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Improving the Cost Estimation of Space Systems

Past Lessons and Future Recommendations

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Preface

In response to historically high cost growth in the acquisition of space systems, the Under Secretary of the Air Force, in accordance with National Security Space (NSS) Acquisition Policy,¹ directed the Air Force acquisition community to support the development of independent, accurate, and timely cost analyses to make the acquisition of NSS systems more realistic in terms of estimated costs. In turn, the former commander of Air Force Space Command (AFSPC), Gen Lance W. Lord, and the former commander of the Air Force Space and Missile Systems Center (SMC), Lt Gen Michael Hamel, asked RAND Project AIR FORCE to assess cost-estimating requirements and capabilities of SMC cost-estimating organizations—as well as their resources, tools, methods and processes—and to recommend an enhanced approach to cost analysis aimed at improving cost-estimating for space systems and increasing the understanding of factors that influence their cost.

The study was sponsored by the former commander of SMC, General Hamel. The project technical monitor was Col Delane Aguilar, SMC/FMC. The research was conducted within the Resource Management Program of RAND Project AIR FORCE as part of a multiyear study entitled “Air Force Space Systems Costs.” The initial data collection was completed in May of 2006 and the final update was provided in February of 2007, with frequent updates in between. The final briefing was presented to General Hamel on March 13, 2007, and

¹ National Security Space Acquisition Policy (NSSAP), Number 03-01, December 20, 2004.

to Gen Kevin P. Chilton, the former commander of Air Force Space Command, on March 21, 2007.

This monograph should interest government personnel involved in cost estimation and acquisition of defense systems, the military space acquisition communities, and those concerned with current and future acquisition policies.

RAND Project AIR FORCE

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Summary

Background

A review of the acquisition programs of the Department of Defense (DoD) and the military services shows that they have a history of cost growth. This is especially true for space systems. An analysis of the data contained in Selected Acquisition Reports (SARs) reported from the late 1960s to 2004 shows that the average total cost growth factor for completed Major Defense Acquisition Programs (MDAPs) was 46 percent. This percentage was calculated by comparing the actual final acquisition costs of a program to its cost estimates presented in the SAR published at the program's Milestone B decision (MS B)¹ when the program was approved for system development and demonstration (SDD). The same comparison at MS C—the program approval for production—reveals that cost growth had not been eliminated. In fact, it averaged about 16 percent for all MDAPs. The study also reveals a systematic bias toward underestimating the development cost for space

¹ Most DoD weapon systems acquisition programs follow guidelines set forth in U. S. Department of Defense, Department of Defense Instruction 5000.2, Subject: Operation of the Defense Acquisition System, May 12, 2003. This instruction divides the defense acquisition management process into five separate milestones, which represent key decision points; the first three are commonly referred to by their letter designations A, B, and C. MS B is the decision point to transition from technology development to system development and demonstration. For programs approved prior to 2003, we used the equivalent milestone designation.

systems; this underestimation was higher than the underestimation for other weapon system types included in the analysis.²

AFSPC and SMC asked PAF to examine the cost-estimating process for some existing high-visibility programs and to provide recommendations based on lessons from these programs. Moreover, RAND was asked to assess the cost-estimating requirements and capabilities of SMC cost-estimating organizations—along with their resources, tools, methods, and processes—and to recommend an improved approach to cost analysis.

The primary mechanisms PAF used to carry out its analysis were an in-depth examination of two projects selected by the Air Force, the Space Based Infrared System (SBIRS)-High and the Global Positioning System (GPS); extensive interviews with all the space System Program Offices (SPOs) at SMC; discussions with other agencies and organizations that estimate the cost of acquiring systems; a supply-and-demand analysis of cost analysis personnel workload data from SMC; and a review of academic literature on organizational structure and weapon-system acquisition documents.

Conclusions

Although the SBIRS-High program had remarkably stable requirements from 1996 through 2005, it encountered many difficulties keeping to its planned budget and schedule. Our analysis shows that the SBIRS-High program experienced high cost growth of 300 to 350 percent after MS B and that most of this growth resulted from inappropriate cost and schedule estimates made by the contractor and accepted by the government.

With respect to GPS, which was chosen because of its reputation as a well-managed program, our analyses indicate that while the pro-

² Mark Arena, Robert S. Leonard, Sheila E. Murray, and Obaid Younossi, *Historical Cost Growth of Completed Weapon System Programs*, Santa Monica, Calif.: RAND Corporation, TR-343-AF, 2006; and Obaid Younossi, Mark V. Arena, Robert S. Leonard, Charles Robert Roll, Jr., Arvind Jain, and Jerry M. Sollinger, *Is Weapon System Cost Growth Increasing?* Santa Monica, Calif.: RAND Corporation, MG-588-AF, 2006.

gram had an aggregate cost underrun, significant components of that program experienced substantial cost growth. Much of that growth stemmed from cost-estimating errors. Also worthy of note is the fact that the program requirements changed substantially.

Both programs had poor results from the portions of the contracts that were awarded under the Total System Performance Responsibility approach. Also, both programs benefited from satellites in their predecessor programs that remained operational substantially longer than anticipated. In general, both programs significantly underestimated the technical risks and their potential effect on costs.

Beyond cost-estimating errors and decisions that caused program changes, the research team identified several broad problem areas endemic to the overall SMC cost-estimating function that also contributed to inaccurate estimates. The downsizing in the space industry in the 1990s reduced the number of contractors and raised the stakes for those remaining with respect to obtaining government contracts. The dwindling contractor base fostered a sense that failure to win one of the few remaining space contracts could result in the demise of the space sector of the company, and thus contractors were tempted to underbid contracts to win them. This all occurred at a time when space programs were becoming increasingly complex. The subsequent turbulence in the space industry, with plant closings, mergers, and shifting contractor personnel from one place to another, complicated the entire process of project management.

Furthermore, the acquisition process as a whole fostered optimistic cost estimates. Institutional and budgetary factors tended to erode the objectivity of the cost-estimating process, particularly the lack of independence of the cost analysts from the program offices. Moreover, the implementation of acquisition reform also fostered optimistic estimates and eroded the government's ability to oversee contractor activities. The organizational structure and distribution of responsibilities contributed to problematic estimates, as did inadequate numbers of experienced analysts and a lack of relevant data and methods to deal with space system complexities. Limited cost, programmatic, technical, and schedule data—along with insufficient coordination among cost analysts and engineers—created problems that were exacerbated

by the lack of adequate risk-assessment processes and methods, including independent assessments of programmatic, technical, and schedule assumptions.

With respect to assessing the cost implications of technical risk, both the SBIRS-High and GPS programs lacked rigor. In part, this was due to the effects of acquisition reform described above, but it also resulted from overreliance on contractor capabilities. Technical experts focused on identifying risk in specific technologies but underestimated the risk associated with the integration effort required for a complex system. Risk assessments were not always made, and those that were sometimes lacked rigorous fact-finding to support the assessments of technical content. Furthermore, up-to-date data were lacking and were inaccurate in some instances. Also, there is evidence to suggest that some risk assessments were not entirely independent and objective, having been done by the SPO, by the prime contractor, or by contracted support personnel. Some methodological limitations, such as the selection of cost-probability distributions, may also have contributed to estimating errors. Perhaps the biggest single challenge for cost estimation in these programs was the development of credible methodologies for determining technical risk, quantifying it, and incorporating the risk assessment into the cost-estimating process to produce a credible estimate.

All of this notwithstanding, the research indicates that much cost growth falls beyond the purview of the cost-analysis profession. Costs increase for a number of reasons, some of which are avoidable and some of which cannot be avoided.

A considerable portion of the cost analysis is done by systems engineering and technical assistance (SETA) contractors, who appear to carry out much of the day-to-day work for SMC. Military personnel have excellent cost analysis and quantitative skills, but they typically rotate out after one assignment and rarely serve again in a cost-estimating position. With respect to demand for future cost analysts, if we assume that the staff can accomplish the cost-estimating tasks *more* efficiently, then the demand for cost analysis will never exceed supply. If the staff accomplishes the cost-estimating tasks *less* efficiently, then demand will exceed supply about one-quarter of the time. But assum-

ing the workforce can be freely assigned to where it is most needed, by and large, SMC had an adequately sized workforce to meet its projected demands, except for one peak period in 2007—as long as the future portfolio of SMC programs remains about the same as today in terms of size and complexity. Finally, our review of the SMC cost-analysis organization suggests that it would benefit from a different organizational structure.

Recommendations

Our specific recommendations are as follows:

Institute Independent Program Reviews

We recommend that independent teams of experts work along with cost estimators to perform independent reviews in conjunction with major program reviews and milestones. Mechanisms or processes should be developed so that cost analysts can draw on broader SMC technical expertise as resources for objective and independent technical and schedule assessments, the two key factors in credible cost estimates. We recommend that SMC's chief engineer be required to review and coordinate all programmatic, technical baseline, and schedule assumptions, as contained in the Cost Analysis Requirements Description (CARD). SMC must have long-term organizational accountability not only for cost estimates, but also for programmatic, technical, schedule, and risk assessments. (See pp. 71–99 and 145–146.)

Place Special Emphasis on Technical Risk Assessment

Good cost estimates hinge on accurate technical inputs. Independent, rigorous formal technical risk assessments are needed to support all cost estimates and should be routinely updated. All cost and technical risk assessments should be cross-checked using alternative methodologies (e.g., historical analogies compared with parametric analyses). The quality of the inputs to the technical assessments should be improved by collecting and making available more relevant data and increasing visibility into contractor's capabilities. The level of technical expertise

and the communications among technical, program, and cost experts should be enhanced. (See pp. 45–69.)

Adopt a Hybrid Cost Organizational Structure for SMC

A hybrid structure, which includes the strengths of both centralized and decentralized organizations, has the most potential benefits and the fewest limitations. In particular, increasing the independence of the analysts performing major cost estimates will improve the reliability of the estimates and SMC's reputation as an organization whose cost numbers can be trusted. This change will require significant support from senior SMC leadership, as we discuss below. (See pp. 127–139.)

Realign and Strengthen the Future Financial Management (FM) Organization by Reassigning Cost-Estimating Tasks

We recommend that the cost tasks be divided between cost staff in the comptroller organization and the program offices. Cost-estimating tasks should be done within the SPO when the focus is on program execution, where changing priorities or rapid responses are common, for functions required to manage the day-to-day activities of the program, where the official position for effective interaction with SPO personnel is needed and where processes are unique to the program. The comptroller's cost staff should perform the tasks when independent analysis is a priority, experienced government leadership is required, economies of scale exist, flexibility in assignments is desired, skill sets and tasks fall outside the SPO mission, and workload and priorities are generally predictable. (See pp. 128–130 and 140–141.)

Require Major Estimates to Be Led by Experienced and Qualified Government Analysts

Contractor support staff should not lead major cost estimates. However, contractor support plays an important role in data collection, building cost models, documenting the results, and other technical assistance. SMC and Air Force human resources organizations will need to support the new staffing approach. The current approach to hiring, personnel assignments, civil service grade structure, and military force development regulations may need to be reassessed to attract

and retain competent cost analysts in SMC. Furthermore, we note that a few experienced analysts can be more effective than many inexperienced ones. (See pp. 130 and 138–141.)

Implement Best Practices from Other Cost Organizations

Our team met with various organizations performing cost analysis and collected best practices. Interviewees overwhelmingly agreed that sound initial estimates are critical and should be appropriately resourced. Other widely supported best practices consist of

- including analysts with technical/engineering, financial/business management, economics, mathematics, and statistics backgrounds in cost-estimating teams
- updating annual program cost and risk estimates
- keeping a track record of each estimate
- reviewing and archiving all major estimates
- emphasizing monthly Earned Value Management analysis as a management tool. (See pp. 131–133 and 159–168.)

Standardize Cost Data Collection and Improve Current Databases

In addition to historical cost information, the SMC Comptroller's cost staff should also collect historical programmatic, technical, and schedule data and archive it for future use. We encourage regular data exchanges with internal Air Force organizations, such as the Air Force Cost Analysis Agency, and external organizations, such as the National Reconnaissance Office and NASA, as a critical aspect of this data collection. (See pp. 193–202.)

Acknowledgments

The research and analysis presented in this monograph would not have been possible without the support of Gen Lance Lord, former Commander of Air Force Space Command, and Lt Gen Michael Hamel, former commander of the Space and Missile Systems Center.

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Air Force Organizations

- AFMC/Aeronautical Systems Center (ASC/FMC)
- AFMC/Electronics Systems Center (ESC/FMC)
- Air Force Cost Analysis Agency
- Deputy Assistant Secretary of the Air Force (Cost and Economics)
- Offices and programs within SMC
 - Financial Management
 - SBIRS
 - GPS
 - AEHF
 - TSAT

- LR
- Space Radar SPO

Nongovernmental Organizations

- Tecolote Research, Inc.
- The Aerospace Corporation

Other Government Organizations

- Office of Secretary of Defense/Cost Analysis Improvement Group (CAIG)
- Naval Air Systems Command (AIR-4.2)
- Naval Sea Systems Command (NAVSEA 017)
- National Reconnaissance Organization

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Abbreviations

ACAT I	acquisition category I
AEHF	Advanced Extremely High Frequency System
AFBMD	Air Force Ballistic Missile Division
AFCAA	Air Force Cost Analysis Agency
AFIT	Air Force Institute of Technology
AFMC	Air Force Materiel Command
AFSCN	Air Force Satellite Control Network
AFSPC	Air Force Space Command
AFSPC/CC	Air Force Space Command Commander
ALARM	Alert Locate and Report Missiles
AO	announcement of opportunity
APB	acquisition program baselines
APDP	Acquisition Professional Development Program
ARGOS	Advanced Research and Global Observation Satellite
ASIC	application-specific integrated circuit
ASC	Aeronautical Systems Center
AWS	Advanced Warning System
BMDO	Ballistic Missile Defense Organization
BSTS	Boost Surveillance and Tracking System
CADRe	cost analysis data requirement

CAIG	Cost Analysis Improvement Group
CAIV	Cost As an Independent Variable
CARD	Cost Analysis Requirements Description
CCDR	Contractor Cost Data Report(s)
CCRM	Continuous Cost Risk Management
CCS-C	Command and Control System—Consolidated
CDR	critical design review
CEH	Cost-Estimating Handbook
CER	cost-estimating relationship
COTS	commercial-off-the-shelf
CRIMS	Cost Risk Identification and Management System
DCGF	development cost growth factor
DAE	Defense Acquisition Executive
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DoDCAS	DoD Cost Analysis Symposium
DRB	Defense Resources Board
DSB	Defense Science Board
DSCS	Defense Satellite Communications Systems
DSP	Defense Support Program
EAC	estimate at completion
EELV	Evolved Expendable Launch Vehicle
EMD	engineering and manufacturing development
EMI	electromagnetic interference
ESC	Electronic Systems Center
ESMD	Exploration Systems Mission Directive
EV	earned value
EVM	earned value management
EVMS	earned value management system
FEWS	Follow-on Early Warning System

FFRDC	federally funded research and development center
FOC	full operational capability
FPGA	field programmable gate array
FTE	full-time equivalent
FY	fiscal year
FYDP	Future Years Defense Program
GAO	Government Accountability Office
GBS	Global Broadcast Service
GIG	Global Information Grid
GPS	Global Positioning System
GPS IIR-M	Global Positioning System IIR-M
GPS IIF	Global Positioning System IIF
GEO	geosynchronous earth orbit
HEO	highly elliptical earth orbit
HQ	headquarters
IA&T	integration, assembly, and test
IBR	integrated baseline review
IC	intelligence community
ICA	independent cost assessment
ICBM	intercontinental ballistic missile
ICE	independent cost estimate
IMS	integrated master schedule
IOC	initial operational capability
IPA	Independent Program Assessment
IPAO	Independent Program Assessment Office
IPT	integrated project team
IRT	independent review team
IPS	Interim Polar System
JET	joint estimating team
JPO	Joint Program Office

KPP	key performance parameters
LRMCR	launch and recovery mission configuration review
MCR	mission configuration review
MCS	mission control station
MDAP	major defense acquisition program
MilCon	military construction
MILSATCOM	military satellite communication
MS	milestone
MTPO	MILSATCOM Terminal Programs Office
MSFC	Marshall Space Flight Center
NAR	non-advocate review
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NMD	National Missile Defense
NOAA	National Oceanic and Atmospheric Administration
NPR	National Performance Review
NRO	National Reconnaissance Office
NSA	National Security Agency
NSS	National Security Space
O&M	operations and maintenance
OCS	operational control segment
OCX	operational control system
ONCE	One NASA Cost Engineering Data Base
ORD	Operational Requirements Document
OSD	Office of the Secretary of Defense
PA&E	Program Analysis and Evaluation
PAF	Project AIR FORCE
PCA	pointing control assembly
PD	program director

PDR	preliminary design review
PEO	program executive officer
PM	program manager
POC	point of contact
POE	program office estimate
POM	Program Objective Memorandum
PPBS	Planning Programming and Budgeting System
QRLV	Quick Reaction Launch Vehicle
R&D	research and development
RFP	request for proposal(s)
RRW	relative risk weighting
SAMP	Single Acquisition Management Plan
SBIRS	Space Based Infrared System
SAR	Selected Acquisition Report
SCEA	Society of Cost Estimation and Analysis
SDD	system development and demonstration
SDIO	Strategic Defense Initiative Organization
SEI	Software Engineering Institute
SEIT/PM	systems engineering integration and test/ program management
SES	Senior Executive Service
SETA	systems engineering and technical assistance
SLOC	software lines of code
SLRS	Spacelift Range System
SMC	Air Force Space and Missile Systems Center
SMC/CC	Air Force Space and Missile Systems Center Commander
SPO	System Program Office
SR	Space Radar
SRR	system requirements review

SSTS	Space Surveillance and Tracking System
STP	Space Test Program
SV	space vehicles
TMD	theater missile defense
TSAT	Transformational Communications Satellite
TSPR	total system performance responsibility
TT&C	telemetry, tracking and command
TWAA	tactical warning and attack assessment
TY\$	then-year dollars
USCM	Unmanned Space Vehicle Cost Model
USD(A)	Undersecretary of Defense (Acquisition)
USAF	U.S. Air Force
USecAF	Undersecretary of Air Force
WBS	work breakdown structure
WGS	Wideband Gapfiller Satellite

Introduction

Background

Previous work by RAND Project AIR FORCE (PAF) concluded that the Department of Defense (DoD) and the military departments have historically underestimated the cost of new weapon systems. Analysis of the data contained in Selected Acquisition Reports (SARs), reported between the late 1960s to 2004, showed that the average total cost growth for completed major defense acquisition programs (MDAPs) (adjusting for procurement quantity changes) was 46 percent from the Milestone (MS) B estimate and 16 percent from the MS C decision point when the estimate in the final SAR is compared to the respective estimates at each milestone. This study also revealed a systematic bias toward underestimating the cost for space systems, which was higher than the costs for other weapon system types included in the analysis.¹

A companion study on the trend of cost growth over the past three decades also showed that development cost growth for that period has not improved, despite many attempts to reform the acquisition pro-

¹ Mark Arena, Robert S. Leonard, Sheila E. Murray, and Obaid Younossi, *Historical Cost Growth of Completed Weapon System Programs*, Santa Monica, Calif.: RAND Corporation, TR-343-AF, 2006.

cess.² We emphasize here that the cost estimates reported in the SAR do not reflect a specific cost estimate performed by the cost-estimating functions within the DoD; rather, they are the department’s President’s Budget position. In some cases, the cost estimate may differ substantially from the budget request.

Table 1.1 shows the average development cost growth factor (DCGF) five years after the MS B decision. The DCGF is defined as the ratio of the cost estimate reported in the SAR dated about five years after the MS B date to the cost estimate reported in the SAR at MS B. The mean values are between 1.16 and 1.92 and the values of 1.64 and 1.91 correspond to satellites and launch vehicles respectively. Similarly, median values are between 1.13 and 1.88, and the highest value of 1.88 corresponds to the DCGF of satellites.

Figure 1.1 shows the total annual acquisition budgets in then-year dollars (TY\$) for the nine largest ongoing space programs

Table 1.1
Average DCGF at Five Years After MS B, by Program Type

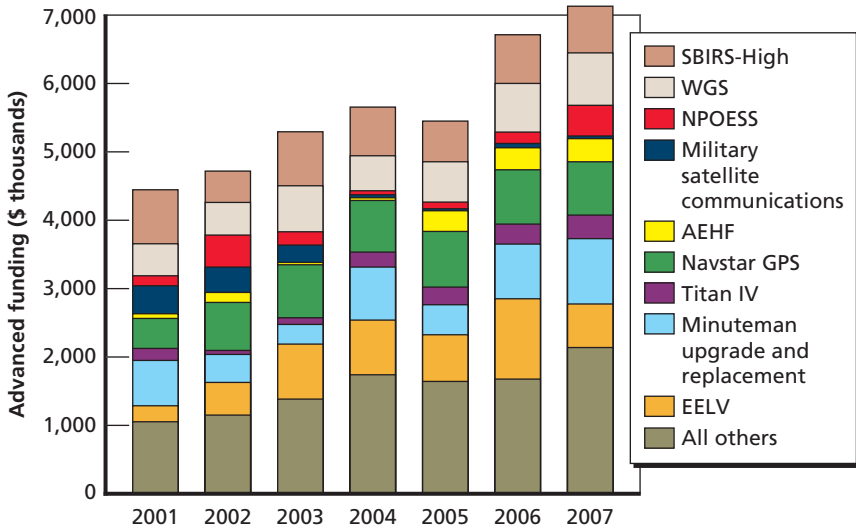
Program Type	N	Mean (Standard Deviation)	Median
All programs	76	1.45 (0.80)	1.22
Aircraft	15	1.16 (0.16)	1.13
Cruise missiles	5	1.75 (0.95)	1.43
Electronic aircraft	5	1.59 (0.31)	1.65
Electronics	19	1.20 (0.22)	1.22
Helicopters	8	1.92 (1.48)	1.58
Launch vehicles	3	1.91 (1.53)	1.15
Missiles	14	1.50 (1.04)	1.30
Other	1	1.25	1.25
Satellites	3	1.64 (0.50)	1.88
Vehicles	3	1.81 (1.06)	1.21

SOURCE: Younossi et al. (2006).

² Obaid Younossi, Mark V. Arena, Robert S. Leonard, Charles Robert Roll, Jr., Arvind Jain, and Jerry M. Sollinger, *Is Weapon System Cost Growth Increasing?* Santa Monica, Calif.: RAND Corporation, MG-588-AF, 2006.

Figure 1.1

Total Air Force Space Acquisition Annual Budgets in TY\$, 2001–2007, and Size of Largest Programs



NOTES: SBIRS = Space-Based Infrared System; WGS = Wideband Gapfiller Satellites; NPOESS = National Polar-Orbiting Operating Environment Satellite System; AEHF = Advanced Extremely High Frequency System; EELV = Evolved Expendable Launch Vehicle.

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at SMC from 2001 through 2007, compared with each other and with the annual budget value of all other acquisition programs at SMC. There was a steady increase between 2001 and 2007, with the exception of a slight decline in 2005. The figure also shows that the nine largest programs made up well over two-thirds of the total SMC space system acquisition budgets during this period.

In response to this high cost growth in the acquisition of space systems, the Under Secretary of the Air Force, in accordance with National Security Space (NSS) Acquisition Policy³ directed the Air Force to support the development of independent, accurate, and timely cost analyses to make the acquisition of NSS sys-

³ National Security Space Acquisition Policy (NSSAP), Number 03-01, December 20, 2004.

tems more realistic in terms of estimated costs. In turn, the former Air Force Space Command Commander (AFSPC/CC) General Lance Lord and the Air Force Space and Missile Systems Center Commander (SMC/CC) Lt. General Michael Hamel asked PAF to assess the cost-estimating requirements and capabilities of SMC cost-estimating organizations, as well as their resources, tools, methods and processes, and to recommend an enhanced approach to cost analysis aimed at improving cost estimation for space systems and increasing the understanding of factors that influence their cost.

Purpose

The purpose of this project was to conduct research and analysis that would lead to recommendations for changes in SMC organization, personnel, methods, and processes that would result in more credible and realistic cost estimates of space systems.

Methodology

Our general objectives were to determine the root causes of the high cost growth experienced by space systems at SMC and to provide SMC with specific recommendations and suggestions for improvement. Our research approach combined qualitative and quantitative methods and relied on analysis of both primary and secondary data sources. Specifically, we interviewed 111 people, recategorized cost data in the SARs to better incorporate program history, developed a model of the demand for cost analysis personnel, surveyed program offices for a current snapshot of personnel and workload, and reviewed internal government documents as well as published reports. We conducted three different types of interviews: one set that contributed to our case studies, one set that provided additional SMC-related insights, and a third set that involved cost analysis personnel from outside organizations. Table 1.2 lists both the types of organizations and the types and number of people interviewed within each interview category.

Table 1.2
Organizations and the Number of Interviewees

Interview Type	Number
Case studies	55
SBIRS-High	17
GPS	10
Personnel who worked on both SBIRS-High and GPS issues	28
SMC Interviews	42
Program managers; deputy program managers; directors	3
Program control chiefs; cost analysts; earned value analysts	39
Other cost analysis organizations	14
Air Force agencies	9
Other government agencies	5
Total	111

Case Study Analysis

Our case studies featured an in-depth analysis of the cost-estimating process of two programs selected by SMC: the Space Based Infrared System (SBIRS)-High program and the Global Positioning System (GPS). In part, this analysis involved a quantitative analysis of the Selected Acquisition Reports (SARs) and a recategorization of the reported cost variance data into a consistent RAND-developed taxonomy that allowed an easy and consistent comparison of the causes of cost growth across programs. Another part of the analysis, our qualitative approach, was based on semi-structured interviews of 55 senior program officials, cost analysts, engineers, and others during 34 separate interview sessions.⁴ We also reviewed available internal documents and published reports.

During the interviews, we asked each interviewee to explain (1) his or her beliefs about the reasons for cost growth, (2) details of

⁴ For more detail discussion of unstructured and semi-structured interviews, see Bernard H. Russell, *Research Methods in Anthropology: Qualitative and Quantitative Approaches*, 3rd ed., Walnut Creek, Calif.: Altamira Press, 2002.

how the cost-estimation process was conducted during various points in the program, (3) how risk analysis assessments were conducted and integrated into the cost-estimating process, and (4) “lessons learned” from the program cost-estimating process and how it might have been done better. A minimum of two to a maximum of four RAND project team members conducted each interview. Each took detailed and extensive interview notes. Generally, one person later transcribed the notes; the notes were then circulated to the other participants for corrections, additions, or further comments. Occasionally, the notes were sent back for review by the interviewee. Only those issues that the study team agreed were corroborated by several individuals and supported by internal documents and published reports are documented in this monograph. We report the results of our case study analysis in Chapters Two, Three, and Four.

SMC Interviews and Workload Analysis

We also interviewed 42 members of SMC System Program Offices (SPOs) and, through a survey, collected data on cost-analysis personnel and workload. The individuals we interviewed included managers and cost and technical analysts from both government and contractors hired to support the day-to-day function of an SMC program office. We relied on both semi-structured and unstructured interviews. We provided the questions listed in Appendix A in advance of interviews to provide context and help the interviewees prepare. These questions were also given to various SMC organizations before the interviews to guide our discussions and ensure consistent treatment of all programs. However, during the interviews the RAND project team asked other open-ended questions to cover issues unique to each program. As in the case study analysis, one person generally transcribed the interview notes, which were then circulated to the other team members for corrections, additions, or further comments. Here, our focus was on whether systemic problems existed at SMC or whether the issues were unique to the case study programs. Appendix B presents findings from interviews with SMC program offices that dealt with issues other than those specifically supporting the separate case studies.

We also developed a model to analyze current and future cost analysis personnel requirements, incorporating survey data from all current SMC programs. The data were derived from two survey instruments: the first asked cost analysis functional leaders to identify all military, civil service, and contractor cost and earned value analysts; to detail their acquisition, cost, and earned value experience; and to summarize their level of education, Acquisition Professional Development Program (APDP) qualification, and pay grade. The second instrument asked unit leaders to assess their entire workload, broken down into nearly 70 tasks; the responses assessed how frequently each task has to be performed, how many analysts are required, and how much time each analyst needs to complete his or her portion of the task.

A time line of survey responses can be found in Table 1.3. For each office, type of survey, and date, the version number of the response is listed. Chapter Five presents the results of this modeling effort.

Cost Analysis “Best Practices”

To understand how a successful cost-estimating organization should use cost analysis, the research team interviewed 14 directors and technical directors of several government cost-analysis organizations out-

Table 1.3
Survey Responses

Office	Supply Survey			Demand Survey	
	May 2006	October 2006	February 2007	October 2006	February 2007
GPS	1	2	2	1	1
EELV (LR)	1	1	3,4	1	2
SBIRS-High	1	2	3	1	1
MILSATCOM	1	1	1	1	2,3
Space Radar	1	2	2	1	1
SMC/FMC	1	2	2	1	1

NOTES: EELV (LR)= Evolved Expendable Launch Vehicle (part of the Launch and Range Systems Wing); MILSATCOM = military satellite communication; FMC = Cost Directorate.

side of SMC who are responsible for performing similar cost-analysis functions. Those organizations include the Air Force Material Command (AFMC) Aeronautical Systems Center (ASC), AFMC Electronic Systems Center (ESC), Air Force Cost Analysis Agency (AFCAA), National Reconnaissance Office (NRO), Naval Air Systems Command (NAVAIR), Naval Sea Systems Command (NAVSEA), Office of the Secretary of Defense (OSD), and the National Aeronautics and Space Administration (NASA). The interviews are summarized in Appendix B.

We also reviewed the literature on space program histories, assessed the organizational and reporting structures of cost functions, and looked at cost-estimating data, methods, and processes.

The results of these interviews and document reviews were compared with the findings of the case studies and the SMC interviews to form the basis for our “best practice” recommendations. Chapters Six and Seven present the results of this effort.

Organization of Monograph

The monograph contains seven chapters and five appendixes. Chapter Two presents the two case studies that the research team used as its analytic point of departure, on SBIRS-High and GPS, as well as the results of the interviews with SMC cost and program management personnel. Chapter Three discusses the technical risk-assessment process related to cost estimation on the two case study programs. Chapter Four describes the nontechnical factors that contributed to the cost variances for the two case study programs, including institutional pressures, the acquisition environment at the time, and acquisition reform. Chapter Five analyzes the SMC workforce. Chapter Six presents our analysis of alternative ways of organizing SMC, and Chapter Seven presents the study's conclusions and recommendations.

The first of the five appendixes contains the questionnaire researchers used to guide their interviews. The second provides a summary of interviews of SMC programs other than our two case studies. The third lists the programs managed by SMC. The fourth discusses

the details of our cost analysis workload and personnel model, and the fifth describes the cost-estimating process tools, methods, and data assessment for space systems.

Analysis of the Magnitude and Sources of Cost Growth in the SBIRS-High and GPS Programs

Introduction

An understanding of how and why costs have grown over time in the SBIRS-High and GPS programs is essential to provide context for our findings and recommendations. The first step is to determine a baseline from which the costs of the programs are tracked. Total expected acquisition expenditures for weapon systems are initially estimated at the time of commitment to major development activities. Within the DoD acquisition system, this typically occurs at MS B. The estimate developed in support of this milestone provides budget guidance and sets expectations regarding the funding required throughout system acquisition. Changes to this estimate, regardless of which future year's budgets are affected, disrupt DoD's financial management. The department is well served when these disruptions are minimized, which is best accomplished by program acquisition estimates at MS B that accurately project the weapon system's ultimate acquisition cost.

In the vast majority of MDAPs, the cost of the weapon system increases after MS B.¹ Much of this cost growth is beyond the purview of the cost analysis profession at the time of committing to major

¹ See Younossi et al., 2006; Arena, Leonard, et al., 2006; David McNicol, "Growth in the Costs of Major Weapon Procurement Programs," IDA Paper P-3832, 2004; and Jeffrey A. Drezner, Jeanne M. Jarvaise, Ron Hess, Daniel M. Norton, and Paul G. Hough, *An Analysis of Weapon System Cost Growth*, Santa Monica, Calif.: RAND Corporation, MR-291-AF, 1993.

development in space systems. Cost increases result from numerous causes, some of which are avoidable and others of which either cannot or should not be avoided. If the cost estimate at MS B were “perfected,” all cost growth would still not be avoided. To isolate that portion of cost growth that can reasonably be avoided through improvements to cost-estimating capability at SMC, RAND applied its cost-variance categorization methodology to the cost variances identified in the 1996 through 2005 SARs for our two case study programs.²

The next step in describing the cost growth history of these programs is to define boundaries for our analyses. This is not difficult in the case of the SBIRS program, which began in earnest in November 1996 with the declaration of MS B and award of the development contract. For the GPS program, setting the boundaries is more complex because the history of the program is more complicated. Here, we briefly describe the key aspects that drove our choice of boundaries; a more detailed explanation of the program’s history appears in Chapter Three.

The GPS program has a long history dating back to the 1970s, and it has produced several different versions of new GPS satellites. Development contracts were awarded for replacement IIF series satellites and the modernization of the operational control segment (OCS) in April 1996. At that time, the IIR satellites were in production. These three efforts represented the vast majority of GPS acquisition efforts (by value) under way in 1996 through 2005, as reported in the SARs. April 1996 marked the beginning of major development on two of the three pieces of the program; those are the two pieces we chose to track in detail. Selecting estimates in the 1996 time frame as our baseline for both programs provides the additional advantage of having similar time lines for both programs.

² See Joseph G. Bolten, Robert S. Leonard, Mark V. Arena, Obaid Younossi, and Jerry M. Sollinger, *Sources of Weapon System Cost Growth: Analysis of 35 Major Defense Acquisition Programs*, Santa Monica, Calif.: RAND Corporation, MG-670-AF, 2008.

Categorization and the Magnitude of Cost Variances³

The RAND cost-variance categorization follows the methodology from a RAND PAF study entitled “Sources of Cost Growth.”⁴ Using the data from the SARs of 35 MDAPs, that study developed cost growth categories oriented toward the causes of cost growth. The categories apply to all four acquisition-funding categories: development, procurement, acquisition-related operations and maintenance (O&M), and military construction (MilCon). Table 2.1 briefly summarizes the cost-variance categories.

The primary aim of the methodology is to separate “Errors” from “Decisions.” *Errors* are generally defined as inaccurate initial estimates of cost, schedule, and technology development to accomplish the original work scope and to meet original capabilities as defined at MS B. This includes difficulties caused by overconfidence in the maturity of relevant technologies and overoptimistic efficiency expectations from the companies contracted to design, build, and test the systems. *Decisions* involve program changes within the control of an entity of authority—program office, SMC, Air Force, OSD, Congress, and the President. They include adding, removing, and changing requirements; acquisition strategy changes including quantity, rate, and contracting strategy; fundamental program content change; and affordability or priority changes at levels above the program that add or remove funding without changing requirements.

The approach of distinguishing between errors and decisions is consistent with a similar methodology previously developed by the Institute for Defense Analysis.⁵ In addition, the RAND methodology has been vetted and approved by the Office of the Deputy Assistant Secretary for Cost and Economics. The assignment of cost variances into categories and subcategories based

³ We use the term *cost variance* instead of *cost growth* to cover both cost growth (overrun) and cost underrun.

⁴ This study is detailed in Bolten et al., 2008.

⁵ See McNicol, 2004.

Table 2.1
Summary Definitions of RAND Cost-Variance Categories

Category	Definition
Errors	
Cost estimation	Program rebudgeting caused by an inappropriate initial estimate of costs
Schedule estimation	Program rebudgeting and rescheduling caused by an inappropriate schedule plan
Technical issues	Program replanning and rebudgeting resulting from significant technology development or implementation problems
Decisions	
Requirements	Changes in program requirements, either with or without additional funding
Affordability	Decision by OSD, the service, or Congress to change the program because of changed priorities (reprogramming decisions)
Quantity	Increase or decrease in the quantity of systems built
Schedule changes	Decision by OSD, Congress, or the service to change the program schedule (extend, contract, or restructure)
Inter- or intra-program transfers	Transfers of planned funding within a program (between development and procurement or O&M) or between programs
Financial	
Exchange rate	Program cost changes associated with differences between predicted and actual exchange rates
Inflation	Program cost changes associated with differences between predicted and actual inflation
Miscellaneous	
Error corrections	Variances from errors in the SARs
Unidentified	Unexplained variances
External events	External event affecting program cost, schedule, or technology

SOURCE: Bolten et al., 2008.

on this methodology can be difficult and somewhat subjective. As a result, the reader should view any single value for a category—Errors, Decisions, and so forth—as having significant uncertainty, and values in the subcategories should be viewed as having even larger uncertainty in relative terms.

Errors

The Errors category is composed of three subcategories: cost estimates, schedule estimates, and technical issues. Variances that fall into the cost estimation subcategory are revised cost estimates that are associated with meeting the required capabilities as defined at the program's MS B. Variances that fall into the schedule estimation subcategory are those causing changes to dates for any program milestone occurring after MS B. Estimate revisions of costs or schedule within the Errors category may or may not involve increased work scope, but they do not include revised estimates resulting from changes in the system's requirements.

Variances that fall into the technical issues subcategory are those associated with developing, qualifying, and fielding the hardware systems, subsystems, and software that provide the capability specified at MS B. Difficulties with developing these and any replacement hardware or software (should the former be abandoned or found inadequate) fall into this subcategory. Difficulties in developing technologies that provide capability beyond that specified at MS B are not included in the technical issues subcategory.

The descriptions of cost variances in the SARs vary in quality from program to program and within any single program over time. Some are quite specific in describing causal relationships resulting in cost growth, while others are brief and ambiguous. Reading the general narrative provided in each SAR provides an overview of the program's status and concerns at that point in time. Reading the cost variance explanations in this context strongly suggests that many cost and schedule estimating errors are the result of technical issues but are not often explicitly identified as such in the variance explanation. This perception was confirmed in our expert interviews with individuals associated with the SBIRS-High and GPS programs. As a result, we believe that technical issues almost certainly played a larger part in cost growth than we are able to demonstrate conclusively using our SAR categorization methodology. We believe that cost growth attributed to the cost and schedule subcategories are overstated, while that attributed to the technical issues subcategory is understated. Fortunately, all of these variances are captured within the same overall Errors category.

Decisions

The Decisions category includes program changes that are within the control of an entity of authority—the program office, SMC, the Air Force, OSD, Congress, or the President. Decisions is composed of five subcategories: requirements, affordability, quantity, schedule, and inter- and intra-program transfers. The requirements subcategory includes cost growth associated with increases and decreases in desired capability of the system. Also included are all subsequent cost estimate, schedule estimate, and technology-related cost increases associated with requirements changes. Note that these same subcategories are found under the Errors category, but such variances—those that are associated with requirements added to the program after its MS B—are considered cost growth associated with the decision to change the system's desired capability.

Requirements are occasionally scaled back without the reporting of an associated cost avoidance (or savings). This typically occurs at the time of a program re-baseline during the major development phase, when some maturing system components are not providing the required capability. If the anticipated performance is close to what was originally specified, a decision is often made to relax slightly the original requirement rather than incur significant additional cost and schedule slippage to achieve the original specification. The effect of relaxing requirements without reporting associated cost avoidance is the underestimation of the cost, either to meet the relaxed requirement or to meet the original requirement. We are not able to correct for this underestimation.

The affordability subcategory is primarily made up of the results of reprogramming decisions affecting the program's funding. These reprogramming actions, usually budget cuts within the Future Years Defense Program (FYDP), are not associated with requirements changes and are beyond the program's control. A higher authority—SMC, the Air Force, OSD, Congress, or the President—typically institutes them. Affordability variances tend to be small but can add up over time. They are usually accounted for as cost savings because funding is usually taken from a program. Some programs simply can do with fewer resources in the short term; thus, “nibbling” at their budgets

has no long-term effects. We believe that in other programs most of what is “saved” in this subcategory is more than offset by increased cost growth realized years later that shows up in other variance categories. We have no way of accounting for this effect.

The quantity subcategory consists primarily of changes in the total number of units acquired. Cost growth associated with units transferred between program phases—typically, development and procurement—are included in this subcategory. Support item quantity changes and other program changes associated with a change in the number of primary items (satellites in our two programs) are also included in the quantity subcategory. While quantity changes can be reasonably described as a form of requirements change, we chose to report them in a separate subcategory under Decisions.

The schedule subcategory applies when development milestones or production rates are changed by choice, not because of technical problems and not to free up funding to apply against cost growth in other portions of the program. These changes often take the form of budget cuts and are therefore production rate cuts in the program’s FYDP funding to free up resources for short-term priorities external to the program. Schedule change decisions with cost growth consequences are at times made in satellite programs because the space vehicles are not needed as quickly as previously thought. Delaying these satellites allows for incorporation of additional capability, the additional cost of which is accounted for in the requirements subcategory.

