Electronics Cost Research Literature Review

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1: EXECUTIVE SUMMARY

Electronic hardware are a component of every major weapon system and information system that the cost estimating community is called on to estimate. This report contains a review of 15 electronics hardware-related cost estimating methodology reports and databases spanning developed 1997-2015. The reports reviewed include four different ACDB databases, including the Army's C4ISR database that is actively kept up to date under DASA-CE sponsorship; a series of electronics and radar studies performed by Technomics under sponsorship of various organizations; an extensive look into airborne radar history and costs by the RAND Corporation; a detailed performance based commercial electronics cost model developed by the PACER Corporation; an electronics board area size and technology-based model developed by Tecolote; and a UAV payload cost-performance model developed by Technomics. These reports reviewed in this study are shown in Table 1-1 below.

Table 1-1 Electronics Literature Review Reports

Study Name	Study Year	Database	Methodology Discussed	Equation Forms Available	CERs Available	Statistics Available
C4ISR ACDB	2013	X				
Avionics ACDB	2014	X				
Electronics ACDB	1997	X				
Airborne Avionics & Electronics ACDB	2002	X				
Comm/Elec Cost Model	1998	X	X	X	X	X
Communications CERs for JTRS	2002		X	X	X	X
PACER 2003 (COTS Electronics)	2003		X	X	X	X
COTS	2012		X	X	X	X
Dev Support CERs	2010		X	X	X	X
FORECAST	1995		X	X		
RAND Select Airborne Radars	2008	X	X	X	X	N/A

Ground Radar 2009	2009	X	X	X	X	X
Ground Radar 2013	2012/2013	X	X	X	X	X
Radar Development Support CERs	1998		X	X	X	X
CPERs for UAVs	2007		X	X	X	X

The Army C4ISR ACDB database is the only database actively receiving sponsorship today. The database covers a wide-range of ground and aircraft communications, radar, and electronic warfare systems, drawing upon ACAT I Contractor Cost Data Reports (CCDR), Cost Performance Reports (CPR), and in the case of smaller programs, contract prices. This report recommends migration of all the CCDR reports in the ACDB databases to CADE, and that the C4ISR ACDB databases be modernized and continue to serve as a repository for non-CCDR data. The report also recommends a long-term roadmap be established for moving all cost data to CADE and a systematic program be developed to identify and sustain non-CCDR electronics data in CADE. The remaining three electronics ACDB databases are out of date or small in size, but have unique systems for which data is not elsewhere. The data in these three ACDB databases should be consolidated in the CADE or the C4ISR ACDB database, as appropriate.

The pace of development toward smaller, more capable solutions means that robust modelling of digital electronics requires developing a long-term data repository of electronic board costs and prices, characteristics, and performance parameters. This database should not duplicate CCDR data, but rather focus on vendor-level price data, as CCDR data reporting is generally not detailed enough in the near term to support digital electronics hardware cost estimating needs, and the CADE program has to complete current development before taking on future tasks. Some of the data that cost analysts use directly or indirectly for commercial off the shelf (COTS) or modified COTS electronics in cost models is price-based, as they represent prices prime contractors pay to sub-tier vendors with no additional insight, or where the government does not collect cost data. This database and resulting parametric equations will require regular biannual update to remain useful to the cost estimating community.

NCCA also recommends establishing a traditional cost model based on CCDR and other traditional cost estimating sources and a price-based model for COTS electronics based on performance. This provides the analyst two alternative approaches to modelling electronics costs.

Finally, NCCA recommends establishing regular training courses in electronics cost estimating, covering specialized defense electronics and commercial-off-the-shelf electronics.

The review focuses on electronics hardware, with databases in the first few entries, and the cost estimating methodologies in the remaining entries. Several reports include software data in their scope and this is discussed as part of the review of these reports, but a more complete overview of software methodologies and databases is provided in a software literature review to be released separately by NCCA. In addition, the scope of this review did not include commercially-marketed models such as PRICE-H and SEER. NCCA is open to including these in a future update to the literature review as resources permit. The report provides a summary of the CERs and the content of the data sets, but all proprietary data has been removed or masked to allow for wide dissemination of this literature review. The actual reports and databases, or points of contacts to obtain them, are available from the Cost Research and Tools Division at the Naval Center for Cost Analysis.

2: HISTORICAL COST RESEARCH

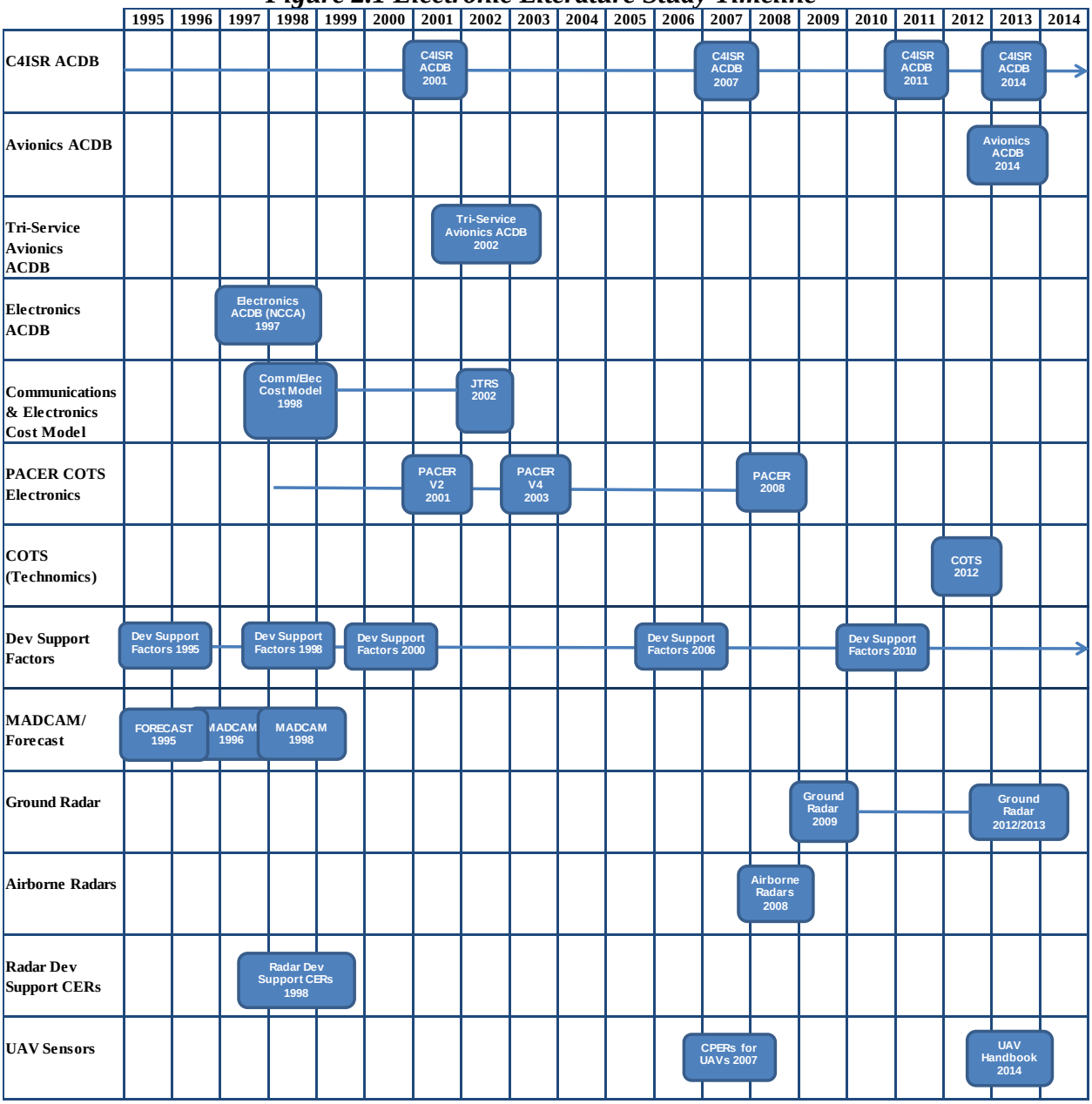
The research in Electronics cost estimating is marked by a breadth of studies covering several related commodities. The following studies were reviewed, encapsulating the current state of the art in electronics cost research reflecting the focus areas for this review.

1. "Avionics Automated Cost Database (ACDB) as of 2014," Technomics, Inc., for NCCA, 2014.
2. "C4ISR Automated Cost Database (ACDB) as of 2014," Technomics, Inc., for ODASA-CE, 2014.
3. "Electronics Automated Cost Database (ACDB)", NCCA, 1997
4. "Tri-Service Airborne Avionics & Electronics Automated Cost Database (ACDB)", AFCAA, 2002
5. "Communications and Electronics Cost Model II", Technomics, Inc., 1998
6. "Communications WBS & CERs for the JTRS Estimate," Technomics, Inc., for Army, 2002. (JTRS, Army, 2002).
7. "Performance Activated COTS Electronics Relationships (PACER) Version 4," PACER Corporation, as of 2003.
8. "Commercial Off The Shelf (COTS) Estimating Metrics for Increased Cost Accuracy Study," Tecolote Research, Inc., for Society of Cost Estimating and Analysis (SCEA) / International Society of Parametric Analysts (ISPA)[1], 2012.
9. "Development-Only Acquisition Support Cost Factors and Estimating Relationships," Tecolote Research, Inc., for Hanscom Air Force Base, 2010.
10. "First Order Electronic Cost and Sizing Tool (FORECAST)," Tecolote, Inc., for HQ Space and Missile Systems Center under Contract F33657-90-D-0051, 1995.
11. "A Cost, Technical, and Industrial-Base Review of Selected Airborne Radars", Rand for National Defense Research Institute, 2008
12. "Ground Radar Cost and Schedule Estimating Model FY09," Technomics, Inc., for AFCAA, 2009.
13. "Ground Radar Cost and Schedule Estimating Model FY12/FY13 Update," Technomics, Inc., for AFCAA and NCCA, 2013.
14. "Development Support CERs for Radar Programs," Technomics, Inc., for Naval Surface Warfare Center Dahlgren Division (NSWCDD), 1998.
15. "Cost Performance Estimating Relationships (CPERs) for UAV Payloads," Technomics, Inc., presented at DoDCAS 2007.

Figure 2.1 depicts a timeline of the studies examined.

[1] SCEA and ISPA have since merged to form the International Cost Estimating and Analysis Association (ICEAA).

Figure 2.1 Electronic Literature Study Timeline[2]



[2] Relationships between specific studies are marked with a solid line. The "Communications WBS & CERs for the JTRS Estimate" develops hardware step-down (from Development to Production), non-recurring, software development, and support CERs that build upon the hardware CERs developed in the "Communications and Electronics Cost Model II" study. The PACER model had been updated since its inception. The Ground Radar 2012/2013 study contained multiple updated CERs from the Ground Radar 2009 previous version, due to an increase in dataset size.

2.1 C4ISR AUTOMATED COST DATABASE (ACDB)", TECHNOMICS, INC., FOR ODASA-CE, 2014

The Automated Cost Database (ACDB) functionality is part of the Automated Cost Estimating Integrated Tools (ACEIT) software suite developed by Tecolote Research, Inc. Report Wizard is the ACEIT software tool that allows the user to access information in the ACDB. Specifically, Report Wizard allows a user to create and view reports of database contents; export raw data (cost data in then-year dollars (TY$)); export mapped and normalized data; perform data queries; view cost, technical, and programmatic specifications for systems and their components; and view helpful reference documents that have been attached in their native application (e.g., Adobe Acrobat for PDFs).

The records within ACDB adhere to the following hierarchical structure: System Type → System → Model → Contract → Task → Source Document. Commodities are organized by system type, system, and model, while source documents are organized by contract, task name, and source document type.

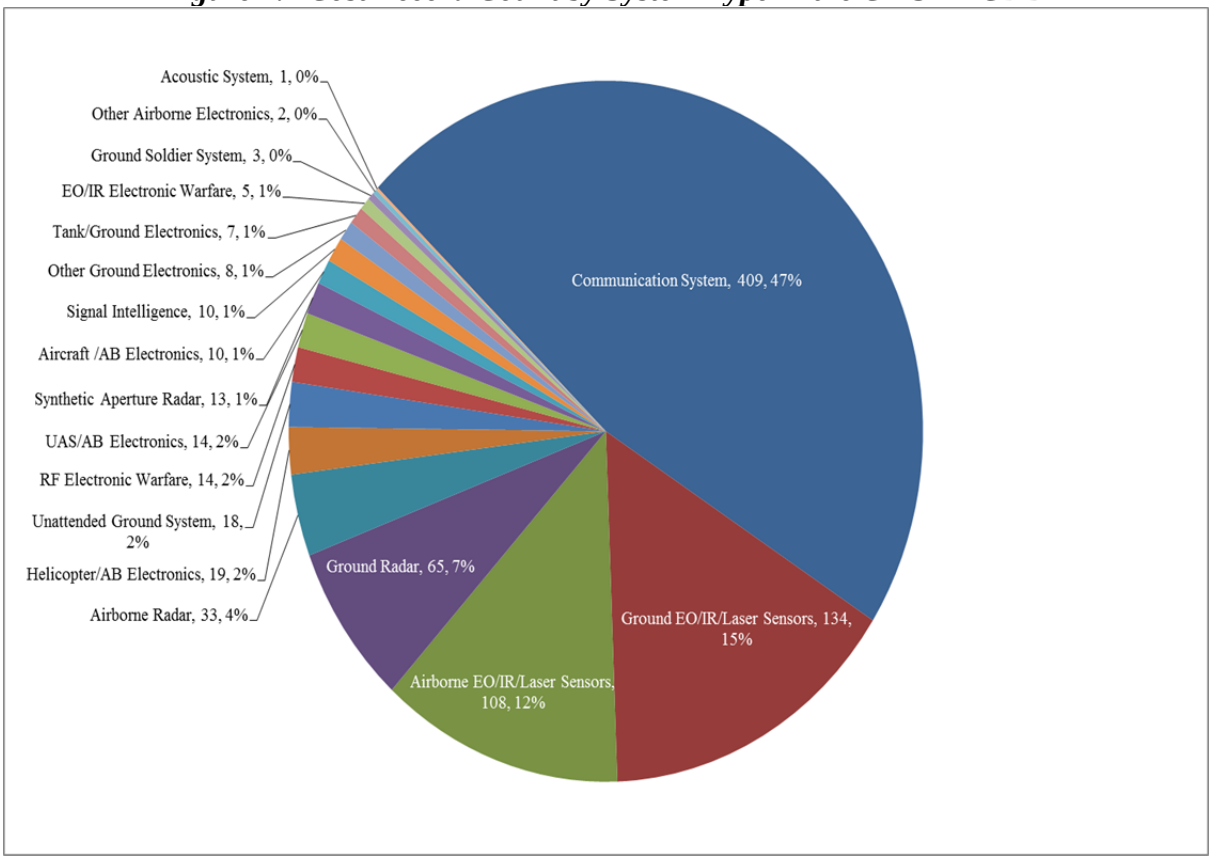
Over the years, various sponsors have developed four ACDB datasets housing cost, technical, programmatic, and other information used to create cost estimates for new systems. The C4ISR ACDB reviewed here, the Avionics ACDB reviewed in section 2.2, the NCCA Electronics ACDB reviewed in section 2.3, and the Tri-service Airborne Avionics and Electronics ACDB reviewed in section 2.4. The C4ISR ACDB house the datasets associated with Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance electronics systems and are each repositories of cost, technical, programmatic, and other information used to create cost estimates for new systems.

2.1.1 DESCRIPTION OF DATASET

As of December 2014, there were 18 system types, 142 total systems, 220 total models, and 873 total cost records housed in the C4ISR ACDB. The following graphic, Figure 2.2, displays the 18 system types. Following the name of each system type is the number of cost records for that specific system in the C4ISR ACDB and the percent of the total. The data

set is comprised of Contractor Cost Data Reports (CCDRs), contract performance reports, and contract prices.

Figure 2.2 Cost Record Count by System Type in the C4ISR ACDB



2.1.2 DESCRIPTION OF CERS

ACDBs are datasets of cost, technical, and programmatic data; but do not include CERs. Data within the C4ISR ACDB are utilized for CER development and can be downloaded into a spreadsheet for analysis.

2.1.3 STRENGTHS AND WEAKNESSES

The dataset within the C4ISR ACDB is extensive as a result of years of sustained updates and now contains 873 records.

The FoxPro backbone ACDB architecture is more than 20 years old and is a desktop installation. This allows data to be quickly extracted and converted in spreadsheet form for further analysis, but requires updates via CD, and on occasion, the database structure must be updated using the ACDB DDK (Developer Kit) tool housed within ACEIT. This requires help desk support for any analyst doing this for the first time.

The C4ISR database is available online via the Army's Joint Integrated Analysis Tool (JIAT). JIAT requires training to use effectively and is much slower to extra data from than ACDB. Because it is online, JIAT is a good source for obtaining the data from the latest data set.

2.2 "AVIONICS AUTOMATED COST DATABASE (ACDB)", TECHNOMICS, INC., FOR NCCA, 2014

The history of the commodity Automated Cost Databases (ACDB) and the ACEIT software, in addition to the ACDB purpose and layout is discussed in Section 2.1.

The Avionics database, which exists in both ACDB and spreadsheet form, contains data on four major airborne sensors and electronic war electronics. The ACDB version was developed with the intention of merging the data set into the Army C4ISR database. This did not happen, but the Avionics ACDB modules and the Excel spreadsheets remain available for analyst use.

2.2.1 DESCRIPTION OF DATASET

Table 2-1 displays the systems and models for both the Radio Frequency (RF) Electronic Warfare (EW) system type and for the Airborne Electro-Optical (EO) / Infrared (IR) / Laser Sensors system type. The model designations are from the Joint Electronics Type Designation System (JETDS) for United States military electronics and communications equipment, wherein the three letters represent platform, type of equipment, and purpose, respectively. ALQ models refer to Airborne Countermeasures Multipurpose / Special

Equipment, the ALR model refers to Airborne Countermeasures Receivers, and the ASQ model refers to Airborne Special / Combination Multipurpose / Special Equipment.

Table 2-1 System Type, System Name, and Model of the Avionics ACDB Data

System Type	System	Model
RF Electronic Warfare	Integrated Defensive Electronic Countermeasures (IDECM)	ALQ-214
RF Electronic Warfare	Tactical Jamming System (TJS)	ALQ-218
RF Electronic Warfare	Radar Warning Receiver (RWR)	ALR-67
Airborne EO/IR/Laser Sensors	Advanced Targeting Forward-Looking Infrared (ATFLIR)	ASQ-228

Table 2-2 documents the number and type of records for each of the systems in the Avionics ACDB. The Cost Data Summary Reports (CDSRs), using DD Form 1921, are the DoD standard for cost reporting. The Contract Performance Reports (CPRs) and legacy Cost/Schedule Status Reports (C/SSRs) are the standard for earned value management (EVM) reporting and can be important sources of historical cost data, especially for complete or near-complete contracts.

