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MANUFACTURING COST IMPACTS OF ELECTRONIC BOXES DUE TO THE VARIOUS BASING MODES

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INTRODUCTION

This report documents the electronic box cost analysis performed by Tecolote Research, Inc. for the U.S. Army Strategic Defense Command (SDC) Cost Analysis Office, Huntsville, Alabama, under Contract DASG60-84-C-0061. The objective of this work was to develop various techniques of estimating recurring hardware theoretical first unit (T_1) costs of electronics boxes found in each of the different basing modes (e.g., airborne, ground mobile, and space) and then to compare or quantify the cost impacts of one basing mode versus another.

This task was initially funded in September 1984. During the twelve months that followed, cost and technical data on tactical and strategic missiles and tactical aircraft was collected and analyzed. The final product in this effort was a report* which documented cost estimating relationships (CERs) developed to estimate the following airborne equipment:

- Receivers
- Transmitters
- Digital Processors
- Antenna Assemblies
- Analog Electronics
- Inertial Platform Assemblies
- Power Conditioning and Inverter/Converter Electronics
- Other Equipment

In September 1985, a second task was funded to continue developing CERs for electronic boxes in the different basing modes. Under this task, work in four areas resulted: (1) additional cost and technical data were collected on airborne electronic boxes, with the original CERs expanded and

*Horak, J. A., "Airborne Electronics Cost Models," Tecolote Research, Inc., CR-0082, August 1985.

recalibrated; (2) cost and technical data on airborne electrooptical equipment were collected and analyzed, and CERs were developed; (3) cost and technical data on ground mobile electronic boxes were collected and analyzed, and CERs were developed; and (4) support was provided to the SDC Cost Analysis Office in developing cost estimates for the ERIS seeker and radar configurations in the SRS study.

The expanded and recalibrated airborne electronics CERs and the ground mobile electronics CERs were documented in sections 2 and 3 of Airborne and Ground Mobile Electronic Box Analysis.*

The expanded CERs for airborne electronics were developed for the following ten types of equipment:

Receivers
Transmitters
Digital Processors
RF Antenna Assemblies
Analog Electronics
Inertial Sensor Assemblies
Inertial Platform Assemblies
Gyroscope Assemblies
Power Conditioners
Batteries

CERs for ground mobile electronics were developed for the following eight types of equipment:

Receivers/Exciters
Transmitters
Digital Processors

*Horak, J. A., "Airborne and Ground Mobile Electronic Box Analysis," Tecolote Research, Inc., CR-0146, September 1986.

Antenna Assemblies
Analog Electronics
Power Conditioners
Displays and Controls
Shelters

The airborne electronics and ground mobile electronics data sets were documented in two separate "proprietary" appendices, which cannot be released without written approval of the U.S. Army Strategic Defense Command Cost Analysis Office, Huntsville, Alabama. The airborne electro-optical (E/O) CERs were documented in a separate contract report (CR-0149).

In October 1986, a third and final task was funded under Contract DASG60-84-C-0061 to complete the data sets and to analyze the cost comparisons between electronic boxes in the various basing modes. Under this task, work in three areas resulted: (1) additional cost and technical data were collected and normalized on two aircraft programs (APG-66 radar and APY-1 radar) and on the Phalanx Close-In Weapon System (CIWS); (2) additional physical parameters were collected on aircraft and missile programs currently included in the missile and aircraft data bases; and (3) cost and technical data on space electronic boxes was obtained, normalized, and analyzed.

The U.S. Air Force Space Division Cost Analysis Office and the U.S. Army Strategic Defense Command Cost Analysis Office cooperated in jointly funding work in this third area (analysis of space electronic boxes). Space Division funding resulted in the development of CERs for the Communications and Telemetry, Tracking and Command (TT&C) Subsystems and the various electronic box CERs within the Communications and TT&C Subsystems in the sixth edition of the Unmanned Spacecraft Cost Model. The hardware items to which CERs were developed in the Unmanned Spacecraft Cost Model are shown below:

Communications Subsystem
Telemetry, Tracking and Command (TT&C) Subsystem

Antennas
Microwave Ferrite Devices
Receivers
Receivers/Exciters
Digital Electronics
Analog Electronics
Transmitters/Amplifiers
Tape Recorders
Transponders

It should be noted that in generating cost estimates for space, airborne, or ground mobile electronic systems, CERs developed specifically for black boxes of that basing mode (presented in CR-0146 for airborne and ground systems and the sixth edition of the Unmanned Spacecraft Cost Model for Space Systems) should yield better estimates than the CERs presented here in this documentation. Credence to this observation is supported by examining the standard errors of the questioned CERs. In most cases, the standard errors of the curve fits are lower for the individual basing mode CERs (CR-0146 and Unmanned Spacecraft Cost Model) than for the basing mode comparison analysis presented here in this documentation. This effect is primarily due to the omission of variables in this basing mode comparison that were included in the individual basing mode CERs which have explanatory value for one particular basing mode but not for all the basing modes.

Again, the main objective of this analysis is to first prove or disprove there are differences in cost due to the basing mode and second to quantify these differences. These quantified differences (cost factors) can be used to help estimate costs of future systems designed in environments or basing modes where these systems have previously not been built. This can be done by using data bases on existing systems manufactured for a particular basing mode to estimate costs for electronic systems in that basing mode and then applying a basing mode-to-basing mode factor to yield a cost estimate for that system in an alternative (or new) basing mode or environment. It is hoped that the factors presented in this analysis will help generate credible cost estimates for such systems as space based radars, interceptors, C^3 installations, airborne and spaceborne laser systems, and other concepts being studied for near future development.

The CERs developed in this analysis which compare the costs of one basing mode versus another use the physical variables of weight and volume and the physical/performance variable of power as the means of comparison. In other words, a dollars per pound, dollars per cubic inch, and dollars per watt is quantified for each type of generic electronic box in each of the basing modes (shipborne, ground mobile, missile, aircraft, lower earth orbit space, and high earth orbit space). This is done by regressing weight, power, and volume versus cost and adding dummy variables to the equation to stratify the cost differences between one basing mode and another. In some cases where negligible cost differences (measured statistically) between one basing mode and another resulted, data was combined to form a composite factor for these two or more basing modes. This occurred quite often in the power CERs.

CERs for each electronic box and antennas were developed at the theoretical first delivered hardware unit. For shipborne, ground mobile, missile, and aircraft systems, this is equivalent to the first production unit. For space systems, this is equivalent to the first flight unit.

The costs included in the CERs are for the total recurring hardware with G&A. Included in the recurring hardware cost is the cost for all manufacturing touch labor and material, manufacturing support costs, which include all other recurring manufacturing costs directly associated with the manufacture of the product, and sustaining engineering costs. Sustaining engineering includes all the engineering costs directly related to the manufacture of the product and does not include any systems engineering/program management. Fee is not included in the cost and must be added to bring the cost to the government price.

The recurring hardware T_1 costs shown in this document are the costs of the contractor who assembled the electronic boxes into a working assembly or system. Integration and assembly costs of the boxes into an assembly or system have been allocated to the hardware boxes. Integration of the electronic boxes into a missile guidance section, integration of electronic boxes into an airborne, ground or shipborne radar system, or integration of the electronic boxes into a space communications or telemetry, tracking and command subsystem is included in the box costs used to develop these CERs. Missile guidance section integration costs were found to range from 9 percent of the recurring hardware cost in small airframes to a high of 20 percent in larger airframes. Radar integration costs were found to range from 8 percent to a high of 25 percent of hardware costs. For space systems, integration and assembly were typically allocated to the hardware by the prime contractor or included in a support line item, which also included manufacturing support and sustaining engineering. All of these items were allocated to the hardware.

All costs shown in this document are expressed in FY86 dollars. The shipborne, ground mobile, missile, and aircraft cost data were normalized to FY86 dollars using the Bureau of Labor Statistics Employment and Earnings Index, Standard Industrial Classification Number 3662. This index depicts the average wage rate of manufacturing workers in the radio and television electronic equipment industry. A listing of the index is shown in table 1.1. The space cost data was normalized to FY86 dollars using wage rates approved by Space Division for space related programs.