The inter- or intra-program transfers subcategory applies when work content and its associated funding are moved between program phases or are removed from or added to the program. These variances do not represent “true” cost growth in either an estimating or budgeting sense because any change in the program’s expected cost is not a reflection on the accuracy of the MS B cost estimate. Funding and associated work content transferred between a program’s phases produce a zero-sum result for the program as a whole; thus, there is no cost growth at that level. When viewed at a higher level of aggregation, funding and associated work content transferred to or from the program to another also has a zero-sum cost effect because there is

no effect on the total funding ultimately needed to meet the required capability.⁶

Other Categories of Sources of Cost Variance

The RAND cost variance methodology identifies two additional variance categories: financial changes and miscellaneous. These variance categories are viewed as being beyond the control of the cost estimation community and program management, and they are external to the program government entities. They do not originate from either a mistake or a decision.

The Financial category applies to cost growth variances resulting from two sources: differences between expected inflation rates and their actual values, and variances resulting from changes in exchange rates. This latter variance source only applies to systems with significant foreign content, and thus does not apply to our two case study space systems.

The Miscellaneous category includes SAR error corrections, unidentified variances, and external events. The external events subcategory applies to cost variances resulting from an event beyond the control of stakeholders. Examples are ship program cost growth resulting from the devastation of a hurricane or other natural phenomena, launch vehicle program cost growth resulting from shifting of payload types to various launch vehicle programs in the aftermath of the loss of the space shuttle *Challenger*, and aircraft program cost growth resulting from protracted strikes at key contractor locations. This category is seldom used and is not used in either of the space system programs examined here.

The unidentified costs subcategory applies only when a cost variance is of unknown origin. This occurs when cost estimates and variances in successive SAR reports are not mathematically connected (no audit trail), and when programs are divided with no guidance regarding which prior variances belong to each piece of the program. The error corrections subcategory applies when variances are described as

⁶ Note that in the RAND Cost Growth Database intra-program transfers are specifically excluded from the cost growth factor calculations for the reasons cited above.

corrections from “errors” in prior reports with no further information given. This last subcategory is seldom used, and is not used in either of our space system programs.

Underestimation of Errors; Overestimation of Decisions

At one or more points after MS B, programs typically re-baseline their plan for the remainder of the system’s acquisition phase. A new plan is developed for the remaining execution of development and production that includes updated cost, schedule, and performance specifications providing the desired capabilities. If the program’s requirements have not changed substantially since their specification at MS B, then this re-baselining does not create a problem with our cost-variance categorization methodology because the additional costs can be clearly assigned to the appropriate Errors or Decisions category, depending upon the reasons behind the re-baselining. However, if requirements have changed substantially before the re-baseline or as part of it, then the variances associated with the re-baseline are at least partially, but may not be wholly, a result of the new requirements. This is where a problem occurs.

Some contextual information must be kept in mind to get a better understanding of the problem. The new program execution plan that is associated with an updated program baseline necessarily includes cost estimates and milestone schedules covering the remainder of the system’s acquisition phase. If requirements exceed those defined at MS B, then the planned system design meets the original requirements plus those added since that time. Inherent in such a plan, and an imbedded subset thereof, are updated plans to provide the system capability defined at MS B. Any difficulties associated with that effort *that were not previously acknowledged and accounted for as cost variances* are now incorporated into the new baseline. When difficulties have not been disclosed before the re-baseline, they are almost never specifically disclosed at the time of the re-baseline. As a result, their associated cost growth is not separately identified within the re-baselined program plan.

The practice of folding the plan’s higher estimates into a re-baselined program to meet the requirements defined at MS B, as well

as those defined since then, is referred to in the acquisition community as “getting well.” It is a common practice because few MDAPs have stagnant system requirements over their considerable acquisition time lines and because SARs are congressionally mandated “oversight” documents required by that very entity with the power to enhance, scale back, or cancel the program’s funding. The former point provides ample opportunity for the “get well” scenario to present itself; the latter provides strong incentives for the program leadership to take best advantage of the added requirements to fold into the new plan all the “fixes” it knew would be required but was slow to acknowledge fully internally and report externally.

The result for our cost variance allocation scheme is that, within the variance(s) reported as part of a program re-baseline, we cannot break out that portion of cost growth and schedule slips associated with the original system capabilities from that portion associated with the added requirements. Absent this insight, we are obligated to allocate all cost variance recognized at the time of a program re-baseline to the added requirements, that is, the requirements category of Decisions. This has the effect of underreporting cost growth in the Errors category and overreporting it in the Decisions category.

The implications for our two space programs are as follows: SBIRS-High has had relatively little change in requirements; thus, the issue most likely does not apply. GPS has had tremendous requirements growth; thus, the issue almost certainly has caused underestimation of cost growth attributed to the Errors category, along with a corresponding overestimation of cost growth attributed to the Decisions category.

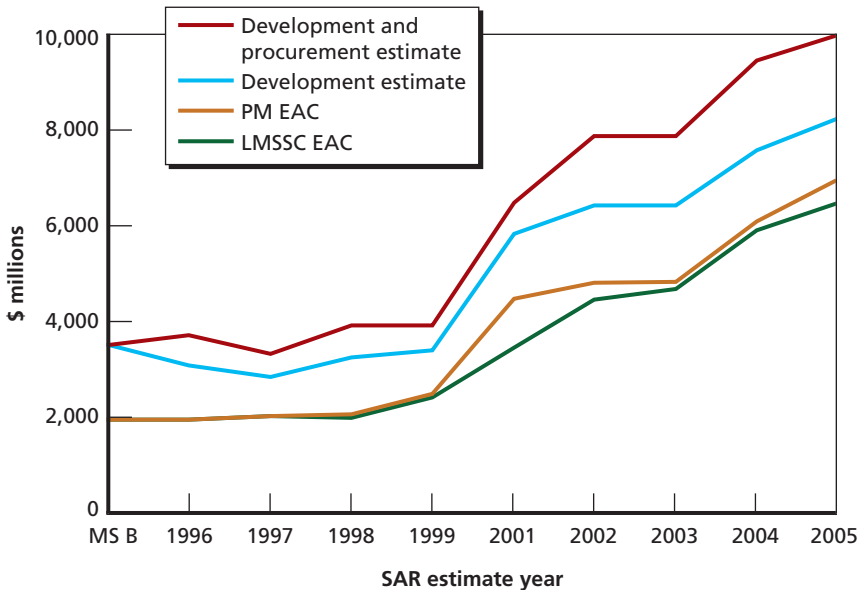
The RAND cost variance methodology strives to identify the main causes of cost growth. The methodology is far more useful than that used in the SARs, but it suffers somewhat from insufficient contextual information provided by the SARs. More-detailed variance background information would enhance the accuracy of assigning variances to the causal categories. In the absence of that information, the methodology provides a reasonable gauge for the relative proportions of cost growth attributable to errors, decisions, and other causes in any MDAP.

We now turn to a chronological description of cost growth in the SBIRS-High and GPS, citing the major events and potential causes over ten years in each program.

Categorization and Magnitude of SBIRS-High Cost Variance

Figure 2.1 shows estimates for SBIRS-High program segments at various points in the past—year-end in all cases except the point of origin on the far left. These estimates were taken from the program’s annual SARs. The lack of data for 2000 resulted from the absence of a SAR at the end of that year. Four estimates are tracked. The aggregate cost for

Figure 2.1
SBIRS-High Program Cost Estimates over Time



NOTES: PM EAC = Program manager estimate at completion; LMSSC = Lockheed Martin Space Systems Company.

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developing and procuring two highly elliptical earth orbit (HEO) payloads, five (or fewer) geosynchronous earth orbit (GEO) satellites, and the ground segment controlling the constellation are shown in the top line.⁷ The line just below it contains estimates for only the development portion of the program. This funding is a subset of the prior one. The bottom two lines show the program manager's and prime contractor's estimates at completion (EACs) for the engineering and manufacturing development (EMD) contract for the program.⁸ The lines overlap from the MS B date through 1999. At some points thereafter, the program manager's EAC is higher than that of the contractor.

The SBIRS-High program enjoyed remarkably stable requirements from 1996 through 2005 but encountered much difficulty keeping to its planned budget and schedule. The result was that an inordinate number of new Acquisition Program Baselines (APBs) and more than 200 cost variances were identified in the program's SARs over the ten years. The chronology of APBs, selected cost variances, and key contextual information about the program's progress are described below.

The program's original MS B baseline was established on October 3, 1996. The associated cost estimate was part of a Defense Acquisition Executive (DAE) APB for the complete acquisition program. The program consisted of five GEO satellites, two HEO payloads, a ground control segment, and software that facilitated functioning of the SBIRS system and its integration with the existing Defense Support Program (DSP) satellites and their system software. The program was to be funded almost entirely with development money; it contained no procurement funding. The acquisition program estimate was \$3.66 billion and included annual funding through fiscal year (FY)06. The initial value of the EMD contract and its EAC was just \$1.905 bil-

⁷ Cost growth in the program's acquisition-related O&M was substantial, and growth in MilCon was also significant. However, we chose to concentrate our analysis on the development and procurement portions of the program because, in aggregate, they account for more than 90 percent of program funding.

⁸ Note that the EMD effort is a subset of the total development effort. The latter also includes developmental activities occurring prior to the program's EMD phase.

lion, which was far less than the total program estimate.⁹ These values are above the “MS B” at the left-hand side of the x-axis of Figure 2.1.

Shortly after the EMD contract was awarded, its scope was significantly reduced, but the EMD contract value was left unchanged. The program content reduction in scope removed the final two GEO satellites from EMD and put them into a newly created production program. The absence of an EAC cut associated with the EMD program content reduction in scope implies that the program office expected that the effort remaining in the EMD contract—the designing, building, testing, and delivering the two HEO payloads and first three (no longer five) GEO satellites—would be more costly than the contract value at MS B. We believe the program office’s estimate at the time of MS B anticipated that the contractor would have difficulty keeping within the contract value and reflected this in a program baseline estimate that was far higher than that of the program’s primary contract.

The program adopted its second APB estimate about one and a half years after the MS B, on March 19, 1998. Cost estimates associated with this ABP are similar to those shown above “1998” on the x-axis of Figure 2.1. The new DAE-approved APB officially recognized the moving of the final two GEO satellites, GEOs 4 and 5, from the EMD program into the new procurement program. The total SBIRS program was now expected to cost \$4.15 billion through FY06. Note that the top line in Figure 2.1 shows a value of less than \$4 billion in 1998. This value represents development and procurement efforts only, with the difference accounted for in acquisition related O&M and MilCon funding.

As Figure 2.1 shows, cost growth recognized by the program was relatively low in its first three years after MS B. The program’s total expected cost increased about 11 percent, or about \$400 million. This is a modest amount compared with other MDAPs at this point in the acquisition process. A number of changes in the program over that period contributed to both cost estimate increases and decreases.

⁹ The major contracts in an MDAP typically account for 85 to 90 percent of the program’s total funding. In estimates at the MS B for SBIRS, only 52 percent was accounted for in the primary contract.

The first was the moving of the final two GEO satellites from the EMD phase to the newly created procurement phase in November 1996. One month later, in December 1996, a cost increase of \$188 million was recognized and associated with the creation of the procurement program.¹⁰ Based upon the perceived progress made by the contractor as indicated at numerous design milestones for both the space and ground segments, the program lowered its cost estimate for the five GEO satellites by \$285 million in the December 1997 SAR. This was done in spite of the recognition of a four-month delay in both the space and ground segment software development and the delivery of all GEO satellites, and a three-month delay in HEO sensor delivery.

During 1998, the program recognized a two-year or longer delay in the planned date for the first and all subsequent GEO launches, eight-month slips in each HEO sensor delivery, a 33-month slip in the “Increment 2” capability,¹¹ and a 27-month slip in initial operational capability (IOC). These schedule slips resulted from the longer life expectancy of the existing DSP satellites, the desire to synchronize the program with the new schedule for the National and Theater Missile Defense program, and the desire to free up FY00 funds. These schedule slips added \$494 million to the total expected cost.

Around the same time, the third GEO satellite was moved from the EMD program to the procurement program, and funding for the fourth and fifth GEOs in the procurement program was cut, with a net funding change of \$90 million removed from the program. The reduction in EMD contract scope—removal of the third GEO—was carried out without adjusting the development contract value (EAC), again indicating cost growth in the remaining work content of the EMD contract. Block II requirements providing additional capability to the third through fifth GEO satellites, along with \$215 million in funding, were also added in 1998. These decisions, along with a number of smaller program cost variances and additional schedule slips of two

¹⁰ The linking of the \$188 million with the establishment of a production phase is not stated in the SAR—this information came from our interviews.

¹¹ The program is broken up into Increment 1 and Increment 2. The latter essentially represents the functioning of the fully operational SBIRS system.

and six months in the Increment 1 software development and testing and the first HEO sensor delivery date, respectively, resulted in an APB with a total program estimate of \$4.15 billion.

After another 18 months, the DAE approved the program's third APB on August 13, 1999.¹² The primary purpose of this APB was to recognize the prior two-year stretch-out of the program, with funding now planned through FY08. The total program cost estimate remained \$4.15 billion. Major cost variances leading up to the new baseline during 1999 included purchase of GEO satellites three through five as a block with associated savings of \$155 million, an additional \$190 million increase from prior estimates for the program restructure, and revised inflation indices saving the program \$145 million.

Cumulative SBIRS-High Program Cost Variances

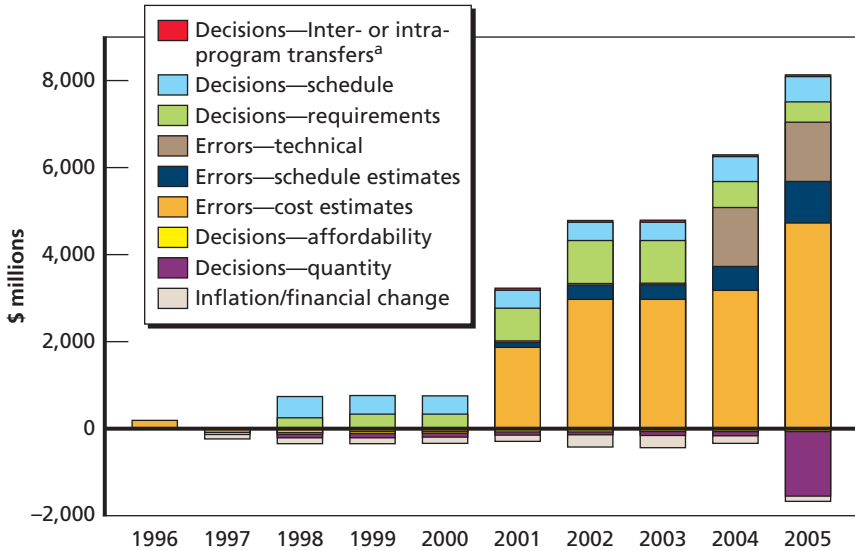
As noted earlier, over the ten-year period some 200 variances were reported in the SBIRS-High program SARs. The total included 81 in development; 60 in procurement; 18 in MilCon; and 41 in acquisition-related O&M. Variances were reported in such a way that they could not be broken out among the primary pieces of the program: GEO satellites, HEO payloads, and the ground segments.

Figure 2.2 presents the changes in the development plus procurement program estimate over time by variance category, showing the net of cost growth plus cost underrun in each subcategory and accumulation over time. Nine subcategories in all apply to the program: three in the Errors category and five in the Decisions category. The Inflation/financial change category is shown in light gray. Of these nine, five caused substantial positive cost growth, one caused minor positive cost growth, one caused a substantial cost underrun, and two caused minor cost underruns.

The program experienced over \$8 billion in positive cost variances, with all but about \$1 billion falling into the three Errors subcategories of cost estimates, schedule estimates, and technical issues. Just

¹² This is counted from MS B; thus, this third APB is the second since the MS B baseline was established.

Figure 2.2
Cumulative Variances in SBIRS-High Development and Procurement over Time Using RAND Methodology



^aQuantities are either zero or too small to show.

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under \$0.5 billion in cost growth was accounted for in the decisions-related requirements subcategory, and just over \$0.5 billion in cost growth was accounted for in the decisions-related schedule subcategory. The program also had, on net, a small cost growth in the inter- or intra-program transfers subcategory of the Decisions category.

The only subcategory with a substantial cost underrun is quantity within the Decisions category, at about \$1.5 billion. Also within the Decisions category was a small cost underrun in the affordability subcategory. The program experienced relatively small cost underruns in the inflation/financial changes category.

SBIRS-High Cost Problems Bottom Line

Most of the program's cost growth resulted from errors in the form of inappropriate cost and schedule estimates made by the contractor and accepted by the government. However, much underlying evidence suggests that these estimating errors were rooted in technical

problems—both in understanding the difficulty of technological design solutions required to deliver the SBIRS capability and in understanding the integration and test efforts required to ensure that the design solutions were robust. The program's SARs were slow to acknowledge cost growth, waiting four years into development to do so in earnest. Specific technical issues contributing to cost growth were not identified until eight years after the MS B.

The program's acquisition costs increased dramatically. The total program cost estimate grew from \$3.66 billion at MS B for a program including five GEO satellites to \$10.16 billion in March 2006 for a program with just three of those satellites. If we do some crude calculations to normalize for content—that is, adding back into the program the expected cost of the two deleted satellites and adjusting for requirements added to the program—the total program estimate rises to somewhere between \$10.8 and \$13.1 billion. This is three to three and one-half times the MS B estimate.¹³

Categorization and Magnitude of Global Positioning System Cost Variance (IIR, IIF, and OCS Segments)

The desired capabilities of the GPS program changed substantially between 1996 and 2005. GPS Block IIR-M and IIF satellites are the latest generation of operational satellites to populate the nominal 24-satellite constellation that provides highly accurate, space-based, radio-positioning, and navigation services for military and commercial users.¹⁴

¹³ The minimum number is the March 2006 baseline estimate of \$10.16 billion plus the \$1.147 billion in funding removed from the program when the fourth and fifth GEO satellites were removed, less the roughly \$0.471 in positive cost variances on net associated with added requirements. The maximum number is the March 2006 baseline estimate plus two times (representing the value of each the fourth and fifth GEO satellites) the current \$1.723 billion estimate for the planned single GEO satellite production program less the same positive cost variance for added requirements.

¹⁴ This overview of the early phases of the GPS program is drawn largely from Scott Pace, Gerald P. Frost, Irving Lachow, David R. Frelinger, Donna Fossum, Don Wassem, and Monica M. Pinto, *The Global Positioning System: Assessing National Policies*, Santa Monica,

The program originally began in 1973 with 12 GPS I developmental satellites designed and manufactured by Rockwell International (now Boeing). The first operational GPS space vehicles (SVs) were Block II and IIAs, also developed by Rockwell, first launched in February 1989. In 1983 the Air Force awarded Rockwell a contract to build 28 Block II/IIA satellites. Block IIs differed in weight and shape compared with Block Is and had superior security and integrity features. In addition, Block II satellites launched after 1989, designated Block IIAs, had much improved capabilities for autonomous operation. The launch of the 24th Block II in March 1994 completed the GPS constellation, which consisted of 24 Block II/IIs and one Block I. Rockwell built four additional Block IIAs as spares. In 1995, the Air Force announced that the GPS constellation had achieved full operational capability (FOC). The last Block IIA was placed in orbit in November 1997.

In June 1989, the Air Force awarded a contract for 20 GPS Block IIRs with an option for six more, the next-generation replacement space vehicles for the II/IIs. The Block IIR was developed by General Electric (now Lockheed Martin) after an open competition. The first IIR was launched in 1997. Block IIRs are modestly more capable satellites intended to replace Block II/IIs to maintain a nominal 24-satellite constellation.

In June 1995, the Air Force released a draft request for proposals to industry for 33 Block IIF follow-on satellites to replace the IIAs and IIRs. Like earlier generations of GPS SVs, the Block IIF was originally envisioned as broadly meeting the same high-level operational requirements but with important, though relatively modest, performance improvements. Boeing won the contract for up to 33 Block IIFs in April 1996 after an open competition. Initially the Air Force awarded Boeing a procurement contract for 6 Block IIFs with options for the remaining 27.

However, the GPS modernization program went through a major restructuring in 2000. The IIF modernization effort that began in

1996 became much more complex by January 1999 with Vice President Gore's announcement of two additional civilian signals for GPS. In June 1999, a new operational requirements document (ORD) and new key performance parameters (KPP), including jam resistance from space, backward compatibility, and system-level time transfer, were added to the desired system capabilities.

Key to the adoption of new capabilities for satellites not yet launched was the longer life expectancy of GPS satellites already in orbit. As of the end of 1999, almost the entire operational GPS constellation consisted of Block II and IIA satellites. During 1997, the life expectancy of the Block II satellites increased from an estimated 6.5 years to 8.5 years. Between 1996 and 1999 that for the Block IIA satellites increased from 6.5 years to 10.6 years. These longer life expectancies meant that replacement satellites would be needed years later than originally anticipated. This created the opportunity to upgrade replacements before their launch.

These circumstances led to the late 1999 Defense Resources Board (DRB) approval for modification of up to 12 IIR satellites with a second civilian signal and full-earth coverage of the military signal. These upgraded IIR satellites were designated IIR-Ms. Also approved was the modification of the first six IIF satellites with a second and third civilian signal and full-earth coverage of the military signal. Congress approved the modernization plan in August 2000.

In addition to the capability enhancements, a large fraction of the envisioned program was transferred into a future GPS system. This shift is discussed in more detail below.

These changes considerably confound our ability to measure and categorize GPS program cost variances, and thus our categorization of cost variances is not as precise as we would like. Contrary to perceptions commonly found in the media and within the defense acquisition community, we believe that the program's cost growth and schedule slippage during this period are considerable—when adjusted for content—and that the program is not quite as good a model for an efficient and effective acquisition of a space system as is sometimes thought.

Our analysis of the GPS program excludes the major program segments that occurred before 1996. Specifically, we exclude the initial

development effort for the system in the 1970s and 1980s that included the 12 Block I satellites and the initial constellation of production satellites—the 28 Block II and IIA satellites. We also exclude those program segments that represent the far-term future of the program—that is, the Operational Control System (OCX) ground segment capability and the Block III satellites.

We measure cost growth from a baseline of the May 3, 1996, Air Force Acquisition Executive APB, which had a value of \$8.98 billion for 78 satellites.¹⁵ At that time, the first efforts to modernize the existing GPS constellation occurred. The modernization OCS contract and the design and production contract for the first six follow-on (IIF) satellites were awarded in April 1996. These contracts were awarded to Boeing, which was not the contractor that designed and built the IIR satellites in production at the time.

The Boeing contract was awarded at a much lower value than expected, and as a result \$580 million was removed from the program estimate by the end of 1996. This “savings” was short-lived because recognition of underestimation of costs for current and future work in each of the years 1997, 1998, and 1999 resulted in \$860 million added to program estimates. The multiyear procurement strategy for FY99-04 satellite buys was abandoned in 1998; the same strategy for FY05-08 was likewise abandoned in 1999. The combined effect of these acquisition strategy changes was an increase of \$230 million. During those two years, the FY00 satellite buy was cancelled, as were the FY01 and 02 satellite buys. The cancellation of these nine satellites, made possible by the longer-than-expected life of the satellites in orbit, saved the program an estimated \$250 million. Also, in the late 1990s, estimates for future inflation declined markedly, reducing the program estimate by \$400 million. The combined effect of these cost variances was a net decrease of \$140 million in the aggregate estimate for development and production of GPS.

The modernization effort that begun in 1996 became much more involved by January 1999 with Vice President Gore’s announcement

¹⁵ This baseline estimate and all subsequent baseline estimates exclude all acquisition costs for the 40 Block I/II/IIA satellites.

of two additional civilian signals for GPS, as described above, which added costs estimated at \$426 million.¹⁶ Cost growth associated with the new capabilities amounted to \$1.56 billion by the end of 1999. As a direct result of all the changes, the existing IIF program was put on hold in October 1999.

Before the planned upgrades, the overall capabilities of the IIR satellites built by Lockheed Martin and those of the IIF satellites built by Boeing were intended to be approximately the same. Also before the upgrades, each contractor was responsible for developing the OCS functions for its own satellites, with the intent that they coordinate efforts to ensure interoperability. Our interviews revealed that this arrangement did not work well—i.e., the two contractors did not effectively coordinate their continuing OCS development efforts. When the new capabilities were approved in 1999, the program office saw the need to change the contractual arrangement between the two contractors to ensure an integrated OCS for all GPS satellites. In October 1999, the Lockheed Martin OCS efforts were consolidated under the Boeing modernization OCS contract, with Boeing taking the overall lead.

As of the end of 1999, the IIR satellite contract with Lockheed Martin called for 21 satellites, 18 of which were already delivered. Three of those 18 had been launched, but none of the three was fully operational.¹⁷ This left 15 completed and three in-production IIR satellites that had not yet been launched and were therefore potentially available for upgrading with the added capabilities. The upgrade contract for the IIR satellites called for the upgrading of as many as 12 of these satellites. The implication was that the remaining six IIR satellites would be required to be in orbit before the upgrade on any IIR was complete. The upgraded satellite configuration was designated IIR-M.

None of the six IIF satellites originally placed on contract with Boeing in 1996 was delivered by the time work was stopped in Octo-

¹⁶ This estimate included \$130 million in funding provided by the U.S. Department of Transportation.

¹⁷ The first was lost in a launch failure, the second experienced continuing on-orbit test problems but attained basic functionality, and the third, which was recently launched, was undergoing on-orbit testing.

ber 1999. Congress approved the modernization of all IIF satellites; thus, the six partially completed satellites and all subsequent build-from-scratch IIF satellites required additional development and manufacture to meet the newly specified capabilities. Upgrades to both the Lockheed Martin IIR and Boeing IIF satellites were put on contract just after the August 2000 congressional approval.

In addition to the capability enhancements, a large fraction of the envisioned program was transferred into a future GPS system. Its satellites were designated GPS III, and their new associated ground segment was named OCX. The development funding for GPS III and associated OCS functionality transferred out of the program resulted in \$680 million being removed from the current program; the procurement funding for 36 GPS satellites and associated OCS operations transferred out of the program resulted in \$3,300 million being removed from the current program. The creation of the future GPS III and OCX programs reduced the number of new satellites yet to be produced in the current GPS program from 42 to six.

In February 2002, all the above changes were incorporated into a new APB. The new APB was the first time the program baseline had been updated since May 1996. The full modernization effort included two additional civilian signals, full-earth coverage military code, and increased power in the military signal. The APB approved by the Under Secretary of the Air Force (USecAF) was valued at \$5.12 billion. This figure included the original purchase of the 21 IIR satellites, the modification of 12 of the IIR satellites with a new civil signal and full earth coverage for the military signal, the original purchase of six IIF satellites and their subsequent modification with two new civil signals and full earth coverage for the military signal, and the purchase of six all-new IIF satellites with all the capability of the prior six modernized IIF satellites. In total, 33 satellites are in the baseline number: 9 IIR, 12 IIR-M, and 12 IIF, or 36 fewer satellites than the program plan had called for just two years earlier.¹⁸

¹⁸ Sixty-nine satellites were planned as of the end of 1999, a reduction of nine from the May 1996 baseline.

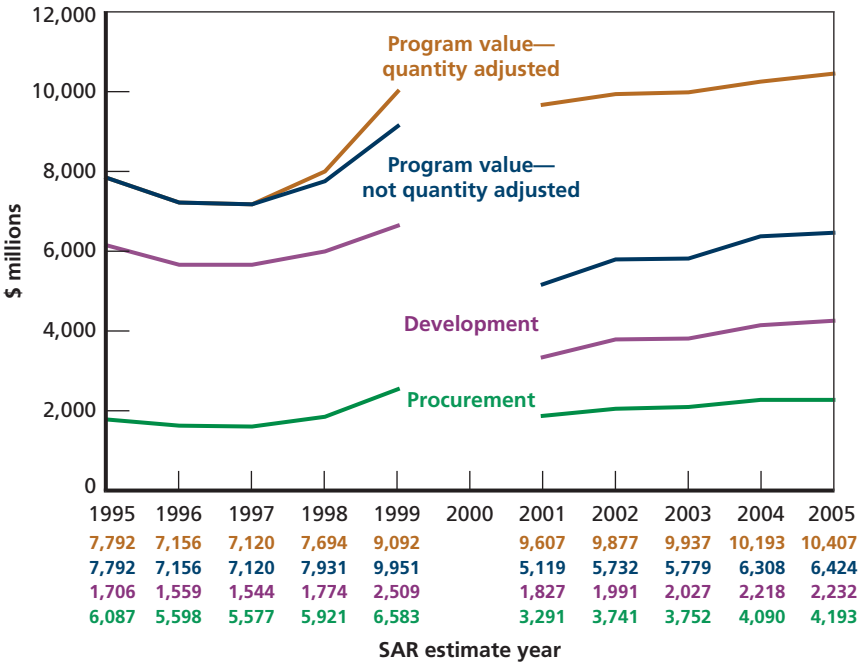
The 2002 re-baseline was preceded by an extended period of requirements analysis. In our view, this added considerable technological complexity and requirements to both the space and ground GPS segments. The new capabilities represented what amounted to a generational update of the system. The differences between the old and new systems probably should have precipitated the declaration of a new MDAP by the relevant Defense Acquisition Authority. Doing so would have required new MS B authority, and that process would have illuminated both the costs and benefits of the next generation of GPS. It is not clear why restructuring as a new program was not pursued.

Continuing evolution of requirements and other factors led to yet another new program baseline dated Feb 14, 2003, representing the third APB in ten years. The USecAF APB, which had a program value of \$5.73 billion, called for 37 satellites in total, with the modernization of eight existing IIR satellites, rather than 12. This baseline included four additional newly built satellites with an associated \$288 million for their production, and mandated that a “Flexible Power” capability be added to all IIR-M and IIF satellites, with an associated \$300 million added to the program.

Over the next three years, program costs continued to grow. Some \$200 million was added for IIF satellite and OCS cost growth resulting from ground system manufacturing difficulties. In 2004, three satellites and \$237 million were added to the current program plan because of schedule slips in developing the future GPS III program, and increases in cost estimates for OCS resulted in an additional \$210 million. In 2005, more functionality was transferred out of the program to the future GPS III and OCX, removing \$190 million from the current program and adding years of additional OCS support for the IIF program at a cost of \$170 million.

Figure 2.3 shows the total GPS IIR, IIR-M, IIF, and OCS program values over time. The break in the year 2000 resulted from the absence of a SAR at the end of that year. Note that the total program value (as shown in the blue line) is substantially less after 2000 than it was before 2000, and is about 17 percent lower in 2005 than it was in 1995. This decline resulted from the removal of about half the

Figure 2.3
A Ten-Year Look at SAR Cost Estimates for GPS Development and Procurement



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total planned satellites from the program. Adjusted for satellite quantity change (orange line), the program’s total value increased by \$2.6 billion, or about 34 percent, from 1996 through 2005.¹⁹ The value of program expenditures for development increased by about a third over the ten years, while that for procurement decreased by about a third.

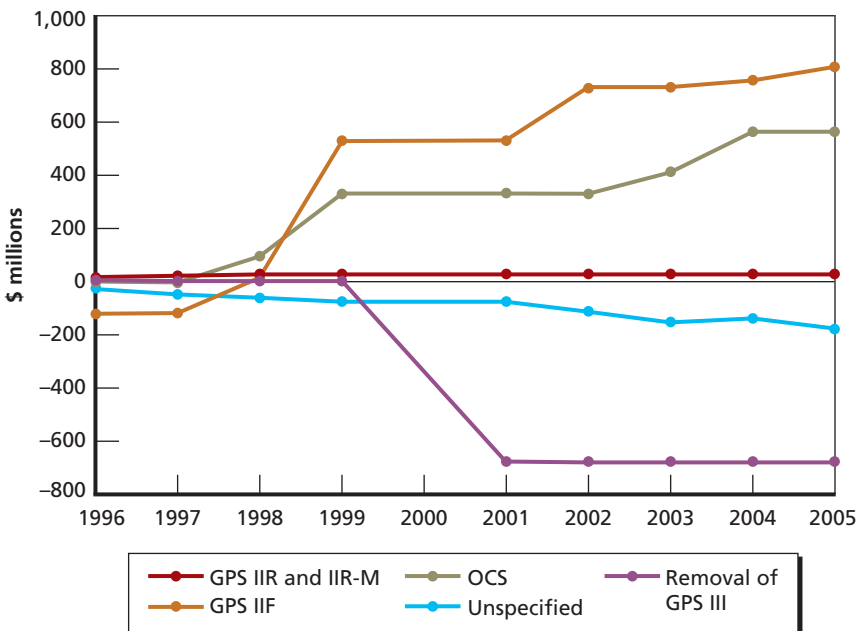
Over the ten-year time frame, GPS program SARs reported some 169 cost variances. The total included 67 in development and 102 in procurement. The acquisition program does not include funding from

¹⁹ The quantity adjustment was made using the average unit procurement cost for those units remaining in the program in each year’s estimate for the entire production run. The per-satellite adjustment value is unique to each annual estimate, steadily increasing from about \$95 million in 1999 to about \$105 million in 2005.

O&M or MilCon accounts. We were able to allocate most of the variances to their applicable program segment—IIR-M satellites, IIF satellites, and OCS ground segment—in the development program.

The cumulative development variances over time for each program segment are shown in Figure 2.4. Those directly attributed to the IIR satellites (red line) are quite small when combined with the later modernization of eight of them. The cumulative development variance for the IIF satellites (orange line) is more than \$800 million, and that for OCS development (gray line) is almost \$600 million. These increases are somewhat offset by two areas of decreases. Almost \$200 million in cumulative development cost underrun was not identified with specific program segments (blue line), and almost \$700 million in future development efforts was transferred to the GPS III satellites and their OCX ground segment (purple line).

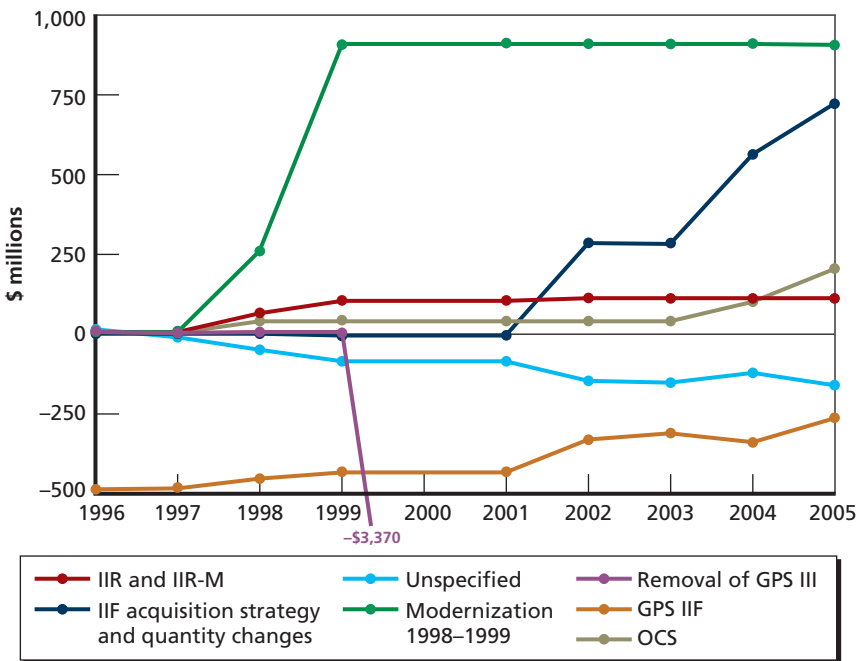
Figure 2.4
Cumulative Development Cost Variance, by Program Segment over Time



The time trends in the figure suggest that beginning in 1999, when the costs of added capabilities began to come into better focus, a decision to shift many of these capabilities to the following generation's system was made. Had this not been done, the development cost growth in the program would have been at least the currently measured \$500 million plus the \$700 million transferred to the future GPS space and ground segments.

Cumulative procurement variances over time for various activities are shown in Figure 2.5. We have attempted to allocate variances to specific efforts in the program and to specific events that occurred over the ten-year time frame.

Figure 2.5
Cumulative Procurement Cost Variance, by Program Segment or Specific Effort over Time



The modernization effort defined during 1998 and 1999 (green line) added more than \$900 million in cost growth to the production program. All this growth occurred by the end of 1999, meaning that it represented early estimates of the costs of adding the new capabilities defined by the end of that year to future GPS satellites. The aggregate cost growth represents an approximate \$18.8 million per unit cost increase for each of the 48 satellites remaining in the planned production program at the time.²⁰

The initial IIF effort was put on contract in 1996 (orange line) with a \$490 million reduction in the cost estimate, almost all of which resulted from the lower-than-expected contract value awarded to Boeing. The contract value reduction portion amounted to \$37.5 million less for each of the 12 satellites covered by the contract and its options. The contract was signed for an amount much lower than that the program office expected and was almost certainly a result of Total System Performance Responsibility (TSPR) and other acquisition reform policies of the time.²¹ Over the next ten years, that reduction shrank to about \$19.2 million per satellite. Note that none of the 12 satellites has yet been delivered, and, according to our program office interviewees, their costs continue to grow.

The second piece of IIF cost growth (dark blue line) covers changes in the configuration and some of the changes in the quantity of IIF satellites to be procured. The cost estimates for these efforts grew by more than \$700 million. It appears that these changes did not begin until after the modernization program was defined—that is, after the February 2002 baseline was established. However, before that date, nine satellites were removed from the planned program. The associated \$246 million in cost savings was essentially offset by \$241 million in increases for acquiring the remaining satellites, which was attributed to changes in the acquisition strategy from multiyear procurement to

²⁰ As of December 1999, the program contained 69 satellites. Of those, 21—all IIR models—were complete or nearing completion and were not yet considered for upgrading to the IIR-M configuration. This leaves 48 satellites in the program to which added capabilities applied at the time.

²¹ See Chapter Four for a more comprehensive discussion of the cost-estimating issues associated with TSPR and other acquisition reform measures.

annual satellite buys. All of the \$700 million in growth in 2002–2005 is attributable to the quantity increases from 33 to 40 and additional changes in acquisition strategy.

When we combine the two lines directly associated with the IIF satellite program on Figure 2.5, we observe a net increase of \$438 million for a program that will procure two fewer satellites and that has yet to deliver a completed satellite ten years after the original contract award.

The transfer of 36 satellites (the program quantity was reduced from 69 to 33 between 1999 and 2001) and future ground system capability from the current program to the future GPS III and OCX segments (purple line) resulted in \$3,370 million in cost underrun. This entire amount represents the transfer of work scope to a newly created follow-on program and was made possible in large part by the extraordinary lengthening in the average life expectancy of the Block IIA and IIR satellites.

The cumulative procurement variance for IIR satellite design fixes and technology development problems (red line) is just over \$100 million. All of this growth took place before 2003, which makes sense because all IIR satellites were delivered by the end of 2001.

The cumulative procurement variance for the OCS ground segment (gray line) is about \$200 million. Growth in this element was small until 2004, at least partially because of the functionality transferred out of the program to the future OCX segment at the end of 2001. We believe that most of the growth in this effort was reported in the modernization variances through 1999 and that some of the growth has not yet been reported because the work is far from complete. Information provided from our interviews strongly suggests there will be substantial additional cost growth in the OCS segment in the future.

About \$160 million in cumulative procurement cost underrun was not identified with specific program segments or activities (light blue line). These variances were mostly associated with inflation adjustments, reprogramming of funds out of the program, and program wide support function estimate changes.

We were not able to identify specific cost growth in the IIR-M effort. The effort was not mentioned in a single one of the 102 procure-

ment cost variances. It is likely that much of the cost growth before 2002 is in the funding removed from the program when the follow-on GPS III and OCX efforts were created and associated funding was transferred out of the current program at the end of 2001.²² After 2001 the cost growth is most likely buried within the reduced number of satellites to be modernized, which declined from 12 to eight without associated cost estimate adjustments. Wherever this cost growth is, we believe that it will continue because the work is not complete.²³ In addition, according to our interviews, the contractor has requested and been granted reimbursement for several hundred million dollars more in overruns. These sources of cost growth are not reflected in the data extending to the end of 2005.

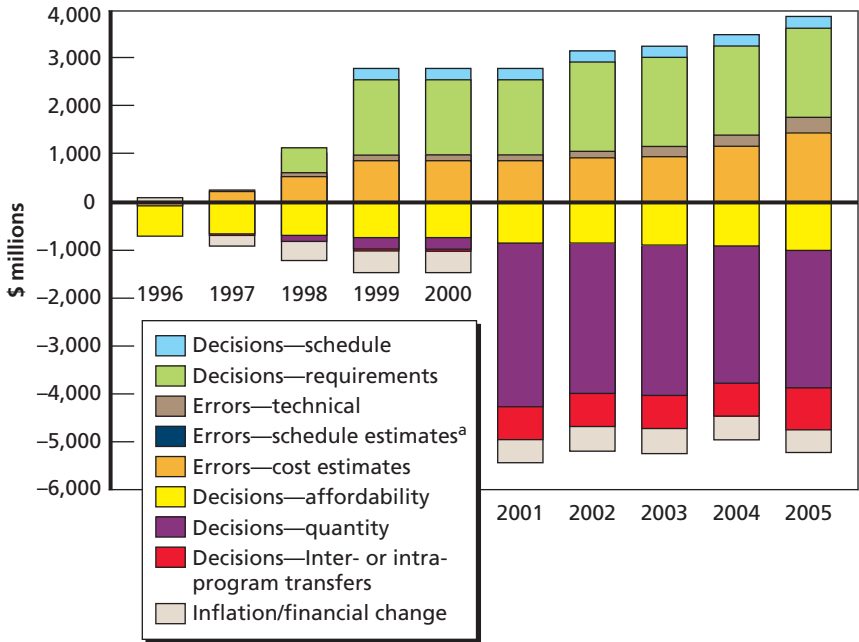
The changes in the development plus procurement program estimates over time by RAND cost growth categories are shown in Figure 2.6. Cost growth and underrun in each subcategory are summed. Nine subcategories in all apply to the program: three in the Errors category, five in the Decisions category, and the Financial category. Of these nine, four caused substantial positive cost growth, and four caused substantial negative cost growth.