Table 2-2 Number of Avionics ACDB Records by Source Type

Model	# of CDSR	# of Contract Prices	# of CPR	# of Accounting Records	# of C/SSR	Total
ALQ-214	4	12	1	3	0	**20**
ALQ-218	11	0	1	0	0	**12**
ALR-67	8	15	0	0	1	**24**
ASQ-228	4	4	2	0	0	**10**
Total	**27**	**31**	**4**	**3**	**1**	**66**

The WBS used in the database is similar to MIL-STD-881C, but break out general and administrative (G&A) costs, and management reserve.**Error! Reference source not**

found..3 highlights the WBS elements contained in the Avionics ACDB. X's denote data available for the specified system.

Table 2-3 NCCA Avionics ACDB Contents

Data Available in the Avionics ACDB	System	Advanced Targeting Forward-Looking Infrared (ATFLIR)	Radar Warning Receiver (RWR)	Tactical Jamming System (TJS)	Integrated Defensive Electronic Counter-measures (IDECM)
	Model	ASQ-228	ALR-67	ALQ-218	ALQ-214
WBS Type: AIRBORNE EO/IR/LASER SENSORS					
WBS Element					
TOTAL - AIR EO/IR/LASER SENSORS		X			
UNDISTRIBUTED BUDGET					
MANAGEMENT RESERVE					
COST OF MONEY		X			
GENERAL AND ADMINISTRATIVE		X			
PROFIT/ FEE/ LOSS		X			
OVERHEAD		X			
WARRANTY					
OTHER NON-DIRECT COSTS					
SUBTOTAL		X			
EO SENSOR (CONTRACT PRICE)					
LASER RANGEFINDER/DESIGNATOR (CONTRACT PRICE)					
OTHER LASER (CONTRACT PRICE)					
IR SENSOR (CONTRACT PRICE)					
EO/IR/LASER SENSORS (CONTRACT PRICE)		X			
PRIME MISSION PRODUCT (PMP)		X			
PLATFORM INTEGRATION		X			
SUPPORT COSTS (BELOW-THE-LINE)		X			
OTHER					
WBS Type: RF ELECTRONIC WARFARE					
WBS Element					
TOTAL - RF ELECTRONIC WARFARE SYSTEM			X	X	X
UNDISTRIBUTED BUDGET				X	X
MANAGEMENT RESERVE				X	X
COST OF MONEY			X	X	X
GENERAL AND ADMINISTRATIVE			X	X	X
PROFIT/ FEE/ LOSS			X	X	X
OVERHEAD					
WARRANTY					
OTHER NON-DIRECT COSTS			X		X
SUBTOTAL			X	X	X
RF ELECTRONIC WARFARE SYSTEM (CONTRACT PRICE)					X
PRIME MISSION PRODUCT (PMP)			X	X	X
PLATFORM INTEGRATION				X	X
SUPPORT COSTS (BELOW-THE-LINE)			X	X	X

2.2.2 DESCRIPTION OF CERS

ACDBs are datasets of cost, technical, and programmatic data, but do not include CERs. Data within the Avionics ACDB are utilized for CER development and can be downloaded into a spreadsheet for analysis.

2.2.3 STRENGTHS AND WEAKNESSES

The database structure and dataset size of the Avionics ACDB allows for the data to be easily navigable and traceable in the database. An additional strength is that records are derived from a variety of sources: CDSRs, contracts, CPRs, accounting records, and C/SSRs.

The FoxPro backbone ACDB architecture is more than 20 years old and is a desktop installation. This allows data to be quickly extracted and converted in spreadsheet form for further analysis. The Avionics database is not available online via a relational database.

Additionally, the Avionics ACDB only has four systems.

The information in this review for the Avionics ACDB represents the status of the database as of 2014.

2.3 "ELECTRONICS AUTOMATED COST DATABASE (ACDB)", NCCA, 1997

The history of the commodity Automated Cost Databases (ACDB) and the ACEIT software, in addition to the ACDB purpose and layout is discussed in Section 2.1.

The Electronics ACDB was sponsored by NCCA in the late 1990s and houses data associated with airborne, shipboard, and ground-based electronics systems.

2.3.1 DESCRIPTION OF DATASET

Table 2.3 summarizes the systems included in the database. The data in the database was compiled in 1997 and the dates of the program contract's ranges from 1980 to 1993.

The model designations are from the Joint Electronics Type Designation System (JETDS) for United States military electronics and communications equipment, wherein the three letters represent platform, type of equipment, and purpose.

Table 2.2-4 System Type, System Name, and Model of the Avionics ACDB Data

System Type	System	Model
RF Electronic Warfare	Advanced Self Protect Jammer (ASPJ)	ALQ-65
RF Electronic Warfare	Radar Warning Receiver (RWR)	ALR-67
RF Electronic Warfare	Pulse Doppler X-Band Fire Control Radar	APG-63
Airborne Fire Control Radar	Pulse Doppler X-Band Multi-Mode Radar	APG-65
Airborne Fire Control Radar	Pulse Doppler X-Band Multi-Mode Radar	APG-68
Airborne Fire Control Radar	Pulse Doppler X-Band Multi-Mode Radar	APG-71
Airborne Fire Control Radar	Pulse Doppler X-Band Multi-Mode Radar	APG-73
Airborne Surveillance Radar	Pulse Doppler S-Band Air & Sea Surveillance Radar (AWACS)	APY-1
Integrated ASW Combat System	Submarine Combat System	BSY-1

Integrated ASW Combat System	Submarine Combat System	BSY-2
Integrated ASW Combat System	Undersea Warfare / Anti-Submarine Warfare Combat System	SQQ-89
Surface Ship Sonar	Tactical Towed Array Sonar (TACTAS)	SQR-19
Surface Ship Sonar	Active/Passive Hull Mounted Sonar	SQS-53C
Real-time Sensor Netting	Cooperative Engagement Capability (CEC)	USG-2/3/4
Computer	Mission Computer Upgrade (MCU)	E-2C MCU
Surface Combat System	Aegis Weapons System MK7	MK7 Aegis
Mobile Ground Based Radar	Terminal High Altitude Area Defense (THAAD) Ground Based Radar (GBR)	THAAD GBR

Table 2.4 documents the number and type of records for each of the systems in the Avionics ACDB. The Cost Data Summary Reports (CDSRs) and Functional Cost Hour Reports (FCHRs) are part of DoD's Contract Cost Data Reporting (CCDR) system. The Contract Performance Reports (CPRs) is the standard for earned value management (EVM) reporting, and are important sources of historical cost data, especially for complete or near-complete contracts.

Table 2.2-5 Number of Avionics ACDB Records by Source Type

Model	# of CDSR	# of FCHR	# of CPR	Total
ALQ-65	5	4		**9**
ALR-67	1	2		**3**
APG-63	1			**1**
APG-65	2			**2**
APG-68	1			**1**
APG-71	2			**2**
APG-73	1	1	1	**3**
APY-1	1			**1**
BSY-1			4	**4**
BSY-2			6	**6**
SQQ-89	5	2	1	**8**

SQR-19	1		4	**5**
SQS-53C			5	**5**
USG-2/3/4	1			**1**
E-2C MCU	1			**1**
MK7 Aegis	7		2	**9**
THAAD GBR	1			**1**
Total	**30**	**9**	**23**	**62**

Data within the Electronics ACDB can be downloaded into a spreadsheet for analysis.

2.3.2 DESCRIPTION OF CERS

ACDBs are datasets of cost, technical, and programmatic data; but do not include CERs.

2.3.3 STRENGTHS AND WEAKNESSES

The dataset within the Electronics ACDB covers several different kinds of electronics systems including avionics, sea-based sonar, submarine combat systems, radars, and ground-based radar systems. The database has not been updated in nearly 20 years and is likely not a useful source for estimating digital electronics, but is likely a unique source of data in readily extractable form for several of the legacy systems listed therein, such as the sonars.

The FoxPro backbone ACDB architecture is more than 20 years old and is a desktop installation. This allows data to be quickly extracted and converted in spreadsheet form for further analysis. The Electronics database is not available online via a relational database.

2.4 "TRI-SERVICE AIRBORNE AVIONICS & ELECTRONICS AUTOMATED COST DATABASE (ACDB)", AFCAA, 2002

The history of the commodity Automated Cost Databases (ACDB) and the ACEIT software, in addition to the ACDB purpose and layout is discussed in Section 2.1.

The Tri-Service Airborne Avionics and Electronics Systems ACDB houses the datasets associated with various airborne electronics systems and are each repositories of cost, technical, programmatic, and other information used to create cost estimates for new systems.

2.4.1 DESCRIPTION OF DATASET

Table 2.5 includes 406 cost records for the systems in the following table.

Most of the model designations are from the Joint Electronics Type Designation System (JETDS) for United States military electronics and communications equipment, wherein the three letters represent platform, type of equipment, and purpose, respectively.

Table 2.2-6 System Type, System Name, and Model of the Avionics ACDB Data

System Type	System	Model
EW Evaluation Simulator	Air Force Electronic Warfare Evaluation Simulator (AFEWES) Upgrade Program	AFEWES
EO/IR Target/ Navigation	Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) Navigation & Targeting Pod	AAQ-13/14
EO/IR Missile Warning	Passive UV Missile Warning System	AAR-44
EO/IR Target/Navigation	Infrared Search & Track (IRST)	AAS-42
EW Expendables	Countermeasure System	ALE-18
EW Expendables	Chaff Dispenser	ALE-28
EW Expendables	Electronic Countermeasures Dispensing Systems with Chaff	ALE-29
EW Expendables	Chaff Dispenser Pod	ALE-38
EW Expendables	Countermeasures Dispenser System	ALE-39
EW Expendables	Electronic Countermeasures Dispensing Systems	ALE-40
EW Expendables	Electronic Countermeasures Decoy Protection System	ALE-45
EW Expendables	Electronic Countermeasures Dispensing Systems	ALE-47
EW Expendables	Countermeasures, Towed Decoy Protection System	ALE-50

EW RF Jammer	Internal Jamming System	ALQ-100
EW RF Jammer	Pod Jammer	ALQ-101(V)
EW RF Jammer	Pod Jammer	ALQ-119(V)
EW RF Jammer	Internal Jamming System	ALQ-126
EW Radar Warning Receiver	Radar Warning Receiver	ALQ-128
EW RF Jammer	Pod Jammer	ALQ-131(V)
EW RF Jammer	Pod Jammer	ALQ-131(V) Blk 1
EW RF Jammer	Pod Jammer	ALQ-131(V) Blk 2
EW RF Jammer	Internal Jamming System	ALQ-135(V)
EW RF Jammer	Pod Jammer	ALQ-136(V)
EW RF Jammer	Internal Jamming System	ALQ-137
EW Radar Warning Receiver	Radar Warning Receiver	ALQ-153
EW RF Jammer	Internal Jamming System	ALQ-161
EW RF Jammer	Airborne Self Protection Jammer (ASPJ)	ALQ-165
EW RF Jammer	Internal Jammer System	ALQ-172(V)
EW RF Jammer	Pod Jammer	ALQ-184
EW RF Jammer	Internal Jamming System	ALQ-189
EO/IR Jamming	Advanced Threat Infrared Countermeasures Common Missile Warning System (ATIRCM/CMWS)	ALQ-212
EW RF Jammer	Internal Jamming System	ALQ-41
EW RF Jammer	Internal Jamming System	ALQ-49
EW RF Jammer	Internal Jamming System	ALQ-51
EW RF Jammer	Internal Jamming System	ALQ-51A
EW RF Jammer	Internal Jamming System	ALQ-55
EW RF Jammer	Pod Jammer	ALQ-71
EW RF Jammer	Pod Jammer	ALQ-72
EW RF Jammer	Pod Jamming System	ALQ-81
EW RF Jammer	Pod Jammer	ALQ-87
EW RF Jammer	Pod Jamming System	ALQ-88
EW RF Jammer	Internal Jamming System	ALQ-91
EW RF Jammer	Internal Jamming System	ALQ-92
EW RF Jammer	Internal Jamming System	ALQ-94
EW Radar Warning	Radar Warning Receiver	ALR-45

Receiver		
EW Radar Warning Receiver	Radar Warning Receiver	ALR-46
EW Radar Warning Receiver	Radar Warning Receiver	ALR-56A
EW Radar Warning Receiver	Radar Warning Receiver	ALR-56C
EW Radar Warning Receiver	Radar Warning Receiver	ALR-56M
EW Radar Warning Receiver	Radar Warning Receiver	ALR-62
EW Radar Warning Receiver	Radar Warning Receiver	ALR-621
EW Radar Warning Receiver	Radar Warning Receiver	ALR-67
EW Radar Warning Receiver	Radar Warning Receiver	ALR-69
EW Radar Warning Receiver	Radar Warning Receiver	ALR-74
EW Radar Warning Receiver	Radar Warning Receiver	ALR-94
Radar – Airborne Attack	Airborne Fire Control Radar	APG-63
Radar – Airborne Attack	Airborne Fire Control Radar	APG-65
Radar – Airborne Attack	Airborne Fire Control Radar	APG-66
Radar – Airborne Attack	Airborne Fire Control Radar	APG-68
Radar – Airborne Attack	Airborne Fire Control Radar	APG-70
Radar – Airborne Attack	Airborne Fire Control Radar	APG-71
Radar – Airborne Attack	Airborne Fire Control Radar	APG-73
Radar – Airborne Attack	Airborne Fire Control Radar	APG-77
Radar – Airborne Attack	Airborne Fire Control Radar	APG-78
Radar – Airborne Attack	Airborne Fire Control Radar	APG-79
EW Radar Warning Receiver	Radar Warning Receiver	APR-25

EW Radar Warning Receiver	Radar Warning Receiver	APR-26
EW Radar Warning Receiver	Radar Warning Receiver	APR-27
EW Radar Warning Receiver	Radar Warning Receiver	APR-36
EW Radar Warning Receiver	Radar Warning Receiver	APS-107D
EW Radar Warning Receiver	Radar Warning Receiver	APS-109A
Airborne Processor	Airborne Processor	AYK-14
Radar – Airborne Attack	Multi-mode X Band Pulse-Doppler Systems	AWG-9
Aircraft System Level Avionics	B-1B Offensive Avionics	B-1
Aircraft System Level Avionics	C-130 Gunship	C-130 Gunship
Radar – Surveillance	E-2C Airborne Mission Computer Upgrade (MCU)	E-2C MCU
Aircraft System Level Avionics	F/A-18E/F APG-79 Integration	F/A-18E/F
Aircraft System Level Avionics	F-16 Peace Vector IV	F-16
Aircraft System Level Avionics	F-22	F-22
Airborne Processor	F-22 Common Integrated Processor (CIP)	F-22 CIP
Airborne Mission Equipment	F-22 Fiber Optic Transmitter Receiver (FOTR)	F-22 FOTR
Airborne Mission Equipment	F-22 Fiber Optics & High Speed Data Bus	F-22 EMD
Aircraft System Level Avionics	Longbow Apache AH-64D Phase 2	Longbow Apache
EO/IR Target/ Navigation	RAH-66 Electro-Optic Sight System (EOSS)	RAH-66 EOSS
Airborne Mission Equipment	RAH-66 Helmet Integrated Display Sight System (HIDSS)	RAH-66 HIDSS
Communication, Navigation, and ID System	RAH Integrated Communications Navigation and Identification Avionics (ICNIA)	RAH-66 ICNIA
Airborne Processor	RAH-66 Mission Computer Cluster (MCC)	RAH-66 MCC

Radar – Airborne Attack	RAH-66 Radar	RAH-66 Radar
Aircraft System Level Avionics	RAH-66	RAH-66
Aircraft System Level Avionics	V-22 Osprey	V-22 Osprey
Airborne Processor	Very High Speed Integrate Circuit (VHSIC) Core Processing System	VHSIC

Table 2.6 documents the number and type of records for each of the systems in the Avionics ACDB. The Cost Data Summary Reports (CDSRs) and Functional Cost Hour Reports (FCHRs) are part of DoD's Contract Cost Data Reporting (CCDR) system. The Contract Performance Report (CPRs) is the standard for earned value management (EVM) reporting. The Cost/ Schedule Status Reports (CSSR) are from programs where EVM standards are not required, Contractor Funds Status Reports (CFSRs) provide contract funding status, and contract documents are other documents including contracts, contract prices, price lists, and other contractor supplied reports with financial information.

Table 2.2-7 Number of Avionics ACDB Records by Source Type

Model	# of CDSR	# of FCHR	# of CPR	# of CSSR	# of CFSR	# of Ktr	Total
AFEWES				1			**1**
AAQ-13/14	22	15	4	3			**44**
AAR-44				1	1		**2**
AAS-42						4	**4**
ALE-18	1						**1**
ALE-28	1						**1**
ALE-29	1						**1**
ALE-38	1						**1**
ALE-39	1						**1**
ALE-40	2						**2**
ALE-45	1						**1**
ALE-47	2	1		1	1		**5**
ALE-50				5			**5**
ALQ-100	1						**1**

ALQ-101(V)	1						**1**
ALQ-119(V)	1						**1**
ALQ-126	1						**1**
ALQ-128	1						**1**
ALQ-131(V)	2	1	1	1	2		**7**
ALQ-131(V) Blk 1	1						**1**
ALQ-131(V) Blk 2	1						**1**
ALQ-135(V)	1		9	1	4		**15**
ALQ-136(V)	2						**2**
ALQ-137	1						**1**
ALQ-153	2	2	2	1			**7**
ALQ-161	8						**8**
ALQ-165	9	7					**16**
ALQ-172(V)			11		4		**15**
ALQ-184	1						**1**
ALQ-189	1						**1**
ALQ-212	1		1				**2**
ALQ-41	1						**1**
ALQ-49	1						**1**
ALQ-51	1						**1**
ALQ-51A	1						**1**
ALQ-55	1						**1**
ALQ-71	1						**1**
ALQ-72	1						**1**
ALQ-81	1						**1**
ALQ-87	1						**1**
ALQ-88	1						**1**
ALQ-91	1						**1**
ALQ-92	1						**1**
ALQ-94	1						**1**

ALR-45	1						**1**
ALR-46	1						**1**
ALR-56A	1						**1**
ALR-56C			2	7	5		**14**
ALR-56M	1	1		3			**5**
ALR-62	1		1		1		**3**
ALR-621	1						**1**
ALR-67	14	15		2		1	**32**
ALR-69	1						**1**
ALR-74	1						**1**
ALR-94	2	2					**4**
APG-63						6	**6**
APG-65	13	13	1				**27**
APG-66	5	3	3				**11**
APG-68	7	7	5	1			**20**
APG-70	7	7					**14**
APG-71	9	2	1			2	**14**
APG-73	7	4	1				**12**
APG-77	2	2					**4**
APG-78	6	3	2			4	**15**
APG-79	2						**2**
APR-25	1						**1**
APR-26	1						**1**
APR-27	1						**1**
APR-36	1						**1**
APS-107D	1						**1**
APS-109A	1						**1**
AYK-14						11	**11**
AWG-9	9						**9**
B-1	1						**1**
C-130 Gunship	1						**1**
E-2C MCU	1						**1**
F/A-18E/F	3						**3**
F-16	2						**2**
F-22	1						**1**
F-22 CIP	1	1					**2**

F-22 FOTR	1						**1**
F-22 EMD	1	1					**2**
Longbow Apache	1						**1**
RAH-66 EOSS	1						**1**
RAH-66 HIDSS	1						**1**
RAH-66 ICNIA	1						**1**
RAH-66 MCC	1						**1**
RAH-66 Radar	1						**1**
RAH-66	1						**1**
V-22 Osprey	1						**1**
VHSIC			2	2			**4**
Total	**197**	**87**	**46**	**29**	**18**	**28**	**406**

2.4.2 DESCRIPTION OF CERS

ACDBs are datasets of cost, technical, and programmatic data; but do not include CERs.