TABLE 1.1

Bureau of Labor Statistics Employment and Earnings Index
Standard Industrial Classification Number 3662
(Radio and TV Electronic Equipment)

Fiscal Year	Indicators*
74	2.715
75	2.440
76	2.235
76T	2.142
77	2.049
78	1.898
79	1.721
80	1.563
81	1.433
82	1.294
83	1.189
84	1.116
85	1.050
86	1.000
87	0.961

*The indicators represent the change in wage rate between the middle of the fiscal year in question and the middle of FY86.

2

BASING MODE CERs

This section documents the basing mode CERs developed in this analysis.

Cost and technical data was collected and normalized on the following shipborne, ground mobile, aircraft, and space systems.

Shipborne Systems

- Aegis SPY-1A Radar
- Phalanx Close-In Weapon System (CIWS)

Ground Mobile Systems

- Patriot Radar Unit and Engagement Control Station
- TPQ-36 Weapon Locating Radar
- TPQ-37 Weapon Locating Radar
- TPS-59 Radar
- Pershing II Ground Equipment

Missiles

- Phoenix (AIM-54C)
- Sparrow (AIM-7M)
- HARM (AGM-88A)
- Patriot (MIM-104)
- Pershing II
- Tactical Anti-ship Cruise Missile (TASM)
- Nuclear and Tactical Land Attack Cruise Missile (TLAM)
- Standard Missile II

Aircraft

- Airborne Warning and Control System (AWACS) APY-1 Radar
- F-16 APG-66 Radar
- F-18 APG-65 Radar
- F-16 APG-63 Radar
- LANTIRN Navigational Radar
- Target Acquisition and Designation Sight/Pilot Night Vision Sensor (TADS/PNVS)

Space

- Low Earth Orbit (LEO)
  - Atmospheric Explorer (AE)
  - Defense Meteorological Satellite Program (DMSP)
  - High Energy Astronomy Observatory (HEAO)
  - P78-1
  - STP Small Satellites (S3)
  - Orbital Space Observatory (OSO-1)
- High Earth Orbit (HEO)
  - Applications Technology Satellite (ATS A-E)
  - Applications Technology Satellite (ATS F)
  - Defense Satellite Communications System (DSCS-III)
  - Global Positioning Satellite (GPS 9-11)
  - Fleet Satellite Communications Spacecraft (6-8)
  - Intelsat IV
  - Intelsat V
  - Initial Defense Communications Satellite Program (IDCSP)
  - Marisat
  - Nato III
  - Tactical Communications Satellite (TACSAT)
  - Unidentified Satellite

In this analysis, the electronic box and antenna data were segregated into the following groups:

Receivers/Exciters
Transmitters
Digital Electronics
Analog Electronics
Power Conditioners
Antennas

Three CERs (except for antennas) were developed using the physical characteristics (weight, power, volume) of the boxes as drivers for each of the six hardware groups. As mentioned earlier, dummy variables were added to the curve fits to quantify stratifications in the cost data due to the type of basing mode from which the equipment operates. The CERs are structured as the product of terms in which the first term is a function of a continuous variable (either weight, power, or volume) and several discrete valued terms which reflect each of the basing modes. Each discrete valued term takes on one of two values (either one (1) or some value higher) depending on whether that basing mode applies through selection of the proper dummy variable. These discrete terms are arranged such that the continuous first term represents shipborne systems and selection of any other basing mode results in a factor which multiplies the basic shipborne estimate. If equipment in the other basing modes were not found to cost significantly different (statistically) than the shipborne equipment, those data points were combined with the shipborne data points to calibrate the continuous first term. Only when the other basing modes were statistically found to cost more than shipborne equipment were dummy variables added for that basing mode to the CERs. Combining basing mode data occurred quite frequently in the power CERs. Additionally, missile and aircraft data points were often combined to calibrate a joint coefficient due to statistical insignificance and inconclusiveness when these basing modes were treated separately.

The relationships developed here are presented with statistics and some general observations are made about the data and the curve fits. The CERs estimate the recurring cost of the theoretical first (T_1) delivered hardware unit in FY86 thousands of dollars, including G&A and excluding fee and recurring systems engineering/program management.

2.1 RECEIVERS/EXCITERS

Receivers and exciters are low power RF equipment which initially receives and processes the RF or microwave signal in a radar design. The receiver typically sets the signal-to-noise ratio of the incoming signal by amplifying it using a low noise gallium arsenide (GaAs) field effect transistor (FET) transistor chain. Additional functions such as channel balancing, attenuation, gain control, mixing, and often RF detection are also performed in the receiver. Receivers captured in this data set operate in the 130 to 16,000 MHz region. Exciters typically generate the RF signals used for transmission and mixing throughout the radar design. Oven controlled crystal oscillators are typically used to generate the basic signals. These signals are then phase controlled and then processed through chains of frequency multipliers, which bring the RF frequencies to their desired levels. This receiver/exciter category includes low power RF equipment operating between 1 and 16,000 MHz.

The three relationships developed to estimate receiver costs are ones in which the weight of the receiver/exciter box, the input power to the receiver/exciter, and the volume of the box are the cost drivers. Included in the cost, weight, power, and volume values are all the active and passive components, housing, and interconnect associated with the receiver/exciter. The range of the receiver/exciter data for all the basing modes is shown in table 2.1.

The weight-based CER for receivers/exciters is shown in figure 2.1. In this curve fit, each basing mode was calibrated to cost slightly different than the other basing modes. This is represented by a dummy variable for each basing mode except shipborne equipment. Shipborne

TABLE 2.1

Range of Receiver/Exciter Data

	Parameters			
	# Points	Low Value	Average	High Value
Shipborne				
Costs ($K)	5	179.3	563	982
Weight (lbs)	5	51	679	1,300
Input Power (watts)	3	1,000	1,267	1,600
Volume (in^3)	4	3,465	37,136	58,925
Ground Mobile				
Costs ($K)	8	14.4	1,562	8,052
Weight (lbs)	6	7.2	641	2,762
Input Power (watts)	6	220	2,318	9,600
Volume (in^3)	7	10.1K	55.3K	58.9K
Missile				
Costs ($K)	11	28.8	130.4	436.5
Weight (lbs)	11	3.5	10.8	30.8
Input Power (watts)	10	11.8	32.8	68.0
Volume (in^3)	11	32.6	164	510
Aircraft				
Costs ($K)	5	239.7	543	3,244
Weight (lbs)	5	18.2	63.7	459.4
Input Power (watts)	4	303.1	743	1,950
Volume (in^3)	4	450	11.7K	41.5K
Low Earth Orbit Space				
Costs ($K)	5	23.6	57.5	91.1
Weight (lbs)	4	1.25	1.9	2.5
Input Power (watts)	3	0.7	1.35	2.4
Volume (in^3)	3	38	54	65
High Earth Orbit Space				
Costs ($K)	30	30.1	692	6,907
Weight (lbs)	24	0.6	14.6	84
Input Power (watts)	11	1.5	16.5	62.1
Volume (in^3)	14	4	544	3,845

Receivers/Exciters

$$UC_{1,FY86,\$K} = 2.77(\text{Weight})^{0.896}\ e^{1.05(Grd)}\ e^{1.71(Msl)}\ e^{1.91(A/C)}\ e^{2.33\ (LEO)}\ e^{3.34\ (HEO)}$$

t-values →	(1.82)	(11.09)	(2.58)	(3.66)	(4.40)	(3.93)	(7.44)
Basing Mode Factors →			(x2.86)	(x5.53)	(x6.75)	(x10.3)	(x28.2)

$R^2 = 82.5$

$\bar{R}^2 = 80.3$

$S = \left\{ \begin{matrix} +91.8\% \\ -47.8\% \end{matrix} \right\}$

55 Data Points

Ship-5	A/C-5
Grd-6	LEO Space-4
Msl-11	HEO Space-24

F = 37.7

48 Degrees of Freedom

RMS % Error = 39.4%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Weight = Weight of the Receiver/Exciter in pounds (lbs).