The program experienced about \$3,870 million in cost growth, with about \$1,440 million in the Errors subcategory of cost estimates, \$330 million in the Errors subcategory of technical issues, \$240 million in the Decisions subcategory of schedules, and \$1,860 million in the subcategory of requirements. The subcategory of quantity dominated the cost underrun, accounting for \$2,860 million of the total \$5,240 million in cost underrun. Decisions associated with inter- or intra-program transfers, mostly development funding in the form of transferring capability to the GPS III and OCX future segments,

²² This is done by underreporting the costs associated with the portion of the program transferred out and using the balance of that value, the retained funds, to “get well” on cost growth within the remaining program content.

²³ As of December 2005, three of the eight IIR-M satellites had been delivered; one had been launched.

Figure 2.6
Cumulative Variances in GPS Development and Procurement over Time
Using RAND Methodology



^aQuantities are either zero or too small to show.

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accounted for \$880 million in cost underrun, and inflation changes accounted for the \$480 million in cost underrun. The remaining \$1,020 million in cost underrun came from the subcategory of affordability, resulting from dozens of incidents where the GPS program became a “bill payer” for other programs. Variances in the GPS SARs were described in such a way that the Errors subcategory of schedule was not used, though undoubtedly it should apply to some subset of the total variance in decisions.

GPS Cost Variance Bottom Line

The development and production contract for the GPS IIF follow-on satellites was awarded in 1996 under a TSPR arrangement to a new con-

tractor at an “optimistic” low price. During the mid-1990s, awarding contracts with these characteristics was common and a product of the overall defense budget environment and acquisition reform culture of the time. This acquisition approach added much higher uncertainty to these satellites’ cost, schedule, and technical performance outcomes.

The GPS program was used as a bill payer for other programs that were in financial need throughout the ten-year period. In addition, the contract EAC for the OCS modernization increased from \$12 million in April 1996 to \$747 million in December 2005. This illustrates the ever-increasing requirements—especially between 1998 and 2001—that complicated both the space and ground segments and drove much of the cost growth. A strong argument can be made that a new MS B should have been declared with the new APB of late 2001 and early 2002.

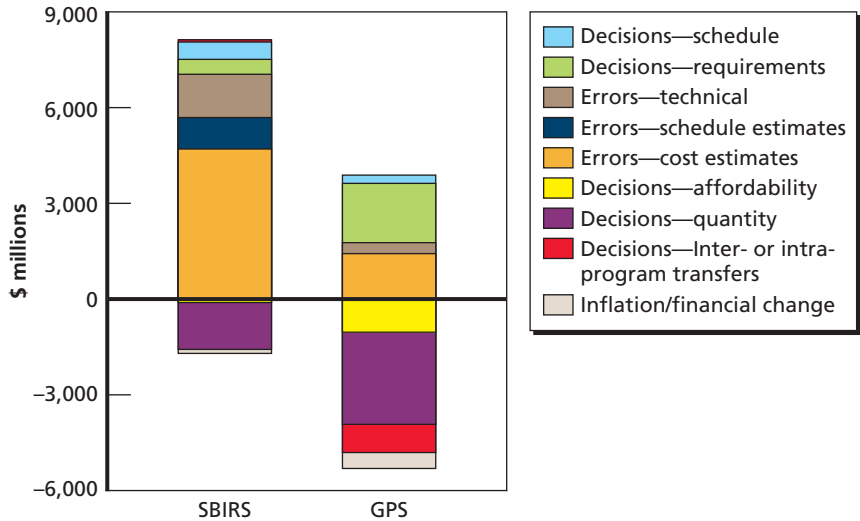
If the GPS II and IIA satellites from the 1980s had not lasted considerably longer than expected and the GPS III satellites and associated OCX had not been moved into a future, separate program, the GPS program would not have been the bill payer that it was. In essence, the program unexpectedly inherited a capability that allowed it to delay launching replacement satellites. At the same time, it was able to push off onto its successor program many of the capabilities that were added as new requirements during the ten-year period covered in our analysis. Because of the modernization difficulties in all the program’s current segments—the IIR-M, IIF, and OCS—it would have experienced mission deficiencies if these added capabilities had been time-critical.

Comparing Cost Variances in the Two Space Programs

The relative fractions of cost growth distributed among the RAND variance categories for the two programs are shown in Figure 2.7. Some similarities between the programs include the following:

- Cost estimate errors account for a substantial portion of cost growth.
- Quantity was cut substantially to reduce total program value.

Figure 2.7
Comparison of Cost Growth Contributors, by the RAND Cost-Variance
Categorization Methodology



RAND MG690-2.7

- Decisions to add requirements and change schedules were sources of cost growth.
- Technical difficulties were errors with significant associated cost growth.
- Inflation was a source of cost underrun.

Figure 2.7 does not tell the whole story. Other similarities between the two programs include the following:

- Both programs experienced poor outcomes from the portion of their program awarded under a TSPR contract.
- Both experienced huge values of total variance—cost growth and cost underrun—over the ten-year period, \$9.1 billion in GPS and \$9.8 billion in SBIRS.
- Both were “saved” by satellites from their predecessor programs that have remained operational substantially longer than expected.

While both programs experienced substantial cost growth in content-adjusted terms, there were significant differences, including those listed below:

- Initial and final program values were quite different: \$3.7 billion to \$10.2 billion in SBIRS-High; \$7.8 billion to \$6.4 billion in GPS.
- SBIRS-High experienced extremely high cost growth (by historical standards) attributable to the Errors category.
- GPS experienced more-typical cost growth in Errors and in the Decisions subcategory of requirements.
- SBIRS-High SARS were slow to recognize cost growth in the program's first four years; GPS SARS consistently recognized cost growth during that same time frame.
- Except for quantity reductions in both programs, SBIRS-High experienced little cost underrun; GPS experienced much more.
- The Air Force spent much more than planned on SBIRS-High over the ten-year period but less than planned on GPS.
- SBIRS-High experienced very little requirements changes (by historical standards); GPS experienced dramatic requirements changes.

Technical Risk Assessment Relating to Cost Estimation for SBIRS-High and GPS

Introduction

In this chapter, we analyze the technical risk assessments in the cost-estimating processes for the SBIRS-High and GPS modernization programs (OCS, IIR-M, and IIF) to gain insights into factors that may have contributed to the underestimation of costs. Several studies on national security space acquisition have cited technical risks as one of the key factors that contribute to cost growth.¹ Technical risks, such as immature technologies or a compressed testing schedule, lead to technical difficulties that could eventually result in failures in meeting the technical performance. As a result, redesigns and rework may be required, which slow the progress of the program and cause schedule slips and cost growth. It is not surprising that underestimation of technical risks was one of the key factors that contributed to cost estimation errors in SBIRS-High and GPS, as the SAR analysis in Chapter Two showed.

Identifying potential technical difficulties associated with developing a system is a critical component in the cost-estimating process. It is equally critical to quantify the potential cost uncertainty in the cost

¹ GAO, *Defense Acquisitions: Despite Restructuring, SBIRS High Program Remains at Risk of Cost and Schedule Overruns*, GAO-04-48, October 2003; Defense Science Board, *The Future of the Global Positioning System*, Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, October 2005; and Booz Allen Hamilton, "Space Systems Development Growth Analysis," briefing, Los Angeles, Calif., August 2, 2002.

estimates due to technical risks. Understanding the technical risks of a program and how they contribute to its costs is of paramount importance. Arena, Younossi, et al. (2006) discuss risk and uncertainty in detail and explore how risk should be treated in cost estimation.² Here we focus on detailed technical risk assessment processes from SBIRS-High and GPS. The objective of this analysis is to identify broad lessons learned from the two programs to extract some principles that can be applied to technical risk assessments in cost-estimating processes in general. These general principles can be used to enhance the technical risk assessment processes in either existing programs or future programs to improve the cost-estimating capability.

We begin with an overview of the technical issues that the SBIRS-High and GPS programs have experienced and discuss what may have caused these technical difficulties. These technical issues provide some insight into what types of technical risks might have been missed or underestimated throughout the development phases. We then examine how technical risks were assessed and then translated into potential effect on costs in these two programs. We analyze the data, the methods, and the processes (personnel, information flow, etc.) used in the assessments to identify potential factors that may have contributed to underestimation of the types of technical risks that the SBIRS-High and the GPS programs experienced and to underestimation of cost implications. We conclude with a summary of observations and recommendations based on the analysis.

Overview of Technical Issues in SBIRS-High and GPS

SBIRS-High

SBIRS-High is being acquired in two increments. Increment 1 is an upgrade to the ground segment for operating the DSP satellites. It consolidates the DSP and other facilities into a single mission control sta-

² Mark Arena, Obaid Younossi, Lionel Galway, Bernard Fox, John C. Graser, Jerry Sollinger, Felicia Wu, and Carolyn Wong, *Impossible Certainty: Cost Risk Analysis for Air Force Systems*, Santa Monica, Calif.: RAND Corporation, MG-415-AF, 2006.

tion. Increment 2 includes HEO sensors, to be put on separate host satellites, and GEO satellites, as well as an upgrade to Increment 1 to operate the HEO and the GEO satellites.

Since the inception of the program, SBIRS-High has encountered a host of technical problems that eventually led to schedule slips and cost growth. Early in the program, SBIRS-High experienced technical difficulties with sensor development; examples include the sensor chip assembly needed for sensor detector arrays and pointing control assembly software development. The control gyro reference assembly also failed during its life testing and had to be fixed. In 1999, Increment 1 failed its developmental and operational testing and continued to experience problems with ground software that resulted in a two-year slip. In 2001, a major design change occurred late in the design phase. The GEO design had to add a 12-foot sunshade for off-axis solar radiation rejection. The prior design allowed off-axis solar radiation to impinge on the focal plane array when the sensor line of sight is near the sun. This problem degraded sensor performance and, if left unaddressed, would have led to a failure to meet the KPP.³

Once the program entered the testing phase for the HEO sensor, multiple technical problems were found. In 2000, the HEO flattener lens failed during the first random vibration test. The lens came out of its mounts due to design deficiencies. Then the corrector lens failed during the second test in 2001. These failures required redesign and rework, which added to cost growth.

After the program restructure in 2002, serious electromagnetic interference (EMI) problems were found during the integration of the first HEO sensor with the host bus. The sensor had 148 EMI frequencies that did not meet the EMI tolerance requirements, which could have adversely affected the operations of the host satellite.⁴ Making design modifications to correct this problem added one year to the

³ Timothy Bonds, Richard Mesic, Jon Grossman, Gary McLeod, Joel Kvitky, David Vaughan, Rosalind Lewis, Manuel Cohen, Robert Leonard, James Bonomo, Lionel Galway, Mel Eisman, and John Graser, *Assessing Selected Space-Based Infrared System—High (SBIRS-High) System Risks*, Santa Monica, Calif.: RAND Corporation, May 2003. Government publication; not available to the general public.

⁴ GAO, 2003.

schedule. After the first HEO sensor delivery, SBIRS-High continued to experience technical issues, for example, in GEO signal processing software development and HEO-2 payload software qualification testing.

GPS IIR-M, IIF Modernization, and OCS

The modernization of IIR and IIF faced some difficulty with implementing the new secure military (M-code) signal. The contractor assumed that the National Security Agency (NSA) already had a chip that had the M-code algorithm. However, it turned out that the NSA had neither the chip nor the algorithm. The contractor had to work with the NSA in a special access environment to develop the algorithm, which added a number of complexities.⁵

IIR-M had another major technical issue with a new circuit board that was required for the M-code. IIR-M used a field programmable gate array (FPGA) commercial chip, and the FPGA had a reliability problem that delayed the program by six to eight months. FPGA was a new-technology item, and its failure mode was not well understood. Normally, an application-specific integrated circuit (ASIC) is used, but an ASIC takes longer to program. Because of a schedule problem and the general emphasis on commercial off-the-shelf technologies (COTS), the IIR-M program decided to use the commercial FPGA.

Unlike IIR-M, the IIF modernization program used an ASIC chip for the M-code, but it experienced other technical difficulties. The contractor tried to fit everything on one ASIC and spent much time optimizing the design. Eventually, IIF ended up with two ASIC chips, which added complexity in development to deal with the interface between the two chips. Additionally, the M-code implementation on IIR-M and IIF turned out to be incompatible, and the IIF design had to be changed. The government believes that the IIF design did not function properly, although the contractor disputed this.

There have also been technical issues during integration, assembly, and testing (IA&T) in IIF and IIR-M due to late deliveries from suppliers and quality issues with some parts. In some cases, specifications

⁵ It is U.S. government policy that all encryption must be done through the NSA.

had not properly flowed down to the subcontractors, and less-stringent commercial standards were used. IIF has also been experiencing problems with developing test plans. The engineers at one of the contractor's sites were responsible for developing the test plans and delivering them to another site for IA&T. However, the IA&T staff could not execute the test plans because the plans did not have specific detailed procedures. At the time of this study, the contractor had proposed that the IA&T facility develop the test procedures.

Delivery of OCS capabilities has continued to be delayed since the beginning of the program. Currently, OCS operates the GPS constellation as block IIA satellites. Due to the continuing delays in capability delivery, the software elements that are necessary for operating the flexible power and the new signals on IIR-M and IIF have been removed from the program. OCX, the new control segment program, will be implementing these capabilities. As a result, OCS will operate IIR-M and IIF as IIR satellites when OCS is complete.

Early in the program, OCS was directed to maximize the use of COTS because it was assumed that use of COTS software products would save significant costs. However, OCS experienced difficulties with modifying multiple COTS software systems and integrating them. Changing much of the COTS software was challenging because there was no design documentation; small changes in inputs and outputs translated into large rewrites of the software because engineers lacked knowledge about the details of the COTS software that was to be used for OCS. Software reliability also became an issue because the requirement for software reliability for a national security application is much higher than that for the commercial world. In addition, there were obsolescence issues with the COTS during development. Keeping up with COTS upgrades added to the technical problems because any upgrade to any software product required a rework on other products due to the large number of interfaces.

Potential Causes of Technical Difficulties in Development of SBIRS-High and GPS

According to our interviews and our literature review, these technical problems had multiple causes. In SBIRS-High, some of these technical

problems have been attributed to inadequate systems engineering, an aggressive schedule, TSPR, overly aggressive adoption of commercial standards and practices for military applications, a lack of process controls at both prime contractors and subcontractors, and the reduction in the acquisition workforce.

Increment 1 ran into technical difficulties partly due to overreliance on COTS software products and software reuse. The program underestimated the technical risks associated with COTS. The problem with the off-axis solar radiation on the GEO design was discovered when the contractor produced a better thermal model after the critical design review (CDR). It is not clear why the problem was discovered so late in the design phase.

On the EMI matter, our interviews suggest that it was a process failure. The EMI requirements were very stringent because SBIRS-High is a multiple-payload spacecraft. There was an EMI design review in 2000, and there was a concurrence on the EMI control plan. However, the subcontractor did not implement the plan. Another factor that may have contributed to the EMI problem is that no contractor was clearly responsible for integrating the HEO sensor with the host bus. The SBIRS prime contractor was responsible for the HEO sensor only.

Some technical aspects were difficult to forecast early in the program. For a system as complex as SBIRS-High, system integration and flight and ground software turned out to be much more difficult than estimated in part because of a lack of a historical analogue. The report from the SBIRS-High Independent Review Team in 2001 stated that the complexity of developing engineering solutions to meet system requirements was not well understood by program and contracting officials.

Some of the technical difficulties experienced in IIR-M and IIF have been attributed to inadequate contractor capabilities and underestimation of the complexities of working through NSA. For IIF, additional factors such as lack of domain knowledge on the contractor's part and instability of the contractor's program infrastructure, may have contributed to the technical problems. The contractor moved development and production work from one location to another on

several occasions, which led to staffing issues and high turnover rates. This degraded organic capability to develop the system.

The Defense Science Board (DSB) report on GPS in 2005 stated that many of the technical problems that OCS faced since the beginning of the program have been attributed to substantial use of COTS and multiple contractor changeovers.⁶ Our interviews also indicated that the contractors' lack of domain knowledge and poor program management may have contributed to some of the technical problems.

In general, both programs significantly underestimated technical risks and their potential effect on costs. At SBIRS-High source selection, the government's technical assessment was not thorough enough to capture the technical risks associated with system integration and software. Technical experts focused on identifying and assessing risks associated with key technologies and underestimated the integration effort required for a complex system like SBIRS-High. The experts also did not focus on the ground software. Flight software was underestimated because of lack of historical perspective (i.e., the DSP had no flight software). Those responsible for OCS underestimated technical risks associated with using COTS for controlling a unique system such as GPS.

Our interviews also indicated that technical risks may have been underestimated, and these risks had ripple effects due to the complex interrelationships of various components and subsystems.⁷ Both the SBIRS-High and GPS IIF programs experienced technical problems that led to a "standing army" effect; that is, the production and IA&T staff were essentially placed on standby because of delays in development from unanticipated technical issues. For instance, the HEO EMI problem caused a major disruption to IA&T while the EMI problem was being corrected. In GPS IIF, the original program was already in production when the modernization decision was made. When technical issues in development of the modernized IIF delayed the development schedule, the contractor had to carry production people at a lower

⁶ Defense Science Board, 2005.

⁷ By *ripple* or *cascade effect*, we mean that a technical problem triggered a chain of other technical problems.

work rate until development was finished. The GPS IIF program may have also underestimated risks in technical executability due to inadequate contractor capabilities, an inadequate industrial base, and the complexities associated with working with the NSA.

A review of the technical issues in the SBIRS-High and GPS programs indicates that technical risks associated with COTS and software reuse, contractor capabilities, systems integration of a complex system, and potential ripple effects were unanticipated and hence underestimated.

Technical Risk Assessment and Quantification Processes on the SBIRS-High and GPS Programs

The SBIRS and GPS programs did not always conduct technical risk assessments to support cost estimates. In this monograph, we specifically address the processes used at key points in the programs: in SBIRS-High at source selection and at the 2002 and 2006 EACs, and in GPS at the 2001 program office estimate (POE).

At source selection, the SBIRS-High program office performed cost estimates of the proposed contractors' designs that included technical risk assessments. Since source selection, the SBIRS-High program office has completed several full-up EACs, which included technical assessments in 2002 and 2006 to support program re-baselines. Other EACs were based on contractor's estimates without a technical risk assessment on the program office's part.

At source selection, the SBIRS-High program office implemented the Relative Risk Weighting (RRW) technique, a component of the Cost Risk Identification and Management System (CRIMS) process, to assess technical risks and to determine the cost-probability distributions. CRIMS was developed by the Space and Mission System Center Cost Directorate (SMC/FMC) in the early to mid-1990s. Since source selection, the CRIMS process has not been implemented in SBIRS-High. The program office developed different risk assessment and quantification methods in 2001, and the program office has continued to use the same approach. The approach is somewhat similar to the CRIMS RRW method but in a simplified form.

For OCS and GPS IIF, we were unable to retrieve detailed information about the cost-estimating process at the beginning of the programs in 1994 and 1996, respectively. According to our interviews, the contractors generated the estimates for these programs before 2001. When the modernization decision was made in 2001, formal POEs for IIR-M, IIF, and OCS were completed. In recent years (the past three years or so), there has been no formal technical risk assessment process to support cost estimation in GPS IIF, IIR-M, and OCS. For IIR-M and OCS, this is partly due to the fact that these programs are in late phases of execution. The program office primarily relies on “actuals” to conduct earned value (EV) analysis for cost estimates rather than on a formal technical risk assessment. The technical risk assessment process in GPS has changed since the 2001 POE, and it primarily applies to the program’s future segments—GPS III and OCX. GPS IIF had only partially implemented the current methods and processes in its EAC in 2006, and thus we will not discuss GPS’s current processes in this monograph.

Our information about the technical risk assessment processes used in cost estimation came from multiple sources. We interviewed SBIRS-High SPO personnel and systems engineering and technical assistance (SETA) contractors who provide cost-estimation support, as well as Aerospace Corporation technical support personnel.⁸ We also interviewed current and prior GPS SPO personnel and received documentation on the 2001 POE cost-estimating processes. The information about the risk assessment methods and processes for the 2001 POE is solely based on the 2001 POE report for IIF and OCS. We assumed that the technical risk assessment and quantification processes for the IIR-M cost estimates were similar, if not identical, to those for the IIF and OCS in 2001 because the same SETA support personnel developed the POE for IIR-M as well.

The technical assessments that supported the 2002 and 2006 EACs had five risk categories and five uncertainty levels. Table 3.1 shows these categories and the criteria for each uncertainty level. The

⁸ The Aerospace Corporation is a federally funded research and development center (FFRDC) that provides technical support to various SMC programs.

Table 3.1
SBIRS-High Risk Survey in 2002 and 2006 EAC

Risk Category	Uncertainty Level				
	1	2	3	4	5
Required technical advance (science)	Nothing new	Minor modifications only	Major modifications	At state of the art	Beyond state of the art
Technology status (engineering)	In use	Prototype exists	Under development	In design	Concept stage
Complexity	Simple	Somewhat	Moderately complex	Highly complex	High complexity and uncertainty
Personnel/equipment	Expert personnel with equipment with excess capability	Trained personnel with equipment with demonstrated capability for this application	Mixture of trained and new personnel with equipment that appears to have the capability to do the job	Insufficiently trained personnel with equipment with known inadequacies	Untrained, inexperienced personnel with no useful equipment
Schedule quality	Duplicate of past OR schedule more than 25% expanded	Similar to past OR schedule expanded greater than optimum	Validated OR near optimum (adequate slack time)	Inadequate analysis OR schedule compressed more than optimum	Unknown or unsupported schedule OR schedule more than 25% compressed

SBIRS-High program office developed the definition of the risk categories and the criteria for the uncertainty levels based on the Maxwell risk criteria matrix (MRCM).⁹ There is no document containing a detailed definition of the categories or criteria for these uncertainty levels. However, for the 2006 EAC, the cost estimators trained the assessors on this risk assessment method to clarify the ground rules and assumptions of the method as well as the definitions and the criteria of the risk categories and uncertainty levels.

The GPS programs took three approaches to technical risk assessment: (1) hardware work breakdown structure (WBS) elements (IIF hardware and OCS hardware) whose cost estimates were based on cost-estimating relationships (CERs), (2) hardware WBS elements whose cost estimates were analogy-based, and (3) software (IIF flight software and OCS software) WBS elements. For CER-based hardware WBS elements, there were ten risk categories: required technical advance, technology status, complexity, dependence on other WBS items, corporate experience level, manufacturing precision, reliability, producibility, schedule estimate, and schedule duration. The definitions of these categories and the extreme ends of the uncertainty levels (i.e., the lowest and the highest) were documented. This risk assessment framework did not apply to the analogy-based hardware WBS elements. Instead, technical experts directly provided the lower-bound, most likely, and upper-bound multipliers to be applied to the costs of IIR analogous elements as a means to account for risk factors.

Technical risk assessment for software elements followed the method that was incorporated in a commercial cost-estimating model called SEER. The model had 33 risk categories, which are referred to as *complexity attributes* in SEER.

⁹ The program office had SETA support for cost estimation and it developed the risk assessment methodology. MRCM is a risk assessment framework developed by F. D. Maxwell of the Aerospace Corporation in the mid-1980s. The matrix identifies risk-drivers and a range of risk levels. See David R. Graham, "New Initiatives in Program and Project Management," NASA Presentation, 2005 NASA Cost Estimating Symposium, New Orleans, La., April 12–14, 2005, for more detailed information.

Potential Factors That Contributed to Underestimation of Technical Risk Assessment

Based on our analysis of the key components in the technical risk assessment processes in the SBIRS-High and GPS programs—data sources, technical risk assessment and quantification methodologies, staff involved in the processes, information flow among the staff—we found that the following factors may have contributed to inadequate technical risk assessments:

- data availability and quality issues
- credibility issues in technical risk assessments
- limitations in risk quantification methodology.

Data Availability and Quality Issues

We found that incomplete and unreliable contractor data, lack of up-to-date integrated information, and limited visibility into contractors' capabilities in the SBIRS-High and GPS programs may have limited the programs' ability to identify all technical risks.

For instance, SBIRS-High still lacked a fully integrated management system as of the 2006 EAC. Integrating the schedules of the prime contractor and the subcontractor has been an ongoing challenge because of the two schedule software products that they use. For GPS IIF, an integrated master schedule (IMS) is not on the contract as a Contract Data Requirements List item. The contractor's schedule is presented to the SPO, but it is difficult to understand and evaluate.

GPS IIF and OCS have also experienced problems with their data-reporting systems for earned value. EV data provide insights into technical executability issues that the contractor may be experiencing. Our interviews indicated that the contractor had an inadequate long-term plan and made optimistic claims regarding what work content had been accomplished. As a result, the contractor's cost performance index and schedule performance index were never realistic, and its EV data appear to have been of questionable quality. OCS presented an additional challenge for accessing subcontractors' data. As a part of the

contract, the prime contractor is responsible for providing its data but not that of the subcontractors.

We have also found that an up-to-date comprehensive view of the programs was not always available for a thorough technical assessment. Integrated information on the program is necessary to be able to identify interrelationships among risks (e.g., how technical risk in one WBS element might affect other WBS elements) such as ripple effects. As mentioned earlier, the IMS, which provides an integrated view of the schedule, has not been available in complete form.

Additionally, SBIRS-High and GPS did not conduct integrated baseline reviews (IBRs) regularly even though these programs underwent significant changes throughout development. SBIRS-High's first IBR was held in 1999 at the time of the Joint Estimate Team (JET) re-baseline. When the program was re-baselined in 2002, an IBR was held after the EAC. Our interviews also indicated that the 2002 IBR did not have adequate representation from all the major disciplines (technical, schedule, and program experts). When the program was replanned in 2004, the SPO did not conduct an IBR because the SPO claimed that the shoulder-to-shoulder review that took place with the contractors at that time was sufficient.¹⁰ For the most-recent EAC in 2006, an IBR preceded the EAC. Because the GPS programs relied on the contractor's cost estimates prior to 2001, it appears that they did not conduct IBRs during that period. Since 2001, IIR-M has not conducted an IBR, and the most recent IBR on OCS was in 2003. IIF conducted an IBR in 2003, and IIF was preparing for another IBR in 2006 at the time of this research.

The SBIRS-High SPO's visibility into the contractor's work was also limited as a consequence of TSPR.¹¹ GPS IIR-M and IIF had a sim-

¹⁰ In the *shoulder-to-shoulder* process, personnel from the contractor and the government sit together and review the data and reconcile any differences as necessary.

¹¹ TSPR is explained in detail in Chapter Four. The key aspects of TSPR are the following: (1) The contractor formulates and proposes its own technical design solution to meet high-level DoD performance requirements, (2) The contractor, with minimal government oversight and direction, is responsible for implementing the proposed solution through the development process. (3) The contractor is relieved of what are assumed to be costly and cumbersome reporting requirements to reduce burdensome overhead costs.

ilar challenge because they were also executed in a TSPR-like approach due to acquisition reform. In this environment, technical staff reviewed only high-level documents, and they were discouraged from any further detailed review of the contractor's work.

Before TSPR, the level of oversight was much more significant. For example, government personnel typically attended tests and conducted plant visits to the prime contractor as well as at the subcontractors' sites to evaluate the facilities, the personnel, and process controls. Critical design reviews were carried out with data packages, design analysis reports, risk analyses, and mitigation plans in a formal structured way. The TSPR environment removed this level of rigor for monitoring and assessing contractor's capabilities. As a result, the program offices possessed limited information for conducting thorough and accurate technical risk assessments.¹²

Factors Reducing the Credibility of Technical Assessments

Technical risk assessments are based on expert judgment and are fundamentally subjective. As a result, the credibility of the assessments depends on the experts' level of expertise and the level of subjectivity. We concluded that the technical risks in the SBIRS-High and GPS programs may have been underestimated because of

- inadequate level of expertise
- lack of independence
- lack of bases for judgment
- flaws in elicitation methods.

Inadequate Level of Expertise. Because technical risk assessment is based on expert judgment, it is critical that technical experts with appropriate domain knowledge assess both the technical content and the technical executability of the program. Inadequate levels of technical expertise may have affected the quality and the thoroughness of the technical assessments on the SBIRS-High and GPS programs.

¹² See Chapter Four for a more comprehensive discussion of the historical context and cost estimating issues associated with TSPR, COTS insertion, and other acquisition reform measures.

The number of Aerospace Corporation personnel, who primarily provided critical technical support for SBIRS-High, had been significantly reduced by the time the contract was awarded in 1996. By the late 1990s, the Aerospace support staff had been reduced to less than half of its original size in 1994. This was due to the assumption that TSPR would require much less in-house technical expertise in the program office. The GPS program also experienced reductions in Aerospace support due to acquisition reform in the 1990s.

In the SBIRS-High 2002 and 2006 EACs, project officers, integrated product team (IPT) leaders (e.g., space IPT, ground segment IPT), and—in some instances—Aerospace technical experts conducted the program office's risk assessments. The project officers were primarily junior officers and in general had limited experience and expertise.

EV data provide insights into technical risks and schedule risks. But the EV analysts in the SBIRS-High and GPS programs lacked the expertise to understand the content of the work and what the data meant in terms of how the program might be affected. Because of the SPO's limited resources, they received limited support from the technical experts; the SPO technical workforce was focused on the technical aspect of the program and support for the EV analysts was minimal.

Given that technical risk assessments are ultimately used to quantify cost uncertainties, a thorough and accurate technical risk assessment requires an integrated and interactive effort between the technical and cost experts. However, there was insufficient communication between the technical and cost experts in the risk assessment processes of the SBIRS-High and GPS programs. In these risk assessment processes, the technical experts filled out surveys or questionnaires, and the cost estimators translated the information into probability distributions without any feedback to the technical experts on their assessments. In some cases, technical experts were required to quantify cost effects, as in the case of the GPS 2001 POE for some of the WBS elements. Technical assessments with inadequate communication between technical and cost experts appear to have degraded the accuracy of the assessments since most technical experts lack cost expertise.

Lack of Independence: Reliance on Contractor's Assessments and SPOs as Advocates. Technical risk assessments in the SBIRS-High

and GPS programs lacked independence because they were based primarily on the contractor's and the SPO personnel's judgment, with little outside disinterested input. Given that these assessments are subjective, there is a possibility of biases as a result of the program environment and pressures from senior leadership in the SPO, which may have caused the risks to be inaccurately assessed.

During the SBIRS-High source selection, budget pressures, the rushed environment, and optimism about TSPR and "best commercial practices" may have played a role in influencing the technical risk assessment. Little uncertainty about the technical parameters that drive the costs was assumed in assessing configuration risks. For example, the cost estimate included a spacecraft weight growth factor of 17 percent compared with a typical historical growth factor of approximately 50 percent. Additionally, there was no software growth assumption in the cost estimate. It was assumed that the contractor design included a sufficient margin. By 2002, the GEO SV dry weight had grown over 50 percent, and the software equivalent Software Lines of Code (SLOC) had grown by about 250 percent.

Our interviews indicate that the environment during the 2002 re-baselining also posed similar challenges for the SBIRS-High program. Due to the 2002 Nunn-McCurdy breach,¹³ there was significant institutional pressure to keep the revised cost estimate down and to fix the program to protect it from the real possibility of cancellation. This environment may have influenced the judgment of the contractor and the SPO about the level of remaining technical risks in the program. For instance, even after 2002, both the HEO and GEO payload development efforts encountered a series of additional technical issues that led to further schedule delays and cost growth. In the risk survey that supported the 2002 EAC, all the GEO and HEO payload WBS elements were rated at the moderate risk level or lower. Only seven WBS elements out of about 80 received a risk rating of high (triangular prob-

¹³ A "Nunn-McCurdy" unit cost breach occurs when an MDAP experiences an increase of at least 15 percent in program acquisition unit cost or average procurement unit cost. A unit cost breach of more than 15 percent requires formal notification to Congress. A unit cost breach of 25 percent or more requires a recertification of the program by the Secretary of Defense, which includes the development and certification of new unit cost estimates.

ability distribution's high-end multiplier of 2.0), and they were mostly ground segment elements. It is unclear if an independent assessment would have yielded a higher risk assessment.¹⁴

Part of the SBIRS-High risk assessment processes in 2002 and 2006 relied on the contractor's assessment. The SPO used the contractor's point estimates and technical risk assessments as the baseline. The contractor presented its list of specific risk items, and the SPO worked with the contractor to adjust the assessment either by adding or deleting risk items and by adjusting the probability of occurrence and costs of risk items. Because the baseline risk items and their costs were those of the contractor, the risk assessment may have been either incomplete (i.e., all risks may not be identified thoroughly) or evaluated in a more optimistic light (i.e., the probability of occurrence and cost were underestimated), given that the contractor has its own incentives that may bias the technical assessment.

Lack of Bases for Judgment and Rigor in Technical Assessment.

One of the main flaws in the technical risk assessments in the SBIRS-High and GPS programs was that acquisition reform and use of COTS were assumed to bring cost savings. There was no fact-finding or rigorous analysis to support the technical risk assessment of these practices and products.

Technical risks associated with TSPR were not adequately assessed at SBIRS-High source selection. The TSPR environment and the focus on COTS led to removal of military standards and specifications and reduction in government oversight. This, in turn, led to process control and quality control issues that resulted in serious technical problems, such as the HEO EMI problem. The GPS programs experienced similar problems with the contractors. There was no fact-finding or historical perspective to support the assumed benefits of acquisition reform.

Technical risks associated with COTS were assumed to be low without an in-depth assessment of the implementation of COTS. For

¹⁴ An independent RAND study at the time explicitly noted that additional technical risks existed beyond those identified during the re-baseline and would likely result in additional technical problems and cost growth. The study findings were published in Bonds et al., 2003, but this report was not released to the general public, nor was it widely circulated within the Air Force.

example, implementing COTS software for GPS's telemetry, tracking and command (TT&C) turned out to be a difficult problem because TT&C for GPS is unique and much more complex than for commercial satellites (which are primarily communications satellites); there are more satellites to control in the GPS constellation and GPS has its own unique infrastructure to control its satellites. Similarly, SBIR's GEO bus was assumed to be low risk because it was based on a commercial bus (the bus was assumed to be a recurring cost rather than a nonrecurring cost). However, the GEO bus experienced significant configuration changes and weight growth because of unique military requirements. Again, no rigorous technical risk assessment supported the initially assumed low risk.

Flaws in the Elicitation Process. Cost analysts often draw on the expertise of engineers, managers, and other experts for subjective probability distributions to represent the uncertainty in technical and other program inputs that form the basis of the cost estimate.¹⁵ They do so to account for the uncertainty that results from the lack of thorough understanding of the technology, the impact of future economic conditions, overoptimism on the part of program advocates, and the like. Lack of clarity in the elicitation process for cost-probability distributions (e.g., merely surveying expert judgment for information), combined with a minimal number of experts, may have caused variances in experts' judgment and created opportunities for bias, leading to unintended misjudgments about technical risks. In fact, experts often disagree and are prone to bias just as laypersons are.¹⁶ Lavallo and Kahneman argue that executives routinely exaggerate the benefits of major projects and discount their costs. They often assume "the best scenario" and forget to account for the difficulties and schedule delays that are an

¹⁵ Lionel A. Galway, *Subjective Probability Distribution Elicitation in Cost Risk Analysis: A Review*, Santa Monica, Calif.: RAND Corporation, TR-410-AF, 2007.

¹⁶ See M. Granger Morgan, "Choosing and Managing Technology-Induced Risk," *IEEE Spectrum* (18)12, 1981, and William D Ruckelshaus, "Risk, Science, and Democracy," *Issues in Science and Technology* 1(3), 1985.

inherent part of complex projects.¹⁷ Arena, Younossi, et al. (2006) provide a detailed discussion of the key biases relevant to cost estimation.

Recall that in SBIRS-High and GPS, technical experts assessed technical risks by rating the WBS elements' risk levels in various risk categories. The risk categories and the criteria for the various uncertainty levels guided the assessment. However, in SBIRS-High's 2002 and 2006 risk assessments, the definitions of the risk categories and the criteria for the uncertainty levels lacked clarity and precision (see Table 3.1). No formal documentation with clear definitions and instructions guided the technical experts. As a result, each evaluator may have had his or her own interpretations of what types of uncertainties should be considered in each risk category, based on their individual experience. The evaluators' definitions of risk categories and criteria for the uncertainty levels may have been inconsistent with what the cost estimators intended. Because technical experts focus on technical performance, they may overlook certain types of technical uncertainties that can have large cost implications. In the SBIRS-High's 2006 EAC, however, training on the risk assessment method for the risk evaluators became mandatory and provided better guidelines for the evaluators.

The 2001 GPS risk assessment process had similar shortcomings. For example, only the extreme endpoints of the uncertainty scale (i.e., 0 and 10) were defined in the instruction. One evaluator's criteria for a score of 5 may have differed from another's criteria, which may have also differed from the cost estimator's criteria. GPS's 2001 elicitation process had another weakness in that only one expert provided the assessment per WBS element. Given the lack of clarity and precision in the risk survey, this further created an opportunity for inaccurate technical risk assessment for cost-estimating purposes.

Limitations in Risk Quantification Methodology

Even if the technical risk assessments are thorough and accurate, accurately translating the subjective assessments into cost implications in a quantitative way is yet another challenging step in the cost estimation

¹⁷ Dan Lovallo and Daniel Kahneman, "Delusions of Success: How Optimism Undermines Executives' Decisions," *Harvard Business Review*, July 2003.

process.¹⁸ We observed that the following factors in the risk quantification processes in SBIRS-High and GPS may have led to underestimation of cost estimates:

- potential errors in selecting applicable cost-probability distributions
- limitations of the risk quantification methods for capturing large potential cost growth.

Errors in Selecting Applicable Cost-Probability Distributions.

At SBIRS-High source selection and during formulation of the GPS 2001 POE, the normalized cost-probability distributions were unique to each WBS element to account for each WBS element's unique characteristics that drive the relationship between the risk level and cost uncertainty. However, the quantification method used for SBIRS-High since 2001 does not lend itself to developing tailored distributions. It uses four normalized triangular distributions that correspond to four risk levels. That is, WBS elements in the same risk level category have the same normalized cost-probability distribution. Using a standard set of probability distributions to quantify risks for all WBS elements may under- or overestimate risks in some WBS elements. For example, a "high-risk" hardware element may experience a different cost-uncertainty profile than a "high-risk" software element. The accuracy of these probability distributions is also uncertain because the distributions were selected based on a SAR analysis of all DoD programs conducted in 1992.¹⁹ It is uncertain if the average data from all DoD programs applies to space programs, especially given the increases in the level of complexity in space programs since the time of the SAR analysis.

¹⁸ Arena, Younossi, et al., 2006, present a comprehensive assessment of various risk analysis methods and a policy prescription for how to address risk in cost estimation.

¹⁹ The Analytic Sciences Corporation (TASC) conducted the study. It identified three distributions (high points at 1.1, 1.4, and 2) but the SBIRS-High SPO added the fourth distribution to account for the very high risk software WBS element. See Shishu Gupta, David Olsen, David Hudak, and Jennifer Keenan, "Cost Risk Analysis of the Strategic Defense System," TR-9042-2, Revision 1, Arlington, Va.: TASC, 1992, for more details.

The overall risk level and ultimately the endpoints of the triangular cost-probability distributions depend on the numerical weightings of the risk categories and the numerical scale values of the uncertainty levels (see Table 3.1). There are some weaknesses in how these parameters were developed in both the SBIRS-High and GPS programs. In the 2002 and 2006 SBIRS-High processes, the relative weighting on the risk categories was dispensed with (i.e., all risk categories had equal weighting) and the uncertainty level scale was assumed to be linear from 1 to 5 for all risk categories. The technical experts who evaluated the risk level did not provide any input regarding the relative importance of the risk categories or the intensity scale of the uncertainty levels. The cost estimators calculated the overall risk level as the average of all the uncertainty levels in all risk categories. As a result, the overall technical assessment could have been skewed if one of the risk drivers (e.g., technology maturity level) had greater cost implications than others (e.g., personnel, equipment). The equal weighting was also applied even if a risk category might have not been applicable to certain WBS elements. In the 2006 EAC, the risk evaluators were instructed to rate the uncertainty level as "lowest" if a risk category did not apply to the WBS element being evaluated. As a result, the contribution from the nonapplicable risk category would cause the overall risk score to be underestimated. The GPS risk assessment method, which was similar to the SBIRS-High's 2002 and 2006 processes, also neglected the relative importance of the risk categories, hence potentially introducing errors at the quantification step.