2.4.3 STRENGTHS AND WEAKNESSES

The dataset within the AFCAA ACDB covers a wide variety of electronics, some of which are available in readily extractable form only here. The database has not been updated in more than 10 years, limiting its useful as a source for estimating digital electronics hardware.

The FoxPro backbone ACDB architecture is more than 20 years old. This architecture provides fast responses to user queries, but is not available online. AFCAA has not sponsored any recent updates to this database.

2.5 "COMMUNICATIONS AND ELECTRONICS COST MODEL II", TECHNOMICS, INC., 1998

The purpose of the study was to develop a cost and technical database for communication and ground electronic systems as well as a cost model used to estimate these systems. The database allowed for the development of a cost model that consists of a set of cost estimating relationships (CERs) to estimate the manufacturing costs of the electronic assemblies (i.e., circuit cards, modules or assemblies) in electronic boxes and electrical / mechanical / structural assemblies of a communication or ground electronic system. The developed CERs estimate the manufacturing cost based on the physical composition of the assemblies, relevant performance parameters, and physical parameters. The CERs for the electronic assemblies of electronic boxes, for instance, were determined based on the physical dimensions and characteristics of the assemblies (i.e., module volume; the circuit card area, and the types and counts of the components mounted on the circuit cards; and performance parameters such as frequency of operation). The CERs for electrical / mechanical / structural assemblies, on the other hand, were based on physical characteristics such as aperture, weight of the assembly, and the number of axes.

2.5.1 DESCRIPTION OF DATASET

The database for communication and ground electronic systems consisted of military programs in the Demonstration and Validation (DEMVAL) and Engineering and Manufacturing Development (EMD) phases of development[3] and contractor funded developments of commercial hardware. Seven programs operating in frequency between 30 Megahertz (SINCGARS) and 45 Gigahertz (SMART-T and SCAMP) populated the communications database. The communications database comprised voice (SINCGARS) and data (such as EPLRS and JTIDS) systems functioning as man-portable and vehicular

[3] In the acquisition process, the Demonstration and Validation (DEMVAL) phase is currently known as the Technology Development (TD) phase. The System Development and Demonstration (SDD) phase, which is mentioned in other studies within this review, is currently known as the Engineering and Manufacturing Development (EMD) phase.

equipment. Hardware elements included in this database are the communication radio box with its electronic circuit card assemblies (CCAs) and modules, dish antennas, pedestals, power distribution units, generators, and pallets.

The ground electronics database contains five electronic boxes or assemblies housed within a tank fire control system. The electronic boxes carry out analog and digital signal and data processing, display formatting and biasing, power conditioning and interfacing. Commercially-developed signal and data processors and input/output CCAs containing microprocessors, memory, and input/output chips and interface electronics are also included in the database. In summary, the resulting ground electronics database that was analyzed essentially consisted of three separate ground electronics databases (MIL-SPEC communications, tank fire control electronics, and commercially-developed electronic CCAs).

Cost and technical data for the electronic and electrical / mechanical / structural assemblies came from several sources, primarily government project offices. Communication system data was collected primarily from the project offices within the Army's Communications-Electronics Command (CECOM). Ground fire control systems data were collected primarily from the Tank-Automotive & Armament Command (TACOM) Abrams Project Office; with additional technical data on the M1A2 Fire Control development collected from the Picatinny Arsenal. Some cost and technical data was obtained from analysts at the United States Army Cost and Economic Analysis Center (USACEAC), now ODASA-CE. Finally, cost and technical data were collected from the vendors of the commercially-developed hardware.

Each program included in the dataset is listed below, and further summarized in the study.

- Enhanced Position Location Reporting System (EPLRS)
- Joint Tactical Information Distribution System (JTIDS)
- Single Channel Antijam Man-Portable communications terminal (SCAMP)
- Single Channel Ground Air Radio Set (SINCGARS)
- Secure Mobile Anti-jam Reliable Tactical Terminal (SMART-T)
- Improved Abrams Tank M1A2
- Commander's Independent Thermal Viewer (CITV)
- Commander's Integrated Display (CID)
- Hull / Turret Electronics Unit (HTEU)
- Fire Control Electronics Unit (FCEU)
- Commercially Developed Hardware

2.5.2 DESCRIPTION OF CERS

The study examined and developed CERs for the following hardware items comprising a communication and ground electronic system.

- Dish Antennas
- Pedestal Assemblies
- Communication Radio/Ground Electronics Box
    - RF Power Amplifier CCAs
    - RF Receiver CCAs
    - Microwave Integrated Circuit (MIC) Assemblies
    - Synthesizers and IF electronics CCAs
    - Signal Processors/COMSEC CCAs
    - Data Processors and Control Electronics CCAs
    - Digital Input/Output CCAs
    - Power Converter and Regulator Modules
    - Servo and Analog Electronics CCAs
- Interface Devices
- Power Distribution Units/Power Control Units
- Generators
- Pallets

CERs were developed from the communication and ground electronic systems database in order to estimate the manufacturing costs of the electronic assemblies of the electronic boxes and the electrical / mechanical / structural assemblies in the Demonstration and Validation (DEMVAL), and Engineering and Manufacturing Development (EMD) phases of development. Where necessary, technology advance variables were added to the CERs. Differences in cost for EMD and DEMVAL programs were calibrated where data was

available. Dummy variables were also included in the analog, digital, and power converter CERs to capture ruggedization.

The manufacturing cost derived from these estimates represents the fabrication, assembly, inspection, and test (FAIT), manufacturing support, and sustaining engineering. The CERs exclude program level costs such as system engineering, program management, and data. The costs included the cost of money, G&A, and fee (when awarded).

Table 2-8 outlines the CERs by hardware element that were developed as part of the study. Information regarding the range for each independent and dependent variable by each hardware element may be found in the study. Each of the CER developments predict manufacturing costs in dollars (Mfg $). For 1.1 Dish Antennas and 1.2 Pedestal, "Mfg $" is defined as the manufacturing cost of the prototype units in development ***or*** the recurring cost of the first production unit (T_1). For all subsequent CER elements, "Mfg $" is defined as the manufacturing cost of the prototype units in development. CER inputs that are marked with an asterisk in a given function are binary variables that are used for several CERs Definitions are provided in Table 5.2

Table 2-8: Communications and Electronics Cost Model II CERs and Required Inputs

Code	CER Element Name	Required Inputs
1.1	Dish Antennas	Mfg $ = *f* (Ant Dia, Prod*, Qty) where • Ant Dia = the diameter of the antenna in feet. • Qty = the quantity of development units (or takes the value of 1.0 to estimate the recurring production T_1 cost).
1.2	Pedestal	Mfg $ = *f* (Ant Dia, Prod*, # Axes, Qty) where • Ant Dia = the diameter of the antenna in feet. • # Axes = the number of stabilized axes. • Qty = the quantity of development units (or takes the value of 1.0 to estimate the recurring production T_1 cost).
1.3	Communication Radio/ Ground Electronic Box	See sub-elements below

1.3.1	RF Power Amplifier Modules	Mfg $ = *f* (Vol, Freq, IMPATT*, Xmtr Assy*, Qty) where • Vol = volume of the module or assembly in cubic inches (in.^{3}). • Freq = the output center frequency of the RF power amplifier in MHz. • Qty = the number of units manufactured in development.
1.3.2	RF Receiver Modules	Mfg $ = *f* (Vol, Freq, RF Assy*, Qty) where • Vol = volume of the module or assembly in cubic inches (in.^{3}). • Freq = the input center frequency of the receiver in MHz. • Qty = the number of units manufactured in development.
1.3.3	Microwave Integrated Circuit (MIC) Assemblies	Mfg $ = *f* (GHz, Area, Qty) where • GHz = the center frequency of the highest frequency band in the assembly in GHz. • Area = the mounting area of the MIC/MMIC alumina substrates in square inches (in²). The mounting area can be the area of a carrier board inside the RF module or the mounting surface area inside a RF module. • Qty = the number of units manufactured in development
1.3.4	Synthesizer and IF Electronics Modules	Mfg $ = *f* (Vol, Freq, NDI*, Assy*, Qty, RF) where • Vol = volume of the module or assembly in cubic inches (in.^{3}). • Freq = the maximum frequency generated by the synthesizer or used in the intermediate frequency electronics in MHz. • Qty = the number of units manufactured in development. • RF = the ruggedization factor (specifications for each of the four RF levels may be found in the study).
1.3.5	Signal Processor / COMSEC CCAs	Mfg $ = *f* (Area, Density, %IC, Qty, D&V*, Yr-78, RF) where • Area = the total usable area (in²) of the circuit card (both front and back if double sided) that the components are mounted on. • Density = the total number of electronic components (ICs, resistors, capacitors, etc.) per square inch (in²) of usable circuit card area. • %IC = the number of ICs divided by the total number of electronic components on the circuit card. • Qty = the number of units manufactured during the development. • Yr-78 = the year the development was complete minus 1978.
1.3.6	Data Processor and Control Electronics CCAs	
1.3.7	Digital Input/ Output CCAs	

		• RF = the ruggedization factor (specifications for each of the four RF levels may be found in the study).
1.3.8	Power Converter and Regulator Modules	Mfg $ = *f* (Vol, Hyb*, D&V*, Qty, RF) where • Vol = volume of the module or assembly in cubic inches (in.^{3}). • Qty = the number of units manufactured in development. • RF = the ruggedization factor (specifications for each of the four RF levels may be found in the study).
1.3.9	Analog and Servo Electronics CCAs	Mfg $ = *f* (Area, Density, %IC, Qty, Yr-78, RF) where • Area = the total usable area (in²) of the circuit card (both front and back if double sided) that the components are mounted on. • Density = the total number of electronic components (ICs, resistors, capacitors, etc.) per square inch (in²) of usable circuit card area. • %IC = the number of ICs divided by the total number of electronic components on the circuit card. • Qty = the number of units manufactured during the development. • Yr-78 = the year the development was complete minus 1978. • RF = the ruggedization factor (specifications for each of the four RF levels may be found in the study).
1.4	Interface Devices	Mfg $ = *f* (Vol, NDI*, KD*, CP*, Mini*, D&V*, Qty) where • Vol = the volume of the interface device in cubic inches (in³). • Qty = the number of units manufactured in development.
1.5	Generators	Mfg $ = *f* (lbs, Qty) where • lbs = the weight of the generator in pounds (lbs). • Qty = the number of prototypes in development.
1.6	Power Distribution Units (PDUs)/ Power Control Units (PCUs)	Mfg $ = *f* (lbs, Qty) where • lbs = the weight of power distribution unit or power control unit in pounds (lbs). • Qty = the number of prototypes in development.
1.7	Pallets	Mfg $ = *f* (lbs, Manport*, Qty) where • lbs = the weight of the pallet in pounds (lbs). • Qty = the number of prototypes in development.

Table 2.8 is a binary variable key for the CER elements mentioned above. The first part of the definition indicates a binary value of (1), while the second part of the definition represents a binary value of (0).

Table 2-9 Communications and Electronics Cost Model II Binary Variable Key

Input	Definition
Prod	A production T_1 estimate, OR a development estimate.
IMPATT	IMPact Avalanche Transit Time (IMPATT) devices, OR Pseudo High Electron Mobility Transistor (PHEMT) devices.
Xmtr Assy	An RF transmitter assembly (i.e., an assembly consisting of more than one module including waveguide and RF connectors), OR a single RF power amplifier module (i.e., amplifier components enclosed in a single module).
RF Assy	An RF receiver assembly (i.e., an assembly consisting of more than one module including waveguide and RF connectors), OR a single RF receiver module (i.e., RF components enclosed in a single module).
NDI	A Non-Developmental Item (off-the-shelf MIL-SPEC), OR a non-NDI item.
Assy	A synthesizer or IF electronics assembly (i.e., an assembly consisting of more than one module including waveguide and RF connectors), OR a single RF module (i.e., synthesizer of IF components enclosed in a single module).
D&V	A DEMVAL program, OR an Engineering and Manufacturing Development (EMD) program.
Hyb	If the module is assembled in a hybrid form (i.e., no discrete packaging), OR if the module is assembled with discrete components packaged in their own containers.
KD	A Keyboard/Display, OR an autonomous interface device (i.e., keyboard display, processor, power supply, I/O, structure).
CP	A control panel, OR an autonomous interface device (i.e., keyboard, display, processor, power supply, I/O, structure).
Mini	Estimating a miniaturized interface device (i.e., one using hybrid packaging vs. discrete packaging techniques), OR a non-miniaturized interface device.
Manport	A man-portable system, OR a fixed site or vehicle system.

2.5.3 STRENGTHS AND WEAKNESSES

This study develops a very comprehensive set of CERs to determine the manufacturing cost of electronic assemblies of electronic boxes and electrical / mechanical / structural

assemblies for both the DEMVAL and EMD phases of development. The overall CER methodology is clear and well-explained, as are the inputs to each hardware element CER. A weakness of the study is that the dataset and technology is more than 15 years old and out of date.

2.6 "COMMUNICATIONS WBS & CERS FOR THE JTRS ESTIMATE", TECHNOMICS, INC., 2002

The Joint Tactical Radio System (JTRS) cost estimate was sponsored by the USACEAC, now ODASA-CE. The purpose of the study was to create a hardware step-down equation (from development to production), and CERs for non-recurring, software development, and support elements. These cost analyses utilized data from the Communications/Electronics (C/E) Database and were to complement the hardware CERs developed in the "Communications Cost Model II." The CERs in the "Communications Cost Model II" were previously discussed in Section 2.5, and served as the baseline tool used to estimate the JTRS system hardware. The authors of the study assert that the step-down equation is essential for transforming development manufacturing hardware estimates from the "Communications Cost Model II" to production hardware estimates.

2.6.1 DESCRIPTION OF DATASET

As mentioned, the two datasets used in the Communications WBS & CERs for the JTRS Estimate were derived from the Communications Cost Model II and the C4ISR Database. The Communications Cost Model II database housed military programs in the Demonstration and Validation (DEMVAL) and Engineering and Manufacturing Development (EMD) phases in addition to commercial hardware developments that were contractor funded. The C/E Database comprises 18 systems of U.S. Army and commercial communications and electronic programs in the DEMVAL, EMD, and Production acquisition phases. The non-recurring, software development, and support CERs were developed from nine of these 18 programs, listed below:

- Enhanced Position Location Reporting System (EPLRS)
- Joint Tactical Information Distribution System (JTIDS)
- Multifunctional Information Distribution System (MIDS)
- Single Channel Anti-jam Man-Portable communications terminal (SCAMP)
- Single Channel Ground Radar Set (SINCGARS)
- Secure Model Anti-jam Reliable Tactical Terminal (SMART-T)
- Joint Surveillance Target Attack Radar System (JSTARS)
- Battlefield Combat Identification System (BCIS)
- Near Term Digital Radio (NTDR)

Finally, cost and technical data for the electronic and electrical / mechanical / structural assemblies were collected from government project offices, USACEAC, and the Army Communications-Electronics Command (CECOM).

2.6.2 DESCRIPTION OF CERS

For the step-down CER analysis, data were available for the BCIS, JTIDS, NTDR, and SMART-T programs. The first step-down methodology involved determining the first theoretical unit (T_1) and the learning curve slope coefficient (b) by comparing program hardware costs by production lot. To maintain consistency with the Communications Cost Model II, all production rate analyses assumed Cumulative Average (CUMAV) Theory. The production T_1 was divided by the development T_1 for each program to determine Development-to-Production step-down factors for each program. These factors were then averaged for a single step-down factor, which is provided in the study. The second methodology developed a CER based on development hardware dollars of programs used in the production rate analysis. The CER and its input variables for this second methodology are as follows:

Prod T_1 = *f* (Step-down factor*Dev T_1)

where

- Step-down factor = a constant
- Dev T_1 = *f* (Dev Hdw $, Qty)

  where

  - Dev T_1 = the development T_1
  - Dev Hdw $ = the total recurring cost of the prototype units built
  - Qty = the quantity of prototype units built in development

The two methodologies yield different step-down factors, but the authors explain that a common step-down factor has been validated since the methodologies achieve a similar result.

The Communications Cost Model II developed CERs to estimate the manufacturing costs of electronic assemblies in electronic boxes as well as electrical / mechanical / structural assemblies within a communication or ground electronic system. The CERs estimate manufacturing costs based on the relevant physical characteristics (i.e., volume, circuit card area, type and count of components on the circuit cards) and performance parameters (i.e., frequency of operation and power output). CERs for electrical / mechanical / structural assemblies were based on physical characteristics of the assembly such as aperture and weight. The hardware elements for which CERs were developed in the Communications Cost Model II and used to estimate the hardware cost of JTRS, are displayed below.

- Dish Antennas
- Pedestal Assemblies
- Communication Radio/ Ground Electronics Box:
    - RF Power Amplifier CCAs
    - RF Receiver CCAs
    - Microwave Integrated Circuit (MIC) Assemblies
    - Synthesizers and IF Electronics CCAs
    - Signal Processor/COMSEC CCAs
    - Data Processor and Control Electronics CCAs
    - Digital I/O CCAs
    - Power Converter and Regulator Modules
    - Servo and Analog Electronics CCAs
- Interface Devices
- Power Distribution Units/ Power Control Units
- Generators
- Pallets

Further detail on the CERs may be found in the "Communications and Electronics Cost Model II" literature review in Section 2.5.

