

IDA PAPER P-3020

FUNCTIONAL COST-ESTIMATING RELATIONSHIPS FOR SPACECRAFT

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February 1996

Prepared for
Director, Ballistic Missile Defense Organization

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19960523 134

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Contract DASW01 94 C 0054

Task T-R2-597.13

PREFACE

This paper was prepared by the Institute for Defense Analyses (IDA) for the Director, Ballistic Missile Defense Organization, under a task entitled "Spacecraft Costs." The objective of the task was to develop a model for estimating spacecraft costs to be used in estimating Strategic Defense System (SDS) spacecraft costs.

This work was reviewed within IDA by Robert C. Oliver and William J. E. Shafer.

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I. INTRODUCTION

A. BACKGROUND

In 1988 when the former Strategic Defense Initiative Organization (SDIO) reviewed the costs of space-based antimissile defense systems such as the Space-based Interceptor and Brilliant Pebbles, questions arose concerning the use of traditional weight-based cost-estimating models, such as those developed by the Air Force Space and Missile Systems Center. Such models are product-oriented (provide estimates according to a hardware work breakdown structure), and SDIO needed a cost model that used performance cost drivers in conjunction with weight-based cost drivers in conjunction.

In addition, SDIO was interested in the functional breakdown of the spacecraft work breakdown structure. The Air Force spacecraft cost model is product-oriented and does not estimate cost by function (engineering and manufacturing). SDIO needed a cost model that addressed the engineering and manufacturing costs of the hardware elements.

To address these issues, SDIO, now the Ballistic Missile Defense Organization (BMDO), asked the Institute for Defense Analyses (IDA) to develop a spacecraft cost model at the spacecraft subsystem level using performance and physical characteristics other than weight as much as possible. The model was to be used as a cross-check to estimates generated by the Air Force cost model. Because SDIO wanted functional CERs that were developed using current programs, IDA was to update the Air Force database of satellites with more recent satellite programs.

SDIO was interested in what performance and programmatic cost drivers would provide insight into the differences in cost among Department of Defense (DoD), National Aeronautics and Space Administration (NASA), and commercial satellites. These cost drivers would help analysts quantify differences in satellite designs and characteristics.

Even though SDIO has become BMDO whose mission emphasizes theater missile defense, space-based systems are still important to the overall BMDO objective (e.g., the Space-based Laser).

B. APPROACH

IDA began by studying the cost models in use in the late 1980s and early 1990s. We found that the most frequently used models—Unmanned Space Vehicle Cost Model, Sixth Edition (USCM6) [1], Unmanned Spacecraft Cost Model, Fifth Edition (USCM5) [2], and the NASA Cost Model (NASCOM) [3]—used weight-based cost drivers most of the time. Also the USCM6 did not have any programs developed after 1982. IDA obtained the USCM7 [4] technical and cost data (actual program costs) from the Air Force Space and Missile Systems Center (SMC) and from satellite manufacturers.

After analyzing the data, we decided to develop cost-estimating relationships (CERs) for hardware elements by engineering and manufacturing activities. Nonrecurring (design, development, and testing) and recurring (fabrication, assembly, and integration) CERs were developed at the level of the satellite subsystem hardware using multiple regression. We also developed nonrecurring and recurring CERs at the level of the satellite program (items and activities not attributed to any particular subsystem).

We felt that by using functional CERs, our model would help analysts systematically time-phase their estimates by accounting for manufacturing costs that occur after engineering costs in the development phase. Current time-phasing techniques apply factors that are based on analogous programs. Also, our models de-emphasize weight-based cost drivers, which should improve estimates for the smaller and more capable (higher power, longer life, etc.) satellites of the future.

We showed our preliminary results to contractors and interested parties in the government and used their suggestions and experience to improve our CERs.

C. SCOPE

Our CERs account for the costs of the contractor's space portion of satellite programs but not the ground stations and launch vehicle costs. All the subsystems of the spacecraft bus are covered. We also provide CERs to estimate the communications payload of communications satellites. Other types of payloads, for example, surveillance, weather, and instruments (for experiments), are not addressed.

Also included are the costs of ground support equipment used in the design and production of the spacecraft and the costs of pre-launch, launch, and initial orbital operations support activities.

Government costs (project office) and system engineering and technical assistance contractors costs are not addressed in this study. The satellite control center's operating and support costs are also excluded.

D. RESULTS

By using weight-based parameters in conjunction with physical and performance specifications and programmatic cost drivers, we were able to develop a spacecraft cost model that is not overwhelmingly weight-based. Programmatic factors that reflect the requirements and acquisition environments in which the satellites were acquired were shown to significantly influence satellite costs. Segregating hardware subsystem costs by engineering and manufacturing functions provided insight into the cost breakdown of an estimate and explicitly highlights the functional cost drivers.

We found the following programmatic cost drivers to be significant :

- Prototype—Programs where prototypes were built in the development phase had higher costs.
- Design Newness—Programs involving significant new designs cost more in the development phase.
- Follow-On Acquisition—Satellites built by the same contractor as follow-on units to previous production lots cost less than new acquisitions.
- Missions—Communications missions cost more than other types of missions. Scientific missions cost less than other types of missions due to the shorter life on orbit. Operational satellites cost more than experimental ones that are not required to operate around the clock.
- User—NASA satellites cost less than DoD satellites to acquire due to differences in missions and acquisition requirements.
- Expendable Launcher—Satellites deployed by expendable launchers cost less than satellites launched by the Space Shuttle.
- Survivability—Satellites with antijamming and nuclear radiation hardening cost more than ones that do not have these features.
- Orbit—Satellites operating in low earth orbit cost less than satellites operating in higher orbits.
- Stabilization—Satellites with three-axis stabilization cost more than spinning and single-axis stabilized ones.
- Design Life—A satellite with a longer operating life costs more than one with a short life.

The following significant cost drivers are related to performance and other non-weight factors.

- Beginning-of-Life Power—High-power satellites are more capable and cost more.
- Solar Array Area—High-power satellites are more capable and cost more.
- End-of-Life Power—Longer life satellites require higher end-of-life power in order to function during their intended on-orbit life or design life.
- Aluminum Content—Composites are lighter and more expensive than aluminum.
- Steady State Low Temperature—Satellites operating at lower temperatures require more capable thermal control equipment.
- Number of Communications and Data-Handling Channels—Satellites with more channels are more capable and require more communications equipment.
- Telemetry, Tracking and Control (TT&C) Power—High-power TT&C subsystems are more capable and cost more.

We also found the following weight-based variables to be significant because larger satellites have larger and heavier subsystems, which cost more:

- Spacecraft Total Dry Weight (without fuels for propulsion subsystem)
- Structure Weight
- Thermal Control Subsystem Weight
- Attitude Determination and Control Subsystem (ADCS) Weight
- Sensor Components Weight (in the ACDS)
- Reaction Control and Propulsion Subsystem (RCPS) Weight
- TT&C Subsystem Weight
- Communications Payload Weight

By augmenting the performance and physical characteristic variables with programmatic cost drivers, we were able to enhance the capability of the models. By accounting for the different missions and acquisition strategies of the satellites in the database, we were able to produce models that can be used to estimate a wider range of satellite programs.

We used the CERs in the fall of 1993 to evaluate several space-based surveillance satellite options using different designs and technologies. The CERs provided estimates that made engineering sense.

II. METHOD AND DATABASE

A. METHOD

The method used to develop the CERs to estimate spacecraft costs was used previously by IDA for work done for the Defense Information Systems Agency (DISA) and BMDO [5 and 6]. We assumed that costs are related to programmatic, physical, and performance characteristics in an exponential form:

$$\text{Cost} = f(X_i/A, B_i) \quad i = 1, \dots, n \quad (\text{II-1})$$

where Cost represents the nonrecurring or recurring cost for a given subsystem or activity, X_i represents the programmatic, performance, or physical characteristic explanatory variable, and A and B_i are the parameters to be estimated.

We used the log transformed form of Equation II-1 to fit our data. In instances where we could not fit the equation using the log transformed form, we used a linear relationship.

The CERs that were developed using the log transformed form take on the intrinsically linear form $\text{Cost} = AX^B$. To estimate the coefficient of this equation, we transformed the equation to a logarithmic form and then applied ordinary least squares linear regression. To do this, the equation was transformed to a log-log form. The classical normal regression assumption is that the residuals are additive and normally distributed in log-log space with an expected value and mode of zero. When the equation is transformed from the log-log form back to its original form, the assumption implies that the resulting residuals are multiplicative and distributed *lognormally* with a mode of one. Because the lognormal distribution is right-skewed, the expected value and mode of the residuals were no longer equal; therefore the expected value is not one as desired. Because of this, the unadjusted multiplicative equation would yield values of the dependent variable that correspond to the mode. We made an adjustment to address the re-transformation bias so that the CER would yield the expected value [7].

The adjustment was made to the relevant CERs by adding one-half of the regression mean square error ($\hat{\sigma}^2$) to the intercept term of the log-log equation before its transformation into the multiplicative form. After the intercept term was transformed into a

multiplicative constant, we calculated an adjustment factor (adjusted constant term/unadjusted constant term) where the adjustment factor is always greater than one. In reporting the estimating relationships, we reported the adjusted multiplicative equation along with the factor, so the equation can be back-adjusted to yield the mode (most likely value).

We modeled the recurring cost as a first-unit production cost (T1). This is the first flight unit built in the production phase. This assumption is similar to those used for the USCM6 and NASCOM models.

B. DATABASE

The database used in our study comprised 23 programs, as shown in Table II-1. We used the data from the update to USCM6 (USCM7) and functional cost, provided by TRW, Incorporated, and Rockwell International Corporation. The database includes recent satellite programs such as the Defense Support Program satellites 18-22 built in the late 1980s.

Table II-1. Satellite Database

Program	Mission	User	Contractor
Atmospheric Explorer (AE)	Scientific	NASA	RCA
Advanced Technology Satellite (ATS-F)	Communications	NASA	Fairchild
Combined Radiation Release Experiment Satellite (CRRES)	Scientific	NASA/DoD	Ball
Defense Meteorological Satellite Program (DMSP-5D1)	Weather	DoD	General Electric
Defense Support Program (DSP 14-17)	Surveillance	DoD	TRW
Defense Support Program (DSP 18-22)	Surveillance	DoD	TRW
Fleet Satellite Communications (FLTSATCOM 1-5)	Communications	DoD	TRW
Fleet Satellite Communications (FLTSATCOM 6-8)	Communications	DoD	TRW
Global Positioning System (GPS 9-11)	Navigation	DoD	Rockwell
Global Positioning System (GPS 12)	Navigation	DoD	Rockwell
Global Positioning System (GPS 13-40)	Navigation	DoD	Rockwell
Global Positioning System (GPS 1-5)	Navigation	DoD	Rockwell
Gamma Ray Observatory (GRO)	Scientific	NASA	TRW
Intelligence Satellite (INTELSAT) IV (I-4)	Communications	Commercial	Hughes
Initial Defense Communications Satellite Program (IDCSP)	Communications	DoD	Ford Aerospace
Defense Satellite Communications System (DSCS-3A)	Communications	DoD	General Electric
NATO Communications Satellite System (NATO-3)	Communications	DoD	Ford Aerospace
Orbiting Solar Observatory (OSO-I)	Scientific	NASA	Hughes
P-72-2	Scientific	DoD	Rockwell
P-78	Scientific	DoD	Ball
S3	Scientific	DoD	Boeing
Tactical Communications Satellite (TACSAT)	Communications	DoD	Hughes
Tracking and Data Relay Satellite System (TDRSS 1-6)	Communications	NASA	TRW

We obtained the Goddard and Marshall Space Flight Center satellite databases from NASA but were unable to use them because costs were not segregated by engineering and manufacturing functions.

C. WORK BREAKDOWN STRUCTURE

The functions and corresponding activities in the work breakdown structure (WBS) used in our study are shown in Table II-2. Nonrecurring costs apply to design, development, test, and prototype manufacturing activities in the engineering and manufacturing development (EMD) phase. Recurring cost functions are fabrication, assembly, integration, and sustaining engineering activities in the production phase. Program-level nonrecurring and recurring cost functions (those not associated with any single hardware element) and their corresponding activities are also shown in Table II-2.

Table II-2. Spacecraft Functional Cost Categories

Function	Activities/Items Included
<i>Subsystem Level</i>	
Hardware Engineering (nonrecurring)	Design, development, planning, studies, etc.
Hardware Manufacturing (nonrecurring)	Fabrication, assembly, tests, subsystem tooling, etc.
Hardware Manufacturing (recurring)	Fabrication, assembly, integration, tests, etc.
<i>Program Level</i>	
Hardware Engineering (recurring)	Sustaining engineering
Integration and Assembly (nonrecurring and recurring)	Spacecraft integration and assembly
Program Management and Data (nonrecurring and recurring)	Management, reviews, cost and schedule management, documentation, etc.
System Engineering (nonrecurring and recurring)	Reliability, quality control, studies and analyses, standardization, safety engineering, etc.
System Test and Evaluation (nonrecurring and recurring)	Verification, inspection, and qualification tests and procedures
Aerospace Ground Equipment (nonrecurring)	Mechanical and electrical fixtures, tools, equipment, etc.
Launch Operations and Orbital Support (recurring)	Pre-launch and launch operations and support

Subsystem hardware and associated equipment are shown in Table II-3. For each subsystem, we developed nonrecurring and recurring functional (engineering and manufacturing) CERs.

Table II-3. Spacecraft Subsystem Equipment

Subsystem	Equipment
Structure	Central and expendable structures, mechanisms (despin equipment, etc.), and interstage
Thermal Control	Blankets, louvers, paints, insulation, heaters, radiators, etc.
Attitude Determination and Control	Sensors, processors, gyroscopes, pendulums, magnetometers, etc.
Reaction Control/Propulsion	Nutation dampers, gravity gradient equipment, magnetic torques, inertia wheels, etc.
Electrical Power Supply	Solar array, gimbal, solar drive, batteries, power distribution units, wire harness, regulators, etc.
Telemetry, Tracking, and Command	Antennas, receivers, transponders, transmitters, analog and digital electronics, etc.
Communications Payload	Antennas, receivers, transponders, transmitters, analog and digital electronics, etc.

D. COST DRIVERS

In addition to performance and physical characteristic cost drivers, we considered the following programmatic cost drivers in our CER development:

- Mission—communications, surveillance, scientific, weather, or navigation
- User—DoD, NASA, or commercial
- Acquisition Strategy (Prototype/Protoflight)—quantifies the added cost in EMD to build a prototype
- Design Newness—differentiates new design efforts where similar components have not been built on previous programs from follow-on efforts where components have been used and flight-proven
- Spacecraft Total Dry Weight—provides the relative size of a satellite
- Production Quantity—gives the relative magnitude of the total program
- Design Life—gives the mission design life of the spacecraft in months
- Beginning-of-Life Power—provides the relative capability of a satellite
- Orbit—stratifies the altitude of the spacecraft (low, medium, and high)
- Operational/Experimental—represents the duty cycle of the spacecraft
- Nuclear Radiation Hardening Level—quantifies the added cost to harden against nuclear weapons [8]

- Contract Year—a time-trending variable to capture changes over time
- Launch Year—another time-trending variable to capture changes over time

These programmatic cost drivers allowed us to stratify the cost data by mission, user, and any measure of program size and feature we hypothesized as having an effect on the subsystem hardware and program-level costs. As revealed in the next two chapters, we found some of these cost drivers to be significant.

For the subsystem hardware, we considered a number of variables, many of which proved to be significant. Table IV-4 lists the variables considered for our subsystem hardware CERs.

Table II-4. Spacecraft Subsystem Variables Considered

Subsystem	Variables Considered
Structure	spacecraft weight, structure weight, mechanism weight, nuclear hardening level, aluminum content, truss/shell design, solar array area, design life, expendable launch vehicle or space transportation system deployment
Thermal Control	Orbit type, nuclear hardening level, thermal control system weight, steady state high and low temperatures, beginning-of-life power, end-of-life power, design life
Attitude Determination and Control	stabilization type, spacecraft weight, attitude control system weight, sensor suite weight, digital electronics weight, design life, nuclear hardening level, sensor type, pointing accuracy, orbit type
Reaction Control/Propulsion	stabilization type, spacecraft weight, reaction control subsystem weight, propellant weight, tank volume, design life, specific impulse, maneuverability, burn time, orbit
Electrical Power Supply	beginning-of-life power, end-of-life power, solar array area, number of cells, number of batteries, capacity, nuclear hardening level, design life, electrical power supply weight, duty cycle, cell efficiency, orbit type
Telemetry, Tracking, and Command	number of channels, frequency, survivability, design life, subsystem weight, number of commands, orbit type, autonomy (cross linked), encryption, digital electronics weight, data rate, antenna gain, power
Communications Payload	same as for telemetry, tracking, and command (above)

III. SUBSYSTEM HARDWARE COST-ESTIMATING RELATIONSHIPS

A. STRUCTURE

1. Definition

The structure serves as the central frame of the space vehicle, providing mechanical support for all subsystems. It provides stability for the onboard sensors required to determine spacecraft "health" and heat paths required for thermal control. The structure must be designed to withstand launch loads, ground qualification and acceptance test loads, and on-orbit loads, shocks, and vibration.

The spacecraft structure consists of the central structure frame, all extendible structures (such as booms for solar arrays and sensors), all mechanisms, and the interstage. Mechanisms are devices "employed onboard the spacecraft to carry out various important functions, like antenna deployment, antenna pointing, solar array deployment, solar array (pointing), despin drive, etc." [9, pp. 64-71, 253]. The most common structural material is aluminum honeycomb due to its high stiffness and strength-to-weight ratio. Composite materials, if they are used, are typically used as outer sheets bonded to an aluminum honeycomb core [9, p. 71].

The interstage is commonly included in structure costs. The interstage is the "structural connection between the spacecraft and the launcher" [9, p. 74]. Its purpose is to separate the spacecraft from the launcher, usually by means of a pyrotechnic device and a set of compressed helical springs.