Additionally, for the GPS 2001 POE and SBIRS-High's 2002 and 2006 processes, cost estimators determined the uncertainty level scales without any input from technical experts and without any basis. For example, there was no basis for selecting a linear scale rather than an exponential, logarithmic, or some other mathematical function. In the CRIMS method, technical experts determined the weighting and the scales, but these parameters were still based on expert judgment (and thus subjected to the weaknesses discussed in previous sections), and they lacked any sound analytical basis for establishing the mathematical relationship between those parameters and the cost-probability distributions.

Throughout both programs, none of the risk quantification results were revisited or cross-checked using other methods for validation or as a “sanity check.” The lack of rigorous analysis to support the selection of cost-probability distributions and the lack of validation may therefore have contributed to underestimating the level of cost uncertainty in these programs.

Methodology Limitations in Quantifying Potentially Large Cost Growth. One of the limitations in using the statistical method in the cost estimate is that technical risks are only quantified as the variance of the cost-probability distribution (the spread of the distribution). As a result, if the point estimate is significantly underestimated, the cost estimate may still be underestimated even at a reasonably high confidence level. This approach may not adequately capture the effect of technical uncertainties that can lead to large cost growth.

For the SBIRS-High’s 2002 and 2006 EACs, some of the technical risks were deterministically quantified to adjust the point estimates. The point estimate included specific risk items whose probabilities of occurrence were estimated to be 75 percent or greater. However, this approach has some weaknesses: There is no solid analytical rationale for using 75 percent as the threshold, and the rating of the probability of occurrence is subjective. For the 2002 EAC, the total cost of the risk items whose probabilities of occurrence were below 75 percent was fairly significant. Their full value was 2.5 times that of the risk items above the threshold. Given the high level of subjectivity involved in this approach, a more-rigorous analysis, cross-check, or sensitivity analysis on the assessment of the probability levels and the threshold level might have resulted in a different outcome.

Modeling risk correlation is another challenge in quantifying risk. As mentioned earlier, the SBIRS-High cost estimate at source selection did not include risk correlation, and thus the cost uncertainty due to technical risks may have been underestimated. In later processes, risk correlation was added in the cost models. For the SBIRS-High EACs in 2002 and 2006, relatively large correlations were assumed among all WBS elements. However, cost estimators determined these values, and there were no analyses or standards to support the quantification of correlations. For GPS, correlation was captured by quantifying the

commonality between the WBS elements based on expert judgment. Correlation was also introduced as one of the risk categories (“dependence on other WBS elements”) to assess the effect on cost uncertainties. Again, the values used to quantify the correlations were not substantiated by any analysis or historical database. Furthermore, the risk quantification methods used by these programs model risk correlation such that it affects the variance of the total cost-probability distribution. As a result, risk correlation that leads to large cost growth, such as cascading effects and “standing army effects,” may not have been adequately captured, even with conservative values for risk-correlation coefficients.

Capturing risk correlations at a detailed level is complex. Although selecting an arbitrary number for correlation is better than setting the correlation to zero, some validation of the correlation values is needed to estimate the cost. Additionally, a separate analysis may be required to explicitly quantify technical risk correlations that could lead to a large cost growth, requiring adjustments to the point estimate as necessary.

Summary Observations

Many challenges are associated with identifying technical risks, evaluating them, and translating them into cost effects. It is inherently difficult to forecast future technical problems and any resulting cost growth they might incur. Program managers often assume “the best scenario” and forget to account for the difficulties and schedule delays that are an inherent part of complex projects. A large number of factors drive technical risks, and many of them are interrelated. However, accuracy and confidence in technical risk assessments can be improved with rigorous processes and methods.

Technical risk assessments in the SBIRS-High and GPS programs lacked rigor, partly because of limited resources and acquisition reform that reduced in-house expertise, as well as optimism and overreliance on contractors’ capabilities. The cost estimates did not always include a formal technical risk assessment and quantification to support the cost estimates. The technical risk assessments that were conducted lacked

rigorous fact-finding analysis to support the assessments of technical content (e.g., COTS) and technical executability (e.g., TSPR).

The level of up-to-date data on technical baseline, integrated schedule, and earned value was inadequate for thorough up-to-date identification and evaluation of technical risks. Key data sources were unreliable or lacked regular updates. The SBIRS-High and GPS SPOs' visibility into contractor's capabilities was also limited.

Because technical risk assessments are fundamentally subjective, certain aspects of the technical assessment methodologies and processes may have created opportunities for unintended misjudgment about the level of technical risk. The SPOs' in-house level of expertise (both the number of experts and their level of experience) was inadequate. The risk assessment process may have been influenced by a lack of institutional independence: It was conducted mainly by SPO personnel or contracted support personnel (including FFRDCs), and the prime system contractor, none of whom were disinterested observers. No truly independent technical assessment supplemented the SPOs' technical risk assessment in the early phases of the programs. Institutionally independent cost estimates, such as those conducted by the OSD Cost Analysis Improvement Group (CAIG) on SBIRS-High after the first Nunn-McCurdy breaches, depended largely on the same technical risk assessments as the SPO and contractor estimates. Not surprisingly, those cost estimates proved to be more realistic, but they also did not adequately reflect the true amount of technical risk that still remained in the program. Limited communications between the technical experts who conducted the assessment and the cost estimators who used the information may have introduced further unintended errors in the risk-assessment process as well as in the process of translating the technical risks in terms of cost implications.

There were limitations in the methodologies for quantifying the technical risks in terms of their cost implications, which may have contributed to cost-estimating errors. The justification for selecting applicable cost-probability distributions and correlation models lacked solid technical grounds. The quantification methods had limitations in cap-

turing factors that could contribute to potentially large cost growth. Given that any method has some limitations, some form of validation or cross-check with a different method or model could have minimized potential cost-estimating errors.

Other Nontechnical SBIRS-High and GPS Contributing Factors

Overall Case Study Findings on the Causes of Cost-Estimation Errors

This chapter examines some of the major programmatic factors that contributed to “inappropriate cost estimates” or cost-estimation errors identified by the RAND SAR categorization methodology in the SBIRS-High and GPS programs. It presents our overall findings from our two case studies and provides some more-detailed discussion and documentation of those findings, with the key exception of those areas related to the technical risk-assessment and quantification process, which are discussed in the preceding chapter. It also describes the context in which acquisition decisions were being made.

As noted previously, the true causes of cost-estimation errors are difficult to discern with confidence solely from SARs. Based on our interviews, we concluded that the RAND SAR cost-variance categorization methodology most likely underestimates the scale of cost growth that should be attributed to “technical issues” in the Errors category, at least for SBIRS-High and GPS. This is mainly because the SARs are often ambiguous about the sources of cost growth. The RAND cost-variance methodology generally assigns cost variances to the “technical issues” subcategory only when they are clearly called out in the SAR as causing the cost variance. It became clear from our extensive interviews with program experts that technical issues were responsible for far more cost variance (which we placed in the cost estimation errors subcategory) than the SARs identify directly.

Analysis of our extensive interviews with numerous senior government and contractor support officials who were involved in the cost-estimating and technical risk-assessment processes on these two programs between 1996 and 2005 led us to the overarching conclusion that *the entire acquisition process as whole resulted in optimistic cost estimates*. Multiple, complex, and interrelated causes led to optimistic cost estimates, including organizational, budgetary, and institutional factors. We isolated the following three main categories of causal factors that led to overoptimistic cost estimates and other cost errors for both programs:

- TSPR and acquisition reform as implemented did not achieve the expected benefits in both programs.
- The cost-estimating process was organizationally too closely associated with bureaucratic interests that held advocacy positions, making independent, disinterested cost analysis more difficult.
- Inadequate cost-estimation and risk-assessment methods and models were used in both programs.

In the remainder of this chapter, we examine the first two points in greater detail. Chapter Three documented the third finding.

Acquisition Reform, TSPR, and the Abdication of Rigorous Program Oversight

Both SBIRS-High and the original GPS IIF development programs were formally launched in 1996 at the height of the Clinton administration's attempt to implement a wide range of acquisition reform measures, many of which were intended to bring about radical change in the way DoD had historically developed and acquired major weapon systems and military space systems. Nearly all senior officials we interviewed identified acquisition reform in general, and the TSPR reform concept, in particular, as root causes contributing to the initial lack of credible cost estimates on both the SBIRS-High and GPS moderniza-

tion programs.¹ The fundamental problems for cost analysts with the way acquisition reform measures were implemented in our case study programs in the 1990s were fourfold. TSPR and acquisition reform had the following effects:

- They eliminated the requirements for contractors to provide the necessary cost and technical data to support independent government assessments.
- They rationalized the reduction in manpower and functional expertise in the SPOs, which hindered the SPOs' ability to monitor and assess contractor performance.
- They fostered an environment that facilitated SPOs' abdication of their traditional role of independently assessing contractor performance.
- They led to overestimation of cost savings from the insertion of COTS hardware and software and other acquisition reform measures.

The remainder of this section discusses the background of acquisition reform and TSPR in the 1990s and how they affected SBIRS-High and GPS.

Following the collapse of the Soviet Union in 1989 and the end of the Cold War, the decline in the defense budget accelerated and policymakers looked forward to reaping the benefits of a large "peace dividend" that was expected to result from the emergence of a more-stable, lower-threat world environment. Defense planners became increasingly interested in reforming the defense acquisition system to make it more efficient and less costly and to increase positive symbiotic interactions with the civilian economy and commercial technology development.

Reform efforts dramatically accelerated and were broadened to the whole federal government after the election of President Bill Clinton in 1992. In March 1993, President Clinton established an inter-agency task force, later called the National Performance Review (NPR), headed up by Vice President Al Gore and aimed at making "the entire

¹ We explain the TSPR concept in greater detail later in this section.

federal government less expensive and more efficient.”² The NPR produced a massive overview report with 384 recommendations presented to the president in September 1993.³ It was accompanied by no fewer than 15 “government systems” reports, including one on “Reinventing Federal Procurement,” and 20 major studies on reforming the most important federal agencies, including the DoD. The DoD report noted that “the DOD acquisition system must undergo a fundamental, top-to-bottom transformation.”

The report put forward three guiding principles for acquisition reform. The first focused on radically reducing the regulatory and government oversight burden placed on defense contractors by DoD and encouraging the adoption of commercial best business practices. The second and third principles aimed at strengthening the overall national and defense industrial bases through much greater emphasis on the use of commercial technologies and products by DoD and defense contractors.⁴

William Perry, the new Secretary of Defense in the Clinton administration, became a strong advocate of far-reaching reform for the defense acquisition system. In early 1994, he launched a wide range of major defense acquisition reform initiatives aimed at increasing efficiency, reducing costs, and enhancing civil-military industrial and technological integration.⁵ In accordance with the principles enunciated in Vice President Gore’s NPR reports, Secretary Perry’s reform efforts emphasized reduction in the government regulatory and oversight activities imposed on defense contractors, adoption of best business commercial practices by both the government and defense con-

² “Remarks by President Clinton Announcing the Initiative to Streamline Government, March 3, 1993,” cited in *A Brief History of Vice President Al Gore’s National Partnership for Reinventing Government During the Administration of President Bill Clinton, 1993–2001*.

³ Office of the Vice President, National Performance Review, *From Red Tape to Results: Creating a Government that Works Better and Costs Less*, Washington, D.C., September 1993b.

⁴ Office of the Vice President *Department of Defense, Accompanying Report of the National Performance Review, Part 1 of 2*, Washington, D.C., September 1993a.

⁵ See William Perry, Secretary of Defense, *Acquisition Reform: A Mandate for Change*, Statement to U.S. Congress House Armed Services Committee and Government Affairs Committee, February 9, 1994.

tractors, and the maximum use of COTS technologies and products in defense acquisition programs.⁶ Darleen Druyun, who was appointed Principal Deputy Assistant Secretary of the Air Force for Acquisition and Management in 1993, became a strong advocate of acquisition reform, wielding unprecedented influence over Air Force acquisition programs.

Throughout the 1990s, OSD and the services promulgated a bewildering array of acquisition reform directives. Probably the most important thrust of the overall effort, however, was the goal of radically reducing the DoD regulatory and oversight burden placed on industry. DoD suppliers have historically been subjected to a vast and complex body of unique regulatory and oversight requirements. Acquisition reformers argued that these measures were largely unnecessary and led to significant economic inefficiencies that forced DoD to pay a large “regulatory premium” for goods and services. Furthermore, according to the reformers, DoD reporting and oversight regulations artificially separated the defense industrial base from the rest of the national high-technology industrial base, prevented defense contractors from increasing efficiency by adopting “best commercial practices,” discouraged participation of “best-of-breed” commercial firms in defense programs as DoD suppliers, and shut off DoD from easy access to dramatic new high-technology developments taking place in the commercial sector. The reformers’ solution to these alleged problems was to reduce or eliminate special DoD regulations and oversight as much as possible.

By 1996, a variety of major statutory and regulatory changes aimed at reducing regulation and oversight of contractors and transferring developmental responsibility and power to contractors had coalesced into the concept called Total System Performance Respon-

⁶ RAND reports that investigate and evaluate various aspects of these reform efforts include Mark Lorell, Julia Lowell, Michael Kennedy, and Hugh Levaux, *Cheaper, Faster, Better? Commercial Approaches to Weapons Acquisition*, Santa Monica, Calif.: RAND Corporation, MR-1147-AF, 2000; Mark Lorell and John C. Graser, *An Overview of Acquisition Reform Cost Savings Estimates*, Santa Monica, Calif.: RAND Corporation, MR-1329-AF, 2001; and Mark A. Lorell, John C. Graser, and Cynthia R. Cook, *Price-Based Acquisition: Issues and Challenges for Defense Department Procurement of Weapon Systems*, Santa Monica, Calif.: RAND Corporation, MG-337-AF, 2005.

sibility.⁷ The most important non-statutory regulatory changes flowed from Secretary Perry's 1994 memorandum cited above that banned use of military specifications and standards on DoD contracts without an explicit waiver, in order to promote the use of COTS technology and parts and commercial best-business practices by defense contractors. This was the basis for the move away from detailed technical specifications in DoD Requests for Proposals (RFPs), toward performance specifications in which the government called out desired high-level system performance outcomes and contractors provided the technical design solutions to meet the performance outcomes. In summary, the TSPR acquisition concept brought together all these initiatives into a single comprehensive strategy. The key aspects of the TSPR concept were as follows:

- The contractor formulates and proposes its own technical design solution to meet high-level DoD performance requirements.
- The contractor, with minimal government oversight and direction, is responsible for implementing the proposed solution through the development process.
- The contractor is relieved of costly and cumbersome reporting requirements to reduce what are assumed to be burdensome overhead costs.⁸

TSPR was implemented side by side with another major initiative called Cost As an Independent Variable (CAIV). The CAIV concept placed a tremendous emphasis on reducing cost and providing maximum value to the government for the taxpayer's dollar. The CAIV con-

⁷ The most important statutory changes flowed from the Federal Acquisition Streamlining Act of 1994, the Defense Acquisition Management Reform Act of 1995, and the Federal Acquisition Reform Act of 1996. See Lorell and Graser, 2001; and Michael H. Anderson, *A Study of the Federal Government's Experiences with Commercial Procurement Practices in Major Defense Acquisitions*, Master of Science in the Management of Technology Thesis, Alfred P. Sloan School of Management and The School of Engineering, Massachusetts Institute of Technology, June 1997.

⁸ The catch phrase at the time was "insight, not oversight." For a more extensive discussion of the TSPR concept, see Major Henry P. Pandes, "Total System Performance Responsibility—Defense Logistics," *Air Force Journal of Logistics*, Summer 2001.

cept aimed at placing as much emphasis on cost as had been traditionally placed on system performance. The goal was to find the “knee of the curve,” where cost-effectiveness, or performance for the dollar, was maximized. The practical effects of the heavy emphasis on CAIV, however, translated into heavy pressures on contractors to meet demanding performance requirements at much lower—often unrealistically low—cost compared with what would have typically been thought possible in the past. The acquisition reformers thought contractors could do this successfully by incorporating much more advanced commercial technology and COTS components, by adopting “best business practices” from the commercial business sector, and by eliminating the allegedly costly DoD “regulatory burden” placed on defense contractors. Past RAND studies, as well as this study, suggest that these expectations for cost savings were not well thought out or verified by senior DoD advocates before their widespread adoption throughout the DoD acquisition process.⁹

A key aspect of the TSPR concept was a dramatic reduction in contractor data and documentation reporting requirements. “Insight, not oversight” was interpreted as eliminating the need for much of the large quantity of traditional formal documentation in government format, such as highly detailed Statements of Work and the extensive data reporting requirements traditionally laid out in formal Contractor Data Requirements Lists. As a result, the TSPR concept dramatically reduced the documentation and reporting requirements for contractors, including the reporting and documentation of technical and cost data. This of course was bound to have a significant effect on the SPO’s ability to undertake traditional cost and technical risk analysis.¹⁰

Both the SBIRS-High and GPS modernization development programs were launched in a TSPR and CAIV environment. The SBIRS-High development effort was touted with considerable fanfare as one of

⁹ See Lorell and Graser, 2001.

¹⁰ For an optimistic discussion of the early phases of SBIRS-High as an acquisition reform streamlining pilot program, see Major Jay A. Moody, *Achieving Affordable Operational Requirements on the Space based Infrared System (SBIRS) Program: A Model for Warfighter and Acquisition Success?* Student Research Paper, AU/ACSC/97-0548, Air Command and Staff College, March 1997.

DoD's first major acquisition reform pilot programs, chosen to demonstrate and test the acquisition reform concepts announced by Secretary Perry in his 1994 memorandum, especially TSPR, CAIV, and COTS insertion. For example, in 1995 SBIRS-High was one of the first DoD programs to employ a Single Acquisition Management Plan (SAMP), which was part of the effort at a dramatic reduction in paperwork and contractor reporting requirements. In the case of SBIRS-High, the SAMP consolidated 20 documents that in the past typically would have added up to around 1,000 pages into a SAMP that was only 37 pages long. Formerly long and detailed planning documents such as the Acquisition Plan, Acquisition Strategy Plan, Test and Evaluation Master Plan, Acquisition Program Baseline, Integrated Logistics Support Plan, and Risk Assessment were radically shortened and all folded into this one short SAMP. The Cost and Financial Management section of the SBIRS-High SAMP took up a mere four pages; Program Content, only two pages; and the Program Reviews and Oversight section, only three pages. In contrast, the section on Acronyms and Related Programs took up a full nine pages of the SAMP. This is not surprising, because SBIRS-High was established in complete conformity with the TSPR concept, where government oversight and guidance were to be kept to a minimum, and maximum program and technical responsibility were to be transferred to the contractor.¹¹

Major reductions in the DoD workforce, particularly in the acquisition field, reinforced the Clinton administration's push for acquisition reform, founded on reduced government oversight and the transfer of greater design and technical responsibility to contractors. In 1995, in accordance with the Clinton administration's goal of streamlining government, the DoD established the goal of reducing its workforce by 25 percent by the end of FY00. After two years, the DoD acquisition workforce had already been reduced by almost 16 percent, nearly two-thirds of the required five-year goal. As one Government Account-

¹¹ See James Clausen and Leonard Sadaukas, Office of the Deputy Assistant Secretary of Defense, Deputy Chief Information Officer, *Blueprint for Establishing Risk-based Governance of IT Investments in a Net-centric Department of Defense*, Version 1.0, 13 April 2005, pp. 48–49.

ability Office (GAO)¹² study noted in 1998, DoD was reducing its acquisition workforce “at a significantly higher rate than it reduced its overall workforce.”¹³ Other data show that, from 1994 through 1997, the SBIRS-High SPO workforce declined by about 40 percent. During the same period, the support staffing provided by FFRDCs and SETA contractors at the SBIRS-High SPO went down by over 50 percent.¹⁴ This is important, because SMC SPOs have historically depended heavily on SETA contractors, such as Tecolote Research, and FFRDCs, such as the Aerospace Corporation, to support cost and technical risk analyses.

This all occurred when the SBIRS-High and GPS IIF and IIR-M programs were being defined, launched, and moved through initial full-scale development. Thus, the dramatic reductions in SPO personnel, which took place beginning in 1995, coincided and reinforced the trend toward reducing oversight and transferring technical and cost responsibility to the contractor, which was also being encouraged simultaneously by TSPR and other acquisition reform measures.

Adding to the challenges for cost analysts was DoD’s sharply increased emphasis on using COTS technology, parts, subsystems, and software on satellites to reduce costs and shorten schedules. Greater use of COTS was, of course, a central theme of Secretary Perry’s acquisition reform initiatives. Unfortunately, experience now suggests that the use and integration of COTS hardware and parts, especially software, has proven far more technically challenging than originally anticipated by the acquisition reform theorists. As in the case of other acquisition reform measures, there is no evidence that DoD seriously set out to test and validate the widely held assumptions that the use and insertion of COTS components, software, and technologies would dramatically reduce costs.¹⁵

¹² Formerly the General Accounting Office.

¹³ Government Accountability Office, *Defense Acquisition Organizations: Status of Workforce Reductions*, Letter Report, GAO/NSIAD-98-161, June 29, 1998.

¹⁴ Booz Allen Hamilton, 2002, p. 174.

¹⁵ For a detailed discussion of some of these challenges, see Lorell et al., 2000.

As a result, we found that the two most pernicious specific aspects of acquisition reform affecting the cost-estimating process for our case studies were

- overoptimistic initial program estimates based on unsubstantiated assumptions regarding savings from less regulatory oversight, the use of COTS, and “best business practices”
- abdication of the government responsibility and capability to provide oversight and to track contractor progress and keep cost estimates current.

Numerous senior officials we interviewed told us that huge unsubstantiated savings were assumed and factored into the initial program estimates for SBIRS-High and, to a lesser agree, the GPS modernization program. One interviewee told us that something on the order of \$3 billion in savings was credited to TSPR in the original SBIRS-High program estimate. Additional savings were credited to the use of COTS. Some have claimed that initial cost-modeling efforts using standard cost assessment tools produced much higher cost estimates, but these were rejected by senior Air Force leadership as outdated and unable to account for the expected acquisition reform savings. Yet none of these assumed savings from acquisition reform and TSPR had ever been analytically demonstrated or validated. We note that the simultaneous consolidation of the aerospace industry and the reduction of the government’s acquisition workforce coalesced with the above factors to create an environment that made accurate cost estimation particularly challenging.

Even more unfortunate, acquisition reform and TSPR, combined with SPO downsizing, made it far more difficult to assess the realism of contractor cost estimates (as well as technical designs and risks) and track and assess contractor performance once a program was under way, which may explain why SBIRS-High’s serious problems took so long to be recognized. For example, during the source selection process on SBIRS-High, acquisition reform permitted the competing con-

tractors to submit contractor-unique work breakdown structures.¹⁶ It proved difficult to correlate these with the standard government WBS guidelines. Also as a result of TSPR, contractor cost estimates were provided down only to the relatively high level of WBS Level 3, which is the space vehicle level, thus providing government analysts with little insight into the technical and cost assumptions behind the contractor cost estimates.

The SBIRS-High SPO also did not have enough personnel or people with adequate training to interpret contractor EV reports properly once development was under way. The contractors reported in their own company formats, designating and sometimes shifting their baselines, thus making the reports difficult for government analysts to interpret. TSPR also resulted in the failure to clarify a common understanding and definition of categories for the Contractor Cost Data Reports at source selection. Final agreements and understandings in this area did not occur until years after the SBIRS-High program launch.

In the case of GPS IIF and OCS, acquisition reform and “best business practices,” combined with SPO downsizing, appear to have contributed to the failure of the SPO to make adequate assessments of the contractor’s capabilities to implement the program and to track the program’s progress. Major developmental and production issues emerged in these programs as a result of poor execution by the contractor. However, the SPO had little warning until the problems became major, because it was neither able nor willing to track contractor performance closely. In addition, the heavy acquisition reform emphasis on COTS insertion also appears to have directly contributed to underestimation of the cost of the GPS modernization effort. (Chapter Three discussed the technical challenges encountered in integrating COTS hardware and software in much greater detail.) Apparently all these challenges added significantly to cost and failed to produce the expected overall savings.

¹⁶ The WBS organizes a project into smaller components so it can be developed and managed more effectively.

Organizational Pressures and the Cost-Estimating Process: The Example of the Early Phases of SBIRS-High

The ability to generate realistic and credible cost estimates during key periods in the history of our two cases appears to have been negatively affected by the dominant influence exercised by program offices over the cost-estimating process and by the failure of senior Air Force leadership to insist on objective cost and technology risk assessments because of budgetary or other institutional reasons.

Many of the institutional challenges that we identified as having apparently influenced SMC cost analysts can be particularly well illustrated by reviewing the early phases of the SBIRS-High program, but they can also be detected at various other times during the history of the SBIRS-High program and during certain phases of the GPS program. These circumstances are closely linked to budgetary politics and the competition among program offices and among the services for scarce acquisition dollars. Program offices competing for funding tend to lose objectivity and become advocates for specific systems, as do the services when encouraged by DoD to form joint programs. As one interviewee summed up the problem in a rather oversimplified but dramatic manner, “Program Managers generally will not allow realistic cost estimates of their programs because the result could be loss of budget or program termination.”

While it is difficult to prove these assertions conclusively, little doubt exists among the expert observers whom we interviewed that bureaucratic, budgetary, and service politics sometimes undermine efforts to produce objective, credible cost estimates. One of the clearest-cut and most well-documented cases took place during the early concept development phases of SBIRS-High. The early history of SBIRS-High is extremely complex and convoluted; what follows is a high-level summary of the basic outlines to illustrate the importance of truly independent cost estimates.¹⁷

¹⁷ We note here and elsewhere that, while organizational independence is extremely important for cost analysts, it is not necessarily sufficient for credible, realistic cost estimates. As we

In the late 1980s and early 1990s, several system concepts both within and outside of the Air Force were competing for selection as the replacement system for the Air Force DSP satellite system.¹⁸ Selection of an appropriate system concept and architecture proved difficult and contentious. The threat was complex, and opinions differed widely on future projections of the threat as well as on how best to meet it. Complicating matters further, these debates took place while DoD was launching its extensive array of acquisition reform measures.

AWS, FEWS, and ALARM

Numerous candidate concepts were advanced as potential DSP follow-ons. The leading contenders included several candidate concepts originally advanced by the Strategic Defense Initiative Organization (SDIO, later the Ballistic Missile Defense Organization or BMDO), an “official” Air Force program that eventually became known as Follow-on Early Warning System (FEWS), and an unofficial Air Force program called DSP II, a proposal for an upgraded version of the existing DSP. Disagreements over requirements and program leadership complicated selection of a candidate. This was particularly true after the collapse of the Soviet Union in 1989 reduced the threat of a massive nuclear intercontinental ballistic missile (ICBM) strike. In addition, the Iraqi invasion of Kuwait in 1990 and the first Gulf War raised the importance of the tactical and theater ballistic missile threat and also showed that space-based infrared assets could be used for tactical battlefield intelligence purposes.¹⁹

Beginning in 1979, the Air Force began examining a follow-on system concept for the DSP called the Advanced Warning System

argued in Chapter Three, independent, high-quality technical risk assessments and methodologies for cost analysts are of at least equal, and probably greater importance.

¹⁸ DSP has served for over three decades as the main U.S. space-based strategic infrared detection system for ballistic missile launches and nuclear detonations.

¹⁹ For the background on relevant SDIO activities during this area, see BMDO, *Harnessing the Power of Technology: The Road to Ballistic Missile Defense from 1983-2007*, September 2000.

(AWS).²⁰ In 1984, DoD took AWS away from the Air Force and transferred the responsibility for developing a DSP mission follow-on system to SDIO. In September 1987, SDIO's architecture plan was approved. It included the Boost Surveillance and Tracking System (BSTS) in higher inclined geosynchronous orbit as a replacement for DSP, and a totally new system called Space-Based Surveillance and Tracking System (SSTS) in medium orbit (the forerunner of what became SBIRS-Low). This combination was intended to fulfill both the ballistic missile defense missions and the tactical warning and attack assessment (TWAA) missions.

Following the collapse of the Soviet Union and the first Gulf War, the SDIO architecture was adjusted. Theater Missile Defense (TMD) became the first priority, and the Army and Navy took the near-term lead with various ground and sea-based anti-missile systems. National Missile Defense (NMD) became a lower priority, leading to the eventual elimination of the BSTS program by SDIO and the restructuring of some of the BSTS program components into the Brilliant Eyes and Brilliant Pebbles programs. After spending nearly \$1 billion on BSTS, DoD decided to discontinue funding the program in April 1990.

In October 1990, Congress transferred the BSTS mission area back to the Air Force. The Air Force initially focused on the TWAA mission, once again naming the all-new system AWS as a reference back to 1984 when the Air Force had lost the original AWS program to BMDO. However, although the Air Force strenuously objected, OSD soon thereafter recommended terminating AWS because of potentially unacceptably high costs and high technical and schedule risk. This decision was based on a study conducted by the DoD Office of the Comptroller that concluded that an upgraded existing DSP could meet

²⁰ The following account has been pieced together from interviews and a variety of published documents, including General Accounting Office, *Early Warning Satellites: Funding for Follow-On System Is Premature*, NSIAD-92-39, November 1991; General Accounting Office, *Military Space Programs: Comprehensive Analysis Needed and Cost Savings Available*, T-NSIAD-94-164, April 14, 1994; U.S. House of Representatives, Committee on Government Operations, Subcommittee on Legislation and National Security, *Strategic Satellite Systems, Testimony of Guido William Aru, Project Leader, The Aerospace Corporation*, February 2, 1994; and John T. Correll, "Fogbound in Space," *Air Force Magazine* (77) 1, January 1994. Also see BMDO, 2000.

most of the BSTS and TWAA mission area requirements at a much lower cost.

By April 1991, the Air Force had responded by proposing a smaller and cheaper version of its original AWS concept, called FEWS, which partially met the TWAA mission and which was planned to exceed the existing DSP capabilities. One of the most important new technical aspects of FEWS was that it included data processing capability on board the space vehicle and communication cross links. OSD argued that this new system concept was potentially too costly and technically risky, recommending at a minimum that the onboard processing requirement be eliminated. This view was confirmed by a draft 1991 DSB task force study, as well as an Air Force study of alternatives conducted around the same time, both of which found that an upgraded DSP was the most cost-effective and lowest-risk solution.

Throughout this period, the Air Force position itself was far from unified. Originally SMC had one “basket SPO” that included separate offices for DSP, FEWS, and Brilliant Eyes, each with a colonel as program manager. The DSP program office continued to advocate DSP II to meet aspects of the DSP follow-on system missions, the FEWS office pushed derivatives of BSTS and Brilliant Pebbles, and the Brilliant Eyes office advocated variants of the original SSTS. All three programs were competing for funding and for mission areas, each supported by a different contractor team. Meanwhile, the Program Executive Office (PEO) fought to preserve Air Force control over the overall space infrared surveillance mission area against perceived encroachments from the intelligence community (IC). In this competition for mission area control and budget, each of the specific system proposals and program offices had advocacy cost estimates associated with it, often driven by the contractors, and thus no unified Air Force and SMC position initially existed to counter IC “encroachment” on the newly reacquired Air Force mission area.

However, during 1992, FEWS emerged as the preferred Air Force system at the highest leadership levels, and indeed soon evolved into the highest-priority Air Force space program. By October 1992, AFSPC had completed a draft operational requirements document for FEWS, but opposition to the new system continued at OSD and elsewhere on

cost and technology risk grounds, preventing validation of the document by the Joint Requirements Oversight Council.

Eventually, Congress requested a new study comparing the cost-effectiveness of FEWS and an upgraded DSP. This led to an extensive and sometimes vitriolic debate in and out of the Air Force regarding the relative cost-effectiveness of various proposed upgraded versions of DSP compared with FEWS. This included allegations presented formally to Congress that senior Air Force echelons had suppressed a study sponsored by the Air Force DSP program office, the Aerospace Corporation, and the DSP lead contractors recommending acquisition of DSP II rather than FEWS.²¹

After the alleged suppression of this document, the leaking of the study to Congress led to the recommendation in June 1993 that the cost-effectiveness of DSP upgrades be once again compared with FEWS. This review, carried out by the Under Secretary of Defense for Acquisition (USD(A)), was supported by a special technical group composed of experts from several FFRDCs. The technical group produced the so-called "Everett study" in October 1993. The Everett study concluded that future space-based infrared surveillance capability requirements could be met by a much smaller, less expensive, and less technologically complex SV than the proposed Air Force FEWS satellite and that the focus should shift more toward the theater ballistic missile defense and battlefield tactical support mission areas. A key recommendation of the Everett study was that the SV should be light and small enough to be launched from a medium-sized launch vehicle rather than the much more costly Titan IV heavy launch vehicle that FEWS would require. Because of these findings and other issues, OSD cancelled the FEWS program in late 1993.²²

In response to the Everett study and the cancellation of FEWS, the Air Force proposed yet another all-new system in February 1994 to replace DSP called Alert Locate and Report Missiles (ALARM). Also at this time, the Air Force moved to end the feuding among SMC

²¹ See U.S. House of Representatives, 1994.

²² The requirement for a smaller SV that could be placed in orbit by a medium-weight launch vehicle essentially ruled out both FEWS and DSP II variants as too large and heavy.

program offices and headed toward a more unified position at SMC to better counter what appeared to some to be OSD and IC threats to its control of the infrared space surveillance mission. To reduce expected costs and counter OSD objections, the proposed initial ALARM satellites would not have onboard processing and cross-link communications and would be capable of launch from medium-lift launchers through the use of new miniaturization technologies, but it would later be upgraded with increased capabilities. However, GAO and other outside critics continued to question the cost-effectiveness and affordability of ALARM, viewing it essentially as a downsized and stretched-out reincarnation of FEWS.

OSD Summer Study

The continuing controversy led to yet another study to assess requirements and competing system proposals. This was an OSD Summer Study led by a Senior Steering Group and sponsored by the Deputy Assistant Secretary for Intelligence and Security. The Summer Study group met from June through September 1994 and was under heavy pressure to provide a single definitive answer quickly because of the severe time constraints imposed by the OSD budget process and schedule. Because of the demise of FEWS, OSD had to have its new fall budget position settled and coordinated by the end of the summer.

The Summer Study ignited a hectic competition among at least three major design contenders and institutional players. With a central focus on system affordability, the competition placed great pressure on the contractors, as well as on the cost estimators in the program offices representing each contending system, to generate the lowest plausible cost estimates. Each contender was represented by a program office or other government entity and an associated contractor team that viewed its study as effectively the last one in a long line of similar studies, thus making it a “must win” situation. Competing program offices increasingly behaved like advocates for specific design proposals and industry teams, rather than as objective evaluators of requirements and design concepts. The Air Force PEO followed the broad Air Force agenda of saving ALARM, while SMC program offices followed their more specific agendas driven by their respective contractors. SDIO and its

supporting contractors strongly pushed Brilliant Eyes. The IC championed its own design and contractor team, especially its “heritage” sensor payload, which had already been used on another classified program. According to participants in the Summer Study whom we interviewed, the cost estimates presented by the competing teams became increasingly less credible over the course of the summer, as the bidding war escalated along with claims for ever-increasing capabilities at lower cost. As a result, the Summer Study was unable to conduct thorough and objective cost-benefit analyses of the competing concepts because the contractor cost and technical submissions were increasingly seen as lacking in credibility.

Nonetheless, the 1994 Summer Study successfully determined the ultimate system architecture for SBIRS-High: four GEO SVs and two HEO payloads.²³ To save money, it also recommended use of the BSS 601 standard commercial satellite bus and, perhaps most important, called for use of modified versions of the IC heritage sensors on all of the GEO and HEO satellites. With two heritage sensors each on the four GEO SVs and one each for the HEO payloads, for a total of ten, this use of an essentially common sensor package for all satellites was expected to result in much lower unit procurement costs. In addition, the recommended reuse of existing software from the heritage sensor was also intended to reduce costs. Since the IC had presented actual cost numbers for the heritage sensor based on its use on a classified program, the Summer Study participants were reasonably confident about the cost estimates for at least this one critical area.

The Summer Study recommended that all SDIO active missile defense requirements be moved to the Brilliant Eyes follow-on (later SBIRS-Low) and that procurement of this system be deferred pending a final decision in FY00. The Summer Study also recommended the establishment of a joint program office led by the Air Force but including the IC to facilitate provision of the heritage sensor. Finally, the Summer Study assumed that a streamlined acquisition approach similar to that used by the IC would be adopted to save costs. The cost

²³ The HEO sensor payloads would be hosted on a classified satellite.

estimates produced by the Summer Study were based on all the above assumptions.

Senior Air Force leaders were allegedly not happy with the findings of the Summer Study, because they essentially endorsed the IC design concept and architecture instead of ALARM and called for use of the IC heritage sensor payload for all satellites. According to some Summer Study participants and other officials, senior-level Air Force leaders strongly opposed granting the IC a significant role in designing, developing, and managing a future system, which was considered to be rightfully an Air Force–dominated effort.

In the wake of the Summer Study, the Air Force brought in a new program manager to SMC in early 1995 to end the feuding among the different program offices in the SMC basket SPO and to help build a more unified Air Force position. Two of the three program directors were reassigned, and FEWS, DSP, and Brilliant Eyes were consolidated into a single program office under the new program manager. The new system program office was named the Space Based Infrared System. Now all requirements were to be satisfied by a single program. The Air Force then funded a pre-EMD design concept competition between two contractor teams. One included the contractor that had developed and integrated the DSP SV, teamed with the heritage sensor contractor originally advocated by the IC and effectively endorsed by the OSD Summer Study. The other team was led by one of the former FEWS contractors teamed with the DSP payload contractor and included only a paper design for an all-new sensor payload.²⁴ During the course of

²⁴ Some Air Force interviewees argued that the difference in the relative maturity of the two competing sensor designs is often exaggerated. They claim that the heritage sensor, as used in the new proposal from the DSP contractor team, required considerable modification, and that the new paper design for a sensor offered by the other contractor, benefited from earlier hardware experience on the DSP sensor and Defense Meteorological Satellite Program (DMSP). Some interviewees pointed out that the second prime contractor (Lockheed Martin) at one point had approached the heritage sensor contractor to form a second team to develop their own design that would also have used a modified version of the heritage sensor. This indeed was allegedly the preferred solution of the senior civilian leadership in SAF/AQ—that is, both primes teaming with the heritage sensor subcontractor. However, it is alleged that the heritage sensor contractor declined to team with Lockheed Martin, preferring to remain in its existing team for business reasons.

this competition, the Air Force moved further away from the Summer Study findings and closer to the earlier preferred all–Air Force ALARM concepts. For example, the original ALARM long-term requirement for SV onboard data processing migrated back into the program.²⁵

Nonetheless, the competition between the two contractors, along with major budgetary constraints, pressured both contractors to keep their cost estimates as close as possible to those that had emerged from the 1994 OSD Summer Study, even though those estimates were based on key assumptions regarding a variety of technical issues that were no longer necessarily valid, such as no onboard processing and use of a common modified heritage sensor payload on all SVs.

In late 1996, the Air Force completed its down-select process; Lockheed Martin, a former lead contractor on FEWS and ALARM, was the winner. Many officials involved with the program at the time believed that the winning contractor's program cost estimates, as well as the official program office estimates, which were roughly similar to the Summer Study estimates based on completely different assumptions, were extremely optimistic and that the overall program was seriously underfunded. This was particularly true since the Lockheed Martin proposal did not include the modified heritage sensor and software, but rather had an all new scanner and starer for each GEO satellite and a scanner for the host HEO satellites.

This brief and admittedly incomplete recounting of the early pre-development stages of SBIRS-High illustrates some of the problems that occur when the cost-estimating process is controlled or heavily influenced by major program stakeholders that have become advocates for specific systems and contractor design teams. The lack of a truly independent cost-estimating capability with a strong independent voice inhibited the objective cost-benefit analysis within the Air Force of competing Air Force systems (DSP II, FEWS, ALARM, Brilliant Eyes). In addition, the lack of independence of the cost-estimating process and the institutional and bureaucratic parochialism exhibited by all participants in the Summer Study, including the Air Force, the IC,

²⁵ One interviewee argued that this requirement was restored mainly because the Army, which would be an important user, strongly supported it.

and the SDIO, all undermined the ability of the 1994 OSD Summer Study participants to conduct fully transparent, credible, objective cost-benefit analyses of the various options to fulfill the space-based infrared surveillance mission. Of course, this situation was hardly the fault of the Air Force alone. For example, the IC constantly touted its lower-cost figures for its heritage sensor but refused to share its cost methodology, databases, or costing assumptions with the Air Force, OSD officials, or even with the Summer Study participants.²⁶

This less-than-optimal situation was not unique to the pre-EMD period of SBIRS-High, or indeed to SBIRS-High itself. For example, during 2002 when SBIRS-High was being re-baselined due to Nunn-McCurdy breaches²⁷ and had to be recertified to continue, significant pressures were apparently felt by the SPO cost estimators to keep the estimates fairly optimistic because the program was clearly at risk of being cancelled. Outside, independent observers at the time argued that the estimates produced by the SPO during the re-baselining were unjustifiably optimistic because of remaining unresolved technology risks.²⁸ It appears that the continuing lack of independence in the cost-estimating process was a major contributing factor to this optimism.