Data from the C/E Database allowed for the development of 1) production T_1, 2) non-recurring, 3) software development, 4) development support, and 5) production support CERs to accompany the hardware CERs from the Communications Cost Model II. Hardware recurring and non-recurring dollars was the principal cost driver used in creating the support

CERs, with a dummy variable used to distinguish whether a program was of the production or development phase.

Table 2-10 lists the CERs, by WBS element, and their corresponding inputs for the JTRS estimate. CER inputs that are marked with an asterisk in a given function are binary variables, for which there are definitions provided in Table 5.4

Table 2-10: JTRS Estimate CERs and Required Inputs

Code	CER Element Name	Required Inputs
1.1	Hardware	See Communications and Electronics Cost Model II Review, Section 2.5
1.1.1	Power Amplifier	Mfg $ = *f* (Power, Center Freq, Prod*, COTS*, Qty) where • Mfg $ = the manufacturing cost of the prototype units in development. • Power = the output of the power amplifier in watts. • Center Freq = the output center frequency of the RF power amplifier in MHz. • Qty = the quantity of prototype units built in development.
1.2	Non-Recurring	Dev NR $ = *f* (Dev Rec $, Qty) where • Dev NR $ = the development non-recurring cost. • Dev Rec $ = the manufacturing cost of the prototype units built. • Qty = the quantity of prototype units built in development.
1.3	Development Support	Dev Supt $ = *f* (Hdw Rec + NRE, 2ndary Dev*, Qty) where • Dev Supt $ = the total development support cost. • Hdw Rec + NRE = the total development recurring and non-recurring cost. • Qty = the quantity of the prototype units built in development.
1.3.1	Systems Engineering/ Program Management	SE/PM $ = *f* (Hdw Rec + NRE, Prod*) where • SE/PM $ = the total SE/PM cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.3.2	System Test & Evaluation	System T&E $ = *f* (Hdw Rec + NRE, Prod*) where • System T&E $ = the total system T&E cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.

1.3.3	Data	Data $ = *f* (Hdw Rec + NRE, Prod*) where • Data $ = the total data cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.3.4	Support Equipment	Supt Equip $ = *f* (Hdw Rec + NRE, Prod*) where • Supt Equip $ = the total support equipment cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.4	Procurement Support	Proc Supt $ = *f* (Hdw Rec + NRE) where • Proc Supt $ = the total procurement support cost. • Hdw Rec + NRE = the total procurement recurring and non-recurring cost.
1.4.1	Systems Engineering/ Program Management	SE/PM $ = *f* (Hdw Rec + NRE, Prod*) where • SE/PM $ = the total SE/PM cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.4.2	System Test & Evaluation	System T&E $ = *f* (Hdw Rec + NRE, Prod*) where • System T&E $ = the total system T&E cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.4.3	Support Equipment	Supt Equip $ = *f* (Hdw Rec + NRE, Prod*) where • Supt Equip $ = the total support equipment cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.4.4	Spares	Spares $ = *f* (Hdw Rec + NRE) where • Spares $ = the total spares cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.4.5	Data	Data $ = *f* (Hdw Rec + NRE, Prod*) where • Data $ = the total data cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.
1.4.6	Warranty	Warranty $ = *f* (Hdw Rec + NRE) where • Warranty $ = the total warranty cost. • Hdw Rec + NRE = the total recurring and non-recurring cost.

1.5	Production T_1	Prod T_1 = *f* (Dev Hdw, Qty) where • Prod T_1 = the production T_1 cost. • Dev Hdw $ = the total cost of prototypes built. • Qty = the quantity of prototype units built in Development.
1.6	Software Development	S/W Dev $ = *f* (Dev NR $) where • S/W Dev = the software development cost. • Dev NR $ = the development non-recurring cost minus any software development.

Table 2-11 is a binary variable key for the CER elements mentioned above. The first part of the definition indicates a binary value of (1), while the second part of the definition represents a binary value of (0).

Table 2-11 JTRS Estimate Binary Variable Key

Input	Definition
Prod	A production program OR a development program.
COTS	If a program employs commercial-off-the-shelf technology, OR not.
2ndary Dev	A program with more than one development (i.e. MIDS LVT & LVT 2 Developments), OR a program with only one development.

2.6.3 STRENGTHS AND WEAKNESSES

The study presents a comprehensive list of CERs developed for the JTRS estimate in terms of hardware, non-recurring elements, development support, procurement support, production T_1, and software development. The size of the dataset is sufficient so that the CERs are credible. The CERs are straight-forward and the methodology behind the CERs may be applicable to analogous systems. The main weakness is that the study, and possibly the dataset, is somewhat dated.

2.7 "PERFORMANCE ACTIVATED COTS ELECTRONICS RELATIONSHIPS (PACER) VERSION 4", PACER CORPORATION, 2003[4]

The Performance Activated COTS Electronics Relationships (PACER) Model is a series of cost estimating relationships enabling cost analysts to estimate commercial-off-the-shelf (COTS) electronics prices using key performance characteristics. The model estimates electronics hardware and integration at the board, box, and system level and produces forecast error bounds for each cost element. The tool provides CERs for many electronic components. These include various processor and memory boards; analog-to-digital (A/D) and digital-to-analog (D/A) converter boards; storage devices; input/output and receiver boards; backplanes, power supplies and enclosures; servers and routers; workstations; MIL-STD-1553 data busses; Inertial Measurement Units; Batteries; and box level integration. As of December 2003, the model contained 19 CERs. The performance characteristics used as independent variables are based on common industry standards and metrics of performance for electronics hardware. For example, CERs may include processor capability metrics, memory type and size, board size, sampling rates, year on market, number of channels, quantity, angular velocity, power, temperature range, radiation hardening, vibration, shock, and similar other variables. The CERs are developed using log-linear regression techniques. The datasets underpinning the equations vary in size but can include over a thousand distinct boards as in the case of the data/signal processor CER. The CERs have many variables and are available in an Excel Visual Basic graphic user interface to simplify their use. Applications include virtually all electronics systems using COTS electronics, including avionics, AIS/C3I systems, and space-based electronics. In addition, several CERs are provided for electronics with military or dual purpose applications, such as MIL-STD-1553 data bus boards, inertial measurement units (IMUs), and small batteries.

The written report underlying the model provides extensive technical details on the key characteristics of each type of electronics, the underlying cost drivers, and key considerations

[4] PACER Version 4 dated December 2003 is the last version of the model still extant in government model sponsor records. Additional information was taken from *2008 Institute for Defense Analysis (IDA) Cost Research Workshop: Contractor Data Reporting Systems, July 2008, Document #D-3571.)*

in accurately inputting the quantitative variables for the CERs. The model and associated documentation is unique in the depth of engineering knowledge going into specifying the model equations and the ability to communicate key aspects of that knowledge to the model user. Though the government does not have an up to date version of the model, the PACER Corporation has continued to maintain many of the cost estimating relationships with updated data and use them in cost-performance optimization studies in support of private sector corporations.

2.7.1 DESCRIPTION OF DATASET

Each of the Cost Estimating Relationships has an underlying data set of electronics boards or components collected by PACER Corporation through many years of talking to board manufacturers and reviewing product sheets. The data set consists of ***price***[5] and technical information to support the independent variables for each of the CERs.

Table 2.11 shows the number of data points associated with each of the CERs in PACER version 4.0 published in December 2003. Note that each data point reflects a unique board-rate-performance specification combination, and many individual boards are available in various quantities with quantity discounts, and may have different ways of expressing a key performance metric. For example, one board may have several entries reflecting quantities of 1, 2, 4, and 50 units, and also have different entries for performance for each quantity, such as millions of operations per second or millions of floating point operations per second. Even with this caveat, several of the CERs, such as data-signal processor boards, have thousands of boards in the data set reflecting a wide range of board manufacturers and configurations.

Table 2-12 PACER Data Points

CERs	# Data Points

[5] Cost (without fee) information at the board level is often not available via Department of Defense cost reporting. The PACER model collects data on prices and technical data for commercially available boards. The price includes any profit made by board manufacturer.

Data-Signal Processors Boards	32,639
Memory Boards	7,428
A/D & D/A Converter Boards	2,400
Receiver Boards	922
Waveform/Signal Generator Boards	302
Digital Parallel I/O Boards	392
Storage Devices	840
Power Supplies-Backplanes-Enclosures	4,691
Box Level Integration	197
AIS Systems-Servers-Workstations	9,094
Routers-Hubs-Switches	914
Mil-Std-1553 Data Bus Boards	976
Serial Input/Output Boards	806
Inertial Measurement Units	36
Batteries	28

The December 2003 model documentation does not include the raw data, though it provides the range for each of the independent variables within each CER. The government has seen the data set underlying Version 2.0 of the model (December 2001).

Given the rapid advance of commercial electronics technology since 2003, most of the CERs (and all the ones using digital electronics technology) within the reports available to the government are out of date, but the detail of the data set and CERs indicate what can be done through engineering knowledge and diligent data collection.

2.7.2 DESCRIPTION OF CERS

Each CER comes with an extensive technical description, key data ranges, summary statistics, and detailed descriptions of each of the input parameters. The input parameter descriptions come with helpful advice on how to quantify the inputs given various scenarios,

such as measuring the additional size in square centimeters when a board has a mezzanine board attached to it. Table 2.11 below lists the CERs. Some of the variables were summarized or omitted for brevity, but most drivers are presented.

Table 2-13 PACER V4.0 COTS Electronics CERs

CER Name	Required Inputs
Data-Signal Processor Boards	*f* (Throughput Metrics, FPGA Gates, Memory, Ruggedness, Size, Quantity, Year) where • Throughout Metrics = *f* (MIPS or MOPS or MFLOPS or Fast Fourier Transforms or SPEC92 or SPEC95 or SPEC2K) • FPGA = *f* (# Gates, # Chips) • Memory = *f* (DRAM, S/DIMM,SRAM, Socket Flash, Flash Disk) • Ruggedness = *f* (Vibration, Temperature Range, Radiation Hardening) • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid) • Quantity = # boards purchased per purchase • Year = Processor Chip Year for processor(s) associated with board Note appendix A provides many board/processor combinations with which to calibrate the model
Memory Boards	*f* (Memory, Network, Ruggedness, Size, Quantity) where • Memory = *f* (DRAM, S/DIMM, FLASH, SRAM, FIFO, Year) • Network = *f* (Node Speed, Redundant Data Transfer, # Nodes, Node Transfer Distance) • Ruggedness = *f* (Vibration, Shock, Temperature Range, MIL-STD-883, Conduction Cool, Ceramics, Total Dose (radiation), Single Event Upset) • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid) • Quantity = # boards purchased per purchase
Analog-to-Digital and Digital-to-Analog Boards	*f* (# A to D Converters, # of AD Bits, # of D to A Converters, # of DA Bits, Sampling Frequency, Current Loop Termination, Current/Volt Outputs, # Clocks,

	Memory, Ruggedness, # CPUs, size, and Quantity) where • Sampling Frequency = Kilo-samples/ Sec • Current Loop Termination = Whether has current loop termination, or not • Current/ Volt Output = Whether has both current and voltage outputs, or not • Memory = *f* (DRAM, S/DIMM, FLASH, SRAM, FIFO, Year) • Ruggedness = *f* (Vibration, Shock, Temperature Range, Conduction Cooling) • #CPUs = # of Microprocessor ICs • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid) • Quantity = # boards purchased per purchase
Receiver Boards	*f* (# Microprocessors, # of Transformers, # Digital Channels, # Analog Channels, Bandwidth, Outputs, # of A to D Converters, # of D to A Converters, Memory, Ruggedness, Size, Quantity, Year) where • Bandwidth = Maximum bandwidth in Hz • Outputs = # of output channels • Memory = *f* (SRAM, FIFO, Year) • Ruggedness = *f* (Vibration, Shock, Temperature Range) • #CPUs = # of Microprocessor ICs • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid) • Quantity = # boards purchased per purchase • Year = Year board produced.
Waveform/Signal Generator Board	*f* (Channels, Bits, Tuning, MS/Sec, Stability, Memory, Size, Quantity) where • Channels = # Output Channels • Bits = Resolution of Controlling Digital Code • Tuning = Resolution of Tuning Steps in Hz • MS/Sec = Millions of Mega-samples per second (speed at which output frequencies can be generated) • Stability = Pulses per minute (frequency reference) • Memory = *f* (SRAM) • Size = cm^2 for board (sizes for many different

	standard board form factors provided as an aid) • Quantity = # boards purchased per purchase
Digital Input/Output Boards	*f* (Digital I/O, Ruggedness, Bus, Options, Memory, Quantity) where • Digital I/O = *f* (Ports, DigInBits, DigOutBits, Size) • Ruggedness = *f* (Vibration, Shock, Temperature Range, Conduction -Cooled, Ceramic) • Bus = Bus type • Options = *f* (Optical isolation, Buffers, # Clocks, Program Control Interrupt Generation, Change of State monitoring, Latched Inputs, Latched outputs, Relay Output, Analog to Digital Converter, Onboard Processor, Control and Status Register) • Memory = *f* (Flash, FIFO, SRAM, Year) • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid) • Quantity = # boards purchased per purchase
Storage Devices	*f* (Drive, Physical, Interface Options, Ruggedness, Accessories) where • Drive = *f* (Megabtyes (Storage Size), # drives, RPM, # Storage Device Systems) • Physical = *f* (Solid State, Removable, PCMIA, form factor, control, RAID, Fiber channel interconnect, Megabytes, Year) • Interface Options = *f* (Wide SCSI , IDE, Narrow SCSI) • Ruggedness = *f* (Shock, Temperature Range, Hermetically Sealed) • Accessories = *f* (Chasses, Digital Audio Tape, Advanced Intelligent Tape, Floppy, CD, Magneto-Optical, Quantity, Year) The storage device CER has a binary variable that allows the user to estimate the cost of the accessories without storage media.
Power Supplies, Backplanes, and Enclosures	*f* (Power Supplies, Enclosures, # Fans, Ruggedness, Backplane) where • Power Supplies = *f* (Watts, Maximum Output Voltage, AC/DC capable input, Redundancy,

	ATX, Temperature, Quantity) • Enclosures = *f* (Volume cm^3, MIL-STD-38999 Connectors, Cooling Type, Water Tight, Altitude, Temperature, Quantity) • # Fans = # Cooling Fans • Ruggedness = *f* (Vibration, Shock) • Backplane = *f* (# Slots, size in cm^2, Double side Backplane, % ISA connectors, VME64 connectors, Cooling Type, Quantity)
Box/System Level Integration	*f* (Integration, Hardware, Options) where • Integration = *f* (Other System Costs, # Systems Procured, # Items in System, First Unit, COTS system) • Hardware = *f* (# Digital Boards, # Receiver Boards, # Analog Boards, # Boxes) • Options = *f* (Militarized System, Custom S/W required) Note the coefficients on this CER are different for the first unit than for subsequent units, to reflect the higher integration costs associated with the first unit.
AIS Systems-Servers-Workstations	*f* (Throughput Metrics, Server, Graphics, Operating System, Memory, SEWP, Storage, Power, Monitor) where • Throughout Metrics = *f* (SPEC95 or SPEC2K) • Server = *f* (Non-Solaris or Solaris, # CPUs, MB Cache, Max # Power Supplies, Base Memory, Available Date, Purchase Date, # Cabinets, CPU date) • Graphics = Graphics Quality • Operating System = *f* (Open VMS, Windows, LINUX, Tru64, Solaris) • Memory = *f* (MB, Max MB, Available Date, Purchase Date, Solaris) • SEWP = Scientific and Engineering Workstation II contract (SEWP different than GSA prices) • Storage = *f* (IDE or SCSI, GB, RPM, # Disk Drives, Purchase Date) • Power = *f* (Number of Power Supplies, Watts) • Monitor = *f* (Monitor Size, Purchase Date, LCD)
Routers-Hubs-Switches	*f* (Switching, Port Type, MAC, Router Memory, Chassis, Purchase Date)

	where • Switching = (Hubs/Layer 2 switching or Layer 2-4 switching or Router only) • Port Type = *f* (# WAN slots, # Token Ring Ports, f(# Modem Ports by Port Type)) • MAC = Medium Access Control (serves as indicator variable between hubs and switches) • Router Memory = DRAM Memory if router • Chassis = *f* (# Module Slots, Card Chassis (no stand-alone capability without cards, management function)) • Purchase Date = Date LAN Device will be purchased
Mil-Std-1553 Data Bus Boards	*f* (MIL-STD-1553, Timing & Memory, Ruggedness, Size, Quantity) where • MIL-STD-1553 = *f* (# Dual Redundant 1553 Channel per Board, 1553 Monolithic Chips,# Microprocessors, Single or Dual or Full 1553 Function board, # of remote Terminals Simulated by board) • Timing & Memory = *f* (IRIG (Inter-range Instrumentation Group) Generator or Decoder, SRAM) • Ruggedness = *f* (Vibration, Shock, Temperature Range, Conduction Cooling) • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid). PC-104 form factor has its own dummy variable to better fit the equation • Quantity = # boards purchased per purchase
Serial Input/Output Boards	*f* (Serial, Memory, Ruggedness, Size, Quantity, Year) where • Serial = *f* (Local Operating Network (LON) Port Interface type, kilo-bauds per second (kbps) modem speed, # Serial Channels, Bus Controller, # Ethernet Channels, # Microprocessors, 8 bit bus (binary), Modular boards (binary)) • Memory = *f* (MB Flash, MB SRAM, Year) • Size = cm^2 for board (sizes for many different standard board form factors provided as an aid). • Ruggedness = *f* (Vibration, Shock, Temperature Range, Conduction Cooling)

	• Quantity = the quantity of units manufactured in development or production. • Year = board purchase year
Inertial Measurement Unit	*f* (MEMS IMU or other IMU, Degrees per Hour, Mg, Navigation Processor, GPS sensor, Quantity) where • MEMS IMU is a binary variable to distinguish a MEMS IMU from other kinds of IMUs • Degrees per Hour = biased stability of the rate channels in degrees per hour • Mg = biased stability of the acceleration channels in mgs • Navigation Processor = a binary variable indicating built-in navigation processor • GPS sensor = a binary variable indicating built-in GPS sensor • Quantity = the quantity of units manufactured in development or production
Batteries	*f* (mAH, Volts, Li-Ion, Smart, Volume, Quantity) where • mAH = Milliamp hours (battery capacity) • Volts = # of volts battery is rated • Li-Ion = binary variable either Lithium Ion battery or a Nickel Metal Hydride/Lithium Anode Thermal battery • Smart = binary variable for built-in chip for optimizing battery charging process • Volume = volume of battery in cm^3 • Quantity = the quantity of units manufactured in development or production

Many of the CERs have a data set and a large number of independent variables. Due to their length and complexity, we present the CERs in simplified form here. Analysts using the CERs are strongly advised *thoroughly* read the documentation for the CER. Each of the variables has a specific quantitative metric or a binary choice associated with it. For example, vibration is usually measured by power spectral density, g^2/Hz and DRAM (Dynamic Random Access Memory) is measured in mega-bytes. The report not only defines the variables but provides helpful examples of their application.