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The nonrecurring engineering CER for structure takes an exponential form and is expressed as a function of the structure subsystem weight (STRCWT) and a prototype indicator for whether the program used a prototype to demonstrate capability (PROTO). The resulting CER is shown in Equation (III-1).

$$NR_E = 178 \times STRCWT^{0.47} \times 2.93^{PROTO} \quad (III-1)$$

(1.98, .0762) (3.69, .0042)

N = 13 Adj. R² = 0.78 (linear) SEE = 2,239

The t-scores and probability levels are in parentheses below the parameter estimates.¹ N is the number of observations. SEE is the standard error of the estimate, which is in the dimension of the dependent variable and indicates better fit for smaller values.² We computed the adjusted R² value in the original (Cartesian) linear space for the log-transformed CERs.³

The sample for the equation contains the following thirteen systems: AE, DSCS-3A, FLTSATCOM 1-5, GPS 1-5, GPS 12, IDCSP, I-4, NATO-3, OSO-I, P-72-2, P-78, S3, and TDRSS 1-6.

A scatter plot showing actual versus predicted costs using Equation (III-1) is shown in Figure III-1. The independent variable STRCWT has a sample average of 418 pounds and a range of 142 pounds to 1,030 pounds. The nonrecurring engineering costs range from \$1.6 million to \$16.3 million with the average equal to \$5.7 million in FY 1992 dollars.

The regression results indicate that a 1-percent change in structure weight results in a 0.47-percent change in nonrecurring engineering structure cost. The weight of the spacecraft structure is highly dependent on the spacecraft configuration and complexity. As mission requirements drive spacecraft configuration and complexity, the configuration and complexity drive the weight and the cost. For the same structure weight, a program with a prototype costs approximately three times higher than a program without a prototype. In the prototype approach, which is applicable to entirely new designs and missions, dedicated, fully instrumented qualification hardware is fabricated and exposed to the full qualification test program both at the equipment and the integrated system levels [12, p. 395].

¹ The t-score is the statistic that tests the null hypothesis that the coefficient in Equation (III-1) is equal to zero against the alternative hypothesis that the coefficient is not equal to zero [10, p. 20]. The t-score is the ratio of the regression coefficient to its standard error. A t-score of about 2.0 implies ~95% confidence that the coefficient is not zero. Higher t-scores imply greater confidence in rejecting the null hypothesis. An analogy to this statistic might be the signal-to-noise ratio. Lower probability values indicate greater statistical significance.

² Reference [11, p. 118].

³ The R² is a measure of the fit of a regression equation. An adjustment is made to lessen the effect of increasing the R² value through the addition of independent variables. The adjusted R² modifies the R² to penalize the model containing additional variables when compared with alternative regression models [11]. An R² of 1.00 indicates a perfect fit.

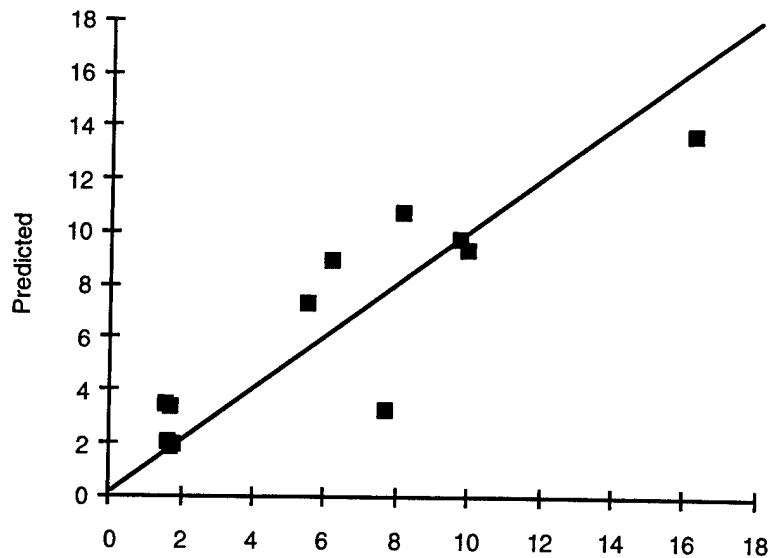


Figure III-1. Actual and Predicted Nonrecurring Engineering Structure Cost (Millions of FY 1992 Dollars)

b. Nonrecurring Manufacturing CER

The nonrecurring manufacturing CER for structure takes a linear form and is expressed as a function of the percentage of aluminum content (ALUM), an indicator for whether an expendable launch vehicle was used (ELV), an indicator for whether the mission was scientific or not (SCI), and the solar array area in square feet (ARRAREA). The resulting CER is shown in Equation (III-2).

$$NR_M = 15,315.6 - 62.6(ALUM) - 6,731.4(ELV) - 2,328.2(SCI) + 4.3(ARRAREA) \quad (III-2)$$

(2.16, .0535)
(4.70, .0006)
(1.96, .0758)
(2.08, .0614)

N = 16

$R^2 = 0.82$

SEE = 1,571

The sample contains the following sixteen systems: AE, ATSF, DMSP-5D1, DSCS-3A, DSP 14-17, FLTSATCOM 1-5, GPS 1-5, GPS 12, GRO, IDCSP, I-4, NATO-3, OSO-I, S3, TACSAT, and TDRSS 1-6.

The actual and predicted costs of our model are compared in Figure III-2. The sample averages of the variables ALUM and ARRAREA are 89 percent and 185 square feet, respectively. The ranges of these variables are 50 to 100 percent and 20 to 884 square feet, respectively. The nonrecurring manufacturing costs range from \$0.09 million to \$13.9 million with the average equal to \$4.2 million in FY 1992 dollars.

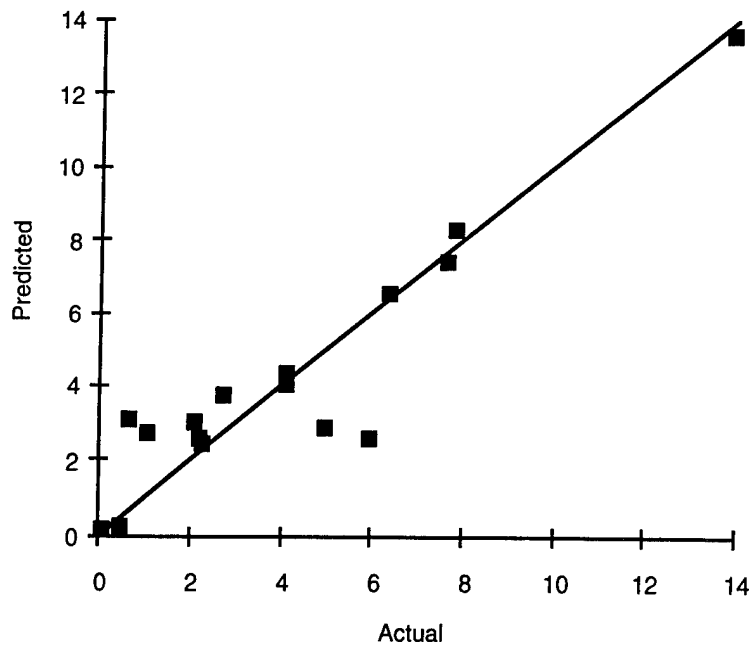


Figure III-2. Actual and Predicted Nonrecurring Manufacturing Structure Cost (Millions of FY 1992 Dollars)

The regression results indicate that nonrecurring manufacturing structure costs decrease about \$62,600 for each increase of one percentage of aluminum. The most common structural material is aluminum. Aluminum is lightweight, strong, readily available, easy to machine, and low in material cost [13, p. 392]. Advance materials, such as beryllium, boron/aluminum, and graphite/epoxy, result in additional material and manufacturing cost [14, p. 48]. For each increase of one square foot in the solar array area, nonrecurring manufacturing structure costs increase \$4,300. An increase in solar array area affects support requirements, which in turn affects the nonrecurring manufacturing cost. The data also show that using an expendable launch vehicle decreases nonrecurring manufacturing costs about \$6.7 million. Type of launch vehicle has implications for such diverse factors as spacecraft mass and configuration, launch window and mission profile, on-board propulsion requirements, and so on. The expendable launch vehicle has simpler design complexity (cylindrical) and less mass, and aerodynamic considerations naturally restrict the payload fairing (or envelope), thus the spacecraft configuration may be constrained by the size and shape of the payload volume [15, chap. 7]. Therefore, the nonrecurring manufacturing cost of the structure of spacecraft using expendable launch vehicle is less. Also, a science mission is approximately \$2.3 million less in nonrecurring manufacturing structure cost than non-science missions. This is relative to the preparation

of the production process, especially for the nonrecurring manufacturing cost for the spacecraft structure. The spacecraft mission dictates the production quantity. Scientific mission spacecraft are manufactured in small quantities, only one or two in most cases. Therefore, there would be no need to set up an efficient production process to support series of production as is the case with other types of missions (e.g., communications). Thus the nonrecurring manufacturing cost for the first few units would be less.

c. Recurring Unit One Manufacturing CER

The recurring unit one manufacturing CER takes a log-linear form and is expressed as a function of the percentage of aluminum content (ALUM) and the solar array area (ARRAREA). The resulting CER is shown in Equation (III-3).

$$T1_M = 3949.9 - 57.7(ALUM) + 822.1 \times \ln(ARRAREA) \quad (III-3)$$

(2.46, .0276) (2.47, .0272)

N = 15

Adj. R² = 0.60

SEE = 1,331

The sample contains the following fifteen systems: ATSF, DMSP-5D1, DSCS-3A, DSP 14-17, DSP 18-22, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, IDCSP, I-4, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6.

A scatter plot showing actual versus predicted costs using Equation (III-3) is shown in Figure III-3. The sample averages of the variables ALUM and ARRAREA are 82 percent and 172 square feet, respectively. The ranges of these variables are 0 to 100 percent and 20 to 884 square feet, respectively. The recurring unit one manufacturing costs range from \$0.2 million to \$7.5 million, the average cost being equal to \$2.6 million in FY 1992 dollars.

The regression results indicate that recurring unit one manufacturing cost for structure decreases about \$57,700 for each increase in aluminum of one percent. This result is to be expected since aluminum is readily available, easy to machine, and low in raw material cost [13, p. 392]. The data also shows that recurring unit one manufacturing cost increases at a decreasing rate with increases in solar array area (i.e., there are economies of scale). As the solar array increases, the structural support needed also increases; thus, unit one manufacturing cost increases.

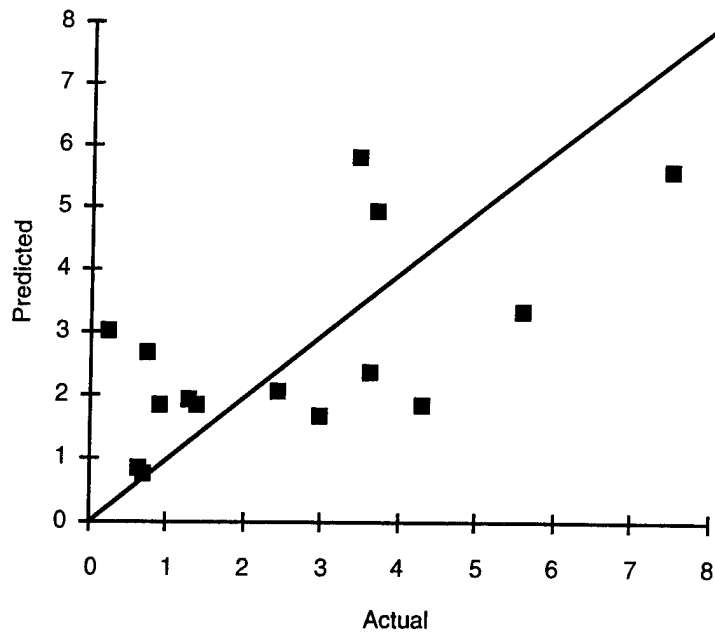


Figure III-3. Actual and Predicted Recurring Unit One Manufacturing Structure Cost (Millions of FY 1992 Dollars)

B. THERMAL CONTROL

1. Definition

The primary function of the thermal control system (TCS) is to maintain nominal temperatures for all components on board a spacecraft regardless of external environment and operations modes. That requires heating the spacecraft while in earth's shadow and cooling the spacecraft while in the sun. Temperature can be decreased by radiating the heat energy via radiator into deep space. Temperature can be increased by using absorbers, which absorb solar or albedo energy with high-absorption or electrically generated heat via a solar array and electronic boxes or even though energy previously stored in batteries and heaters.

Temperature control is achieved by one of two methods: passive and active methods. Multilayer insulation blankets, second surface mirrors, paints, tapes, and louvers are used in the passive control method external to the spacecraft to control the temperature by radiation. Internally, flat mounting surfaces for good thermal contact, interface filters (namely, silicon grease) to improve the interface conduction, doublers, Teflon standoffs for conductive insulation, and heat pipes are used. Some of the components used for active thermal control are heater wire or mats and peltier elements [9, p. 249-251].

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The nonrecurring engineering CER for thermal control takes an exponential form and is expressed as a function of the thermal control weight (TC_WT), steady state high temperature (HITEMP) of the spacecraft's thermal system, and a prototype indicator for whether the program used a prototype or not to demonstrate capability (PROTO). The resulting CER is shown in Equation (III-4).

$$NR_E = 0.000153 \times TC_WT^{0.76} \times HITEMP^{2.93} \times 2.11^{PROTO} \quad (III-4)$$

(4.92, .0027) (2.47, .0485) (3.20, .0187)

N = 10

Adj. R² = 0.77 (linear)

SEE = 1,136

The sample consists of data from the following ten systems: AE, ATSF, DMSP-5D1, DSCS-3A, FLTSATCOM 1-5, GPS 1-5, GPS 12, OSO-I, TACSAT, and TDRSS 1-6.

A scatter plot of the actual versus predicted costs using Equation (III-4) is presented in Figure III-4. The sample average of the variables TC_WT and HITEMP are 67 pounds and 87 degrees Fahrenheit (F), respectively. The ranges of these variables are 11 pounds to 151 pounds and 70 degrees to 104 degrees F, respectively. The nonrecurring engineering costs for the thermal control system range from \$0.7 million to \$7.3 million with the average cost equal to \$2.9 million in FY 1992 dollars.

The regression results indicate that a 1-percent change in thermal control weight results in a 0.76-percent change in nonrecurring engineering thermal control cost and a 1-percent change in high temperature results in a 2.93-percent change in nonrecurring engineering thermal control cost. The weight of a thermal control subsystem is highly dependent on the desired temperature limits of the spacecraft [14, p. 48]. For extreme temperatures, additional active thermal control may be required. Active designs tend to be heavier and cost more than passive designs [13, p. 371]. For the same thermal control weight and high temperature, a prototype program is approximately two times as costly as a non-prototype program. As previously stated, although prototyping can help one see how specific subsystems contribute to the system's overall effectiveness, the effort involved can be time-consuming and costly [12, p. 395].

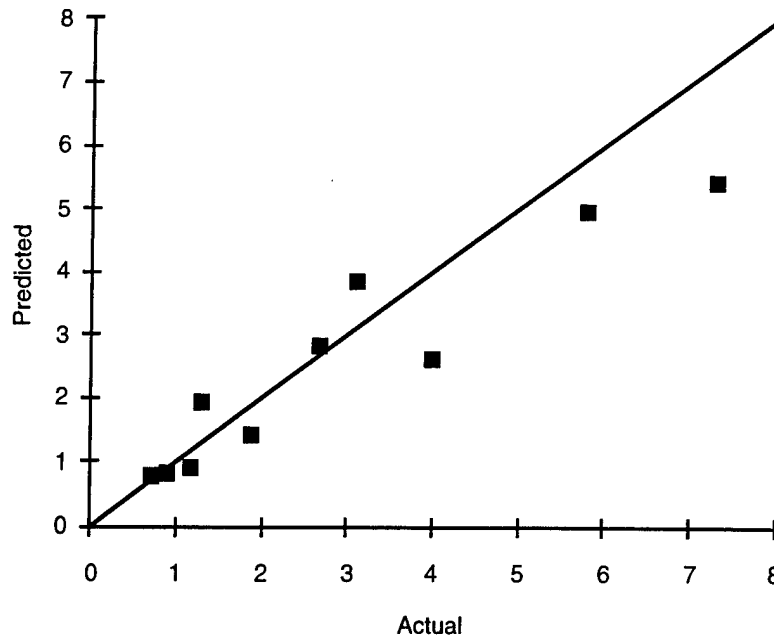


Figure III-4. Actual and Predicted Nonrecurring Engineering TCS Cost (Millions of FY 1992 Dollars)

b. Nonrecurring Manufacturing CER

The nonrecurring manufacturing CER for thermal control takes an exponential form and is expressed as a function of the spacecraft's design life (DESLIFE), steady state low temperature (LOTEMP) of the thermal system, and a prototype indicator for whether or not the program used a prototype to demonstrate capability (PROTO). The resulting CER is shown in Equation (III-5).

$$NR_M = 2466.8 \times DESLIFE^{1.094} \times LOTEMP^{-1.71} \times 3.47^{PROTO} \quad (III-5)$$

(8.13, .0005) (5.27, .0033) (6.00, .0018)

N = 9

Adj. R² = 0.99 (linear)

SEE = 111

The sample contains data from the following nine systems: AE, ATSF, DMSP-5D1, DSP 14-17, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, OSO-I, and TDRSS 1-6.

A plot of the actual versus predicted costs using Equation (III-5) is presented in Figure III-5. The sample averages of the variables DESLIFE and LOTEMP are 47 months and 31 degrees F, respectively. The ranges of these variables are 12 to 120 months and 14 to 41 degrees F, respectively. The nonrecurring manufacturing costs range from \$0.1 million to \$4.3 million, with the average equal to \$1.0 million in FY 1992 dollars.