Nor was our other case study, GPS, immune to similar problems, although they were on a much smaller scale. It appears that when GPS

²⁶ Some Air Force interviewees argued that the true root cause of SBIRS-High cost growth problems should be sought not in the estimating process but in the budgeting process. They point out that the official Air Force estimate at the beginning of the program was higher than the contractor's estimate but that the original official budget was lower than both the Air Force and even the contractor's optimistic estimate. They insist that the unrealistic budget forced the contractor to cut discretionary but crucial areas during the first three years of the program, such as system engineering, quality assurance, and vendor surveillance. They argue that these were the root causes of the technical problems. However, others maintain that it is highly likely that the program would still have encountered significant technical problems and cost growth, even if the budget had covered the full original official Air Force estimate, given the enormous cost growth experienced by the program over its history. The original official Air Force estimate was only tens of percent different from the contractor estimate. Yet cost growth to date has been well in excess of 200 percent.

²⁷ As noted earlier, a "Nunn-McCurdy" unit cost breach occurs when a MDAP has an increase of at least 15 percent in program acquisition unit cost.

²⁸ As reported in Bonds et al., 2003.

was extensively restructured in 1999–2000 to include modernization of the IIF and IIR-M satellites, SPO cost estimators developed overly optimistic estimates, particularly for GPS IIF and for OCS. Although it is more difficult in this case to demonstrate with certitude, it seems likely that funding constraints and the preference of the SPO leadership to move the program forward without a major program milestone review influenced the cost estimates and contributed to its optimism.²⁹

As we have already noted, however, institutional independence does not necessarily guarantee high-quality, credible cost estimates. For example, in 2002, a new official SBIRS-High program cost estimate, independent of both the program office and the Air Force, eventually became the new baseline for the program. This estimate was developed by the OSD CAIG. Although the estimate was higher than the SPO estimate, even this baseline had been severely breached by 2004–2005, requiring a new Nunn-McCurdy recertification process. Therefore, it could be argued that the independence of the cost-estimating process produced only modestly better results than those produced by the SPO. We do not necessarily disagree with this conclusion. While we argue that independence is an important factor, it is not a sufficient condition for producing credible cost estimates in and of itself. Perhaps most important, accurate assessment of technology risk and maturity must be incorporated into cost estimates in a more effective manner, as we discussed at length in Chapter Three.

We argue below that the government acquisition authorities must also conduct rigorous oversight and assessments of contractor proposals before contract awards, and of contractor progress after contract awards, to generate and maintain credible cost estimates. Finally, and perhaps most important, as we argued in Chapter Three, an independent, objective, and well-informed technical risk-assessment process directly supporting the cost-estimating process is critical for the generation of credible cost estimates.

²⁹ Again, the important issue of credible and independent technical risk assessment as it relates to the GPS program is discussed in Chapter Three.

The Context: A Changing Defense Industrial Base in the 1990s

In this section, we conclude by once again summarizing and briefly reviewing the broader context regarding the industrial base environment in which these programs were launched and that played a role in increasing the challenges facing cost estimators and other program officials, as well as contractors. These contextual factors greatly complicated the challenges posed to credible cost estimating by the new emphasis on TSPR and acquisition reform that arose in the early 1990s.

Two contextual factors are particularly relevant: (1) industry downsizing and smaller numbers of large programs leading to increased competition among the remaining prime contractors, which tempted contractors to overpromise with unrealistic bids at a time when their capabilities to deliver were declining and the ability of SPOs to recognize unrealistic bids was decreasing; and (2) the rapidly increasing inherent technological complexity and difficulty of military space development programs. The point is to reemphasize that even if credible cost estimating on the SBIRS-High and GPS programs had not been negatively affected by the acquisition reform policies and organizational and institutional issues discussed above, it would have faced serious challenges due to the unique historical industrial base and technological background environments in which the programs were launched.

Industry Downsizing and Growing Competition for Fewer Programs

The decade of the 1990s was a period of declining defense budgets, which led to a further decline in new program starts and downsizing and consolidation of the aerospace defense industrial base. These factors strongly encouraged acquisition reform as a means to reduce system procurement and operating costs and also spurred DoD acquisition workforce reductions. Defense industry employment peaked in 1987 and fell thereafter. This decline rapidly accelerated with the fall of the Berlin Wall in 1989 and the onset of a recession in 1990. Hundreds of thousands of aerospace jobs disappeared in the early 1990s. Fewer students entered aerospace engineering programs, and

foreign competition for commercial launch services and commercial satellite programs appeared to be growing dramatically. The U.S. space industry was forced to downsize and consolidate. According to one accounting, the number of major space companies in the United States declined from 20 to three (Boeing, Lockheed Martin, and Raytheon) from the mid-1980s through 1997.³⁰ One of the foremost military satellite contractor sites lost approximately two-thirds of its engineering and technical staff during this period. With increasing frequency, experts voiced concerns about the declining skill base of the space industry and the long-term ability of the U.S. aerospace industry to maintain a global leadership in this new environment.³¹

Downsizing and consolidation, which were taking place throughout the 1990s, could often be highly disruptive for ongoing programs, including our case studies. A good example is the numerous changes that affected the prime contractor developing the GPS IIF SV during this period. The prime contractor for the GPS IIF was Boeing Space and Intelligence Systems (S&IS) headquartered in Seal Beach, California. However, throughout the IIF contract, the prime contractor experienced considerable turbulence due to mergers and industry restructuring, leading to numerous changes in the designated development and manufacturing sites, as well as issues regarding clashes in corporate cultures.

GPS government program officials believe that this turbulence negatively influenced the development and production program. In 1996, the Air Force awarded the original IIF contract to North American Rockwell Aerospace in Seal Beach and Anaheim, California, the original developer of the GPS Blocks I and II. In late 1997, the Boeing Company bought Rockwell and acquired the Rockwell Aerospace Seal Beach facility and, with it, the GPS IIF program. In 2000, Boeing purchased the Hughes satellite manufacturing operations, for-

³⁰ Michel Andrieu and Pierre-Alain Schieb, "Space: The Forgotten Frontier?" *OECD Observer*, April 2003.

³¹ Typical expressions of those concerns can be found in Vice President's Space Policy Advisory Board, *The Future of the U.S. Space Industrial Base: A Task Group Report*, Washington D.C., November 1992.

merly Hughes Space and Communications Company, in El Segundo, California, for \$3.75 billion, and renamed it Boeing Satellite Systems. During this period, Boeing acquired McDonnell Douglas, as well as Rocketdyne Aerospace facilities in Canoga Park.

Boeing spent several years reorganizing and shifting development and production work among its newly acquired space and information technology facilities in Southern California. Development work on the GPS IIF was moved from Seal Beach to Anaheim, then back to Seal Beach, and finally to Huntington Beach. SV production was moved from Seal Beach to El Segundo. In addition, integrating the corporate cultures of the former Hughes El Segundo engineers with the new Seal Beach headquarters created its own set of challenges. According to GPS government program officials, the frequent changes, reorganizations, and problems with integrating formerly separate corporate cultures led to significant challenges for the program and have likely contributed to technical problems, cost growth, and schedule delays.

Declining defense budgets in the 1990s also meant fewer major programs. As industry consolidation continued, the remaining aerospace giants became locked in fierce competitions to win the shrinking number of major new programs. Imbued with the principles of acquisition reform, the government managers of new space R&D efforts focused enormous attention on attempting to reduce procurement and life cycle costs through greater use of COTS technology and parts and the transfer of more program responsibility to contractors. The surviving contractors heard the government's message that they had to provide better products, at less cost, with fewer human and dollar resources, and with much less government supervision and oversight. Desperate to win the relatively few remaining new large-scale contracts, companies gladly promised to satisfy the government's requirements at the lowest possible costs—while not always being certain how this could be done. Intense competitive pressures and a very strong emphasis on reducing costs, combined with the new relaxed environment of minimal government oversight and contractor reporting requirements promoted by acquisition reform measures, were bound to encourage unusually optimistic contractor cost estimates and technical risk assessments at a time

when the government acquisition community was reducing its ability to monitor and validate contractor estimates and assessments.³²

These trends all coalesced at a time when military space systems were becoming dramatically more technologically sophisticated and complex. The databases used in traditional space cost-estimating models became increasingly obsolete in this environment, and acquisition reform measures eliminated much of the routine collection of new cost and technical data that had been common in the past. The increased technological complexity of proposed new military space systems challenged the technical and system engineering knowledge of the government acquisition officials tasked with the job of assessing proposals and contractor progress—at a time when the acquisition workforce was experiencing significant downsizing.

Increased Complexity of Space Systems

A variety of factors coalesced in the 1990s, leading to the emergence of much more complex space “systems of systems.” The system-of-systems concept gained wide favor beginning in the 1990s as a key component of the “Revolution in Military Affairs.”³³ A system of systems is composed of multiple separate systems, subsystems, sensors, and other components all netted together into a single complex interactive system.³⁴ According to one expert definition, systems of systems

³² A much more detailed discussion of acquisition reform and its effects on the case study programs follows below.

³³ For example, see Admiral William A. Owens, Vice Chairman, Joint Chiefs of Staff, *The Emerging U.S. System-of-Systems*, National Defense University Strategic Forum, No. 63, February 1996.

³⁴ A basic definition from the period states: “Systems of systems are large scale concurrent and distributed systems that are comprised of complex systems.” See V. Kotov, *Systems of Systems as Communicating Structures*, Hewlett Packard Computer Systems Laboratory Paper, HPL-97-124, 1997, p. I-15. Another emphasizes information superiority: “In relation to joint warfighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance, and Reconnaissance (ISR) Systems.” See W. H. Manthorpe, “The Emerging Joint System of Systems: A Systems Engineering Challenge and Opportunity for APL,” *Johns Hopkins APL Technical Digest* 17(3), 1996, p. 55–60.

are characterized by “complex combinations and interdependencies of technologies, operations, tactics, and procedures.”³⁵

The much-increased complexity of military space systems netted together into larger systems of systems posed many new challenges for the space acquisition and cost-estimating communities. The so-called Young Report, a widely influential joint Air Force/DoD study published in 2003 on the growing challenges in the space acquisition process, pinpointed the system-of-systems concept involving multiple users and extensive user requirements as a major contributor to the causes of cost growth on military space systems. It noted that the proliferation of users and requirements led to increasingly complex systems of systems, which greatly increased the difficulty of managing cost, schedule, and risk.³⁶ At the same time, the complexity of individual systems, subsystems and technologies was also increasing, as sensors and other payloads became technologically more sophisticated, and much more complex processing and software tasks migrated to space vehicles.

These trends toward greater system and “system of systems” complexity arose at the same time that the government was transferring more system engineering and design responsibility to the contractor, and reducing government oversight and guidance, in accordance with acquisition reform concepts and measures.

Adding to the challenges for cost analysts was DoD’s dramatically increased emphasis placed on using COTS technology, parts, subsystems, and software on satellites to reduce costs and shorten schedules. Greater use of COTS was a central theme of DoD’s acquisition reform initiatives in the 1990s. As noted elsewhere, later experience suggests that the use and integration of COTS hardware and parts, and espe-

³⁵ Dennis J. Anderson, James E. Campbell, and Leon D. Chapman, *Evaluating A Complex System of Systems Using State Modeling and Simulation*, presentation at the National Defense Industrial Association Systems Engineering Conference, San Diego, Calif., October 20–23, 2003.

³⁶ Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, *Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs*, Washington, D.C., May 2003, p. 2.

cially software, proved far more technologically challenging than originally anticipated by the acquisition reform theorists.³⁷

The two contextual trend areas briefly touched on above—industry downsizing, reduced numbers of programs, and increased competition; and increased space system and technological complexity—significantly affected the space defense industrial base environment in the 1990s, complicating the challenges confronting industry as well as government cost analysts and other acquisition professionals. Combined with the emergence of TSPR and the increasing popularity of new acquisition reform measures strongly advocated by the Clinton administration, these contextual factors contributed to the difficulties encountered by the cost analysis community in the mid 1990s when SBIRS-High and GPS IIF were entering development.

Summary Observations

In summary, a careful review of the history of the cost-estimating processes in the SBIRS-High and GPS programs suggests the following:

- Organizational and bureaucratic independence from the program office is an extremely important, though not sufficient, condition for ensuring the generation of credible cost estimates.
- Rigorous oversight, monitoring, and assessment of contractor costs and cost data, throughout all phases of the proposal process and continuously throughout program execution, are critical for the development of credible cost estimates.

Finally, our case studies demonstrate that the single biggest challenge for the cost-estimating process has been the development of credible methodologies and approaches for determining technology risk, quantifying technical risk, and incorporating the technical risk assess-

³⁷ For a detailed discussion of some of these challenges, see Lorell et al., 2000, and Chapter Three of this monograph.

ment into the cost-estimating process in order to produce a credible final cost estimate, as discussed at length in Chapter Three.

The next chapter examines the current organization and workload of the SMC financial organization to see what needs to be done so that future programs can reduce the types of challenges encountered by the SBIRS-High and GPS programs in the past.

SMC Organization and Cost Analysis Workforce Assessment

This chapter contains three parts. It begins with a description of the Space and Missile Systems Center organization, continues with a more detailed discussion of the SMC Financial Management (SMC/FM) organization, and concludes with an analysis of the supply and demand for cost-analyst staffing at SMC. The analysis is a snapshot of current staffing; note that we do not make any judgment on the quality of the workforce.

Description of Space and Missile Systems Center

This section describes SMC, providing some details about its history, organization, and staffing and distinguishing among civil service, military, and contractor personnel. It also describes the staffing of similar cost-estimating organizations.

History

What is now the Air Force Space and Missile Systems Center began in the mid-1950s as the Western Development Division of the Air Research and Development Command. It was soon renamed the Air Force Ballistic Missile Division (AFBMD), reflecting its primary mission of developing strategic missiles. By 1961, AFBMD had assumed responsibility for development of most military space systems and the boosters to launch them. Over the next 30 years, the organization went

through a succession of name changes, as the responsibilities for strategic missile development were first moved to a separate command and later restored. In 1992, the functions were recombined for the last time, and the command was renamed Space and Missile Systems Center.

As a result of the desire to foster better integration between the developers and users of space systems, in 2001 SMC was transferred from Air Force Materiel Command to become the acquisition arm of Air Force Space Command (AFSPC). AFSPC also has responsibility for space launch and flight operations. Since 2002, the SMC commander has assumed the added responsibilities of program executive officer for space, reporting to the space acquisition executive.

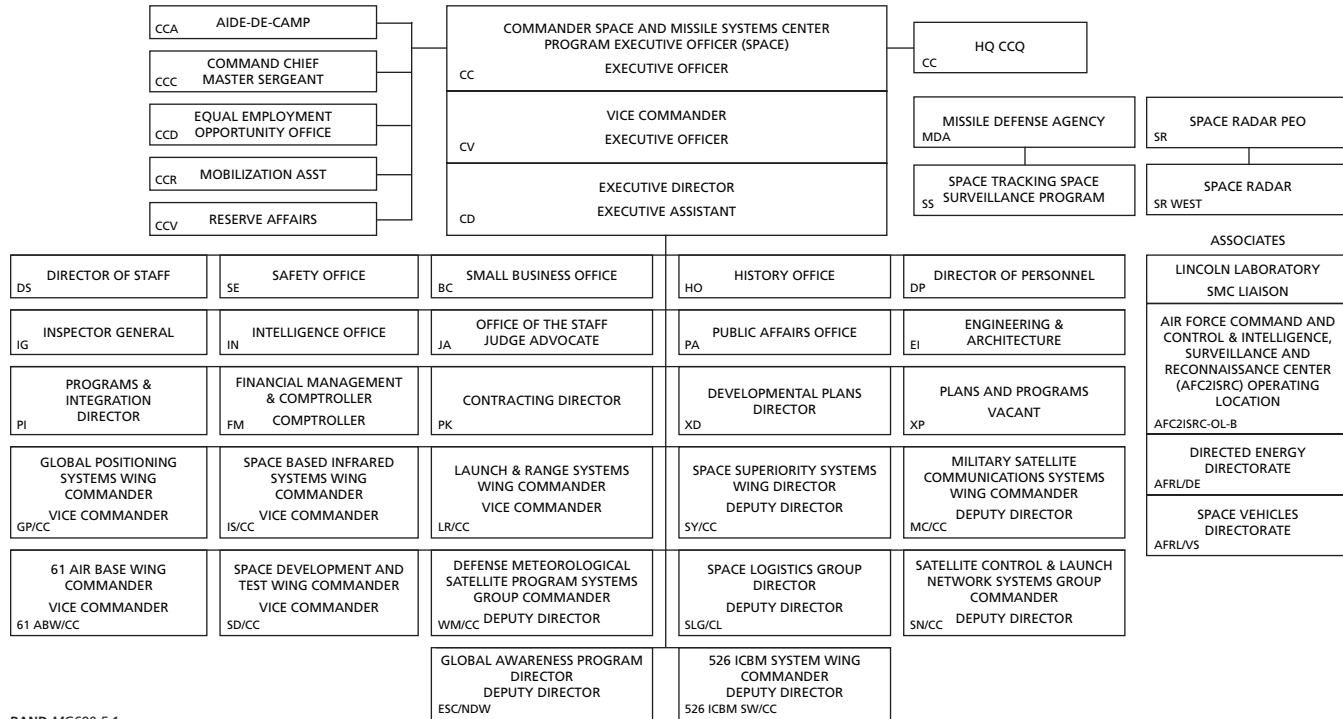
Organization

The Space and Missile Systems Center recently reorganized its approximately 6,800-person workforce to parallel the wing/group/squadron structure of an Air Force operational command. SMC is now structured into six wings, 21 groups, 12 squadrons, 20 divisions, two system offices, and the 61st Air Base Wing. As shown in Figure 5.1, these organizations roughly parallel the previous system program directorates, program offices, and staff functions. General descriptions of the major SMC programs appear in Appendix B. The intent of the reorganization, which has also been implemented at other Air Force acquisition centers, is to “. . . provide respective commanders with strengthened authority, accountability, and responsibility.”¹

While in some respects this reorganization simply renames the existing elements, which retain their previous personnel and functions, its advertised objective of giving the unit commander increased authority and flexibility over the organization may have significant effects on the more specialized functions such as cost analysis. It appears that in the new organization each commander will have nearly complete responsibility for setting staffing levels and skill mix, as well as evaluating all personnel assigned to his or her organization. Although this approach has advantages for the mainstream functions of planning and

¹ Air Force Space and Missile Center, Office of Public Affairs, Press Release No. 06-07-06, 2006.

Figure 5.1
SMC Organization



RAND MG690-5.1

executing the program, it may also have the unintended consequence of effectively isolating assigned cost analysts within the organizational stovepipe of the program, limiting training, career development, cross-fertilization, and functional independence. The cost analysis functional staff office (SMC/FMC) is located in the Financial Management and Comptroller's office, which reports to the SMC commander.

Staffing of the Cost Function

Up until the mid-1990s, the cost analysts at SMC were assigned either to the Comptroller's staff (SMC/FMC) and or to one of the system program offices. The SMC/FMC staff generally performed independent cost estimates (ICE) and analyses, directed cost research to improve cost tools and methodologies, assisted programs offices as needed, and set cost analysis policies for the Center. For a variety of reasons, cost analysis activities and experienced personnel gradually migrated from the staff to the program offices. This process culminated with the complete dissolution of the FMC organization as a directorate in the mid-1990s and reassignment of its responsibilities to other staff organizations or to the program offices. In parallel with the reduced emphasis on USAF cost analysis, general reductions across the acquisition workforce resulted in a reduced capability on the part of the USAF to effectively manage complex acquisition programs. In 2005, the SMC commander reestablished the cost analysis organization as a directorate within the Comptroller's staff.

At SMC, government cost analysis positions are staffed by a combination of civil service personnel, military officers, and SETA contractors. We briefly discuss each personnel category below.

Civil Service

In the Air Force, the cost analysis function is considered part of the financial management (FM) career field, which also encompasses budget and accounting and finance specialties. Over the course of a civil service career, most Air Force FM personnel will be assigned to at least two of these functional areas at various times. While finan-

cial management skills and experience are no doubt useful for cost analysts, the more specialized skills and experience requirements for cost analysis are not necessarily interchangeable with those of the other financial management specialties. For example, cost analysis typically requires a higher level of quantitative skills (primarily probability and statistics) and less accounting than most other FM positions. Also, cost analysts in acquisition commands must often deal with technical issues in some depth to ensure that technology risk is appropriately reflected in their estimates. Similarly, experience with a variety of programs in different phases of the acquisition cycle is important for a cost analyst to develop the perspective needed to identify and assess cost, technical, and programmatic risk in new programs. The box below provides an example of the criteria for mid-level acquisition cost estimators at the National Reconnaissance Office (NRO).

Skills

In-depth knowledge of principles, theories, and methods of cost analysis, including developing cost-estimating relationships and designing cost-estimating methods and models, economic analysis, and statistical analysis

Independent assessments of cost, technical and schedule baselines, identifying risk, and potential cost effects

Strong knowledge of mathematics, economics, finance, and statistics

Knowledge and understanding of key technical and performance characteristics of complex satellite systems as they relate to cost

Strong computer skills, especially in statistics, spreadsheets, and presentation applications

Experience

Four years of progressively responsible acquisition cost analysis experience (two years with master's degree in operations research, cost analysis, finance, business administration, engineering, physics, mathematics or computer science, or other quantitative analysis field)

Education

Bachelor's degree in engineering, physics, operations research, cost analysis, mathematics, or master's degree in finance, economics, or business administration with at least 20 credit hours in a quantitative field, such as operations research, economics, engineering, mathematics, statistics, or physics

Military Personnel

Nearly all of the military personnel assigned to SMC as cost analysts are recent graduates of the cost analysis master's degree program at the Air Force Institute of Technology (AFIT). The minimum curriculum consists of four statistics core classes, six courses covering subjects in econometrics, probability and statistics, regression and time series forecasting, advanced cost estimating, cost-risk estimating, life-cycle-costing, economics, engineering economic analysis and activity-based costing, along with a capstone course and 12 hours of thesis research. In addition, full-time Air Force students must complete additional courses in simulation, acquisition management, quantitative decision-making, and decision analysis.²

Based on our interviews with the program control chiefs and cost leaders in the SMC program offices, these graduates come to SMC with an excellent knowledge of quantitative analysis and cost analysis techniques. Their practical experience in applying these techniques and learning the ins and outs of the acquisition process is typically acquired on the job. In nearly every case, they were viewed as being valued members of the cost organizations. However, some frustration was also expressed because by the time they had become highly productive members of the team, these officers frequently rotated out to a position that did not involve cost analysis, due to either short-term deployment requirements or to normal military rotation. Anecdotal evidence indicated that, for most AFIT-trained cost analysts, the future would not include another cost analysis assignment because of limited opportunities for increasingly responsible cost analysis positions. Thus, their considerable potential in a hard-to-fill career field was lost to the Air Force after one (or at most two) assignments.

Contractor Support

A considerable portion of the cost analysis at SMC is provided by SETA (also known as Advisory and Assistance Services) contractors. These contractors generally work under multiyear, competitively awarded contracts that provide cost analysis and other FM support under indi-

² Air Force Institute of Technology Web page, 2007.

vidual delivery orders. These delivery orders specify the nature of the support to be provided and the labor hours to be expended. The contractor provides the required number of hours, by labor category, as specified in the delivery order. The contractor is also responsible for planning, managing, and executing each delivery order, subject to government review. Each delivery order is funded by the program or staff organization supported.

Based on our interviews and head count data, much of the day-to-day cost analysis work at SMC appeared to be done by support contractors. In several cases, the contractor employees had considerably more cost experience in a particular program than did their government counterparts.³ While there seemed to be a high level of satisfaction with the quality of contractor support at SMC, this situation highlights the need for qualified government leadership to ensure that the contractor's priorities and products are in fact meeting the needs of the government.

Cost Analysis Staffing at Other Organizations

As part of our research into various approaches to structuring, staffing, and managing cost analysis organizations, we interviewed a variety of other government and support contractor organizations. These organizations had approximately similar missions or environments to those of SMC and thus could provide experiences and insights that might be relevant to SMC.

To determine how comparable cost analysis groups recruit, hire, and retain their analysts, we asked the following organizations about their staffing and personnel development practices:

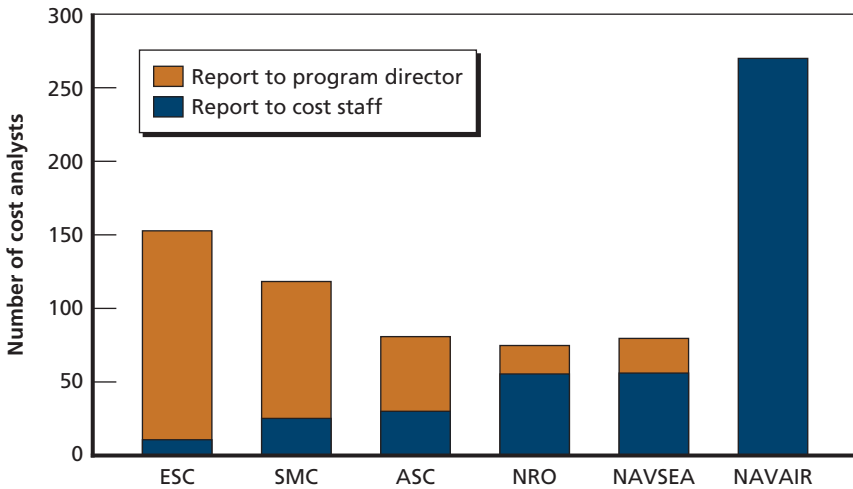
- The Aerospace Corporation
- Air Force Aeronautical Systems Center
- Air Force Cost Analysis Agency
- Air Force Electronic Systems Center

³ Since contractors are directly funded by the SPOs, they should not serve as a main point of contact for cost-estimating functions. Doing so might give the impression of bias, whereas the government employee not in the direct reporting chain may be more independent.

- NASA
- National Reconnaissance Office
- Naval Air Systems Command
- Naval Sea Systems Command
- Office of the Secretary of Defense (PA&E)
- Tecolote Research, Inc.

In nearly every case, these organizations try to recruit candidates who have mathematics, science, or engineering backgrounds. Equally important was the breadth of experience in various acquisition programs. However, all acknowledged that candidates with these credentials tend to be in short supply. To address this shortage, most organizations used a combination of recruiting entry-level science and engineering graduates and qualified civil service employees in other specialties; career-development through training and professional certification; rotational assignments; and grade structure. Most also augmented staff capabilities with varying degrees of contractor support.

NAVAIR and Tecolote Research have formal training programs in cost analysis and the acquisition process for entry-level cost analysts. Several other organizations had some type of cost analysis orientation as part of their entry-level financial management training, but no specialized training focused on cost practitioners. With these exceptions, most in-house cost analysis training is done “on the job” by working under the supervision of one or more experienced cost analysts. Rotational assignments for entry-level analysts and periodic rotation of journeyman analysts into positions with different responsibilities broaden skills and perspectives. Figure 5.2 compares the SMC/FMC cost function to other comparable organizations. Each bar in the figure represents the total number of cost analysts in each organization. The blue portion indicates the number of analysts located in a central cost organization; the orange part shows the number of analysts reporting directly to program directors or managers.

Figure 5.2**Comparisons of SMC/FMC Personnel with Other Cost Organizations**

RAND MG690-5.2

Retaining personnel with skills and experience that are in high demand is a challenge for many government organizations. Most cost organizations we interviewed emphasized the importance of providing an attractive career path for their analysts. Appropriate grade levels, including nonsupervisory GS-14/15s, were considered important to remain competitive with other employment opportunities (including other specialties within the FM career field.) For example, about 10 percent of NAVSEA, NAVAIR⁴ and NRO cost analysts are GS-15s, and each organization is led by a member of the Senior Executive Service (SES). Several also attempted to emphasize and promote the attractive aspects of a career in cost analysis by such actions as the following:

- Exposure to and participation in many different aspects of program definition and management

⁴ NAVAIR also supports the program office budgeting activities, which are traditionally accomplished by the program offices in many other organizations.

- Opportunities for innovation, since few “textbook” approaches are appropriate for all estimating situations
- Satisfaction and recognition that comes from providing advice to decisionmakers that is valued and acted upon
- The intellectual challenges of working with state-of-the-art technologies and cutting-edge applications.

Another common problem faced by the cost analysis organizations we interviewed is obtaining adequate support from independent technical experts. Often, the people most qualified in a subject area are those already working for the program as government, contractor, or FFRDC employees. It can be difficult for these people, who have invested their best efforts and credibility in developing the current program approaches, to distance themselves from their work and objectively assess the true technical and programmatic risk. Because of the general shortage of engineers and scientists experienced in relevant defense technologies, cost organizations are using a variety of approaches to obtain this expertise. The NRO Cost Group, in addition to using its technically oriented government and contractor cost personnel, has support contracts in place to provide independent subject-matter experts. The NAVAIR Cost Division has senior cost analysts, who are also subject matter experts, on staff to participate in Non-Advocate Reviews, oversee cost research projects, and provide consulting help to the programs as needed. (Several of our interviewees mentioned instances in which technical or schedule problems first raised by the cost analysts were later confirmed and addressed by the program management or the system contractor.)

Summary

SMC recently implemented a new organizational structure using the wing/group/squadron paradigm of the operating forces. This organization is intended to increase the authority and accountability of the program manager. Even before this latest change, the cost analysis function has been migrating from the center staff to the program offices over the past 10–15 years. These trends may have had the unintended consequence of weakening the SMC’s cost analysis capability, particu-

larly in its role of providing independent cost and risk assessments to leadership both within and outside of the program.

Today, a mix of civil service, military, and support contractor personnel perform SMC cost analysis functions. Within the Air Force, cost analysis has traditionally been considered a subset of financial management for purposes of organizational structure and career development. While there are areas of commonality, many functions and skills required in cost analysis differ from those required for the specialties of budget and accounting and finance. The lack of senior cost analysis positions, compared with those in other FM specialties, tends to discourage civil service and military personnel from pursuing the multiple cost assignments needed to develop the in-depth expertise required.

To gain perspective on organizational, process and staffing issues, we interviewed leaders in other cost analysis organizations with responsibilities, functions, and environments similar to those at SMC. Nearly all these organizations told us they placed a high priority on developing a workforce with analytical and technical skills and were reasonably successful in providing this workforce with an attractive career path to encourage further development and retention. They also differed from SMC in that their cost analysts, while dedicated to working on specific programs, reported to a strong functional organization rather than to the program manager they were supporting. This was seen as promoting objectivity, higher and more consistent standards, and improved career development. Several of the organizations also noted the value of having access to technical experts who were likewise independent of the program office to assist in surfacing potential problems early and developing objective assessments of risk.

SMC Cost Analysis Workforce Assessment

The first part of this chapter described the SMC organization and how its cost function compares to some other cost functions in the government. In this section, we first describe the current cost analysis workforce available at SMC, grouped by personnel source, education, expe-

rience, and unit. We then detail the work the units must undertake to complete their missions. Finally, we model how the current staffing could better meet projected future demand, under current organizational principles and the alternative suggested in Chapter Six.

Data Source and Survey Instrument Details

Data for cost analysis workforce supply and demand were acquired from each of the Acquisition Category I (ACAT I) SPOs at SMC, SMC/FMC, and the Space Radar SPO. Two survey instruments were sent:⁵ the first instrument asked cost analysis functional leaders to identify all military, civil service, and contractor cost and EV analysts; to detail their acquisition, cost, and EV experience; and to summarize their level of education, Acquisition Professional Development Program (APDP) qualification, and pay grade. The second instrument asked unit leaders to assess their entire workload, broken down into nearly 70 tasks; the responses assessed how frequently each task comes up, how long each task takes to complete, and how many analysts are required. Note that the workforce supply data do not contain a measure of individual effectiveness or quality. However, although the data do not specify the quality of work performed with varying numbers or skill levels of personnel, it is clear that individuals with similar workforce characteristics can excel at different tasks and that many different combinations of workers can form equally effective teams to complete acquisition tasks.

RAND received multiple responses from SMC for both datasets: cost analysis workforce supply in June 2006, supply and demand in November 2006, and updates to both from then until February 2007. The earliest supply datasets contained complete experience, education, training, and pay grade information for all analysts. However, the most recent version accurately reflects total numbers of personnel only;

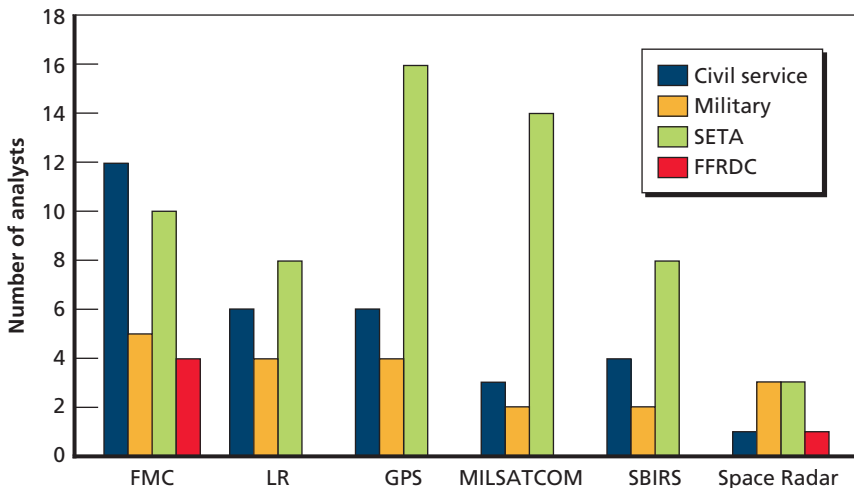
⁵ Each SPO determined the best means to obtain these data. This led to some inconsistency in the interpretation of years of experience measures, with some SPOs reporting “acquisition” experience to be equal to the sum of cost and earned value experience, while other SPOs treated “acquisition” experience as years in the acquisition community. But this method of acquiring data has its benefits, as well: Each SPO was able to provide workforce demand data to best fit its own scheduling and management methods.

these are presented in Figure 5.3. Figures 5.4 and 5.5 come from the most recent iteration that contains a complete description of analyst characteristics. Hence, bars for the latter figures do not sum to current personnel totals. However, the patterns are similar across all iterations of data.

Cost Analysis Workforce Supply

The current cost analysis staffing profile of the Space and Missile Systems Center is a mix of civil service, military, SETA contractor, and FFRDC personnel.⁶ To meet expected staffing needs, these 116 personnel are employed unevenly among FMC and the SPOs. In Figure 5.3, we see that in every unit, nonorganic personnel are the dominant cat-

Figure 5.3
Personnel Assigned to Major SMC SPOs⁷

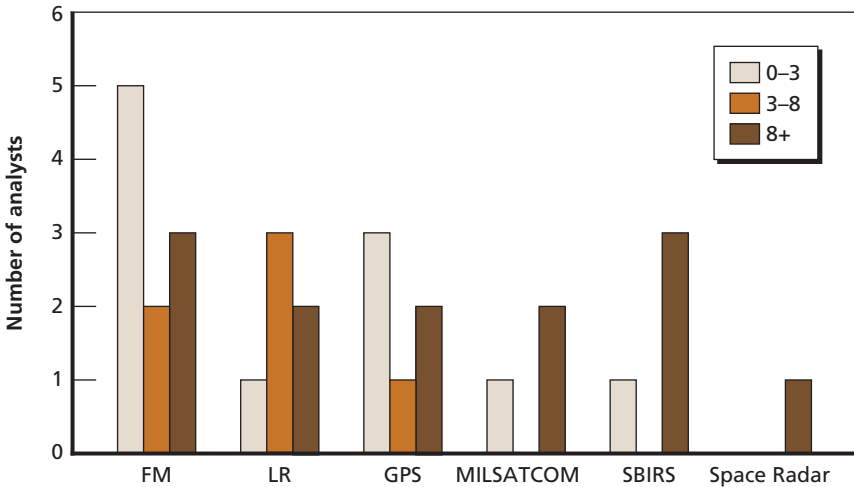


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⁶ The FFRDC is represented by The Aerospace Corporation analysts providing technical assistance.

⁷ Data on 11 SETA and FFRDC personnel for FMC were not collected in the survey instrument, but are listed in Figure 5.3; SETA personnel are utilized at FMC, but are generally brought in on an as-needed basis. Information about them was obtained through interviews with FM personnel. The rest of the figures draw on data for the remaining 107 personnel.

Figure 5.4
Number of Civil Service Cost Analysts, by Unit and Cost Experience



RAND MG690-5.4

egory in terms of numbers; only Space Radar has more military than civil service personnel.⁸ As can be seen in Figure 5.4, which shows the number of civil service analysts by unit and level of cost experience, some units have a mix of more-experienced and less-experienced civil service personnel working with the SETA contractors, whereas Space Radar has only one experienced civil service analyst.

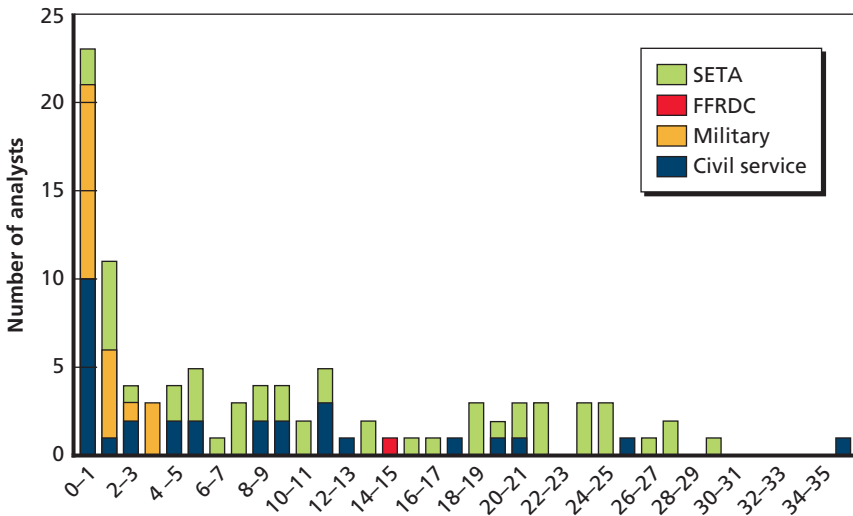
It would be natural to show data on education level, pay grade, and various experience levels of personnel within units next, but in this case neither the education nor the experience level of civil service and-contractor personnel provides additional information, since they are highly correlated and have similar patterns.⁹

However, military cost analysts currently fit a different and quite narrow pattern: a master's degree in cost analysis or related discipline

⁸ Here *organic* refers to government employees, that is, both members of the civil service and military. *Nonorganic* encompasses SETA and FFRDC analysts.

⁹ In the dataset, EV experience, cost experience, and acquisition experience are highly correlated. RAND was tasked with looking primarily at cost capabilities, so cost experience was chosen as the primary measure in this study.

Figure 5.5
Years of Cost Experience and Source

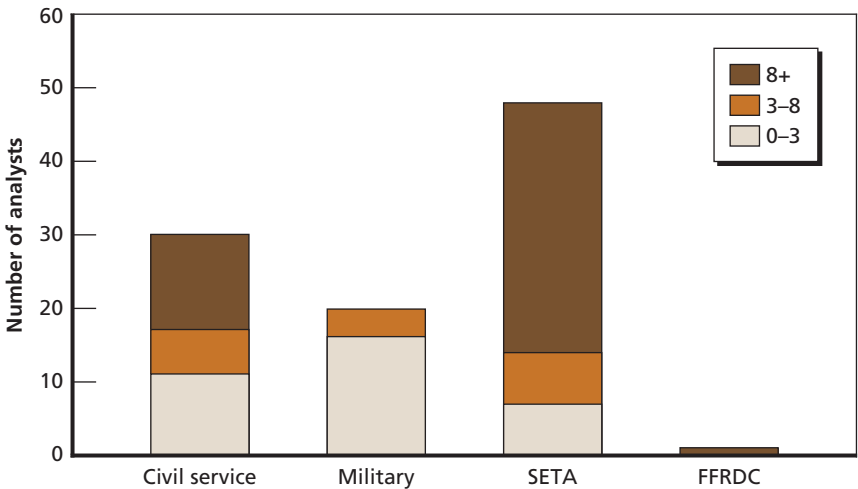


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with fewer than five years of cost analysis experience. The experience component of SMC cost analysts is presented in Figure 5.5, which shows the number of years of cost experience by year. Remarkably, over 20 percent of all personnel have less than one year of experience, and 40 percent have fewer than five, whereas all military personnel have fewer than five years of experience. As described earlier in this chapter, the current career path of military officers does not allow them to specialize in acquisition cost analysis or reward them for doing so. Indeed, few will have more than one tour in cost analysis in an entire USAF career.