Given the long length of several CERs and the on/off switch nature of several variables, PACER has provided a graphic user interface to go along with the model report to allow analysts to more easily use the CERs. PACER has also provided VBA Excel code for the equations for the earlier Version 2.0 of the model to NCCA.

2.7.3 STRENGTHS AND WEAKNESSES

Each of the cost estimating relationships in PACER comes with a well written summary of the technology and content in the electronic board, AIS system, or electronic device being estimated. The CERs are underpinned by a very large data price and technical characteristics data set ranging in size from thousands of circuit boards for the data/signal processor boards and memory boards to several dozen for more specific applications, such as batteries and IMUs.

The CERs are exceptionally well documented in the report, with a detailed definition of each of the independent variables and helpful guidance for developing model inputs in proper context. The CERs comes with the information needed to develop uncertainty bounds in support of risk analysis. The level of detail in the report and CERs reflects a deep knowledge of the technology, a drive for collecting data, and a talent for discerning the salient cost-performance drivers in the technology.

Because of the number of independent variables associated with the CERs make it difficult to casually apply in an Excel model, the PACER model comes with a GUI which allows a user to enter inputs and obtained calculated results in the form of a structured model output.

The model is price-based, not cost based, and so reflects the price charged to the customer, not the actual cost of manufacture. In practice, the government has not collected cost information at the board level except in selected ACAT I electronics programs which had a cost reporting requirement to the level of detail. The major defense contractors integrating

electronics are not likely to have this information unless they manufacture the electronics themselves. The prime contractors would obtain many of the components listed in this report from second tier vendors and may not have detailed cost information, but rather price information similar to that captured in this report.

The government currently does not currently sponsor this model and the last report the government has is from 2003. The report is therefore out of date given the subsequent evolution of electronics technology, particular for digital boards, memory, and AIS systems. The PACER Corporation has kept a number of the CERs up to date through 2014 in support of private sector clients.

The government had limited access to the data during model development and does not have the data set associated with version 4 of the model, though it has data from earlier models.

Overall, the report is an outstanding example of basing CERs on robust data sets and informed understanding of the engineering and design relationships underpinning the performance-price relationship.

2.8 "COMMERCIAL-OFF-THE-SHELF (COTS) ESTIMATING METRICS FOR INCREASED COST ACCURACY STUDY", TECOLOTE RESEARCH, INC., 2012

This 2012 SCEA/ISPA presentation identified a recurring problem in the estimating/pricing of Commercial-Off-The-Shelf (COTS) hardware and software where estimates based purely on on-line prices are consistently higher than the actual costs proposed and awarded under contracts. The presenters posited that on-line prices do not capture market forces that tend to result in lower COTS pricing in contracts. They present an approach to identify the impact of these market forces to provide increased accuracy of future COTS estimates.

2.8.1 DESCRIPTION OF DATASET

The available data they started with include:

- Negotiated COTS Hardware and Software unit prices and quantities where:
  - Procurement scenarios reflect purchase by a prime through a subcontractor in a competitive environment
  - Specific hardware and software products with known quantities were procured through Firm Fixed Price contracts
  - Cost growth above contract award value was only possible if contract modifications increased quantities procured
- Negotiated annual maintenance support prices by product
- On-line prices from various websites for cost drivers

A total of 24 Lists of Materials (LOMs) were sorted by part number and vendor from 20 different contracts. Five LOMs were on one contract, the remaining 19 LOMs were on the remaining 19 contracts. Eight websites were selected based on size and variety of vendor to research on-line pricing for single quantity of each item on the LOMs. The selected sites are provided below:

- PEPPM.org
- Insight.com
- CDW.com
- PCConnection.com
- PCMall.com
- SoftChoice.com
- TechDepot.com
- Zones.com

Interestingly, when comparing initial LOMS bid on the contract to on-line retail websites, the study authors observed that the retail websites were a better predictor of vendor prices.

2.8.2 DESCRIPTION OF CERS

The presenters developed metrics (ratios and simple formulas, as opposed to CERs) to assist in improving future COTS estimating accuracy:

Contract Procurement Price = *f* (list)

where:

- list = vendor list price

Contract Procurement Price = *f* (mean (μ) on-line vendor prices)
where:

- mean (μ) on-line vendor prices = average of multiple on-line vendor prices

Maintenance Support = *f* (initial HW$ + initial SW$)
where:

- HW$ = hardware initial price
- SW$ = software initial price

Maintenance Support = *f* (proposed price)
where:

- Proposed price = vendor quote

2.8.3 STRENGTHS AND WEAKNESSES

On-line prices can be more quickly obtained than vendor quotes, so the fact that the mean of on-line prices is a better predictor of initial procurement costs than the vendor quotes is fortuitous. Additionally, ACEIT's statistics tool, CO$TAT was used to calculate best fit distributions using Distribution Finder, resulting in relatively good statistics. While several common distributions were calculated, Beta distributions, based on the Standard Error of Estimate (SEE) to Fit mean, provided the best overall fit.

To effectively use these metrics, detailed Lists of Materials to the part number are necessary. This level of detail is likely not present at or prior to Milestone (MS) A unless detailed analogies to other COTS-based systems can be generated. Therefore, these metrics are more useful later in the development/implementation of COTS-based systems (MS B, MS C).

2.9 "DEVELOPMENT-ONLY ACQUISITION SUPPORT COST FACTORS AND ESTIMATING RELATIONSHIPS", TECOLOTE RESEARCH, INC., 2010

This study examines the relationship between acquisition support costs to Prime Mission Product (PMP) on C4I development-only programs managed by the Air Force's Electronic

Systems Center (ESC) at Hanscom AFB, MA. Acquisition support in developmental programs is relatively consistent. Historically, these relationships have been used to derive generally representative cost estimates for ESC-type systems when more specific methodologies were not available.

The relationship of support costs to PMP on ESC programs was first published as a study with associated guidance in 1985. The findings were known as Kanter's Factors, and they were based upon the simple average of Level 2 Acquisition Support Work Breakdown Structure (WBS) elements, including Systems Engineering, Program Management, System Test and Evaluation, Training, and Data, as a percentage of program PMP (Hardware, Software, Integration and Assembly). The factors have been consistently refreshed by incorporating more recent program data, first in 1990 and then in 1993, 1995, 1998, 2000, 2006, and finally 2010.

2.9.1 DESCRIPTION OF DATASET

A data call went out for program cost actuals to update data reported since 2006, leading to a total of 43 new or updated cost observations on 26 programs. The data was captured in the WBS displayed in Table 2-14.

Table 2-14: 2010 Study Update Work Breakdown Structure

SYSTEM
DEVELOPMENT
PMP
INTEGRATION, ASSEMBLY, TEST, & CHECKOUT
DEVELOPED ITEMS
HARDWARE (Dev)
SOFTWARE (Dev)
NON-DEVELOPED ITEMS
HARDWARE (NDI)
SOFTWARE (NDI)
SUBCONTRACTED ITEMS
HARDWARE (Sub)
SOFTWARE (Sub)
OTHER/ACQUISITION SUPPORT (Sub)
TRAINING

PLATFORM INTEGRATION
PECULIAR SUPPORT EQUIPMENT (PSE)
SYSTEM TEST & EVALUATION (ST&E)
SYS/PROG MGMT
SYSTEM ENGR (SE)
PROJECT MGMT (PM)
DATA
OPERATIONAL SITE ACTIVATION (OSA)
COMMON SUPPORT EQUIPMENT(CSE)
INDUSTRIAL FACILITIES (IF)
INITIAL SPARES & REPAIR PARTS
OTHER DEVELOPMENT

The complete ESC C4I database includes 144 total developmental cost observations on 64 programs.

ADVANCED COMMUNICATIONS SYSTEMS	JSTARS
Air Force Mission Support System (AFMSS)	JTRS GMR
Air Operations Center	JTRS HMS
AMC C2 INFORMATION PROCESSING SYSTEM	KG-247
AUTOMATED WEATHER DISTRIBUTION SYSTEM	KG-3X
Battle Control System	Land Warrior
Battlefield Airborne Communications Node	MAC COMMAND & CONTROL UPGRADES
Warfighter Information Network - Tactical	MICROWAVE LANDING SYSTEMS (MLS)
Cobra Dane	MIDS JTRS
Combat Key Generator	MILSTAR
COMMAND CENTER PROCESSING AND DISPLAY SYSTEM-REPLACEMENT	MILSTAR AF TERMINALS
Common Link Integration Processing	MINIMUM ESSENTIAL EMERGENCY COMMUNICATIONS NETWORK (MEECN)
DCGS	Minuteman MEECN Program
DIRECT	Mission Planning System
DISTANT EARLY WARNING RADAR STATIONS	Modified Mini Receive Terminal
DUAL FREQUENCY MEECN RECEIVER	MPS
E-3 AIRBORNE WARNING AND CONTROL SYSTEM	NATIONAL AIRSPACE SYSTEMS (NAS)
Force XXI Battle Command Brigade & Below	NATIONAL SECURITY AGENCY (NSA) PROGRAM
FOREIGN MILITARY SALES (FMS)	NATO Mid Term
GENERAL INTELLIGENCE SKILL TRAINING	NATO Mid -Term
Global Transportation Network	Navigation Warfare
Ground Multimode Terminal	Navy Multiband Terminal
HAVE QUICK IIA/SATURN-AN/URC-126(V) RADIO	NORAD CHEYENNE MOUNTAIN COMPLEX (NCMC) - SPACE DEFENSE SYSTEMS
IBS	NORAD CHEYENNE MOUNTAIN COMPLEX (NCMC)-TACTICAL WARNING/ATTA
IFF Mode 5 Crypto Modernization	RAPID EXECUTION AND COMBAT TARGETING (REACT)
Integrated DAMA-GATM	Remote Minehunting System
Integrated Maintenance Data System	Soldier Radio Waveform
Joint Interface Control Officer (JICO) Support System	SPACE SURVEILLANCE NETWORK (SPACETRACK)
Joint STARS	Theater Battle Mgt Core Syst
JOINT SURVEILLANCE AND TARGETING ATTACK RADAR SYSTEM	Time Critical Targeting Functionality Program
JOINT TACTICAL INFORMATION DISTRIBUTION SYSTEM (JTIDS) DEVEL	Upgraded Early Warning Radar
JOINT WORLDWIDE MILITARY COMMAND & CONTROL SYS (WWMCCS) INFO	

Table 2-15, which was extracted verbatim from the study, lists the programs included in the analysis. Analysis of the data sources and costs led to further refinement and the removal of various data anomalies and duplications. The final dataset used for the updated analysis

included 108 cost observations with reporting dates ranging from 1987 to 2009. These 108 cost observations were not identified in the study.

The ESC dataset was expanded in this update with applicable ACAT I electronic systems and comprised:

1) Contract Performance Reports (CPRs).
2) Cost/Schedule Status Reports (CSSRs), which have been eliminated from future reporting by EVM policy.

ADVANCED COMMUNICATIONS SYSTEMS	JSTARS
Air Force Mission Support System (AFMSS)	JTRS GMR
Air Operations Center	JTRS HMS
AMC C2 INFORMATION PROCESSING SYSTEM	KG-247
AUTOMATED WEATHER DISTRIBUTION SYSTEM	KG-3X
Battle Control System	Land Warrior
Battlefield Airborne Communications Node	MAC COMMAND & CONTROL UPGRADES
Warfighter Information Network - Tactical	MICROWAVE LANDING SYSTEMS (MLS)
Cobra Dane	MIDS JTRS
Combat Key Generator	MILSTAR
COMMAND CENTER PROCESSING AND DISPLAY SYSTEM-REPLACEMENT	MILSTAR AF TERMINALS
Common Link Integration Processing	MINIMUM ESSENTIAL EMERGENCY COMMUNICATIONS NETWORK (MEECN)
DCGS	Minuteman MEECN Program
DIRECT	Mission Planning System
DISTANT EARLY WARNING RADAR STATIONS	Modified Mini Receive Terminal
DUAL FREQUENCY MEECN RECEIVER	MPS
E-3 AIRBORNE WARNING AND CONTROL SYSTEM	NATIONAL AIRSPACE SYSTEMS (NAS)
Force XXI Battle Command Brigade & Below	NATIONAL SECURITY AGENCY (NSA) PROGRAM
FOREIGN MILITARY SALES (FMS)	NATO Mid Term
GENERAL INTELLIGENCE SKILL TRAINING	NATO Mid -Term
Global Transportation Network	Navigation Warfare
Ground Multimode Terminal	Navy Multiband Terminal
HAVE QUICK IIA/SATURN-AN/URC-126(V) RADIO	NORAD CHEYENNE MOUNTAIN COMPLEX (NCMC) - SPACE DEFENSE SYSTEMS
IBS	NORAD CHEYENNE MOUNTAIN COMPLEX (NCMC)-TACTICAL WARNING/ATTA
IFF Mode 5 Crypto Modernization	RAPID EXECUTION AND COMBAT TARGETING (REACT)
Integrated DAMA-GATM	Remote Minehunting System
Integrated Maintenance Data System	Soldier Radio Waveform
Joint Interface Control Officer (JICO) Support System	SPACE SURVEILLANCE NETWORK (SPACETRACK)
Joint STARS	Theater Battle Mgt Core Syst
JOINT SURVEILLANCE AND TARGETING ATTACK RADAR SYSTEM	Time Critical Targeting Functionality Program
JOINT TACTICAL INFORMATION DISTRIBUTION SYSTEM (JTIDS) DEVEL	Upgraded Early Warning Radar
JOINT WORLDWIDE MILITARY COMMAND & CONTROL SYS (WWMCCS) INFO	

Table 2-15: Programs Included in Analysis

2.9.2 DESCRIPTION OF CERS

Traditional univariate factors are derived by dividing the cost of the MIL-STD WBS acquisition support element by the cost of PMP for each program, and then taking the average of these ratios to arrive at the factor. Traditional univariate cost factors and linear

regressions are discouraged primarily because they do not represent the best possible general relationships in the dataset. Though many program classification schemes were reviewed for meaningful relationships, the best relationship for the largest subset of programs was discovered by identifying each program as belonging to one of the following groups: Information Technology Programs; Command, Control, and/or Communications Programs (C2/COM); Sensor Programs; and Avionics Programs.

Information Technology (IT) Programs: A development program consisting of software development and implementation of computer-based software applications, primarily to convert, store, protect, process, transmit, and securely retrieve information. Though many "IT" programs acquire significant (generally COTS) hardware, this is not well represented in the underlying dataset. Rather, "IT" here represents programs acquiring a software capability in which little to no specific additional hardware was required.

Total Support Cost for IT Programs	SUPPORT = *f* (DEV_SW) where • SUPPORT = STE + SEPM + TRAIN + DATA + PSE + OSA + CSE + IF + IS + OTHER • DEV_SW = Software development labor (design, code, and unit testing at the software increment level). Does not include license costs of non-developmental software.

Command, Control, and/or Communications Programs (C2/COM): A development program consisting of software **AND** concurrent hardware development for C2/COM systems. Examples of programs include: Ground Multimode Terminal (GMT), JTRS Ground Mobile Radio (GMR), and Minuteman MEECN Program (MMP).

Total Support Cost for C2/COM Programs	SUPPORT = *f* (DEV_PME) where • SUPPORT = STE + SEPM + TRAIN + DATA + PSE + OSA + CSE + IF + IS + OTHER • DEV_PME = All developmental software and hardware labor and equipment (does not include non-development hardware such as unmodified COTS, nor licensing of non-developmental software)

Sensor Programs: Programs primarily consisting of the development of actual sensor hardware, with or without software development. Examples of sensor programs would include radar programs or radar equipment (such as antennas, radomes, and amplifiers) and/or other sensor/tracking equipment.

Total Support Cost for Sensor Programs	SUPPORT = f (PMP) where • SUPPORT = STE + SEPM + TRAIN + DATA + PSE + OSA + CSE + IF + IS + OTHER • PMP = Prime Mission Product (Total HW and SW used to accomplish the primary mission of the defense materiel item including integration, assembly, test, and checkout)

Avionics Programs: Programs primarily consisting of the development of electronic systems for use on aircraft or satellites, comprising communications, navigation, display and management. Program data from airborne systems was mapped to this category, rather than the C2/COM or Sensor categories. Early in the analysis, avionics programs distinguished themselves due to extreme max and min values. Data on avionics programs, perhaps more than any other program type, appear to require close scrutiny in regard to program content and contracting strategy. Often, the airframe developer may be responsible for the avionics deck, which is a much different type of work than a subcontractor upgrading a particular avionics box. The researchers considered several subsets in describing avionics data, but

determined that there were too few observations for meaningful top-level parametric analysis.

Total Support Cost for Avionics Programs	SUPPORT = f (DEV_PME) where • SUPPORT = STE + SEPM + TRAIN + DATA + PSE + OSA + CSE + IF + IS + OTHER • DEV_PME = All developmental software and hardware labor and equipment (does not include non-development hardware such as unmodified COTS, or licensing of non-developmental software)

2.9.3 STRENGTHS AND WEAKNESSES

The researchers of this study strongly discourage the use of these "factors" as a primary methodology, or even a crosscheck without consideration of the overall variance in the data. Keep in mind that these factors do not estimate PMP at all, but on the contrary require a separate estimate of PMP as an *input* for estimating associated support costs. A strength of the study is the thoroughness of the data analysis. However, the standard deviations within the descriptive statistics are extremely high due the wide range of C4I program data collected. Applying these factors as an estimating methodology should be done within the identified groups above (IT, C3, Sensor, and Avionics) where the data tends to be more homogenous.

The provided CERs should not be used as a stand-alone cost estimating methodology. They are best applied as a top-level crosscheck, without concern to phasing the results. If used for estimating purposes (lacking program description detail), where estimate phasing is required, it would not be appropriate to assume the acquisition support remains a constant percentage of PMP throughout a given program schedule.

