.

Magnetometers. Magnetometers are simple, reliable, lightweight sensors that measure both the direction and size of the earth's magnetic field. Spacecraft attitude is determined by comparing the measured values to the earth's known field. Accuracy of attitude determination using a magnetometer is not as good as with sun sensors or horizon sensors. Typical attitude determination accuracy is in the range of 0.5 to 3 degrees.

Reaction Control Techniques. A brief description of various reaction control techniques is presented below. Even though some techniques employ thrusters for attitude control, those components are now captured in the Propulsion subsystem.

Gravity-Gradient. Gravity-gradient control uses the inertial properties of a vehicle to keep it pointed toward earth. Gravity-gradient control operates on the principle that an elongated object in a gravity field tends to align its longitudinal axis through the earth's center. This technique is used on simple spacecraft in near-earth orbits without yaw orientation requirements, often with deployed booms to achieve the desired inertias. Frequently, dampers are included in the design of gravity-gradient spacecraft to reduce small oscillations around the nadir vector caused by disturbances.

Gravity-Gradient and Momentum Wheel. In the simplest gravity-gradient attitude controlled spacecraft, only two orientation axes are controlled. The orientation around the nadir vector is unconstrained. To control this third axis, a small, constant-speed momentum wheel is placed along the axis perpendicular to the nadir and velocity vectors.

Passive Magnetic. The passive magnetic technique of achieving attitude control is implemented by placing permanent magnets on board the spacecraft to force spacecraft alignment along the earth's magnetic field. This is most effective in near-equatorial orbits where the field of orientation stays almost constant for an earth-pointing vehicle.

Pure Spin Stabilization. Pure spin stabilization is a passive control technique in which the entire spacecraft rotates so that its angular momentum vector remains approximately fixed in inertial space. Spin-stabilized spacecraft (spinners) utilize gyroscopic stability to passively resist disturbance torques about two axes. Spinners survive for long periods without attention, provide a thermally benign environment for components, and provide a scanning motion for sensors. Pure spin-stabilized systems, also called single-axis stabilized systems, are designed to point only one of the three satellite axes (vertical, horizontal, or directional; roll, pitch, yaw), using the spinning portion of the satellite as a gyroscope to stabilize the axis.

Dual Spin Stabilization. In the dual-spin-stabilization technique, the spacecraft has two sections spinning at different rates about the same axis. Normally, one section, the rotor, spins rapidly to provide angular momentum, while the second section, the stator or platform, is despun to keep one axis pointed toward the earth or sun. Dual spin stabilization results in added complexity due to the addition of a platform bearing and slip rings between the sections. The added complexity can increase cost and reduce reliability compared to pure spin stabilization. Dual spin stabilization is considered to be another case of spin stabilization and does not merit another category in attitude control.

Three-Axis Control. Spacecraft stabilized on three axes are more common today than those using spin or gravity-gradient stabilization techniques. Three-axis control provides the satellite with the capability of maneuvering. This stabilization technique is more expensive, more complex, and potentially less reliable compared to the other stabilization techniques. There are two basic approaches to three-axis control: zero momentum and bias momentum.

Bias momentum systems often have just one wheel, with its spin axis mounted along the pitch axis, normal to the orbit plane. The wheel is run at a nearly constant, high speed to provide gyroscopic stiffness to the vehicle, just as in spin stabilization, with similar nutation dynamics. Around the pitch axis, however, the spacecraft can control attitude by torquing the wheel, slightly increasing or decreasing its speed. Periodically, the pitch wheel must be desaturated, as in zero-momentum systems using thrusters or magnets.

Zero momentum systems can be accomplished in one of three ways: three wheels, control moment gyros (CMG), or thrusters. Using the three-wheel approach, a satellite has reaction wheels that respond to disturbances on the vehicle. When a sensor detects a satellite pointing error, a signal is generated which results in the speeding up of a reaction wheel (which was initially at rest). The torque generated by the wheel corrects the satellite attitude and leaves the wheel spinning at low speed, until another pointing error speeds the wheel again or slows it down. If the wheel approaches saturation speed, external torques must be applied, usually with a thruster or magnetic torquer, to force the wheel speed back to zero. This process, called desaturation, momentum unloading, or momentum dumping, can be done automatically or by command from the ground.

When high torque is required for large vehicles or fast slews, a variation of three-axis control is possible using CMGs. These devices work like momentum wheels on gimbals. Control of CMGs is complex, but their available torque for a given weight and power make them an important design consideration.

Zero momentum biased attitude control can also be achieved through the use of propulsion subsystem thrusters. The majority of satellites employ thrusters in conjunction with passive control equipment to vary the translational velocity, angular momentum, and other orbital parameters in a very precise manner. This form of attitude control will be discussed in length in the Propulsion subsystem section.

Mechanical Reaction Control Components. Mechanical reaction control components typically include nutation dampers, wobble dampers, gravity booms, magnetic torquers, solar-pressure vanes, aerodynamic vanes, gravity gradient devices, inertia wheels, and any associated electronics.

In addition to costs for ADCS hardware items, any non-hardware accounts for effort directly associated with the attitude control subsystem are included in the USCM8 definition of space vehicle ADCS costs.

B.3.1.2.4 Electrical Power Supply Subsystem

The EPS subsystem generates, converts, regulates, stores, and distributes all electrical energy to and between space vehicle components. EPS systems typically use solar cells to generate power and an electrochemical device to store the energy. Nuclear energy, another type of power generation, has had only limited use in space to date. It is typically used only for deep space missions and is not included in USCM8.

Batteries and fuel cells, which have only been used on manned missions, are the basic electrochemical devices for storing electric power. Both can be designed for either one-time use or for recyclable operation. Space vehicle batteries fall into two categories: primary batteries and secondary batteries. Primary batteries (e.g., mercuric oxide zinc), seldomly used on satellites, are used for a continuous source of energy and are not rechargeable. (They might be used for space vehicles with very short mission durations, e.g., experimental satellites.) Secondary batteries (e.g., nickel cadmium and nickel hydroden) are rechargeable and are used in combination with other primary energy sources (which keep them charged). Fuel cells are very similar to primary batteries. The major difference is that "the fuel cell is supplied with fuel and oxidizer from external tanks and rejects the reaction products, whereas the battery uses chemicals sealed into it during manufacturing."[16] Whenever total energy requirements exceed 10,000 watt-hours, fuel cells are preferred to batteries because of the weight savings.[17] Because USCM is an unmanned space vehicle cost model, the EPS CERs do not estimate the cost of fuel cells.

The solar EPS configuration relies on solar cells, which can be made of silicon or gallium arsenide. The solar cells, which convert solar photons (sunlight) directly into electricity, are laid out in arrays that can be grouped into two distinct classes: paddles and body-mounted cylindrical arrays (earlier designs were hexagonal or spherical). The paddles, which are usually employed with three-axis stabilized satellites, must be pointed toward the sun. This involves the use of sun sensors and a solar array drive to rotate the paddles as the satellite proceeds along its orbital path. A compromise method employs fixed paddles, and the space vehicle is directed for optimum sun orientation within a particular orbit. Body-mounted solar arrays are found on one-axis spin-stabilized satellites, with or without despin platforms, with solar cells mounted on the outer skin of the satellite. The rotation provides for varying exposure of the solar cells to the sun, resulting in an overall solar-cell power plant efficiency of a few percent, even though individual cells can attain 10- to 20-percent efficiency for silicon solar cells and greater than 20 percent efficiency for gallium arsenide cells.[18] As a result of this feature, more solar cells are required for the same amount of power than are required for a given paddle design. However, the requirement of more solar cells may be offset by the reduced requirement for axis stabilization.

Typical equipment includes solar cells, bus regulators, chargers, converters, power distribution units, batteries, and wire harnesses. In addition to costs for these hardware items, any non-hardware accounts for effort directly associated with the EPS subsystem are included in the USCM definition of space vehicle EPS costs.

As EPS subsystems increase in capacity, they incorporate more cost-impacting alternatives. For larger and more complex systems, it is beneficial to break down the EPS subsystem into its major components, estimate these using dedicated CERs (available in this USCM), and aggregate the results to arrive at an EPS subsystem cost. A brief description of the EPS component-level systems follows.

Power Generation. This category encompasses all components used in the transformation of solar energy into electrical power. It includes solar panels, solar array drives, and associated electronics. The USCM estimates the cost of solar power generation systems that use silicon , gallium arsenide, and high efficiency silicon solar cells; it does not estimate the cost of systems powered by fuel cells or nuclear energy.

Power Storage. Components included in this category are primary batteries, secondary rechargeable batteries, and the electronics for charging secondary batteries with power generated while in space. The focus is on systems that contain NiCd and NiH2 secondary batteries.

Power Conditioning and Distribution (PCD). This category encompasses components used in distributing energy from the power supply source to the power-consuming equipment throughout the space vehicle. It also includes components used in modifying the raw power of the supply to satisfy electrical requirements of onboard, power-consuming equipment. It includes wire harnesses, switching electronics, inverters, converters, regulators, protective circuitry, and battery conditioning electronics.

B.3.1.2.5 Telemetry, Tracking, and Command Subsystem

All satellites, regardless of their mission or capability, require TT&C. Telemetry is defined in the SCF Spacecraft Systems course as "the science of transmission of inaccessible data to accessible locations."[19] Space telemetry is the measurements taken by remote sensors on a satellite and transmitted to a ground station. Telemetry data, whether analog or digital, is of two general types: primary payload or mission data, and space vehicle health and status data. Primary payload data varies depending on the satellite's mission; general space vehicle health and status is "fairly consistent regardless of the type mission. This data consists of pressure, temperatures, flow rate, voltages, current, and events that are present throughout the satellite system, subsystems and components."[20] Tracking involves locating a specific satellite in time and space, and following its movements as a function of time. Satellite tracking allows telemetry to be acquired, data to be provided for orbit determination, and commands to be sent. Commanding provides ground control over the satellite while it is in the line of sight of a ground station. "Commands may be sent for accomplishing any of the following functions: ascent control, orbit adjust, reentry by separation, engine ignition or cutoff, control of internal systems, on-off control, switch-over, control of sequential events that must operate in a predetermined manner, or control of a spaceborne timer which in turn controls a predetermined sequence of events."[21] Most commands are generated by the Satellite Test Center (STC) and relayed over land lines, submarine cables, microwave relay, and satellite links to one of seven remote tracking stations (RTS). Later, when directed, the RTS sends them to the satellite. "Two types of commands exist: real-time and stored programs. The satellite receives and acts on real-time commands immediately. Stored program commands activate satellite systems and sensors when the satellite is not in the RTS's line of sight."[22]

TT&C subsystems can be divided into three basic groups, according to space vehicle missions: communications, near-earth sensor (apogee < 25,000 miles above sea level), and deep space sensor (apogee > 25,000 miles above sea level). A communications satellite TT&C subsystem does not need the data handling or storage capacity required for a sensor-oriented TT&C subsystem. The deep space TT&C subsystems are normally developed under much stricter requirements than the near-earth or communications TT&C subsystems. If the space vehicle is a communications satellite, the costs for the communications (mission) hardware and non-hardware effort are collected under the communications payload subsystem.

In all, the TT&C subsystem performs one or more of the following functions: measures important space vehicle platform conditions; processes this information as well as mission data; stores data; transmits data to the ground; receives and processes commands from the ground and initiates their execution; and provides a tracking capability. According to the AFSC Space Handbook, typical equipment includes "analog/digital converters, coders, digital electronics (digital storage units, command distribution units, programmers) or computers, signal conditioners (filters, modulators, integrators), format control units, transmitters, antennas, receivers, decoders, switching relays, tape recorders, amplifiers, and clocks."[23]

The basic TT&C functions, excluding the processing of mission control data, are performed by a digital telemetry unit (which organizes space vehicle data for telemetering to the ground), a command decoding and distribution unit (which handles commands received from the ground), and a data processor that controls the two. The digital telemetry unit multiplexes signals from numerous space vehicle health and status data sources, converts analog data from individual sources into digital data, and sends the coded bit stream to the TT&C transmitter for relay to the ground.[24] The command decoding and distribution unit provides a similar, reversed interface between uplinked command signals and elements under TT&C control. Command signals are conditioned and routed to individual units. The processor, which controls operations and timing of the telemetry unit and distribution unit, may be a special purpose processor or a general purpose computer.

In addition to costs for the hardware items discussed above, any non-hardware accounts for effort directly associated with the TT&C subsystem are included in the USCM definition of space vehicle TT&C costs. When technical definition is available, it is beneficial to break out the TT&C subsystem into its major components and aggregate the results to arrive at a TT&C subsystem cost. See Section B.3.1.3 for descriptions of the Comm/TT&C component-level areas.

B.3.1.2.6 Propulsion

The propulsion subsystem provides thrust to alter the spacecraft's velocity and angular momentum. Most spacecraft, except for the simplest of spacecraft, require some form of thrust control. Low earth orbit (LEO) satellites require a significant amount of propulsion to maintain their orbital parameters due to atmospheric drag and orbital decay.

Geosynchronous earth orbiting (GEO) satellites use a significant amount of propellant for attitude control in order to maintain their long mission life. There are essentially two types of propulsion systems captured in USCM8: integral propulsion systems (IPS) and propellant reaction control systems (that sometimes incorporate an apogee kick motor [AKM]). IPS incorporates the AKM functionality of orbit boosting with the stationkeeping requirements of the propellant reaction control equipment.

Except for the most of simplistic designs, all satellites contain some form of propulsion system. In the extreme case, an all-thruster system can be used to maintain attitude control . The latter is the third zero-momentum reaction control approach. It is a simple system that is used for short duration burns to provide high torque when needed. Thrusters are used for several different purposes: orbit insertion, momentum dumping, and orbit changes. Thrusters can use different methods of achieving thrust: monopropellant, bipropellant, and pressurized gas systems. In a monopropellant reaction control system, a single working fluid is burned. The burning is the manifestation of both chemical and thermodynamic changes that provide thrust. In a bipropellant system, two propellants, a fuel and an oxidizer, are injected separately into a chamber where they react with each other to form combustion products. The combustion products are ejected through a nozzle, providing the required thrust. The third approach is a pressurized gas system. In a pressurized gas system, thrust is developed from the rapid expansion of a gas stored under pressure. Although the pressurized gas system is highly reliable, the size and mass of the required tankage limits its use to space vehicles that require only short action-time thrusting. A brief description of the propulsion component-level systems follows.

Propellant RCS. This suite captures the simplistic propellant systems that don't utilize electric propulsion thrusters or integral tanks and plumbing. This suite only provides stationkeeping functionality and minor orbit maneuvers throughout the spacecraft's lifetime. Satellites that utilize a Propellant RCS often require an AKM to impart the required delta V for operational orbit insertion. Typical propellant components include fuel lines, fuel tanks, pressure isolation valves, propellant filters, pressure transducers, thrusters, gas jets, and any associated electronics.

Apogee Kick Motor. The AKM suite, also referred to as the apogee boost motor, provides reaction force for the final maneuver into orbit and for orbit changes. It is used to insert the space vehicle into synchronous or low-earth orbit. Typically, it consists of solid rocket motors, explosive squibs, nozzle control mechanisms, and thrust sensing and shut-down controls, as well as necessary cabling, wiring, and plumbing. If solid rocket motors are not used, the subsystem consists of liquid rocket engines, along with tankage, plumbing, and fuel control systems that support the particular design. Only solid rocket motors are included in USCM8.

In addition to costs for the hardware described above, any non-hardware accounts for effort directly associated with the rocket injection motor system are included in the USCM definition of space vehicle AKM costs. The existing and near-term technology of this subsystem is established, though future technology designs might include plasma propulsion.[25] Propulsion costs include those hardware and non-hardware accounts for the rocket injection motor.

Integral Propulsion System. The IPS consolidates the AKM and propellant RCS systems into a single system that provides on-orbit stationkeeping and orbital insertion from launch vehicle separation. In the past, the plumbing, valves, and tanks associated with the apogee kick motor would signify an entirely independent system from the attitude control propulsion elements. The tanks and plumbing of the two systems are now combined to produce a consolidated propulsion subsystem, whereby the established solid rocket motor is replaced by a bipropellant mixture of hydrazine and nitrogen tetroxide. Integral propulsion systems typically incorporate some form of electrical propulsion components (e.g., ion engines and thrusters) to reduce conventional chemical propellant requirements and achieve higher specific impulse (although at significantly lower thrust and tremendous power requirements). These systems utilize a power processor to transform the spacecraft bus voltage to the appropriate levels required by the thruster before accelerating the propellant, commonly hydrazine, through the nozzle. The processors also initiate firing sequences and regulate duration. Typically, the spacecraft control processor (SCP) performs the required processing and a power control unit (PCU), specifically dedicated to the electric propulsion (i.e., not the spacecraft PCU), maintains the appropriate thruster power requirements. USCM maps the SCP in the ADCS or TT&C digital electronics depending on the processor's total functionality, while the electric propulsion's PCU is captured in the EPS PCD. For modeling purposes, all the processors were incorporated in a single methodology rather than having an ADCS processor and a TT&C processor CER.

B.3.1.3 Communications Payload (Comm)

Comm payloads have almost a one-to-one correspondence with TT&C in their functions and hardware employed. All satellites will have a TT&C subsystem, but not all will have a Comm payload subsystem. Only satellites that have a communications mission will have a separate Comm payload.

Communications (mission equipment) subsystems perform a transmission repeater and signal conditioning function. Signals and/or transmissions received from the ground are handled differently depending on whether the communications subsystem is passive or active. A passive system will not alter the received signal in any way before retransmission. An active system may amplify, and/or in some way modify, the received signal before retransmission.

Much of the communications subsystem equipment is similar to the TT&C's. Typical equipment includes receiving antennas, receivers, exciters, traveling wave tube amplifiers (TWTA), solid state power amplifiers (SSPA), transmitters, transmitting antennas (earth coverage, narrow beam, shaped beam, phased arrays), RF switches, switch control units, signal processors, digital processors, modems, and crypto cards.

When technical definition is available, it is beneficial to break out the Comm/TT&C subsystems into their major components, estimate these using dedicated CERs (available in this USCM), and aggregate the results to arrive at subsystem costs. A brief description of the Comm/TT&C component-level areas follows.

B.3.1.3.1 Transmitter

This category encompasses all equipment and electronics required to transmit a signal to ground stations via the onboard antenna(s). Typical components in this category include transmitters, upconverters, power amplifiers (one or several stages), beacons, modulation circuitry, transmit/receive switches, and transmitter power conditioners. The transmitters are distinguished by whether the power amplifiers are solid state or TWTAs. Amplifiers increase current to the signal-making device, making the signals more powerful and easier to receive. Because USCM8 contains a significant amount of data on beacons, we have made this a separate category. Beacons are transmitters that send repeated signals to the ground station for identification and satellite tracking. They can use both types of power amplifiers but have been separated from other transmitters due to their relatively simple role.

B.3.1.3.2 Receiver

This category encompasses all equipment and electronics required for command or signal reception from a ground station or another satellite. Typical components in this category include signal-generating devices, local oscillators, downconverters, and low noise amplifiers.

B.3.1.3.3 Exciter

The exciter category represents equipment that provides the payload (in some cases the TT&C subsystem as well) with reference frequencies for upconversion and downconversion. Typical examples include master oscillators and frequency synthesizers that supply the payload with local oscillation frequencies.

B.3.1.3.4 Transponder

This category includes all equipment that performs a transceiver function. It is defined as transmitter, receiver, and amplifier contained in one box that automatically transmits a signal when triggered by an interrogating signal. This WBS element is used only if the costs cannot be separately identified as transmitter and receiver components.

B.3.1.3.5 Digital Electronics (Signal/Data Processor)

This category encompasses all components that process digital signals. Typical components include processors, encoders, and decoders. There are multiple components that receive analog inputs, convert the data to digital, and pass on the digitally processed information. These analog-to-digital units (and vice versa) are captured in this category regardless of the percentage of analog-processed information.

B.3.1.3.6 Analog Electronics

This category includes those hardware components that process analog waveforms/signals at intermediate/video frequencies down to direct current (dc). Typical components include relays, power supplies, interface electronics, control electronics, and analog drivers.

B.3.1.3.7 Radio Frequency Distribution

This category includes those electronics that guide and filter radio frequency (RF) signals, such as waveguides, filters, couplers, power dividers, switching devices such as multiplexers and demultiplexers, mixing gates, distribution hardware (e.g., coaxial cabling), phase shifters, and other ferrite devices.

B.3.1.3.8 Antenna

This category of components is used for converting electrical signals into electromagnetic waves upon transmission and vice-versa upon reception. The antennas are further broken down into two classes: (1) omnidirectional antennas (i.e., whip, dipole, conical, and bicone) and (2) directional (i.e., slotted arrays, helicals, horns, solid reflectors, and multibeam antennas [MBA]). Antenna hinges and other secondary antenna structures are captured in the Structure subsystem whenever the cost and weight could be identified separately. The antenna system includes the feed system, beam forming network (BFN), antenna, and gimbal drive mechanisms.