Grd = 1 for Ground Mobile System, 0 otherwise.

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO > 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.1. Receiver/Exciter weight CER.

receiver/exciters are estimated by the intercept and the weight value to the 0.896 exponent. Other basing mode receivers are estimated by the intercept and weight to the 0.896 power, plus a multiplicative factor to adjust for the basing mode. On a weight basis, shipborne is the cheapest basing mode, following by ground mobile, missile, aircraft, low earth orbit space, and the most expensive, high earth orbit space. The dummy variable factors which are multiplied to the intercept term for each basing mode are shown below the t-values of the estimated coefficients. Below these values are the statistics of the curve fit as well as the make-up of the data set used in the regression.

The input power CER for receiver/exciters is shown in figure 2.2. In this CER, the missile and aircraft data points were combined to yield a composite basing mode factor (the value is 2.45). Also, ground mobile data points were combined with ship equipment.

The volume CER for receivers/exciters is shown in figure 2.3. In this CER, ground mobile data points were combined with the shipborne data points. This CER is the only one presented in this analysis where low earth orbit space equipments cost less than missile and aircraft equipments, in this case on a dollars per cubic inch basis.

2.2 TRANSMITTERS

Transmitters are amplifying devices which amplify the low power RF or microwave signal generally received by the exciter to a power level for output through the radar antenna. The transmitter can contain its own signal generating device (exciter), but usually consists of chains of amplifiers powered by its own high voltage power supplies. Solid-state transmitters employ chains of amplifier circuitry which build the RF power to its desired output level. Tube transmitters usually employ driver amplifiers which power high output tubes (TWTs, CFAs, klystrons) to the desired RF output level. Transmitters in this data set operate from 137 to 16,000 MHz.

Receivers/Exciters

$$UC_{1,FY86,\$K} = 2.33(\text{Power})^{0.868}\ e^{0.897(\text{Msl \& A/C})}\ e^{2.93(\text{LEO})}\ e^{3.21(\text{HEO})}$$

t-values → (1.23) (9.44) (2.29) (3.78) (6.30)

Basing Mode Factors → (x2.45) (x18.7) (x24.8)

R^2 = 82.7

$\bar{R}^2$ = 80.6

S = { +94.3% / -48.5% }

37 Data Points	
Ship-3	Msl-10
Grd-6	LEO Space-3
A/C-4	HEO Space-11

F = 38.3

32 Degrees of Freedom

RMS % Error = 57.3%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Power = Input power to Receiver/Exciter box in watts.

Msl & A/C = 1 for Missile/Interceptor/Aircraft, 0 otherwise,

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO > 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.2. Receiver/Exciter input power CER.

Receivers/Exciters

$$UC_{1,FY86,\$K} = 0.531(\text{Volume})^{0.727}\ e^{1.38(LEO)}\ e^{1.80(A/C)}\ e^{1.82(Msl)}\ e^{2.90\ (HEO)}$$

t-values →	(-1.03)	(12.42)	(2.78)	(5.48)	(4.74)	(8.29)
Basing Mode Factors →			(x3.97)	(x6.05)	(x6.17)	(x18.2)

$R^2 = 89.6$

$\bar{R}^2 = 88.2$

$S = \left\{ \begin{array}{l} +69.1\% \\ -40.8\% \end{array} \right\}$

43 Data Points

Ship-4	Msl-11
Grd-7	LEO Space-3
A/C-4	HEO Space-14

F = 64.0

37 Degrees of Freedom

RMS % Error = 51.3%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Volume = Volume of the Receiver/Exciter box in cubic inches (in^3).

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO > 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.3. Receiver/Exciter volume CER.

Three CERs were developed for transmitters. The first CER is a weight based relationship, the second an RF output power curve fit, and the third is driven by the volume of the transmitter box. Included in the transmitter costs and characteristics are all the analog and microwave components, the structure, and the power supply. The range of the cost and physical characteristic data of the transmitters used in this analysis is shown in table 2.2.

The weight based CER for transmitters is shown in figure 2.4. Ground mobile and shipborne equipment were combined in this relationship and are estimated by the weight value and the intercept. The costs of the other four basing modes are captured by the addition of dummy variables (factors).

The RF output power (generated by the transmitter unit) CER is shown in figure 2.5. In this relationship, the frequency of operation in megahertz and a dummy variable for solid state transmitters were added to the equation. Shipborne, ground mobile, and aircraft transmitters were all combined to calibrate the intercept term. Missile, low earth orbit space, and high earth orbit space transmitters were all found to cost more (on a dollars per output watt basis) than ground, shipborne, and aircraft transmitters.

The size CER (using volume of the transmitter box as the cost driver) is depicted in figure 2.6. In this analysis, shipborne equipment was combined with ground mobile equipment and missile transmitters were found to not cost significantly more or less than aircraft transmitters, which were not found to cost no more or less than low earth orbit space transmitters. Thus, missile, aircraft, and low earth orbit space transmitters were combined to jointly calibrate a composite basing mode factor as shown in figure 2.6.

TABLE 2.2

Range of Transmitter Data

	Parameters			
	# Points	Low Value	Average	High Value
Shipborne and Ground Mobile				
Costs ($K)	7	37.7	3,289	13,761
Weight (lbs)	6	35	4,632	20,200
RF Output Power (watts)	6	312	9,185	32,000
Volume (in^3)	5	33,817	411.1K	1,426K
Missile				
Costs ($K)	5	85.5	245	424.6
Weight (lbs)	5	11	23.2	32.6
RF Output Power (watts)	5	6	25.5	46.7
Volume (in^3)	5	156	715	1,589
Aircraft				
Costs ($K)	5	211.4	564	8,193
Weight (lbs)	5	69	118	3,566
RF Output Power (watts)	4	120	10.5K	41K
Volume (in^3)	4	1,152	159K	629K
Low Earth Orbit Space				
Costs ($K)	6	17.7	82.3	159.6
Weight (lbs)	5	1.2	3.1	7.0
RF Output Power (watts)	5	1.0	5.8	20
Volume (in^3)	3	36	80	162
High Earth Orbit Space				
Costs ($K)	26	54.7	370	1,344
Weight (lbs)	23	0.8	7.2	28.3
RF Output Power (watts)	11	1.0	20.6	88.6
Volume (in^3)	12	12	363	1,780

Transmitters

$$UC_{1,FY86,\$K} = 2.68(Weight)^{0.857}\ e^{1.32(A/C)}\ e^{1.74(Msl)}\ e^{2.60(LEO)}\ e^{3.30(HEO)}$$

t-values →	(2.11)	(14.14)	(4.49)	(4.79)	(5.65)	(8.60)
Basing Mode Factors →			(x3.74)	(x5.70)	(x13.5)	(x27.1)

$R^2 = 89.1$

$\bar{R}^2 = 87.7$

$S = \left\{ \begin{matrix} +57.2\% \\ -36.4\% \end{matrix} \right\}$

44 Data Points

Ship-2	Msl-5
Grd-4	LEO Space-5
A/C-5	HEO Space-23

F = 62.1

38 Degrees of Freedom

RMS % Error = 44.7%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Weight = Weight of the Transmitter in pounds (lbs).

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft system, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO > 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.4. Transmitter weight CER.

Transmitters

$$UC_{1,FY86,\$K} = 1.15(Power)^{0.550}\ (Freq)^{0.333}\ e^{0.426(S.S.)}\ e^{0.589(Msl)}\ e^{0.852(LEO)}\ e^{1.86(HEO)}$$

t-values →	(0.07)	(13.18)	(4.88)	(2.17)	(2.23)	(2.48)	(6.92)
Basing Mode Factors →				(x1.53)	(x1.80)	(x2.34)	(x6.42)

$R^2 = 94.8$

$\bar{R}^2 = 93.6$

$S = \begin{Bmatrix} +40.5\% \\ -28.8\% \end{Bmatrix}$

31 Data Points: Ship-2, Grd-4, A/C-4, Msl-5, LEO Space-5, HEO Space-11

$F = 73.5$

24 Degrees of Freedom

RMS % Error = 28.6%

where

$UC_{1,FY86,\$k}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Power = RF output power of the Transmitter in watts.