2.10 "FIRST ORDER ELECTRONICS COST AND SIZING TOOL (FORECAST)", TECOLOTE RESEARCH, INC., 1995

This report provides a summary of and suggested improvements to the existing Microwave and Digital Cost Analysis Model (MADCAM) by addressing known limitations to the model. Specifically the paper addresses three limitations: input details; Gallium Arsenide (GaAs) Microwave Integrated Circuit (MIC) versus Monolithic Microwave Integrated Circuit (MMIC) Technology; and Cost Risk. The recommended improvements are provided as a separate Excel based model available from the author.

The study begins with a little background by identifying the basic building block in modern military electronics hardware as the "electronic box." The "box" typically consists of a set of "boards" (electronic parts mounted on a printed circuit board) mounted in slots in a metal enclosure. The slots in the enclosure are connected electrically so that circuits are made between boards. The enclosure is also designed to provide cooling and mechanical protection for the boards. Electronic boxes are distinguished by the following three features: 1) function, which is almost always some form of digital or analog signal processing; 2) technology, which is generally the materials and manufacturing processes of their most important electronic parts; and 3) basing mode, which in this case is either space or earth. The size of an electronics box is largely determined by these features, as is its cost. For example, a multifunction box is larger and costs more than a single function box; an advanced technology box will be smaller and draw less power than its older counterpart, but will probably cost more; and a space-qualified box will cost far more than an earth-based box.

MADCAM is an open-data model for estimating the theoretical first unit (T_1) costs of electronic boxes.

The study discusses the utility and value of the MADCAM model as a cost estimating tool, but emphasizes that it does require the analyst to provide very detailed inputs, which may not be available depending upon the stage of the program. The FORECAST model attempts to mitigate the shortfalls in the MADCAM model by generating the details needed by

MADCAM from a very limited set of inputs. Specifically, FORECAST significantly simplifies inputs for estimating the cost of electronic boxes as follows:

- **Total Board Area:** A sizing model estimates total board area based only on box volume.
- **Parts Technology Allocations:** Analog parts technologies and their percent of total board area may be specified by first selecting box function and then specifying a qualitative level of box design complexity (i.e., high, medium, or low). The user may then accept, modify, add, or delete any of the analog specifications.
- **GaAs Technologies:** The user need only specify the GaAs frequency(s) and the first year of manufacture (1985 to 2000). A set of scaling rules adjusts the costs for frequency and MIC or MMIC manufacturing process.
- **Cost Risk:** Configuration uncertainties for total board area (a function of box volume and installed power uncertainties) and parts technologies percent of total board area are combined analytically with part technologies cost uncertainties to yield an estimate of the total cost risk distribution for an electronic box.

The study then makes recommendations for future improvements in both the MADCAM and FORECAST models. These recommendations include: 1) an expanded database, beyond space assets, as predominantly captured in MADCAM; 2) a more controlled data-gathering method for consistently measuring the percent of total board area dedicated to a particular parts technology; 3) an improved analog selection technique to efficiently handle an expanded database, such as a "classification tree"; and 4) a more refined set of sizing and scaling relations which reflect the system basing mode. The final section of the study report provides a tutorial on how FORECAST, an Excel-based model, works.

2.10.1 DESCRIPTION OF DATASET

The MADCAM database of predominantly space system boxes was used in developing the specific models in FORECAST: sizing, determining the total board area as well as the parts technology allocation to the total board area; scaling, for estimating Gallium Arsenide (GaAs) technology as a function of frequency and year of manufacture; and finally risk, as a function of configuration and cost uncertainty.

The database underlying MADCAM comprises 42 data points (35 with actual cost and seven vendor quotes), including 10 from Milstar I, five from the Solid State Module programs, 12 from

the Defense Satellite Communications System (DSCS) III, five from the Defense Support Program (DSP) 1, three from Milstar CORE terminals, and seven from Milstar II medium data rate (MDR) payload. This database covers a wide range of electronic boxes from the very small (2.5 pounds and 2 watts) to the very large (100 pounds and 500 watts), and it allows a wide range of digital and microwave part technologies to be included in the same box.

2.10.2 DESCRIPTION OF CERS

Total Board Area: This section defines the methodology, using the MADCAM database, to better define the total board area. Since the user may only have available the box outside volume and installed power, various functions of these two parameters were hypothesized and tested using statistical regression analysis techniques for their ability to predict total circuit board area. The best predictor of total circuit board area was a simple function of the box outside volume:

$$\text{Total Board Area} = f\,(\text{Box Outside Volume})$$

Parts Technology Allocation: This section notes that in the early stages of a program, parts technology allocations may not be known. It develops an approach to improve estimating the parts allocations by inferring analog parts technologies and their percent of total board area based only on box function and a rough determination of box complexity. The study then develops a classification tree using basing nodes (Space, Earth) as the starting point, and considering the function (Data Handling, LNA (Low Noise Amplifier), Down-converter, T/R Module) and Design Complexity based on VHSIC (Very High Speed Integrated Circuit)/ LSI (Large Scale Integration) and substrate material (GaAs, Si RF).

GaAs Technology Scaling: This section describes the approach to scaling GaAs technologies based on manufacturing year and frequency. The combined model based on both year of manufacture and frequency is:

$$\text{GaAs \$K per sq.in.} = f\,(\text{Frequency, Year})$$

Cost Risk: This section describes the methodology for quantifying configuration and cost uncertainties. The study indicates that there are two sources of uncertainty in estimating electronic boxes, using either the MADCAM or FORECAST models; the values of the underlying cost-driving variables, and the cost estimating relationships (CERs) or factors.

Configuration uncertainty captures the band around the possible changes in the basic cost driving variables. MADCAM and FORECAST identify four cost driving variables in their models:

- Total board area;
- Parts technology percent allocation;
- Enclosure outer volume; and
- Box installed power.

The study uses triangular risk distributions for all four variables – smallest possible value, largest possible value, and most likely – and provides default modal multipliers for the most likely values.

Cost uncertainty establishes a band around the cost estimate showing the probable error in the estimate. The study references a previous study (unidentified) that made an assessment of the uncertainty associated with parts technology cost multipliers. In both models, this uncertainty is measured in $K per square inch for each parts technology. A triangular distribution was assumed for the probability density function with the minimum and maximum modal cost multipliers for the following technologies:

- Gallium Arsenide (GaAs)
- Silicon Monolithic Integrated Circuits in RF Systems (Si RF)
- Surface Acoustic Wave (SAW) – Digital
- SAW – Crystal
- Very High Speed Integrated Circuit (VHSIC)
- Lesser Scale Digital

Box Cost Risk: In determining box cost risk, the study identifies two sources of uncertainty in estimating electronics boxes: the estimates of the board area required for the particular part technology, and the cost per unit area.

In order to use the FORECAST methodology, it is necessary to have estimates of the means and standard deviations for the three primary variables: total board area, parts technology percent allocation, and parts technology unit cost. The triangular statistical distribution was selected and fitted with the appropriate parameters to produce estimates of the unknown means and standard deviations for each of the three component pieces. These values were then used to calculate the coefficient of variation (CV) for all three variables.

While the costs, and risks, for the previous three variables are based on an engineering build-up approach, the risk associated with the module Assembly, Integration & Test (AI&T), box AI&T, and manufacturing support costs are based on factors of other costs, and normally computed as simple arithmetic averages. If the cost estimate is generated by multiplying an initial estimate by a factor, the study's approach consists of multiplying the standard deviation of the original estimate by the constant to obtain the new standard deviation.

These beta distribution parameters along with the minimum and maximum total sums are then used to describe the beta distribution for the electronic box cumulative cost distribution.

The study concludes with an assessment of average error in explaining the MADCAM database, indicating that the FORECAST should prove to be a useful cost estimating tool for any electronics boxes that fall within the design range of the data.

2.10.3 STRENGTHS AND WEAKNESSES

The model provides an enhancement to the existing MADCAM model with a means of improving the accuracy of electronics box cost estimates, especially those with limited technical definition. The model database relies heavily on space-based assets and should try to incorporate additional electronics box data from ground, aviation, and ship systems.

2.11 "A COST, TECHNICAL, AND INDUSTRIAL-BASE REVIEW OF SELECT AIRBORNE RADARS", RAND NATIONAL DEFENSE RESEARCH INSTITUTE, 2008

The RAND Radar 2008 study provides an overview of the technical and industrial base underpinnings of most modern U.S. military airborne radars and provides extensive cost information on each of these radars. This study remains one of the best sources of information for government cost analysts developing estimates for modern radar programs.

The study report is divided into 4 sections, plus 8 appendices. The first section provides an overview of the technical workings and components of radars and a history of radar development from the 1940s to the present. This section provides context to a cost analyst for understanding the underlying technologies for the various radar systems described in the study. This includes the history from the original magnetron-based radars to the current Transmit/Receive (T/R) Active Electronically Scanned Array radars.

The second section provides the recent history of the key radar contractor and subcontractor industrial base. The consolidation of the radar prime contractors since the 1980s is discussed, as are the key MMIC suppliers.

The third section provides a comparison of selected modern pulse Doppler and electronically scanned arrayed airborne radars necessary for analogy-based estimation. This section includes comparisons of development costs, production unit costs, weights, module counts, and development headcount profiles at the radar level. In some cases, the comparisons extend into the subcomponent level, showing the development and recurring production cost for each component. The software counts are shown by radar. Finally, the systems engineering and program management costs are compared.

The fourth section reviews the challenges facing analysts developing radar cost estimates given the small number of data points that reflect current technology and recommends an

analogy-based approach. The authors note that they have arranged the report to be of maximum utility to analysts developing analogy-based estimates.

Appendices A-H provides a technical and cost overview of 8 different radar families, including 3 pulse Doppler radars and 5 electronically scanned array radars. Note several radar families have multiple radars, with later versions being upgrades of earlier versions, all of which are described in that appendix.

2.11.1 DESCRIPTION OF DATASET

Each program included in the dataset is listed below, and further summarized in the study.

- AN/APG-63 (F-15)
- AN/APG-63V1 (F-15)
- AN/APG-63V2 (F-15)
- AN/APG-65 (F/A-18 A/B)
- AN/APG-66 (F-16 A/B)
- AN/APG-68 (F-16 C/D)
- AN/APG-70 (F-15E)
- AN/APG-73 (F/A-18 C/D)
- AN/APG-73 RUG I
- AN/APG-73 RUG II
- AN/APG-77 (F-22)
- AN/APG-77V1 (F-22)
- AN/APG-79 (F/A-18 E/F)
- AN/APG-81 (F-35)
- AN/APQ-181 (B-2)
- AN/APQ-181 RMP (B-2)
- MP-RTIP (Global Hawk)

Note that the AN/APG-81, AN/APQ-181 RMP, and MP-RTIP radars were in development at the time the study was done and the data for these radars represent engineering designs and estimated costs.

Data tables and charts provide comparisons among radars within the main body of the study. The comparisons come with commentary on the differences among radars.

- Development costs
- Development cost-weight plots for AESA radars
- Major component costs and weights for APG-77 and APG-79
- Breakout of development costs by major cost elements
- Development Schedules
- Peak Development cost vs % of schedule complete
- Peak Development head count
- Production 100th Unit Cost by Weight
- Production Learning Curves
- Breakout of Prime Mission Equipment costs for mechanically steered arrays
- Breakout of Prime Mission Equipment costs for active electronic arrays
- Step-down from EDM to Production costs
- Development and Production Cost Data by Prime Mission Equipment sub element
    - Antenna/Arrays
    - Transmitter
    - T/R Module (including cost per channel)
    - Receiver/Exciter
    - Power Supply
    - Processor
- Software cost and line of code counts
- Systems Engineering and Program Management costs and factors
- Test and Evaluation costs and factors

The radars are presented in greater detail within the appendices following the main body of the report. The appendices provide information from the main body of the report in greater detail, as well as program histories and unclassified technical characteristics of the radars. Production quantities and production unit costs are shown as well as development expenditure profiles at lower WBS levels.

2.11.2 DESCRIPTION OF CERS

The study notes that were the dataset properly stratified between mechanically and electronically steered array radars, the resulting two data sets would be too small to reliably develop cost and schedule estimating relationships through parametric means. Instead, the authors recommend the use of analogies and factored relationships using the data and comparisons provided within the study. Sufficient programmatic and technical background

is provided to identify the most appropriate analogies at the total and most component levels. The full range of data can be used as crosschecks.

2.11.3 STRENGTHS AND WEAKNESSES

RAND 2008 is well documented and provides the cost analyst a plethora of relevant information on radar development history, industrial base, costs, and schedule. The information provided empowers the analyst to identify appropriate estimating analogies for develop and production costs at the total and subcomponent level, and provide range-based sanity checks.

The study does not address operating and support costs, and because it contains highly proprietary information, distribution is strictly limited to government employees known to the holder of the study.

2.12 "GROUND RADAR COST AND SCHEDULE ESTIMATING MODEL FY09", TECHNOMICS, INC., 2009

This study includes the development of cost and schedule models that estimate complete radar program costs (development and production) and an updated ground-based radar database. Types of ground-based radar arrays included in this study are the following: frequency and gimbal scanned planar arrays; active end-fed arrays; and active phased arrays.

CERs were created for child-level and summary-level WBS elements to support cost estimating in early development (pre Milestone A) or later in development and production (post Milestone A), depending on analyst inputs as described in Section 2.12.2. This approach provides the analyst the flexibility to have more detailed cost outputs once requirements and technical designs are firmly established.

The schedule estimating model incorporates relationships based on the characteristics of the program with outputs including the estimated duration of the program, monthly expenditures, and major milestones.

In addition to the cost and schedule models that were developed, the accompanying updated ground-based radar database provides the cost, technical, schedule, and programmatic dataset supporting the cost and schedule relationships in an Excel workbook.

2.12.1 DESCRIPTION OF DATASET

The dataset behind the cost and schedule models in this study is found in the Ground-Based Radar Database. This database is an Excel workbook with hyperlinks to raw cost data, normalized cost data, technical parameter data, schedule data, and program description and history information. This dataset comprises nine radar development programs, five radar production programs, and five separate transmit/receive (T/R) module programs as shown in Table 2-16.

Table 2-165: Ground-Based Radar Database

Development	THAAD DEMVAL THAAD UOES THAAD SDD Ground Based Radar Prototype (GBR-P) Sea-Based Test X-Band Cobra Judy Replacement (CJR) S-Band Cobra Judy Replacement (CJR) X-Band TPQ-47 Development TPS-59 Development
Production	Forward Based X-Band (FBX-T) (Units 1-4) Forward Based X-Band (FBX-T) (Unit 5) TPS-59 Production TPS-75 Production TPS-78 Production
T/R Modules	F-18 AESA T/R Module (Dev & Prod) MIRFS (JSF) T/R Module GPM-1 T/R Module (Prod) GPM-2 T/R Module (Dev & Prod) Northrop MP-RTIP T/R Module (Dev)

Raw cost data sources include Contract Performance Reports (CPRs), Cost and Software Data Reports (CSDRs), and accounting records. The raw cost data format is included in the database, along with a record that normalizes and maps the raw cost data to a standard radar cost model WBS. Overall, there are 140 cost records included in the database. Program description and historical data vary by program, with some example sources including the commercial Defense and Aerospace Competitive Intelligence Service (DACIS) website or the program's Cost Analysis Requirements Description (CARD).

2.12.2 DESCRIPTION OF CERS

As mentioned previously, the CERs developed in this study estimate development and production costs, which include recurring hardware, nonrecurring engineering, and development and production support costs. See
Table 2-17 for the WBS included in the study and whether there is an associated CER. Additionally,
Table 2-17 shows the required inputs for the CER. Binary variables (also known as indicator or dummy variables) are indicated by an asterisk in the function. Table 2-18 provides the binary variable definitions (e.g., 1 for ship based radars, and 0 for fixed site or ground mobile radars). Some programs in the dataset had lower NRE costs to develop the hardware since the program was an evolution of a prior legacy system. To account for this, the authors examined historical data, quantified the effects, and applied fixed coefficients in the CER without estimating it in the curve fit (i.e., a priori knowledge). This allows the CERs that estimate a new program to more accurately estimate NRE costs and production learning curves based on user inputs. Also, a priori knowledge was used for step-down coefficients.

With these CERs, it is possible to estimate the cost of the Technology Demonstration (TD), Engineering and Manufacturing Development (EMD), and Production phases for a program. All CERs in the study were developed in FY2008 dollars and include cost of money (COM) and general and administrative costs (G&A). However, costs do not include fee. For the complete CERs and associated statistics, refer to the study itself.