B.3.1.4 Program-Level Costs (SEPMD)

"Program-level" includes those accounts for program management, reliability, planning, quality assurance, systems analyses, project control, and other costs that cannot be related to any specific area of activity. A brief description of the grouping of program-level activities follows.

B.3.1.4.1 Program Management

This category includes all effort associated with defining, planning, directing, and controlling company functions, subcontractors, and suppliers in order to accomplish program objectives.

B.3.1.4.2 Systems Engineering

This category includes all effort associated with the engineering organization, which allocates and controls the distribution of system-level requirements and specifications to lower level subsystems and equipment items. Also included are costs associated with controlling system-level documents such as specifications, weights, reliability, program equipment units, and quality assurance.

B.3.1.4.3 Data

This category includes costs for program-related graphic and written information, whether technical or non-technical. Most data requirement costs which fall into this category are controlled by a contract data requirements list (CDRL) attached to the system's contract.

B.3.2 Aerospace Ground Equipment (AGE)

AGE refers to ground support equipment (electrical and mechanical), required to support the space vehicle during ground test and preparation for flight operations. All AGE costs are categorized as nonrecurring. In addition to costs for plant equipment, special materials handling equipment, tooling and test equipment, any non-hardware accounts for effort directly associated with AGE are included in the USCM definition of AGE costs.

B.3.3 Launch and Orbital Operations Support (LOOS)

LOOS includes those accounts for any effort associated with prelaunch planning, launch and ascent, and initial on-orbit operations. The prelaunch activities include bus and payload preparation, as well as interface activities with the launch vehicle. The Eastern and Western Test Ranges provide test, launch, and range support capability for program test, evaluation, and support activities. The Air Force Satellite Control Facility (AFSCF) support in the prelaunch period includes planning, telemetry compatibility testing, training, facilities and equipment, space-vehicle-to-AFSCF compatibility testing, and scheduling.

The launch and ascent period includes final assembly, checkout, and fueling; liftoff; telemetry, pre-launch TT&C, and recovery operations; and post-processing of liftoff data. Final on-orbit support includes maintenance of the ADCS operation; attitude and orbit control; support of on-orbit testing; routine monitoring and fault detection of space vehicle subsystem functions; and support of anomaly investigation and correction. This period ends when the newly deployed satellite is turned over to the operational user, typically after a period of two to three weeks. All LOOS costs are categorized as recurring.

B.4 Nonrecurring and Recurring Costs

Space vehicle costs (both development and production) were segregated between nonrecurring and recurring efforts.

If nonrecurring and recurring costs were not explicitly segregated in the historical cost data, a time-phased method was used to determine the break between the two. For USCM cost data grouping, the completion of prototype qualification tests signaled the end of nonrecurring costs, while the release of design drawings to flight hardware manufacturing signaled the beginning of recurring costs. This segregation of nonrecurring and recurring costs was accomplished at the work package (component or subassembly) level.

B.4.1 Nonrecurring Costs

Nonrecurring costs are associated with all of the effort/activity of designing, developing, manufacturing, and testing a space vehicle qualification model. For those systems that use the protoflight concept, nonrecurring costs include only that portion of the protoflight costs which can be identified as nonrecurring. Additionally, the costs of acquiring program-peculiar support equipment such as mechanical and electrical AGE are also considered nonrecurring.

B.4.2 Recurring Costs

Recurring costs are associated with all of the effort/activity of fabricating, manufacturing, integrating, assembling, and testing of the space vehicle flight hardware. Additionally, all effort associated with the launch and orbital operations support of a program are considered to be recurring costs.

Contractors typically accumulate recurring program costs in-total, rather than by specific production units. As a result of this practice, historical data had to be adjusted to reflect a theoretical first unit cost for the purpose of developing the recurring CERs. This adjustment was accomplished by assuming a cumulative average learning curve with a 95-percent slope. Using this assumption and the number of units consecutively produced for each space vehicle program, the set of first unit costs was obtained for use in generating the recurring cost CERs.

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MIL-HDBK-881A Space Systems WBS

The material in this appendix is excerpted directly from the handbook.

(Extract from *Department of Defense Handbook: Work Breakdown Structures For Defense Material Items*, Appendix F, 30 July 2005.)

MIL-HDBK-881A
APPENDIX F

APPENDIX F: SPACE SYSTEMS WORK BREAKDOWN STRUCTURE AND DEFINITIONS

F.1 SCOPE

This appendix provides the Work Breakdown Structure and Definitions for the Space Vehicle, Ground Command, and Launch Vehicle. Definitions for WBS elements common to the space system and all other defense materiel items are in Appendix I: Common Elements, Work Breakdown Structure and Definitions

F.2 APPLICABLE DOCUMENTS

If there are high cost/high risk elements that must be reported below Level 4 for Space Subsystems and/or for Ground Systems of the WBS, users should reference the National Reconnaissance Office (NRO) Standard Work Breakdown Structure (NRO SWBS) in order to ensure consistency in reporting. The NRO SWBS can be found at the following site:

http://www.acq.osd.mil/pm/currentpolicy/wbs/Releasable SWBS-locked.doc

F.3 WORK BREAKDOWN STRUCTURE LEVELS

Level 1	Level 2	Level 3	Level 4
Space System			
	SEIT/PM and Other Common Elements		
	Space Vehicle (1….n as required)		
		SEIT/PM and Other Common Elements	
		Spacecraft Bus	
			SEIT/PM and Other Common Elements
			Structures and Mechanisms Subsystem
			Thermal Control Subsystem
			Electrical Power Subsystem
			Attitude Control Subsystem
			Propulsion Subsystem
			Telemetry, Tracking, and Command Subsystem
			Spacecraft Bus Flight Software
		Communication / Payload	
			SEIT/PM and Other Common Elements
			Communication (1…n as required)
			Payload (1…n as required)
			Communication/Payload Flight Software (1…n as required)
		Booster Adapter	
		Space Vehicle Storage	
		Launch Systems Integration	
		Launch Operations & Mission Support	
	Ground (1…n as required)		
		SEIT/PM and Other Common Elements	
		Ground Terminal Subsystems	
		Command and Control Subsystem	
		Mission Management Subsystem	
		Data Archive/Storage Subsystem	
		Mission Data Processing Subsystem	
		Mission Data Analysis and Dissemination Subsystem	
		Mission Infrastructure Subsystem	
		Collection Management Subsystem	
	Launch Vehicle		

F.3.1 Application of Common WBS Elements (Appendix I). Common WBS Elements must include, as a minimum, systems engineering, integration and test, and program management (SEIT/PM). Common elements are found throughout all levels of a WBS and are located one WBS level below the product oriented WBS they support (e.g., structures and mechanisms SEIT/PM would be captured at Level 5 below the Structures and Mechanisms Subsystem). Other common elements, such as training or data, as applicable, may be included here. The table above is not complete without the application of common elements

F.4 DEFINITIONS

F.4.1 Space System. The complex of equipment (hardware/software) and all of the resources associated with the design, development, production, integration, assembly, test, and operation of the entire Space System.

Includes, for example:

a. Space Vehicle; Ground; Launch Vehicle; and any mission equipment or other items necessary to provide an operational capability in space.
b. Any efforts done within a development/acquisition contract and includes such things as Operation and Maintenance Plans and Integrated Logistic Support Plans

F.4.2 Space Vehicle (1… n as required). A complete space vehicle in a multiple or dissimilar space vehicle configuration. It contains all of the resources associated with the design, development, production, integration, assembly, and test to include verification testing of each space vehicle as required. List each unique configuration as a separate space vehicle using sequential indices for each configuration; e.g., first configuration is Space Vehicle 1, second configuration is Space Vehicle 2, etc.

Includes, for example:

a. The design, development, and production, integration, assembly, test, and checkout of complete units (i.e., the prototype or operationally configured units which satisfy the requirements of their applicable specification, regardless of end use)
b. Sub-elements to the space vehicle -Spacecraft Bus, Communication/Payload; Booster Adapter; Space Vehicle Storage; Launch Systems Integration; Launch Operations and Mission Support (F.4.2.1-F.4.2.6)

F.4.2.1 Spacecraft Bus. The principal operating space vehicle that serves as a housing or platform for carrying a payload and other mission-oriented equipment in space.

Includes, for example:

a. Structure, power, attitude determination and control, and other equipment characteristic of a spacecraft bus
b. All design, development, production, and assembly, test, and checkout efforts to provide the spacecraft bus as an entity for integration with other WBS Level 3 elements (i.e., Communication/Payload Equipment) hardware elements
c. Sub-elements to Spacecraft Bus-Structures and Mechanisms (S&M); Thermal Control (TCS), Electrical Power (EPS), Attitude Control (ACS), Propulsion (PS), Telemetry, Tracking, and Command (TT&C) subsystems; Bus Flight Software where the software cannot be broken out to the subsystem or component level; (F.4.2.1.1-F.4.2.1.8)

NOTE: On more complicated Space Vehicles, there may be an integrated multi-processor system that performs functions for both the Bus and Payloads. In these cases it is acceptable to consider the Multi-Processor system as a single payload or as part of a specific payload. The Multi-Processor System may integrate functions normally included under ACS, TT&C, Communication & other payloads. The relevant point is to keep the cost in a single element and not allocate over multiple WBS elements.

F.4.2.1.1 Structures and Mechanisms Subsystems. The complete structures and mechanisms subsystem that supports all space vehicle subsystems, including deployable elements, during launch, and on-orbit injection.

Includes, for example:

a. All the resources associated with the design, development, fabrication, assembly, quality control/assurance, and test to include verification testing of spacecraft bus structure, mechanisms, structures with integral (non-removable) thermal control, pyrotechnics, and support equipment
b. Equipment compartments, trusses, frames and shells for carrying primary loads; and secondary structures for equipment support; structural assemblies for interfacing with the booster adapter and/or with the launch vehicle
c. All load carrying devices, such as payload equipment panels that are provided to Communication/Payload equipment supplies for supporting Communication/Payload Equipment components
d. Cables, harnesses, and end items which deploy and support solar arrays, antennas and other spacecraft components to the extent that the mechanisms are separable from the components they support

Excludes, for example:

a. Positioning elements that are identified with specific elements they support, such as solar array positioners
b. Payload fairings which are included in the launch element
c. Small equipment compartments or pallets that house Communication/Payload electronics are part of Communication/ Payload element
d. Booms which are used to exclusively support Communication/Payload equipment components or assemblies in the Communication/Payload element

F.4.2.1.2 Thermal Control System. The thermal control subsystem maintains the temperatures of all spacecraft bus components, and those Communication/Payload suites without their own thermal control provisions, within acceptable limits during ground test, launch and on-orbit operations.

Includes, for example:

a. All the resources associated with the design, development, fabrication, assembly, quality control, and test to include verification testing
b. Active or passive components including cryogenic devices, liquid loops, electric cooling, multi-layer thermal insulation blankets, surface coatings (thermal paint), mirrors with optical coatings, coatings, thermal tape, heat pipes, heat sinks, insulation, conductive structures, louvers, sun shields, active coolers, heaters, thermisters, thermostats, shutters, thermal conducting elements, and radiator panels/fins, coatings, insulation, louvers, sun shields, and thermal control subsystem flight software (including algorithm development), and support equipment.

NOTE 1: In cases where Communication/Payload contains its own thermal control provisions, the thermal control components are included in the Communication/Payload WBS element

NOTE 2: **When a space vehicle structure item has integral (non-removable) thermal control provisions such as heat sinks, then that item and its integral provisions are included within the Structures and Mechanisms Subsystem**

F.4.2.1.3 Electrical Power Subsystem. This subsystem generates, converts, regulates, stores, and distributes electrical energy to spacecraft bus and Communication/Payload suites.

Includes, for example:

a. All the resources specifically related to and limited to the design, development, fabrication, assembly, quality control, and test to include verification testing of electrical power subsystem
b. Power generation, conditioning, and storage; Electric Power Subsystem software; support equipment; and electrical harnesses and cables
c. Electric power generation: solar array (to include substrates, solar cells, support structure), solar array positioner (to include drive assembly and drive electronics), radioisotope thermionic generator, other power sources,
d. Electric power conditioning: power control electronics (to include junction boxes and pyrotechnics/heater controls), power conversion electronics (to include inverters, converters and regulators), power dissipation devices (to include shunt resistor banks and dissipators)
e. Electric power storage: rechargeable batteries (to include cells, support structure and interconnects), charge control electronics

F.4.2.1.4 Attitude Control Subsystem. This subsystem determines and controls spacecraft orbital positions, attitudes, velocities and angular rates using onboard sensors and torque application devices. It may also send control signals to propulsion subsystem components (e.g. thrusters), electrical power subsystem solar array positioners, and communication/ payload positioner electronics.

Includes, for example:

a. All the resources specifically related to and limited to the design, development, fabrication, assembly, quality control, and test to include verification testing of the Attitude Control Subsystem
b. Attitude determination: attitude reference (to include star trackers/sensors, earth (horizon) sensors, sun sensors, magnetometers), inertial reference (to include inertial reference unit, rate gyros, accelerometers), Bearing and Power Transfer Assembly (BAPTA), and Global Position System (GPS) Receiver
c. Attitude control: gyro stabilization devices (to include reaction wheels, momentum wheels, control moment gyros, energy storage devices (flywheels)), magnetic control devices, spin control devices, control electronics),
d. Attitude control subsystem flight software, and attitude control subsystem support equipment
e. May also include sensors, electronics and mechanical devices for safe-mode control of the space vehicle

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.2.1.5 Propulsion Subsystem. This subsystem provides thrust for attitude control and orbit corrections as required to accomplish the specified mission. It also provides thrust for orbit injection and changes.

Includes, for example:

a. All the resources specifically related to and limited to the design, development, fabrication, assembly, quality control, and test to include verification testing of the propulsion subsystem
b. Tanks, plumbing, thrusters, solid rocket motors, liquid propellants, and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.2.1.6 Telemetry, Tracking, and Command (TT&C) Subsystem. This subsystem performs functions such as: formatting and transmitting telemetry (on narrowband links); accepting, decoding, verifying, and storing uplink commands; and generating command and control signals for the spacecraft bus and communication/payload suites based on uplink commands and/or internally generated data. The TT&C subsystem may also: provide timing signals to the spacecraft bus and communication/payload suites; perform on-board attitude determination, ephemeris calculations and attitude control equipment control (if these are not performed by dedicated attitude control computers/electronic components); and perform thruster control, electrical power monitoring/and control (if these are not performed by dedicated propulsion subsystem and electrical power subsystem components, respectively).

Includes, for example:

a. All the resources specifically related to and limited to the design, development, fabrication, assembly, quality control, and test to include verification testing of the TT&C
b. Passive radio frequency (RF) components (such as antennas, RF plumbing), other RF (such as transmitters, receivers, transponder, modulators, demodulators, power amplifiers, traveling wave tube assembly, solid state power amplifiers, GPS receivers, downconverters, and upconverters), other electronics (such as processors, solid state memory, decoders, command units, telemetry units, command sequencers, timing units, frequency generators, signal conditioners, and data switches), TT&C System Software (including algorithm development), and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.2.1.7 Spacecraft Bus Flight Software. All resources required to design develop, code, test, document, install, integrate and verify flight software for performing spacecraft functions.

Includes, for example:
a. Designing, developing, coding and testing those functions that are implemented in firmware (e.g. by microcode programming).
b. Algorithm development

NOTE 1: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

NOTE 2: If flight software cannot be separated to the Spacecraft Bus subsystems or between the Spacecraft Bus and the Communication/Payload equipment, then the combined resources will be combined in this WBS. Otherwise, Software for performing Spacecraft Bus subsystems function or Communication/Payload equipment functions is included in the appropriate subsystem or Communication/Payload Equipment WBS elements.

F.4.2.2 Communication/Payload. In some space vehicles a communications suite is the primary payload; in others, it is a secondary, but integral, element to transmit primary payload data to the ground segment and receive payload tasking from the ground segment. Thus, these two functions are combined at this level and segregated at Level 4 of the WBS.

Includes, for example:
a. All of the resources associated with the design, development, production, integration, assembly, and test to include verification testing of communication/payload suite
b. Communication suites, payload suites, flight software, and support equipment
c. Sub elements to communication/payload – communication, payload and communication/payload flight software (4.2.2.1-4.2.2.3)

Excludes, for example
a. Integration and assembly of the communication/payload into a spacecraft which is captured at the space vehicle level
b. Remote command and telemetry units supporting communication/payload which are in the TT&C subsystem

F.4.2.2.1 Communication. The Communication suite transmits and/or receives mission data between the host space vehicle, ground stations, and other space vehicles. The Communication suite may or may not include TT&C signals multiplexed with mission data.

Includes, for example:
a. All of the resources associated with the design, development, production, integration, assembly, and test to include verification testing of the Communication WBS, which consists of one or more Communication suites in a multiple Communication suite configuration
b. All required Communication suites

c. Structures and Mechanisms, Thermal Control, Optics, Sensor Package, Laser Photonics, Power Supplies, RF Electronics, Digital Electronics, Data Storage, Communication Antennas, Communication Flight Software (including algorithm development), Communication Support Equipment.

F.4.2.2.2 Payload. The Payload is the component of a space vehicle that performs the space mission. It may require support from the host vehicle bus, such as power and positioning, from ground systems and from other space systems.

Includes, for example:

a. All of the resources associated with the design, development, production, integration, assembly, and test to include verification testing of the Payload WBS, which consists of one or more Payloads in a multiple payload configuration
b. Remote command and telemetry components that interface with the Payload equipment and the TT&C subsystem for purposes of commanding Payload suites and monitoring their status
c. Hardware components such as antennas and efforts that are used for both TT&C and mission data transmit/receive functions
d. Structures and Mechanisms, Thermal Control, Optics, Sensors, Lasers, Power Supplies, RF/Analog Electronics, Digital Electronics, Data Storage, Payload Antennas, Payload Flight Software (including algorithm development), Payload Support Equipment

Excludes, for example:

a. Hardware components and efforts that are devoted exclusively to TT&C functions (except the command and telemetry interfaces described above)

F.4.2.2.3 Communication/Payload Flight System Software. All resources required to design, develop, code, test, document, install, integrate and verify flight software for performing Communication/Payload functions.

Includes, for example:

a. If some of the functions are implemented in firmware, then includes designing, developing, coded and testing of those functions (e.g. by microcode programming).
b. Algorithm development

NOTE 1: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

Note 2: If Communication/Payload cannot be separated between the Spacecraft Bus and the Communication/Payload equipment, then the combined resources will be carried in the Spacecraft Bus WBS.

F.4.2.3 Booster Adapter. The booster adapter provides the mechanical and electrical interface between the launch vehicle's uppermost stage and the space vehicle. It can be as simple as a snap ring device, but it is usually a more complex structural assembly. In some cases, the booster adapter may be integral with the space vehicle. Also, in other cases, it may be purchased along with the launch vehicle.

Includes, for example:

a. All of the material and effort associated with the design, development, production, integration, assembly, and test of the Booster Adapter
b. Adapter structures, attachment and release devices, thermal control, instrumentation, and umbilical provisions

F.4.2.4 Space Vehicle Storage. Those costs of holding portions of the space system while awaiting use of the system being stored, prepared for storage, or recovered from storage. It can include the costs of holding portions of the space vehicle while waiting for the use of test facilities and equipment or the completion of other portions of the space vehicle.

The storage period typically starts when production testing is complete and continues until the space vehicle is ready for shipping to the launch site.

Includes, for example:

a. Planning, preparation, storage, maintenance, removal, refurbishment, and retesting of the space vehicle and/or its subsystems
b. Costs for storage facility use and environmental control equipment

Excludes, for example:

a. Final space vehicle assembly after storing portions of the vehicle

F.4.2.5 Launch System Integration. The engineering studies and analyses required to integrate a space vehicle with its launch vehicle. This effort typically is performed by the space vehicle developer.

Includes, for example:

a. Space vehicle contractor studies, analysis, and tests supporting the integration of the space vehicle with the launch vehicle
b. Launch system integration hardware, if any, provided by the space vehicle contractor

Excludes, for example:

a. Booster adapter which is represented within its own WBS
b. Integration activities performed by the launch vehicle provider, which are included in the Launch Segment portion of the WBS

F.4.2.6 Launch Operations and Mission Support. Launch operations are those efforts performed by the provider(s) of the space vehicle and payload(s) to prepare for and support space vehicle launches, primarily at the launch base and, to a lesser degree, the space vehicle factory. Mission support is performed by the same providers for initial on-orbit checkout of the space vehicle and may also continue through the operational phase of the program.

The mission support period typically begins shortly after launch and ends when the space vehicle achieves initial operational capability.