A more compact way to look at the same experience information can be seen in Figure 5.6, which shows the number of analysts by source. While roughly ten civil service personnel have more than eight years of experience, the vast reservoir of experience—the “institutional memory”—is held by more than 30 contractor personnel with more than eight years of experience. And, of the half dozen contractor per-

Figure 5.6
Number of Analysts, by Source and Years of Cost Experience



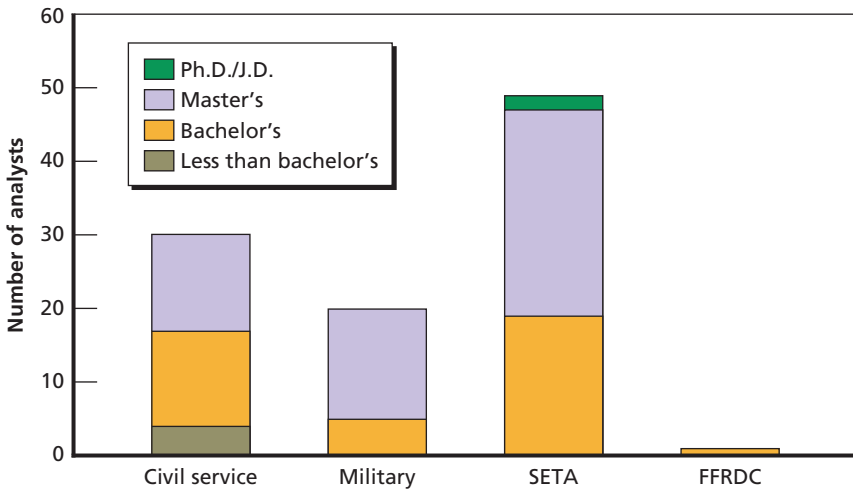
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sonnel with fewer than three years of experience, three have master’s level degrees and two have more than 15 years of EV experience (details not shown).

However, that does not imply that the civil service personnel with fewer than three years of cost experience do not also provide significant institutional memory. In fact, as can be seen in Figure 5.7, four civil service personnel lack bachelor’s degrees; not shown is the fact that one of them has four, and the other zero years of cost experience, yet they have 17 and 20 total years of acquisition experience, respectively.

Figure 5.7 also shows that the vast majority of military personnel have master’s degrees, including degrees in cost analysis (from the Air Force Institute of Technology) or MBA degrees. While slightly less than half of civil service personnel have master’s degrees, slightly more than half of contractor personnel have master’s degrees. However, while half the civil service personnel with master’s degrees have more than eight years of cost experience, three-quarters of contractor personnel with master’s degrees have more than eight years of cost experience.

Figure 5.7
Number of Cost Analysts, by Source and Education



RAND MG690-5.7

Cost experience and education, while considered qualitatively indicative of capability and performance, do not provide hard information about the ability of a worker to perform some or all the tasks required of an analyst in the acquisition community. That is where APDP¹⁰ level might have been useful. But APDP is essentially a management program, not an independent test of ability; as such, it sets minimum criteria for education, training, and experience. As a result, APDP levels are highly correlated with both degree level and years of cost analyst experience and cannot serve as an independent measure of effectiveness or quality. Additionally, once at the GS-13 level, almost all civil service analysts achieve and maintain APDP level III, as can

¹⁰ In response to the 1989 Defense Management Review, the Assistant Secretary of the Air Force (Acquisition) established an Acquisition Career Development Program that applies to officers, enlisted, and civilian personnel occupying acquisition positions. U.S. Department of Defense, *Acquisition Career Development Program*, DoD 5000.52M, November 1995, established the specific standards to be met by individuals filling acquisition positions. To ensure acquisition professionals meet these standards, the Air Force enacted a process through which they can be certified at level I (basic), level II (intermediate), and level III (advanced).

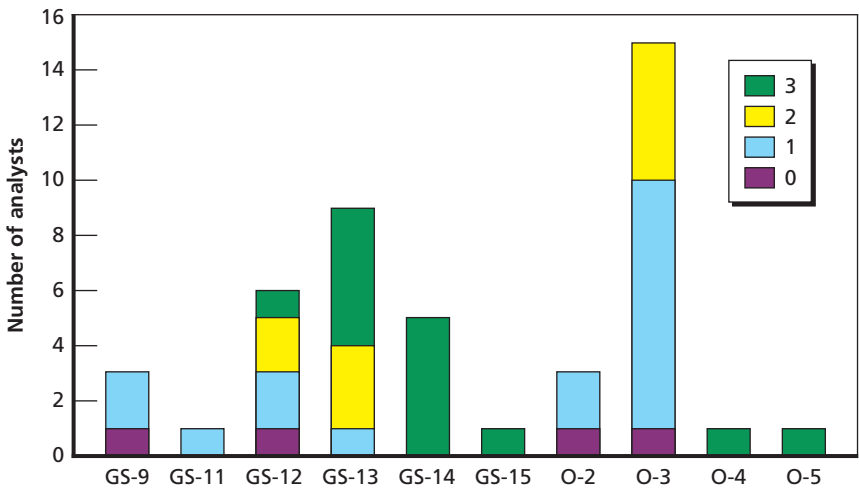
be seen in Figure 5.8. Few military cost analysts obtain the experience necessary to qualify for APDP level III.

Cost Analysis Workforce Demand

Listing the number and qualifications of personnel assigned to units is a far easier task than describing the diverse tasks that every analyst will perform in any single year. Figure 5.9 sums the cost analysis workforce demand provided by SMC, with the number of work-hours in individual task elements aggregated into categories representing the broad mission that is being supported.

The cost analysis workload demand survey sent to all SPOs was an Excel spreadsheet listing dozens of typical tasks a SPO might undertake. For each task, the SPO leader was requested to list the number of people assigned to a task, the frequency with which they are assigned to perform it, and the length of time it takes for them to complete it. Although

Figure 5.8
Number of Organic Cost Analysts, by Pay Grade and APDP Level



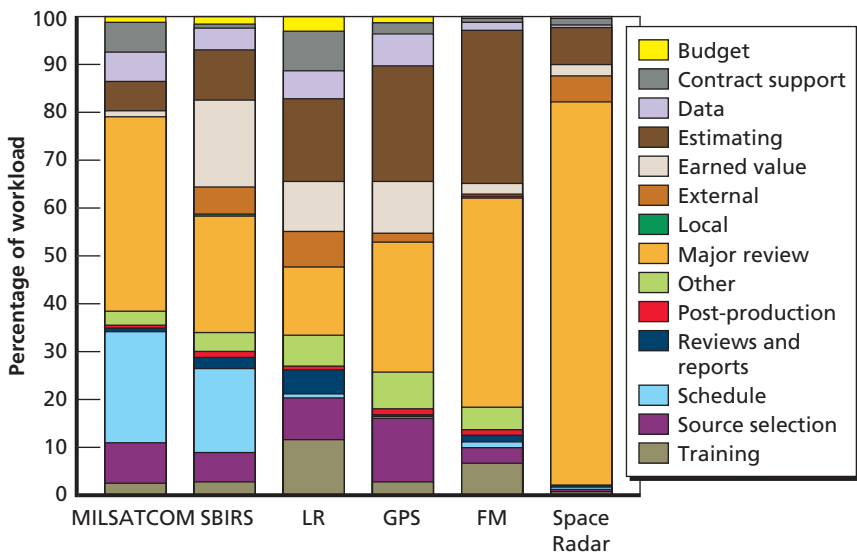
NOTE: O-2, O-3, O-4, and O-5 correspond to First Lieutenant, Captain, Major, and Lieutenant Colonel, respectively.

the survey was meant to be comprehensive, several respondents added tasks they believed were not clearly subsumed under other categories.

RAND aggregated the individual tasks into several functions. For example, a few of the tasks included in the “estimating” function are “perform annual program office estimate reviews,” “perform cost-benefit analyses,” and “maintain cost analysis requirements description.”

As can be seen in Figure 5.9, which shows data reported by SMC and narrowed into functions (not modeling output), the vast majority of tasks are related to major reviews. Estimating is important for some units, and scheduling is important for others. Tasks relating to external communications, such as answering the GAO’s inquiries, account for six to eight percent of time for SBIRS, Launch Vehicles and Ranges, and Space Radar, but take up much less time for other units; other tasks, mostly relating to training, conferences, and other human resource matters, take up the remainder of the time.

Figure 5.9
Percentage of Work-Hours for Each Unit, by Task

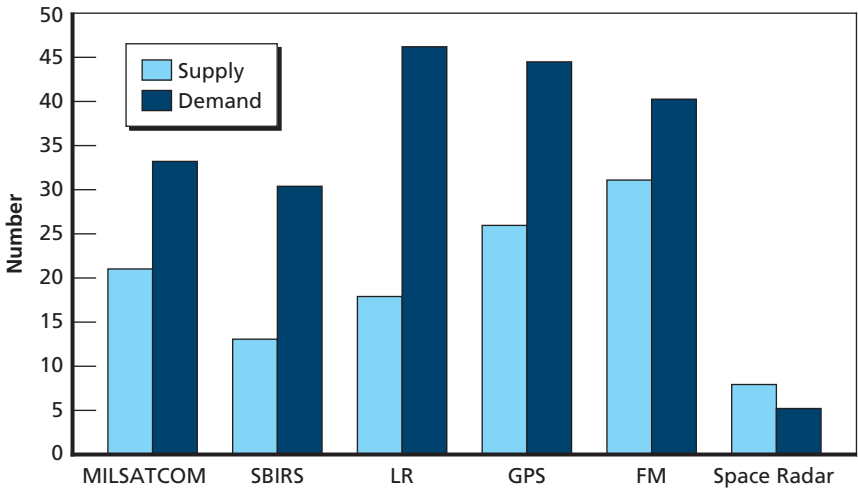


Cost Analysis Supply Versus Demand

The two survey instruments can be used to compare current cost analysis workforce versus self-reported workload demand. In the aggregate, SMC reported that 116 organic and contractor personnel were available for work, and that 200 work-years of effort were demanded of them. As can be seen in Figure 5.10, only Space Radar, with eight people on staff and five person-years worth of work demanded of them has an adequate supply of cost analysts to meet its workload demand. The reported data from Space Radar suggest a different imbalance in which the demand is less than supply. All others are unbalanced. SBIRS and LR report that they need more than twice the number of current personnel; GPS and MILSATCOM report that they need 75 percent more.

But these figures are not necessarily inconsistent, for several reasons. First, the supply figure is a snapshot of recent history; contractor and military personnel movement into and out of SPOs is a constant process. Second, the demand figure is a projection; the demand survey asked extensive, detailed, and difficult questions about workload, to which the respondent had to apply best judgment without reference

Figure 5.10
Worker Supply and Workforce Demand at SMC, by SPO



to comprehensive historical data. The respondents did not specify their risk levels along with their point estimates. Hence, the results are likely to be “conservative,” that is, they are likely to reflect beliefs about the upper bound of the workload.

Basics of the Cost Analysis Workforce Model¹¹

Snapshots of current staffing supply and near-term cost analysis workforce demand cannot provide an estimate of how well future workforce supply will meet future workforce demand. To address concerns about a long-run overdemand, RAND created a dynamic monthly forecasting model that estimates the number of personnel required to complete cost analysis, schedule, budget, and EV tasks at SMC, while assuming that current staffing supply will remain constant. Although it provides a reasonable picture at all time periods, the model is especially targeted at determining periods of peak demand.

In the model, the primary workforce drivers are major reviews. To determine the requirement for each of these reviews, RAND developed a “base case” for the number of analysts required in a month during which a review is under way. For each type of major review (milestone review or source selection), the required set of analysts with various experience levels (0–3, 3–8, or 8+ years of experience) was determined by the expert judgment of the RAND team. A detailed overview of the model and its assumptions is included in Appendix D.

We made two major modifications to this base case: (1) the scale of the project as measured by cost¹² and (2) the amount of time before and after a review due date.¹³ To this we added secondary and tertiary workforce drivers.

¹¹ During the analysis, a detailed set of assumptions and results of the workforce model were sent to SMC for verification. Except for concerns that types of work were not initially addressed, RAND received no comment about the accuracy or the adequacy of its workforce model.

¹² The base case is for programs of less than \$1 billion in total budget. Programs between \$5 billion and \$10 billion have 50 percent greater demand. Programs over \$20 billion have 80 percent greater demand.

¹³ The time pattern is for seven months before and one month after the due date. Half a team is needed for initial startup and documentation cleanup. In between, the multiplier of the

The secondary drivers are continual demands for a fixed amount of budget preparations and EV calculations that each unit must complete regularly, regardless of how large the demands are from the primary workforce drivers.¹⁴ The tertiary drivers are activities that are more schedule-flexible, such as training, estimating, scheduling, database development activities, and other studies. In addition, there are absences due to illness, vacation, and family time.

SMC supplied RAND with a list of estimated dates for all major milestone reviews and source selections in the near future. RAND assumed that three years would pass between major reviews, permitting the extension of the model past 2010.

The outputs of the model are shown in Table 5.1. For each SPO and FM, the first column contains the median monthly demand for cost analysts from January 2006 to December 2010.¹⁵ The second column contains the current manpower available to meet demand. The

Table 5.1
Cost Analysis Workload Model Runs Summary Results at Each SPO and FM (from January 2006 to December 2010)

Organization	Median Demand	Supply	Percent of Months $75\% \times D > S$	Percent of Time $D > S$	Percent of Months $125\% \times D > S$
MILSATCOM	25.5	19	54	100	100
SBIRS	8.4	14	2	13	28
L&R	46.7	18	100	100	100
GPS	26.3	26	19	51	93
Space Radar	5.6	8	0	4	23
FMC	32.0	31	0	64	100

base case ranges from 1 to 1.75. The base case represents staffing needed between 120 and 60 days before a review due date.

¹⁴ To better simulate the budget process, the monthly work required was transformed to peak at the end of the fiscal year. In addition, budget work was doubled in calendar year 2009 to meet the prospective demands of the next Quadrennial Defense Review.

¹⁵ In this stochastic model, the demand in any given month can vary; however, the median demand across 60 months is relatively stable. Data for median demand and the percentage of months that demand exceeds supply are the mean values for ten iterations of the model.

three columns on the right indicate how frequently different levels of demand for cost analysts exceeds current supply.

To interpret Table 5.1: In roughly 4 percent of all months, the demand denoted by the letter D for analysts in Space Radar exceeded supply denoted by the letter S. If we assume that demand will be met with a staff of higher quality, effectively lowering demand for analysts by 25 percent, then Space Radar demand will never exceed supply. However, if we assume that demand will be met with a staff of lower quality, effectively increasing demand for analysts by 25 percent), then Space Radar demand will exceed supply in 25 percent of months.

The 125 percent column, representing a cost analysis workforce with lower training, experience, and productivity, indicates that the number of analysts needed to complete work can be nearly double the current supply.¹⁶ The 75 percent column, representing a higher-quality workforce, is roughly equal to current surveyed manpower, indicating that reorganization, combined with measures to increase the productivity of the SMC workforce can be a viable alternative to increasing the quantity of personnel.

The 75 and 125 percent figures are intended to help address concerns that both supply and demand numbers are “soft.” First, civil service, especially military supply, will constantly be affected by turnover, and many SETA contractors are brought in on an as-needed basis. Second, workforce demand is a “most likely” estimate, sensitive to any of a number of very detailed assumptions. Absent from the RAND model is any quantification of the quality of the cost analysis workforce at SMC. Hence, it is important not to focus on the “gap” between the cost analysis workforce supply and demand; for management purposes, it would be better to think about how best to keep the variable supply in rough alignment with the constantly shifting demand, rather than how to keep a fixed supply markedly higher than an exactly determined requirement.

One possible solution for the periods when demand is greater than supply is to hire more SETA contractors. An alternate solution is to reorganize or reassign SMC cost analysts so that peak loads in one

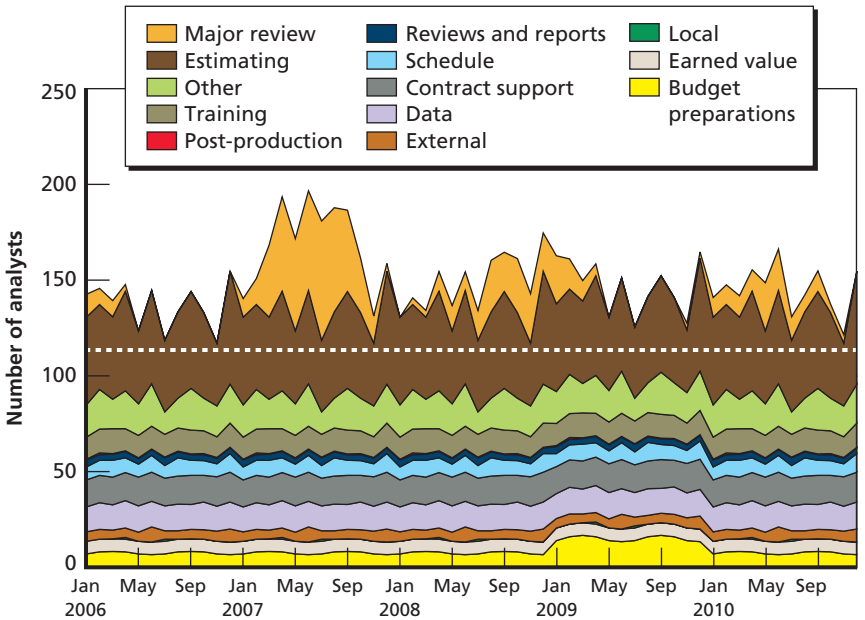
¹⁶ The extra 25 percent is applied to all types of work.

unit can be filled with personnel currently located in another unit. The summary result of such a combination can be seen in Appendix D, which contains a build chart that shows the total workforce demand by component for all of SMC. (The actual model runs are included in Appendix D.)

Figure 5.11 represents RAND’s best aggregate projection of future SMC cost analysis workforce demand, given the portfolio of current programs and configurations. Modeling suggests that SMC can better meet the demand under our recommended reorganization because cost analysts would be free to move from program to program and report to a central cost group. The details of this organizational structure will be discussed in the next chapter.

The organizational improvements described in this document will affect the staff’s efficiency at accomplishing cost-estimating tasks. Increased efficiency means fewer hours or people required to complete

Figure 5.11
Meeting Demands Better Through Reorganization

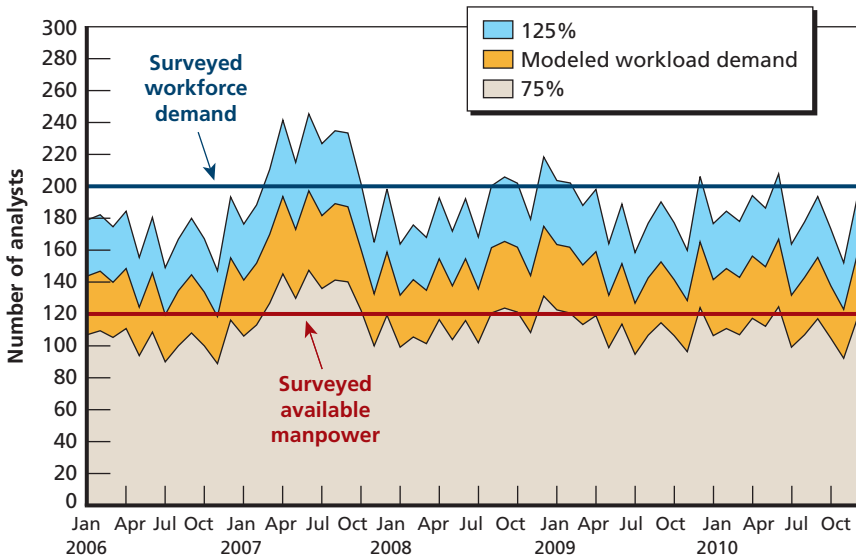


tasks, decreasing overall workload demand. Decreased efficiency implies higher workload demand. To show the effects of higher and lower efficiency in completing tasks, Figure 5.12 utilizes the arbitrary 75 to 125 percent band around the modeled workload demand (the dotted line in Figure 5.11). In addition, the current staffing supply (116) and workforce demand (200) lines are also drawn across the figure. We can see that 75 percent of forecasted demand exceeds current surveyed manpower for 29 percent of months, while 100 percent and 125 percent of demand always exceed current supply.

Summary

The first part of this chapter reviewed the history and current organization of cost analysis functions at SMC. The rest of the chapter accounted for the cost analysis workforce supply and demand currently available at SMC. In aggregate numbers of analysts, the cur-

Figure 5.12
Modeled Workforce Demand with 75 Percent and 125 Percent Bounds



rent SMC workforce is dominated by support contractors, who retain the bulk of the institutional memory. However, at least one experienced civil service analyst heads the cost group at each SPO. And while there are fewer civil service personnel than contractors, they have similar experience profiles. Unfortunately, military analysts have limited career field opportunities, as seen in their truncated experience profile.

SMC reported that workload demand was far higher than workforce supply. However, a model of workload that permits the workforce to move freely within SMC, with assumptions vetted by SPO leaders, suggests that SMC can better meet its workload demands through reorganization and taking other measures to increase the productivity of its workforce. Providing such incentives as training, better pay, improved working conditions, and a competitive benefits package could help attract highly qualified analysts from other government organizations and industry.

Organizational Structure and Other Organizational Issues

This monograph has described a number of problems endemic to the SMC cost-estimating function. As we have seen, the acquisition process as a whole has resulted in optimistic cost estimates. Institutional, cultural, and budgetary factors—particularly the lack of independence of the cost analysts from the program offices—reduced the objectivity of the cost-estimating process. Less-than-optimal organizational structure and responsibilities led to problematic estimates, as did inadequate numbers of experienced and qualified analysts and a lack of relevant data and methods to deal with the complexities of space systems. Limited and insufficient cost, programmatic, technical, and schedule data, along with insufficient coordination among cost analysts, created problems that were further exacerbated by the a lack of adequate risk-assessment processes and methods, including independent assessments of programmatic, technical, and schedule issues.

In some cases, these problems are caused directly by certain aspects of the SMC organizational structure. In others, the problems are driven by other factors, but issues of organizational structure and process play a part. We took a two-pronged approach to examining the issues and the alternatives. We first reviewed the literature to analyze organizational alternatives and found that a key aspect was whether staff functions were organized into separate departments, whether they were integrated into line organizations, or whether a hybrid structure was used. This is termed *departmentalization*, but we also refer to it as how *centralized* the cost organization is. We then looked at other

cost organizations to see how they were organized, and departmentalization immediately stood out as a key aspect of their organizations. Other cost organizations also provided lessons learned that in many cases offer useful insights for SMC.¹

This chapter describes the existing SMC cost organization in this context, reviews the alternatives and their advantages and disadvantages, and finally makes a recommendation as to how the SMC cost function could be organized more effectively. It also discusses some issues regarding how the cost function should interact with other organizations inside and outside of SMC, and some ideas for workforce management. It closes with a description of the aspects of a successful organizational change.

Issues of Cost Analysis Organizational Design

The problems we identified that interfered with the production of accurate cost estimates are to a great extent related to issues of organization—structure and processes. This section briefly describes some of these issues to provide context for a better understanding of the challenges SMC faces. Those challenges are not unique to SMC; how to organize work has been the subject of investigation for hundreds of years. Adam Smith’s 1776 discussion of pin manufacturing is an early example.² Richard Scott says, “One of the most difficult and critical of all decisions facing organizations is how work is to be divided—what tasks are assigned to what roles, roles to work units, and units to departments.”³ The question of *how* to organize is key.

An important insight from the literature is the concept of departmentalization as a means to organize work. Should support functions be in separate departments? Or should they be part of the product (pro-

¹ We focused on learning lessons on what to do and what not to do from working-level cost analysis groups—in particular, ASC, ESC, NAVAIR, NAVSEA, and NRO.

² Adam Smith, *An Inquiry into the Nature and Causes of the Wealth of Nations*, 1776.

³ W. Richard Scott, *Organizations: Rational, Natural and Open Systems*, 5th ed., Upper Saddle River, N.J.: Prentice Hall, 2003.

gram) groupings within the organization? We will see that cost analysis is a necessary function in every program office, yet it benefits from a high level of central coordination to ensure that all analysts have access to the latest tools and the most up-to-date data—resources that should be shared among all SMC analysts. Also, cost analysts are in a distinct career field with highly specialized knowledge that comes from years of experience best learned from other experts. The costs of coordination across units without centralized organization are relatively high. For analysts to stay as current as possible, these costs would need to be born by every distributed product organization. This would call for some degree of departmentalization to keep cost analysts coordinated.

More formally, the organizational literature offers many different approaches for structuring work. Daft lays out four basic alternatives.⁴ A *functional* structure divides distinct functions into individual departments, which are coordinated through managers above the departments in the corporate hierarchy. (Coordination of efforts is a major issue in any organizational design.) A *divisional* grouping divides the organization into product lines, each of which has representatives of all functions (e.g., manufacturing, marketing, finance) located within it and reporting to its management. A *geographic* grouping is similar, but divisions are made by area rather than by product, so that each division might have multiple products. A *multifocused* grouping, which involves a structural form usually called a *matrix* or *hybrid* structure, cuts across two of the above groupings.

How do these alternatives map to the cost function at SMC? Our interviews revealed that the divisional alternative most closely characterizes current operations. Numerous departments (SPOs) focus on specific products, with integrated cost and other functions. Daft cites research indicating that the weaknesses of this approach include the lack of economies of scale for functions (cost-estimating would be included here) and reductions in deep functional competence and

⁴ Richard L. Daft, *Organizational Theory and Design*, 6th ed., 1998, Cincinnati, Ohio: Southwestern College Publishing, 1998. This textbook provides a useful summary of research conducted by many original sources. However, the topic is an exceedingly rich one that is difficult to describe completely in one source. Scott's (2003) description of the field is another useful source for understanding these issues.

technical skills.⁵ Coordination, integration, and standardization across departments are also difficult. These are, in fact problems that SMC has faced. In our interviews, we ascertained where most significant cost analysis work responsibilities are currently performed at SMC. These are displayed in Table 6.1.

As can be seen from Table 6.1, SMC is heavily program-centric, with most of the cost analysis functions performed in the SPOs and some participation by the FMC staff. The two items with question marks were those where it was not clear who had overall responsibility for accomplishing the task. In some cases, the SPO was doing them; in others, it was the FMC staff.

Table 6.1
Where Cost Analysis Responsibilities and Tasks Are
Currently Found

Work Responsibilities and Products	SMC/FMC	SPOs
Program acquisition strategy, technical baseline (CARD)		x
Milestone estimates, cost proposal evaluations		x
Budget estimates, excursions, SAR input		x
EV analysis + IBRs		x
Develop cost models, tools, and cost, technical and program databases	?	?
Represent cost function to outside organizations	x	
Recruitment, training, career development of cost analysts	?	?

NOTES: CARD = Cost Analysis Requirements Description. An x means that the task takes place within the relevant organization. A question mark (?) means that RAND was not able to ascertain where the work took place.

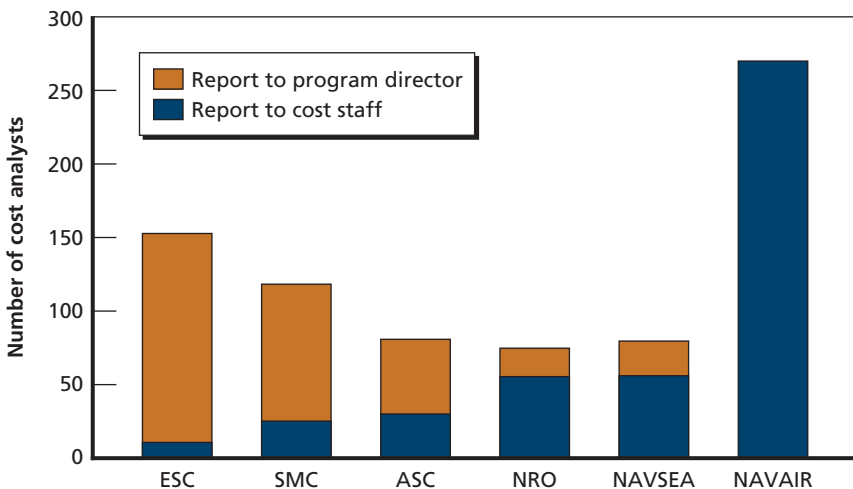
⁵ Daft, 1998, p. 219.

Structure of Other Cost Organizations

We interviewed analysts and managers associated with other military cost organizations both inside and outside the Air Force.⁶ The nature and availability of data prevented us from linking organizational structure to the success of cost-estimating outcomes. (That is, does one type of organizational structure produce more accurate estimates? Program differences may make this comparison less meaningful as well, since comparing vastly different classes of programs may not provide any real insights into the challenges of estimation.)

Figure 6.1 compares the number of SMC cost analysts with those in other Air Force organizations, such as ASC and ESC, as well as with those in non-Air Force organizations, such as NRO, NAVSEA, and NAVAIR. The blue portion of each bar shows the number of analysts reporting to a centralized cost organization, and the orange portion

Figure 6.1
Comparisons of SMC/FMC Personnel with Other Cost Organizations



RAND MG690-6.1

⁶ Our research efforts focused on military cost organizations purchasing similarly complex systems.

represents the number of analysts reporting directly to program directors (PDs). As the figure shows, the number of analysts reporting to the PD is much higher for SMC and ESC. Further, the figure also indicates that the number of analysts reporting to a cost organization is smaller at SMC than in the non-Air Force cost organizations

In fact, one can claim that the SMC cost capability is currently situated primarily within the SPOs. There is a very small centralized FMC staff that plays a minimal role in creating cost estimates. It has a GS-15 as its leader and two GS-14s as the deputies, one in charge of cost estimation and the other in charge of EV analysis. A proposed new FMC organization would be composed of 26 analysts, including ten civil service and five military, located within this department and reporting to its leadership. The vast majority of the actual cost analysis is now performed in the program offices themselves by analysts who report to the SPO leadership. ESC has a similar structure and has a GS-15 as the head of the cost staff.

NRO and NAVAIR have highly centralized cost departments that perform work for program offices as needed. Very few cost analysts report directly to the PM. Both of these organizations have about 10 percent of their cost staff in GS-15 positions.

ASC has a hybrid structure: Some cost analysts are located in the SPOs, working on budget, EVM, and other day-to-day cost requirements. Others are located in a small, centralized staff, which is responsible for producing cost estimates for major milestone reviews. There are two GS-15 level analysts. While the total number of analysts is small, ASC analysts are generally very senior and experienced.

Interviews conducted with the other organizations led to several observations that were shared by most, if not all of them. The general agreement was that the cost function must be insulated from the bureaucratic pressures of the programs if analysts are to provide objective estimates. For those organizations within the Air Force, there was concern that the “wing, group, squadron” organization will erode this insulation and hence the required objectivity of the cost analysts. We also learned that support contractors are useful in many ways. They provide analytical support ranging from major estimates to regular budget work. However, they should be managed by qualified govern-

ment estimators. Usually, program offices fund the contractor support, which could hinder contractors' objectivity because they may be under subtle or direct pressure to shape estimates to please their customer.

Another finding was that efforts should focus on sound initial estimates to provide the foundation for later work. They are far preferable to efforts spent on multiple estimate reviews ("build in quality rather than inspect in quality"). Generally, reviews take the initial estimates as their starting points, so major weaknesses in the initial estimate may not be corrected during the estimate review process. Therefore, initial estimates need emphasis and resources. In addition, a few well-qualified, experienced analysts will likely be much more effective than many inexperienced ones.

The other cost organizations also indicated that the maintenance of a historical track record of estimates is a key management tool. Having a detailed estimate to reference builds credibility, particularly if the final program budgeted amount is significantly lower than the original objective cost estimate. They can then counter claims of bad cost estimation, which will increase their credibility as creators of reasonable estimates.⁷ A track record also allows for the long-term assessment of individual analysts and the accuracy of analytical tools. A track record maintained over time creates a stronger sense of ownership over the estimate that might motivate a more careful original estimate. The other cost organizations also have found that the identification of major sources of technical risk early in the program is critical to estimating success. Whatever approach is used to measure technical risk should be robust and should reflect the difficulties of developing individual subsystems as well as integrating them into the final system. Our interviews also showed that many successful cost analysts have a

⁷ One reviewer of this document raised the concern that cost analysts may artificially inflate their initial estimates to avoid the risk of underestimation. However, if the cost estimates end up being greater than the final actual cost, it could be tracked as a problematic cost estimate, just as an underestimate would be. A greater danger is that program managers lack incentives to underrun costs, so if a budget was based on an overestimation and was greater than what was really needed, program managers may spend more money than necessary and resources would not be most efficiently allocated for the overall Air Force. Offering program managers incentives to underrun their cost estimates could counter this problem.

technical background. As will become clear, these findings helped us develop our recommendations for SMC.

Alternatives for SMC and Our Recommendations

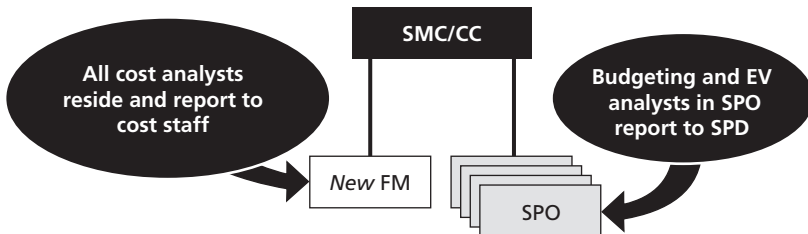
What do these structural alternatives mean for SMC? The three alternatives—a separate centralized cost department, decentralized analysts, and a hybrid structure—all have different implications for the SMC cost function.

Separate Department

The first alternative is a separate cost department managed as part of SMC's FM organization. In this structure, all cost analysts would report to the cost staff. SPOs would have separate analysts to develop recurring budgets and EV estimates and analyses. Figure 6.2 portrays a centralized cost organization.

Having a separate cost department offers numerous strengths. Most important, this structure should maximize the objectivity and independence of the cost analysts. Analysts would report to—and have their performance reviews conducted by—the financial management chain of command instead of the program office structure. Being officially part of the program offices has the potential for both overt and

Figure 6.2
Centralized Organization



indirect pressures. Presumably, analysts would feel less overt pressure from the program office to keep their estimates low to increase the likelihood that programs would be funded initially.

A strong cost department can offer an effective senior voice to represent the cost community to SMC leadership and to external organizations. The head of the department should be of sufficiently high rank—SES level—to represent the cost function effectively in discussions with other senior leaders, such as general officer program managers. Strong leadership in the department can obtain necessary resources for the cost function, influence SMC policies that affect the cost function, and so forth. For example, it could foster better interactions with the staff engineering function, so that cost analysts get the required technical assistance. Strong leadership in the cost department can also represent SMC cost analysts at external functions, which may control resources or other benefits, such as the SAF/FMC and the AFCAA staffs. Finally, strong leadership can interact effectively at cost-estimating conferences, such as the DoD Cost Analysis Symposium (DoDCAS) and meetings of the Society of Cost Estimation and Analysts (SCEA), with the FFRDCs, and so forth.

A distinct cost department also has career development implications. A central cost organization has the potential to offer more-effective career development through managed assignments and training. It could provide a resource for cost analysts looking to improve their skills and could offer a clearer hierarchy for promotions. It could better manage hiring, training, and other aspects of career development. It could provide a structure for sharing new and useful tools and techniques and lessons learned, for the benefit of all.

A related benefit is the development of an expert ability to evaluate analysts on the quality of their analysis as well as a way to capture analyses and compare estimates with eventual program performance. This would give analysts a powerful reason to continually improve their estimates.

However, *a separate department also has distinct disadvantages*. First, it may make cost analysts less accountable to the program managers, who might not be able to provide incentives for timely performance. Second, SMC operates in a larger Air Force context. The Air

Force is going to a “wing, group, squadron” organizational construct that is designed to give program managers more control over resources. A separate cost department directly conflicts with this structure.

Third, unless cost analysts are located in the program offices and have frequent opportunities to interact with engineers and other SPO personnel, they may know less about specific programs and have fewer technical insights. Space systems are complex and are growing ever more so, making technical issues a significant driver of cost. Understanding the complexities of individual systems is key to creating good estimates, and being in the SPO on a continuous basis for some period of time facilitates that understanding.

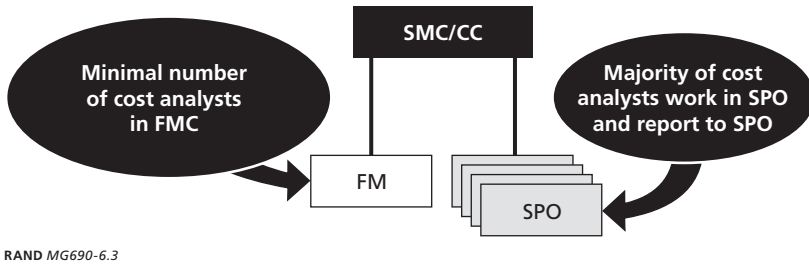
Finally, it may be difficult to find funding for a centralized department. The program offices would have to pay additional “taxes” for certain costs incurred by a central cost function. Whether this total would be higher than current “taxes” is unknown, but we would expect there to be some negotiation.

Full Integration with Line Organization

In the second alternative, most or all of the cost analysts would be hired by, managed by, and located within individual program offices, with little functional integration with analysts at other SPOs. The central FM organization would have few analysts. (This most closely represents the current FMC structure at SMC.) Again, this approach has both benefits and limitations. In many cases, these are the reverse of the benefits and limitations of the centralized structure. Figure 6.3 depicts the second organizational structure. Integration with the line organization offers PDs direct control over cost analysis resources. PDs can set the priorities and manage the work of the analysts within their divisions. One implication is that analysts may thus be more responsive since they are supporting the person to whom they directly report.

A second and important benefit of this approach is that long-term experience within a SPO could enhance the technical and programmatic knowledge of cost analysts on that system. As we have described, space systems are extremely complex technically. Developing a deep understanding of the technical issues will help analysts develop

Figure 6.3
Decentralized Organization



their cost estimates by giving them insight into what the most appropriate estimating tools or analogous systems might be.

However, full integration within the SPOs also poses risks. The most significant concern is the potential effect on the objectivity of cost estimates. This may be due to direct or indirect pressures. Directly, the PD may try to sway the cost estimate to fit the expected budget availability or overall cost goals. One subtle metric for success for PDs is whether their programs are funded. If they are concerned that cost estimates are too high, they may fear that they will not be able to convince the Air Force or Congress to justify spending as much as expected to acquire that particular capability. As a result, they may pressure their cost analysts to manage the estimating process so as to generate optimistic numbers. Although this may not be a directed “estimate-to-budget” order, it could amount to the PD arguing over the technical details of the estimate until enough programmatic adjustments are made that the estimate itself falls within the desired budget amount. And if PDs hire and manage the careers of estimators within their programs, they can reward and punish compliant or recalcitrant analysts.

The lack of a strong central cost department removes a central voice for a number of policy issues. These would include data collection and data sharing with other organizations, best practices in estimating tool development and tool use, and other issues regarding estimating approaches. Without a clearinghouse to enhance the sharing of these issues among SPOs, estimators may not engage in the continuing education necessary to remain abreast of the best new approaches. And the

lack of a strong central voice for cost may mean that the objective cost perspective is not adequately represented to SMC's PEO.

A last concern is the limitation on career development and progression for individual cost analysts. While estimators might be quite successful within their SPOs, they may not have the same kind of career opportunities that derive from a more formal career management approach. A separate cost department can offer a defined career track with broader training and development opportunities. The size of SPOs or the program's position in its life cycle may limit the number of cost estimators and limit lateral experience reassignments or even advancement. Certainly, estimators can apply for other jobs within SMC, but until those jobs open up there may be little reason to invest in learning new skills that may not apply to their current programs. Having a centralized department that takes a proactive approach to career development offers analysts a more distinct career path by providing a wider range of experience and training opportunities.

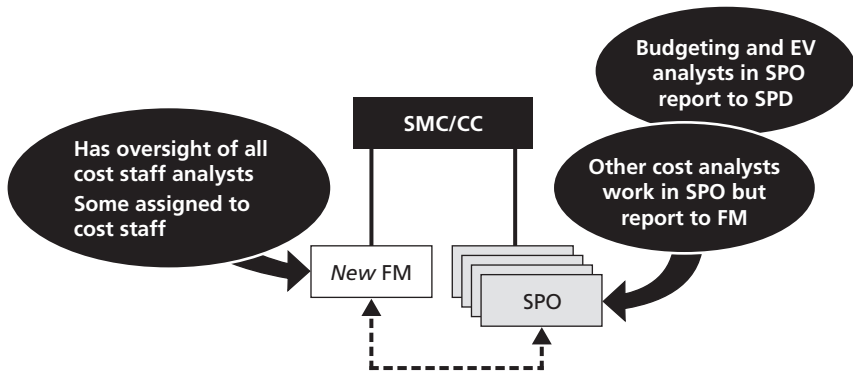
Hybrid Structure

The third alternative offers some of the features of both the centralized cost department and the decentralized integration of analysts with line organizations. Under this approach, a *new* FM would have oversight over all cost analysts, with many assigned to the central FM cost staff.⁸ Other cost analysts would be located in SPOs but report to FM. Budgeting and EV analysts would be located within the SPOs and report to the PM. This approach has many of the benefits of both approaches described above, with a few limitations of its own. Figure 6.4 displays such an organizational structure.

In this structure, the cost staff would be responsible for producing major cost estimates for milestone reviews, source selections, Nunn-McCurdy breaches, or other specific cost estimates requested by management at all levels. The SPO analysts would be responsible for maintaining and updating the estimates between major reviews, developing budgetary estimates required by the Planning Programming and

⁸ We italicize the word "new" here to emphasize that we are talking about a new organization with a different mission and function from those of the current FM organization.

Figure 6.4
Hybrid Organization



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Budgeting System (PPBS), and periodic EV analyses. This approach maximizes flexibility in moving analysts to meet the peak workloads of individual SPOs. If cost analysts are “owned” by the central cost department, then the department can deploy and redeploy expert analysts as needed to meet major estimating requirements.