Table 2-17: Ground-based Radar WBS & CER

Code	WBS Element Name	Required Inputs
1.1	Recurring Hardware	*f* (X.A.P.O, Apr, Freq, Ave Prod*, Qty, First Lot Prod*, Ship*, Phased Array*, End-Fed Array*, Follow-on Dev*) where • X.A.P.O = the total average output power of the transmitter or the total average output power of the T/R module multiplied by the number of T/R modules in the antenna, in kilowatts (kW). • Apr = the aperture of the radar antenna in square feet (sq ft). • Freq = the radar average operating frequency in gigahertz (GHz). • Qty = the quantity of units manufactured in development or production.
1.1.1	Antennas	*f* (# Elements, Freq, Qty, Follow-on or Prod*, Phased Array*, Thinned Array*) where • # Elements = the number of radiating elements in the antenna. • Freq = the radar average operating frequency in gigahertz. • Qty = the quantity of units manufactured in development or production.
1.1.1.1	Antenna Arrays	*f* (# Elements, Qty, Follow-on Dev*, Ship*, Ave Prod*) where • # Elements = the number of radiating elements in the antenna. • Qty = the quantity of units manufactured in development or production.
1.1.1.1.1	T/R Modules	*f* (T.M.P.P.O., Freq, Yr Tech Intro, Qty_{Cum}, Qty_{Prior}) where • T.M.P.P.O = the transmit/receive module peak power output, in watts. • Freq = the radar (or T/T module) average operating frequency in gigahertz. • Yr Tech Intro = the year the T/R module technology was introduced (i.e., the first year the module was built in quantities greater than 10). • Qty_{Cum} = the quantity of units of this design manufactured prior to this lot plus the units manufactured in this lot. • Qty_{Prior} = the quantity of units of this design

		manufactured prior to this lot.
1.1.1.1.2	Power Supply	*f* (Ave Pwr Out, # Supplies/Radar, Follow-on Dev*, Qty, First Lot Prod*) where • Ave Pwr Out = the average power output by the supply in watts. • # Supplies/Radar = the number of supplies in the radar design. • Qty = the quantity of units manufactured in development or production.
1.1.1.1.3	Beam Steering Unit	*f* (# Elements, Follow-on Dev*, Qty, First Lot Prod*) where • # Elements = the number of radiating elements in the antenna. • Qty = the quantity of units manufactured in development or production.
1.1.1.1.4	Other Array	CER not developed
1.1.1.2	Pedestal/Gimbal	*f* (Bearing Dia, Wt Ped/Gimbal, # Movable Axes, Qty, Ave Prod*, Fixed Site*, Follow-on Dev*) where • Bearing Dia = the bearing diameter of the platform/pedestal in feet. • Wt Ped/Gimbal = the total weight of the pedestal/gimbal assembly (i.e., the weight of the antenna, gimbal and pedestal assembly) in thousands of pounds (Klbs). • # Movable Axes = the number of axes that move in the design (1 for rotating pedestals and 2 for azimuth/elevation pedestals). • Qty = the quantity of units manufactured in development or production.
1.1.2	Cooling Unit/Power Distribution Unit	*f* (X.A.P.O., Follow-on Dev*, Qty, First Lot Prod*, Ave Prod*, PDU Only*, Cooling Only*) where • X.A.P.O. = the total average output power of the transmitter or total average output power of the T/R module multiplied by the number of T/R modules in the antenna, in kilowatts (kW). • Qty = the quantity of units manufactured in development or production.
1.1.3	Receiver/Exciter (REX)	*f* (Weight, Follow-on Prod*, Ave Prod*, Qty) where • Weight = weight of the assembly in pounds (lbs). • Qty = the quantity of units manufactured in development or production.
1.1.4	Transmitter (On-Array or Off-Array)	*f* (X.A.P.O., Freq, Follow-on or Prod*, Qty, Ave Prod*)

		where • X.A.P.O. = the total average output power of the transmitter or total average output power of the T/R module multiplied by the number of T/R modules in the transmitter design, in kilowatts. • Freq = the radar average operating frequency in gigahertz (GHz). • Qty = the quantity of units manufactured in development or production.
1.1.5	Back End Group	Summary-level CER not developed
1.1.5.1	Signal/Data Processors	*f* (Weight, Follow-on or Prod*, Qty, Ave Prod*) where • Weight = the weight of assembly in pounds (lbs). • Qty = the quantity of units manufactured in development or production.
1.1.5.2	Controls & Displays	*f* (# Controls/Displays, COTS*, Incl Other Equip*, First Lot Prod*, Qty) where • # Controls/Displays = the number of controls and displays estimated. • Qty = the quantity of units manufactured in development or production.
1.1.6	Integration & Assembly	*f* (Hdw Rec Subtotal, Follow-on Dev*, Ave Prod*) where • Hdw Rec Subtotal = the total hardware cost estimated for the radar assemblies.
1.2	Non-recurring Engineering	*f* (Total Hdw Rec $, Follow-on Dev*, First Prod Lot*) where • Total Hdw Rec $ = the total hardware cost estimated for the radar assemblies plus recurring integration and assembly.
1.2.1	Radar HW NRE	*f* (Total Hdw Rec $, Follow-on Dev*, First Prod Lot*) where • Total Hdw Rec $ = the total hardware cost estimated for the radar assemblies plus recurring integration and assembly.
1.2.2	Software Development	*f* (Total Hdw Rec $, Follow-on Dev*, First Prod Lot*, D&V*) where • Total Hdw Rec $ = the total hardware cost estimated for the radar assemblies plus recurring integration and assembly.
1.3	Development and Production Support	*f* (Total PMP $, Follow-on Dev*, System of System*) where • Total PMP $ = the total non-recurring and recurring

		hardware cost of the radar development.
1.3.1	System Engineering/Program Management	*f* (Total PMP $, D&V*, System of System*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.1.1	Systems Engineering	*f* (Total PMP $, Follow-on Dev*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.1.2	Program Management	*f* (Total PMP $, D&V*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.2	System Test and Evaluation	*f* (Total PMP $, # Elements, Follow-on Dev*, Ship*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development. • # Elements is the number of radiating elements in the antenna.
1.3.3	Training	*f* (Total PMP $, First Lot & Ave Prod*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.4	Data	*f* (Total PMP $, D&V*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.5	Peculiar Support Equipment	*f* (Total PMP $, Ship*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.6	Operational/Site Activation	*f* (Total PMP $, Fixed Site*) where • Total PMP $ = the total non-recurring and recurring hardware cost of the radar development.
1.3.7	Initial Spares and Repair Parts	

Table 2-18 is a binary variable key for the CER elements mentioned above. The first part of the definition indicates a binary value of (1), while the second part of the definition represents a binary value of (0).

Table 2-18: Ground-based Radar Binary Variable Key

Input	Definition
Ave Prod	Estimating an average production unit (i.e., a unit after the ninth

	production unit), OR estimating a development unit or early-on production unit (i.e., the first 9 production units).
Cooling Only	Estimates of only the cooling unit, OR estimates of both the PDU and the cooling unit.
COTS	Commercial-off-the-shelf equipment, OR unique hardware (i.e., developed specifically for the program).
D&V	DEMVAL (or TD) program, OR EMD (or SDD) or production program.
End-Fed Array	Radars employing active end-fed array antennas, OR radars employing active phased array antennas or passive planar array antennas.
First Lot & Ave Prod	Estimating production units, OR estimating a development unit.
First Lot Prod	Estimating the first lot of production, OR estimating development units or an average production unit (i.e., after the ninth production unit).
Fixed Site	Fixed site radars, OR ship and ground-mobile radars.
Follow-on Dev	Follow-on developments, a radar development that utilizes many of the same components and assemblies developed in a prior program (i.e., where a significant portion of the radar design is from a prior program or hardware developed in a prior program is reused in new program), OR new development program or a production program.
Follow-on or Prod	Follow-on developments, a radar development that utilizes many of the same components and assemblies developed in a prior program (i.e., where a significant portion of the radar design is from a prior program or hardware developed in a prior program is reused in new program) or for estimating the first lot of production, OR a new development program.
Incl Other Equip	Also estimating other peripheral equipment sometimes bought with the controls and displays (i.e., communications, routers, PDUs, switched, etc.), OR estimating only the controls and displays.
PDU Only	Estimates of only the PDU, OR estimates of both the PDU and the cooling unit.
Pedestal	Radar employing a two-axis pedestal/gimbal assembly, OR radars without a two-axis pedestal/gimbal assembly.
Phased Array	Radars employing active phased array antennas, OR radars employing active end-fed array antennas or passive planar array antennas.
Prod	Estimating a production program, OR estimating a development program.
Ship	Ship-based radars, OR fixed-site or ground mobile radars.
System of Systems	Radar developed as part of a system of system (i.e., developed as a system integrated with an interceptor, launcher and BMC4 component), OR radar developed independently from an interceptor, launcher and BMC4 component.
Thinned Array	Thinned array antenna (i.e., not all the antenna elements are active or populated), OR fully populated antenna array (i.e., all the antenna elements are active or populated).

In addition to the cost estimating relationships developed in the study, schedule estimating relationships (SERs) are included. The first SER estimates the schedule length of development or production in months. The second equation estimates the average monthly expenditure of a radar development or early-on production lot. The third and final equation estimates the time in the schedule when major milestones of the radar development program will occur. Factors are applied to total schedule length to calculate the month when the milestone is estimated to occur. Table 2.16 below contains required inputs of the SERs. Binary variables are indicated by an asterisk in the function, and the binary variable definitions are provided above in Table 2-18.

Table 2-19: Schedule Estimating Relationships

Schedule Estimating Relationship	Required Inputs
Radar Schedule Length	*f* (Ave Pwr Out, D&V*, Follow-on Dev*, Prod*, Ship*, Phased Array*, Qty) where • Ave Pwr Out = the total average output power of the transmitter or total average output power of the T/R module multiplied by the number of T/R modules in the antenna, in kilowatts (kW). • Qty = the quantity of units manufactured in development or production.
Radar Expenditures	*f* (Apr, Center Freq, D&V*, Follow-on Dev*, Prod*, Ship*, Pedestal*, Phased Array*, Qty) where • Apr = the aperture of the radar antenna in square feet (sq ft). • Center Freq = the radar average operating frequency in gigahertz (GHz). • Qty = the quantity of units manufactured in development or production.
Radar Schedule Milestones	Schedule length or duration in months, estimated with the Radar Schedule Length SER

2.12.3 STRENGTHS AND WEAKNESSES

This study presents CERs for every WBS element for ground-based radar, resulting in great flexibility for the cost analyst. The dataset is large enough for the CERs to be valuable, and the ability to tie in schedule estimating is desirable. Additionally, the accompanying Excel

database with the entire cost, technical, program, and schedule data for an analyst to use individually is extremely beneficial. Fixed coefficients were used in the creation of the Recurring Hardware and child-level WBS elements. Use of fixed coefficients helped the authors preserve the degrees of freedom of the curve fit; however, it also introduces the potential for bias in the CERs. Overall, the accompanying database, CERs for the entire ground-radar WBS, and scheduling estimating methods all come together to make a valuable ground-radar cost and scheduling model.

2.13 "GROUND RADAR COST AND SCHEDULE ESTIMATING MODEL FY12/13 UPDATE", TECHNOMICS, INC., 2013

The original "Ground Radar Cost and Schedule Estimating Model" study, reviewed above in Section 2.11, was completed in September 2009. The following review will focus on the updates performed in FY12/13.

Sponsored by the Air Force Cost Analysis Agency (AFCAA), the FY12/13 update added three large fixed-site radar programs in the dataset of the estimating model. As a result, a total of five CERs were updated (top-level), and all schedule estimating relationships were updated. Additionally, a few sections of the study were modified to include more detailed program and technical variable definitions, modeling assumptions (such as more information on using a priori knowledge to fix coefficients in a regression analysis), and tips for using the model.

2.13.1 DESCRIPTION OF DATASET

The dataset behind the cost and schedule models in this study is found in the Ground-Based Radar Database. This database is an Excel workbook with hyperlinks to raw cost data, normalized cost data, technical parameter data, schedule data, and program description and history information. The FY12/13 updated study includes Development data for three additional large fixed-site radar programs, in italics in Table 2.19 below.

Table 2-20: Ground-Based Radar Database Programs

Development	THAAD D&V THAAD UOES THAAD SDD Ground Based Radar Prototype (GBR-P) Sea-Based Test X-Band Cobra Judy Replacement (CJR) S-Band Cobra Judy Replacement (CJR) X-Band TPQ-47 Development TPS-59 Development *PAVE PAWS Sites 1 & 2* *PAVE PAWS Sites 3 & 4* *Cobra Dane*
Production	Forward Based X-Band (FBX-T) (Units 1-4) Forward Based X-Band (FBX-T) (Unit 5) TPS-59 Production TPS-75 Production TPS-78 Production
T/R Modules	F-18 AESA T/R Module (Dev & Prod) Northrop MIRFS (JSF) T/R Module GPM-1 T/R Module (Prod) GPM-2 T/R Module (Dev & Prod) Northrop MP-RTIP T/R Module (Dev)

2.13.2 DESCRIPTION OF CERS

2.13.3

Table 2.2020 shows the CERs that were updated in the FY12/13 version of this study. Two CERs were included for the Radar Hardware Nonrecurring Engineering WBS Element, for a total of five new CERs across the four WBS elements. The CER from the original study was updated, and a second CER was developed that does not include total hardware cost as an input variable.

Table 2.20: Ground-based Radar Updated CERs

Code	WBS Element Name	Updated
1.1.1	Antennas	X
1.2	Non-recurring	X
1.2.1	Radar HW NRE	X

	Engineering	
1.2.2	Software Development	X

Below, Table 2.19 lists the inputs for each CER and highlights, in bold, any additional inputs required for the CERs compared to the 2009 study. Binary variables are noted with an asterisk, and the definition for these variables can be found in Table 2-22.

Table 2.22-21: Ground-based Radar WBS Required Inputs for FY12/13 Update

Code	WBS Element Name	Required Inputs
1.1.1	Antennas	*f* (# Elements, Freq, Qty, Follow-on Dev or First Lot Prod*, **Fixed Site***, Phased Array*, Thinned Array*) where • # Elements = radiating elements in the antenna. • Freq = radar average operating frequency in gigahertz (GHz). • Qty = number of units manufactured in development or production.
1.2	Non-recurring Engineering	*f* (Tot HW Rec, Follow-on Dev*, First Lot Prod*, **Fixed Site*)** where • Tot HW Rec = hardware cost estimated for radar assemblies plus recurring integration and assembly.
1.2.1	Radar HW NRE Engineering	***CER 1, from 2009 study:*** *f* (Tot HW Rec, **# Elements**, Follow-on Dev*, First Lot Prod*, **Fixed Site*)** where • Tot HW Rec = hardware cost estimated for the radar assemblies plus recurring integration and assembly. • **# Elements = Number of radiating elements in the antenna.** ***CER 2, added in FY12/13 update:*** *f* (# Elements, Follow-on Dev*, First Lot Prod*, Fixed Site*) where • # Elements = number of radiating elements in the antenna.
1.2.2	Software Development	*f* (Tot HW Rec, Follow-on Dev*, First Lot Prod*, **Fixed Site*,** D&V*) where • Tot HW Rec = total hardware cost estimated for the radar assemblies plus hardware (recurring) integration and assembly.

Table 2-22 is a binary variable key for the CER elements mentioned above. The first part of the definition indicates a binary value of (1), while the second part of the definition represents a binary value of (0).

Table 2-22: Ground-based Radar Binary Variable Key for FY12/FY13 Update

Input	Definition
Active	Radars employing active phased arrays or end-fed array antennas, OR radars employing passive planar array antennas.
Active Phased Array	Active phased array antennas, OR active end-fed array antennas or passive planar array antennas.
Ave Prod	Average production unit (i.e. a unit after the ninth production unit), OR a development unit or early-on production unit (i.e. the first 9 production units).
D&V	DEVMAL (or TD) program, OR EMD (or SDD) or production program.
Follow-on Dev	For follow-on developments, a radar development that utilizes many of the same components and assemblies developed in a prior program, OR for a new development program or a production program.
First Lot Prod	Estimating first lot of production, OR development units.
Follow-on Dev or First Lot Prod	For follow-on developments, a radar development that utilizes many of the same components and assemblies developed in a prior program or for estimating the first lot of production, OR a new development program.
Fixed Site	Fixed site radars, OR ship and ground-mobile radars.
Phased Array	Radars employing active phased array antennas, OR for radars employing active end-fed array antennas or passive planar array antennas.
Prod	Production program, OR development program.
Thinned Array	Thinned array antenna (i.e., not all the antenna elements are active or populated), OR for a fully populated antenna array (i.e., all the antenna elements are active or populated).
Ship	Ship based radar, OR for fixed site or ground mobile radar

In addition to the updated CERs, all schedule estimating relationships (SERs) were updated. In Table 2.23, the updated inputs for the SERs are highlighted in bold, and binary variables are noted with an asterisk and defined in Table 2-22. For more description of SERs, see Section 2.11.

Table 2-23: Schedule Estimating Relationships

Schedule Estimating Relationship	Required Inputs
Radar Schedule Length	*f* (X.A.P.O., Freq, D&V*, Qty, Ship*, Fixed Site*, Active*, Follow-on Dev*, Prod*) where • X.A.P.O. = total average RF output power of the transmitter or the average RF output power of the T/R module multiplied by the number of T/R modules in the antenna, in kilowatts (kW). • Freq = the radar average operating frequency in gigahertz (GHz). • Qty = number of units manufactured in development or production.
Radar Expenditures	*f* (Apr, Freq, Qty, Ave Prod*, Qty, Active Phased Array*, Follow-on Dev*) where • Apr = aperture of the radar antenna in square feet (sq ft). • Freq = radar average operating frequency in gigahertz (GHz). • Qty = number of units manufactured in development or production. • Binary Variables: D&V, Ship, Pedestal Note: 3 inputs eliminated from SER found in 2009 study.
Radar Schedule Milestones	*f* (Schedule) where • Schedule = length or duration in months, estimated with the Radar Schedule Length SER. Note: All percentages updated for schedule milestones.

2.13.4 STRENGTHS AND WEAKNESSES

This update to the study includes additional programs in the dataset, which makes the CERs and SERs more flexible, stronger, and valuable. As with the original study, the accompanying Excel database, CERs for the entire ground-radar WBS, and scheduling estimating methods all come together to make a valuable ground-radar cost and scheduling model.

2.14 "DEVELOPMENT SUPPORT CERS FOR RADAR PROGRAMS", TECHNOMICS, INC., 1998

This study focuses on developing Cost Estimating Relationships (CERs) for development support WBS elements that are not a function of Prime Mission Equipment (PME) costs. Typically, development support costs are estimated as a percentage of PME costs, since it is widely assumed that support costs and PME costs are positively correlated. Naval Surface Warfare Center Dahlgren Division (NSWCDD) requested Technomics, Inc., to look into this assumption and develop CERs for development support costs that are not a function of PME costs. In the study itself, two CERs have been developed for most support item elements where one CER is a function of PME costs and the second is a function of other parameters excluding PME.

2.14.1 DESCRIPTION OF DATASET

NSWCDD wanted to leverage an existing database for this study. Therefore, the OSD database for radars, which includes 13 programs, populated half of the dataset. The other half of the dataset was collected from an Army study, which also included 13 programs. The study did not provide the names of the actual programs used in the analysis.

2.14.2 DESCRIPTION OF CERS

Table 2-24 below displays a summary of the study. Two support CERs were developed for most of the support item elements, including one CER with PME as a cost variable and the other CER without PME as a cost variable. The columns "# of Prototypes", "Joint Venture", and "Platform" provide information on whether each of those variables was found to be significant and included in the associated CER or not. Both the Joint Venture and Platform variables require an input of 1 or 0 depending on whether the program is joint venture or not, or an airborne or surface platform.

Table 2-24: Results Summary Table

Support Item	Cost Variable	# Prototypes	Joint Venture	Platform
Total Support	PME	**Yes**	**Yes**	No
	None	**Yes**	No	**Yes**
Tooling & Test Equipment	PME	**Yes**	No	**Yes**
	None	**Yes**	No	**Yes**
Test & Evaluation	PME	No	No	**Yes**
	None	No	No	**Yes**
Systems Engineering	PME	**Yes**	No	No
	None	**Yes**	No	**Yes**
Program Management	Pgm Total (Without PM)	No	**Yes**	No
	None	**Yes**	**Yes**	No
SE/PM	Pgm Total (Without SE/PM)	**Yes**	**Yes**	No
	None	**Yes**	**Yes**	No
Training (All Programs)	None	**Yes**	No	No
Training (Excluding Outlier)	None	**Yes**	No	No
Data	None	No	No	No
Support Equipment	PME	No	No	No
	None	No	No	No

Recommendations for future analysis are included at the end of the study. These recommendations focus on data collection for the programs in the existing database used as the basis for this study. The data collection includes obtaining definitions of the support items for each program and other programmatic information (CLINs, period of performance, contract vehicle, etc.). At the end of the study, the authors compiled a list of questions per support item that need to be answered in order to conduct further analysis. Also, an appendix is provided that gives more detailed statistics for each CER, including number of data points, R squared, and t-statistics.