Launch Operations Includes, for example:

a. Satellite contractor effort associated with pre-launch planning and preparation; launch operations, and initial on-orbit operations provided by the producer/integrator of the Space vehicle and Ground portions of the Space System
b. Pre-launch preparation of the space vehicle for shipping and actual shipping of the space vehicle to the launch site
c. Space vehicle contractor participation in final assembly, checkout, fueling and launch activities
d. Space vehicle contractor telemetry review and analysis during boost phases and initial orbital operations

Mission Support Includes, for example:

a. Space vehicle contractor participation in on-orbit testing; routine monitoring of space vehicle equipment health and status; fault detection; and anomaly investigation and resolution

F.4.3 <u>Ground (1…n as required).</u> The Ground is defined as a fixed, transportable, or mobile assembly of hardware, software, and firmware that has a communications interface with a space vehicle to receive only, or to receive and transmit data generated and mission data collected by the space vehicle. In addition, space vehicle TT&C and mission data may be processed within collocated facilities or alternatively in remotely located facilities. For example, Ground 1 could represent a Space Operations Center and Ground 2 a Network Operations Center or some other type of Command and Control facility.

Includes, for example:

a. All of the resources associated with its design, development, production, procurement, integration, assembly, and test
b. Support for the Space System and Space Vehicle level integration and testing provided by the producer/integrator of the Ground portion of the Space System
c. Sub-elements to Ground-Ground Terminal Subsystem; Command and Control Subsystem, Command and Control System; Mission Management Subsystem; Data Archive/Storage Subsystem; Data Archive/Storage System and Application Software; Mission Data Processing Subsystem; Mission Data Analysis and Dissemination Subsystem; Mission Infrastructure Subsystem; and a Collection Management Subsystem.
d. Ground facilities/building, factory/contractor support facility, initial support and support equipment specific to the ground portion of the space system but are not associated with specific subsystems

F.4.3.1 <u>Ground Terminal Subsystem.</u> This subsystem receives, downconverts, demodulates, and conditions telemetry, tracking, command, and mission (payload) data. In addition, this subsystem generates the radio frequency (RF) uplink, accepts tracking and command signals, and modulates them onto the RF uplink.

Includes, for example:

a. Resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the ground terminal (GT)
b. Antennas, feeds, antenna positioners, antenna support pedestals, radomes, transmitters, receivers, up/down frequency converters, modulators, demodulators, front-end equipment (encryptors/decryptors, synchronizers), etc.
c. Ground terminal facilities/buildings, ground terminal factory/contractor support facility, ground terminal initial support, and ground terminal support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.2 Command and Control Subsystem. The Command and Control subsystem decodes, demultiplexes, and decrypts space vehicle telemetry, generates commands for transmission to the spacecraft, and processes tracking data to generate space vehicle ephemeris. This subsystem supports all Ground subsystems that require the capability to prepare and output commands to, and receive and process data from, the space vehicle while in operation or under test

Includes, for example:

a. Resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the Command and Control Subsystem.
b. Network, computer processing and display hardware such as routers, switches, servers, workstations, storage devices, etc.
c. Software for handling, processing, and executing space vehicle commands, as well as processing and analyzing space vehicle telemetry
d. Command and control ground facilities/building, command and control factory/contractor support facility, command and control initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.3 Mission Management Subsystem. The Mission Management Subsystem receives tasking, generates and provides the daily and longer-term system and mission plans, schedules, and timelines for the locally controlled satellites and ground facilities.

Includes, for example:

a. Resources associated with the design, development, production, procurement, assembly, and test of the Mission Management Subsystem
b. Network, computer processing and display hardware such as routers, switches, servers, workstations, storage devices, etc. plus software for processing tasking requests, generating mission plans, assessing system performance and reporting results

c. Mission management ground facilities/building, mission management factory/contractor support facility, mission management initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.4 Data Archive/Storage Subsystem. The Data Archive/Storage Subsystem receives daily and longer-term system and mission data and provides archive/storage for the locally controlled satellites and ground facilities.

Includes, for example:

a. All the resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the Data Archive/Storage subsystem
b. Network, computer processing and display hardware such as routers, switches, servers, workstations, storage devices, etc.
c. Software (including algorithm development) for compiling, logging, tracking, allocating space, and data retrieval while assessing system performance and reporting results
d. Data archive/storage ground facilities/building, data archive/storage factory/contractor support facility, data archive/storage initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.5 Mission Data Processing Subsystem. The Mission Data Processing Subsystem decodes, demultiplexes, and decrypts digital and/or analog mission data from space vehicle payloads and generates commands for payload control. This subsystem typically performs processing unique to the payload(s) on the space vehicle, as opposed to centralized processing of payload data from different types of space vehicles. This data processing could be pre-processing prior to forwarding mission data to a national processing center and/or complete end-to-end data processing for direct dissemination to users.

Includes, for example:

a. All the resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the Mission Data Processing Subsystem
b. Network, computer processing and display hardware such as routers, switches, servers, workstations, storage devices, etc.
c. Software (including algorithm development) for performing pre-processing operations on the mission data such as reformatting, compressing, combining, and tagging. (It may also perform other "back end" processing functions).
d. Mission data processing ground facilities/building, Mission data processing factory/contractor support facility, Mission data processing initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.6 Mission Data Analysis and Dissemination Subsystem. The Mission Data Analysis and Dissemination Subsystem is responsible for analysis of mission data from the payload(s) on the space vehicle. This mission data analysis could take various forms and could be interactive with a "human-in-the-loop" or automatic.

The dissemination function routes the received data and/or the final analysis products to the appropriate ground subsystems, archive/storage locations, and also to external users.

Includes, for example:

a. All the resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the Mission Data Analysis and Dissemination Subsystem
b. Network, computer processing and display hardware such as routers, switches, servers, workstations, storage devices, etc.
c. Software (including algorithm development) for performing the mission data analysis and dissemination tasks
d. Mission data analysis and dissemination processing ground facilities/building, mission data analysis and dissemination processing factory/contractor support facility, mission data analysis and dissemination processing initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.7 Mission Infrastructure Subsystem. The Mission Infrastructure Subsystem includes all COTS and custom hardware and software needed for 1) the interchange or transfer of wideband, narrowband data, command and control, telemetry, and other support data between system ground subsystems (e.g., between the Mission Data Analysis and Dissemination and Command and Control Subsystems), and 2) the transfer of communications between and among various programs operationally assigned to the ground site.

Includes, for example:

a. Resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the Mission Infrastructure Subsystem
b. Converters, servers, switches, interface units, cabling, etc. that are needed to 1) convert data received by the receive facility, put it in the proper format, and send it to other subsystems within the system ground architecture, and 2) interchange or transfer communications within the ground site
c. Common software(including algorithm development) or operating systems that overarch 1) ground subsystems and are unique to the system ground architecture, and 2) other programs operationally assigned to the ground site
d. Addresses either an in-place Mission Infrastructure Subsystem or the build of a new subsystem. For an in-place system, this WBS addresses the construction, conversion, or expansion of the Mission Infrastructure Subsystem. For a new system, this WBS addresses the design, development, production, procurement, assembly, and test of the Mission Infrastructure Subsystem.
e. Mission infrastructure ground facilities/building, mission infrastructure factory/contractor support facility, mission infrastructure initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.3.8 Collection Management Subsystem. The Collection Management Subsystem receives and analyzes space vehicle mission results, external customer and internal tasking requests, and generates tasking for space vehicles and ground facilities.

Includes, for example:

a. Resources associated with the design, development, production, procurement, assembly, test, and operational site activation of the Collection Management Subsystem
b. Network, computer processing and display hardware such as routers, switches, servers, workstations, storage devices, etc.
c. Software (including algorithm development) for processing mission results, tasking requests, generation of tasks, etc.
d. Collection management ground facilities/building, collection management factory/contractor support facility, collection management initial support and support equipment

NOTE: If lower level information can be collected, use the structure and definitions in Appendix B, Electronic/Automated Software Systems.

F.4.4 Launch Vehicle. This WBS includes the launch vehicle contractors' efforts to receive, store, and transport the launch vehicle and associated ground equipment; to stack and assemble the launch vehicle; to mate the space vehicle and the launch vehicle; to perform integrated system test and checkout; and to track and measure launch vehicle performance during the ascent phase.

This WBS also includes the procurement of commercial-like launch services, launch vehicle integration, and independent verification and validation (IV&V).

If the Booster Adapter is not captured under Space Vehicle, it should be captured within this element. Reference Appendix C Missile Systems for lower level elements associated with this element.

APPENDIX D

NRO WBS

The material in this appendix is excerpted directly from the WBS. The figures were recreated for legibility.

(Extract from *Standard Work Breakdown Structure,* Version 2.2, 7 September 2004

Standard Work Breakdown Structure Overview

National Reconnaissance Office (NRO) Directive (NROD) 82–5 requires the NRO Cost Group to develop and maintain a standard work breakdown structure (WBS) for NRO programs. It also defines a Contract Data Requirements List (CDRL) item called Contractor Cost and Technical Data Report. This CDRL item discusses the reporting of contract costs in accordance with the standard WBS. NROD 82–5 does not require program offices to use the standard WBS as the program WBS, but it does require contractors to map their costs into the standard WBS for the CDRL item delivery. The attached standard WBS and dictionary are provided to guide contractors in submitting contract costs in a consistent format to the NRO Cost Group. The Cost Group will use the standard WBS as the structure for a cost-estimating database at an end item (box or computer software configuration item) level.

The standard WBS was developed to capture the costs of any NRO program, whether it is an operational space program, technology demonstration program, ground station upgrade, or a system of systems. It is structured to accommodate varying levels of detail in available data. This allows data to be reported at either lower levels or at higher levels, if lower level data are not available. The wide range of system engineering, integration and test, and program management levels within the WBS is a prime example of how data are reported at many different levels within a program. The standard WBS is designed to allow data reporting at whatever level they are recorded. Because of this versatility, some WBS elements may be repeated, such as the case of a satellite system that operates with two ground stations. For this situation, the costs for each ground station are reported separately via WBS elements 1.3a and 1.3b, and all lower level elements for each ground station will sum up to their respective ground station. The same scheme applies to multiple and dissimilar spacecraft within a program, which will be reported separately as “spacecraft a” and “spacecraft b.” Thus, there may be a number of elements in the standard WBS that are irrelevant to any individual program, but are necessary for the database structure to account for a varying level of cost data on disparate legacy programs. If cost data are sparse, they still may be mapped into appropriate higher levels of the WBS. Three specific examples below help to illustrate the versatility of this WBS.

Systems Engineering, Integration and Test, and Program Management (SEIT/PM)

There are various levels of SEIT/PM throughout this WBS. The Cost Group prefers that SEIT/PM costs be reported with the item they are supporting. If a contractor does not collect SEIT/PM data at this level, such as a bus subsystem, then the costs should be reported at the next higher-level WBS element, which for this example would be the satellite bus.

Special attention must be paid to integration and test associated with lower level assemblies or components. As an example, the Electrical Power Subsystem (EPS) solar array positioner consists of the drive assembly and drive electronics, which will be integrated and tested. If the resources associated with this integration and testing are available, they should be reported in WBS 1.2a.2.4.2.3.1. If the data do not exist at this low a level, they should be reported in WBS 1.2a.2.4.2.1, which is the next higher level of SEIT/PM.

Anomaly Resolution

Anomaly resolution costs may be incurred in various phases of a program. These costs will be reported in different WBS elements, depending on when they occur. Table 1–1 indicates how to report these costs. If the contract stipulates where to report anomaly resolution costs, comply with the contract specification. If the contract does not contain such a stipulation, report the costs in the appropriate WBS element according to program phase as shown in Table 1–1. If the resources cannot be identified with a specific portion of the acquisition life cycle, then report anomaly resolution costs in WBS 1.2a.8, Launch Operations & Mission Support.

Table 1–1. Mapping of Anomaly Resolution Costs

Anomaly Occurrence	Mapping Location
Contract specifies	As specified in the contract
Resources identified with a specific phase of the acquisition life cycle	
During development	System Engineering at the appropriate level (Bus, subsystem, etc.)
During launch preparation	Launch Operations & Mission Support (WBS 1.2a.8)
During launch and on-orbit checkout	Launch Operations & Mission Support (WBS 1.2a.8)
After system turnover (on-orbit checkout is complete)	Engineering Management, and Test (EM&T) (O&M WBS-TBD) and/or Operations (O&M WBS -TBD) (where ever the cost is incurred)
Resources not identified with a specific phase of the acquisition life cycle	
Launch Operations & Mission Support (WBS 1.2a.8)	

Software Development

The standard WBS contains various levels for software development to enable collecting of these costs at the lowest level possible, preferably with the end item/subsystem it supports. Table 1–2 illustrates how to use the standard WBS for several scenarios.

Table 1–2. Mapping of Software Development Costs

Development Occurrence	Mapping Location
Flight software not specifically identified with the bus, communications, or payloads areas	Bus flight software accounts
Bus subsystem (Thermal Control (TC), Electrical Power Subsystem (EPS), etc.) flight software	Appropriate bus subsystem flight software accounts
Communication / Payload but not further identified	Communication / payload level flight software accounts
Communication suite	Communication suite level flight software accounts
Communication suite subsystem (TC, etc.)	Communication suite subsystem level flight software accounts
Payload but not further identified	Payload level flight software accounts.
Payload suite	Payload suite level flight software accounts
Payload suite subsystem (TC, etc.)	Payload suite subsystem level flight software accounts
Ground subsystems	Appropriate ground subsystem software accounts

Algorithm Development

Similar to the earlier items, algorithm development costs may appear at various levels in the WBS. To help understand where to report these costs, we first provide our definition of algorithm development. The overall algorithm development and coding process occurs in multiple steps:

1. Scientific/engineering/mathematical development of the algorithm
2. Some rudimentary coding of the developed algorithm (this step may be omitted)
3. Final operational language coding of the algorithm to make it efficient and effective.

We define algorithm development as that effort performed by the scientific/engineering/mathematical team. It includes the effort performed in step one and may include the effort in step two if it is performed by the scientific/engineering/mathematical team. If the effort in step two is performed by programmers in the “code and debug” phase of the software development effort, then that effort is defined as software development, not algorithm development.

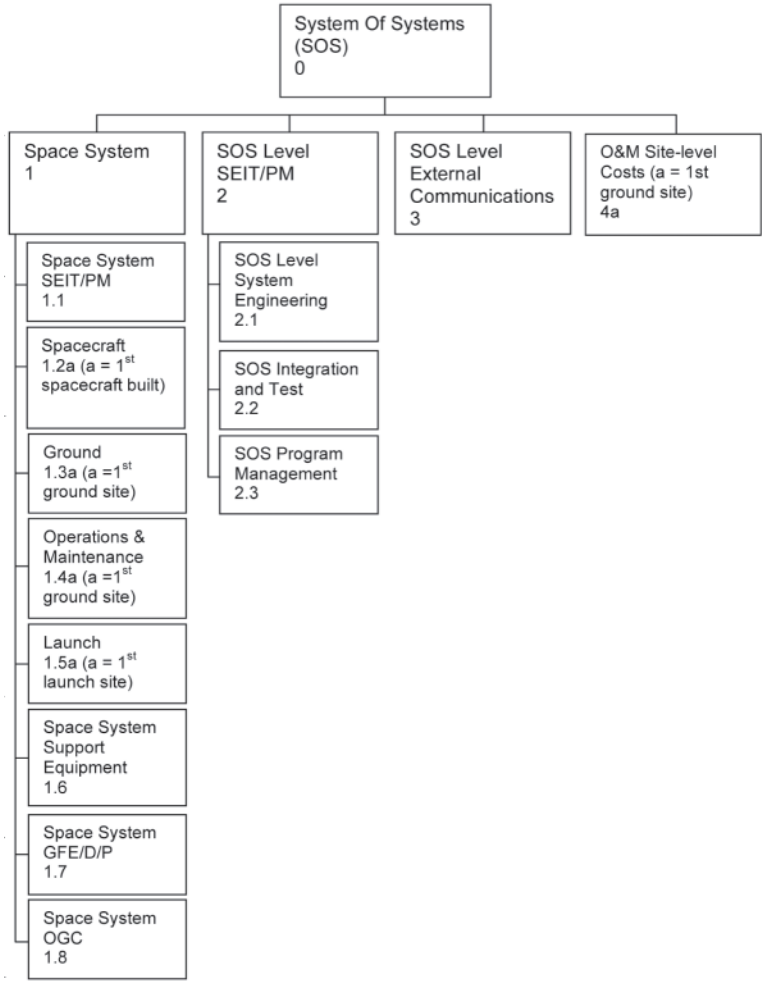
Generally, the scientific/engineering/mathematical algorithm development and any rudimentary coding is performed as a level of effort within the system engineering function. Some organizations perform algorithm development within a software development Integrated Product Team. Thus, there are multiple locations where algorithm development costs may be reported. The Cost Group preference is to associate algorithm development costs with the item/subsystem it supports (see Table 1–3). If mapping cannot be made at this level, then the algorithm development should be booked at the next higher level.

Table 1–3. Mapping of Algorithm Development Costs

Algorithm Development Occurrence	Mapping Location
Algorithm development not specifically identified with flight software for the communications, bus, or payloads areas	Bus flight software SEIT/PM accounts
Bus subsystem (Thermal Control (TC), Electrical Power Subsystem (EPS), etc.) flight software algorithm development	Appropriate bus subsystem flight software SEIT/PM accounts
Communication / Payload flight software algorithm development, but not further identified	Communication / payload level flight software SEIT/PM accounts
Communication suite flight software algorithm development	Communication suite level flight software SEIT/PM accounts
Communication suite subsystem (TC, etc.) flight software algorithm development	Communication suite subsystem level flight software SEIT/PM accounts
Payload suite flight software algorithm development	Payload suite level flight software SEIT/PM accounts
Payload suite subsystem (TC, etc) flight software algorithm development	Payload suite subsystem level flight software SEIT/PM accounts
Algorithm development not specifically identified with a ground subsystem	Ground SEIT/PM accounts
Ground subsystem algorithm development	Appropriate ground subsystem SEIT/PM accounts
Ground subsystem software algorithm development	Appropriate ground subsystem software SEIT/PM accounts

Operations and Maintenance (O&M) Accounts

This section is under development.