Freq = Frequency of Transmitter in megahertz (MHz).

S.S. = 1 for Solid-State Transmitter, 0 for TWT Transmitter.

Msl = 1 for Missile/Interceptor, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO > 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.5. Transmitter RF output CER.

Transmitters

$$UC_{1,FY86,\$K} = 2.88(\text{Volume})^{0.545}\ e^{0.887(\text{Msl, A/C, \& LEO})}\ e^{2.15(\text{HEO})}$$

t-values →	(1.88)	(12.63)	(2.65)	(5.76)
Basing Mode Factors →			(x2.43)	(x8.58)

$R^2 = 90.7$

$\bar{R}^2 = 89.5$

$S = \left\{ \begin{matrix} +55.3\% \\ -35.6\% \end{matrix} \right\}$

29 Data Points

Ship-2	Msl-5
Grd-3	LEO Space-3
A/C-4	HEO Space-12

F = 80.8

25 Degrees of Freedom

RMS % Error = 30.9%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Volume = Volume of the Transmitter Box in cubic inches (in^3).

Msl, A/C, & LEO = 1 for Missile/Interceptor/Aircraft/Low Earth Orbit (LEO) Space System, 0 otherwise (200 miles < LEO < 22,300 miles).

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.6. Transmitter volume CER.

2.3 DIGITAL ELECTRONICS

Digital electronics consists of the various types of electronic boxes which employ digital electronic devices. Boxes such as signal processors, data processors, digital interface units, encoders, decoders, and digital multiplexers all employ a variety of digital components such as processor chips, memories, converters, controllers, timers, decoders, and interfaces, along with biasing and control circuitry. These boxes typically process the information received by the radar after it has been digitized.

Three CERs were developed for digital electronics. One based on weight, one based on input power, and the third based on the size of the digital box. The costs and physical characteristics in this data set include all the components (ICs and discretes), the printed circuit boards, interconnects, housing, and fans in the design of the digital box. The characteristics of the data set (range of values, average values, and number of data points) of the digital electronics set are presented in table 2.3.

The weight based CER for digital electronics is depicted in figure 2.7. In this CER, each basing mode was calibrated differently from the other basing modes. Similar to the weight based CER for receivers/exciters, shipborne equipment is cheapest, followed by ground mobile, missile, aircraft, low earth orbit space, and high earth orbit space equipment.

The input power CER for digital electronics is shown in figure 2.8. Shipborne, ground mobile, missile, and aircraft were all found to be insignificantly different from each other and, thus, were combined in the analysis. Low earth orbit and high earth orbit space were found to cost more than the atmospheric systems as shown by the two significant dummy variables in the curve fit.

TABLE 2.3

Range of Digital Electronics Data

	Parameters			
	# Points	Low Value	Average	High Value
Shipborne				
Costs ($K)	8	73.3	851.6	1,392
Weight (lbs)	8	34	929	1,510
Input Power (watts)	5	2,220	2,660	3,800
Volume (in^3)	8	5,443	40.3K	58.9K
Ground Mobile				
Costs ($K)	8	103.7	861	2,195
Weight (lbs)	7	24	328	1,100
Input Power (watts)	6	80	2,040	7,500
Volume (in^3)	7	2,903	30K	62K
Missile				
Costs ($K)	16	48.8	126.7	514.4
Weight (lbs)	12	5.5	11.8	32.8
Input Power (watts)	10	36.3	102.3	294.4
Volume (in^3)	12	79.2	238	942
Aircraft				
Costs ($K)	6	194.3	1113.5	3,393
Weight (lbs)	6	13.9	130	572
Input Power (watts)	6	234	1,594	4,225
Volume (in^3)	6	317	7,140	37.5K
Low Earth Orbit Space				
Costs ($K)	17	26.3	207	1,247
Weight (lbs)	15	0.7	5.9	30
Input Power (watts)	5	1.4	7.1	10.2
Volume (in^3)	14	17	172	548
High Earth Orbit Space				
Costs ($K)	21	37.0	670	1,448
Weight (lbs)	19	0.8	12.5	27.2
Input Power (watts)	12	0.7	9.6	22
Volume (in^3)	9	231	627	855

Digital Electronics

$$UC_{1,FY86,\$K} = 5.95(Weight)^{0.772}\ e^{0.529(Grd)}\ e^{1.28(Msl)}\ e^{1.84(A/C)}\ e^{2.03(LEO)}\ e^{2.86(HEO)}$$

t-values →	(4.64)	(13.68)	(2.12)	(4.22)	(6.53)	(5.94)	(9.62)
Basing Mode Factors →			(x1.70)	(x3.60)	(x6.30)	(x7.61)	(x17.5)

$R^2 = 86.1$

$\bar{R}^2 = 84.7$

$S = \left\{ \begin{array}{l} +59.7\% \\ -37.4\% \end{array} \right\}$

67 Data Points: Ship-8, Grd-7, Msl-12, A/C-6, LEO Space-15, HEO Space-19

F = 61.3

60 Degrees of Freedom

RMS % Error = 45.4%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Weight = Weight of the Digital Electronics Box in pounds (lbs).

Grd = 1 for Ground Mobile System, 0 otherwise.

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.7. Digital Electronics weight CER.

Digital Electronics

$$UC_{1,FY86,\$K} = 5.93(Power)^{0.703}\, e^{2.44(LEO)}\, e^{3.10(HEO)}$$

t-values → (6.01) (14.95) (8.13) (12.38)

Basing Mode Factors → (x11.5) (x22.2)

R^2 = 85.5

$\bar{R}^2$ = 84.4

S = { +55.7%, -35.8% }

44 Data Points: Ship-5, Grd-6, A/C-6, Msl-10, LEO Space-5, HEO Space-12

F = 78.6

40 Degrees of Freedom

RMS % Error = 41.4%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Power = Input power to Digital Box in watts.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.8. Digital Electronics input power CER.

The third CER, driven by the volume of the digital electronics box, is depicted in figure 2.9. Here again, all the basing modes are calibrated to cost different from each other.

2.4 ANALOG ELECTRONICS

Analog electronics consists of the various types of electronic boxes which employ analog circuitry below the RF frequency of 1 MHz and employ DC electronics to operate controls and displays and to power servo and drive electronics. Analog interface units, phase shifter driver circuitry, seekerhead control electronics, servo control electronics, gimbal motor driver circuitry, and display/controls electronics are all examples of the types of electronics included in the category of analog electronics.

Three relationships based on weight, input power and volume were developed for the category of analog electronics. Included in the cost and the physical characteristics of analog electronics are all the analog components (ICs and discrete components), the printed circuit boards, the interconnect, the housing, and fans in the design. Characteristics of the analog data set are presented in table 2.4.

The weight based CER for analog electronics is depicted in figure 2.10. Here again, all the basing modes were calibrated differently.

The input power CER is shown in figure 2.11. The shipborne equipment was combined with the ground mobile equipment and are calibrated by the intercept term. The missile and aircraft data points were combined to form a composite factor for airborne equipment.

The volume CER for analog electronics is presented in figure 2.12. Ground mobile equipment was not found to cost significantly different than shipborne equipment and, thus, these basing mode data points were combined to calibrate the intercept term. Aircraft equipment was found to cost

Digital Electronics

$$UC_{1,FY86,\$K} = 0.288(\text{Volume})^{0.758}\ e^{0.409(Grd)}\ e^{2.20(Msl)}\ e^{2.38(A/C)}\ e^{2.25(LEO)}\ e^{3.00(HEO)}$$

t-values →	(-2.02)	(13.02)	(1.94)	(8.56)	(6.29)	(6.16)	(9.99)
Basing Mode Factors →			(x1.51)	(x9.03)	(x10.8)	(x9.49)	(x20.1)

$R^2 = 90.2$

$\bar{R}^2 = 89.0$

$S = \left\{ \begin{matrix} +49.8\% \\ -33.2\% \end{matrix} \right\}$

56 Data Points: Ship-8, Grd-7, A/C-6, Msl-12, LEO Space-14, HEO Space-9

F = 75.5

49 Degrees of Freedom

RMS % Error = 33.8%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Volume = Volume of the Digital Box in cubic inches (in^3).