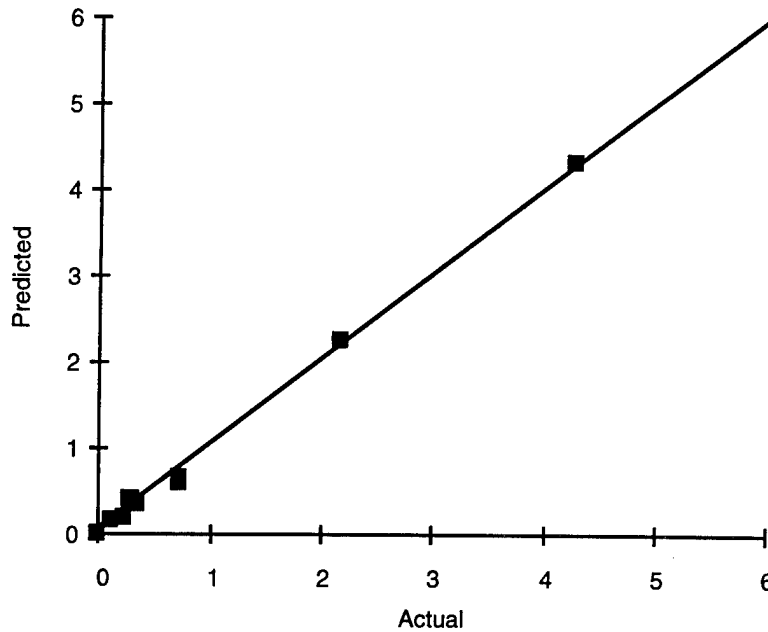


Figure III-5. Actual and Predicted Nonrecurring Manufacturing TCS Cost (Millions of FY 1992 Dollars)

The data show that a 1-percent increase in design life results in approximately a 1.1-percent increase in nonrecurring manufacturing costs. End-of-life properties must be considered in designing thermal control because degradation of some materials is significant [9, p. 249]. Since the amount of degradation is dependent on time, the design life drives the complexity and cost of thermal control. The regression also indicates that a 1-percent increase in the steady state low temperature decreases nonrecurring manufacturing costs by approximately 1.7-percent. If the low temperature is not as extreme, the thermal control system may not be as complex. For example, electrical heaters may not be required. For the same design life and low temperature, a prototype is approximately 3.5 times as costly as a nonprototype program. As mentioned previously, prototyping can be time-consuming and costly.

c. Recurring Unit One Manufacturing CER

The recurring unit one manufacturing CER for thermal control takes an exponential form and is expressed as a function of the spacecraft weight (SC_WT), thermal control weight (TC_WT), and a NASA mission indicator (NASA). The resulting CER is shown in Equation (III-6).

$$T1_M = 1.86 \times SC_WT^{0.60} \times TC_WT^{0.33} \times 0.48^{NASA} \quad (III-6)$$

(4.65, .0006) (2.94, .0123) (3.57, .0039)

N = 16

Adj. R² = 0.80 (linear)

SEE = 142

The following sixteen systems are included in the sample: AE, ATSF, DSCS-3A, DSP 14-17, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, I-4, NATO-3, OSO-I, S3, TACSAT, and TDRSS 1-6.

A scatter plot of the actual versus predicted costs using Equation (III-6) are presented in Figure III-6. The sample averages of the variables SC_WT and TC_WT are 1,998 pounds and 61 pounds, respectively. The ranges of these variables are 340 to 5,083 pounds and 11 to 193 pounds, respectively. The recurring unit one manufacturing costs range from \$0.1 million to \$1.2 million with an average of \$0.5 million in FY 1992 dollars.

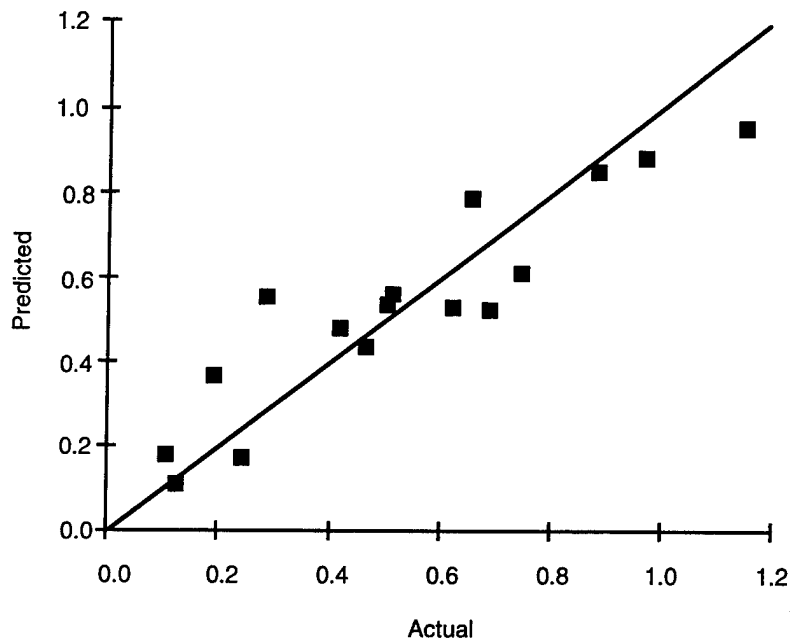


Figure III-6. Actual and Predicted Recurring Unit One Manufacturing TCS Cost (Millions of FY 1992 Dollars)

The regression results indicate that a 1-percent change in spacecraft weight results in a 0.60-percent change in recurring unit one manufacturing cost, and a 1-percent change in thermal control weight results in a 0.33-percent change in recurring unit one manufacturing cost. This appears reasonable since complexity drives weight, which in turn drives cost. For the same spacecraft weight and thermal control weight, a NASA mission is approximately one-half as costly as a non-NASA program. Since NASA missions tend to be experimental and not fully operational, the thermal control system needs to keep only the operating units within the operating temperature limits and the nonoperating units within the nonoperating temperature limits [9, p. 247]. Thus, the thermal control system need not be as complex and costly as a fully operational spacecraft.

C. ATTITUDE DETERMINATION AND CONTROL

1. Definition

The attitude control system (ACS) controls the stabilization, orientation, attitude, and direction of the spacecraft. There are three principal satellite stabilization control techniques: (1) gravity gradient, (2) three axis, and (3) spin [9, p. 156]. Gravity gradient stabilization is suitable for earth-orientation satellites that do not require stringent pointing accuracy. This technique is based on the tendency of the satellite to align itself with its long axis. Three-axis stabilization controls the spacecraft's attitude in three planes: the yaw axis pointed toward the earth, the pitch axis normal to the orbit plane, and the roll axis along the orbital velocity vector. Three-axis stabilization provides accurate control and reliability; however, it requires more subsystem power and weight and is a potential cost driver. The spin-stabilized technique spins the satellite around a rotationally symmetrical axis while the mission equipment carrying the payload is despun to maintain a fixed orientation. The accuracy provided by this technique is not as precise as the three-axis technique; however, it is less expensive than the three-axis technique because only two axes are being controlled.

The spacecraft must also maintain a mission-specific orientation. For example, a communications satellite requires that its antennas be pointed towards the earth. With respect to the attitude of the spacecraft, the ACS senses the attitude and makes necessary adjustments. The ACS is composed of two components: (1) attitude determination and (2) reaction control. The attitude determination system is discussed in this section and the reaction control system is discussed in Section D.

The attitude determination system senses and derives the desired spacecraft orbit and attitude. Sensors and data/signal processors are used to accomplish this. The data and signal processors use input from the attitude sensors to compute the current attitude and orbit of the spacecraft. If adjustments are needed, the reaction control system is activated.

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The nonrecurring engineering CER for the ACS takes an exponential form and is expressed as a function of the ACS sensor suite weight (SEN_WT), a mission indicator for whether the program was a communications mission (COMM), a stabilization indicator for whether spin stabilization was used (SPIN), and a new design indicator for whether the

spacecraft was newly designed or a follow-on production lot or simple modification (DESNEW). The resulting CER is shown in Equation (III-7).

$$NR_E = 971 \times SEN_WT^{0.45} \times 0.30^{SPIN} \times 2.76^{DESNEW} \times 2.08^{COMM} \quad (III-7)$$

(3.04, .0124) (3.51, .0057) (3.12, .0108) (2.59, .0270)

N = 15

Adj. R² = 0.70 (linear)

SEE = 3,924

The sample contains the following fifteen systems: AE, ATSF, CRRES, DMSP-5D1, DSCS-3A, FLTSATCOM 1-5, GPS 12, I-4, IDCSP, NATO-3, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6.

Figure III-7 shows a plot of actual versus predicted costs for Equation (III-7). The sample average of the variable SEN_WT is 18 pounds. The range of SEN_WT is 1 pound to 67 pounds. The nonrecurring engineering costs range from \$0.7 million to \$19.9 million with an average of \$7.45 million in FY 1992 dollars.

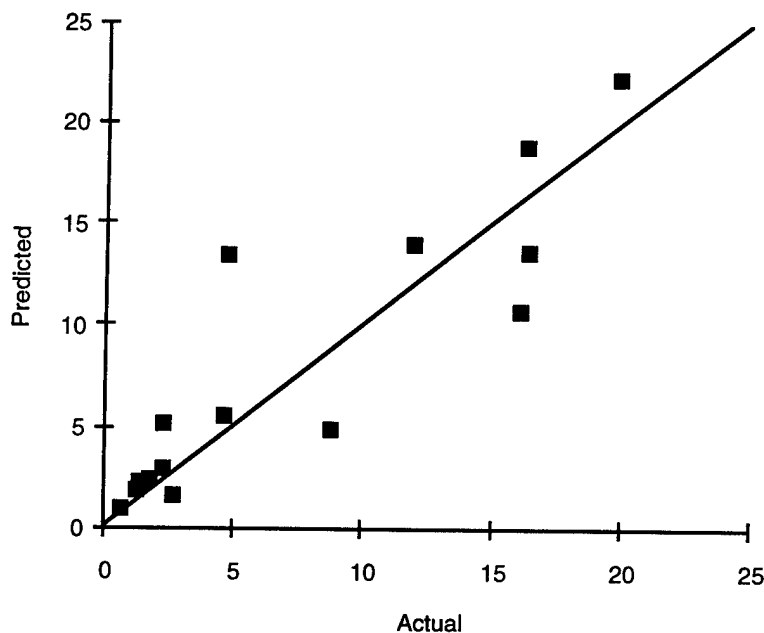


Figure III-7. Actual and Predicted Nonrecurring Engineering ACS Cost (Millions of FY 1992 Dollars)

The regression results indicate that a 1-percent change in sensor suite weight results in a 0.45-percent change in nonrecurring engineering attitude determination and control cost. This seems reasonable, especially since the electronics are included in the sensor suite weight. The data also show that spin stabilization decreases nonrecurring engineering cost by 70 percent. Spin-stabilized spacecraft are less expensive than the three-axis stabilized because only two axes are being controlled. Three-axis stabilization requires complex

subsystems such as sensors and inertial platforms [15, chap. 15]. For a newly designed spacecraft, the nonrecurring engineering cost will be 2.76 times as costly as a follow-on or modification. Because a new attitude determination system will be designed, nonrecurring engineering cost for this subsystem will be more than a follow-on or modification. A communications spacecraft is approximately twice as costly as a noncommunications program. Attitude measuring sensors vary depending upon the mission and accuracy requirements of a satellite. A communications spacecraft must orient its transmitting and receiving antennas toward the coverage zones on the surface of the earth.

b. Nonrecurring Manufacturing CER

The nonrecurring manufacturing CER for ACS takes an exponential form and is expressed as a function of the ACS sensor suite weight (SEN_WT), ACS weight (ACS_WT), and a prototype indicator for whether the program used a prototype to demonstrate capability (PROTO). The resulting CER is shown in Equation (III-8).

$$NR_M = 46.68 \times 4.82^{PROTO} \times SEN_WT^{0.58} \times ACS_WT^{0.36} \quad (III-8)$$

(6.41, .0000) (4.80, .0006) (2.89, .0147)

N = 15

Adj. R² = 0.80 (linear)

SEE = 1,760

The sample contains the following fifteen systems: AE, ATSF, CRRES, DMSP-5D1, DSCS-3A, FLTSATCOM 1-5, GPS 12, IDCSP, I-4, NATO-3, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6.

A scatter plot showing actual versus predicted costs using Equation (III-8) is shown in Figure III-8. The sample averages of the variables SEN_WT and ACS_WT are 18 pounds and 109 pounds, respectively. The ranges of these variables are 1 to 67 pounds and 2 to 295 pounds, respectively. The nonrecurring manufacturing costs range from \$0.3 million to \$11.8 million with the average cost equal to \$3.3 million in FY 1992 dollars.

The regression results indicate that a 1-percent change in sensor suite weight results in a 0.58-percent change in nonrecurring manufacturing cost and a 1-percent change in ACS weight results in a 0.36-percent change in nonrecurring manufacturing cost. Since complexity drives weight, the sensor suite weight and ACS weight drive the nonrecurring manufacturing cost. Also, the electronics are included in the sensor suite weight. The data also shows that a prototype program is 4.8 times as costly as a non prototype program. As mentioned previously, prototyping can be time-consuming and costly.

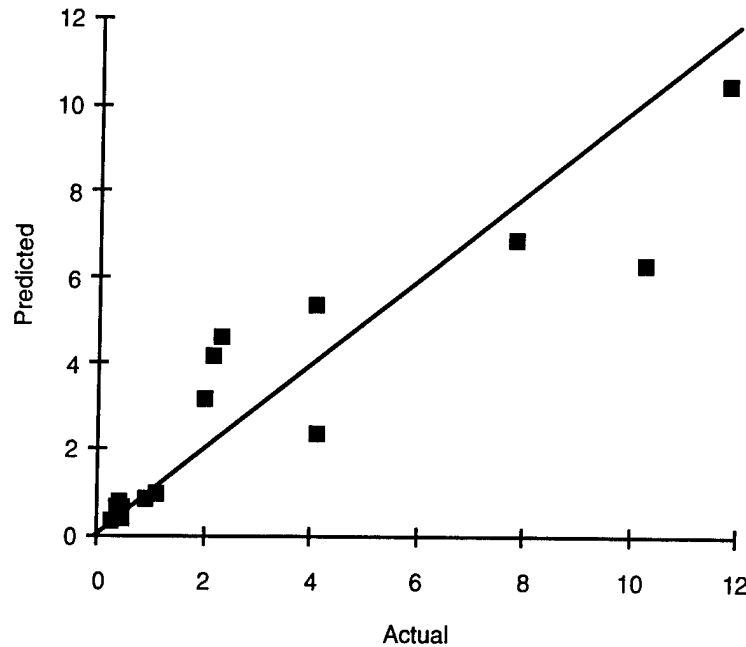


Figure III-8. Actual and Predicted Nonrecurring Manufacturing ACS Cost (Millions of FY 1992 Dollars)

c. Recurring Unit One Manufacturing CER

The recurring unit one manufacturing CER for the ACS takes an exponential form and is expressed as a function of the ACS sensor suite weight (SEN_WT), attitude control subsystem weight (ACS_WT), a stabilization indicator for whether spin stabilization was used (SPIN), and a low earth orbit indicator (LEO). The resulting CER is shown in Equation (III-9).

$$T1_M = 166.70 \times SEN_WT^{0.64} \times ACS_WT^{0.31} \times 0.35^{SPIN} \times 0.60^{LEO} \quad (III-9)$$

(6.38, .0000) (2.51, .0261) (3.45, .0043) (2.02, .0640)

N = 18

Adj. R² = 0.90 (linear)

SEE = 1,070

The sample contains the following eighteen systems: AE, ATSF, CRRES, DMSP-5D1, DSCS-3A, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 9-11, GPS 13-40, IDCSP, I-4, NATO-3, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6.

Figure III-9 is a plot of the actual versus predicted costs from Equation (III-9). The sample averages of the variables SEN_WT and ACS_WT are 18 pounds and 104 pounds, respectively. The ranges of these variables are 1 to 67 pounds and 2 to 295 pounds, respectively. The recurring unit one manufacturing costs range from \$0.7 million to \$14.2 million with an average of \$3.3 million in FY 1992 dollars.

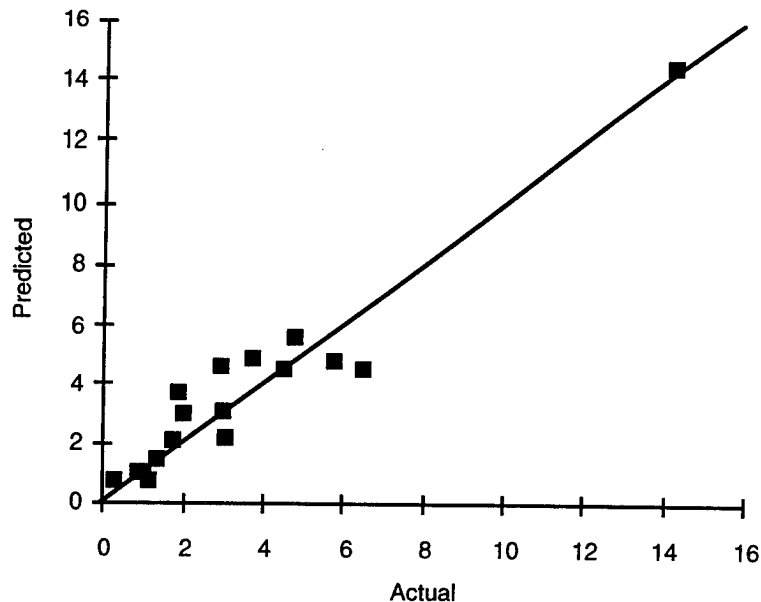


Figure III-9. Actual and Predicted Recurring Unit One Manufacturing ACS Cost (Millions of FY 1992 Dollars)

The data show that a 1-percent change in ACS sensor suite weight results in a 0.6- to 4-percent change in recurring unit one manufacturing cost and a 1-percent change of ACS weight results in a 0.31-percent change in recurring unit one manufacturing cost. For the same sensor suite weight and attitude control subsystem weight, a spin-stabilized spacecraft is 65 percent less costly than a non-spin stabilized spacecraft. Spin stabilization is a passive-control technique and is very economical [15, chap.15]. Also, a spacecraft designed for a low earth orbit is 40 percent less costly than a spacecraft designed for another orbit. The low earth orbit satellites in our database have less demanding missions than the geosynchronous and medium earth orbit satellites. Therefore, their ACS equipment is less expensive.

D. REACTION CONTROL/PROPULSION

1. Definition

The reaction control or propulsion system acts on input from the attitude determination equipment and restores the proper attitude and orbit of the spacecraft. Components of the reaction control system include nutation dampers, gravity gradient equipment, magnetic torques, and inertia wheels.

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The nonrecurring engineering CER for reaction control takes an exponential form and is expressed as a function of the spacecraft weight (SC_WT), a stabilization indicator for whether spin stabilization was used (SPIN), and two mission indicators for whether the program was a communications mission (COMM) or a NASA mission (NASA). The resulting CER is shown in Equation (III-10).

$$NR_E = 9.52 \times SC_WT^{0.72} \times 0.39^{SPIN} \times 0.43^{NASA} \times 2.23^{COMM} \quad (III-10)$$

(3.81, .0025) (2.74, .0178) (2.67, .0206) (2.86, .0143)

N = 17

Adj. R² = 0.60 (linear)

SEE = 1,267

The sample contains the following seventeen systems: AE, ATSF, CRRES, DMSP-5D1, DSCS-3A, DSP 14-17, FLTSATCOM 1-5, GPS 1-5, GPS 12, GRO, I-4, NATO-3, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6.