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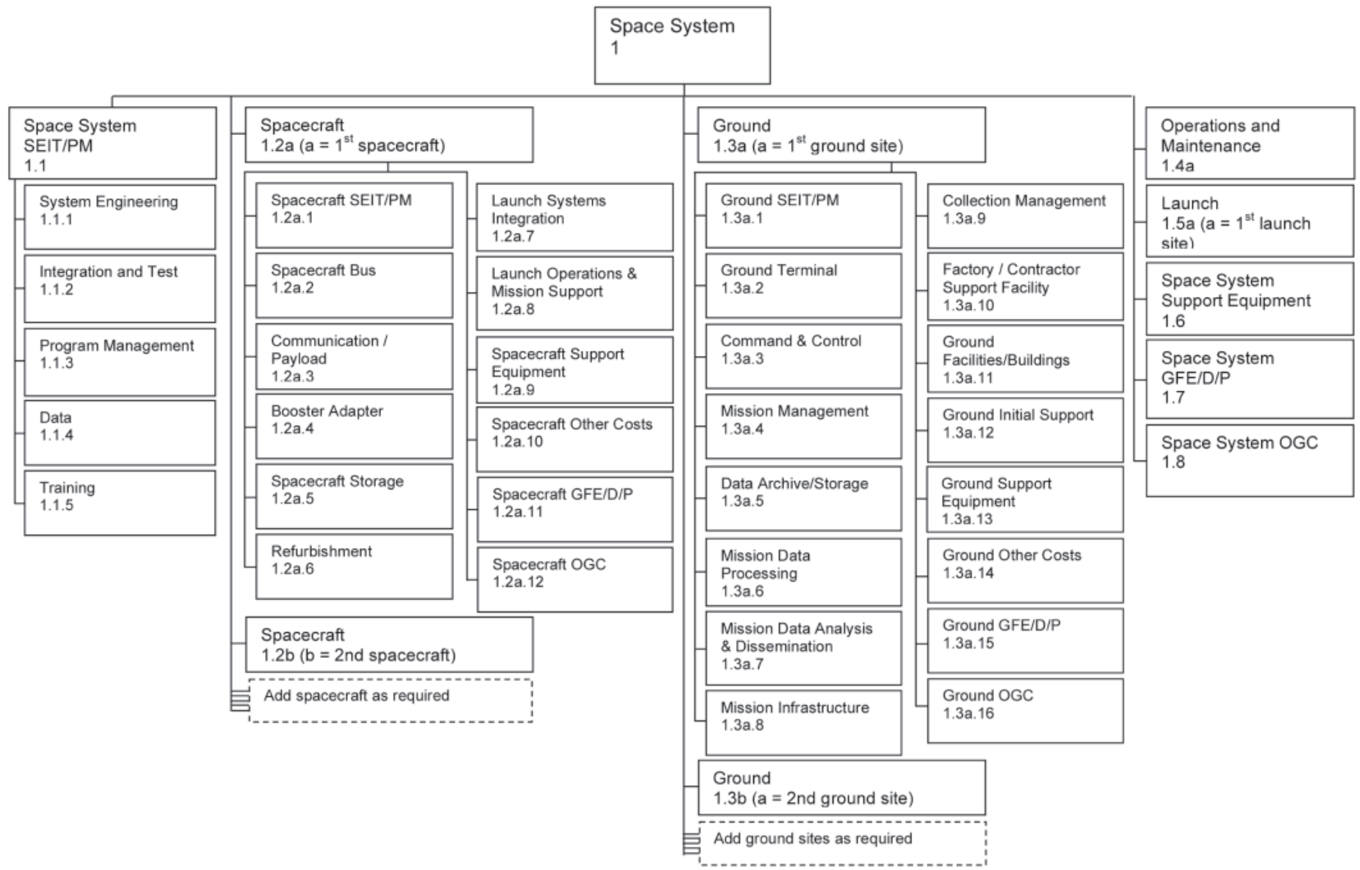
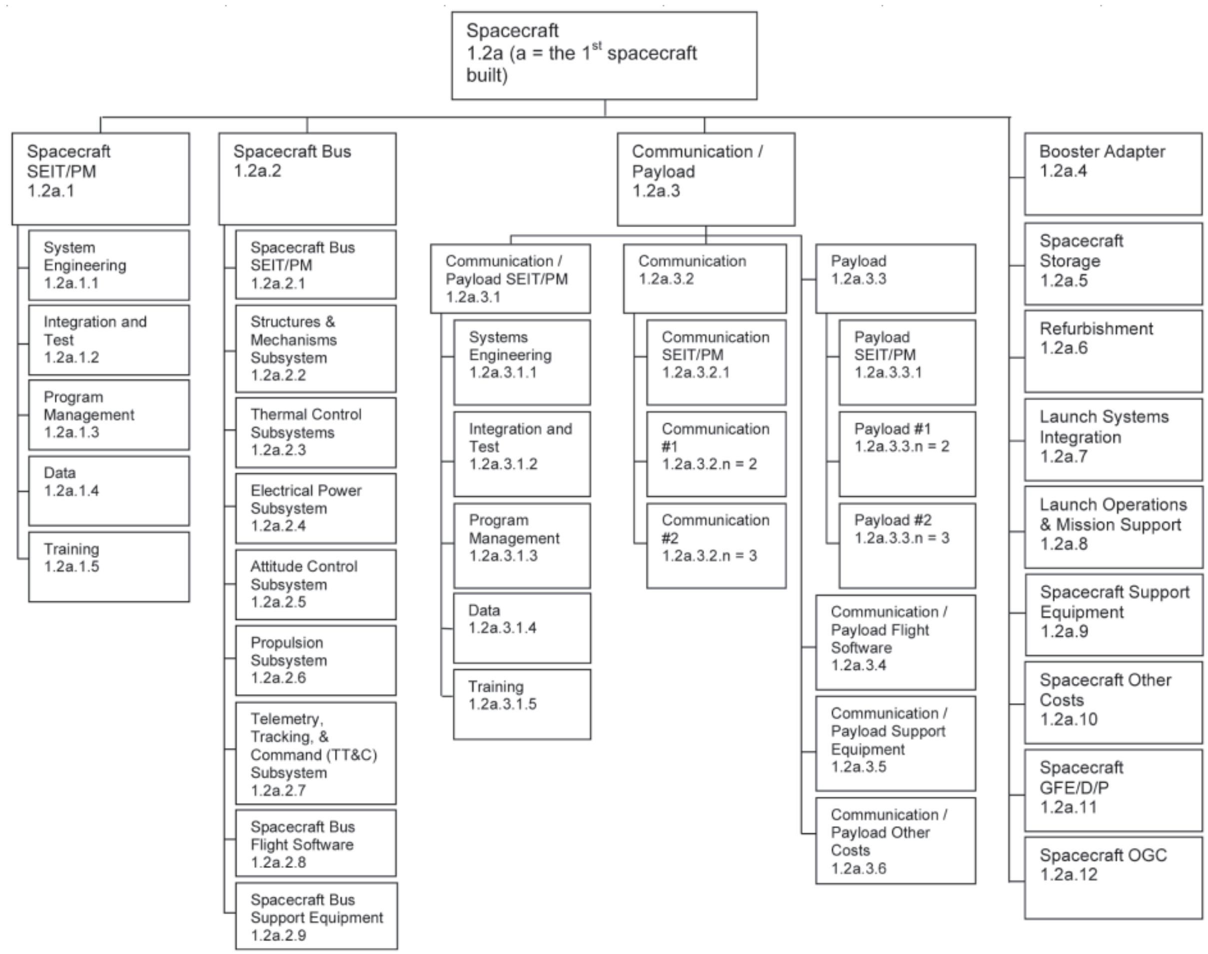

Space System
1
Space System
SEIT/PM
1.1
System Engineering
1.1.1
Integration and Test
1.1.2
Program Management
1.1.3
Data
1.1.4
Training
1.1.5
Spacecraft
1.2a (a = 1st spacecraft)
Spacecraft SEIT/PM
1.2a.1
Spacecraft Bus
1.2a.2
Communication / Payload
1.2a.3
Booster Adapter
1.2a.4
Spacecraft Storage
1.2a.5
Refurbishment
1.2a.6
Launch Systems Integration
1.2a.7
Launch Operations & Mission Support
1.2a.8
Spacecraft Support Equipment
1.2a.9
Spacecraft Other Costs
1.2a.10
Spacecraft GFE/D/P
1.2a.11
Spacecraft OGC
1.2a.12
Spacecraft
1.2b (b = 2nd spacecraft)
Add spacecraft as required
Ground
1.3a (a = 1st ground site)
Ground SEIT/PM
1.3a.1
Ground Terminal
1.3a.2
Command & Control
1.3a.3
Mission Management
1.3a.4
Data Archive/Storage
1.3a.5
Mission Data Processing
1.3a.6
Mission Data Analysis & Dissemination
1.3a.7
Mission Infrastructure
1.3a.8
Collection Management
1.3a.9
Factory / Contractor Support Facility
1.3a.10
Ground Facilities/Buildings
1.3a.11
Ground Initial Support
1.3a.12
Ground Support Equipment
1.3a.13
Ground Other Costs
1.3a.14
Ground GFE/D/P
1.3a.15
Ground OGC
1.3a.16
Ground
1.3b (a = 2nd ground site)
Add ground sites as required
Operations and Maintenance
1.4a
Launch
1.5a (a = 1st launch site)
Space System Support Equipment
1.6
Space System GFE/D/P
1.7
Space System OGC
1.8



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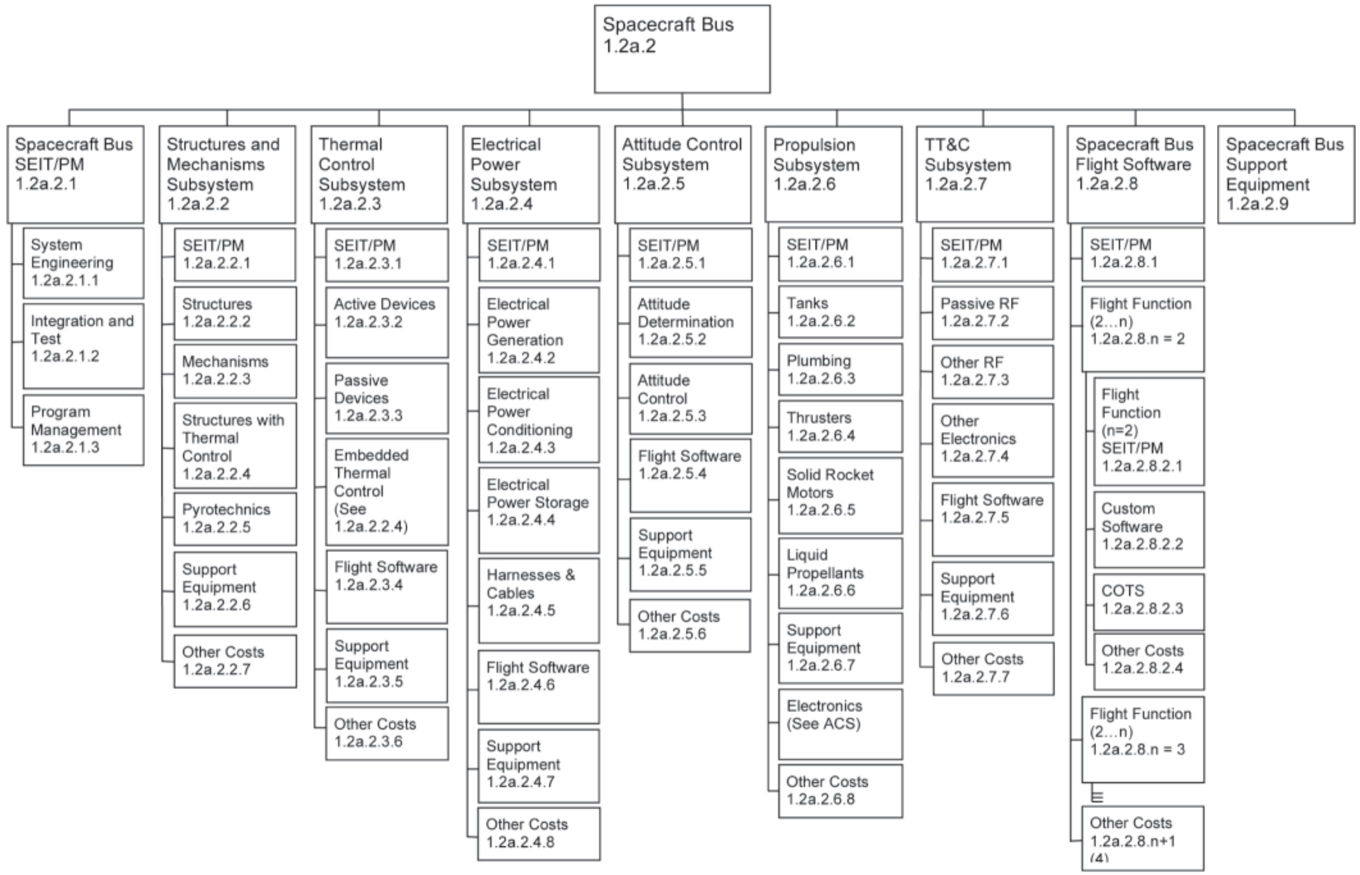
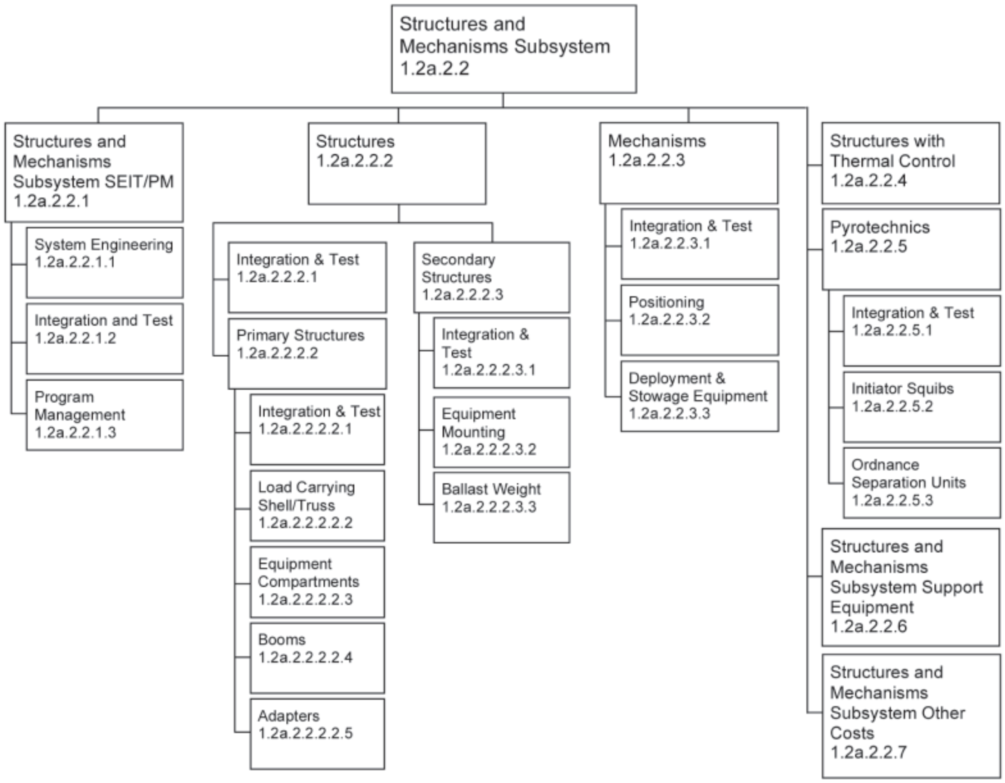


Spacecraft Bus 1.2a.2
Spacecraft Bus SEIT/PM 1.2a.2.1
System Engineering 1.2a.2.1.1
Integration and Test 1.2a.2.1.2
Program Management 1.2a.2.1.3
Structures and Mechanisms Subsystem 1.2a.2.2
SEIT/PM 1.2a.2.2.1
Structures 1.2a.2.2.2
Mechanisms 1.2a.2.2.3
Structures with Thermal Control 1.2a.2.2.4
Pyrotechnics 1.2a.2.2.5
Support Equipment 1.2a.2.2.6
Other Costs 1.2a.2.2.7
Thermal Control Subsystem 1.2a.2.3
SEIT/PM 1.2a.2.3.1
Active Devices 1.2a.2.3.2
Passive Devices 1.2a.2.3.3
Embedded Thermal Control (See 1.2a.2.2.4)
Flight Software 1.2a.2.3.4
Support Equipment 1.2a.2.3.5
Other Costs 1.2a.2.3.6
Electrical Power Subsystem 1.2a.2.4
SEIT/PM 1.2a.2.4.1
Electrical Power Generation 1.2a.2.4.2
Electrical Power Conditioning 1.2a.2.4.3
Electrical Power Storage 1.2a.2.4.4
Harnesses & Cables 1.2a.2.4.5
Flight Software 1.2a.2.4.6
Support Equipment 1.2a.2.4.7
Other Costs 1.2a.2.4.8
Attitude Control Subsystem 1.2a.2.5
SEIT/PM 1.2a.2.5.1
Attitude Determination 1.2a.2.5.2
Attitude Control 1.2a.2.5.3
Flight Software 1.2a.2.5.4
Support Equipment 1.2a.2.5.5
Other Costs 1.2a.2.5.6
Propulsion Subsystem 1.2a.2.6
SEIT/PM 1.2a.2.6.1
Tanks 1.2a.2.6.2
Plumbing 1.2a.2.6.3
Thrusters 1.2a.2.6.4
Solid Rocket Motors 1.2a.2.6.5
Liquid Propellants 1.2a.2.6.6
Support Equipment 1.2a.2.6.7
Electronics (See ACS)
Other Costs 1.2a.2.6.8
TT&C Subsystem 1.2a.2.7
SEIT/PM 1.2a.2.7.1
Passive RF 1.2a.2.7.2
Other RF 1.2a.2.7.3
Other Electronics 1.2a.2.7.4
Flight Software 1.2a.2.7.5
Support Equipment 1.2a.2.7.6
Other Costs 1.2a.2.7.7
Spacecraft Bus Flight Software 1.2a.2.8
SEIT/PM 1.2a.2.8.1
Flight Function (2…n) 1.2a.2.8.n = 2
Flight Function (n=2) SEIT/PM 1.2a.2.8.2.1
Custom Software 1.2a.2.8.2.2
COTS 1.2a.2.8.2.3
Other Costs 1.2a.2.8.2.4
Flight Function (2…n) 1.2a.2.8.n = 3
Other Costs 1.2a.2.8.n+1 (4)
Spacecraft Bus Support Equipment 1.2a.2.9



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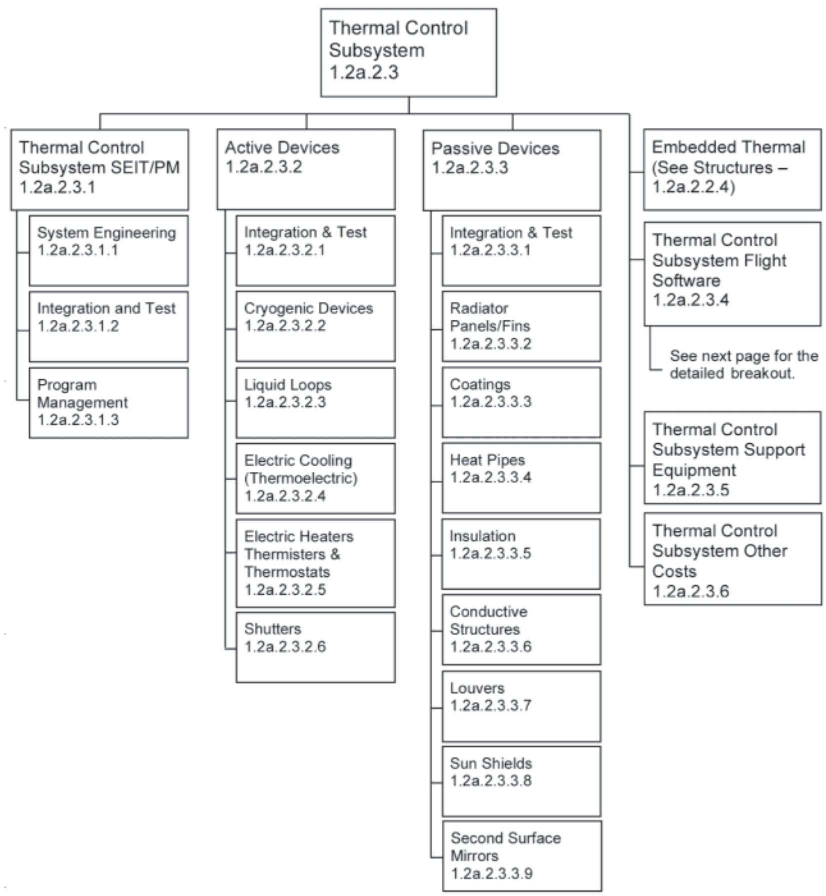

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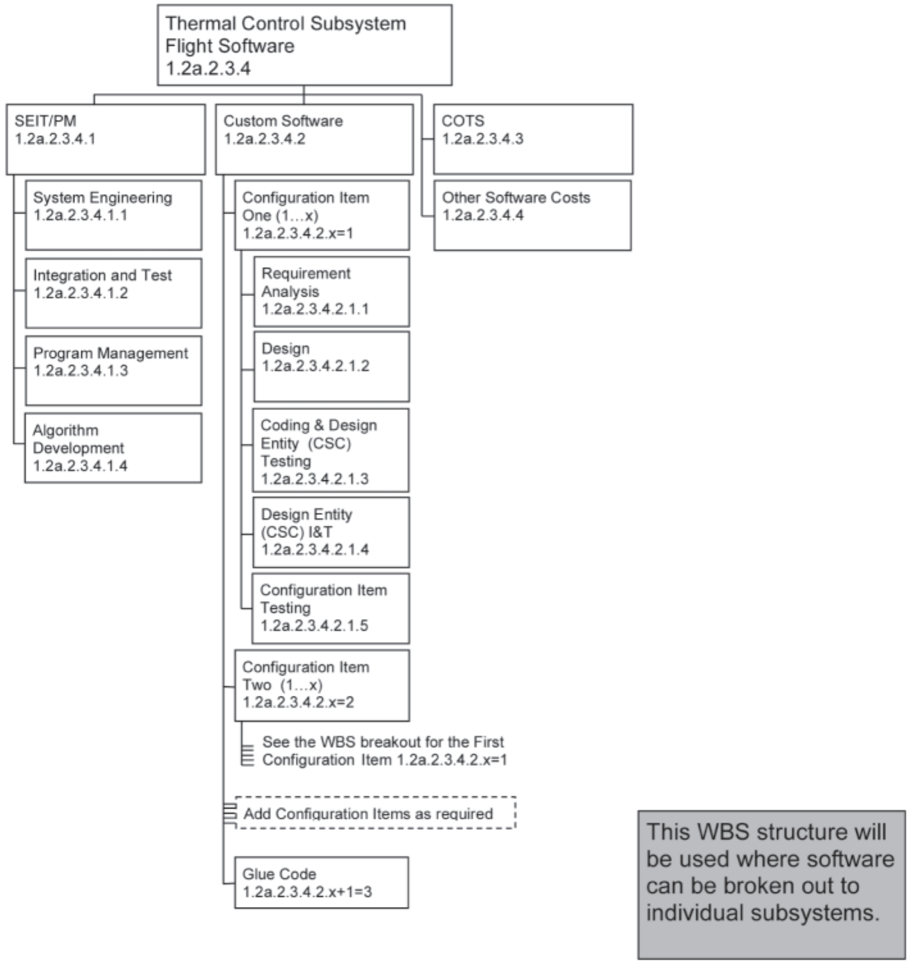