Grd = 1 for Ground Mobile System, 0 otherwise.

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.9. Digital Electronics volume CER.

TABLE 2.4

Range of Analog Electronics Data

	Parameters			
	# Points	Low Value	Average	High Value
Shipborne				
Costs ($K)	9	37.5	388	1,119
Weight (lbs)	9	39	562	1,515
Input Power (watts)	4	550	1,188	2,100
Volume (in^3)	6	3,810	31.4K	58.9K
Ground Mobile				
Costs ($K)	6	39.8	150	372
Weight (lbs)	5	20.5	81	250
Input Power (watts)	6	220	663	2,000
Volume (in^3)	6	1,140	6,581	17.1K
Missile				
Costs ($K)	13	5.6	29.9	109.3
Weight (lbs)	12	0.9	4.6	11.0
Input Power (watts)	10	3.1	17.8	51.3
Volume (in^3)	12	23.6	84.1	240
Aircraft				
Costs ($K)	7	10.9	70.5	190.7
Weight (lbs)	7	2.2	16.8	68
Input Power (watts)	2	21	180	340
Volume (in^3)	6	30	933	4,320
Low Earth Orbit Space				
Costs ($K)	11	33.8	77.0	206.7
Weight (lbs)	9	1.2	4.6	12.6
Input Power (watts)	5	1.0	2.2	4.2
Volume (in^3)	6	28.8	266	877
High Earth Orbit Space				
Costs ($K)	21	5.3	322	2,676
Weight (lbs)	16	0.4	12.4	42.6
Input Power (watts)	4	1.7	11.9	19.0
Volume (in^3)	6	150	586	2,122

Analog Electronics

$$UC_{1,FY86,\$K} = 3.13(Weight)^{0.758}\ e^{0.583(Grd)}\ e^{1.22(Msl)}\ e^{1.25(A/C)}\ e^{2.10(LEO)}\ e^{3.27(HEO)}$$

t-values →	(3.16)	(12.99)	(1.97)	(3.65)	(3.91)	(6.15)	(10.84)
Basing Mode Factors →			(x1.79)	(x3.39)	(x3.49)	(x8.17)	(x26.3)

$R^2 = 88.2$

$\bar{R}^2 = 86.8$

$S = \left\{ \begin{array}{l} +65.7\% \\ -39.6\% \end{array} \right\}$

58 Data Points

Ship-9	Msl-12
Grd-5	LEO Space-9
A/C-7	HEO Space-16

F = 63.3

51 Degrees of Freedom

RMS % Error = 58.3%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Weight = Weight of the Analog Box in pounds (lbs).

Grd = 1 for Ground Mobile System, 0 otherwise.

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.10. Analog Electronics weight CER.

Analog Electronics

$$UC_{1,FY86,\$K} = 1.38(\text{Power})^{0.811}\ e^{0.890(\text{Msl \& A/C})}\ e^{2.91(\text{LEO})}\ e^{3.20(\text{HEO})}$$

t-values → (0.55) (9.03) (2.39) (5.50) (6.95)

Basing Mode Factors → (x2.44) (x18.4) (x24.5)

R^2 = 87.7	**31 Data Points**	F = 46.5
$\bar{R}^2$ = 85.8	Ship-4, Msl-10	26 Degrees of Freedom
S = {+62.3%, -38.4%}	Grd-6, LEO Space-5	RMS % Error = 46.8%
	A/C-2, HEO Space-4	

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Power = Input power to Analog Box in watts.

Msl & A/C = 1 for Missile/Interceptor/Aircraft, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space system (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.11. Analog Electronics input power CER.

Analog Electronics

$$UC_{1,FY86,\$K} = 0.301(Volume)^{0.720}\ e^{1.24(A/C)}\ e^{1.47(Msl)}\ e^{2.04(LEO)}\ e^{3.12(HEO)}$$

t-values →	(-1.94)	(10.74)	(3.67)	(3.86)	(5.43)	(9.47)
Basing Mode Factors →			(x3.46)	(x4.35)	(x7.69)	(x22.6)

$R^2 = 88.9$

$\bar{R}^2 = 87.4$

$S = \begin{Bmatrix} +65.5\% \\ -39.6\% \end{Bmatrix}$

42 Data Points

Ship-6	Msl-12
Grd-6	LEO Space-6
A/C-6	HEO Space-6

F = 57.7

36 Degrees of Freedom

RMS % Error = 55.7%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Volume = Volume of the Analog Box in cubic inches (in^3).

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.12. Analog Electronics volume CER.

slightly less than missile equipment, which is less than low earth orbit space, which is less than high earth orbit space on a dollars per cubic inch basis.

2.5 POWER CONDITIONERS

Power conditioners, often called power supplies, condition input power for use by receivers, processors, analog electronics, and other electronic assemblies. Power from the source (a battery or a generator) is input into these units as AC or DC voltages. The conditioner then transforms the AC voltage to the desired DC voltages or transforms a DC voltage to other DC voltages and often regulates the voltage levels to a desired specification. The input power into a processor or receiver box with a power supply is consumed by both the equipment and the power supply. Typically, a power supply will be approximately 60 percent efficient (i.e., consume 40 percent of the input power) at small power levels and can be as high as 70 to 80 percent efficient at higher power levels.

All the power supplies in this analysis are low voltage power supplies.

Three cost estimating relationships were developed for power conditioners. They are based on weight, output power supplied by the power conditioner, and volume of the conditioner housing. In this analysis, space data points were only available for the weight based CER. Output power supplied by the conditioner and the volume of the conditioner box were not available at the time of this analysis for the low earth orbit and high earth orbit space equipment.

The characteristics of the power conditioner data set are depicted in table 2.5. The number of each basing mode data points is shown, with the range of the costs and physical parameters.

TABLE 2.5

Range of Power Conditioner Data

	Parameters			
	# Points	Low Value	Average	High Value
Shipborne				
Costs ($K)	3	395	585	942
Weight (lbs)	3	1,390	1,565	1,667
Output Power (watts)	0	--	--	--
Volume (in^3)	0	--	--	--
Ground Mobile				
Costs ($K)	3	11.7	38.7	78.4
Weight (lbs)	3	28	90.8	184.5
Output Power (watts)	3	1000	9,302	27.4K
Volume (in^3)	2	777.6	1,684	2,592
Missile				
Costs ($K)	14	2.3	23.8	41.9
Weight (lbs)	13	1.4	9.3	19.0
Output Power (watts)	8	57.8	215	466
Volume (in^3)	11	60	180	314
Aircraft				
Costs ($K)	7	29.1	133	509
Weight (lbs)	7	7.1	60.4	294
Output Power (watts)	7	126	1,737	4,225
Volume (in^3)	7	163	2,084	12.5K
Low Earth Orbit Space				
Costs ($K)	5	14.0	254	562
Weight (lbs)	5	0.6	17.7	50.2
Output Power (watts)	0	--	--	--
Volume (in^3)	0	--	--	--
High Earth Orbit Space				
Costs ($K)	7	214.8	542	1,054
Weight (lbs)	7	9.0	19.3	47.9
Output Power (watts)	0	--	--	--
Volume (in^3)	0	--	--	--

The weight based CER for power conditioners is presented in figure 2.13. Shipborne and ground mobile power conditioners were combined to calibrate the intercept term. Missile, aircraft, low earth orbit, and high earth orbit space conditioners are all calibrated separately.

The CER driven by the output power supplied by the conditioner is shown in figure 2.14. The cost data in this CER was stratified into two sets. One consisting of ground mobile conditioners, and the other comprising missile and aircraft equipment. There were no shipborne conditioners to add to this CER.

The volume CER for power conditioners is shown in figure 2.15. This data set also only consists of ground mobile, missile, and aircraft equipment. Each of these basing modes were found to cost different, as depicted by the relationship.