Figure III-10 shows a scatter plot that compares the actual versus the predicted costs from Equation (III-10). The sample average of the variable SC_WT is 3,079 pounds. The range of SC_WT is 756 pounds to 16,806 pounds. The nonrecurring engineering costs range from \$0.3 million to \$6.5 million with an average of \$2.56 million in FY 1992 dollars.

The regression results indicate that a 1-percent change in spacecraft weight results in a 0.72-percent change in nonrecurring engineering cost. As spacecraft weight increases, more power and thrusters are needed to maneuver the spacecraft; thus, cost is increased. The data also show that spin stabilization decreases nonrecurring engineering cost by approximately 60 percent. Spin stabilization is less expensive than the three-axis technique because only two axes are being controlled. A NASA mission has a similar effect on costs; that is, a NASA program is approximately 60 percent less costly than a non-NASA program. NASA programs have shorter lives which require less propellant. A communications spacecraft is approximately 2.2 times as costly as a non-communications program. Communications spacecraft require more station-keeping to maintain orientation towards the earth. Also, the orbit is geosynchronous, which requires additional devices.

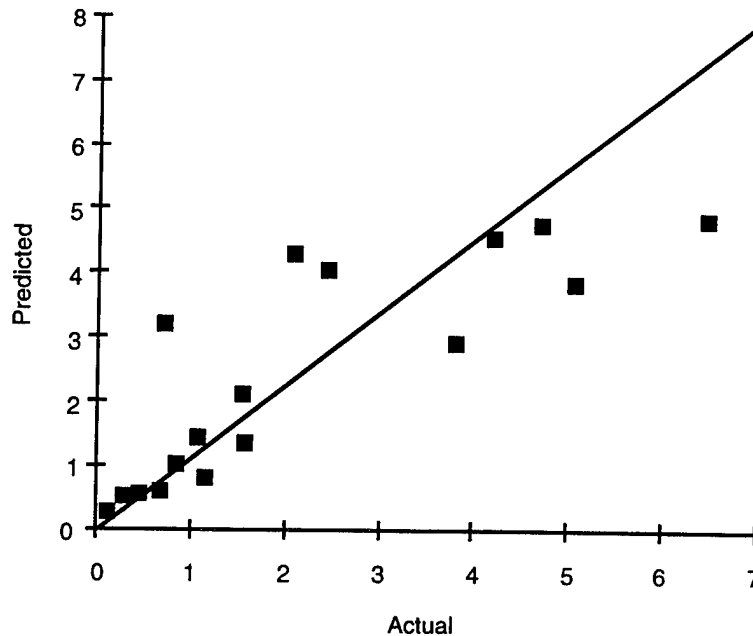


Figure III-10. Actual and Predicted Nonrecurring Engineering Reaction Control Cost (Millions of FY 1992 Dollars)

b. Nonrecurring Manufacturing CER

The nonrecurring manufacturing CER for reaction control takes an exponential form and is expressed as a function of the reaction control system weight (RCS_WT), a geosynchronous orbit indicator (GEO), a stabilization indicator for whether three-axis stabilization is used (3AXIS), and an indicator for whether engine or thrusters are included (ENGINE). The resulting CER is shown in Equation (III-11).

$$NR_M = 26.3 \times 2.86^{GEO} \times 2.83^{3AXIS} \times RCS_WT^{0.40} \times 2.6^{ENGINE} \quad (III-11)$$

(3.32, .0128) (4.17, .0042) (2.73, .0295) (2.03, .0824)

N = 12

Adj. R² = 0.80 (linear)

SEE = 760

The sample contains the following twelve systems: ATSF, DMSP-5D1, DSP 14-17, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 12, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6.

A scatter plot showing actual versus predicted costs using Equation (III-11) is shown in Figure III-11. The sample average of the variable RCS_WT is 113. The range of this variable is 4.3 to 333 pounds. The nonrecurring manufacturing costs range from \$0.1 million to \$4.1 million with an average cost equal to \$1.9 million in FY 1992 dollars.

The regression results indicate that a 1-percent change in reaction control weight results in a 0.40-percent change in nonrecurring manufacturing cost. The data also show

that a spacecraft designed for a geosynchronous orbit is approximately 2.9 times as costly as one designed for a non-geosynchronous orbit. This type of spacecraft may require different devices for the synchronous orbit and for the transfer orbit, which increases cost [14, p. 159]. A three-axis stabilized spacecraft is approximately 2.8 times as costly as a spacecraft that is not three-axis stabilized. Three-axis stabilization is an active control technique and requires momentum storage devices, including momentum wheel, reaction wheels, and control moment gyros. This technique increases complexity, cost, power consumption, and weight [15, chap. 15]. If engine or thrusters are included, the nonrecurring manufacturing cost is about 2.6 times more than a spacecraft without engine or thrusters. Most satellite reaction control systems have engines or thrusters to control attitude and orientation. Simple short-lived experimental satellites do not have engines in their reaction control systems.

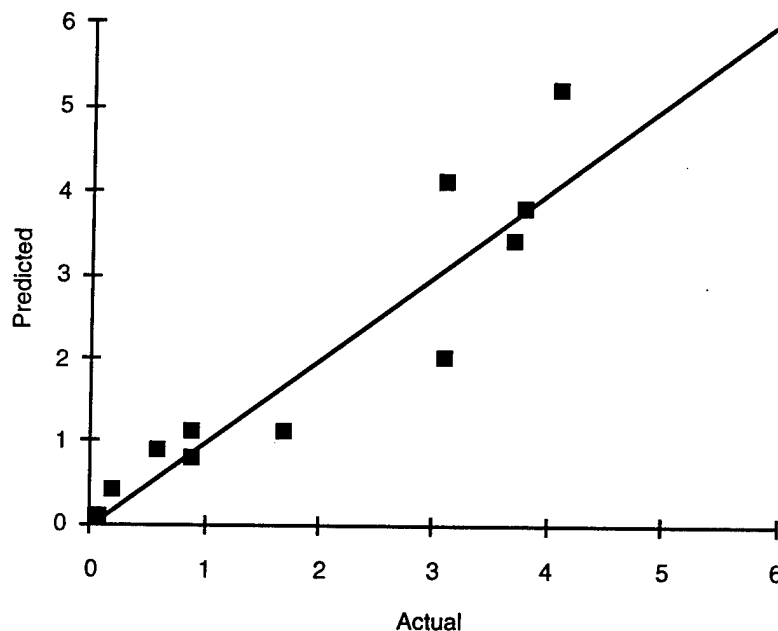


Figure III-11. Actual and Predicted Nonrecurring Manufacturing Reaction Control Cost (Millions of FY 1992 Dollars)

c. Recurring Unit One Manufacturing CER

The recurring unit one manufacturing CER for reaction control takes an exponential form and is expressed as a function of the RCS weight (RCS_WT), design life (DESLIFE), and an indicator for whether engine or thrusters are included (ENGINE). The resulting CER is shown in Equation (III-12).

$$T1_M = 0.91 \times RCS_WT^{0.75} \times DESLIFE^{0.79} \times 3.30^{ENGINE} \quad (III-12)$$

(8.20, .0000) (6.58, .0000) (2.61, .0198)

N = 19

Adj. R² = 0.69 (linear)

SEE = 1,066

The sample contains the following nineteen systems: AE, ATSF, CRRES, DMSP-5D1, DSCS-3A, DSP 14-17, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, GRO, I-4, NATO-3, OSO-I, P-78, S3, and TACSAT.

Figure III-12 is a scatter plot that shows actual versus predicted costs from Equation (III-12). The sample averages of the variables RCS_WT and DESLIFE are 140 pounds and 47 months, respectively. The ranges of these variables are 4.3 to 624 pounds and 6 to 120 months, respectively. The recurring unit one manufacturing costs range from \$31,000 to \$6.5 million with an average of \$2.0 million in FY 1992 dollars.

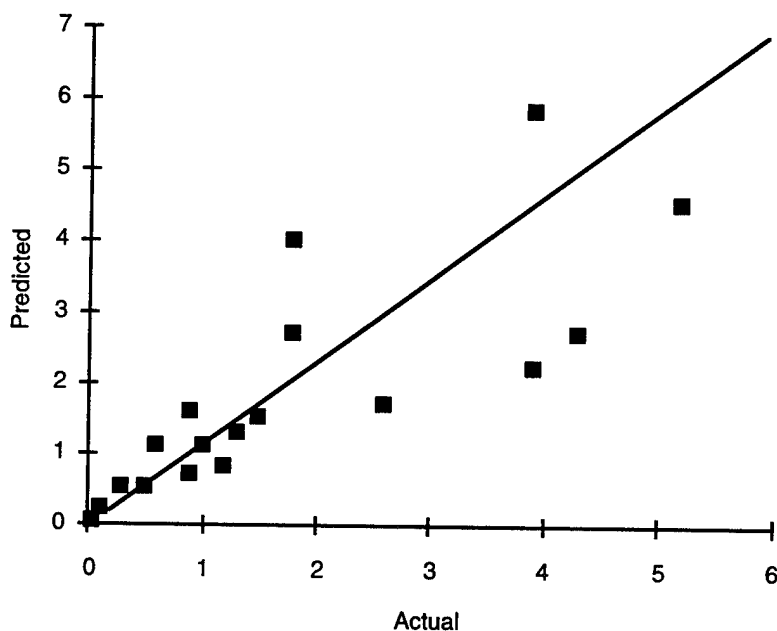


Figure III-12. Actual and Predicted Recurring Unit One Manufacturing Reaction Control Cost (Millions of FY 1992 Dollars)

The data show that a 1-percent change in reaction control system weight results in a 0.75-percent change in recurring unit one manufacturing cost. A 1-percent change in design life results in a 0.79 percent change in recurring unit one manufacturing cost. If engine or thrusters are included, the nonrecurring manufacturing cost is about 3.3 times more than a spacecraft without engine or thrusters for the same reasons previously stated.

E. ELECTRICAL POWER SUPPLY

1. Definition

The electrical power supply (EPS) subsystem is the source of electrical energy for all the space vehicle components, including the payload. The required amount of power depends on the payload requirements and the duration of the mission. The EPS consists of energy source, converter, storage components, and a power conditioning and control system.

The source of power can be solar, electrochemical, or nuclear. The two most common types of EPS currently in use are electrochemical and solar. Nuclear energy has been used for outer planetary missions. For our study, we considered the most common type, solar power sources [9, p. 80]. Solar cells are used to collect the energy that is converted for use throughout the spacecraft. Batteries are used to store the energy during periods of eclipse or when peak power exceeds the potential of the solar cells.

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The EPS nonrecurring engineering cost model takes a log-log form and is expressed as a function of design life (DESLIFE) and beginning-of-life power (EPSBOLP). The resulting CER is presented in Equation (III-13).

$$NR_E = 10.49 \times EPSBOLP^{0.77} \times DESLIFE^{0.37} \quad (III-13)$$

(3.31, .0079) (2.19, .0536)

N = 13

Adj. R² = 0.84 (linear)

SEE = 2667

The sample for this equation includes thirteen spacecraft: AE, ATSF, CRRES, DSCS-3A, GPS 1-5, GPS 12, GPS 9-11, GPS 13-40, I-4, NATO-3, OSO-I, TACSAT, and TDRSS 1-6. Figure III-13 shows actual versus predicted costs from Equation (III-13).

The sample average of the independent variables (EPSBOLP) and (DESLIFE) are 809 watts and 61 months respectively. The ranges are from 170 to 2,400 watts for EPSBOLP, and from 12 to 120 months for DESLIFE. The dependent variable NR_E has a range of \$1.26 million to \$24.99 million and an average of \$7.74 million in FY 1992 dollars.

The regression results indicate that a 1-percent change in beginning-of-life power results in a 0.77-percent change in nonrecurring engineering cost. Also a 1-percent change

in design life results in a change of 0.37 percent change in cost. This result is to be expected; the spacecraft EPS subsystem is conceptualized and designed to meet the power requirements of a spacecraft under consideration. The EPS provides, stores, distributes, and controls spacecraft electrical power. Most important are the demands for average and peak electrical power and the orbital profile (inclination and altitude). In the EPS design, power requirements during eclipse and peak power consumption must be considered in addition to mission type, spacecraft configuration, mission life, and payload definition. Because solar cells and batteries have limited lives, the EPS design must account for power requirement at the beginning of life (BOL) and at the end-of-life (EOL). The average power needed at EOL determines the size of the power source. BOL includes EOL plus power deterioration margin. Therefore, change in the average power needed at BOL also affects the size of the power subsystem design. As one of the EPS design parameters, mission life dictates the size of the power source. Longer mission life (more than seven years) implies extra redundancy design, independent battery charging, larger capacity batteries, and larger arrays [13, p. 354].

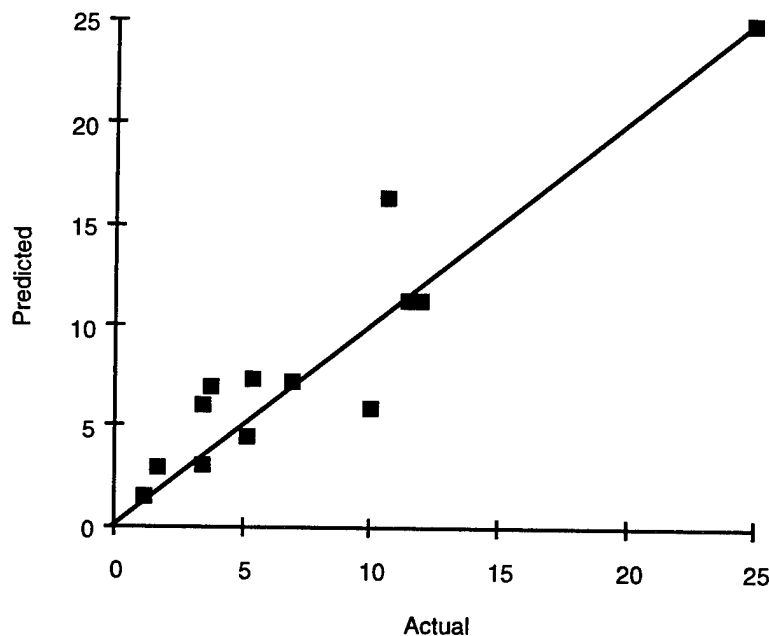


Figure III-13. Actual and Predicted Nonrecurring Engineering EPS Cost (Millions of FY 1992 Dollars)

b. Nonrecurring Manufacturing CER

The EPS nonrecurring manufacturing CER is in log-log form and has two explanatory variables, beginning-of-life power (EPSBOLP) and DESNEW indicator (1/0)

for whether the program is a newly designed spacecraft or a follow-on production lot or a simple modification. The resulting CER is presented in Equation (III-14).

$$NR_M = .07 \times EPSBOLP^{1.54} \times 1.60^{DESNEW} \quad (III-14)$$

(10.30, .0000) (2.32, .0429)

N = 13

Adj. R² = 0.93 (linear)

SEE = 1284

The thirteen spacecraft included in this sample are: AE, ATSF, CRRES, DSCS-3A, DSP 14-17, GPS 1-5, GPS 9-11, GPS 12, I-4, NATO-3, OSO-I, TACSAT, and TDRSS 1-6. A scatter plot showing actual versus predicted costs from Equation (III-14) is shown in Figure III-14.

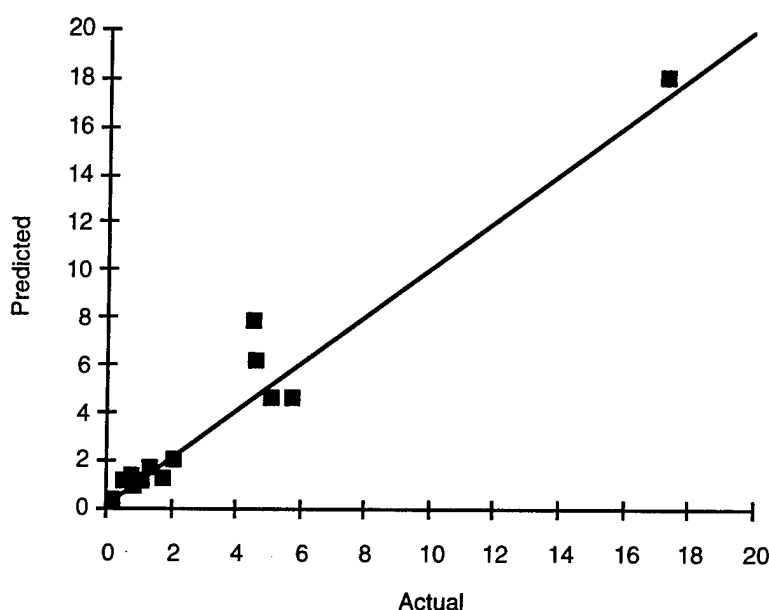


Figure III-14. Actual and Predicted Nonrecurring Manufacturing EPS Cost (Millions of FY 1992 Dollars)

The independent variable EPSBOLP has an average of 859 watts and a range of 170 to 2,400 watts. The average for the dependent variable is \$3.5 million with a range of \$0.3 million to \$18.0 million in FY 1992 dollars. The regression results indicate that a 1-percent change in beginning-of-life power corresponds to a 1.54-percent change in nonrecurring manufacturing cost. A new design EPS subsystem costs 60 percent more than a follow-on production lot or a simple modification one. Manufacturing an EPS subsystem with higher power requires higher weight and complexity of the basic elements. Therefore, the nonrecurring manufacturing cost is driven by the power level required on-board the spacecraft and whether or not the EPS subsystem is a new design.

c. Recurring Unit One Manufacturing CER for the EPS

The recurring unit one manufacturing CER for the EPS is in log-log form and has only one explanatory variable, electrical power supply end-of-life power (EPSEOLP) in watts. The resulting CER is expressed in Equation (III-15).

$$T1_M = 19.52 \times EPSEOLP^{0.88} \quad (III-15)$$

(7.10, .0000)

N = 14

Adj. R² = 0.68 (linear)

SEE = 2,585

The thirteen spacecraft included in this sample are: AE, ATSF, CRRES, DSP 14-17, DSP 18-22, FLTSAT 6-8, GPS 1-5, GPS 9-11, GPS 13-40, NATO-3, OSO-I, TACSAT, and TDRSS 1-6. Figure III-15 shows a scatter plot of the actual versus predicted costs from Equation (III-15).