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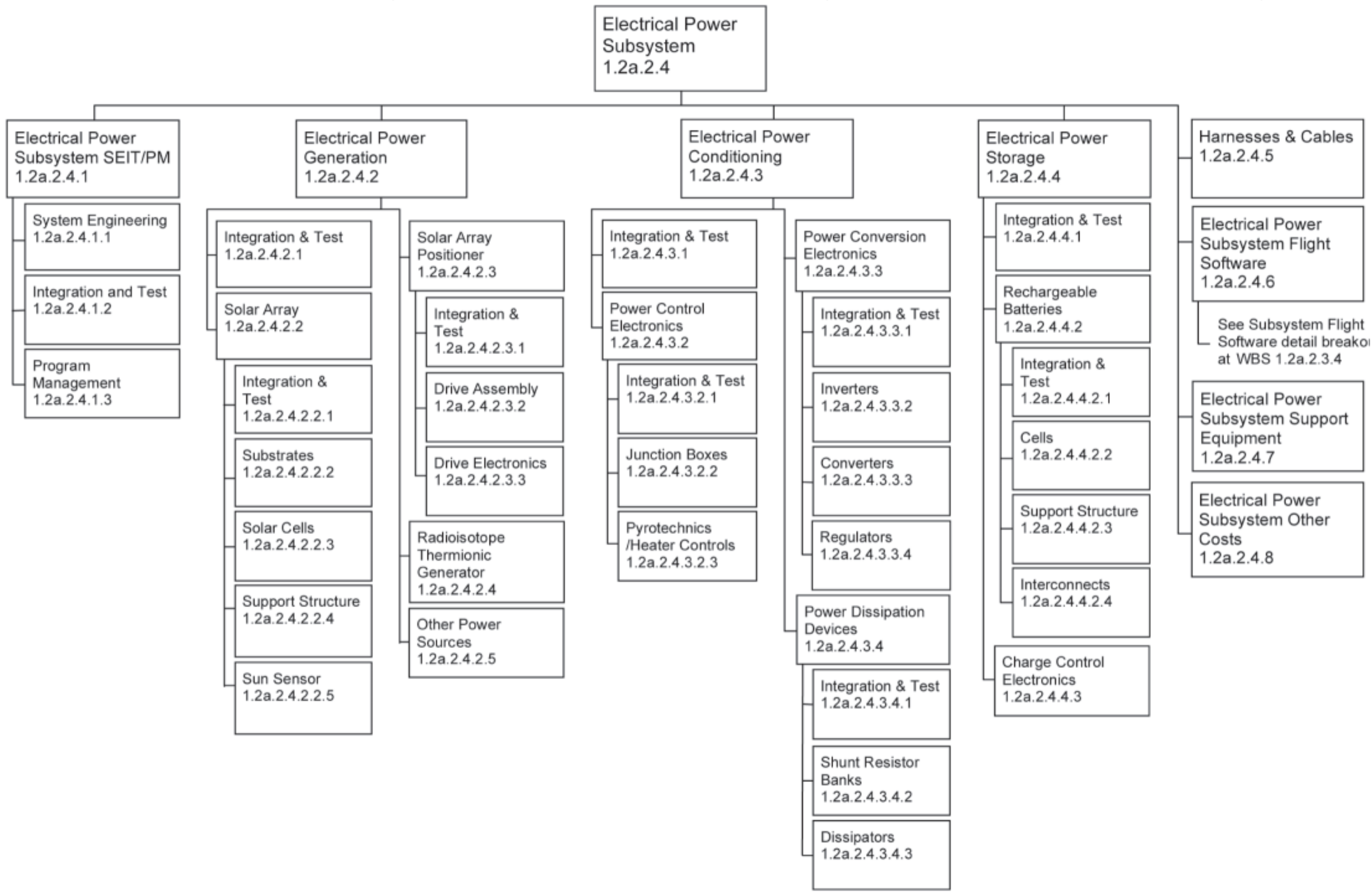
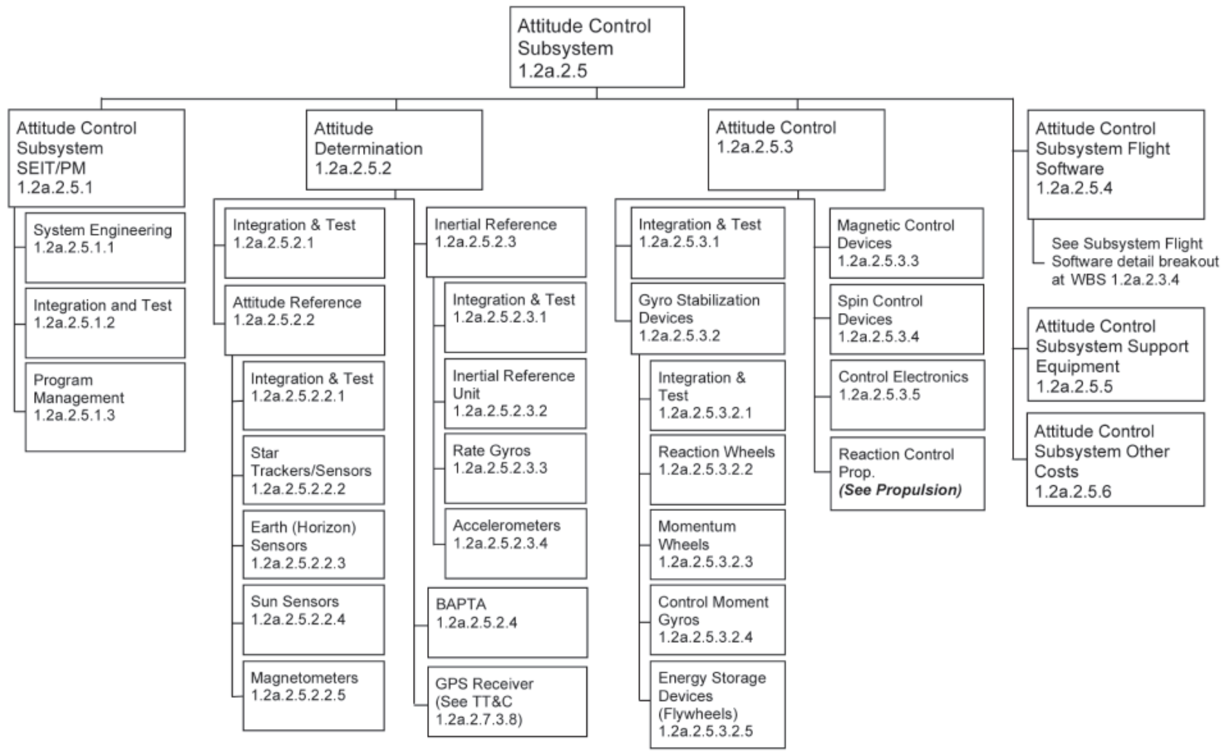

Electrical Power Subsystem 1.2a.2.4
Electrical Power Subsystem SEIT/PM 1.2a.2.4.1
System Engineering 1.2a.2.4.1.1
Integration and Test 1.2a.2.4.1.2
Program Management 1.2a.2.4.1.3
Electrical Power Generation 1.2a.2.4.2
Integration & Test 1.2a.2.4.2.1
Solar Array 1.2a.2.4.2.2
Integration & Test 1.2a.2.4.2.2.1
Substrates 1.2a.2.4.2.2.2
Solar Cells 1.2a.2.4.2.2.3
Support Structure 1.2a.2.4.2.2.4
Sun Sensor 1.2a.2.4.2.2.5
Solar Array Positioner 1.2a.2.4.2.3
Integration & Test 1.2a.2.4.2.3.1
Drive Assembly 1.2a.2.4.2.3.2
Drive Electronics 1.2a.2.4.2.3.3
Radioisotope Thermionic Generator 1.2a.2.4.2.4
Other Power Sources 1.2a.2.4.2.5
Electrical Power Conditioning 1.2a.2.4.3
Integration & Test 1.2a.2.4.3.1
Power Control Electronics 1.2a.2.4.3.2
Integration & Test 1.2a.2.4.3.2.1
Junction Boxes 1.2a.2.4.3.2.2
Pyrotechnics /Heater Controls 1.2a.2.4.3.2.3
Power Conversion Electronics 1.2a.2.4.3.3
Integration & Test 1.2a.2.4.3.3.1
Inverters 1.2a.2.4.3.3.2
Converters 1.2a.2.4.3.3.3
Regulators 1.2a.2.4.3.3.4
Power Dissipation Devices 1.2a.2.4.3.4
Integration & Test 1.2a.2.4.3.4.1
Shunt Resistor Banks 1.2a.2.4.3.4.2
Dissipators 1.2a.2.4.3.4.3
Electrical Power Storage 1.2a.2.4.4
Integration & Test 1.2a.2.4.4.1
Rechargeable Batteries 1.2a.2.4.4.2
Integration & Test 1.2a.2.4.4.2.1
Cells 1.2a.2.4.4.2.2
Support Structure 1.2a.2.4.4.2.3
Interconnects 1.2a.2.4.4.2.4
Charge Control Electronics 1.2a.2.4.4.3
Harnesses & Cables 1.2a.2.4.5
Electrical Power Subsystem Flight Software 1.2a.2.4.6
See Subsystem Flight Software detail breako at WBS 1.2a.2.3.4
Electrical Power Subsystem Support Equipment 1.2a.2.4.7
Electrical Power Subsystem Other Costs 1.2a.2.4.8



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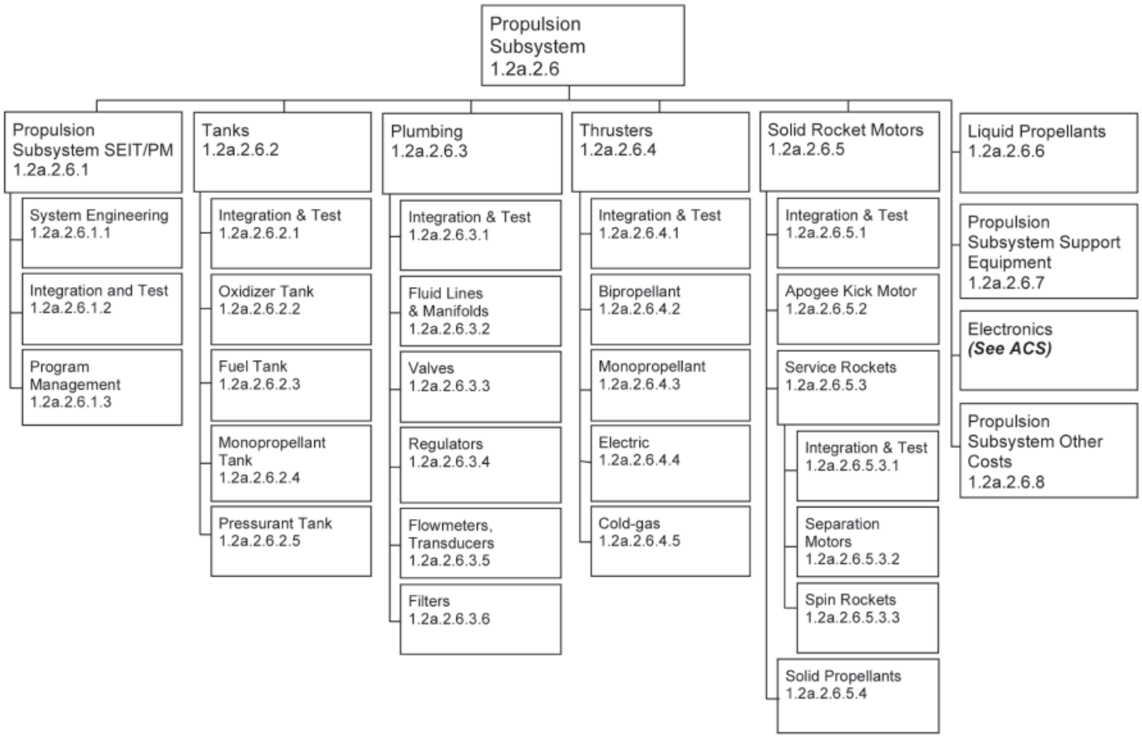

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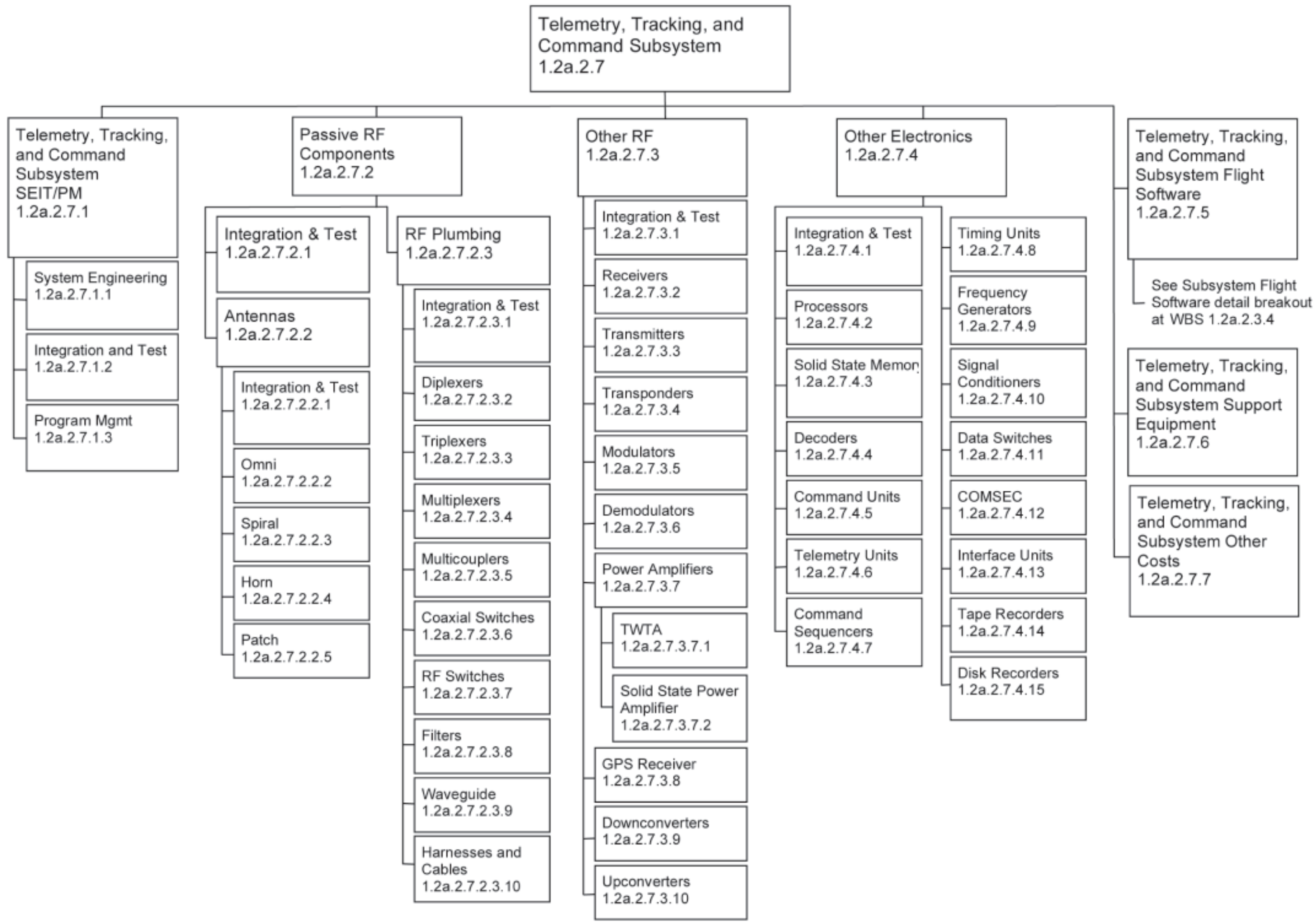

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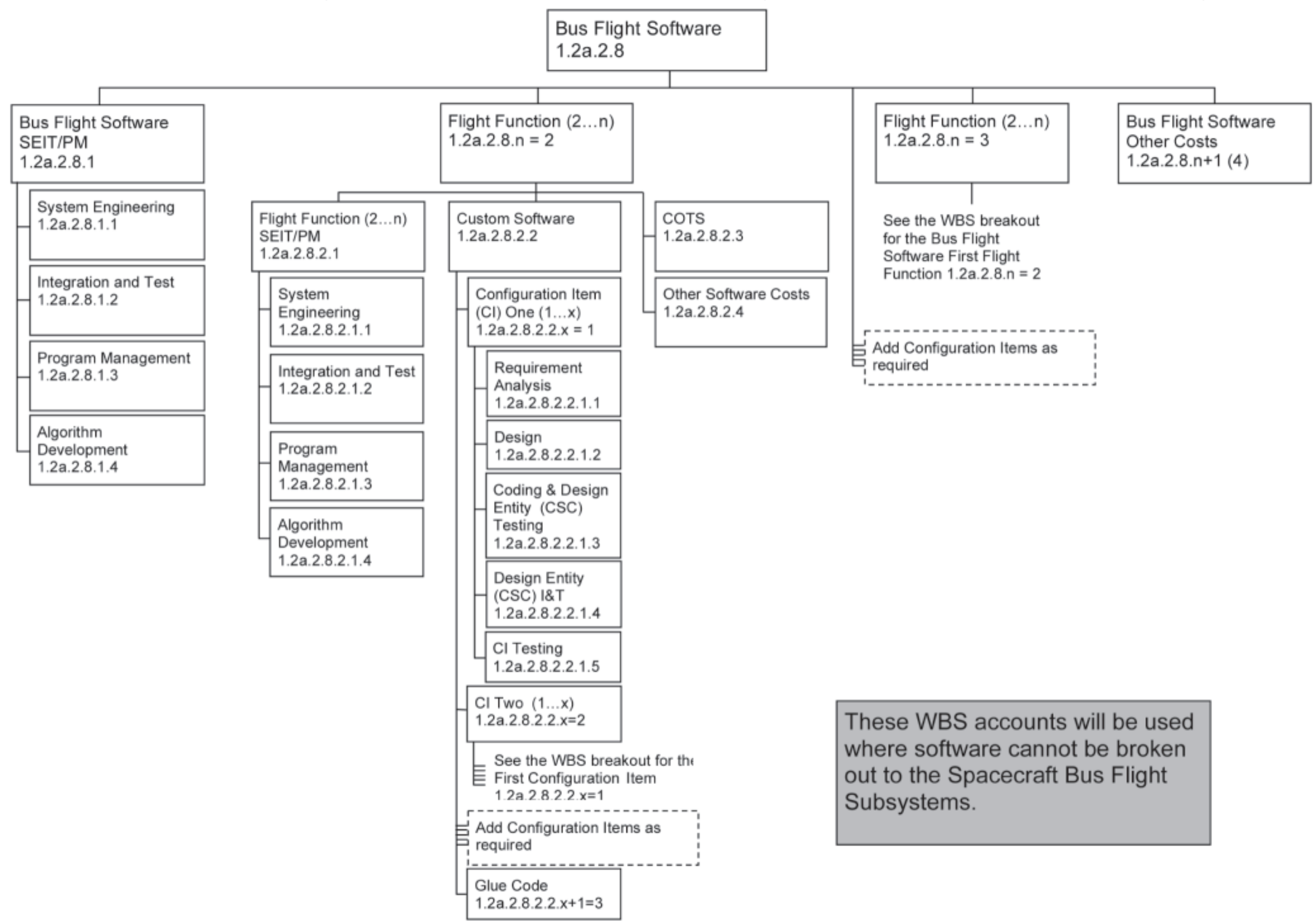

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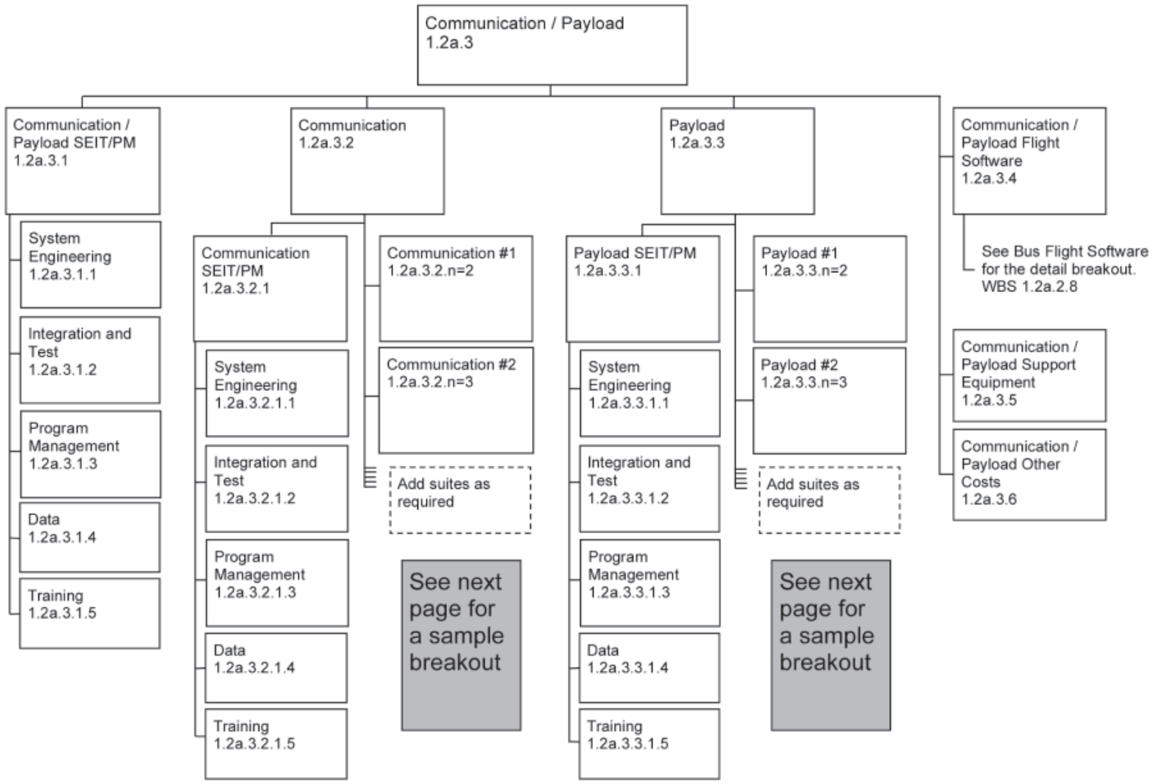