Under this approach, the centrally located analysts would be less subject to direct or subtle pressures from PDs to put a positive spin on their estimates and probably better able to produce objective estimates. One benefit of this approach would be that FM analysts who are truly objective could eliminate the need for a separate ICE within SMC, and, once their credibility is established, possibly within the Air Force as well.

The central FM cost staff could have oversight over cost analysts and effectively manage professional standards and careers. The central organization could develop a recruitment plan that features a regular pipeline of junior analysts into the cost staff as part of their initial training and development as the expert cost analysts of the future. The cost department could also standardize data collection and best practices in estimating tools and techniques and could work with other organizations to share data and insights into best practices in cost-estimation approaches. It could maintain a track record of analyst performance, thus creating a further incentive for objectivity and independence.

Analysts who are located at the SPOs doing budget and other frequent tasks would develop in-depth programmatic and technical knowledge that they could share with analysts from the central organization who are on assignment at the SPO to work on major milestone and other significant estimating events.

However, this approach does not mesh with the “wing, group, squadron” structure that characterizes the Air Force’s preferred approach to designing organizations, an approach that gives the maximum amount of control to line managers, such as PDs. The limitations on their control of estimates may make it difficult to win PD support. This may be an inherent limitation on the ability of SMC to make a change toward a hybrid structure. Furthermore, the issue of funding for a central organization arises again in this structure. PDs would have to agree to be taxed to support centralized analysts unless a separate budget could be established as part of the PPBS process.

Recommendation

Nevertheless, for reasons that follow, our recommendation is that SMC adopt this hybrid approach. In our view, this has the most potential benefits and the fewest limitations. In particular, increasing the objectivity of the analysts performing major cost estimates will improve the reliability of the estimates and SMC’s reputation as an organization whose cost numbers can be trusted. This kind of change will require significant support from senior SMC leadership, as we discuss below.

We also provide recommendations on where work should be performed. Tasks should be conducted within the SPO when the focus is on program execution, where changing priorities or rapid response are common, for functions required to manage the day-to-day activities of the program, where the official position for effective interaction with other SPO personnel is needed, and where processes are unique to the program.

Tasks should be performed in the cost staff when nonadvocate analysis is a priority, experienced government leadership is required, economies of scale and flexibility in assignments are desired, skill sets and tasks are outside the SPO’s primary mission, and workload and priorities are generally predictable. Table 6.2 revises the cost analysis responsibilities

Table 6.2
Where Cost Analysis Responsibilities and Tasks Should Be
Performed Under a Future Hybrid Structure

Work Responsibilities and Products	SMC/FMC	SPOs
Program acquisition strategy, technical baseline (CARD)	P	L
Milestone estimates, cost proposal evaluations	L	P
Budget estimates, excursions, SAR input	R	L
EV analysis + IBRs	P	L
Develop cost models, tools, and cost, technical and program databases	L	P
Represent cost function to outside organizations	L	P
Cost analysts recruitment, training, career development	L	P

KEY: L = leads the effort; P = participates in the effort; R = reviews the product or output of the effort.

previously shown in Table 6.1 as they are currently being accomplished at SMC by rearranging them into the recommended hybrid structure.

As Table 6.2 shows, the SMC cost staff is given the responsibilities and tasks that can benefit most from a centralized structure, where staffing and skill level leveling is critical, where policy decisions or more standardization are desirable (cost models, tools, databases, and documentation), or for responsibilities not germane to the primary functions of the SPOs (such as recruiting and training). But communication and participation by the SPOs and the FM staff in all these responsibilities would be desirable as part of the hybrid structure.

Other Organizational Issues

Workforce Recommendations

We also offer an outline suggestion for the management of the cost analyst workforce to support the new approach. Our alternative gives more responsibility to the central FM cost organization for managing recruitment, training, and career development. This is a new area for

FM but one that can be done effectively with the appropriate support. The key will be close interaction with SMC's human resources function (both military and civil service personnel functions) to gain support for any alternate approach, both to understand the technical and administrative issues involved in career management and to make sure that all the legal requirements are met. As we will describe, these recommendations include having a strong group of expert analysts located at the FM central cost department to be deployed as needed to the SPOs to help with major estimates; a group of mid-level analysts located at program offices to provide day-to-day support to the SPOs while getting more in-depth technical and programmatic insights into specific space systems; and a group of junior analysts on the FMC staff being trained by senior analysts and working on developing their cost analysis skills, learning new tools, and maintaining existing databases.

A "cradle-to-grave" (or "recruitment-to-retirement") approach to managing cost analysts might take the following path. The first step is recruitment. One of the difficulties in recruitment is the fact that SMC is located in Los Angeles, which has a very high cost of living and, based on our interviews at SMC, some perceived concerns about the quality of the local public schools.⁹ This may create difficulties in recruiting skilled analysts from outside the LA area, but there is a large pool of potential employees who have attended local schools or who have family in the area or other reasons for wanting to be based in Los Angeles.

We recommend recruiting analysts from local universities,¹⁰ including the University of California–Los Angeles, the University of Southern California, the University of California–Irvine, and others. There is a wide enough range of high-quality academic institutions in the area for SMC to get a diverse group of recruits, and SMC could aim for getting new employees from a range of institutions and depart-

⁹ This is based on hearsay evidence from interviews conducted at SMC rather than on a systematic assessment of LA schools, so it should not be taken as an official evaluation by RAND.

¹⁰ We suggest that SMC focus on these schools because of the potential difficulty of recruiting analysts to the high-cost Los Angeles area. Those who already live in Los Angeles may be more likely to view the benefits as outweighing the costs.

ments to get varied backgrounds that would allow for a diversity of perspectives and skills. Of particular value would be students who have technical engineering backgrounds, because they would be most likely to understand the complex technical issues involved in space systems and would also have the quantitative skills needed for cost analysts. Graduates with an accounting or finance background with technical aptitude (and perhaps the willingness to pursue a technical graduate degree) would be a strong second choice, as would those with applied math, economics, or other strongly quantitative fields of study.

Yearly numbers of recruits would vary depending on forecasted future needs of programs, as well as retirements and other analysts leaving the FM workforce. Ideally, recruiters would try to hire at least a couple of analysts every year to maintain a pipeline of junior personnel to keep up ties with the local university career placement departments.

Junior analysts would be brought in to work in the central cost department with the senior analysts located there. They could be deployed to the SPOs side by side with senior analysts working on major estimates. They could also work on building and maintaining cost databases and other tools. The junior analysts would receive support for training and development courses, such as those offered through SCEA. The sharing of knowledge among analysts, particularly the transmittal of learning from senior-level to junior-level analysts would start here.¹¹

Mid-level analysts would be deployed to SPOs to work on budgets and other day-to-day cost-estimating tasks required by the SPOs. They would be SPO resources for a couple of tours, reporting to the PD but under the watchful eye of the FM cost department. While at the SPOs, the analysts would work closely with technical and program experts to gain in-depth knowledge of specific space systems and technologies. They would also work with analysts from the central cost

¹¹ Learning within organizations is a rich and complex topic to which Linda Argote's book, *Organizational Learning: Creating, Retaining and Transferring Knowledge*, Norwell, Mass.: Kluwer Academic Publishers, 1999, offers an excellent introduction.

organization in support of special estimating requirements, including milestone reviews.

After a few years working at the SPOs and gaining specific program and technical experience, analysts would rotate back to the cost staff as senior analysts. The central cost organization should have enough high-ranking (GS-13 through GS-15) slots to attract and retain these analysts. They would be responsible for working on and managing major cost estimates, such as milestone reviews, and would be sent to the SPOs as necessary to support this kind of work. They would be responsible for training junior analysts and for working with mid-level analysts while doing the major reviews. They would help decide FM policy on such issues as appropriate data collection and best practices in estimating tools and techniques. A few of the most expert senior-level analysts could be “senior cost managers.” They would help run the system as a whole and also be in line for senior leadership positions.

The central cost organization would be taking an active role in managing the career progression of its analysts, providing opportunities for training and growth in both the central cost organization and at the program offices. However, the cost group may also encounter times where there is a greater demand for its resource—skilled cost analysts—than there is adequate supply to meet. What happens in these cases? SMC will need to develop some kind of organizational process to deal with them. For other resource allocation decisions, analysts have proposed an additional “integration” function that stands above the sources of supply and demand. However, in SMC only the very top leadership stands above both the program offices and the proposed cost group. We do not suggest that SMC top leaders should be engaged in managing these concerns. We do suggest that the cost group and the program offices set up a steering group that meets periodically (quarterly, or as needed) to set policy on assignments and to develop an agreed-upon strategy for managing cases where disagreements about perceived needs and availability of analysts arise.¹²

¹² Leslie Lewis, James A. Coggin, C. Robert Roll, *The United States Special Operations Command Resource Management Process: An Application of the Strategy-to-Tasks Framework*, Santa Monica, Calif.: RAND Corporation, MR-445-A/SOCOM, 1994.

This approach provides a clear mechanism for career progression and skill development. But as with the change in organizational structure outlined above, it would be impossible without sustained senior leadership support for change.

Working More Effectively with Other Organizations

Another important concern is whether the cost department can work effectively with other organizations. There are at least two major classes of organizations that cost analysts should be able to interact with regularly. The first group is the technical staff within SMC. The second group is other cost organizations, particularly those working on space issues.

Technical resources inside SMC, including the Chief Engineer's office, could be a useful resource in a number of ways. Cost analysts could research technical questions in their library (if this resource exists) or by asking the engineers in the Chief Engineer's office. Cost analysts could benefit from any technical training courses or seminars. And cost analysts and engineers could benefit from temporary training assignments in each other's organization. The leadership of SMC would be needed to support these initiatives by helping the cost department develop and maintain the linkages required for this kind of productive exchange of ideas. We also recommend that the SMC Chief Engineer coordinate on all CARDs produced for milestone reviews so that the SMC commander can obtain independent expertise on the programmatic, technical, and schedule underpinnings of each program.

There are also cost organizations outside of SMC with which interaction could be mutually beneficial, from sharing data and tools, to sharing advice, ideas, and lessons learned for current and future programs. The most obvious example is the NRO. While there are some links between the two, our interviews revealed some constraints to an open sharing of some kinds of information. Some of this is due to the sensitive nature of the data, but there are other types of information (e.g., lessons learned, tool development) that could provide a benefit to both sides if there were more formal linkages. Again, SMC leadership, along with the leaders of the external organizations, would need to provide the appropriate support.

Senior Leadership Support Needed for Organizational Change

This chapter has outlined some suggestions for far-reaching changes for SMC's cost capability. We have identified changes to the organizational structure that will increase the independence of the cost-estimating function and in our view will increase the quality of the cost estimates by somewhat insulating the cost estimators from program pressure and creating a formalized approach to career development and training. However, moving from the current situation to the organization that we have laid out in this monograph will require a significant amount of effort. Moore et al. offer a useful summary of one approach to organizational change.¹³ Preparation for change includes developing a case for change, garnering senior leadership support that may include a guiding coalition, and developing an action plan for change. Support for change includes sustained communication, ensuring the right kind of training and skills, providing incentives, and providing the necessary level of resources. Execution of change involves testing and validation, then full deployment, followed by monitoring and refinement.

The case for changing the SMC cost function is clear. Programs have vastly overrun their initial budgets, drawing the attention of top military leadership—and of Congress. Stronger and more objective cost estimates would reduce the risks of cost overruns, particularly if the FM cost department was able to limit the ability of program leaders to shape an estimate that will result in one they think will be funded. Senior leadership support is necessary for the changes outlined above, and links to the need for resources and incentives. Since the change involves multiple organizations within SMC as well as linkages between SMC and external organizations, the commander of SMC needs to be involved. SMC/FM can develop an action plan for change, based on the recommendations provided here. FM needs to provide a consistent message about the change, and also oversee the changes. It

¹³ Nancy Y. Moore, Laura H. Baldwin, Frank A. Camm, and Cynthia R. Cook, *Implementing Best Purchasing and Supply Management Practices: Lessons from Innovative Commercial Firms*, Santa Monica, Calif.: RAND Corporation, DB-334-AF, 2002.

can also make sure the right kind of training and skills are available. And it can monitor and refine the new organizational structure and associated changes to make sure that it is operating as intended.

Daft suggests that successful change has five elements: ideas, need, adoption, implementation, and resources.¹⁴ The present monograph lays out the ideas for change and describes the need. Adoption occurs only when key decisionmakers decide to enact the change, which is why senior leadership support is so important. Implementation comes when the new ideas are in use and may be the most difficult step because without implementation, no change occurs. Finally, resources—time, attention, and investments—are required for successful change, which again argues for senior leadership support. The question of resources is of particular concern in a constrained budget environment, but much of what we suggest involves reallocating existing personnel and improving processes rather than hiring many new workers or making investments in expensive new technologies. However, it is not possible to accurately predict the cost of these changes.

Summary

In this chapter, we have examined a number of issues concerning organizational structure and the link between structure and organizational performance. We offered an alternative organizing scheme and laid out the benefits of making the change, as well as the challenges that SMC will face. Although this change will be difficult, it is nevertheless necessary in order to get improved performance from the cost-estimating function.

¹⁴ Daft, 1998, pp. 292–293.

Conclusions and Recommendations

Compared with other weapon systems, space systems have experienced high cost growth during their acquisition phases, especially in recent years. As a result, the commanders of AFSPC and SMC asked RAND Project AIR FORCE to assess requirements and capabilities of SMC cost-estimating organizations, resources, tools, methods, and processes and recommend an enhanced approach for cost analysis aimed at improving cost estimation for space systems and increasing the understanding of factors that influence their cost.

First, we focused on using a RAND-developed SAR categorization methodology to identify the magnitude and causes of positive cost variances on SBIRS-High and GPS from 1996 through 2005. The results of this research were the following:

- The SBIRS-High acquisition program experienced substantial net positive cost variance, the vast bulk of which can be attributed to cost-estimating errors.
- While the GPS acquisition program overall experienced a net negative cost variance, significant positive cost growth was identified in key components, particularly on the GPS IIF SV and on OCS. While much of this was due to increases in requirements and scope, about half was attributable to cost-estimating errors.

We also noted that our case study programs, both of which were formally launched in 1996, got under way during a period of radical transformation in both the defense space industrial base and government acquisition policy. Some of the most important changes that

affected the ability of the cost analysis community to produce credible cost estimates included

- industry downsizing and consolidation and increased competition for fewer programs
- increased complexity of space systems
- implementation of acquisition reform measures and downsizing of the acquisition workforce.

While these environmental factors were beyond the control of acquisition officials and would have posed special challenges no matter how they were approached, a variety of policy decisions and issues directly related to how SMC conducted cost estimates made this environment even more demanding. Although many factors can be singled out as contributing to cost-estimating errors, we focused on three broad categories of issues that our research revealed were key causal factors on the SBIRS-High and GPS case studies:

- The cost-estimating process appears to have been organizationally too closely associated with bureaucratic interests that held advocacy positions, making independent, disinterested cost analysis more challenging.
- TSPR and other acquisition reform measures transferred design and developmental responsibility to contractors while greatly reducing the government's ability to assess, monitor, and oversee contractor efforts.
- Inadequate cost-estimating and risk-assessment methods and models were used in both programs.

Second, we interviewed personnel from all 12 of the major program offices and concluded that SMC cost estimators must be able to render independent estimates on the likely costs of acquisition programs without feeling corporate pressure to minimize those costs and the inherent risks associated with them to meet preconceived notions asserted by other components of the acquisition process. Further, TSPR and other acquisition reform measures from the 1990s that postulate

savings without underlying proof should either be abandoned or their implementation approach be reconsidered, because as implemented they inhibit government oversight of contractor performance and prevent the collection of needed cost and technical risk data. Also, SMC cost analysts have insufficient cost and technical risk data on new technologies and subsystems now being incorporated into advanced military space systems. This problem could be ameliorated by greater sharing of information, cost data, cost models, and lessons learned among SPOs, other USAF, and other space procurement organizations.

Third, we accounted for the cost analysis workforce supply and workload demands at SMC. In aggregate numbers of analysts, contractors (who retain the bulk of the institutional memory) dominate the current SMC workforce. However, at least one experienced civil service analyst heads each SPO. And while there are fewer civil service personnel than contractors, both groups have similar experience profiles. Unfortunately, military analysts have limited career field opportunities and do not accumulate experience because of limited assignments in the cost-analysis function. In comparison with the number of analysts reported in our workforce supply survey, our demand survey indicates that SMC is currently undermanned by about 10 percent. However, modeling the workload and workforce available and allowing the workforce to be freely reassigned within SMC show that the workforce supply continues to be adequate to meet projected demands, except during one peak period in 2007.

Fourth, we assessed the methods and tools used in cost estimation at SMC. We concluded that most cost models used at SMC are developed as needed using a combination of available databases and locally collected data. As far as we can determine, no formal process is in place to capture locally developed data. The Unmanned Space Vehicle Cost Model (USCM) is the most mature of the data-based models used at SMC. The current version addresses only spacecraft bus and communications payload costs, so other methods must be used for other types of payloads and ground segment costs. A variety of other models are suitable in varying degrees for use in particular circumstances.

Finally, we examined a number of issues about organizational structure and the link between structure and organizational perfor-

mance. We offered an alternative organizing scheme and laid out the benefits of making the change, as well as the challenges that SMC will face. We cautioned that this change will be difficult, yet necessary, to gain improved performance from the cost-estimating function.

Our specific recommendations are as follows:

- *Institute independent technical and schedule reviews.* These reviews should be done in conjunction with cost estimates for major reviews and milestones. A mechanism or process should be created for cost analysts to use broader SMC technical expertise as a resource for objective and independent technical and schedule assessments. We recommend that the Chief Engineer be required to review and coordinate programmatic, technical-baseline, and schedule assumptions found in the Cost Analysis Requirements Descriptions prepared as part of major milestone reviews. Many factors encourage optimistic programmatic assumptions and foster low initial estimates. SMC must have long-term organizational accountability not only for cost estimates, but also for technical, schedule, and risk assessments. Long-term customer insistence on accurate and objective cost estimates, at all levels of the Air Force, is critical.
- *Place special attention on technical risk assessment.* Good cost estimates rely on accurate technical inputs. Independent, rigorous formal technical risk assessments are needed to support all cost estimates and should be routinely updated. All cost and technical risk assessments should be cross-checked using alternative methodologies (e.g., historical analogies compared with parametric analyses). The quality of the inputs to the technical assessments should be improved by collecting and making available more relevant data and increasing visibility into contractor's capabilities. The level of technical expertise and the communications among technical, program, and cost experts should be enhanced.
- *Adopt a hybrid cost organizational structure.* We reviewed both centralized and decentralized organizations. In our view, a hybrid structure that includes the strengths of both centralized and decentralized structures has the most potential benefits and the

fewest limitations. In particular, increasing the objectivity of the analysts who perform major cost estimates will improve the reliability of the estimates and SMC's reputation as an organization whose cost numbers can be trusted. Making this kind of change will require significant support from senior SMC leadership, as we discuss below.

- *Realign and strengthen the future FM organization by assigning cost-estimating tasks as recommended.* There are specific tasks that should be performed by the cost staff within the comptroller's office and others that need to continue being performed by the program office. Cost-estimating tasks should be conducted within the SPO when the focus is on program execution, where changing priorities or rapid response are common, for functions required to manage the day-to-day activities of the program, where the official position for effective interaction with SPO personnel is needed, and where processes are unique to the program. Tasks should be performed in the cost staff when nonadvocate analysis is a priority; when experienced government leadership, economies of scale, and flexibility in assignments is desired; when skill sets and tasks are outside SPO mission; and when workload and priorities are generally predictable.
- *Require major estimates to be led by experienced and qualified government analysts.* Major cost estimates should not be led by contractor support staff. However, contractor support does play an important role in data collection, building cost models, documenting the results, and other technical assistance. The SMC and other USAF human resources functions will need to support the new staffing approach. New hires, personnel assignments, civil service grade structure, and military force development regulations may need to be reassessed to attract and retain competent cost analysts to SMC. A few experienced analysts can be more effective than many inexperienced ones.
- *Implement best practices from other cost organizations.* Our team held discussions with various organizations performing cost analysis and identified best practices. Our interviewees overwhelm-

ingly agreed that sound initial estimates are critical and should be appropriately resourced. Other best practices consist of

- including analysts with technical/engineering, financial/business management, economics, mathematics and statistics educational backgrounds in cost-estimating teams
 - conducting annual program cost and risk estimate updates
 - keeping a track record of estimates
 - reviewing and archiving all major estimates
 - emphasizing monthly earned value management (EVM) analysis as a management tool.
- *Standardize cost-data collection and improve current databases.* In addition to the historical cost information, SMC cost function should also collect historical programmatic, technical, and schedule data and archive them for future use. We encourage regular data exchanges with internal Air Force organizations, such as AFCAA, and external organizations, such as NRO and NASA.

RAND Questionnaire Used in Interviews with All SMC Major Program Offices, January 2006

This appendix includes the questions we provided to the SMC program offices and cost analysis organization.

Questions for SMC Program Offices

To be completed prior to RAND/SMC staff visit to the SPO. Please ensure all information in Part I is unclassified.

PART I

1. Program name
2. PM's name
3. POC at SPO
4. POC at AFSPC for program
5. Is the program an MDAP?
6. When was the last Milestone or major review?
7. What are the upcoming Milestones or major reviews scheduled?
8. When was the last baseline cost/schedule/risk (C/S/R) estimate prepared and date?
9. What were the results by year (TY and FY)
10. What is the number of analysts assigned or matrixed to the SPO who are involved in cost/schedule or risk estimates or earned value analysis?

- a. Full time and part time?
 - b. Military, civil service or contractor?
- 11. How often are C/S/R estimates reviewed? By whom?
- 12. How often is EV data analyzed and briefed? To whom?
- 13. What is your estimate of time/manpower to prepare a full life-cycle cost C/S/R estimate for a Milestone or other major program review? Have you collected actual data on this?
- 14. What is your estimate of the EV manpower workload in the SPO? Have you collected actual data on this?
- 15. What technical support is available to support C/S/R estimating and EV activities?
 - a. Is it organic or contractor?

PART II

Items for discussion during RAND SMC staff visits to SPOs—answers to these questions are on a nonattribution basis. Classified or proprietary data may be discussed or presented but should be clearly identified.

1. How are estimates presented and who gets briefed?
 - a. Are ranges of costs and risk analyses addressed?
 - b. Is anyone at AFSPC briefed for program reviews or on annual Program Objectives Memorandum estimates?
2. How stable has program funding been since the last baseline C/S/R estimate?
3. How stable have program technical activities been since the last baseline C/S/R estimate?
4. How stable has the program schedule been since the last baseline C/S/R estimate?
5. How stable have program requirements been since the last baseline C/S/R estimate?
6. How can the accuracy of estimates be improved?
7. What steps do you see in the C/S/R and EV processes which are not value added?
8. Are additional tools needed to perform your job that you don't have (models, databases)?
9. Is there sufficient manpower to accomplish your required tasks?

Question Sent to Other Cost-Estimating Organizations

1. What is the most difficult aspect of estimating aircraft: airframe, engine, avionics, software? What makes it more difficult?
2. Do you have a formal training program for your estimators? Do you have a program to give them different experiences in estimating (reassignments) or formal mentorship arrangements? Do you recognize/encourage any formal certification programs?
3. From what background do most of your cost estimators come? How do you recruit them?
4. How many cost estimators are in your organization? Can you give us a rough breakdown by experience level? Do you also have surge assets you can use, such as FFRDCs, SETAs, etc? In your view what are the advantages and disadvantages of organic resources over contractor-provided resources? FMC will send charts with organization and experience/grade levels.
5. What is your organizational structure (wiring diagram)? What organizations do you support (directly or indirectly?)
6. How is your organization funded (both staff and external support)?
7. Is retention of estimators an issue? Why do they leave generally?
8. What tools, models, etc. does your organization use? What are the principal shortfalls in current tools and methodologies?
9. How does your organization archive its estimates after completion?
10. Do you keep cost estimates up-to-date on a regular basis or just at the next Milestone, etc.?
11. Do you keep any data on how accurate your estimates were?
12. How does your organization keep cost data from legacy and current systems?
13. How much involvement does your organization have with earned value efforts or data? Do you use it in estimating current or future systems?

14. Is your organization tasked with developing/evaluating contractor proposal estimates and creating a most probable government estimate?
15. How do you estimate manpower and schedule cost-estimating efforts?
16. How many workyears of effort are required for a “typical” DAB costing effort (people and time)? Does this vary widely among different systems or types of estimates/reviews?
17. How do you obtain engineering and other technical assistance for your estimates?
18. What process do you use to get approval/review of estimates by PMs, PEOs, SAEs, etc.?
19. How do you handle situations where other organizations or senior management disagree with your estimates? Is it more desirable to have multiple estimates presented to decisionmakers or a reconciled “single best estimate?”
20. Do you have “red teams,” independent cost estimates, or other second opinion types of efforts as part of your cost-estimating process?
21. Do you track a cost estimate through the PPBS process and compare budget versus estimated?
22. Do you have any advice or lessons learned for someone setting up a “clean sheet of paper” cost-estimating organization?

Findings from Other Interviews

This appendix reviews the findings from interviews with all major SMC program offices that dealt with issues other than those specifically supporting the separate case study effort on SBIRS-High and GPS. RAND interviewed personnel from all 12 of the major SMC space program offices during January 2006 to assess a wide variety of issues affecting cost analysis function, processes, manning, tools, and so forth. A questionnaire prepared by RAND was emailed to each SPO by SMC/FMC in advance of the interviews. The questions that appear in Appendix A were provided to each SPO in advance of our visit to frame our discussion. Interviews lasted between one and two hours and were conducted with a variety of cost analysis, financial management, engineering, and program management personnel from each program. The program offices visited were the Defense Metrological Satellite Program (DMSP), Evolved Expendable Launch Vehicle (EELV), Advanced Extremely High Frequency (AEHF) satellite, Wideband Gapfiller Satellite (WGS), Transformation Communications Satellite (TSAT), Air Force Satellite Control Network (AFSCN), Global Positioning System (GPS) IIR and IIR-M, GPS IIF, GPS IIIA, GPS Operational Control System (OCS and OCX), Space Based Infrared System–High (SBIRS-High), and Space Radar (SR).¹

¹ Months after our visit with the EELV program office, it was incorporated into the Launch and Range Systems (LR) program office.

Summary of SPO Responses

The following tables present the results of the interviews. The matrix shown in Table B.1 presents the objective data from Part I of the questionnaire provided to RAND by the individual programs shown in Appendix A. Not all questions applied to every program; hence, some of the blocks under each category are blank. The first column contains questions from Part I of the questionnaire. Some of the data (for example, the Program Manager's name) were collected to facilitate follow-on contact if needed and are not reproduced. Table B.1 includes only answers that were deemed relevant to the RAND study research objectives.

To preserve the anonymity of the respondents who answered the Part II questions, the following subsections synthesize the results of the interviews rather than attributing responses to individual SPOs. The responses are organized by subject category.

Reporting of Estimates, Audiences, and Content

Four of the programs' cost estimates had been briefed in the recent past at the Headquarters U.S. Air Force (HQ USAF) level, which would have included program management at SMC (PM and PEO). One SPO specifically mentioned it had briefed its EAC to SMC management. The other seven SPOs either did not address the issue or had not been required to brief estimates outside of the SPO itself in recent memory. Due to the constraints of the PPBS process and the focus on point estimates for use with annual budgets, ranges of estimates were not normally addressed, although risk level assessments appeared to be part of the methodology for programs going on for HQ USAF reviews. Annual funding requirements for programs were provided to HQ AFSPC as part of the POM process, but formal briefings to HQ AFSPC audiences did not seem to be a normal part of the process. Only one program office reported a specific briefing to HQ AFSPC.

Table B.1
Matrix of Responses from SPO Interviews

Part I Question	Program					
	DMSP	EELV	AEHF	WGS	TSAT	AFSCN
MDAP/ACAT	IC(space)/ III(ground)	IC	I	I	I	No – II
Last major review	~1995 (last SAR in 1997)	2004	CDR 2004	I/II 2000	IPR 2004	N/A
Upcoming reviews	None	MS III	None	None	IPR(2) 2007	PMR 2006
Last C/S/R estimate	May, 2003 (IBR)	6/2005	2001	2005	2005	N/A
Assigned analysts (FT/PT)	2/3	8/0	4.5/0	3/0	8.5/0 (later said 6 FT)	2/0
Cost reviews/by whom	None	Qtrly DAES/ Annual SARs				N/A
EV briefed/to whom	Monthly/ Qtrly PMRs	N/A (FAR Part 12)	Monthly/ PM	No EV reporting	Monthly/PM + qtrly PMRs	Monthly/PD
Time required for LCC	N/A	8–12 mo/10 personnel	6 mo/7–10 personnel	6 mo/7–10 personnel	6 mo/7–10 personnel	6 mo
EV workload	8–16 hrs/mo/ program	N/A (FAR Part 12)	2 shared FT	2 shared FT	2 shared FT	1 FT
Technical support (organization or contractor)	N/A—program in O&S phase	Both	Aerospace, Tecolote, Prime	Aerospace, Tecolote, Prime	Aerospace, Tecolote, Prime	2 contractors

Table B.1—continued

Part I Question	Program					
	GPS IIR/IIR-M	GPS II-F	IIIA	GPS-OCS-X	SBIRS-High	Space Radar
MDAP/ACAT	I (IIR no longer a program)	I			I	Pre-MDAP (expect I-D)
Last major review						9/04
Upcoming reviews					MS III 2008	7/07 (SRR)
Last C/S/R estimate						7/05
Assigned analysts (FT/PT)	6/0	2/0				8/0
Cost reviews/by whom	N/A					PMRB
EV briefed/to whom	Annually			Monthly/PM		Monthly/PM
Time required for LCC	1 month					6–12 mos
EV Workload						1 FT
Technical support (organization or contractor)	Aerospace	Aerospace		ARINC/Mitre/Aerospace		Both

NA = not applicable; FT = full-time; PT = part-time; SRR = system requirements review; PMR = program management review; PMRB = program management review board.

Program Funding, Technology, Schedule, and Requirements Stability

Table B.2 presents the results of the SPOs’ general perceptions of the relative stability of the funding and of technology, schedule, and requirements for their programs. Many of the “Not Reported” (N/R) scores reflect the acquisition phase of the program, i.e., the end of the acquisition cycle was viewed as inherently stable across the board because little work was left to be accomplished. In other cases, where programs were in early development stages, some assessment of stability was viewed as impossible given the immature nature of the program. It is interesting to note that not all programs viewed themselves as either entirely stable or unstable across the board, as one might expect. The program order in Table B.2 does not correlate with the program order in Table B.1.

Improving the Accuracy of Cost Estimates

SPOs in general did not offer many specific ideas on how to improve the accuracy of cost estimates. A few mentioned that better access to data was needed, especially in those programs that had been managed

Table B.2
SMC Program Office Responses to Questions Regarding
Funding, Technical, Schedule, and Requirements Stability

Program Number	Funding Stability	Technical Stability	Schedule Stability	Requirements Stability
1	N/R	N/R	N/R	N/R
2	S	S	U	S
3	U	U	U	S
4	S	S	U	S
5	U	U	U	N/R
6	N/R	N/R	N/R	N/R
7	S	S	S	S
8	S	N/R	U	U
9	N/R	N/R	N/R	N/R
10	U	N/R	U	U
11	N/R	N/R	U	S
12	U	U	U	U

N/R = none reported; S = stable; U = unstable.

under the TSPR and price-based acquisition concepts, where little data was required from contractors. Inability to collect actual costs from contractors was deemed a problem for government cost estimates. One other item mentioned several times was the need for more cost data on new technologies, which was deemed one of the highest priorities for cost-data collection.

Activities That Added No Value

Oversight by groups outside the PEO/SAE reporting chain was named most often as an activity that did not enhance the quality of cost estimates and consumed time that the analysts could have better spent on their programs. In addition, one program noted that several people were routinely diverted from their normal tasks by the need to answer questions from outside review agencies, including congressional staffers.

Need for Additional Tools

The SPOs in general did not identify significant shortcomings regarding tools and models but did mention data as their number one priority area. Not only was better access to current contractor data required, but also data on new technologies were mentioned as a pressing need.

Adequacy of Staffing

Although selected overtime was expected for high workload peaks, most SPOs seemed satisfied with the level of staffing. This was probably the result of the SPOs' organic workforce having access to augmentation from support contractor personnel to satisfy cost-estimating requirements.

Summary of Key Points from SMC Program Office Interviews

This section highlights and summarizes the key points from the 12 interviews conducted as part of the study. The overall issues are from the discussion of the questionnaire topics as well as other information

that arose during what were often wide-ranging discussions between RAND and the program office personnel.

First, as shown in Table B.2, most program offices felt that requirements had remained stable or did not report problems with requirements. This was especially true in discussions about top-level requirements and key performance parameters. Most SPO analysts believed that overall requirements for their programs, as set forth early in the programs, had not changed significantly. Meeting those requirements with technical solutions was where most of the requirements instability occurred. This was most typically caused by misunderstandings or underestimations by both government and industry of what was required to meet the system-level requirements. Some argued that, in the competitive award environment, contractors were willing to promise almost anything to win the contract award and only later, as they proceeded into development, did the difficulties in meeting those promises arise.

Next, in terms of lessons learned, most SPO personnel had not been involved in a recent formal review up to the HQ USAF and OSD levels. Only three programs (EELV, SBIRS-High, and Space Radar) had undergone such a formal review in the past three years, and two of these were for Nunn-McCurdy breaches, not Defense Space Acquisition Board Milestone decisions. Thus, most SPO personnel had little actual first-hand knowledge of the rigors and workload required to meet a full-blown review and the cost-estimating process and requirements for such reviews.

Most SPO analysts felt that new technologies were not the key problem in their program, but rather the integration of those technologies into an operational system. Although much attention has been placed on using technologies that are reasonably mature (as measured for example on the Technology Readiness Level scales), integration of the diverse technologies and the software required to do so were seen as areas of major risk. However, most analysts maintained that there was insufficient cost data available to estimate the costs of many new technologies.

Although the SPOs generally believed they were adequately performing their earned value and cost-estimating tasks, these sometimes

called for overtime to meet peak workloads, especially during intense periods such as those following the declaration of a Nunn-McCurdy breach. In general, staffing levels were not mentioned as a major problem, probably because support contractor augmentation was available to support the organic workforce. EELV personnel mentioned an upcoming shortage due to the program's transition from a FAR PART 12 program (involving little cost reporting and analysis) into a FAR PART 15 program, which would require much more cost analysis and earned value effort.

The implementation of Total System Performance Responsibility, in which the DoD essentially adopts a hands-off policy with the contractor, was almost universally seen as a mistake given the cutting-edge R&D required to develop space systems. With government oversight minimized under TSPR, programs were often allowed to get well off-track before corrective actions could be implemented. The lack of cost reporting under TSPR was seen as a key problem since financial problems and cost overruns were not detected early in the development phases of several programs.

In some instances, EV analysis was seen as not being performed effectively or not receiving enough management attention. Some of the programs under TSPR did not even have EV reporting. Others had been awarded as fixed-price contracts, which do not involve EV reporting. Some analysts suspected that the EV reporting baselines were inaccurate or even unused by contractors. In response to this situation, SMC has issued guidance requiring monthly EV analysis on all programs where reporting is required.

As stated previously, insufficient access to historical cost data was seen as a critical shortfall by many of the SPO participants. Many SPOs had gathered data on their own programs, but sharing among SPOs was neither regularly required nor routinely accomplished. Not only does this non-coordinated approach inhibit the cost estimators who need the data, but it can also lead to duplicative efforts in gathering the same or similar data. In addition, the lack of data on new technologies, especially those related to payloads, was seen as a problem. In addition, given the limited data on cost, programmatics, schedules, and technologies, cost estimators must have increasingly sophisticated

backgrounds in these areas if they are to make sense of the relevant data that are available.

Finally, the three major cost analysis organizations in DoD dealing with space (SMC, AFCAA, and NRO) do not have an effective and coordinated working relationship to gather, normalize, and share data across all the space systems being developed and deployed. This situation requires senior management involvement to break down organizational barriers and permit freer flow of data among the many space systems being developed. This would help alleviate the concerns noted above about the insufficient data available to SMC cost analysts.

Overall Conclusions from Interviews

RAND's interviews with all 12 of the major program offices at SMC seemed to confirm many of the most important findings that arose from the detailed case study analysis. These might be summarized as follows:

- SMC cost estimators must be able to render independent estimates on the likely costs of acquisition programs without feeling corporate pressure to minimize those costs and the inherent risks associated with them to meet the preconceived notions asserted by other components of the acquisition process. Senior management must foster this concept by asking for frank opinions about potential problems areas, understanding their costs, and requiring documentation and tracking of them.
- TSPR and other acquisition reform measures from the 1990s that postulate savings without underlying proof need to be abandoned because they inhibit government oversight of contractor performance and prevent the collection of needed cost and technical risk data.
- SMC cost analysts have insufficient cost and technical risk data on new technologies and subsystems now being incorporated into advanced military space systems.

- SMC cost analysts consider new technologies, especially issues related to system integration and the associated software development, as the highest risk areas on current space programs.
- Greater sharing of cost data and cost models among SPOs, the Air Force, and other space procurement organizations would be highly desirable.
- Overall manning levels were considered adequate in most SPOs, primarily due to the availability of SETA support contractors to augment organic cost analysis capabilities.
- While we noted that a more centralized, independent cost analysis organization at SMC could help alleviate some of these problems, most SPO representatives opposed losing control over the cost and technology risk-assessment processes.

Summary of Programs Currently Managed at SMC

This appendix provides a condensed overview of the programs managed at SMC during the course of this project.

Advanced Extremely High Frequency System

The Advanced Extremely High Frequency (AEHF) System is a joint service satellite communications system that provides near-worldwide, secure, survivable, and jam-resistant communications for high-priority military ground, sea, and air assets.

Type:	Satellite
Contractor:	Lockheed Martin Space Systems Company
Status:	Satellites ordered; first launch scheduled 2008

Advanced Research and Global Observation Satellite (ARGOS)

ARGOS is an R&D satellite carrying an ion propulsion experiment, ionospheric instruments, a space dust experiment, a high-temperature semiconductor experiment, and the Naval Research Laboratory's hard X-ray astronomy detectors for X-ray binary star timing observations.

Type:	Satellite
Primary contractor:	Boeing
Status:	Operational

The Defense Meteorological Satellite Program

The mission of the Defense Meteorological Satellite Program (DMSP) is to generate terrestrial and space weather data for operational forces worldwide. Currently orbiting satellites include the F-12 through F-16. The program is conducted in conjunction with NASA and the National Oceanic and Atmospheric Administration (NOAA), part of the Department of Commerce. Data are furnished to the civil service community through NOAA.

Type:	Satellite
Primary contractor:	Lockheed Martin Space Systems
Status:	Operational; final launch in 2011

Defense Satellite Communications Systems

As the backbone of the U.S. military's global satellite communications capabilities, the Defense Satellite Communications System (DSCS) constellation provides nuclear-hardened, anti-jam, high data rate, long-haul communications to users worldwide. The system is used for high-priority communication, such as the exchange of wartime information between defense officials and battlefield commanders. The military also uses DSCS III to transmit space operations and early-warning data to various systems and users.

Type:	Satellite
Contractor:	Lockheed Martin Space Systems Company
Status:	Operational

Defense Support Program

The Air Force Defense Support Program (DSP) satellites orbit the earth approximately 35,780 kilometers over the equator. DSP satellites use infrared sensors to detect heat from missile and booster plumes against the earth's background. The DSP constellation is operated from the Space Based Infrared Systems (SBIRS) Mission Control Station (MCS) at Buckley Air Force Base, Colo.

Type:	Satellite
Contractor team:	Northrop Gruman Space Technology and Northrop-Grumman Electronic Systems
Status:	Operational

Interim Polar System

The Interim Polar System (IPS) program element provides protected communications (anti-jam, anti-scintillation, and low-probability-of-intercept) for tactical users in the north polar region.

Type:	Satellite
Primary contractor:	Boeing
Status:	Operational

Milstar

Milstar is a joint service satellite communications system that provides secure, survivable, jam-resistant, worldwide communications to meet essential wartime requirements for high-priority military users. The multisatellite constellation will link command authorities with a wide variety of resources, including ships, submarines, aircraft, and ground stations.

Type:	Satellite
Primary contractor:	Lockheed Martin
Status:	Operational

NAVSTAR Global Positioning System

The Navstar GPS Joint Program Office (JPO) is a joint service effort directed by the U.S. Air Force and managed at SMC, Air Force Space Command, Los Angeles Air Force Base, California. The JPO is the DoD acquisition office for developing and producing GPS satellites, ground systems, and military user equipment. The system includes several generations of satellites: the II/IIA (leaving service), the IIR, IIR-M (entering service), and IIF.

Type:	Satellite
Primary contractor:	Lockheed Martin
Status:	Operational

Space Based Infrared System (SBIRS)

The SBIRS constellation supports missile warning, missile defense, technical intelligence, and battle space characterization. It consists of a system of satellites in highly-elliptical earth orbit (HEO) and geosynchronous earth orbit (GEO). The program consists of several components, including the Mission Control Station (operational since 2001), SBIRS-High (GEO satellites and HEO payloads).