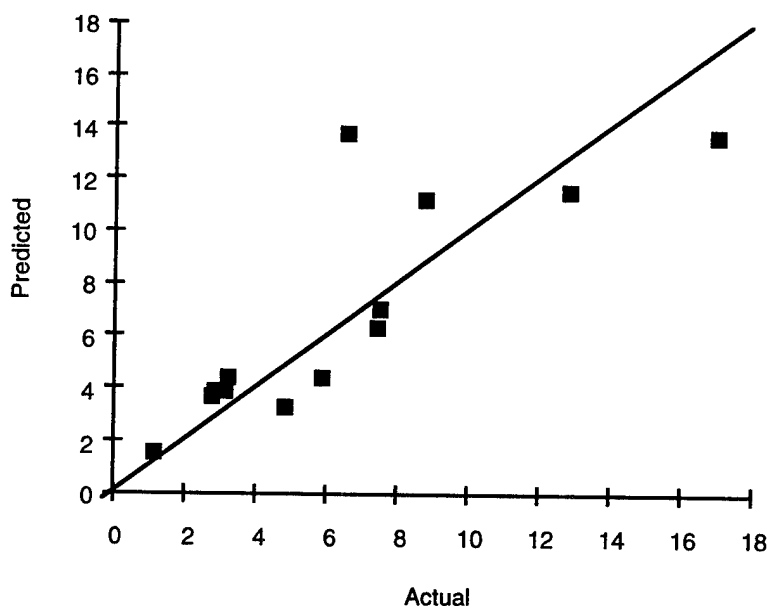


Figure III-15. Actual and Predicted Unit One Manufacturing EPS Cost (Millions of FY 1992 Dollars)

The range of the EPSEOLP is from 140 to 1,700 watts with an average of 758 watts. The dependent variable has an average of \$6.2 million and a range of \$1.2 million to 17.0 million in FY 1992 dollars. Our regression model indicates that a 1-percent change in EPSEOLP leads to a 0.88-percent change in EPS unit one manufacturing cost. In the design process the average electrical power needed at end of life determines the size of the power source [12], and the cost of manufacturing the power source is driven by its size. The EOL power is, therefore, the cost driver for the EPS recurring manufacturing unit one.

F. TELEMETRY, TRACKING, AND COMMAND

1. Definition

The telemetry, tracking, and command (TT&C) subsystem performs three basic functions. Space telemetry involves the measurements taken by remote sensors on a satellite and transmitted to a ground station [9, p. 205]. These measurements are of various aspects of the spacecraft and the environment in which it is functioning, they include positions, pressures, temperatures, voltages, radiation, currents, and events that are present throughout the satellite system, subsystems, and components [17, p. 2–37]. The sensors that measure the data are not included in the telemetry subsystem. Tracking involves locating a specific satellite in time and space, and following its movements as a function of time. For tracking, an earth station sends a ranging signal that the tracking system on the satellite receives and retransmits. This enables ground station to determine “the satellite position [in time and space]...to calculate future orbital motion, pointing data for earth stations, and for firing thrusters to maintain satellite position” [9, p. 205]. Satellite tracking allows telemetry to be acquired, data to be provided for orbit determination, and commands to be sent. Command is the enabling and disabling by ground control of various spacecraft functions while the satellite is in the line of sight of a ground station. “Commands may be sent for accomplishing any of the following functions: ascent control, orbit adjustment, re-entry by separation, engine ignition or cutoff, control of internal systems, on-off control, switchover, control of sequential events that must operate in a predetermined manner, or control of a spaceborne timer which in turn controls a predetermined sequence of events” [17, p. 2–85]. Generally, commands are generated by the satellite control center and relayed over land lines, submarine cables, microwave relays or satellite links to remote tracking stations (RTS). The RTS then sends the commands to the satellite. “Two types of commands exist: real-time and stored programs. The satellite receives and acts on real-time commands immediately. Stored program commands activate satellite systems and sensors when the satellite is not in the RTS’ line of sight” [18, p. 62, 64].

In all, the TT&C subsystem performs one or more of the following functions: measures important space vehicle platform conditions, processes this information and also mission data, stores such data, transmits data to the ground, receives and processes commands from the ground and initiates their execution, and provides a tracking capability. The equipment for accomplishing all TT&C functions includes receiving and transmitting antennas, receivers, transmitters, transponders, analog and digital electronics, and microwave ferrite devices (which include wave guides and coaxial cable, for example).

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The TT&C nonrecurring engineering CER takes a log-log form and is expressed as a function of the number of TT&C transmit channels (CHANLS) and science mission indicator variable (SCIENCE). The resulting CER is presented in Equation (III-16).

$$NR_E = 1374.15 \times CHANLS^{0.75} \times 2.11^{SCIENCE} \quad (III-16)$$

(4.54, 0105) (3.54, .0239)

N = 7

Adj. R² = 0.97 (linear)

SEE = 707

The seven spacecraft included in the sample are: AE, DMSP-5D1, DSCS-3A, GPS 1-5, GPS 12, NATO-3, and S3. Figure III-16 is a scatter plot that shows actual versus predicted costs from Equation (III-16).

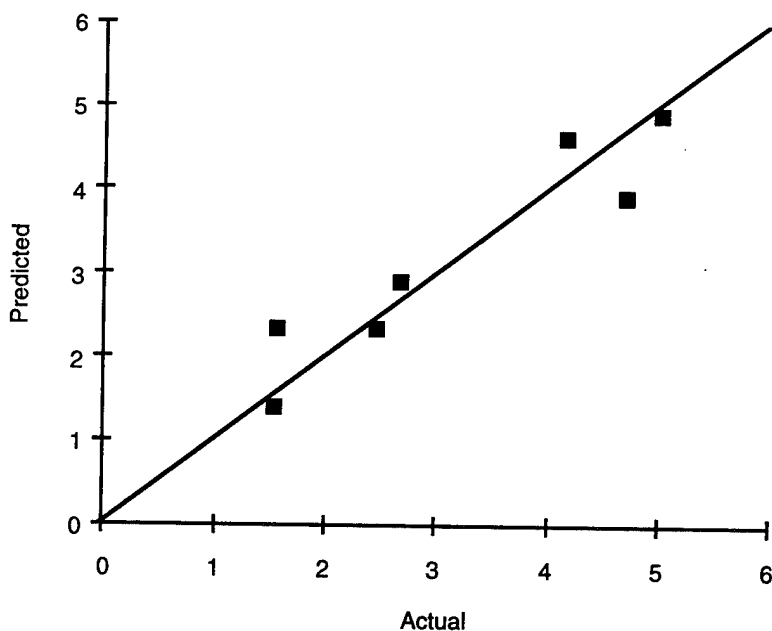


Figure III-16. Actual and Predicted Nonrecurring Engineering TT&C Cost (Millions of FY 1992 Dollars)

The sample average of the independent variables (CHANLS) is 2. The range of this variable is 1 to 5. The dependent variable has an average of \$3.2 million and a range of \$1.5 million to \$5.02 million in FY 1992 dollars. The regression results indicate economies of scale for the number of TT&C channels. For the same number of TT&C transmit channels, science mission spacecraft is approximately two times as costly as a spacecraft designed for other types of mission. This is because the number and accuracy of functions

being monitored in the satellite determines the telemetry data rates, and higher rates of data transmission require higher bandwidth or number of channels and frequencies. Scientific satellites in low earth orbit often need to send rapid sequences of commands in a short period of time, such as during a brief ground station pass [12, p. 360]. Therefore, their data rate is higher, which results in more complex TT&C subsystems.

b. Nonrecurring Manufacturing CER

The TT&C nonrecurring manufacturing CER is in linear form with a negative intercept and a log transformed variable. The model is expressed as a function of the TT&C subsystem weight times TT&C power (TTCWT_PWR), an operational indicator for whether the satellite is operational or experimental (OPERATE), and a prototype indicator for whether the program used a prototype to demonstrate capability (PROTO). The resulting CER is shown in Equation (III-17).

$$NR_M = -17,788.47 + 2,084.96 \ln(TTCWT_PWR) + 4,884.97(OPERATE) + 3,988.21(PROTO) \quad (III-17)$$

(3.40, .0426) (3.15, .0514) (3.15, .0512)

N = 7

Adj. R² = 0.86

SEE = 1,255

The seven spacecraft included in the sample are: AE, FLTSATCOM 1-5, GPS 1-5, NATO-3, P-78, S3, and TDRSS 1-6. Figure III-17 shows the scatter plot of the actual versus predicted costs for TT&C nonrecurring manufacturing.

The adjusted R² indicates 86 percent of the variation in NR_M can be explained by the variables in Equation (III-17).⁴ The sample averages of the independent variables subsystem weight and power are 91 pounds and 56 watts, respectively. The ranges of these variables are 44 to 173 pounds for weight and 10 to 172 watts for power. The dependent variable has an average of \$2.9 million with a range of \$0.2 million to \$9.9 million in FY 1992 dollars.

The CER indicates economies of scale for the subsystem weight times power variable. Holding TT&C subsystem weight and power constant, building a prototype will add roughly \$4 million in 1992 dollars. Operational systems cost about \$5 million more than experimental one.

⁴ The R² is a measure of the fit of a regression equation. An adjustment is made to lessen the effect of increasing the R² value through the addition of independent variables. The adjusted R² modifies the R² to penalize the model containing additional variables when compared with alternative regression model [11, p. 365]. An R² of 1.00 indicates a perfect fit.

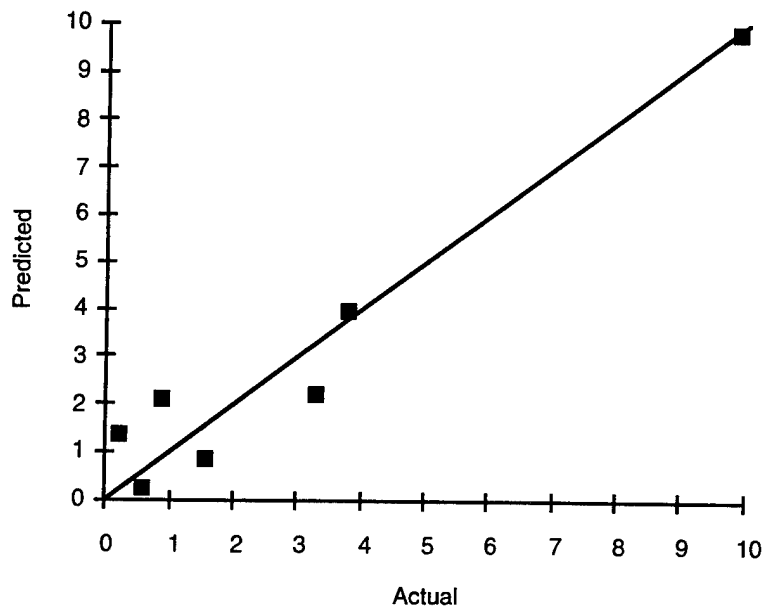


Figure III-17. Actual and Predicted Nonrecurring Manufacturing TT&C Cost (Millions of FY 1992 Dollars)

The negative intercept indicates that caution should be taken when applying the CER to programs that have low values for independent variables. The equation would not be applicable to (1) an operational mission prototype program that has subsystem weight less than 44 pounds and power less than 10 watts; (2) an experimental mission prototype program with subsystem weight less than 54 pounds and power less than 14 watts; (3) an operational nonprototype program with subsystem weight less than 45 pounds and power less than 11 watts; and (4) an experimental mission non-prototype program with subsystem weight less than 147 pounds and power less 35 watts.

Because the TT&C subsystem is designed to suit the mission requirements and the selected ground station(s), its weight and power are the most important factors in the design process. Due to the nature of the mission, the TT&C for an experimental spacecraft may be turned on and off when needed, which means less power and weight, among other things, to build, whereas the TT&C for an operational spacecraft must be in operating mode at all times, which implies higher power, weight, and complexity to build, to support the mission required. Naturally, the nonrecurring manufacturing cost for TT&C subsystem is therefore driven by its weight, power, and type of mission.

c. Recurring Unit One Manufacturing CER

The TT&C recurring unit one manufacturing (T1_M) CER takes a log-log form with three explanatory variables, number of transmit channels (CHANLS), new design

(DSENEW) indicator, and low earth orbit (LEO) indicator. The regression result is presented in Equation (III-18).

$$T1_M = 850 \times \underset{(6.02, .0018)}{CHANLS^{1.27}} \times \underset{(2.64, .0461)}{1.85^{DSENEW}} \times \underset{(4.79, .0049)}{0.24^{LEO}} \quad (III-18)$$

N = 9

Adj. R² = 0.78 (linear)

SEE = 672

The nine spacecraft included in this sample are: AE, DMSP-5D1, FTSATCOM 6-8, GPS 9-11, GPS 13-40, NATO-3, P-78, S3, and TDRSS 1-6. The actual versus predicted TT&C unit one manufacturing costs are shown in Figure III-18.

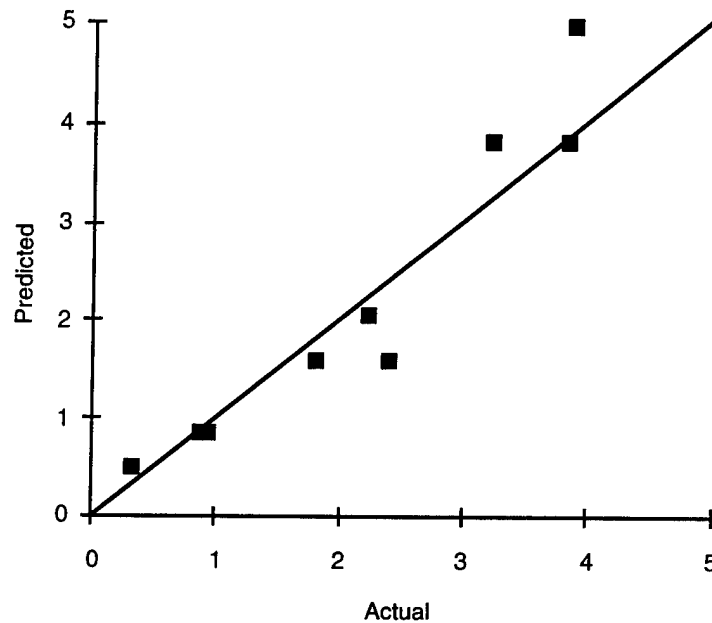


Figure III-18. Actual and Predicted Recurring Unit One Manufacturing TT&C Cost (Millions of FY 1992 Dollars)

The sample average of the independent variable CHANLS is 2 with a range of 1 to 5. The dependent variable has an average of \$2.2 million and a range of \$0.3 million to \$3.9 million in FY 1992 dollars. The regression results indicate that the TT&C unit one manufacturing cost increases at an increasing rate with respect to the number of TT&C channels. A new TT&C design subsystem costs 85 percent more than a modified or follow-on one. Also, the TT&C T1_M of a spacecraft designed for low earth orbit costs 76 percent less than one designed for higher orbit. As expected, the number of transmit channels in the design process is determined by the transmission capacity required to meet the mission (orbit and type of payload), and the orbit plays an important role in the spacecraft/ground station link. The TT&C subsystem for spacecraft in geosynchronous

orbit requires more transmitter power and complexity, among other things, to build, where as the TT&C for a satellite in low earth orbit requires less transmit power and complexity to build due to the satellite's low altitude.

G. COMMUNICATIONS PAYLOAD

1. Definition

The communications payload performs essentially a repeater function. Only satellites with a communications mission will have this subsystem. The purpose of this subsystem is to receive and retransmit signals (often after amplification, reconfiguration, or some other modification) from one part of the world to another. Signals and transmissions received from the ground are handled differently depending on whether the communications subsystem is passive or active. A passive system will not alter the received signal in any way before retransmission. An active system may amplify, reconfigure, and in some other way modify the received signal before retransmission. The package to accomplish this task includes receiving and transmitting antennas, one or more transmitters, one or more receivers, transponders, digital electronics, and auxiliary or support equipment, which consists of analog electronics and microwave ferrite devices.

Antennas, the physical conduit through which the signal is received and transmitted, come in several varieties: dipoles, reflectors, helices, and phased arrays. Transmitters produce, modulate, and amplify the high-power carrier frequency, which is fed into an antenna. Receivers detect, amplify, and demodulate the signals transmitted from ground.⁵ Analog electronics are used to process analog signals, and include relays, power supplies, and interface and control electronics. Microwave ferrite devices guide and condition the communications signals, and include such equipment as waveguides, filters, switching devices such as multiplexers and demultiplexers, and coaxial cable.

Analog electronics, microwave ferrite devices, and communications elements such as oscillators, frequency generators, and synthesizers are common equipment in the sense that they do not have a specialized function such as a transmitting or receiving, but instead run throughout the communications subsystem.

⁵ Reference [9] p. 214-216.

2. Cost-Estimating Relationships

a. Nonrecurring Engineering CER

The communications nonrecurring engineering CER is expressed as a function of the transmit frequency in gigahertz (FREQ), number of transmit channels (CHANLS), and spacecraft design life (DESLIFE). The model takes a log-log form and is presented in Equation (III-19).

$$NR_E = 214.9 \times FREQ^{0.275} \times CHANLS^{1.1} \times DESLIFE^{0.57} \quad (III-19)$$

(2.04, .0871) (4.89, .0027) (1.96, .0977)

N = 10

Adj. R² = 0.90 (linear)

SEE = 18,925

The sample contains the following ten systems: ATS-F, DSCS-3A, GPS 12, GPS 9-11, GPS 13-40, I-4, IDCSP, NATO-3, TACSAT, and TDRSS 1-6. Figure III-19 is a scatter plot of the actual versus predicted costs of Equation (III-19).