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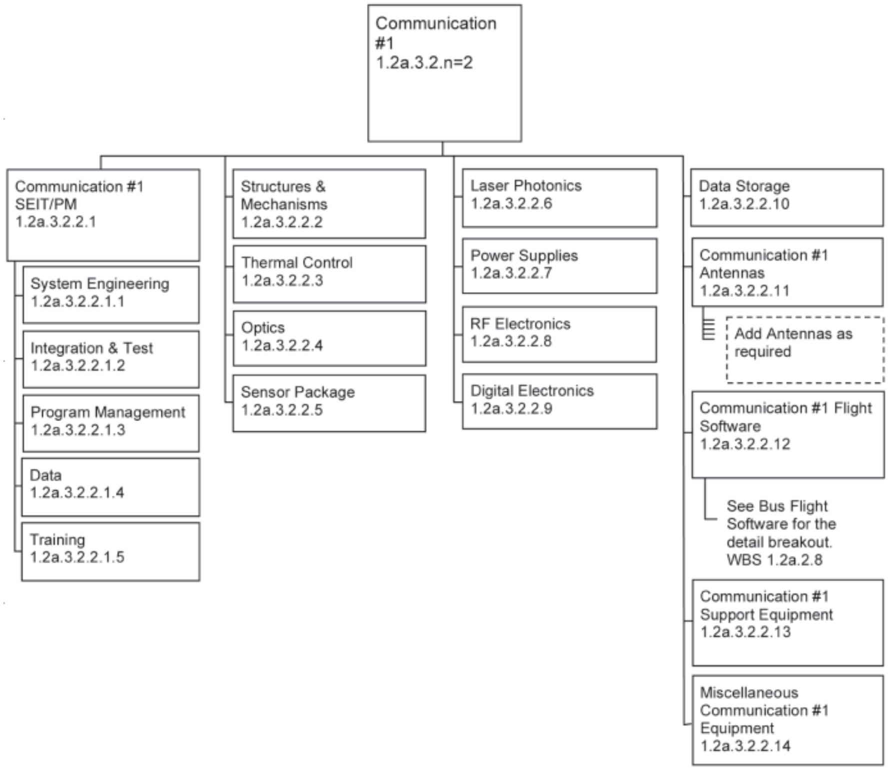

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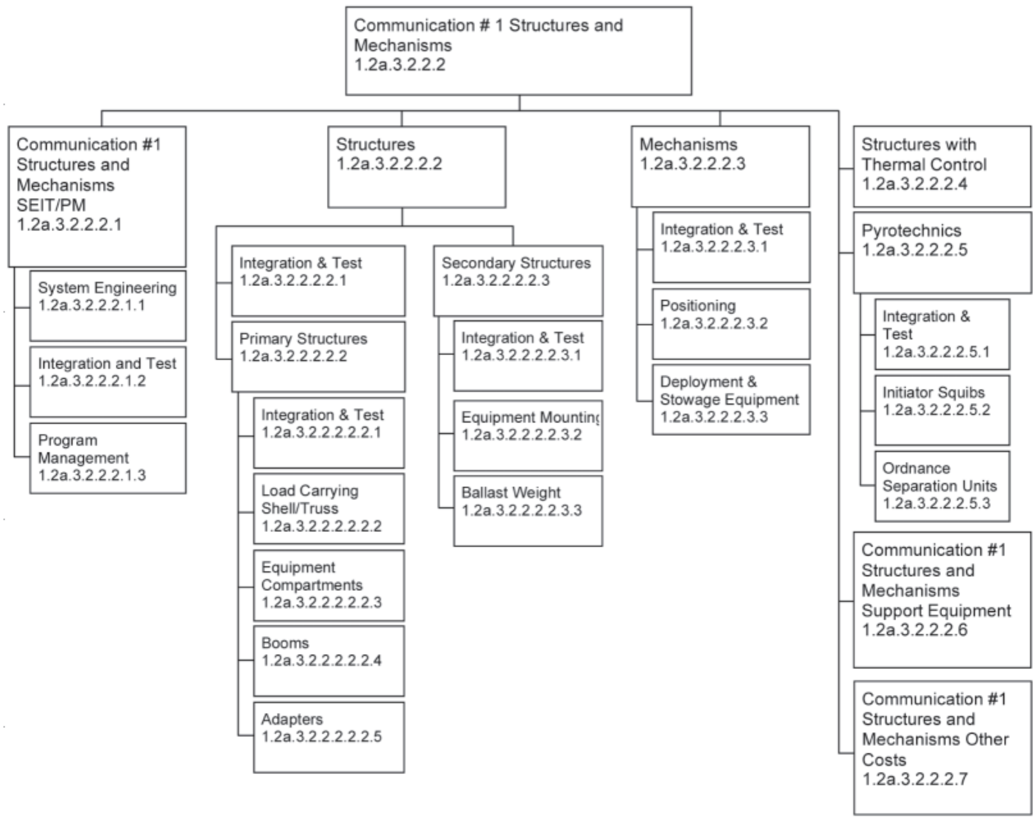

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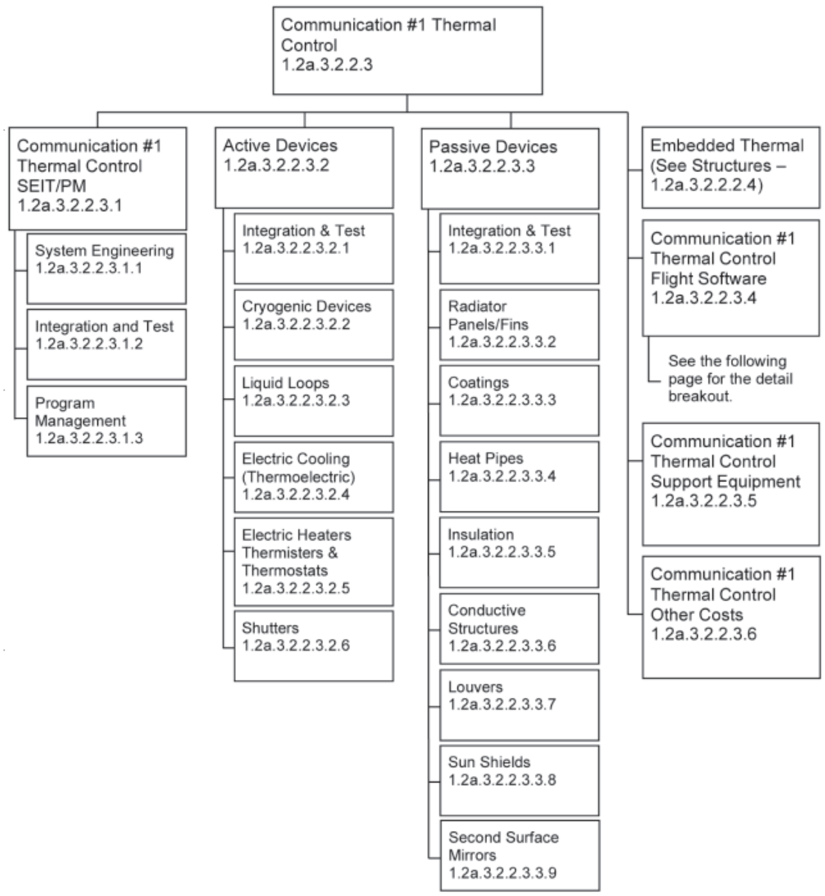

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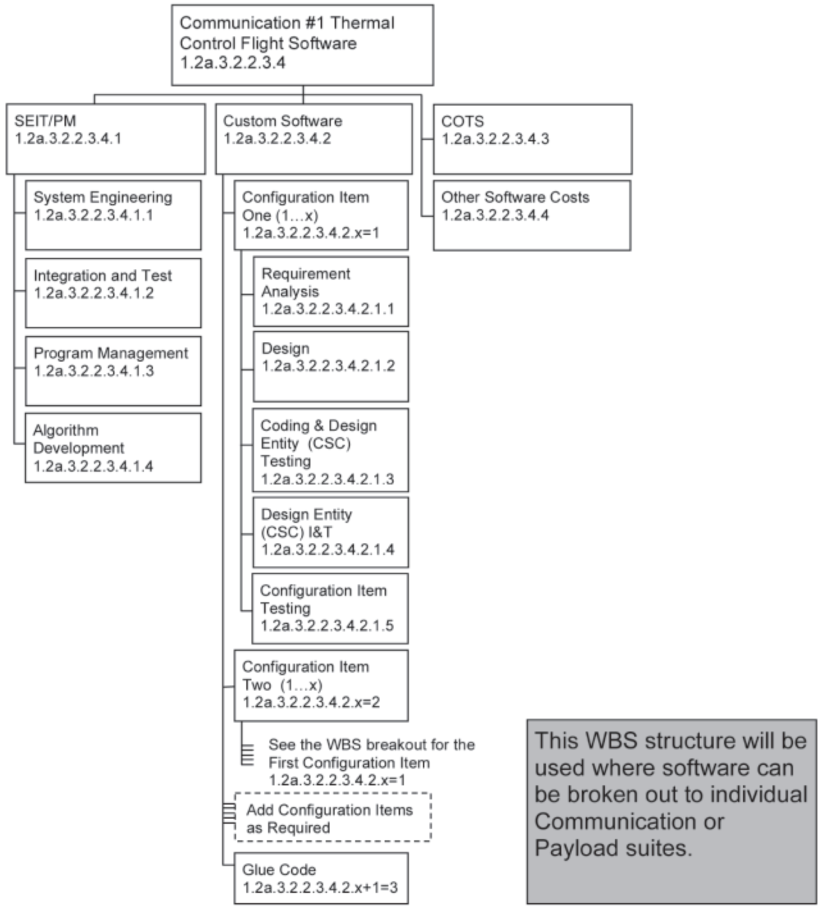

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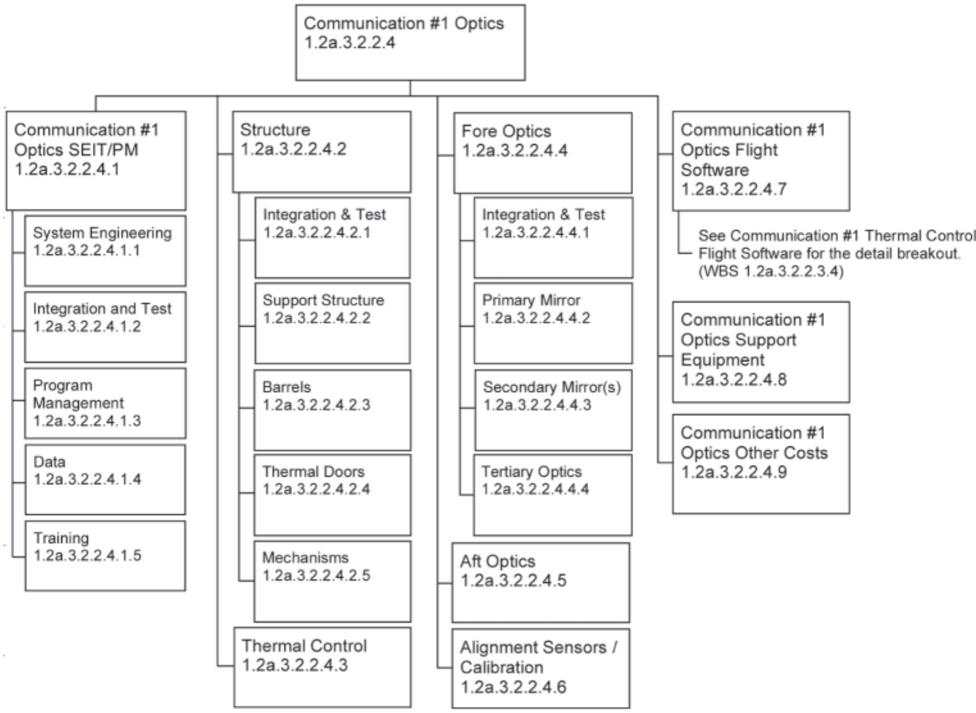

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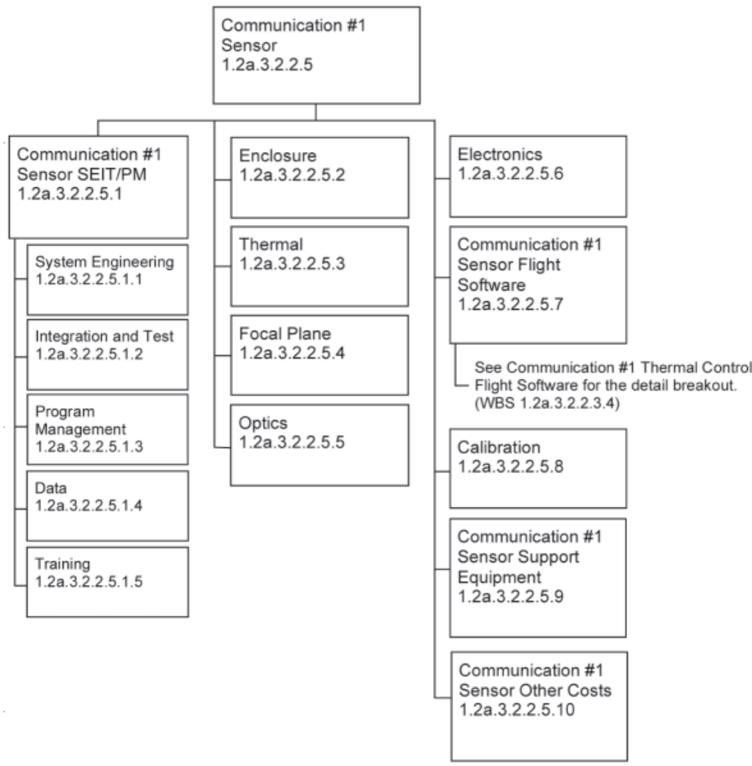

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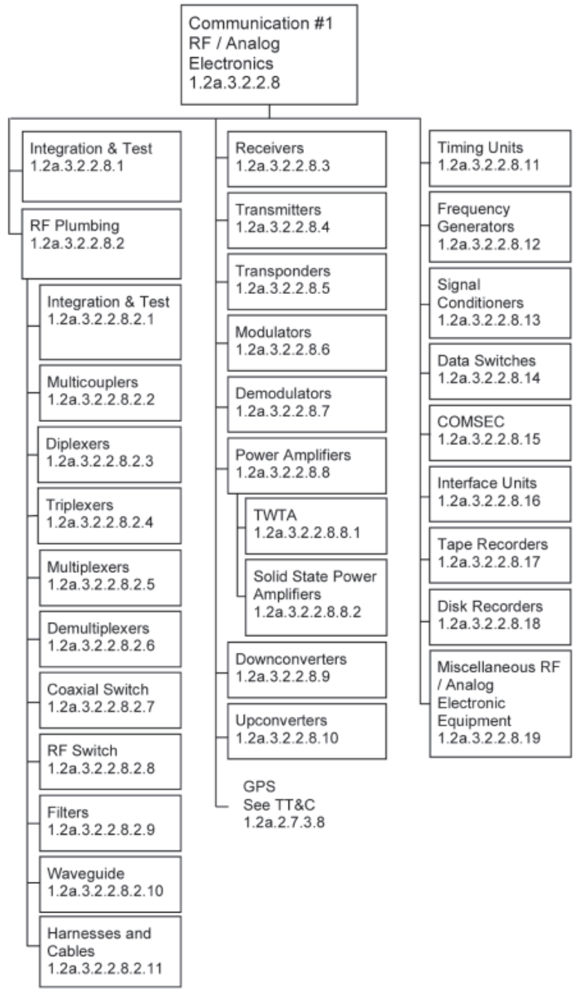

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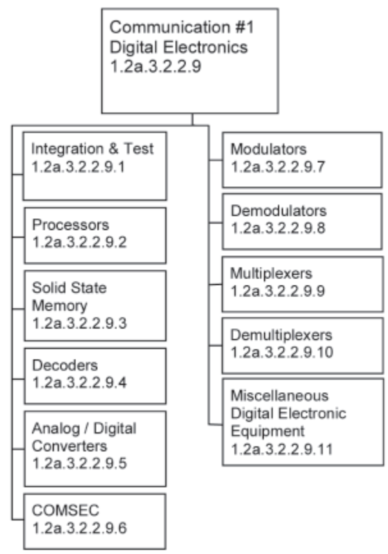

WBS 1.2a.3.2.2.9.2 – Processors: If one processor performs the processing function for multiple Communication or Payload equipment suites, carry the processor in the 1st suite and annotate the remaining suites.

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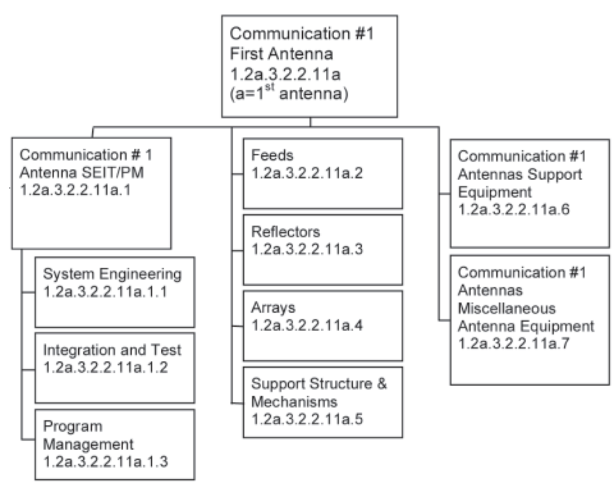

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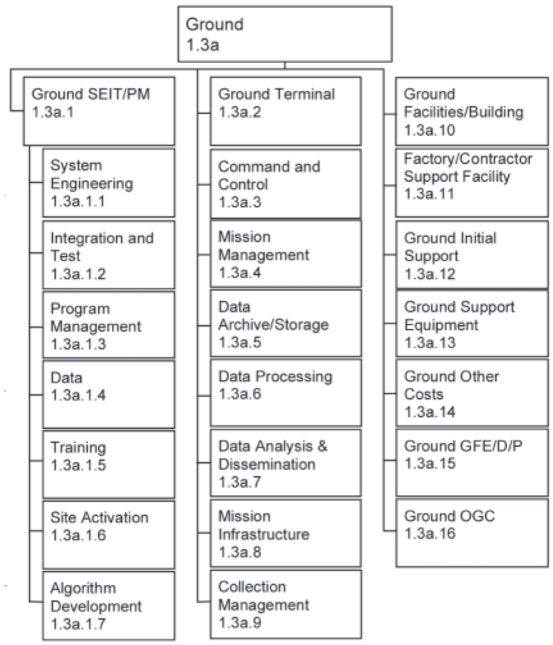

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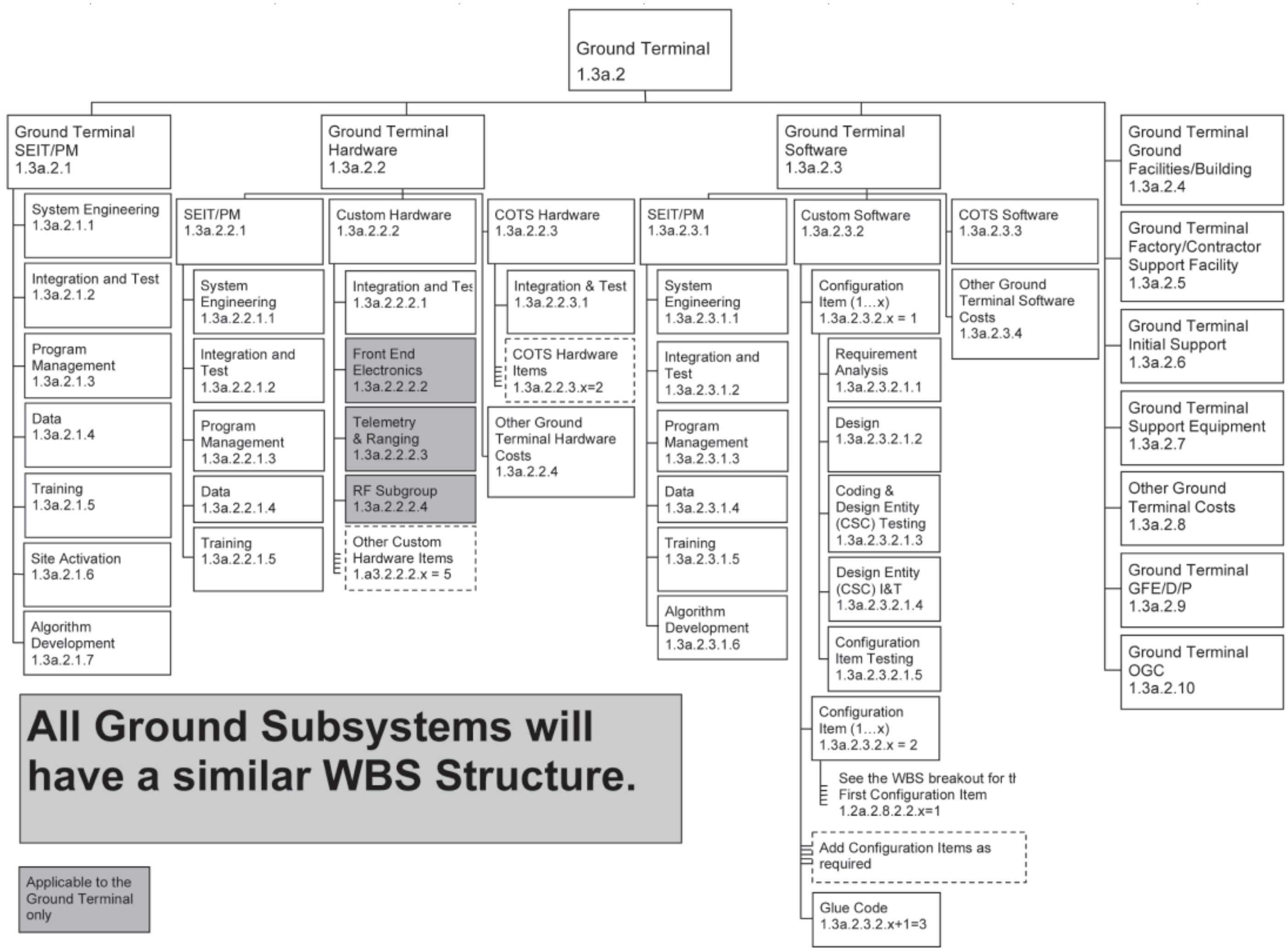

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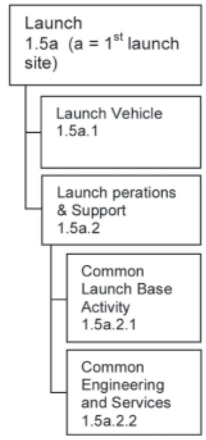

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APPENDIX E

OSD CAIG Criteria for Cost Estimates

The following material replicates the published cost-estimate criteria.