Type:	Satellite
Primary contractor:	Lockheed Martin
Status:	Partially operational (2 of 4 satellites in orbit)

Space Radar (SR)

Space Radar is designed to give ground commanders of all services an eye-in-the-sky view of what is on the ground around them or over a mountain top.

Type:	Satellite
Contractors:	Lockheed Martin and Northrop Grumman
Status:	Concept definition. Demonstrators to be launched in 2008

Transformational Satellite Communications System (TSAT)

TSAT will provide unprecedented satellite communications with Internet-like capability that will extend the DoD Global Information Grid (GIG) to deployed users worldwide and deliver an order-of-magnitude increase in capacity.

Type:	Satellite
Primary contractor:	None
Status:	Systems definition and risk reduction

Wideband Gapfiller Satellite

The purpose of the Wideband Gapfiller Satellite (WGS) project is to provide flexible, high-capacity communications for the military. WGS will provide essential communications services for combatant commanders to command and control their tactical forces. Tactical forces will rely on WGS to provide high-capacity connectivity into the terrestrial portion of the Defense Information Systems Network.

Type:	Satellite
Primary contractor:	Boeing Satellite Systems
Status:	First launch was scheduled for June 2007

Delta II

Delta II is a medium-lift launch vehicle and the workhorse of the Delta family.

Type:	Launch vehicle
Primary contractor:	Boeing Company Expendable Launch Systems
Status:	Operational

Evolved Expendable Launch Vehicle

The EELV is a next-generation launch program designed to replace the existing fleet of launch systems with two families of launch vehicles, each using common components and a common infrastructure. The vehicles are the Boeing Delta IV and Lockheed Martin Atlas V.

Type:	Launch Vehicle
Primary contractor:	Lockheed Martin and Boeing
Status:	Operational

Inertial Upper Stage

The Inertial Upper Stage rocket motor gives the U.S. government the ability to place satellites of up to 5,300 pounds into geosynchronous orbit and 8,000 pounds out of Earth's gravitational field using the Air Force Titan IVB rocket or NASA Space Shuttle.

Type:	Launch Vehicle (booster stage)
Primary contractor:	Boeing Corporation
Status:	Operational, but no planned launches

Minotaur

The Minotaur space launch vehicle, produced for SMC under the orbital/suborbital program, provides a low-cost, reliable solution for launch services of government-sponsored payloads.

Type:	Launch vehicle
Contractor:	Orbital Sciences
Status:	Operational

Minotaur IV

Minotaur IV is a heavier-lift version of the Minotaur currently under development by Orbital Sciences. First launch is scheduled for 2008.

Type:	Launch Vehicle
Contractor:	Orbital Sciences
Status:	Operational

Quick Reaction Launch Vehicle

The Quick Reaction Launch Vehicle (QRLV) program began in FY 2001, and is launching up to eight suborbital vehicles (one QRLV per year) until FY 2008. In addition to supporting DoD operations and exercises, the QRLV launches will also be used for various experiments, ranging from measuring atmospheric attributes to demonstrating new technologies.

Type: Launch Vehicle
Contractor: Orbital Sciences
Status: Operational

MILSATCOM Terminal Program

The MILSATCOM Terminal Programs Office (MTPO) provides SATCOM terminals to combat forces of all Services. It develops, acquires, and operationally deploys communication terminals synchronized to support satellite weapon system operations and provides support for 16,000 aircraft, ship, mobile, and fixed-site terminals.

Type: Support Program
Status: Operational

Satellite and Launch Control Systems Program

The Satellite and Launch Control Systems Program Office serves as the Air Force Satellite Control Network (AFSCN) acquisition agency responsible for network sustainment activities; future architecture planning; and data, communications, and range systems engineering. The program office is the primary interface to the AFSCN users for requirements identification and implementation. This program office is also responsible for the major development efforts of the Spacelift Range System (SLRS). The SLRS consists of ground-based surveillance, navigation, communications, and weather assets centered at Patrick Air Force Base, Fla., and Vandenberg AFB, Calif., used to support space launch missions.

Type: Support Program
Status: Operational

Space Test Program

The DoD Space Test Program (STP) is chartered by the Office of the Secretary of Defense to serve as “. . . the primary provider of mission design, spacecraft acquisition, integration, launch, and on-orbit operations for DoD’s most innovative space experiments, technologies and demonstrations” and “. . . the single manager of all DoD payloads on the Space Shuttle and International Space Station.”

Type:	Support Program
Status:	Operational

Command and Control System–Consolidated

The MILSATCOM Command and Control System-Consolidated (CCS-C) system provides integrated launch and on-orbit command and control functionality for MILSATCOM satellites as the current capability provided by the Air Force Satellite Control Network phases out.

Type:	Command and Control
Primary contractor:	Integral Systems
Status:	Operational

Global Broadcast Service

The Global Broadcast Service capitalizes on the popular commercial direct broadcast satellite technology to provide critical information to the nation’s war fighters. The GBS system is a space-based, high-data-rate communications link for the asymmetric flow of information from the United States or rear echelon locations to deployed forces.

Type:	Command and Control
Primary contractor:	Raytheon
Status:	Operational

SBIRS Mission Control Station

The SBIRS mission control station (MCS) centralizes global command, control, and communications for strategic and tactical warning into a single modern peacetime facility.

Type:	Command and control
Contractor:	None
Status:	Operational

Details of the SMC Cost Analyst Workload Model

Overview

RAND created a dynamic monthly forecasting model that estimates the number of personnel required to complete schedule, cost analysis, budget, and EV tasks at SMC, assuming that the current supply of cost analysts will remain constant. In the model, the *primary* workforce drivers are major reviews. For each type of major review (milestone review or source selection), the required base-case set of analysts with various experience levels (0–3, 3–8, and 8+ years of experience) was determined by the experience and judgment of RAND personnel. Two major modifications are made to this base case: (1) the scale of the project as measured by total acquisition cost and (2) the length of time before and after a review due date.

To this are added secondary and tertiary workforce drivers. The *secondary* drivers are demands for budget preparations and EV calculations that each unit must complete continually, regardless of how large the demands are from the primary workforce drivers. The *tertiary* drivers are activities—such as performing “what-if” scenarios, data collection, and database development, training, and other studies—that have widely varying frequency of occurrence and workload demands. On top of all these demands is the recognition that a given number of personnel will be unavailable for a given amount of time due to illness, vacation, and family leave.

In the step-by-step walkthrough that follows, all tables and figures are excerpted from the RAND model. There are two types of inputs: (1) program-specific and historical data that have been vali-

dated with the latest available estimates and (2) assumptions based on RAND team members' understanding of the staffing process of a program office.

Current Programs

The starting point for the model is a list of all programs under SMC's cost purview, as is shown in Table D.1. In the "Name" field is the relevant SPO or program. In the "Cost Estimate" section, we list an approximate acquisition cost (in millions of TY\$), and base year of those dollars; this will be used to adjust upward the analyst demand for larger programs. The final two columns are "Major Reviews and Source Selections" require the user to enter end dates of major program reviews. When no major review dates were provided to RAND, we assumed a three-year time period in between major reviews. Additional major reviews and hypothetical programs could be added to extend the time line of the analysis.

Workforce Assumptions

The workforce needed—the number of full-time workers "at their desks"—for a major review is determined by using a set of base cases and a set of multipliers. In the baseline workforce shown in Table D.2, we see that the type of personnel demanded is broken in three experience bands: up to three years of experience, three to eight years, and eight or more years.

Table D.2 should be read as follows: the model's base case postulates that milestone review requires two analysts with eight or more years of experience, one analyst with three to eight years of experience, and one analyst with fewer than three years of experience ("1/1/2" for short). The numbers in the table are a first cut, and have not been justified with thorough empirical analysis.

Table D.1
Projected Major Review Dates for Each Program

Program	Cost Estimate (TY \$millions)		Major Reviews			Source Selection
	Total Cost	Base Year				
AEHF	4,602	2002	June 2010	May 2013	May 2016	
WGS	1,456	2001	March 2009	February 2012	March 2015	
TSAT	12,000	2009	September 2007			November 2007
GPS IIR-M	2,574	1979				
GPS IIF	582	2006				
GPS IIIA	7,000	2009	August 2007	September 2008	September 2011	August 2007
GPS OCX	2,000	2009	December 2008	December 2011	December 2014	August 2007
SBIRS-High	7,569	1995	March 2006	February 2009	February 2012	
Space Radar	34,000	2015				
LR	24,856	1995	October 2007	September 2010		

Table D.2
Baseline Workforce

Experience	Milestone Review	Source Selection
0–3 years	1	0.5
3–8 years	1	0.5
8+ years	2	1.0

Next, each base case is multiplied by the appropriate acquisition cost multiplier in Table D.3. This factor is intended as a proxy for scope and complexity of analysis: as the constant-dollar cost of the program increases, the model adjusts the number of personnel needed upward.

Table D.3
Acquisition Cost Multiplier

Cost Range (FY 06 \$M)	Multiplier
0–1,000	1.0
1,000–5,000	1.2
5,000–10,000	1.4
10,000–20,000	1.6
20,000+	1.8

For example, we see in Table D.1 that the cost of LR falls into the \$20-billion-plus category, yielding (from Table D.3) a multiplier of 1.8.

We also see from Tables D.1 and D.2 that LR is projected to be undergoing a milestone review in October of 2007,¹ requiring a baseline 1/1/2 requirement for analysts. After applying the multiplier, we have a requirement of 1.8/1.8/3.6.

However, we know that a review team will have variable efforts over time. Table D.4 shows a notional pattern of how analyst requirements change from the time the project team forms until review due date and cool-down. During the formation of the project team (216 days to 180 days before the due date), the multiplier is 0.5, meaning that a program with a 1.8/1.8/3.6 workforce requirement profile, like the LR example calculated above, requires only half that effort during startup. However, from 60 to 30 days before the due date, there is a multiplier of 1.8, and 3.2/3.2/6.3 analysts are required.

In addition to the primary workforce drivers (the work depending on major reviews), there is work to be done for all time periods, the staffing profile for which is in Table D.5. For each experience band, the model determines the number of personnel required for budget

¹ Note that October 2007 was chosen arbitrarily because no date is currently available and a specific date is required in the model. It is possible to extend the model by using a probability distribution of due dates. Although this would show how schedule risk can affect personnel planning, it would provide unrealistically smooth demand profiles, making the model *less* useful for our purposes.

Table D.4
Time Scheduling Multiplier

Number of Days Before Task Due Date	Multiplier
216–180	0.50
180–120	1.50
120–60	1.00
60–30	1.75
30–0	1.25
0 to –32	0.50

Table D.5
**Budget Preparation and EV
Reporting Workforce**

Experience Band	Budget	Earned Value
0–3 years	0	0
3–8 years	0	0.55
8+ years	1.25	0.55
Total	1.25	1.10

preparations, EV estimates, and completion of major cost estimates. Each SPO and FM requires 1.25 people for budget preparations and 1.1 person for EV work.²

While EV work is assumed to be constant across all months, budget preparations are assumed to be cyclical; the RAND model produces that cycle using the average of two triangular distributions.³ The model takes a program's annual requirement for a budget analyst, and reshuffles it across months within the given fiscal year and adjoining fiscal years. In the aggregate, instead of interpreting the model's results

² The values 1.25 and 1.1 were derived from analysis of the detailed workload demand spreadsheets described below.

³ The seemingly arcane triangular method was chosen for use in an earlier version of the model that had only a single September peak for budget work. Had a two-peak distribution been initially assumed, a less-cumbersome functional form would have been chosen.

in terms of the budget work required of a single analyst in any given month, we interpret the results in terms of total number of analysts required in that month.

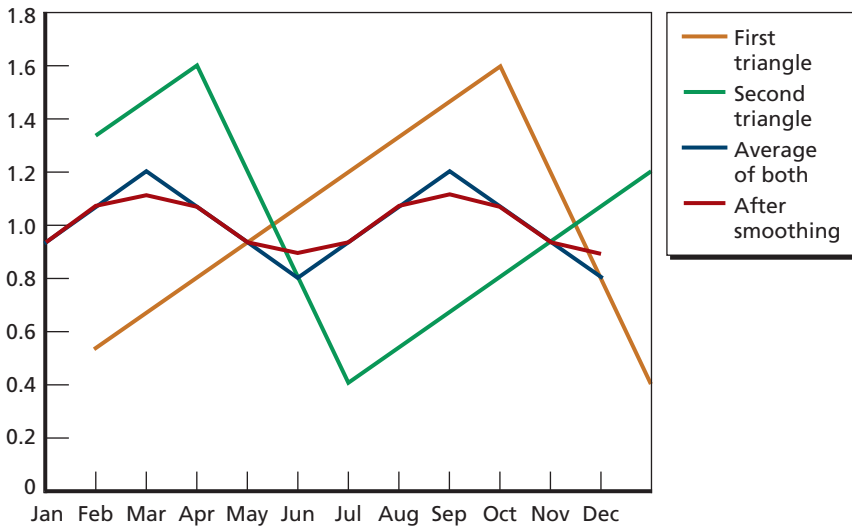
For the mathematics of the triangular distribution to work, the value of the distribution is required to be 0 percent at the starting point and endpoint, arbitrarily chosen so that the first triangle is September (the end of the *previous* fiscal year), and December in the *next* fiscal year.⁴ The peak was chosen to be September, the end of the *current* fiscal year. Once the ends are tied down and the peak chosen, the share of work accrued to each month is determined by simple algebra.⁵ The 16-month distribution is converted into a calendar year by summing the two Octobers, summing the two Novembers, using other values,⁶ and multiplying by 12. The same procedure was performed for a second triangle, with a peak at March, and the ends at the previous March and following June. These triangles are averaged, and the pattern is then smoothed with a three-month moving average. The demand for every budget analyst is then represented by the x-marked smoothed line in Figure D.1—which peaks in March and September. This line represents how the model calculates the requirement for one full-time budget analyst: 0.89 of an analyst in December and June, and 1.11 analysts in August and September. The contribution of this cyclical trend to overall workforce requirements will be seen below.

⁴ Reshuffling across fiscal years has the effect of slightly flattening the final distribution into a shape that better reflects the RAND team's anecdotally based view of how budget work is performed. Choosing an endpoint further into the adjoining fiscal year has little substantive effect on overall results.

⁵ The peak budget work—the height of the triangle—is determined first. For all triangles, $\text{area} = (1/2) \times \text{base} \times \text{height}$. In this case, we have $1 = (1/2) \times 15 \times \text{height}$. (The space between the 16 months creates a base 15 units long, and the area is the work of 1 analyst). Hence, $\text{height} = 2 \div 15$, or 13.33 percent. Note that this is true regardless of which month is chosen. But the value for each month before and after the peak does depend on the peak month. The value at each month before the peak is $(13.33 \text{ percent} - 0 \text{ percent}) \div 12 = 1.11 \text{ percent}$ smaller than the one to its immediate right; the value at each month after the peak is $(13.33 - 0 \text{ percent}) \div 3 = 4.44 \text{ percent}$ smaller than the one to its immediate left.

⁶ Budget personnel requirements are assumed to be doubled in years in FY 2009, when there will be a Quadrennial Defense Review. To implement this, the model doubles the results of triangulation for 2009.

Figure D.1
Triangular Distribution for Budget Preparations



RAND MG690-D.1

The tertiary work category is hard to define comprehensively and even harder to measure. The tertiary inputs used in the model are a summary of all other work—working on other studies and reviews, meeting base concerns, and responding to outside inquiries. The data for this other work come from the survey instrument of workload demand sent to SMC.⁷

The workload demand survey sent to all SPOs was an Excel spreadsheet listing dozens of typical tasks a SPO might undertake. For each task, the manager was requested to list the number of people assigned to a task, the frequency with which they are assigned to perform it, and length of time it takes for them to complete it. Although the survey was meant to be comprehensive, several respondents added tasks they believed were not clearly subsumed in other categories.

⁷ The days unrelated to major reviews and training were summed, divided by the total workload demand, and multiplied by 260.

A sample of tasks included in the tertiary work category include “Coordination with contractors and Govt, data reviews, program office training,” “Serve as Team Leads and Team Members on Source Selection Boards,” “Participate in BPA Qualification Reviews,” and “Develop/improve databases, models, methodologies, including data collections.”⁸

To estimate tertiary work, the RAND model schedules the tasks to be completed and determines the number of people required to complete them by applying a set of rules consistently across tasks and offices. It utilizes office-unique expectations about the frequency and duration of tasks, but averages the manpower required to complete each task occurrence over all offices.

Essentially, for each office, we want to know in which months a task is performed. The model takes (1) the frequency of each task, and (2) the length of each task and randomly assigns a start month for each task. For instance, if a SPO indicated that a task occurred annually, a start month was chosen randomly.⁹ For example, say Task I starts in December, and takes six weeks to complete; it would have a “1” in December, and a “0.5” for January. The rest of the months are “0.” This scheduling was done for all tasks, creating an annual profile of tertiary tasks that was assumed to be identical from one year to the next.

Next, we calculated the median person-months per task across offices¹⁰ by dividing the total person-months by annual frequency and taking the median. The median person-months per task was then

⁸ However, the tasks “Develop cost/schedule/risk estimates for program initiation/major reviews,” “Develop cost/schedule/risk estimates for PEO independent cost assessments,” and “Estimate “what if” options” were categorized by RAND as analysis tasks directly related to program execution. “Participate in Integrated Baseline Reviews (IBRs),” and “Maintain and analyze EV data” were categorized as EV tasks related to program execution.

⁹ If an SPO indicated a task occurred semiannually, one start month was chosen randomly, and the other was assumed to be six months later. If an SPO indicated a task occurred three times a year, one start month was chosen randomly, the second was assumed to be four months later, and the third was assumed to be four months earlier, and so on.

¹⁰ Several tasks had to be broken out into *low* and *high* workload categories, because the offices had very different interpretations of the type of work that should be included in the task. The medians of each subtask were then applied in the model.

spread across each task occurrence uniformly. To continue with the Task A example above, say it took nine median person-months to complete. Those nine person-months would be allocated across each task occurrence, so that $[9/(1 + 0.5)] \times 1 = 6$ people are needed in December and $[9/(1 + 0.5)] \times 0.5 = 3$ people are needed in January to complete Task A.

This was performed for all occurrences of all tasks. The number of people needed in the office to complete all requisite tertiary tasks on any given month was determined by summing across all tasks. The RAND model then filters these tasks into 12 major functions: major review, estimating, training, post-production, reviews and reports, schedule, contract support, data, external, local, earned value, budget, and other. Some tasks were broken equally into two or three functions. Since the schedule of source selection, major review, budget, and earned value functions is estimated separately, their modeling results were separated. In addition, the schedule, external, estimating, and other functions were adjusted for complexity using the factors in Table D.3.

It is important to understand that the workload data are the combination of two sets of judgments: (1) those of respondents who created detailed workload demand schedules referencing limited historical data and (2) those of RAND personnel who categorized tasks and aggregated them across SPOs. Respondents might have listed a smaller or larger number of personnel than they actually need (the errors could go either way; they are variances, not biases). Also, different respondents might categorize work differently, making intra-SPO comparisons difficult to interpret.

Full-Time Equivalents

Now that we have determined the number of people required to complete work, we have to ensure that the model estimates full-time equivalent persons (FTEs). From the survey design, tertiary workloads are already in FTEs, but primary and secondary workloads must be adjusted for periods of unavailability. Days unavailable consist of training, holidays, family and sick leave, and vacation. Table D.6 shows that, out of a 260-day work year, approximately 41–51 days (16–19 percent) of all workdays are spent either on personal time or in training.

For an organization to get a full 260 days of work from analysts with fewer than three years of experience, one needs $1/(1 - 16 \text{ percent}) = 1.19$ analysts on the payroll. This is how the model converts workload demand into a requirement for workers: At any given point, a demand for ten workers on the job is a requirement for 12 on the payroll.¹¹

Now that all workload demand has been specified and periods of unavailability have been taken into account, the model calculates the staffing requirement. Table D.7 illustrates this with arithmetic averages over the size, time, and FTE multipliers. The result shows the average number of analysts needed to be assigned to a SPO—outside of secondary or tertiary demand for personnel, at each month, from January 2006 to December 2010. (See Figure D.2.) The bottom two

Table D.6
Number of Days and Percentage of Time Unavailable

Days			Total Days Unavailable	Percent Unavailable	FTE Multiplier
Full-time work year: 260					
Holidays	10				
Family	5				
Sick	13				
Total	28				
Vacation					
0–3 years	13.0	(+28)	41.0	16	1.19
3–8 years	19.5	(+28)	47.5	18	1.22
8+ years	22.9	(+28)	50.9	19	1.24

¹¹ This assessment of unavailable time is realistic in terms of the number of days, but it could be objected that periods of training and vacation will only be taken in periods of relative slack. This objection is valid, but sensitivity analysis of the model to account for this showed little practical difference in the overall workload demand—except that peaks were slightly lower and valleys were imperceptibly higher.

Table D.7
Primary Workload Demands and Multipliers Yield a Staffing Requirement

	Milestone Review	Source Selection
0–3 years	1	0.5
3–8 years	1	0.5
8+ years	2	1.0
Total	4	2.0
Average Size Multiplier	1.40	1.40
Average Time Multiplier	1.10	1.10
Average FTE Multiplier	1.22	1.22
0–3 years	1.8	0.9
3–8 years	1.8	0.9
8+ years	3.7	1.8
Staffing Requirement	7.4	3.7

areas represent earned value and budget drills; the tan area on top represents manpower required to complete major reviews. All areas in between represent other activities at each SPO and FM.

Figure D.3 represents the aggregate view of the cost analysis workforce profile in the recommended organizational structure—that is, when analysts are allowed to move from one SPO to another SPO based on need. This chart compares the demand for analysts as determined in the model versus the supply recently reported to RAND. On the bottom is a constant base of EV calculations and reporting. The next layer up is cyclical budget document preparations. The “mountainous” regions are periods of major review, and the “valleys” in between are work on everything else. The dotted line is at 116, the current workforce supply.

Figure D.2
Workload Patterns at Each SPO and FMC

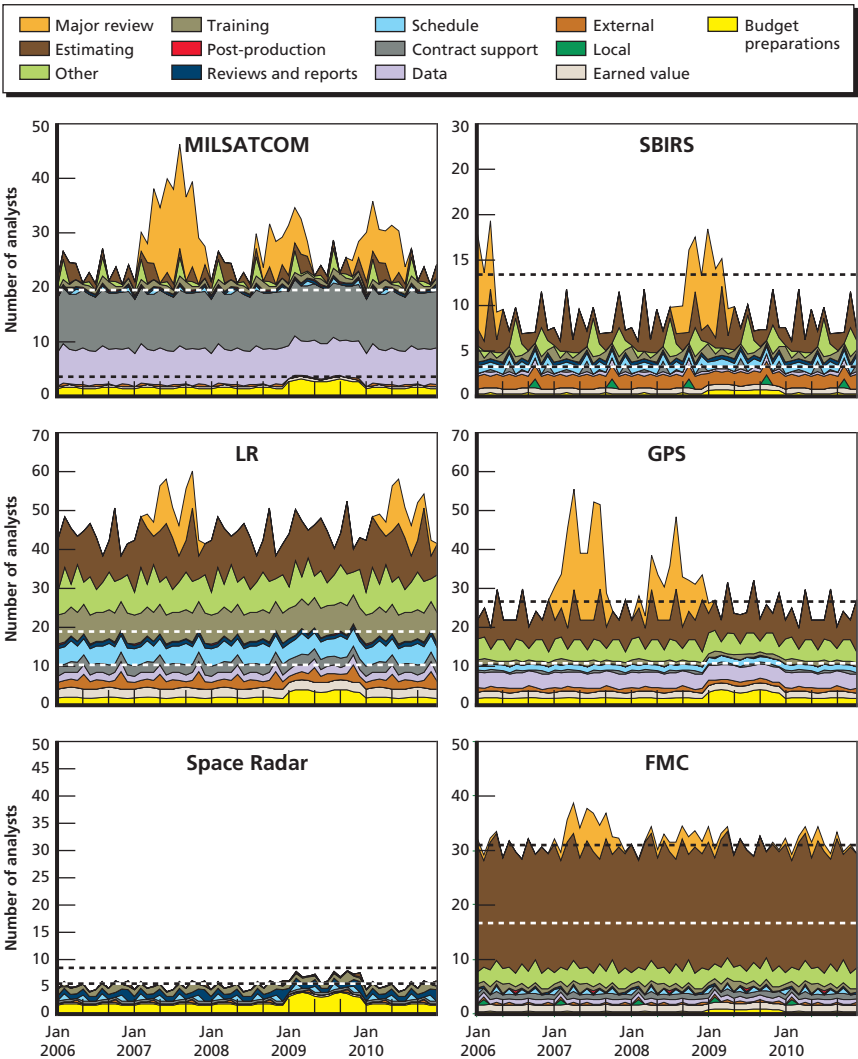
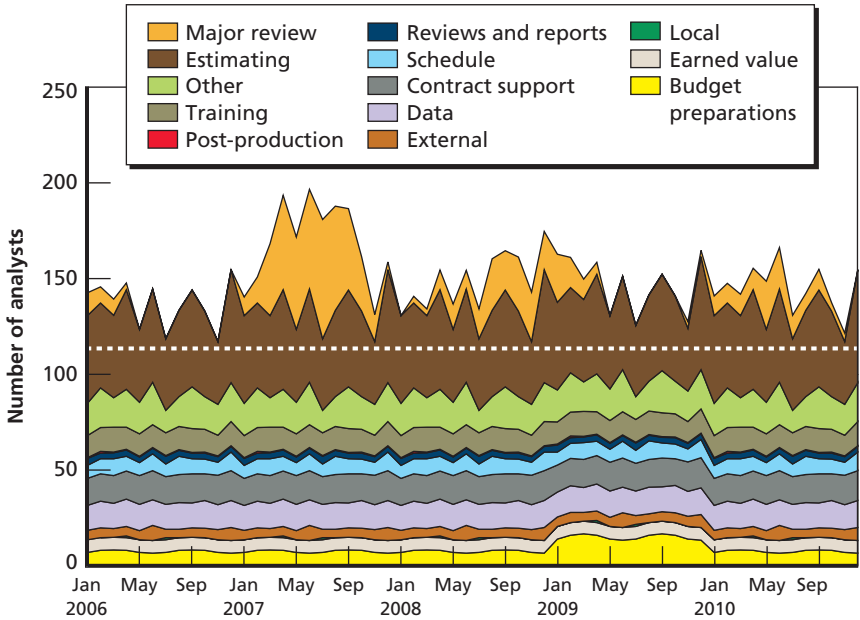


Figure D.3
Cost Analysis Workforce Demand Output from Model



Space Systems Cost-Estimating Tools, Methods, and Data Assessment

Methods, Tools, and Data

At its most fundamental level, cost estimation involves using information from the past to make predictions about the cost of future activities or products. The accuracy of these predictions depends on many factors, such as the similarity of the historical data to the planned product; the experience of the estimator in interpreting and applying available data; and the number of “unknown unknowns” encountered in the design, development, production, and operation of the product or system. In some cases, the estimator can accommodate for these factors, but others can be addressed only by estimating their likelihood and their potential effects on the project.

Methodologies

Estimators use various approaches to develop their predictions of future cost. The most robust methodology involves using a database composed of costs and characteristics of multiple similar projects. From it are developed equations that calculate cost or some intermediate variable (e.g., functionality or size of product) as a function of various physical and technical characteristics. These characteristics, called *parameters* (or sometimes cost drivers), give the technique its name: parametric estimation. The cost-estimating relationships are derived using statistical methods, most often a form of regression analysis. Their accu-

racy depends in part on the number of independent data points, their relevance to the system being estimated, the selection of appropriate parameters, and the variability in the data itself. The accuracy of the resulting estimate also depends on the analyst's understanding of both past and proposed projects. When properly applied, a parametric technique reflects the relevant experience with many projects and provides quantitative measures of confidence in its derived relationships. Although parametric models take considerable time and effort to develop, they can be used in a consistent way to develop estimates or to easily illuminate the effects of varying cost-driving parameters.

If sufficient relevant data are not available to develop CERs, analysts can use an alternative approach called *estimating by analogy*. This technique involves careful comparison of the characteristics of a similar known system, subsystem, component, or activity with those of the item to be estimated and adjustment of the known systems' costs to reflect differences between the two. The accuracy of this method depends heavily on the similarity of the analogous article and the article being estimated. While good cost analysts always attempt to make any adjustments as objectively as possible, this often requires considerable experience because the appropriate amount of adjustment is rarely obvious.

A third method used to develop cost estimates relies primarily on expert judgment. It is generally used where there is little available or relevant historical data on which to base an estimate. It most often occurs when the system or component being estimated has no closely related historical precedent. Estimates are developed by asking subject-matter experts for their estimates of some intermediate characteristic (such as labor hours, weight, software line of code, etc.) and translating them into cost. Usually, high, low, and most likely estimates are solicited to develop a risk distribution. The quality of expert judgment-based estimates depends a great deal on the relevant experience of the expert(s), as well as on how the information is solicited and validated. We discuss the use of expert judgment in greater detail below.

Another estimating approach, often considered a separate methodology, develops an estimate from a summation of many detailed component or process estimates. Usually referred to as *bottom-up* or

engineering build-up, this technique is most often used by industry to develop bid costs. Its appeal to industry is that the data are developed at, and can be tracked to, the level at which the work will be performed, thus providing initial budgets for subsequent management of the work. We do not list it as a separate methodology since its defining characteristic is level of detail rather than estimating approach. The individual components of bottom-up estimates are developed by parametric relationships, analogy, expert judgment, or most often, combinations of all three.

It should be apparent that all of these estimating methodologies depend on access to relevant historical cost and characteristic data. Collecting and normalizing the appropriate data in a form that is useful for cost analysis is a common problem most cost organizations face. Data collection takes time, consistent focus, and significant effort. Some program managers are reluctant to support an effort that does not directly and immediately benefit their program. Others challenge the relevance of collecting data that show the effects of past errors, when the new project is focused on avoiding just such occurrences. Those organizations with robust databases have generally developed them with the strong support of senior management. The database from which SMC's Unmanned Space Vehicle Cost Model (USCM) was developed is such a database. It is discussed in more detail below.

However, SMC faces some additional challenges in maintaining a useful cost analysis database. First, space systems have fewer examples of similar systems, subsystems, or technologies than do other weapon systems. The diverse missions, designs, and technologies used in many aspects of space system development result in few uses of identical components in relation to aviation or missile systems, for example. The challenging operational environment of space results in very specialized components that often have few other applications. The small quantities typical of most space programs make it unlikely that suppliers will make significant internally funded investments in production efficiencies. The weight and performance constraints on space vehicles frequently require highly integrated custom payloads with significant new development content and few economies of scale. Finally, the diverse

needs of various user communities limit the flexibility of developers to address some of these issues.

Because good analogous data for space applications may be difficult to find, estimates may be based on a small number of available data points, projections of dissimilar programs/activities, or expert judgment or contractor-provided information with limited empirical support.

Since there are circumstances in which space program estimators have to rely on expert judgment, it is worthwhile to examine the characteristics of good expert judgment and how to best use it as a source of reliable information for decisionmaking.

Using Expert Judgment

Software engineering researchers have been investigating the accuracy of various cost and schedule estimation methods for many years. The information technology and cost estimation literature reveals a variety of relevant results. For example, Kitchenham et al. evaluated 185 projects that used a combination of eight types of estimation.¹ By far, expert judgment was the most accurate. This may be true for software projects; however, Morgan (1981) and Ruckelshaus (1985) argue that experts often disagree and are prone to biases just as laypersons. On the other hand, Jørgensen analyzed a large body of project results and found the following mixed results:²

- In five studies (of 15), expert judgment was more accurate.
- In five studies, formal estimation models were more accurate.
- In five studies, there was no difference in accuracy between formal estimation models and expert judgment.

¹ Barbara A. Kitchenham, Shari Lawrence Pfleeger, Beth McColl, and Susan Eagan, "A Case Study of Maintenance Estimation Accuracy," *Journal of Systems and Software* 64, November 2002.

² Magne Jørgensen, "Estimation of Software Development Work Effort: Evidence on Expert Judgment and Formal Models," unpublished draft, April 7, 2006a; Magne Jørgensen, "A Review of Studies on Expert Estimation of Software Development Effort," *Journal of Systems and Software* 70(1–2), 2006b, pp. 37–60.

Although cost analysts in general consider formal models preferable to subjective judgment, in fact the body of empirical evidence shows no clear superiority, especially for state of the art projects where little to no data are available.³ Jørgensen suggests seven guidelines for using expert judgment.⁴ His guidelines are based on actual experience, are easy to implement, and are derived from the most recent research on the subject. The last characteristic is particularly important; since both software and hardware development practices have changed over the years, older research may be less relevant.

Incorporating Risk

Risk, the likelihood of an unfavorable outcome and uncertainty is the indefiniteness in outcome—favorable or unfavorable—will be an inherent part of every cost estimate. There are many reasons why risk analysis should be included in cost estimates. For instance, information such as technical requirements used in the cost estimate are often either ill defined or not well understood; further, the economic conditions related to the producers of technologies evolve over time. Thanks to increased emphasis on evaluating and presenting risk as a required part of estimates, most decisionmakers now understand that a cost estimate is either a range of numbers or actually a statistical distribution of probable costs and that selecting an appropriate confidence level is one of the decisions to be made.

Despite this emphasis and continuing research in risk analysis, evaluating and quantifying risk remains one of the more difficult challenges in estimating. While statistically derived parametric models can quantify their *estimating* uncertainty, the uncertainty around the programmatic/technical inputs must be modeled separately. With other estimating methodologies, all the risk must be modeled discretely,

³ Jørgensen, 2006a.

⁴ Magne Jørgensen, "Practical Guidelines For Expert-Judgment-Based Software Effort Estimation," *IEEE Software* 21(3), May–June 2005.

using both historical data and consultation with experts, as described previously.⁵

In some cases it may be difficult to get assistance from qualified experts who are not already involved with the program. To address this issue, at least for key decision point estimates, the Independent Program Assessment (IPA) Team concept was initiated. These teams have proven valuable in providing the milestone decision authority with an independent perspective on the risks faced by the program under review. Unfortunately for the cost estimators, these IPAs are normally constituted only for major program estimates and, even then, much of the cost estimator's work must be done before their assessments are available.

Estimating Tools at SMC

Hardware Models

As a result of the conditions described above, most models used at SMC tend to be developed on an as-needed basis for a specific application using selected data points. Depending on their needs and available resources, some programs may also collect cost, technical and programmatic data to augment the data contained in published databases. Unfortunately, apparently no formal process is in place to ensure locally collected data is added to these databases and thus made available to other SMC organizations. General-purpose CERs are primarily used for common components/activities such as systems engineering integration and test/program management (SEIT/PM). There are, however, several general purpose estimating models available for use in developing rough early stage or rapid turnaround estimates.

The most developed of these models is the USCM. SMC and its predecessor organizations have sponsored the development and maintenance of USCM for over three decades. The model and database are strongest on common bus components, which tend to be more evo-

⁵ For additional information on quantifying risk in acquisition programs see Arena, Leonard, et al., 2006; and Arena, Younossi, et al., 2006.

lutionary from program to program than do payloads, which tend to be more specialized. The current version is weakest on non-communications payloads and non-recurring costs. Its programmatic and schedule data are limited to top-level actuals with limited insight into original plans and changes made during the course of program execution. The current USCM model (Version Eight) and database address only the spacecraft (and communications payload, if any) and do not include data on ground segments. Figure E.1 shows the spacecraft data in USCM from military, commercial or NASA projects categorized by decades. Figure E.2 shows the number of observations included in USM from communication and passive sensor payloads.

In recent years, the data upon which the USCM model is based have been shared with the National Reconnaissance Office (NRO) and NASA. Some attempts are under way to integrate Air Force and NRO estimating tools. Unfortunately classification issues hamper data exchange from the NRO to SMC. The USCM database is currently being expanded and the older data is being renormalized to conform to the new MIL-HDBK 881A work breakdown structure.

Figure E.1
Spacecraft by Decade of Contract Award

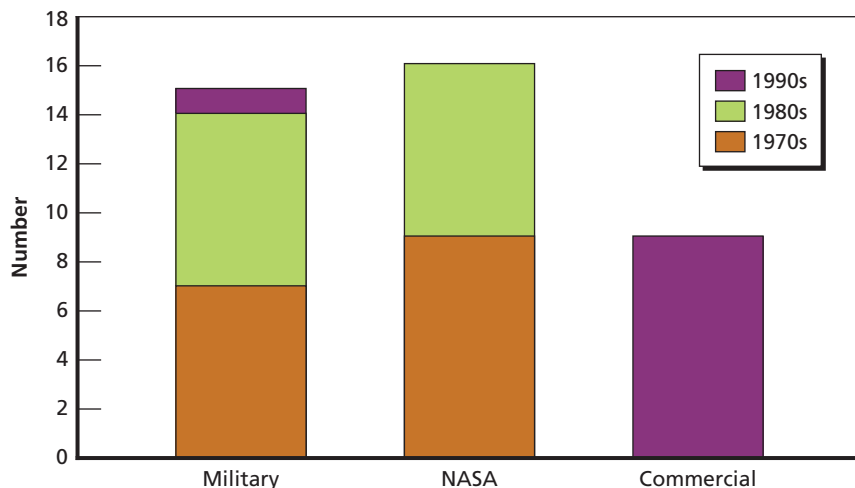
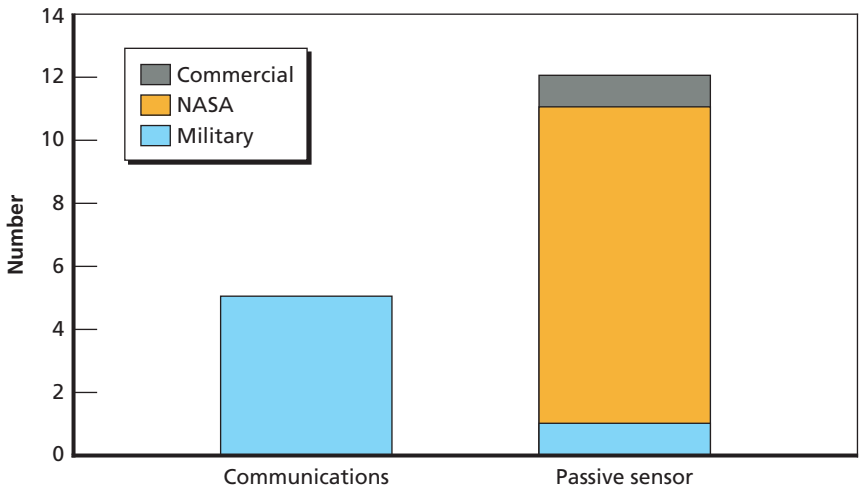


Figure E.2
Payloads and Payload Components



RAND MG690-E.2

In addition to USCM, various other space vehicle models are available at SMC and are used in appropriate situations. Table E.1 summarizes their key features.

Summary

Three fundamental methods are used in estimating the cost of future space systems:

- **Parametric Method.** The known costs of a number of similar articles are mathematically related to the physical, technical, and programmatic characteristics that influence those costs.
- **Analogy.** The known costs of a particular article are adjusted for its differences with the article being estimated.
- **Expert Judgment.** Subject matter experts are asked to characterize the differences and similarities of the article being estimated with related articles or efforts in their experience and these relationships are used to infer the cost of the article of interest.

Table E.1
Space Vehicle Models Available at SMC

Model	Content	Utility for SMC	Remarks
Unmanned Space Vehicle Cost Model	USAF/NASA/commercial spacecraft; communications payloads	Useful for ROM estimates; limited due to scope, age, data documentation	45 data points; many from 1970s; no non-COMM payload or ground segment
Passive Sensor Cost Model	Space sensor components	Limited due to age and quality of data	Older data; planned to be updated and incorporated into next USCM version
NASA/Air Force Cost Model	USAF/NASA; orbital/interplanetary/manned spacecraft; instruments; launch vehicles; engines	Special cases	122 data points; integrated risk and phasing capabilities; heavily adjusted data
Small Satellite Cost Model	Spacecraft <1000 kg; orbital/interplanetary	Special cases	35 data points
PRICE	Commercial general purpose model	Detailed comparisons of relative cost of alternatives	Various specialized modules available
SEER	Commercial general purpose model	Detailed comparisons of relative costs of alternatives	Various specialized modules available

All these methods depend on access to relevant historical costs and characteristics data. Developing databases for cost analysis requires a significant long-term commitment of effort and resources. Because of the limitations in the availability of relevant historical data, space cost analysts must often work closely with subject matter experts to ensure their assumptions, methodologies, and assessments of risk are appropriate.

Evaluating and quantifying risk should be an integral part of any cost estimate. Using the risk information provided by the analyst, the decisionmaker must select an appropriate confidence level for budget formulation and approval.

Most cost models used at SMC are developed as needed using a combination of available databases and locally collected data. As far as we can determine, no formal process is in place to capture locally developed data. The USCM is the most mature of the data-based models used at SMC. The current version addresses only spacecraft bus and communications payload costs, so other methods must be used for other types of payloads and ground segment costs. A variety of other models are suitable in varying degrees for use in particular circumstances.

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