2.6 PHASED ARRAY/PLANAR ARRAY ANTENNAS

There were many types of antennas in the low earth orbit and high earth orbit space data sets. However, there were only phased array antennas in the shipborne and ground mobile data sets, planar array antennas in the missile data set, and planar and phased array antennas in the aircraft data set. Since it was deemed necessary to include a CER that represented structural items exhibiting important microwave transmission properties, it was decided to develop a CER based on weight for phased array and planar array antennas. Even though phased array antennas operate differently than planar array antennas, a CER based on weight would still capture the common elements of structure, waveguide, and combiners/dividers, while it is hoped the cost of phase shifters, driver circuitry, and power supplies of phased array antennas would offset the cost of servo amplifiers, torquers, and gimbals of planar array antennas.

There were no phased array or planar array antennas in the low earth orbit space data set. However, there were four high earth orbit space

Power Conditioners

$$UC_{1,FY86,\$K} = 0.990(\text{Weight})^{0.860}\ e^{1.37(\text{Msl})}\ e^{1.75(\text{A/C})}\ e^{3.29(\text{LEO})}\ e^{3.72(\text{HEO})}$$

t-values →	(-0.03)	(13.91)	(4.41)	(6.27)	(9.37)	(12.52)
Basing Mode Factors →			(x3.94)	(x5.75)	(x26.8)	(x41.3)

$R^2 = 93.7$

$\bar{R}^2 = 92.7$

$S = \left\{ \begin{matrix} +52.2\% \\ -34.3\% \end{matrix} \right\}$

38 Data Points

Ship-3	Msl-13
Grd-3	LEO Space-5
A/C-7	HEO Space-7

F = 95.5

32 Degrees of Freedom

RMS % Error = 62.1%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Weight = Weight of the Power Conditioner in pounds (lbs).

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

LEO = 1 for Low Earth Orbit (LEO) Space System (200 < LEO < 3,000 miles), 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.13. Power Conditioner weight CER.

Power Conditioners

$$UC_{1,FY86,\$K} = 0.659(\text{Power})^{0.520}\, e^{1.36(\text{Msl \& A/C})}$$

t-values → (-0.56) (5.73) (3.99)

Basing Mode Factors → (x3.90)

R^2 = 70.5

$\bar{R}^2$ = 66.6

$S = \left\{ \begin{matrix} +63.0\% \\ -38.7\% \end{matrix} \right\}$

18 Data Points: Grd-3, Msl-8, A/C-7

F = 17.9

15 Degrees of Freedom

RMS % Error = 45.9%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Power = Output power of the Power Conditioner in watts.

Msl & A/C = 1 for Missile/Interceptor/Aircraft, 0 otherwise.

Figure 2.14. Power Conditioner output power CER.

Power Conditioners

$$UC_{1,FY86,\$K} = 0.271(Volume)^{0.593}\ e^{1.71(Msl)}\ e^{2.20(A/C)}$$

t-values →	(-3.31)	(11.75)	(8.[illegible]1)	(12.62)
Basing Mode Factors →			(x5.53)	(x9.03)

R^2 = 95.1

$\bar{R}^2$ = 94.2

$S = \begin{Bmatrix} +23.1\% \\ -18.7\% \end{Bmatrix}$

(20 Data Points: Grd-2, A/C-7, Msl-11)

F = 103.2

16 Degrees of Freedom

RMS % Error = 19.3%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Volume = Volume of the Power Conditioner Box in cubic inches (in^3).

Msl = 1 for Missile/Interceptor, 0 otherwise.

A/C = 1 for Aircraft System, 0 otherwise.

Figure 2.15. Power Conditioner volume CER.

phased array antennas in the data set. The range of the costs and the weights of the ground mobile, shipborne, aircraft, missile, and high earth orbit space antennas are shown in table 2.6.

The weight based antenna CER is depicted in figure 2.16. The shipborne antenna was combined with the ground mobile antennas to calibrate the intercept term in the CER. The missile and aircraft data points were combined to calibrate a composite airborne factor for these two basing modes.

TABLE 2.6

Range of Phased Array/Planar Array Antenna Data

	Parameters			
	# Points	Low Value	Average	High Value
Shipborne & Ground Mobile				
Costs ($K)	5	318.4	5,636	10,067
Weight (lbs)	5	209	4,983	13,050
Missile				
Costs ($K)	7	57.2	135.4	208.8
Weight (lbs)	7	8.5	28.0	50.5
Aircraft				
Costs ($K)	3	151.7	277.7	416.8
Weight (lbs)	3	21.4	56.8	85.0
High Earth Orbit Space				
Costs ($K)	4	91.5	1,093	2,656
Weight (lbs)	4	12.2	68.4	170.7

Phased Array/Planar Array Antennas

$$UC_{1,FY86,\$K} = 2.92(\text{Weight})^{0.905}\ e^{1.05(\text{Msl \& A/C})}\ e^{1.88(\text{HEO})}$$

t-values →	(1.35)	(9.15)	(2.11)	(3.86)
Basing Mode Factors →			(x2.86)	(x6.55)

$R^2 = 94.5$

$\bar{R}^2 = 93.5$

$S = \left\{ \begin{matrix} +52.7\% \\ -34.5\% \end{matrix} \right\}$

20 Data Points: Ship-1, Grd-4, A/C-3, Msl-7, HEO Space-4

F = 92.1

16 Degrees of Freedom

RMS % Error = 39.3%

where

$UC_{1,FY86,\$K}$ = Unit cost of the first delivered Hardware Unit in thousands of FY86 dollars.

Weight = Weight of the Antenna Array in pounds (lbs).

Msl & A/C = 1 for Missile/Interceptor/Aircraft, 0 otherwise.

HEO = 1 for High Earth Orbit (HEO) Space System (10,000 < HEO < 22,300 miles), 0 otherwise.

Figure 2.16. Phased Array/Planar Array Antennas weight CER.

3
RESULTS

This section documents the results of comparing the various basing modes with each other (e.g., Ground Mobile versus Low Earth Orbit Space) and our observations about how these results should be used to generate cost estimates for future systems in basing modes where designs have not been developed and hardware has not been built.

In this section, the quantified cost differences on a dollars per pound, dollars per watt, and dollars per cubic inch basis, estimated empirically by the CERs in section 2, will be referred to as cost differences. These costs represent differences before the electronic boxes have been normalized for functional equivalency. The added cost of procuring an electronic box from one basing mode to another that will be estimated in this section will be referred to as delta cost factors. These delta cost factors are the added cost of procuring a functional equivalent box from one basing mode to another and are the factors which can be applied to ground mobile and airborne designs to yield cost estimates of equivalent airborne and space designs, respectively.

Using design (hardware physical/performance characteristics such as weight, power, and volume) and cost data based on existing systems, cost estimates can be generated for these systems in their basing mode. This can be accomplished for electronic equipment using the CERs developed and documented in section 2 of this report. However, when it is necessary to estimate the cost of a system which operates in a basing mode where no operational hardware has been built and no complete design has been developed, it is impossible to generate a cost estimate in a straightforward fashion. This is because no physical/performance parameters are available to input into a CER and no analogous system cost data is available. Without a developed technical baseline, cost estimators are helpless in generating reasonable cost estimates.

If one wanted to generate a cost estimate of a new airborne system that will perform functionally the same as a given ground design using the ground design parameters as cost inputs, one must first normalize for the physical differences between the two designs. That is to say to generate a cost estimate of an airborne system using weight of the ground system as the cost driver and then applying a cost difference factor (estimated in section 2) that has quantified airborne system weight to cost X times that of ground system weight would in most cases be incorrect. This is because an airborne system designed to operate functionally the same as a ground system will probably weigh less than a ground design. In this example, there is double counting in the cost estimate (e.g., the added cost of the additional weight in the ground design and the added cost of the more expensive airborne weight in the design). The same effect of double counting occurs when generating cost estimates for space systems based on airborne designs when the physical parameters or differences are not normalized. Thus, a comparison of the cost differences in manufacturing an equivalent piece of equipment in the ground mode versus the airborne mode using the physical parameter CERs developed here in section 2 has to normalize (or at least attempt to normalize) for the differences in the physical parameters (which are the CER cost drivers) between the two basing mode designs before the added (or delta cost factor) can be quantified. This normalization can be accomplished by either estimating the change in the physical parameter used to generate the cost estimate or by finding a physical parameter that does not change (or change significantly) from one basing mode to another (i.e., find a physical variable whose design constraint does not change or changes very little from one basing mode to another).