(Extract from *DoD 5000.4-M: Cost Analysis Guidance and Procedures,* December 1992)

Criteria and Procedures for the Preparation and Presentation of Cost Analyses to the OSD CAIG

This implements DoD Instruction 5000.2, Part 10, paragraph A.3.d (reference [a]). In some cases, for the sake of readability, material in Part 10, section A. and Part 13, section C. of DoD Instruction 5000.2, and Part 15 of DoD 5000.2M (reference [b]) is repeated below.

A. Scope of Analysis

1. When there is a preferred alternative, or set of alternatives, that will be briefed to the DAB, or, for delegated programs, to the DoD Component Acquisition Executive, a POE and a DoD CCA should be prepared for each such alternative. A complete description of the alternative(s), the scope of the estimates to be made, and other related assumptions needed for developing the cost estimates will be documented in a CARD (when appropriate, they may be documented as excursions to the preferred alternative(s) or any of the other alternatives briefed), approved by the Program Executive Officer, and used by both the program office (or the office designated by the sponsoring DoD Component if a program office does not exist) and the DoD CCA team. (See Chapter 1 of this Manual.) For joint programs, the common program as agreed to by all participating DoD Components as well as all unique program requirements of the participating DoD Components will be documented in the CARD. The DoD CCA team shall verify the following as they are specified in the CARD:

    a. All resources required (e.g., equipment, software, manpower, facilities) are identified; the complete specifications of these resources (e.g., types, performance and physical characteristics, entire planned program quantities) are included; the full operational and logistic support concepts for the alternative (e.g., deployment plan, activity rates, crew size, crew ratios, stock levels, training, maintenance) are identified; and the requirements for de-commissioning and/or de-militarization and clean-up are fully identified.

b. The schedules planned for design, manufacturing, and testing parts of the development program are consistent with schedules actually achieved by similar programs, and with planned availability of test assets, e.g., items to be tested, test facilities.

c. Planned production rates during low-rate initial production and during the ramp-up to full production are consistent with experience in similar production programs.

d. The data used to calibrate any CERs utilized are consistent with the cases at hand.

e. Any contract prices used to support any parts of the estimates are for present or historical contracts that are consistent with the program at hand; there is evidence that the contract prices used in the estimates are prices of profitable ventures; and it is reasonable to assume that similar prices will be obtained for subsequent contracts.

f. The program described is consistent with current threat, operational requirements, and technical requirement documents; and with contractual documents, including requests for proposals. (see paragraph D.1.f. of DoD Directive 5000.4 (reference [k]).

Should the DoD CCA team find any deficiencies that prevent it making the required verification, that fact should be submitted to the Program Executive Officer for consideration; an unresolved difference shall be documented and its impact separately estimated. The results of the DoD CCA review of the program assumptions will be documented and provided to the CAIG.

2. Unless waived by the CAIG Chair, a POE and a DoD CCA shall be prepared for each alternative (in addition to those to be briefed to the DAB) that the sponsoring DoD Component considered for the decision at hand, following the guidance given in subsection A.1, above. These estimates may be prepared and documented as excursions to any one of the other alternatives, when appropriate.

3. The cost estimates should include all sunk costs and a projection for all categories of the life-cycle costs for the total planned program required to respond to the need as defined in the Mission Needs Statement (MNS), and delineated in the Operational Requirements Document (ORD), System Threat Assessment Report (STAR), Acquisition Program Baseline (APB), and Test and Evaluation Master Plan (TEMP), (DoD 5000.2-M (reference [b]), to include the following:

a. <u>Research and Development (R&D).</u> The cost of all R&D phases (i.e., Concept Exploration and Definition, Demonstration and Validation, and Engineering and Manufacturing Development) should be estimated beginning with program initiation through development. Non-recurring and recurring R&D costs for prototypes, engineering development equipment and/or test hardware (and major components thereof) should be shown separately. Contractor system test and evaluation and government support to the test program should be fully identified and estimated. Support, such as support equipment, training, data, and military construction should be estimated. The cost of all related R&D (such as redesign and test efforts necessary to install equipment or software into existing platforms) should be included. Appropriate use of Contractor Cost Data Reporting (CCDR) will be made in reflecting actual costs and projecting future costs, see Part 20 of reference (b).

b. Investment. The cost of investment (i.e., Low Rate Production, and Production and Deployment phases) should include the total cost of procuring the prime equipment and its support; e.g., command and launch equipment; support equipment; training; data; initial spares; war reserve spares; pre-planned product improvement (P3I) program; and military construction. The cost of all related procurement (such as, modifications to existing aircraft or ship platforms) should be included. Nonrecurring and recurring costs for the production of prime equipment and major support equipment should be shown separately. Appropriate use of CCDR will be made in reflecting actual costs and projecting future costs, see Part 20 of reference (b).

c. Operating and Support (O&S). The cost of O&S (i.e., Operations and Support phase) should include all direct and indirect elements of a defense program. Personnel costs should be based on estimates for officers, enlisted personnel, civilians, and contractors, expressed in terms of the Manpower Estimate Report functional categories (see Part 6 of DoD 5000.2-M (reference [b]) and subsection C.15, below). The O&S estimate should include unit level consumption (consumables, including expendable training stores, and fuel), depot maintenance, sustaining investment, system and inventory management control, and indirect O&S costs. The length of time and costs associated with defense program phase-in, and the length of time and costs associated with steady state operations should be identified. Appropriate use of Visibility and Management of Operating and Support Costs (VAMOSC) Program data (Chapter 4 of this Manual) will be made in deriving these estimates. These O&S cost elements are defined in Chapter 3 of this Manual, and the Operating and Support Cost-Estimating Guide (reference [f]).

4. Cost estimates are to capture all costs of the program, regardless of fund source or management control; they are not to be arbitrarily limited to certain budget accounts or to categories controlled by certain lines of authority.

5. Use of existing assets or assets being procured for another purpose must not be treated as free goods. The "opportunity cost" of these assets should be estimated, where appropriate, and considered as part of the program cost. (For a discussion of "opportunity costs," see page 25 of "Cost Considerations in Systems Analysis."[62]

[62]Fisher, Gene H., "Cost Considerations in Systems Analysis," The RAND Corporation, R-490-ASD, December 1970. Also available from American Elsevier Publishing Company, Inc., New York (Library of Congress Card 76–133272), and Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314 (DTIC Accession Number AD 728 481).

6. Costs of demilitarization, detoxification, or long term waste storage should be included in the cost estimates when the program will require these functions.

7. Program office cost estimates presented to the CAIG should be consistent with estimates used in the Cost and Operational Effectiveness Analyses (COEA). They should also be consistent with estimates used in the Affordability Assessments (IPS, Appendix F of reference (b). Similarly, personnel estimates supporting O&S cost estimates provided to the CAIG should be consistent with the Manpower Estimate Report (Part 6 of reference (b)). The program office should document and explain any inconsistencies between the cost estimates and the Affordability Assessments, or between the cost estimates and the Manpower Estimate Report.

B. Analytical Methods

1. Estimating Approaches. The techniques used to develop the cost estimates shall take into account the stage of the acquisition cycle that the program is in when the estimate is made (such as, demonstration and validation, engineering and manufacturing development, or production). Until actual cost data are available, the use of parametric (statistical) costing techniques is the preferred approach for the development of the cost estimates. It is expected that heavy reliance will be placed on parametric, as well as analog and engineering methods, for Milestone I and II reviews, while projections of cost actuals will be predominantly used for preparing estimates for Milestone III and subsequent reviews. A comparison of several cost estimating methods is encouraged. (See Chapter 6 of "Cost Considerations in Systems Analysis,"[63] and Chapter 1 of "Military Equipment Cost Analysis,"[64] for a discussion of cost estimating methods).

2. Statistical Estimates. When cost estimating relationships (CERs) already available or newly developed are used to make the cost estimates, the specific form of the CER, its statistical characteristics, the data base used to develop the CER, and the assumptions used in applying the CER are to be provided in the cost estimate documentation. Limitations of the CER shall be discussed. Adjustments for major changes in technology, new production techniques, different procurement strategy, production rate, or business base should be highlighted and explained.

3. Engineering and Analogy Estimates. For estimates made by engineering or analogy costing techniques, the rationale and procedures used to prepare such an estimate must be documented. This should include the cost experience used, and the method by which the information was evaluated and adjusted to make the current cost estimate. If an analog estimate is made using complexity factors, the basis for the complexity analysis (including backgrounds of the individuals making the ratings), the factors used (including the ranges of values), and a summary of the technical characteristics and cost driving elements shall be provided.

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[63]Fisher, Gene H., op. cit.

[64]The RAND Corporation, "Military Equipment Cost Analysis," June 1971. Copies can be obtained from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314 (DTIC Accession Number AD 901 477L).

4. Actual Costs. Actual cost experience on prototype units, early engineering development hardware, and early production hardware for the program under consideration should be used to the maximum extent possible from CCDR, see Part 20 of DoD 5000.2-M and the CCDR system pamphlet (references (b) and (1)) and other data sources. If development or production units have been produced, the actual cost information will be provided as part of the documentation. Estimates for Milestone III reviews must be based at least in part on actual production cost data for the systems under review.

5. Pass-Throughs. The DoD CCA must treat all costs of the program independently from the program office. However, the DoD CCA may adopt the POE value of the costs of commercial off-the-shelf (COTS) items, or non-developmental items (NDI) that do not require further modification or system integration. The DoD CCA must, in these instances, identify the specific elements of cost in question, and verify in a manner described in the documentation of the estimate, that they arise from COTS or NDI. Pass-throughs, furthermore, should be checked for accuracy (e.g., for currency of cost data and correctness of calculations). Requests to pass through other elements of the POE must be made in writing to the CAIG Chair 60 days in advance of the CAIG briefing.

6. Sufficiency Review. The sufficiency review method may be used, with the approval of the CAIG Chair, for assessing the adequacy of cost elements in the program cost estimate which are determined to be low-risk and low-cost based on an independent analysis of the program assumptions. The review shall include an evaluation of the techniques and data used to develop the POE and, if available, the use of data from alternative sources to verify the POE. The results of the review will be documented and provided to the CAIG. Requests to use the sufficiency review method must be made in writing, preferably at the CAIG kick-off meeting, but in any case not later than 60 days before the CAIG briefing.

7. Uncertainty Attributed to Estimating Errors (Cost Estimating Uncertainty). Areas of cost estimating uncertainty will be identified and quantified. Uncertainty will be quantified by the use of probability distributions or ranges of cost. The presentation of this analysis should address cost uncertainty attributable to estimating errors; e.g., uncertainty inherent with estimating costs based on assumed values of independent variables outside data base ranges, and uncertainty attributed to other factors, such as performance and weight characteristics, new technology, manufacturing initiatives, inventory objectives, schedules, and financial condition of the contractor. The probability distributions, and assumptions used in preparing all range estimates, shall be documented and provided to the CAIG.

8. Contingencies. If contingency allowance is included, an explanation of why it was required, and a presentation of how the amount of the contingency was estimated, shall be provided. This shall include an assessment of the likelihood that the circumstances requiring the contingency will occur.

9. Sensitivity Analysis. The sensitivity of projected costs to critical program assumptions shall be examined. Aspects of the program to be subjected to sensitivity analysis shall be identified in the DoD CCA of program assumptions. The analysis shall include factors such as learning curve assumptions; technical risk, i.e., the risk of more development and/or production effort, changes in

performance characteristics, schedule alterations, and variations in testing requirements; and acquisition strategy (multiyear procurement, dual sourcing, etc.). Use of statistical analysis to describe sensitivity to critical assumptions is encouraged. The results of the analysis will be documented and provided to the CAIG.

10. Multinational Acquisitions. Program estimates involving multinational acquisitions will include the impact on costs to the U.S. Government of coproduction, license fees, royalties, transportation costs, and expected foreign exchange rates, as appropriate.

C. Presentation of Cost Results to the OSD CAIG

1. Overview. A brief overview of the program, including a description (e.g., performance, physical characteristics) of the hardware involved, wartime operational employment, logistics support concepts, program status, and acquisition strategy (such as, contracting approach, development and production schedules) shall be presented.

2. Alternative Descriptions. A brief description of each alternative to be presented at the DAB, or, if a delegated program, to the DoD Component Acquisition Executive shall be discussed with the preferred alternative, or set of alternatives, highlighted.

3. PM Presentation. The Program Manager's designated representative shall present the CAIG with the POE for each alternative under consideration and explain how each was derived. This presentation shall cover the estimates and estimating procedures at the major subcomponent level (e.g., airframe, engine, major avionics subsystem, etc.). The presentation should focus on the items that are cost drivers and/or elements of high cost risk. For joint programs, the program manager's representative shall brief the entire acquisition program, and each DoD Component shall present its own O&S estimates.

4. Presentation of the DoD Component Cost Analysis. Similarly, the organization preparing the DoD CCA for each alternative under consideration shall present the estimates to the CAIG, with an explanation of how each was derived.

5. Present Value of Alternatives. Where the costs of various alternatives have significantly different time profiles, the net present value of each cost stream should be presented.

6. Preferred Alternative. For the preferred alternative, or set of alternatives, a comparison by cost category in accordance with subsection C. 8., below, will be made of the DoD CCA, the POE, and the DoD Component cost position (the official DoD Component life-cycle cost estimate for the program), and significant differences explained. The results of analyses to determine the sensitivity of costs to variations in program or cost assumptions and program parameters should be presented.

7. Time-Phased Program Estimates. The POE and the DoD CCA shall be shown time phased by fiscal year for all years of the program acquisition (from initiation to

completion of the entire program; i.e., unconstrained by the FYDP years) unless otherwise specified by the CAIG. (The time period should respond completely to the threat or need(s) given in the MNS as delineated in the ORD, STAR, APB, and TEMP). R&D quantities of prototypes, engineering test hardware, and flight test vehicles will be identified separately; procurement quantities will be identified by fiscal year. R&D, investment, and O&S cost estimates shall be shown in constant and current dollars. The POE and the DoD CCA shall be in the same constant year dollars.

8. Estimate Detail. The cost category breakout at the summary levels shall be consistent with the examples on Tables 2–2, 2–3, and 2–4 of this Manual. Further breakout shall be in accordance with the approved CCDR Data Plan (Part 20 of DoD 5000.2-M (reference (b))), and the Operating and Support Cost-Estimating Guide (reference (f)).

9. Relation to FYDP. Comparison of the time-phased life-cycle cost estimate for each alternative, in current dollars, with the latest Future Year Defense Program (FYDP) shall be shown and differences explained. In addition, comparisons with current planning positions (e.g., Program Objective Memoranda, Program Decision Memoranda, Budget Estimate Submissions, or Program Budget Decisions shall be presented.

10. CER Presentation. When CERs are presented to the CAIG as part of the presentation, the use of graphs to present both the basic data and resulting CER is encouraged.

11. CCDR Status. The status of the CCDR Data Plan, or, if implemented, the status of CCDR reporting and the processing of the cost data on the defense program being reviewed shall be presented to the CAIG (see Part 20 of DoD 5000.2-M and the CCDR system pamphlet (references (b) and (1))). If the actual costs of the prototype and development hardware are used as the basis for projections, the supporting cost-quantity curves shall be presented.

12. Cost Track. A cost track in constant “base year” dollars will be shown between the DoD Component cost position and the cost estimates approved at previous DAB reviews, with an explanation of major changes.

13. Unit Cost Comparisons. In all presentations to the CAIG, unit costs in constant dollars at a given unit number (typically 100th unit for aircraft, 1000th unit for tactical missiles) for similar equipment and/or subsystems shall be compared with the POE and DoD CCA unit cost estimates, and differences explained. Comparisons shall also be made at the summary level of flyaway, rollaway or sailaway, procurement unit, and program acquisition unit as defined in Chapter 3 of this Manual. The unit number for which the comparisons are made will be identified on all presentations.

14. Design-to-Cost. The POE, the DoD CCA, and the DoD Component cost position for the preferred alternative, or set of alternatives, will be compared to approved Design-to-Cost objectives established for the program.

15. Personnel Requirements. The total number of personnel (officers, enlisted, civilian, and contractor) expressed in terms of the Manpower Estimate Report functional categories (see Part 6 of DoD 5000.2-M), that are required to operate, maintain, support, and train for the major defense program shall be presented. Support includes personnel involved in security and base operations; training includes personnel involved in operations, maintenance, and support of training devices and simulators. Additionally, estimates should address the specific numbers of personnel required for organizational, intermediate, and depot maintenance.

16. O&S Comparisons. O&S costs for each alternative shall be compared with one or more existing reference systems–preferably including the one to be replaced by the new defense program. The following will be addressed in this comparison:

    a. Major elements of O&S costs, such as Petroleum, Oil, and Lubrication (POL) costs per flying hour, fuel consumption in terms of gallons per flying hour, consumable material, reparable cost per operating hour, and depot costs per operating hour;

    b. Personnel components of O&S costs to include crew size, crew ratio, maintenance manhours per operating hour, and manpower requirements in terms of major skill categories;

    c. Annual O&S costs in terms of typical force structure unit battalion, squadron operating the system. Assumed quantity of equipment and manpower requirement levels should be addressed; and

    d. Potential significant force structure, employment, or maintenance changes that are not part of the approved program, regardless of the DoD Component's position on funding such changes.

APPENDIX F

Cost Risk Checklist

The material in this appendix replicates the checklist from Arena et al., 2006.

(Extract from *Impossible Certainty: Cost Risk Analysis for Air Force Systems* Appendix C, Arena et al, 2006)

Estimating

Cost estimating relationships (CERs) and methods

- Is the standard error (of the forecast) known?
- Does the CER include all recent observations?
- Have any observations been deleted from the regression? Does the inclusion of these observations change the estimate error?
- Are you extrapolating outside the data range?
- How well understood are the values for input factors (independent variables)? What assumptions are implicit in these input values? Do any input factors require subjective evaluation?

Learning/rate/curve assumptions

- What learning slope has been assumed, and how does it compare to similar programs?
- Is there a different break point in the learning curve compared with other programs?
- Does the learning curve flatten?