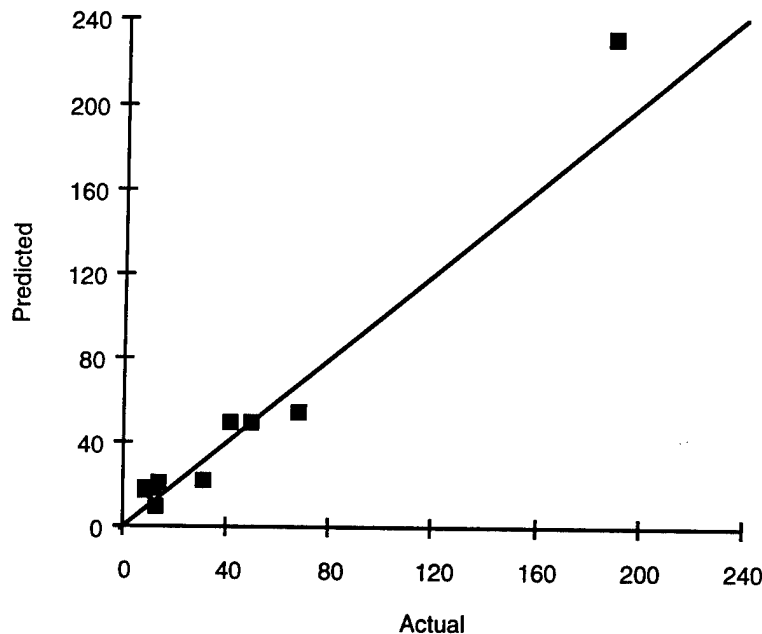


Figure III-19. Actual and Predicted Nonrecurring Engineering Communications Payload Cost (Millions of FY 1992 Dollars)

The sample averages of the independent variables FREQ, CHANLS, and DESLIFE are 6.4 gigahertz, 11 transmit channels, and 74 months, respectively. The ranges of these variables are 0.3 to 20 gigahertz (GHz), 3 to 25 transmit channels, and 24 to 120 months, respectively. The dependent variable NR_E has an average of \$44.0 million and a range of \$9.5 million to \$190.0 million in FY 1992 dollars. Our analysis indicates that a 1-percent

change in the transmit frequency results in a 0.275-percent change in communications payload nonrecurring engineering cost. The results also show diseconomies of scale for the number of communications channels. A 1-percent change in spacecraft design life corresponds to 0.57-percent change in cost. These relationships are to be expected: a communications architecture is a network of satellites and ground stations interconnected by communication links that include the antenna, transmitter, receiver, and control equipment. In the design process, mission life and requirements determine the communication links architecture, size, and complexity. Reference [12, p. 307] lists the following considerations in designing a satellite communications system: (1) type of signal, (2) capacity (i.e., number of channels and frequencies, (3) coverage area, (4) uplink and downlink signal strength and quality, (5) connectivity between different channels, (6) availability, and (7) lifetime.

b. Nonrecurring Manufacturing CER

The nonrecurring manufacturing CER for communications is in log-log form and has two explanatory variables: communications subsystem weight (COMM_WT) and frequency (FREQ). The resulting CER is shown in Equation (III-20).

$$NR_M = 23 \times COMM_WT^{0.75} \times FREQ^{0.43} \quad (III-20)$$

(11.83, .0071) (3.88, .0606)

N = 5

Adj. R² = 0.98 (linear)

SEE = 763

Due to data availability, we can use only five data points for this analysis. The sample includes data from the following five programs: ATS-F, DSCS-3A, IDCSP, NATO-3, and TDRSS 1-6. Figure III-20 is a plot showing actual versus predicted costs from Equation (III-20).

In this sample, the (FREQ) variable has an average of 11 GHz and a range of 6 to 20 GHz, and the communications subsystem weight (COMM_WT) has an average of 447 pounds and a range of 144 to 847 pounds. The dependent variable (NR_M) has an average of \$6.1 million and a range of \$2.2 million to \$11.5 million in FY 1992 dollars. Our NR_M CER shows that an increase of 1-percent in communications subsystem weight results in a 0.75-percent increase in cost, and a 1-percent change in transmit frequency leads to a 0.43-percent change in cost. This result is intuitive because the principal factors that lead the design of each link in the network are the availability of a radio frequency spectrum, coverage area of the satellite antenna beam, and path length between satellite and ground station [13, p. 337]. These factors determine antenna size and transmitter power, which in turn drive the subsystem weight. The nonrecurring manufacturing cost for

communications subsystem is therefore driven by the weight and transmit frequency required.

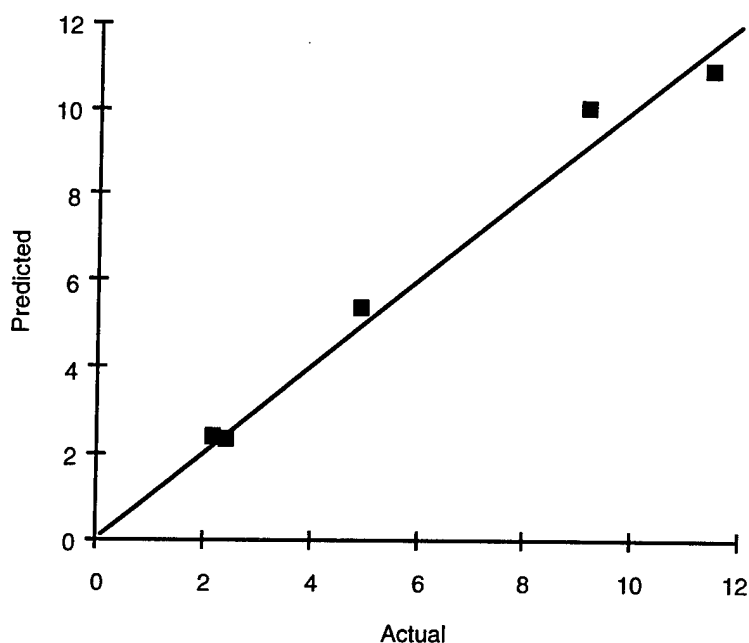


Figure III-20. Actual and Predicted Nonrecurring Manufacturing Communications Payload Cost (Millions of FY 1992 Dollars)

c. Recurring Unit One Engineering CER

The recurring unit one engineering cost is in a log-log form and is expressed as a function of communications subsystem weight (COMM_WT), an antijamming indicator (AJ) for whether or not the spacecraft has antijamming capability, and a modification indicator (MOD) for whether or not the spacecraft is a follow-on production lot built by the same contractor. The resulting CER is shown in Equation (III-21).

$$T1_E = 0.58 \times COMM_WT^{1.31} \times 6.96^{AJ} \times 0.38^{MOD} \quad (III-21)$$

(4.13, .0062) (5.47, .0016) (2.76, .0330)

N = 10

Adj. R² = 0.81 (linear)

SEE = 1,600

For this analysis, our sample contains ten programs: DSP 14-17, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, I-4, NATO-3, and TDRSS 1-6. The actual versus predicted costs of our model are presented in Figure III-21.

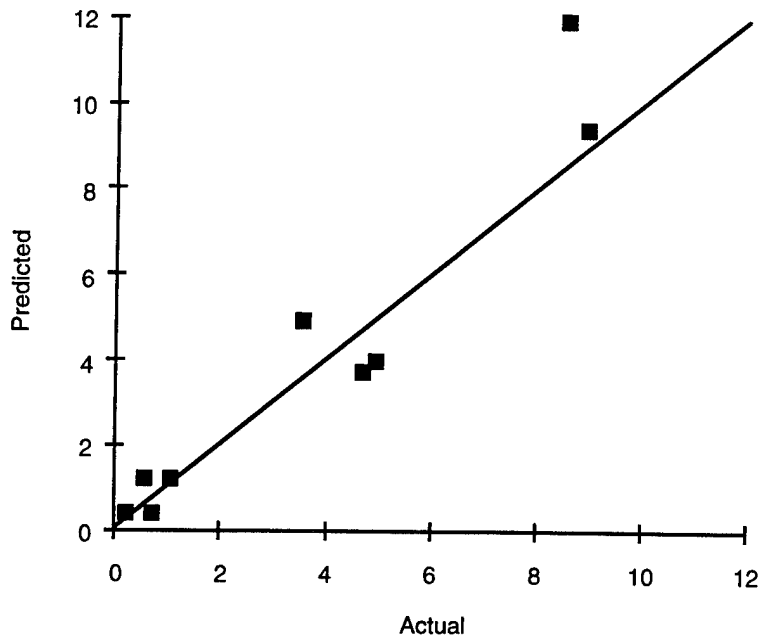


Figure III-21. Actual and Predicted Recurring Unit One Engineering Communications Payload Cost (Millions of FY 1992 Dollars)

The sample average for the independent variable COMM_WT is 373 pounds. The range of this variable is 137 to 847 pounds. The dependent variable T1_E has an average of \$3.4 million and a range of \$0.2 million to \$8.9 million in FY 1992 dollars. The T1_E CER indicates that a 1-percent change in communications subsystem weight results in a 1.31-percent change in cost. Holding communications subsystem weight constant, a spacecraft that has antijamming capability is about seven times as costly as a spacecraft that does not. Our CER also reveals that for the same weight and antijamming capability, a program that is a follow-on production lot with the same contractor cost 62 percent less than a new program. Adding antijamming capability to the communication payload means increased complexity of the design, and a new program means a whole new design. As the mission requirements drive the communications payload weight and complexity, the weight and complexity of the communications subsystem drive the cost of its unit one nonrecurring engineering

d. Recurring Unit One Manufacturing CER

The recurring communications payload unit one manufacturing (T1_M) CER is in log-log form and has two explanatory variables, number of transmit communications channels (CHANLS) and an antijamming capability indicator (AJ). The communications payload T1_M CER is shown in Equation (III-22). Figure III-22 is a plot of the actual versus predicted costs of our model.

$$T1_M = 3880.38 \times \text{CHANLS}^{0.50} \times 1.62^{\text{AJ}} \quad (\text{III-22})$$

(6.90, .0002) (3.37, .0120)

N = 10

Adj. R² = 0.94 (linear)

SEE = 2,636

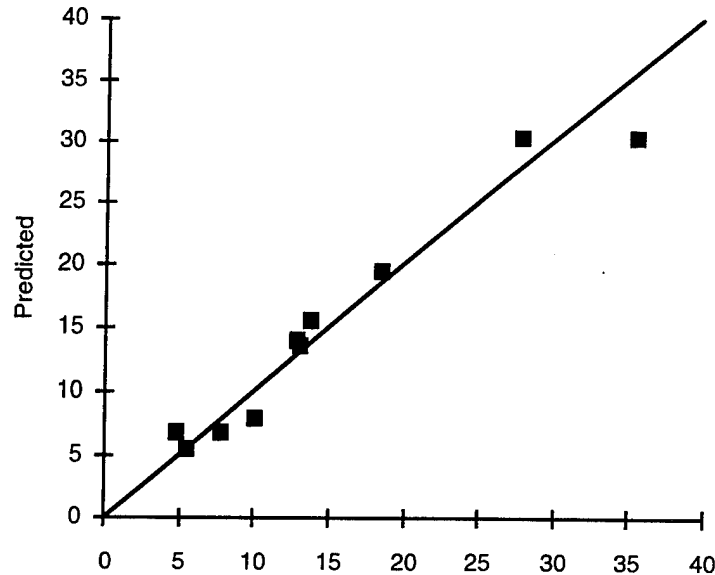


Figure III-22. Actual and Predicted Recurring Unit One Manufacturing Communications Payload Cost (Millions of FY 1992 Dollars)

The sample for this analysis includes ten spacecraft: DSCS-3A, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, I-4, NATO-3, TACSAT, and TDRSS 1-6. The sample average for the independent variable CHANLS is 14. The range of this variable is 2 to 25. The dependent variable T1_M has an average of \$14.0 million and ranges from \$4.9 million to 35.5 million in FY 1992 dollars. Our analysis indicates diseconomies of scale for the number of communication channels variable. Holding the CHANLS variable constant, the communications payload (in unit one manufacturing) that has antijamming capability costs 62 percent more than a spacecraft that does not have antijamming capability. This result is to be expected because the communication capacity is determined by the number of transmission channels,⁶ which in turn determines the bandwidths and frequencies of the communications subsystem, and antijamming means higher complexity. The recurring T1 manufacturing cost is therefore driven by the number of channels and whether or not the spacecraft has antijamming capability.

⁶ In the design of communications system, the parameter capacity is characterized as the number of channels of each type or bandwidth and frequencies [12, p. 307].

H. SUMMARY

This chapter contains the CERs we developed for the following categories of satellite subsystem hardware: structure, thermal control, attitude determination and control, reaction control/propulsion, electrical power supply, and telemetry, tracking, and command. CERs for nonrecurring manufacturing and engineering and for recurring unit one manufacturing costs are included. In the next chapter, we present the CERS for program-level characteristics of satellite programs.

IV. PROGRAM-LEVEL COST-ESTIMATING RELATIONSHIPS

A. HARDWARE ENGINEERING

1. Definition

Program-Level Recurring Engineering (PLRE) is the aggregate of the sustaining engineering activities (not to be confused with system engineering) for all the spacecraft bus hardware subsystems (communications payload recurring engineering cost is not included, see Section III-G). Satellite manufacturers retain engineering staff in the production phase (smaller staff than development phase) to monitor the manufacturing process for the hardware subsystems. This activity includes troubleshooting and responding to problems that arise in the production phase. Since this cost is small for some hardware subsystems, we combined the cost data and developed the CER at the satellite system level.

2. Cost-Estimating Relationship

The recurring PLRE CER takes an exponential form and has five explanatory variables, BOLP, COMM, PROTO, DESNEW, and SURV. The resulting CER is shown in Equation IV-1.

$$\text{PLRE} = 0.2 \times \text{BOLP}^{1.23} \times 2.19^{\text{COMM}} \times 0.45^{\text{PROTO}} \times 3.14^{\text{DESNEW}} \times 2.44^{\text{SURV}} \quad (\text{IV-1})$$

(13.71, .0001) (4.36, .0009) (4.34, .0010) (6.27, .0001) (3.08, .0096)

N = 18

Adj. R² = 0.80 (linear)

SEE = 1,131

The sample consisted of the following eighteen systems: AE, CRRES, DMSP-5D1, DSCS-3A, DSP 14-17, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, I-4, IDCSP, NATO-3, P-72-2, P-78, TACSAT, and TDRSS 1-6. The independent variable for this sample, BOLP, averages 962 watts with a range of 40 to 2,400 watts. The dependent variable, PLRE, averages \$2.4 million and ranges from \$0.05 million to \$8.9 million in FY 1992 dollars. Figure IV-1 shows the actual costs in comparison to the predicted costs derived from Equation IV-1.

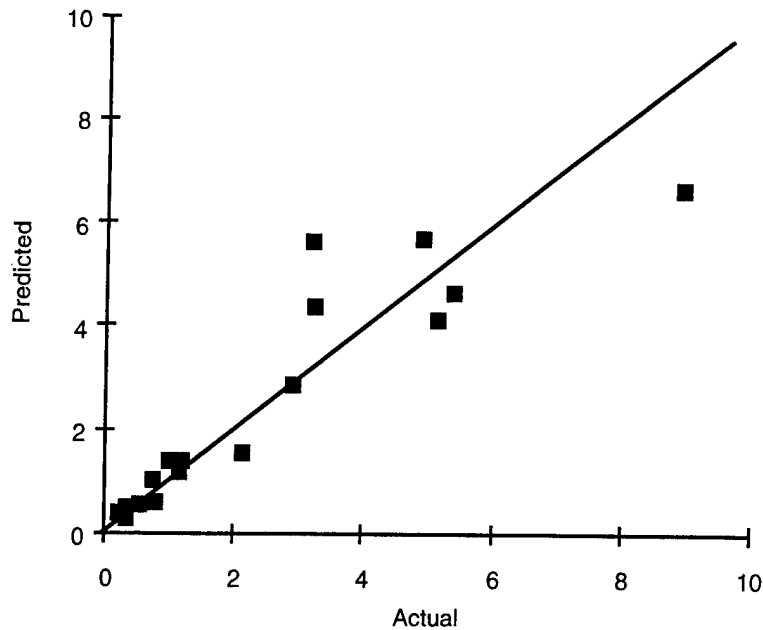


Figure IV-1. Actual and Predicted Recurring Hardware Engineering Cost (Millions of FY 1992 Dollars)

Equation IV-1 indicates that because high-power satellites are more complex, they cost more in the production phase with respect to recurring engineering activities. Satellites with communications and surveillance missions cost more than twice as much as those with other types of missions. Satellites that had prototypes built in the development phase cost about half as much as satellites that did not. The more complex satellites normally have prototypes built for testing before production units are built. The fact that prototypes avoid problems in the production phase is reflected in Equation IV-1. For this cost category, satellites designed and built for the first time, as indicated by the DESNEW variable, cost over three times more than follow-on units with minimal new design work.

B. INTEGRATION AND ASSEMBLY

1. Definition

Spacecraft integration and assembly (I&A) effort includes the costs for integrating and assembling all space vehicle subsystems into an operational space vehicle. The cost of integrating and assembling individual components into subsystems is included at the level of the subsystem total cost and is not accounted for here.

The I&A cost category includes any general or common equipment, materials, tests, or services furnished by or to an integrating contractor, which cannot be readily assigned to specific lower level hardware elements. This includes integration with mission payloads.

Space vehicle assembly and check-out are kept under spacecraft integration and assembly. No hardware is fabricated herein; these are assembled units from sections and kits produced in other WBS elements.

2. Cost-Estimating Relationships

a. Nonrecurring CER

The nonrecurring I&A CER takes a nonlinear form and has three explanatory variables, prototype (PROTO), beginning-of-life power (BOLP), and production quantity (P_QTY). The resulting CER is shown in Equation (IV-2).

$$NR_I\&A = 12.89 \times 2.29^{PROTO} \times BOLP^{0.76} \times P_QTY^{0.28} \quad (IV-2)$$

(3.00, .0241) (6.74, .0005) (2.33, .0590)

N = 10

Adj. R² = 0.87 (linear)

SEE = 1,911

The sample size is ten and consists of the following systems: CRRES, DSCS-3A, FLTSATCOM 1-5, GPS 1-5, GPS 12, GRO, I-4, P-72-2, P-78, and TACSAT. The independent variable BOLP ranges from 260 to 5,000 watts with an average of 1,212 watts. P_QTY averages 5 and ranges from 1 to 28. The dependent variable, NR_I&A, ranges from \$0.9 million to \$14.1 million with an average of \$5.8 million in FY 1992 dollars. Figure IV-2 is a scatter plot of the actual versus predicted costs from Equation (IV-2).