2.14.3 STRENGTHS AND WEAKNESSES

Strengths of the study include that CERs were developed for a low-level of detail for development support item elements. Additionally, multiple CERs were developed for most support item elements, which allows an analyst to choose a primary best-fit and cross-check. Statistics are available for each CER.

However, the results of the study show that in most cases it is statistically favorable to include prime mission equipment cost as a variable. It should be noted that the CERs using PME cost as a variable will be affected by additional uncertainty due to the estimation of the PME input. This statistically favorable outcome is a result of a weakness in understanding the programs and development activities that make up the underlying data in the existing database used for the study. The authors make the case that the CERs with no cost as a variable would be stronger if further data collection was pursued for the programs in the existing database. As this has yet to happen, the CERs that do not use PME costs are not as statistically strong and may not be as useful to an analyst as the CERs that include PME costs. Additionally, another weakness includes lack of insight into the data and the specific 26 programs used to generate the CERs in the study.

2.15 "COST PERFORMANCE ESTIMATING RELATIONSHIPS (CPERS) FOR UAV PAYLOADS", TECHNOMICS, INC., 2007

The following summary provides a review of the study "Cost Performance Estimating Relationships (CPERs) for Unmanned Aerial Vehicle (UAV) Payloads," as presented at DoDCAS, 2007. The objective of this analysis is the development of CPERs that utilize performance and design variables that can be tied back to Army Simulation and Engineering models or requirements as prescribed by the Army. For the purposes of this study, payloads include radar, electro-optical infrared (EO/IR) sensors, lasers, and signals intelligence (SIGINT).

To qualify the analysis and types of data required to support CPER development, the presentation discusses the types of engineering models that support payloads, in particular

point source models and scene models. An example involving radar includes surveillance, tracking, and mine detection, all focusing on specific targets and requiring point source models. However, synthetic aperture radars (SAR) show more context with wider views, requiring scene models.

For payloads requiring a broader view of the scenario, or scene, the range is a function of the probability of detection, orientation, recognition, and identification, and other system design parameters. Specifically, spatial frequency is required to calculate range, and spatial frequency can be derived from the minimum resolvable temperature (MRT) difference curve or from empirical testing.

The CPERs developed include:

- Hardware (recurring development and production)
- Non-Recurring Engineering (NRE)
- Development Support

Performance and design variables may include power output, aperture, number of pixels, frequency, wavelength, and throughput. The following sections address each of these methodologies. Following a general description of each methodology, there are sub-sections on the description of the methodology's dataset and a description of the methodology's CPERs.

It should be noted that Technomics also completed a UAV study in 201# with payload CERs based on a more recent dataset, albeit with a simpler analysis. NCCA updated the study in December 2013.

2.15.1 DESCRIPTION OF DATASET

Cost, technical, and programmatic data were collected on historical UAV Payloads, in particular for radars, EO/IR sensors, laser rangefinders/designators, and SIGINT. Data sources include government and contractors.

Table 2-25 outlines the programs modeled with data from Government and Contractor sources.

Table 2-25: Programs included in analysis

EO / IR / Lasers	***Radar***	***SIGINT***
TUAV	APY-3 (JSTARS)	Guardrail ELINT
Wescam MX-20	Apache Longbow	Guardrail COMINT
Wescam MX-15	Global Hawk	Global Hawk LR-100
Wescam 11 SST	Predator	Global Hawk Hyperwide
FLIR Systems Star SAFIRE II	TUAV	Aeriel V2
FLIR Systems Star SAFIRE III	Lynx	Aeriel V3
IAI POP 100	LynxII	Precision Direction Finding
IAI POP 200		Rio Ratan
IAI POP 300		Prophet Blk 1
MOSP		Prophet Blk 2/3
MOSP 770		

2.15.2 DESCRIPTION OF CERS

The WBS structure is very high level in terms of CPER development. The presentation presents CPERs for development recurring hardware and production recurring hardware, non-recurring engineering, and development support. The following CPER equation forms indicate the input variables, with binary variables marked with asterisks and defined in Table 2.26.

The Development Cost and Production Price for IR sensors is defined as the recurring hardware unit cost of prototype unit(s) built in development or production.

IR Prototype HW $_{REC}$ = *f* (Aperture, FPA Pixels, Stab, COTS*, LWIR*, Prod*, Qty)
where

- Aperture = the diameter of the primary lens or mirror measured in inches
- FPA Pixels = the number of pixels on Focal Plane Array (FPA)
- Stab = the level of stability of the Gimbaled Assembly in micro-radians (microrads)
- Qty = the quantity of units

The Development Cost and Production Price for Laser Designators and Rangers is defined as the recurring hardware unit cost of prototype unit(s) built in development or production.

Laser Designators/Rangers Prototype $HW_{REC} = f$ (Energy/Pulse, PRF, COTS*, Ranger*, Prod*, Qty)

where

- Energy/ Pulse = the energy per pulse transmitted by laser in millijoules (mJ)
- PRF = the pulse repetition frequency of laser in Hertz (Hz)
- Qty = the quantity of units

The Development Cost and Production Price for Radars is defined as the recurring hardware unit cost of prototype unit(s) built in development or production.

Radar Prototype $HW_{REC} = f$ (Aper, Ave Pwr Out, Freq, Prod*, Qty)

where

- Aper = the aperture of the radar antenna in square inches (in^2)
- Ave Pwr Out = the average power output of the transmitter in watts (W)
- Freq = the average output frequency of the radar in gigahertz (GHz)
- Qty = the quantity of units

The Development Cost and Production Price for SIGINT is defined as the recurring hardware unit cost of prototype unit(s) built in development or production.

SIGINT Prototype $HW_{REC} = f$ (IBW, Lot Qty, InclAntRFD*, COTS*, DevYear, ELINT*)

where

- IBW = the total instantaneous bandwidth of system in megahertz (MHz)
- Lot Qty = the number of units manufactured during development
- DevYear = the year development was complete

Development non-recurring engineering (NRE)

The Lot Cost for EO, IR, and laser NRE is defined as the development non-recurring engineering cost of an IR, EO/IR, IR/Laser or EO/IR/Laser payload.

IR, EO, Laser $Eng_{NRE} = f$ (PME Rec, COTS*, Qty)

where

- PME Rec $ = the recurring hardware cost of an IR, EO/IR, IR/Laser, or EO/IR/Laser payload

- Qty = the quantity of units

The Lot Cost for SIGINT NRE is defined as the development non-recurring engineering cost of a SIGINT payload.

SIGINT Eng_{NRE} = *f* (SIGINT Rec, Lot Qty, MinorSWDev*, COTS*)

where

- SIGINT Rec = the recurring hardware cost of a SIGINT
- Lot Qty = the number of units manufactured during development

The Lot Cost for Radar NRE is defined as the development non-recurring engineering cost of a radar payload.

Radar NRE = *f* (PME, COTS*, Joint*)

where

- PME = the total non-recurring and recurring costs
- COTS = a binary variable indicating whether the system contains previously developed hardware, OR no previously developed hardware

Table 2-26 is a binary variable key for the CER elements mentioned above. The first part of the definition indicates a binary value of (1), while the second part of the definition represents a binary value of (0).

Table 2-26 UAV Binary Variable Key

Input	Definition
COTS	Indicates whether the system contains previously developed hardware, OR no previously developed hardware.
LWIR	Indicates an IR sensor that detects energy in 8-12 micron range, OR other range.
Prod	Translates development cost to production price, OR other.
Ranger	Operates at 1.54 micros (eye safe), OR other.
InclAntRFD	Indicates whether an antenna and RF distribution function is included, OR not.
ELINT	Indicates ELINT systems, OR COMINT Systems.
MinorSWDev	Indicates a program with minor software development effort, OR not.
Joint	Indicates whether the program was a joint venture development by two or more prime contractors, OR not.

Note the production recurring hardware CPERs includes recurring systems engineering/ program management (SE/PM) and that the development support CPER includes SE/PM, T&E, Data, Training, Support Equipment, Spares, Tooling, and Test and Evaluation (T&E). As a result, they are very high-level CPERs.

2.15.3 STRENGTHS AND WEAKNESSES

The strengths of this study include the utility of the CPERs across the broad range of payloads for UAVs. CERs each contain information about the goodness of fit, including supporting statistics.

Weaknesses include a lack of detailed information about the analysis. The accompanying more robust documentation and supporting dataset were not available, and therefore the details surrounding the analysis could not be scrutinized. Further, the analysis covers the highest level of the WBS, and it would be beneficial to have CPERs at lower levels of the WBS as well.

3: ASSESSMENT

Table 3-1 summarizes the available information for each study in our review, listed in the order they are presented in this literature review. The literature review surveyed 15 different reports and databases.

Table 3-1 Study Summary

Study Name	Study Year	Database	Methodology Discussed	Equation Forms Available	CERs Available	Statistics Available
C4ISR ACDB	2013	X				
Avionics ACDB	2014	X				
Electronics ACDB	1997	X				
Airborne Avionics & Electronics ACDB	2002	X				
Comm/Elec Cost Model	1998	X	X	X	X	X
Communications CERs for JTRS	2002		X	X	X	X
PACER 2003 (COTS Electronics)	2003		X	X	X	X
COTS	2012		X	X	X	X
Dev Support CERs	2010		X	X	X	X
FORECAST	1995		X	X		
RAND Select Airborne Radars	2008	X	X	X	X	N/A
Ground Radar 2009	2009	X	X	X	X	X
Ground Radar 2013	2012/2013	X	X	X	X	X
Radar Development Support CERs	1998		X	X	X	X
CPERs for UAVs	2007		X	X	X	X

Four of the 15 reports are ACDB databases. The ACDB database program is part of the ACEIT software package and includes a developer kit that allows ACDB databases to be developed and updated. The ACDB database structure provides access to raw and WBS-normalized data for each program in the database via a series of filtering screens. Data can

also be sorted by cost element within the normalized WBS across programs. An analyst can extract the data into a spreadsheet for further analysis, a very useful feature when dealing with older data normally that is only available from other sources via a paper copy or scanned image. The ACDB database often includes technical data, program histories, and attached documents of use to analysts trying to understand the programs underlying the data. The underlying ACDB software is a FoxPro database. ACDB is easy and fast to query, relative to online databases currently in use today, but is considerably more difficult to program and update. In addition, the ACDB database updates are available only via an updated software file, rather than online. The Army has developed a JIAT ACDB application which places the data online, and makes updates simple. Like other online applications, results in slower queries speeds, which is sometimes frustrating for an analyst trying to refine the query to the refined data. In addition, the JIAT user interface for this tool is still being improved.

The C4ISR ACDB is the largest and most actively updated ACDB database, and includes a wide range of communications equipment, sensors (including radars), vehicle electronics, avionics, and other electronics, with a focus toward equipment used by the U.S. Army, but including some equipment procured by other services as well. Where available, the database incorporates Contractor Cost Data Reports (CCDRs) and Cost Performance Reports (CPRs). Many electronics programs of interest are either subcontracted and do not have detailed cost reporting, or are ACAT II or lower programs without a CCDR requirement. As a result, the C4ISR database also collects and reports some contract pricing information for these programs to provide additional data where none would otherwise be available. The Army plans to move the older CCDR data within the C4ISR database into the OSD CAPE database, but no plans have been articulated for the non-CCDR data within the database.

The other 3 ACDB databases are not actively updated, but include some data unavailable in a format ready for analysis elsewhere. The NCCA-sponsored Avionics ACDB is recent and includes cost data on four sensor and electronic warfare systems. The NCCA-sponsored Electronics database is old, but may be a unique source for certain legacy sensors, such as

sonars. The AFCAA-sponsored Tri-Service Airborne Avionics and Electronics database is also old, but includes data in electronic format for several older Air Force avionics programs.

In summary, only one of the ACDB databases are actively updated now.

Four of the 11 remaining reports focus on radars. The RAND radar study published in 2008 provides a comprehensive overview of radar development history, cost, schedule, and programmatic data on most recent major airborne radar programs, and provides the data in a format well-organized for analyzed looking for analogies to draw upon. The report is mostly still up to date, though may not include cost data for some of the most recent development in MMIC substrate materials. The Technomics ground radar series are more recent and focus on ground radars. The report includes cost estimating relationships for major radar components. In addition, the ground radar study includes schedule estimating relationships. None of the radar studies are actively being updated now and the analyst that led the RAND study is no longer at RAND.

Two of the 11 reports focus on developing CERs for communication systems and program support. The CERs between the two reports cover the major components of a deployable communications system, including antennas, electronics, and deployment hardware. None of these reports have been recently updated, but can serve as starting point for future updates.

Two of the reports focus on collecting data on and estimating costs for Commercial-off-the-Shelf (COTS) electronics. A significant portion of the electronics purchased today are either commercial hardware or tailored from commercial hardware based on military requirements. The PACER COTS Electronics cost estimating model was the result of systematically collecting commercial off the shelf hardware electronics data for a wide range of digital circuit boards, receiver boards, and other board types, as well as memory devices, workstations, servers, inertial measurement units, and batteries. In the case of several CERs, such as the digital processor board, the underlying data set includes thousands of data points. The larger data set and the associated degrees of freedom has allowed for the development of

very detailed CERs specific to the performance and physical characteristics of the hardware. The report is extremely well-documented.

The three remaining reports focus on a cost estimating model for circuit boards (FORECAST) based on a data set that is strong influenced by space program needs, a cost-performance model for UAV sensors, and a series of support cost estimating factors for electronics systems. The FORECAST model is out of date, but is an example of a board level model for electronics cost estimating that requires fewer input variables than the PACER model. The UAV sensor model is useful, though becoming out of date. The support cost factors model is very high level, but useful for crosschecks and is periodically updated by the Electronic Systems Command at Hanscom AFB.

The biggest concern emerging from the review of the literature is the lack of sustained capability in two key areas: 1) data needed to support estimating electronics at board and box level, which cost analysts are often asked to do, 2) cost estimating models for both military and commercial-based electronics hardware solutions. The C4ISR database is actively maintained by DASA-CE and captures large-cost Army-focused electronics programs at a high level very well. Given the length of time it takes to complete an acquisition program and provide final cost data, relative to the rapid evolution of digital electronics costs and capabilities, COTs data would significantly benefit to cost analysts forecasting future programs. In addition, the CCDR reports only capture data for the largest programs. Unfortunately, COTS data collection has not been sustained, so the data latency and detail issue remain. Second, none of the cost models and many of the data sets in this report have been actively maintained, which prevents development of models which can be sustained and improved over time based on analyst experiences over time.

None of the studies reviewed here address O&S cost estimating. NCCA has a model for shipboard systems within their Operating and Support Cost Analysis Model (OSCAM) model suite. In addition, the services have the VAMOSC Operating and Support cost databases, which includes data on specific electronics subsystems.

4: NEEDS AND FUTURE RESEARCH

Electronics hardware are included in every estimate performed by cost analysts today, yet the data sets and tools for estimating these costs are severely under-resourced. The recommendations below reconstitute COTs electronics hardware database and estimating methodologies, consolidate historical cost data reports owned by the government into CADE, and focus more attention on the cost of fielding, sustaining, and refreshing electronics.

4.1 COMMERCIAL PRICE AND PERFORMANCE DATABASE & MODEL

Digital electronics technology advances at a very rapid pace, and outside of a few DoD-specific applications, has a far larger commercial industry. Digital processing performance continues to advance at a considerable pace and memory costs fall for given capability levels. Yet, for a given technology, the performance and price vary considerably based on relative processing speeds, ruggedization, and quantities purchased. For estimating applications leveraging commercial digital technology, analysts would benefit heavily from data sets and estimating techniques of commercial-off-the-shelf electronics that are updated on annual basis. Such data sets and CERs are also excellent training tools for electronics cost estimators. The government should re-engage with COTs electronics data sets and models, to serve as a means to estimate programs, and training for new electronics cost estimators.

4.2 GOVERNMENT COST AND TECHNICAL DATABASE DEVELOPMENT

The cost community needs an integrated roadmap for collecting cost, schedule, and programmatic data into an authoritative set of databases. Historical CCDR data should be migrated to the CADE database the OSD CAPE is currently developing. CPR data should either be migrated into CADE or into the C4ISR database. The C4ISR ACDB database should be the authoritative data source for all electronics data not captured in CADE. The data from the remaining three ACDB databases should be migrated to CADE or C4ISR ACBD database and support for three other ACDB databases discontinued. This will make CADE and the C4ISR ACDB database the authoritative data source for CCDR and CPR data

reported to the government. In addition, the price and spares sections for electronics contracts should be captured in the C4ISR database or Contract Prices Database[6].

4.3 MODELS

Several good, well-documented cost models and data sets have been developed for radars, communications electronics, COTS electronics, and electronic circuit boards. None of these studies have been regularly maintained due to resource constraints. The government should coordinate and select 2 to 3 electronics cost models and databases outside of the standard databases to maintain through sustained funding, allowing continuous improvements and lessons learned from past estimates to be incorporated. Specifically, we recommend the ground radar and communications electronics models be combined and updated every three years, the RAND radar study updated every five years, and a COTs electronics model and database updated every two years.

In addition, all efforts should include a schedule dimension to estimating relationships for developmental efforts.

Finally, data should be collected for and cost estimating relationships developed shipboard, ground, and aircraft retrofit costs. Aircraft modification cost studies are covered in the Aircraft literature review, but installation cost estimating techniques are needed across several commodities.

4.4 O&S COSTS

Operating and support (O&S) costs were not included in the historical analyses. In many cases, CERs were developed for NRE, Development, and Production. Government costs were even covered to varying extents, but O&S costs were markedly absent from the studies. With a well-establish Visibility and Management of Operating and Support Costs (VAMOSC) system within DON, and increasing contractor logistics support (CLS) cost

[6] The Contract Price Database is a contract history and price database developed under sponsorship from AFCAA, NCCA, and MARCORSYSCOM and is hosted in CADE. The structure of the database would have to be modified to accommodate the specific price and spares sections from electronics contracts.

reporting via the CSDR process, there is a significant opportunity to improve the understanding and estimation of O&S costs for Electronics.

4.5 TRAINING

Electronics technology complex and rapidly changing, and cost analysts need to be able to engage with program engineers on cost drivers in order to forecast future program costs and schedule. In particular, training courses in radar, communications, electronics development, hardware manufacturing, and COTs performance-cost drivers are recommended, with at least two courses developed to center around estimating models.

5: ADDITIONAL STUDIES NOT REVIEWED

"SHIPBOARD SYSTEMS INTEGRATION",

"COST FACTORS GUIDE", NCCA