Cost reduction initiatives

- What cost reduction initiatives are planned?
- What is their likelihood of success?
- Are the initiatives independent, or do they interact (in other words, are savings double counted or does one depend on the success of another)?
- Are the reductions independent of learning curve assumptions?

Economic/Business

How might rates—wages, overhead, general and administrative costs, etc. change due to a variety of risks (e.g., mergers and acquisition, production line move, restart, shutdown)

- How might wages and benefits increase?
- Is there a collective labor agreement(s) at the site? When was the last labor negotiation? What was the result?
- Does the program involve capital investment by the contractor? Is this investment reflected in overhead rates (depreciation, taxes, maintenance, etc.)

- Is the engineering and manufacturing location(s) established? Are local rates known and approved by a local Defense Plant Representative Office? How stable have rates been historically?
- Are there any worker critical skills shortages? Are security clearances required for working on the program? If so, will there be an adequate pool of qualified workers? What costs will be incurred by processing and marinating clearances? Will special manufacturing areas need to be built? Have additional security costs been included?
- Will the workforce levels expand significantly? If so, will productivity be affected by hiring inexperienced workers?

Vendor/supplier stability

- Are any critical vendors at-risk or having financial difficulty or might leave market
- Are there alternative vendors?
- What would be required to qualify a new vendor (time and cost)?
- What are the inflation indexes (Department of Defense [DoD], service, Office of Management and Budget)?
- Which inflation indexes are assumed?
- Are they specific to the commodity/region/labor type?

Technical

New technology issues

- Does the program use new technology or components that have to be developed or that have never been produced in a factory environment?
- Is a new manufacturing process or technique involved?
- Does a particular technology represent a scale-up or scale-down that has never been achieved (power density, number of sensors, bandwidth, etc.)?
- Are there new materials being used?
- Does the technology represent a new integration of standard systems?

Use of commercial off-the-shelf equipment

- What systems are assumed to be commercially available?
- Will these systems require modification for environment (shock, vibration, electromagnetic, etc.)?
- How long will the manufacture support and produce item?
- What is the cycle rate for such technology in the commercial sector? Can the design accommodate for upgrades in technology?

The potential effect of new technology or unproven technology on development time, testing and evaluation, etc.

- What might be the cost to develop alternative or fallback technology?

- How might extended development and research time delay other aspects of the program?
- How many test articles are needed?
- Is the testing program sufficient (time, test articles, etc.)?

Part or technology obsolescence

- Are there technologies or equipment that will need to be replaced or upgraded over the program (known as technology refresh)?
- Are the commercial derivative components (e.g., computers) that will be obsolete before the program is completed?
- Will sufficient spares parts be available from the vendor?
- Will a production line need to be restarted at some point to manufacture parts or spares?

Schedule

Potential for schedule delays or slippages

- Is there a master integrated schedule?
- Is the schedule networked?
- Is a critical path established?
- Is the schedule resourced (i.e., reflects need and availability for critical resources such as labor and facilities)?
- Is there any slack time for any component or subsystem that is new technology?
- What has been the typical schedule delay for similar programs?
- Does the system need to be fielded rapidly (i.e., schedule driven)?

How might delays affect cost?

- Will program delays increase fixed cost, such as systems engineering/program management?
- Will expediting costs be needed?
- How might a funding reduction extend program duration?

Is there concurrent development of several schedule critical elements?

What are the multiyear assumptions?

Requirements

Have requirements for technical update (i.e., block upgrade) been established?
Is the threat well established?
If the program proceeds under a spiral development process, have the refresh and upgrade points been defined?
Are the requirements testable?
What is the risk of new or changed requirements?

APPENDIX G

Recalculating Crosscheck Prediction Intervals

A *prediction interval* estimates the range of values in which an individual future observation may lie. The crosscheck ranges in Chapter Four are calculated at a 90-percent confidence level, since their most common use is assumed to be making a quick determination as to whether values for a proposed item fall within the range of historical experience. Other confidence levels may be appropriate for such uses as determining end points of component cost probability distributions. This appendix provides instructions on how to construct other prediction intervals, assuming data follow a lognormal distribution. Four parameters are used to calculate a prediction interval:

N—the number of observations (of similar components)
X—the mean of the natural log of costs in the data set
S—the standard deviation of the natural log of the costs in the dataset
a—the probability that the resulting range includes the next observation.

The analyst chooses a, a number between 0 and 100 percent, with greater numbers indicating higher confidence that the interval will include a future article's cost and yielding wider (and perhaps less helpful) intervals.[1] These "confidence" levels commonly range from 70 to 95 percent.

In Microsoft Excel, the following formulas can be used to calculate the lower and upper bounds for the prediction interval from a lognormal distribution:

Lower bound: EXP(X – TINV((100%-a),N-1))*S*((1+1/N)^0.5))

Upper bound: EXP(X + TINV((100%-a),N-1))*S*((1+1/N)^0.5))

The EXP function returns the number "e" (~2.718) to the power in the following parenthesis. The TINV function calculates a "t value," the area under a curve of a "Student's t" distribution to the left of the specified "100%-a." To use these formulas in Microsoft Excel, replace the variables N, X, S, and a with the locations of the cells containing their values.

Notice that X, the mean, is the mean of the natural log of the costs in the data set, and S is the standard deviation of the natural log of the costs. For clarity, the data tables presented

[1] Note that choosing 100 percent will result in a lognormal prediction interval of zero to infinity.

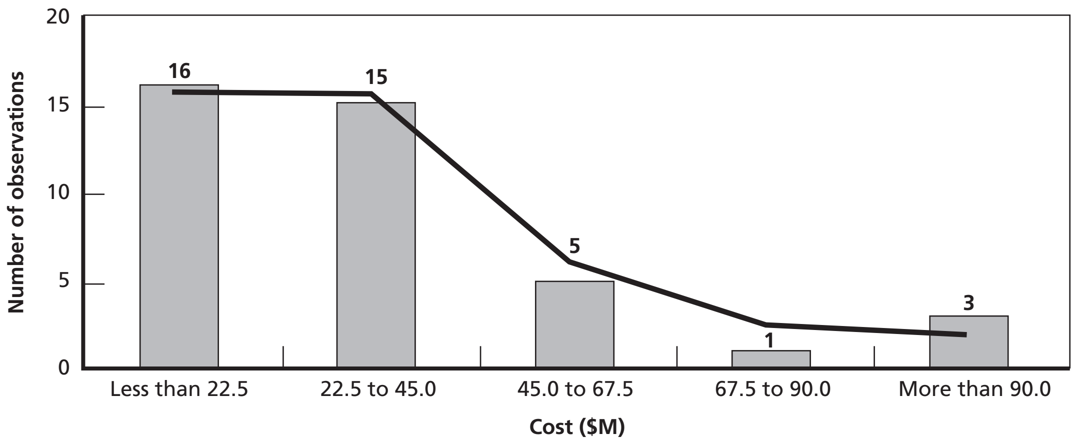
earlier contain the mean and the standard deviation of the costs but not the natural logs of the costs. The tables at the end of this appendix present the values for N, X, and S that must be used to calculate prediction intervals at confidence levels other than 90 percent.

But first, we should note how to interpret the prediction intervals and when to be skeptical about how well they indicate future costs. We are making a common assumption for all subsystems and components that the historical data follow a lognormal distribution, that is, that the spread of the data points "fits" into what one would expect from a lognormal distribution with the same mean and standard deviation as seen in the data. In Figure G.1, the height of the bars indicates the number of spacecraft in the database with the T1 cost ($M) in the interval at bottom; the height of the curve indicates the number of spacecraft calculated to be within each interval if the data are from a lognormal distribution. As we see, the lognormal distribution is an excellent fit for spacecraft T1 cost, but there are many cases for which the fit is poor. If the data seem to fit well, then a prediction interval based on that distribution provides a reasonable and compact way of assessing the likely costs of the future article. But if the data do not seem to fit well—either because there just too few data points to tell, or because the data points are not actually distributed lognormally—the use of a lognormal distribution's prediction interval will not provide a useful guide to future costs and is likely to cause confusion. In such cases, the analyst should simply look at the actual distribution of costs in the crosscheck histograms.

It is also important to understand the sensitivity of prediction intervals to changes in a, the user-specified level of confidence. The results of lowering a can be seen in Figure G.2. In Figure G.2, the curve is the lognormal density function applied to the Spacecraft T1 Cost data; the height of the curve shows the probability of the next observation being within the $2.5 million interval at bottom. Also on Figure G.2 are markings for the 90-percent and 80-percent prediction intervals. When moving from a 90-percent to an 80-percent prediction interval, note that the upper bound of the interval moves considerably more to the left than the lower bound moves to the right. In the particular case of Spacecraft T1 Cost, using an 80-percent prediction interval [11,221, 67,556] as opposed to a 90-percent prediction interval [8,631, 87,833], the lower bound increases by 2591, but the upper bound decreases by 20,278. This asymmetry is also why the mean, X, is not in the center of a prediction interval made from a lognormal distribution.

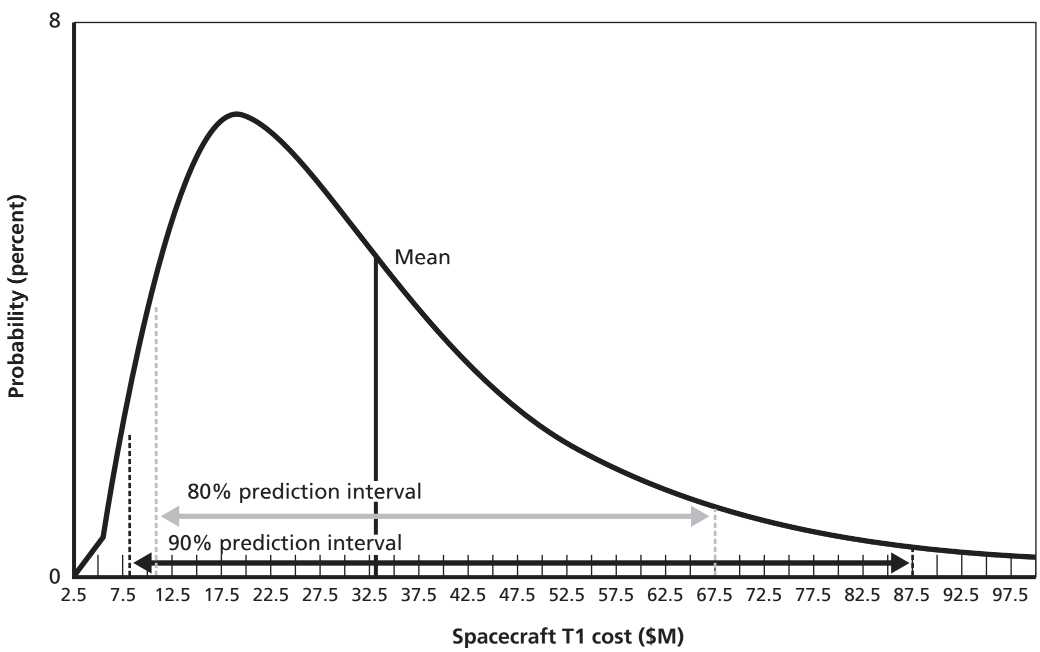
Tables G.1 through G.11, which follow the figures, present the data values for the calculations described previously. Unless otherwise indicated, costs are in T1 ($000).

Figure G.1
Spacecraft T1 Cost and Lognormal Curve



RAND *TR418-G.1*

Figure G.2
Spacecraft T1 Cost—90-Percent Prediction Interval and Lognormal Curve



NOTE: The mean cost is $34,147,000.
RAND *TR418-G.2*

Table G.1
Spacecraft T1 Costs ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
For all missions		40	10.22	0.68
Missions				
Communications		17	10.31	0.29
Environmental		8	10.14	0.66
Experimental		7	9.48	0.72
Navigation		3	9.90	0.23
Sci/Surv		5	11.29	0.35
Dry weights ($000/lb)	(lbs)			
ComNavEnv		28	2.69	0.37
Communications	1,200.7–3,857.3	17	2.68	0.33
Environmental	633.9–3,969.7	8	2.67	0.51
Experimental	340.4–3,219.4	7	2.56	0.59
Navigation	862.3–1,615.7	3	2.75	0.15
Sci/Surv	786.0–11,278.6	5	2.91	0.97
Subsystems				
ADCS		40	8.52	0.86
Communications		24	10.05	0.83
EPS		40	8.87	0.89
IA&T		40	8.90	0.99
LOOS[a]		34	8.16	1.24
Other[a]		35	7.86	2.61
Propulsion		39	7.67	1.06
SEPM		40	9.35	0.87
Structure		40	8.23	0.95
Thermal		38	6.65	1.12
TT&C		39	8.59	0.67
Subsystems ($000/lb)				
ADCS		40	3.63	0.58
Communications		24	4.02	0.55
EPS		40	2.47	0.55
Propulsion		39	2.56	1.03
Structure		40	1.89	0.71
Thermal		38	2.20	0.78
TT&C		38	3.76	0.56

[a] Cost elements not included in the analysis.

Table G.2
ADCS T1 Costs ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Overall weight ranges ($000/lb)	(lbs)			
ComNavEnv	64.1–315.5	28	3.72	0.48
Experimental	22.5–202.0	7	3.17	0.76
Sci/Surv	61.0–1,152.2	5	3.80	0.64
Attitude determination and digital electronics				
Weight range ($000/lb)	(lbs)			
ComNavEnv	14.0–86.5	16	3.61	0.87
Experimental	20.5–44.6	4	3.36	1.15
Sci/Surv	3.8–85.5	3	3.55	1.08
Missions				
ComNavEnv		26	8.01	0.62
Experimental		5	6.51	1.48
Sci/Surv		5	8.34	1.10
Mechanical RCS				
Missions				
ComNavEnvExp		30	7.01	0.57
Sci/Surv		5	8.43	1.38
Reaction wheel assembly, by mission				
ComNavEnvExp		18	5.59	0.33
Sci/Surv		5	7.52	1.04
Momentum wheel assembly				
ComNavEnvExp		7	6.21	0.79

Table G.3
Communications T1 Costs ($000)

ComNavEnv Mission	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Communications subsystem (MILSTAR) ($000/lb)	(lbs) 30.4–2,042.4	28	4.03	0.46
Number of channels (no MILSTAR) ($000/channel)	(no.) 1–10	7	8.37	0.47
	11–25	4	7.45	0.43
	>25	9	6.70	0.30
Number of channels (MILSTAR) ($000/channel)	1–10	8	8.48	0.54
	11–25	4	7.45	0.43
	>25	13	6.79	0.47
Weight ranges ($000/lb)	(lbs)			
Antenna (MILSTAR)	4.4–838.8	26	3.61	0.67
Transmitter (no MILSTAR)	10.1–704.9	20	3.85	0.81
Transmitter (MILSTAR)	10.1–704.9	24	4.10	0.94
Transponder (MILSTAR)	13.8–109.4	6	4.18	0.31

Table G.4
EPS T1 Costs ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Missions				
ComNavEnv		28	9.00	0.70
Experimental		7	7.81	0.66
Sci/Surv		5	9.66	0.97
Weight ranges ($000/lb)	(lbs)			
ComNavEnv	104.3–1,921.1	28	2.43	0.57
Experimental	68.3–494.5	7	2.60	0.64
Sci/Surv	286.5–3,253.0	5	2.54	0.36
Power ($000/watt)	(BOL watts)			
ComNavEnv	173–13,090	26	1.12	0.84
Experimental	100–460	7	2.23	0.23
Sci/Surv	430–5,000	5	2.04	0.41

Table G.4—Continued

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Power output ranges ($000/watt)	(BOL watts)			
	1–1,000	11	2.28	0.34
	1,001–5,000	18	1.45	0.72
	5,001–13,090	9	0.41	0.20
Generation (average unit cost)				
GaAs array				
Area range ($000/$ft^2$)	(ft^2)			
ComNavEnv	30.1– 227	4	2.93	0.30
Weight range ($000/lb)	(lbs)			
ComNavEnv	38.8–502.6	5	3.24	0.16
HeSi array, ComNavEnv				
Area range ($000/$ft^2$)	(ft^2)			
ComNavEnv	351.6–531.8	3	2.01	0.22
Weight ranges ($000/lb)	(lbs)			
ComNavEnv	200.8–278.3	3	2.64	0.17
Si array				
Area range ($000/$ft^2$)	(ft^2)			
ComNavEnv	24–200	14	2.85	0.47
	201–400	6	2.85	0.83
	401–832	6	1.93	0.24
Weight range ($000/lb)	(lbs)			
ComNavEnv	42.3–621.1	20	2.61	0.56
Experimental	10.9–154.0	6	3.16	0.61
Sci/Surv	184.2–1,298.1	3	3.15	0.78
Conditioning and distribution ($000/lb)	(lbs)			
ComNavEnv	86.9–783.3	25	2.48	0.59
Experimental	9.1–345.2	6	2.22	1.18
Sci/Surv	124.5–1,242.3	5	2.44	0.80

Table G.5
IA&T T1 Costs ($000)

	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Missions			
ComNavEnv	28	8.89	0.75
Experimental	7	7.93	0.73
Sci/Surv	5	10.32	0.91
As a percentage of spacecraft T1			
ComNavEnv	28	–132.43%	63.06%
Experimental	7	–155.25%	39.40%
Sci/Surv	5	–96.75%	66.88%
As a percentage of spacecraft plus communications payload T1	17	–200.12%	67.14%

Table G.6
Passive Sensor T1 Costs ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Types				
Cryogenic		5	10.78	0.67
Noncryogenic		4	9.69	0.67
Total weight ($000/lb)	(lbs)			
Cost	32.0–836.6	5	4.28	1.02
Components				
Calibration		5	5.85	1.57
Electronics		7	8.74	1.36
Focal Plane Array		6	8.55	0.93
IA&T		9	8.56	0.95
Pointing Systems		6	7.73	0.75
SEPM		9	8.90	0.76
Structure		8	6.82	1.08
Telescope		9	8.02	1.12
Thermal		9	6.00	2.70
IA&T T1 as a percentage of passive sensor T1 less IA&T and SEPM, all missions		8	–134.17%	66.65%
SEPM T1 percentage of passive sensor T1 less SEPM, all missions		8	–146.18%	75.12%

Table G.7
Propulsion T1 Costs—IPM Versus Propellant RCS and AKM ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Weight ranges for mission and type ($000/lb)	(lbs)			
ComNavEnv: RCS	38.4–190.8	12	3.25	0.53
Experimental: RCS	4.3–120.3	6	2.45	0.84
Sci/Surv: RCS	42.8–608.9	3	2.77	0.54
ComNavEnv: IPS	98.3–343.5	13	2.59	0.53
ComNavEnv: AKM	60.0–701.7	7	1.46	1.77
Experimental: AKM	53.0–614.7	5	1.18	2.44

Table G.8
SEPM T1 Costs ($000)

	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Missions			
ComNavEnv	28	9.38	0.68
Experimental	7	8.46	0.84
Sci/Surv	5	10.50	0.42
As a percentage of (spacecraft plus IA&T) T1			
ComNavEnv	28	–111.20%	45.23%
Experimental	7	–122.68%	38.81%
Sci/Surv	5	–115.09%	50.33%
As a percentage of (spacecraft plus payload + IA&T) T1			
Communications	17	–170.46%	31.76%

Table G.9
Structure T1 Costs ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Missions				
ComNavEnv		28	8.23	0.78
Experimental		7	7.46	1.01
Sci/Surv		5	9.36	0.78
Weight range ($000/lb)	(lbs)			
ComNavEnv	119.2–1,761.5	28	1.98	0.62
Experimental	141.3–1,850.7	7	1.54	0.92
Sci/Surv	184.6–10,729	5	1.83	0.89
	(lbs)			
Average weight costs ($000/lb)	100–250	7	1.96	0.84
	251–500	13	2.04	0.58
	501–1000	13	2.03	0.68
	>1,000	7	1.25	0.62

Table G.10
Thermal T1 Costs ($000)

	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Missions			
ComNavEnv	28	6.75	0.74
Experimental	5	4.88	1.19
Sci/Surv	5	7.87	0.86

Table G.11
TT&C T1 Costs ($000)

	Measurement	Observations (N)	Mean of Lognormal (X)	Standard Deviation of Lognormal (S)
Mission				
ComNavEnvExp		34	8.44	0.50
Sci/Surv		5	9.60	0.85
Channel				
One		17	8.31	0.45
Two		11	7.90	0.52
Weight ranges ($000/lb)	(lbs)			
Total weight	27.8–606.0	38	3.76	0.56
Digital electronics	(lbs)			
ComNavEnvExp	21.1–149.0	28	3.38	0.54
Sci/Surv	48.4–397.5	4	3.39	1.93
Receiver				
ComNavEnv		14	6.19	0.57
Experimental		3	5.07	0.32
Receiver ($000/lb)	(lbs)			
ComNavEnv	5.0–21.2	14	4.08	0.56
Experimental	2.5–4.7	3	3.95	0.18
Transmitter ($000/lb)	(lbs)			
ComNavEnv	5.4–20.9	15	3.72	0.72
Experimental	2.3–13.9	5	3.94	0.61

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