It can be seen from the model that nonrecurring cost for integration increases by a factor of 2.29 if a prototype is built. For every percent increase in BOLP, NR_I&A increases by 0.76 percent. A higher BOLP implies a heavier, more complex, longer life satellite. Every 1-percent increase in production quantity causes nonrecurring integration cost to increase by 0.28 percent.

Two methods are used for qualifying spacecraft: prototype and protoflight. In the prototype approach, which is applicable to entirely new designs and missions, dedicated fully instrumented qualification hardware is manufactured and exposed to the full qualification test program both at the equipment and integrated system levels [12, p. 395]. This approach increases program cost—for hardware and integration and for the schedule effects of one additional spacecraft—all of which is considered nonrecurring. For programs with high production quantities, this approach is more attractive because the increased costs can be amortized over the entire production run—the cost versus risk tradeoff is better. On the other hand, a protoflight approach utilizes the fact that many of the parts and equipment were previously qualified and therefore do not need to be subjected again. Half the full test

duration is saved and the additional hardware and integration costs are eliminated. This is why it is reasonable to say that both larger production runs and the use of a prototype increase NR_I&A cost.

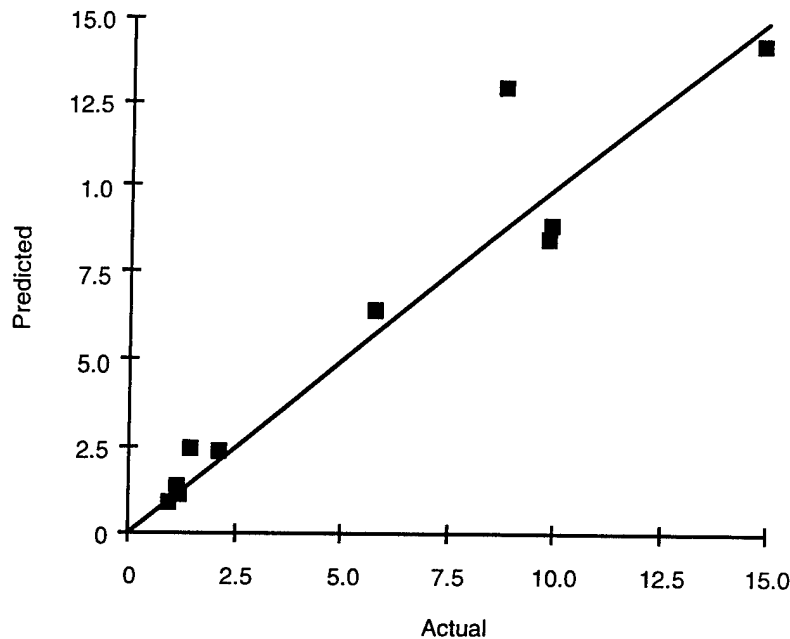


Figure IV-2. Actual and Predicted Nonrecurring Integration and Assembly Cost (Millions of FY 1992 Dollars)

A more complex satellite may indicate a larger payload or more payload subsystems (i.e., more than one mission objective) requiring higher average power consumption and peak load requirements. Therefore, it makes sense that increases in BOLP result in increases to NR_I&A.

b. Recurring First Unit CER

The recurring I&A CER takes an exponential form and has three explanatory variables, spacecraft dry weight (SC_WT), modification (MOD), and operational (OPERATE). The resulting CER, Equation (IV-3), is shown below.

$$T1_I\&A = 0.002 \times SC_WT^{1.88} \times 0.19^{MOD} \times 2.25^{OPERATE} \quad (IV-3)$$

(9.25, .0000) (5.16, .0002) (2.83, .0141)

N = 17

Adj. R² = 0.63 (linear)

SEE = 4,610

This sample comprises data from the following sixteen systems: AE, ATSF, DSCS-3A, DSP 14-17, DSP 18-22, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, IDCSP, I-4, NATO-3, OSO-I, P-72-2, P-78, and TDRSS 1-6. The independent variable

SC_WT average for the sample is 1,922 pounds with a range of 345 to 5,083 pounds. The predicted variable, T1_I&A, has an average cost of \$5.8 million in FY 1992 dollars and ranges from \$0.2 million to \$26.1 million. Figure IV-3 shows a plot of actual versus predicted costs from Equation (IV-3).

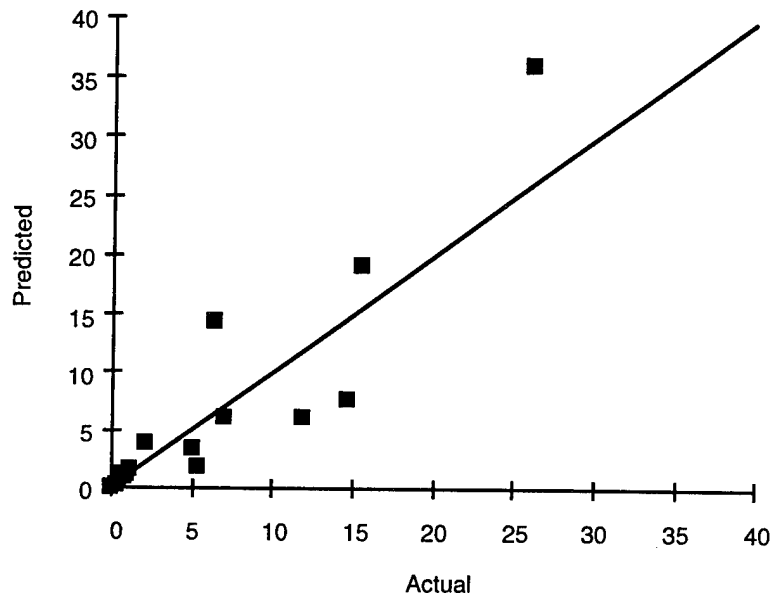


Figure IV-3. Actual and Predicted Recurring Integration and Assembly Cost (Millions of FY 1992 Dollars)

Recurring I&A cost increases by a factor 1.88 percent for every percentage increase in the spacecraft's dry weight. Spacecraft dry weight tends to be a good estimator of cost. Like beginning-of-life power, dry weight indicates the relative complexity and life expectancy of a satellite. A more complex satellite may indicate a larger payload or more payload subsystems (i.e., more weight). The longer life expectancy of a satellite translates into a larger and heavier EPS. Therefore, the more a spacecraft weighs, the more it will cost. Generally, this relationship holds, to some extent, for most spacecraft subsystems.

The CER also shows cost to decrease by a factor of 0.19 if the spacecraft is a modification to an existing design, built as part of a follow-on production lot by the same contractor. It is evident that the first satellite of a newly designed spacecraft experiences several problems not encountered in follow-on or modified spacecraft. Assembling the first unit is particularly difficult because components are seldom available in the best sequence and unexpected interference and test peculiarities always occur [13, p. 437]. Many of the problems that prevail during manufacture of the first satellite disappear in later production units, a decrease in integration cost for modified spacecraft results for this reason.

Modification programs usually use a protoflight approach. With this approach, some of the integration cost for the first unit is accounted for as a nonrecurring cost.

If the satellite is operational, the cost increases by a factor of 2.25. Due to the nature of the mission, an experimental spacecraft may be turned on and off when needed, which means less power and weight, among other things, are required. On the other hand, an operational spacecraft must be in operating mode at all time, which implies higher power, weight, and complexity to support the mission requirement.

C. PROGRAM MANAGEMENT AND DATA

1. Definition

Program management and data (PM&D) effort comprises two separate cost accounts, program management and data. Together, these two cost efforts make up the prime contractor's administrative, management, oversight, and documentation activities to achieve the objectives of the program.

Program management includes the costs of the management required to plan, organize, direct, coordinate, and maintain oversight of the development and production of a system. It includes the business and administrative functions of logistics and logistics support, maintenance support, facilities, personnel and training, testing, and activation of a system. It also includes project management and control, cost and schedule tracking, contract administration, data management, configuration management, vendor and subcontractor liaison, and so on.

The data costs account for any program-related documentation effort, including any requirements set forth in the contract's data requirement list, DD Form 1423 for DoD programs. Control of engineering drawings are also included in this category. It only includes those charges associated with editing, printing, and publishing and includes only such effort that would be reduced or would not be incurred if the data were eliminated.

2. Cost-Estimating Relationships

a. Nonrecurring CER

The non-recurring PM&D CER takes an exponential form and has three explanatory variables, spacecraft dry weight (SC_WT), prototype (PROTO), and communications mission (COMM). The resulting CER is shown in Equation (IV-4).

$$NR_PM\&D = 44.45 \times SC_WT^{0.59} \times 2.86^{PROTO} \times 2.26^{COMM} \quad (IV-4)$$

(3.99, .0004) (3.57, .0865) (2.82, .0040)

N = 17

Adj. R² = 0.68 (linear)

SEE = 5,658

The sample size is seventeen and consists of the following systems: AE, ATS-F, CRRES, DMSP-5D1, DSCS-3A, FLTSATCOM 1-5, GPS 1-5, GPS 12, GRO, IDCSP, I-4, NATO-3, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6. The independent variable SC_WT average for this sample is 2,417 pounds with a range 1,178 to 34,437 pounds. The dependent variable, NR_PM&D, averages \$10.5 million and ranges from \$1.2 million to \$34.4 million in FY 1992 dollars. Figure IV-4 shows a comparison of the actual costs and the predicted costs from Equation (IV-4).

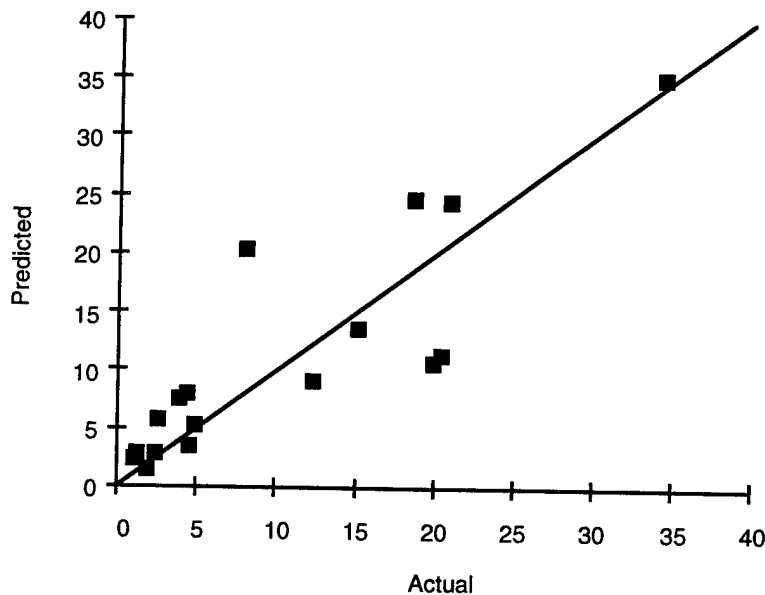


Figure IV-4. Actual and Predicted Nonrecurring Program Management and Data Cost (Millions of FY 1992 Dollars)

For every 1-percent increase in spacecraft dry weight, the cost increases by 0.59 percent. As stated previously, dry weight indicates the relative complexity and life expectancy of a satellite; the more a spacecraft weighs, the more it will cost. If a prototype is built, the cost increases by a factor of 2.86. Since a prototype approach requires one additional spacecraft, nonrecurring program management and data costs would logically increase. Communications mission satellites cost roughly 2.3 times more than other missions. Most communications satellites occupy a geosynchronous orbit. Generally, a geosynchronous satellite is more expensive and the increased cost trickles down to the programmatic level.

b. Recurring First Unit CER

The recurring PM&D CER takes a nonlinear form and has one explanatory variable, spacecraft weight times beginning-of-life power (SCWT_PWR). The resulting CER is shown in Equation (IV-5).

$$T1_PM\&D = 2.28 \times SCWT_PWR^{0.56} \quad (IV-5)$$

(10.03, .0000)

N = 17

Adj. R² = 0.90 (linear)

SEE = 1,576

The independent variable SCWT_PWR is a composite variable. Spacecraft weight averages 1,546 pounds with a range of 340 to 5,083 pounds. Beginning-of-life power averages 753 watts with a range of 40 to 2,192 watts. The values for the first unit recurring PM&D for this sample range from \$0.4 million to \$19.0 million and the average is \$5.4 million in FY 1992 dollars. The sample size for this regression is seventeen and includes: AE, ATSF, DSCS-3A, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, IDCSP, I-4, NATO-3, OSO-I, P-72-2, P-78, S3, and TACSAT. Figure IV-5 shows the actual costs and the predicted costs derived from Equation (IV-5).

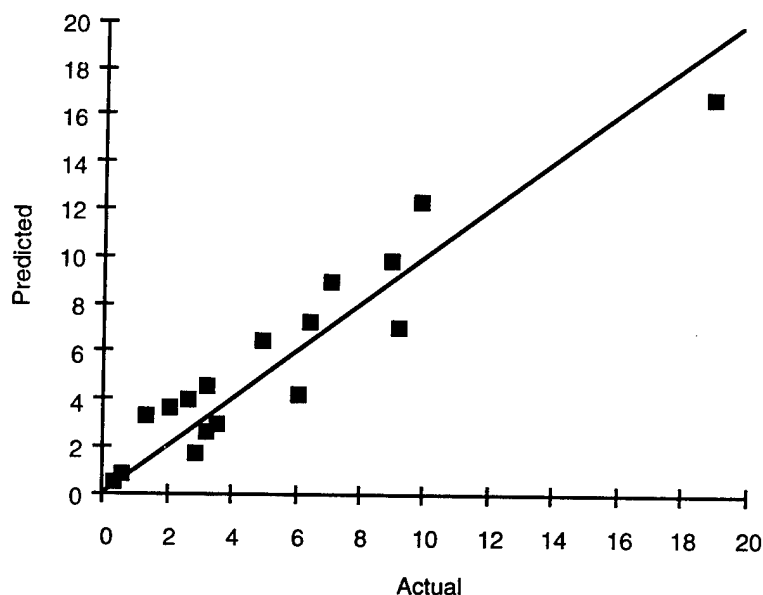


Figure IV-5. Actual and Predicted Recurring Unit One Program Management and Data Cost (Millions of FY 1992 Dollars)

The recurring first unit cost increases by 0.56 percent when the composite variable SCWT_PWR is increased by one percent. Observing the properties of the CER when spacecraft dry weight and beginning-of-life power are varied around their averages, shows an increase in BOLP has slightly more significance than SC_WT. For every 1-watt

increase, the cost increases by 0.07 percent. On the other hand, when SC_WT is increased by one pound, the cost only increases by 0.04 percent. Individually, increasing spacecraft weight and beginning-of-life power indicate a larger, more complex, longer life satellite. Therefore, it stands to reason that their product indicates the same thing.

D. SYSTEM ENGINEERING

1. Definition

System engineering (SE) includes the technical and management efforts of directing and controlling a totally integrated engineering approach to meet the objectives of a program. It includes the system engineering effort to define a system and integrate and coordinate the tasks involved in satellite design and development. It also includes converting an operational need into a description of the system requirements and a suitable system configuration.

This element also refers to any of the technical and management efforts needed to distribute system-level requirements and specifications to lower level subsystems and equipment. Also included are those efforts associated with controlling system-level documents such as specifications, weights, reliability, standardization, and quality control. The following are activities categorized as system engineering: reliability analysis; nuclear survivability design and planning; production and manufacturing engineering; quality assurance and inspection; configuration management; software planning, programming, and testing; corrective actions and troubleshooting; safety engineering; maintainability; mass property analysis; and so on.

2. Cost-Estimating Relationships

a. Nonrecurring CER

The nonrecurring SE CER takes a nonlinear form and has four explanatory variables, operational (OPERATE), communications mission (COMM), spacecraft dry weight (SC_WT), and modification (MOD). The resulting CER is shown in Equation (IV-6).

$$NR_SE = 121.14 \times 3.65^{OPERATE} \times 1.96^{COMM} \times SC_WT^{0.44} \times 0.42^{MOD} \quad (IV-6)$$

(3.76, .0027) (2.20, .0479) (3.15, .0084) (2.12, .0552)

N = 17

Adj. R² = 0.83 (linear)

SEE = 4,825

This sample comprises data from the following seventeen systems: AE, ATSF, CRRES, DMSP-5D1, DSCS-3A, DSP 14-17, GPS 1-5, GPS 9-11, GPS 13-40, GRO, IDCSP, I-4, NATO-3, OSO-I, P-78, S3, and TACSAT. The independent variable SC_WT average for the sample is 2,456 pounds with a range of 340 to 16,086 pounds. The dependent variable, NR_SE, has an average cost of \$12.9 million in FY 1992 dollars. The distribution range for this sample is \$1.6 million to \$33.0 million in FY 1992 dollars. Figure IV-6 shows the actual costs and the predicted costs derived from Equation (IV-6).