The development of usable basing mode delta cost factors in this section begins with the tabulation of the cost differences (the dollars per pound, dollars per watt, and dollars per cubic inch differences) going from one basing mode to another, as quantified in section 2 of this report. This is followed by an analysis which utilizes these results along with knowledge gained working in the area of electronic equipment design to identify the physical parameter that changes the least from one basing mode to another and use its basing mode cost difference as an estimate of the added cost (delta cost) from going from one basing mode to another. In this manner, we develop a set of ground-to-airborne and airborne-to-space delta cost factors which can be applied to cost estimates of ground and airborne designs to generate cost estimates of airborne and space designs in the absence of good engineering baselines.

An examination of the CERs developed in section 2 of this report seems to indicate that there is not a significant cost difference (statistically) between aircraft electronic equipment and missile electronic equipment when compared as a whole (i.e., a weighted comparison between all the different electronic boxes). Most CERs indicate aircraft electronic boxes cost more on a dollars per pound, dollars per watt, and dollars per cubic inch basis. But, a few CERs indicate missile electronics to be more expensive. Even though there are quite a few more CERs where aircraft electronics are more expensive, often the estimated basing mode value of missile equipments is within the standard error of the predicted basing mode value of aircraft equipment. This suggests that missile costs are not statistically different than aircraft costs for these equipment. With this in mind, a composite (equally weighted) aircraft and missile (called airborne) basing mode factor was calculated for each CER presented in section 2 and will represent both aircraft and missile equipments in this basing mode analysis.

This airborne composite cost factor for each CER was compared to the ground mobile basing mode cost factors and the Low Earth Orbit (LEO) space basing mode cost factors to find the cost difference (on a dollars per pound, dollars per watt, dollars per cubic inch basis) between ground mobile and airborne equipment, and between airborne and LEO space equipment. Likewise, LEO space equipment was compared to High Earth Orbit (HEO) space equipment to yield the cost difference between these two basing modes. These computed cost differences are shown in table 3.1 for the weight CERs, table 3.2 for the power CERs, and table 3.3 for the volume CERs.

TABLE 3.1

Weight Basing Mode Cost Differences

	Ground Mobile-to-Airborne Basing Mode Difference	Airborne-to-LEO Space Basing Mode Difference	LEO Space-to-HEO Space Basing Mode Difference	TOTAL: Ground-to-HEO Space Basing Mode Difference
Receivers/Exciters	2.15	1.68	2.73	9.86
Transmitters	4.72	2.86	2.01	27.1
Digital Electronics	2.91	1.54	2.30	10.3
Analog Electronics	1.92	2.37	3.23	14.7
Power Conditioners	4.84	5.54 ^	1.54	41.3
Phased Array/ Planar Array Antennas	2.86	1.00	2.29	6.55

"DO NOT USE AS DELTA COST FACTORS"

TABLE 3.2

Power Basing Mode Cost Differences

	Ground Mobile-to-Airborne Basing Mode Difference	Airborne-to-LEO Space Basing Mode Difference	LEO Space-to-HEO Space Basing Mode Difference	TOTAL: Ground-to-HEO Space Basing Mode Difference
Receivers/Exciters	2.45	7.63	1.32	24.7
Transmitters	1.40	1.67	2.75	6.43
Digital Electronics	1.00	11.5	1.93	22.2
Analog Electronics	2.44	7.54	1.33	24.5
Power Conditioners	3.90	(?)	(?)	(?)
Phased Array/ Planar Array Antennas	n/a	n/a	n/a	n/a

"DO NOT USE AS DELTA COST FACTORS"

TABLE 3.3

Volume Basing Mode Cost Differences

	Ground Mobile-to-Airborne Basing Mode Differnce	Airborne-to-LEO Space Basing Mode Difference	LEO Space-to-HEO Space Basing Mode Difference	TOTAL: Ground-to-HEO Space Basing Mode Difference
Receivers/Exciters	6.11	0.65	4.58	18.2
Transmitters	2.43	1.00	3.53	8.58
Digital Electronics	6.56	0.96	2.11	13.3
Analog Electronics	3.91	1.97	2.93	22.6
Power Conditioners	7.28	(?)	(?)	(?)
Phased Array/ Planar Array Antennas	n/a	n/a	n/a	n/a

"DO NOT USE AS DELTA COST FACTORS"

These basing mode cost differences represent a multiplicative cost factor increase for each type of equipment on a dollars per pound, dollars per watt, and dollars per cubic inch basis, going from one basing mode to the next. In all cases, except in two volume CERs (going from airborne to LEO space), costs on a dollars per unit basis stay the same or increase as one goes from ground mobile to airborne, to LEO space, to HEO space. This is represented by factors greater or equal to one. The far column on the right of each table represents the total cost difference going from ground mobile equipment to HEO space equipment. For example, the weight based cost difference for receivers/exciters of 9.86 for Total: Ground Mobile-to-HEO Space says that HEO space receivers/exciters cost 9.86 times what ground mobile receivers/exciters cost on a dollars per pound basis. Again, these cost differences have not been normalized for functional equivalency (i.e., a pound, watt, or cubic inch of ground electronics is not necessarily functionally equivalent to a pound, watt, or cubic inch of airborne and/or space electronics, etc.).

The factors depicted in tables 3.1 through 3.3 represent cost differences from one basing mode to another for the various electronic boxes and antennas in the data set. To obtain a single factor (a system factor) from one basing mode to another for weight, power, and volume, a weighted sum of these equipment factors was computed. This was done by first examining the data base and for each complete system calculating the percent of total weight, power, and volume that each type of electronic box and the antenna contributed to the system. An average of these values was computed and is shown typically for airborne radars and ground mobile radars in table 3.4.

A system cost difference factor going from one basing mode to another for weight, power, and volume was then calculated by multiplying the basing mode cost difference for each equipment by its relative percentage contribution to the system and summing each equipment's contribution. This analysis is performed in figure 3.1 for the ground mobile-to-airborne system cost factors for weight, power, and volume based on the relative percentage contributions of weight, power, and volume in

TABLE 3.4

Percentage Contribution of Weight, Power, and Volume in Average Airborne and Ground Mobile Radar by Type of Electronic Equipment and Antenna

	Weight	Power Consumed	Volume
Airborne Radar System	100%	100%	100%
Receiver/Exciter	9	6	12
Transmitter	28	47	35
Digital Electronics	16	23	23
Analog Electronics	6	5	8
Power Conditioners	16	17	22
Phased Array/Planar Array Antenna	25	--	--
Ground Mobile Radar System	100%	100%	100%
Receiver/Exciter	6	5	9
Transmitter	31	66	51
Digital Electronics	13	11	16
Analog Electronics	10	4	9
Power Conditioners	13	14	15
Phased Array/Planar Array Antenna	27	--	--

ground mobile radars. Also shown is the airborne-to-LEO and airborne-to-HEO space system cost factors for weight, power, and volume. These airborne-to-space factors were computed using the relative percentage contributions of weight, power, and volume in airborne radars. The power and volume weighted sums for airborne-to-LEO space and airborne-to-HEO space shown in figure 3.1 were divided by 0.83 and 0.78, respectively, to properly normalize for the absence of cost difference factors for power conditioning in this basing comparison.

The system ground mobile-to-airborne basing mode cost difference factors shown in figure 3.1 indicate airborne systems cost 3.56 times that of ground mobile systems on a weight basis, 1.80 times on a power basis, and 4.28 times on a volume basis. Similarly, LEO space systems cost 2.48 times that of airborne systems on a weight basis, 5.14 times on a power basis, and 1.03 times on a volume basis. HEO space systems cost 4.99 times that of airborne systems on a weight basis, 10.1 times on a power basis, and 3.23 times on a volume basis.

An examination of the ground mobile-to-airborne system cost difference factors in figure 3.1 depict the volume CERs changing the most, followed by the weight CERs (i.e., the cost difference factor for volume is greater than the cost difference factor for weight, which is greater than the cost difference factor for power). This would seem to indicate that the volume constraint changes the most, followed by the weight constraint when going from the ground mobile basing mode to the airborne basing mode.

These factors can be used to infer that there is a high payoff in system cost and effectiveness as volume and weight are reduced in airborne designs. This is best illustrated by comparing the volume and weight of an active missile guidance section (a radar employed in a missile platform) with that of ground mobile radar system. Thus, ground mobile and airborne systems cannot be compared on a dollars per cubic inch or dollars per pound basis to determine the delta cost due to the basing mode.

Ground Mobile-to-Airborne (System) Cost Differences

Weight = 0.06(2.15) + 0.31(4.72) + 0.13(2.91) + 0.10(1.92) + 0.13(4.84) + 0.27(2.86) = 3.56

Power = 0.05(2.4[illegible]) + 0.66(1.40) + 0.11(1.00) + 0.04(2.44) + 0.14(3.90) = **[1.80]**

Volume = 0.09(6.11) + 0.51(2.43) + 0.16(6.56) + 0.09(3.91) + 0.15(7.28) = 4.28

Airborne-to-Low Earth Orbit Space (System) Cost Differences

Weight = 0.09(1.68) + 0.28(2.86) + 0.16(1.54) + 0.06(2.37) + 0.16(5.54) + 0.25(1.00) = **[2.48]**

$$\text{Power} = \frac{1}{0.83}\left[0.06(7.63) + 0.47(1.67) + 0.23(11.5) + 0.05(7.54)\right] = 5.14$$

$$\text{Volume} = \frac{1}{0.78}\left[0.12(0.65) + 0.35(1.00) + 0.23(0.96) + 0.08(1.97)\right] = 1.03$$

Airborne-to-High Earth Orbit Space (System) Cost Differences

Weight = 0.09(4.59) + 0.28(5.75) + 0.16(3.54) + 0.06(7.66) + 0.16(8.53) + 0.25(2.29) = **[4.99]**

$$\text{Power} = \frac{1}{0.83}\left[0.06(10.1) + 0.47(4.59) + 0.23(22.2) + 0.05(10.0)\right] = 10.1$$

$$\text{Volume} = \frac{1}{0.78}\left[0.12(2.98) + 0.35(3.53) + 0.23(2.03) + 0.08(5.77)\right] = 3.23$$

ESTIMATED SYSTEM DELTA COST FACTORS

NOTE: Calculation of weighted (system) ground mobile-to-airborne, airborne-to-low earth orbit space, and airborne-to-high earth orbit space basing mode cost differences for weight, power, and volume based on the average percentage contribution of each type of electronic equipment and antenna in the radar system and its basing mode cost difference.

Figure 3.1. Calculations of system cost differences.

The third factor, power, however seems to change the least when going from a ground mobile system to an airborne system. The same basic families of analog and digital componentry are used for airborne systems that are used for ground mobile systems, resulting in approximately the same input power requirements per function. Also, there is no substitution for raw input power when trying to achieve a desired level of output RF power as say in a radar.

These observations lead us to conclude that the 1.80 system cost difference factor for power represents the best estimate of the delta cost from ground mobile-to-airborne systems. This factor could be applied to a cost estimate of a ground mobile design to yield a cost estimate of an equivalent airborne design which is intended to perform the same function.

The airborne-to-LEO space system cost difference factors in figure 3.1 show the power CERs changing the most, followed by the weight CERs and the volume CERs. This suggests that power becomes the most important constraint in designing and producing LEO space systems. Weight seems to be the second most important constraint of the design and volume the least important.

Power on a spacecraft is generated from inefficient solar cells and is stored in batteries for use. Special low power digital and analog circuitry is used extensively in LEO and HEO space electronic systems to conserve power and the cost of generating and controlling its distribution throughout the spacecraft. Also, the addition of power contributes to additions in the thermal control subsystem and costs of the spacecraft. Thus, airborne and space electronics cannot be compared on a dollars per watt basis in determining the delta cost due to the basing mode.

Volume in space systems does not seem to be an important constraint. Volume constraints seem to fall out as a result of the power and weight constraints. LEO space electronics do not cost any more than airborne electronics based on volume as shown by the 1.03 airborne-to-LEO space system cost difference factor computed in figure 3.1. This equal in cost result is difficult to accept when understanding and comparing the manufacturing environment and testing and programmatic differences in procuring airborne equipment from LEO space equipment (i.e., airborne equipment is procured in large quantities in a production environment and should cost less than space equipment procured in small quantities in a development engineering environment).

Weight of the electronics seems to be the constraint that changes the least when going from airborne to LEO space systems. In both basing modes, weight is an important constraint. Weight plays an important part in the aerodynamics of missiles and aircraft as well as determining the type of launch platform needed to launch a payload into space. Thus in both environments, weight constraints are optimized for system effectiveness and to conserve system costs.

These observations lead us to conclude that the 2.48 and 4.99 system cost difference factors for weight represent the best estimates of the delta cost from airborne-to-LEO space and airborne-to-HEO space systems, respectively. The same arguments stated for airborne-to-LEO space factors apply to airborne-to-HEO space factors. These factors could be applied to cost estimates of airborne designs to yield cost estimates of equivalent LEO and HEO space systems.

The estimates of the system delta cost factors between ground mobile, airborne, LEO space, and HEO space are shown in table 3.5. Shown below some of the factors are some of the reasons why equivalent electronic boxes cost more as the basing mode moves from the ground to HEO space. The major reason seems to be due to the increase in reliability associated with a riskier mode of operation and longer operational availability requirements as one moves from ground mobile systems to HEO space systems.

TABLE 3.5

Electronic Systems Delta Cost Factor Results

	Ground Mobile-to-Airborne	Airborne-to-LEO Space	LEO Space-to-HEO Space	Total Ground Mobile-to-HEO Space
Estimated System Delta Cost Factors (Added cost for an equivalent system from one basing mode to another) →	1.80X	2.5X	2.0X	9.0X
Factors causing an increase in cost →	Harsher environment. Added vibrational requirements. use of more expensive parts on a cost-per-functional equivalency basis to save weight and volume to meet performance requirements of system. Added reliability due to riskier mode of operation.	Lower procurement quantities. procurement in engineering development environment versus production environment. Higher reliability to meet operational availability requirements.	Higher reliability to meet more stringent operational availability requirements due to longer design life. Harsher environment.	
Adjusted System Delta Cost Factors (For the productionization of space systems) →	1.80X	$\frac{2.5}{1.64}$ = 1.5X (Where 1.64 is the estimated prototype T_1-to-production T_1 factor for airborne and ground electronic system procurement.)	2.0X	5.4X

Below the system delta cost factors are the adjusted system delta cost factors for the productionization of space systems. Here, the airborne-to-LEO space delta cost factor of 2.5 is divided by 1.64 (the estimated prototype T_1-to-production T_1 factor for airborne and ground electronic system procurement). The result of this calculation indicates that LEO space equipment would only cost 50 percent more than airborne equipment if space equipment were procured in larger quantities and in a production environment like that found in airborne and ground electronic systems. This would drop the total ground mobile-to-HEO space delta cost factor from 9.0 to 5.4.

The author advocates using only the system delta cost factors shown in table 3.5 as added cost factors for scaling up cost estimates in one basing mode to another. Although the system delta cost factors are derived from the box cost factors, it is recommended that one use the system factors shown in table 3.5 even if generating a box cost. The electronic box delta cost factors have more variation in them and might lead to questionable results if used to scale up costs of alternative basing mode box designs.

Although the estimated basing mode delta cost factors can be used to generate cost estimates of conceptual designs, there is no substitute for good engineering baselines for developing credible cost estimates.