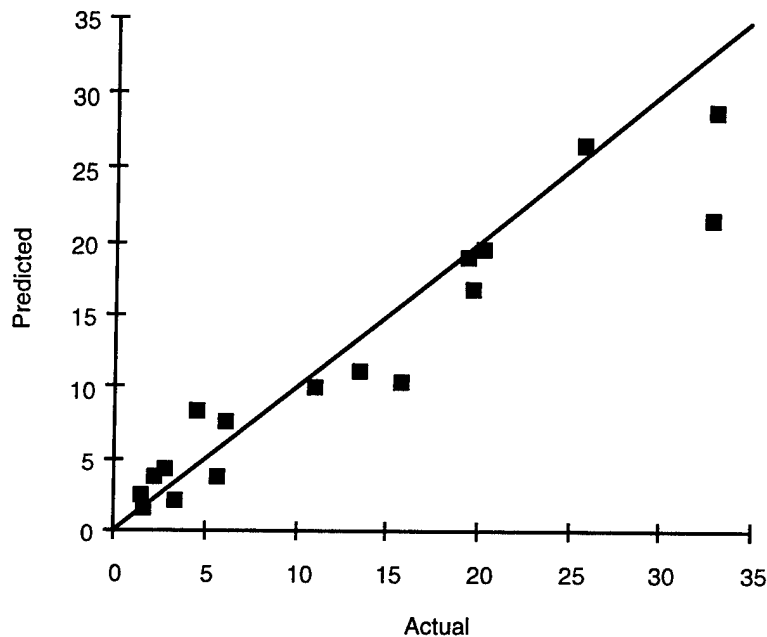


Figure IV-6. Actual and Predicted Nonrecurring Systems Engineering Cost (Millions of FY 1992 Dollars)

Nonrecurring SE cost increases by 0.44 percent for every 1-percent increase in spacecraft dry weight. This CER essentially has three multiplier terms. If the spacecraft being estimated is operational, the cost increases by 3.65 times; if it is a communications satellite, it increases by a factor of 1.96; and if it is a modification to an existing design or a follow-on, the cost decreases by a factor of 0.42. All of these parameters were previously analyzed in the spacecraft I&A and PM&D sections. The same reasons apply here to NR_SE.

b. Recurring First Unit CER

The recurring SE CER takes an exponential form and has five explanatory variables, spacecraft dry weight times power (SCWT_PWR), operational (OPERATE),

prototype (PROTO), modification (MOD), and radiation hardening (RADHARD). The resulting CER is shown in Equation (IV-7).

$$T1_SE = 12.41 \times SCWT_PWR^{0.34} \times 3.60^{OPERATE} \times 0.46^{PROTO} \times 0.46^{MOD} \times 2.94^{RADHARD} \quad (IV-7)$$

(6.19, .0000) (4.58, .0004) (3.79, .0020) (3.33, .0050)

(3.44, .0040)

N = 20 Adj. R² = 0.76 (linear) SEE = 2,360

This sample comprises twenty spacecraft: ATSF, CRRES, DMSP-5D1, DSCS-3A, DSP 14-17, DMSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, GRO, IDCSP, I-4, NATO-3, OSO-I, P-78, S3, TACSAT, and TDRSS 1-6. The independent variable SCWT_PWR is a composite variable. Spacecraft weight has an average of 2,671 pounds with a range of 340 to 16,086 pounds. Beginning-of-life power has an average of 1,150 watts with a range of 40 to 5,000 watts. Radiation hardening has a low value of 0 and a high value of 0.78. T1_SE, the dependent variable, ranges from \$0.4 million to \$20.6 million and averages \$5.6 million in FY 1992 dollars. Figure IV-7 shows the actual costs compared to the predicted costs derived from Equation (IV-7).

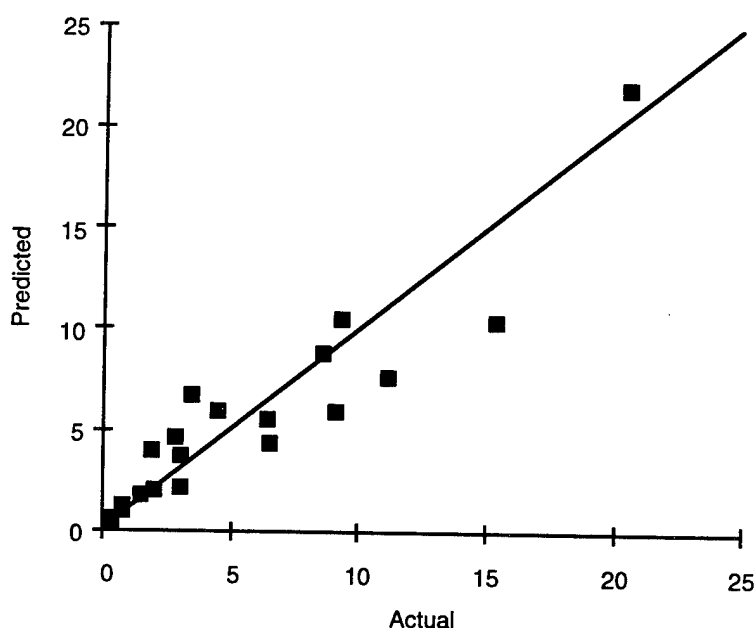


Figure IV-7. Actual and Predicted Recurring Systems Engineering Cost (Millions of FY 1992 Dollars)

The recurring first unit cost increases by 0.34 percent when the composite variable SCWT_PWR is increased by 1 percent. By observing the properties of the CER when

spacecraft dry weight and beginning-of-life power are varied about their averages, you can see that an increase in BOLP has slightly more significance than SC_WT. For every 1-watt increase, the cost increases by 0.03 percent. When SC_WT is increased by one pound, the cost only increases by 0.01 percent. Once again, this variable represents the size and complexity of the spacecraft. A direct relationship exists between SCWT_PWR and cost. If the system is operational instead of experimental, the cost increases by a factor of 3.60. If the spacecraft has a prototype design philosophy, the cost decreases by a factor of 0.46. When the system is a modification to a previous design or a follow-on lot, the first unit of that lot would be 0.46 times cheaper. Operational, prototype, and modification are characteristics already discussed and justified in previous sections. RADHARD captures the nuclear radiation hardening level that is designed into the satellite for survivability against nuclear weapon effects resulting in higher SE costs. Increased hardening is accomplished through increased shielding (suppression algorithms), harder parts (for operate through), or circumvention (requiring a re-initialization and restart). As the hardening level increases, more survivability design and planning are required [8].

E. SYSTEM TEST AND EVALUATION

1. Definition

System test and evaluation (ST&E) refers to the costs associated with all testing required to develop the system and accomplish planned test objectives. This effort spans the development, test, and evaluation (DT&E) and operational test and evaluation (OT&E) phases of a program.

ST&E refers to the use of prototype, production, or specially fabricated hardware to obtain or validate engineering data on the proper interaction of equipment and performance of the system. It includes the detailed planning, conduct, support, data collection and compilation, and report writing as well as all hardware items not allocated to a particular subsystem that are consumed, or planned to be consumed, including the qualification unit. It also includes all effort associated with the design and production of prototypes, specimens, fixtures, and instrumentation in support of the test program. Development, component acceptance, and so on, testing that can be specifically associated with the subsystem element are not included here. Activities accounted for under System Test and Evaluation include: design verification, fabrication inspection, qualification tests, acceptance tests, and test plans and equipment. Typical design verification tests include structural tests (static load tests, model survey), deployment tests (solar array, antennas, experimental booms, and appendages), separation tests, antenna tests (pattern tests, closed

loop tracking tests), and attitude control tests (closed loop functional tests) [13, p. 437]. The qualification test sequence normally matches the flight sequence and includes tests for vibration, shock, and thermal vacuum.

2. Cost-Estimating Relationships

a. Nonrecurring CER

The nonrecurring ST&E CER takes an exponential form and has four explanatory variables, production quantity (P_QTY), beginning-of-life power (BOLP), operational (OPERATE), and modification (MOD). The resulting CER is shown in Equation (IV-8).

$$NR_ST\&E = 11.88 \times P_QTY^{0.38} \times BOLP^{0.75} \times 4.11^{OPERATE} \times 0.17^{MOD} \quad (IV-8)$$

(3.24, .0079) (4.60, .0008) (3.82, .0028) (5.49, .0002)

N = 16

Adj. R² = 0.93 (linear)

SEE = 2,723

The sixteen data points in this sample are: AE, ATSF, DMSP-5D1, DSCS-3A, FLTSAT 1-5, GPS 1-5, GPS 9-11, GPS 13-40, GRO, I-4, NATO-3, OSO-I, P-72-2, P-78, TACSAT, and TDRSS 1-6. The independent variable P_QTY average for the sample is 4 with a range of 1 to 28. Beginning-of-life power has an average value of 1,092 watts and ranges from 170 to 5,000 watts. The dependent variable, nonrecurring ST&E, ranges from \$0.2 million to \$28.9 million with an average of \$11.5 million in FY 1992 dollars. Figure IV-8 shows the actual costs compared to the predicted costs derived from Equation (IV-8).

Observation of this CER shows that every 1-percent increase in production quantity or beginning-of-life power increases nonrecurring ST&E cost by 0.38 and 0.75 percent, respectively. Again, BOLP implies a larger more complex satellite with possibly more than one mission objective (i.e., more payload subsystems). These would require more testing and qualification. If the system is operational, the cost increases by a factor of 4.11; if it is a modification to an existing design, it decreases by a factor of 0.17. An operational satellite must be operating full time; requiring more power, weight, and complexity. Hence a higher cost. As stated previously, a modification to an existing design requires a lot less testing and qualification effort because many of the parts and equipment are previously qualified.

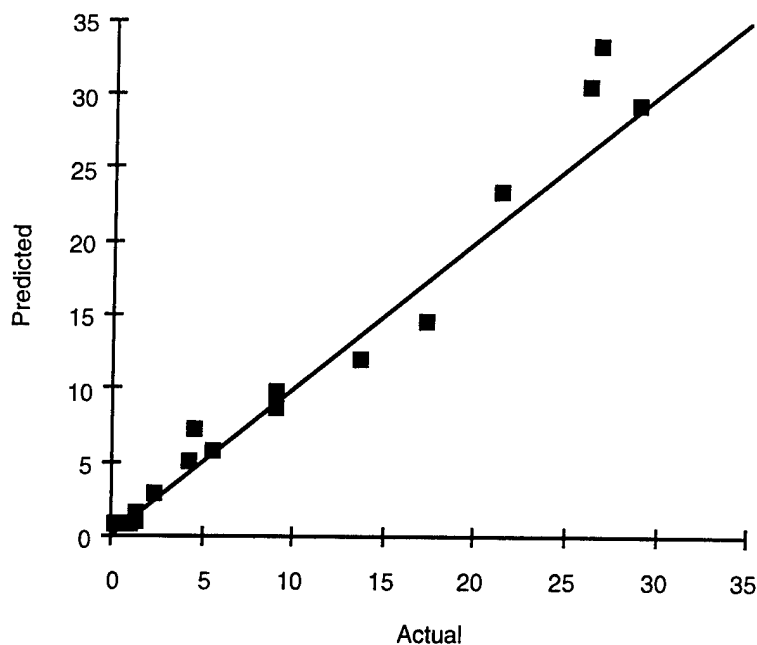


Figure IV-8. Actual and Predicted Nonrecurring System Test and Evaluation Cost (Millions of FY 1992 Dollars)

b. Recurring CER

The recurring ST&E CER takes an exponential form and has two explanatory variables, radiation hardening (RADHARD), and spacecraft dry weight (SC_WT). The resulting CER is shown in Equation (IV-9).

$$T1_ST\&E = 2.23 \times 2.93^{RADHARD} \times SC_WT^{0.99} \quad (IV-9)$$

(2.42, .0288) (4.97, .0002)

N = 18

Adj. R² = 0.66

SEE = 1,570

The independent variable RADHARD has a low value of 0 and a high value of 0.78 for this sample. SC_WT average is 1,425 pounds with a range of 340 to 3,403 pounds. Recurring first unit ST&E values average \$3.5 million in FY 1992 dollars and range from \$0.4 million to \$8.2 million dollars. This sample consists of eighteen data points: AE, ATSF, DMSP-5D1, DSCS-3A, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 9-11, GPS 13-40, IDCSP, I-4, NATO-3, OSO-I, P-72-2, P-78, S3, TACSAT, and TDRSS 1-6. Figure IV-9 shows the actual costs compared to the predicted costs derived from Equation (IV-9).

Recurring first unit ST&E increases by 0.99 percent for every 1-percent increase in spacecraft dry weight. RADHARD captures the radiation hardening level that results in increased cost for increased levels of hardening. Increases in radiation hardening imply

more protection against nuclear effects. Types and levels of hardening depend on the mission, threat, and environment. With more complex and sophisticated hardening methods being employed, the cost of testing increases because of validating harder parts.

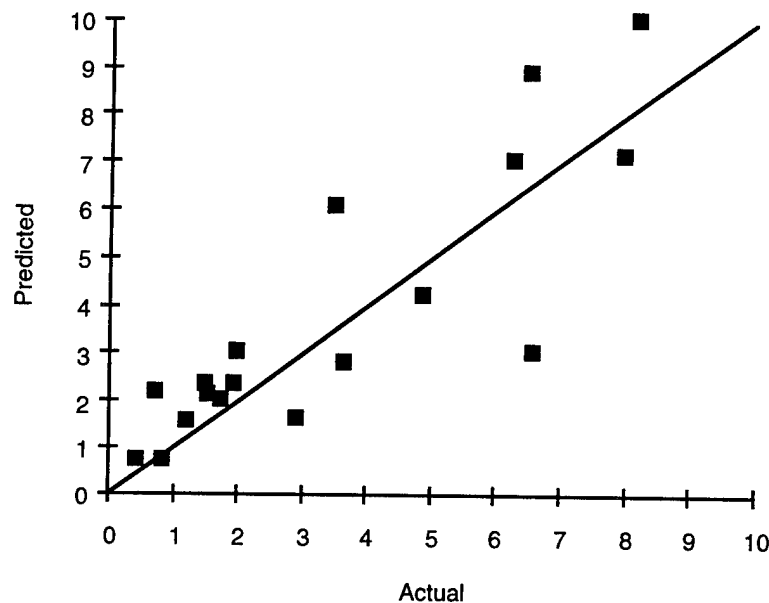


Figure IV-9. Actual and Predicted Recurring System Test and Evaluation Cost (Millions of FY 1992 Dollars)

F. AEROSPACE GROUND EQUIPMENT

1. Definition

Aerospace Ground Equipment (AGE) refers to the nonrecurring ground support hardware required to support the space vehicle during ground test, production, and preparation for flight operations. All AGE costs are categorized as nonrecurring.

AGE includes all items required to support and maintain the system or portions of the system while not directly engaged in the performance of its mission. Among these items are both mechanical and electrical fixtures, tools, and other equipment used to fuel, service, transport, hoist, repair, overhaul, assemble, disassemble, test, inspect, or otherwise maintain the mission equipment.

2. Cost-Estimating Relationship

The nonrecurring AGE CER takes a non-linear form and has three explanatory variables, spacecraft dry weight (SC_WT), operational (OPERATE), and new design (DESNEW). The resulting CER is shown in Equation (IV-10).

$$\text{NR_AGE} = 69.16 \times \text{SC_WT}^{0.34} \times 6.68^{\text{OPERATE}} \times 4.32^{\text{DESNEW}} \quad (\text{IV-10})$$

(3.89, .0025) (10.21, .0000) (8.77, .0000)

N = 15

Adj. R² = 0.82 (linear)

SEE = 6,018

The fifteen data points in this sample are: AE, DMSP-5D1, DSCS-3A, DSP 14-17, GPS 1-5, GPS 9-11, GRO, I-4, NATO-3, OSO-I, P-72-2, P-78, S3, TACSAT, and TDRSS 1-6. The independent variable SC_WT average is 2,584 pounds with a range of 349 to 16,806 pounds. NR_AGE averages about \$11.1 million and ranges from \$0.4 million to \$51.5 million in FY 1992 dollars. Figure IV-10 is a scatter plot showing the actual costs compared to the predicted costs derived from Equation (IV-10).

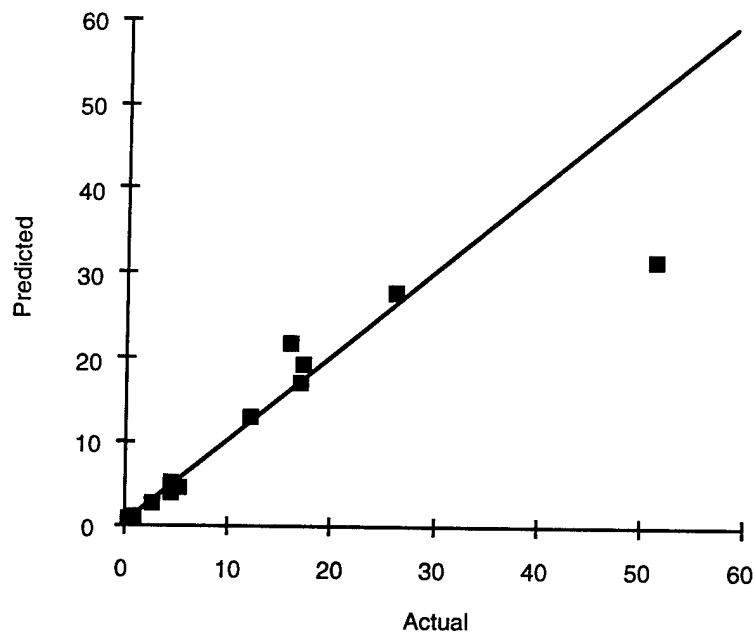


Figure IV-10. Actual and Predicted Nonrecurring Aerospace Ground Equipment Cost (Millions of FY 1992 Dollars)

The model shows that every 1-percent increase in spacecraft dry weight leads to a cost increase of 0.34 percent. If the spacecraft is operational, the cost increases by a factor of 6.68. If it is a new design, the cost increases by a factor of 4.32. A newly designed spacecraft requires new or modified test equipment, fixtures, tools, and other equipment that would already exist for a modified or follow-on spacecraft.

G. LAUNCH OPERATIONS AND ORBITAL SUPPORT

1. Definition

Launch and orbital operations support (LOOS) includes those accounts for any effort associated with prelaunch planning, launch and ascent, and initial on-orbit operations performed by the prime contractor before the system is released to the procuring organization. Activities include bus and payload preparation, as well as interface activities with the launch vehicle and ground controllers. All LOOS costs are considered recurring.

The spacecraft is transported from the manufacturing site to the launch site via aircraft or air-cushioned trailers. Launch-site operations include installing and validating the test equipment (aerospace ground equipment), testing the spacecraft's performance, installing propulsion (apogee kick motor), loading propellant, mating the spacecraft to its launch vehicle, installing ordinance, and monitoring [13, p. 439]. If not already installed, flight batteries are also installed. LOOS captures all of the support costs for these exercises. The cost of the test equipment, usually housed in a launch-site test hangar, and any other support equipment are included in AGE. LOOS includes all activities performed to gain command and control of the spacecraft. The flight segment of a spacecraft begins once orbit is achieved. At this point, the satellite undergoes a series of tests known as early orbit checkout. These comprehensive tests validate components, subsystems, and system interfaces and operations. Engineers and operators detect and analyze any anomalies, calibrate and ensure proper operation of instruments and maneuver the satellite to its mission orbit.

2. Cost-Estimating Relationship

The recurring LOOS CER takes an exponential form and has two explanatory variables, new design (DESNEW) and beginning-of-life power (BOLP). The resulting CER is shown in Equation (IV-11).

$$T1_LOOS = 3.76 \times (2.19)^{DESNEW} \times BOLP^{0.92} \quad (IV-11)$$

(3.70, .0027) (9.02, .0000)

N = 16

Adj. R² = 0.72 (linear)

SEE = 1,400

This sample comprises sixteen spacecraft: AE, CRRES, DSCS-3A, DSP 18-22, FLTSATCOM 1-5, FLTSATCOM 6-8, GPS 1-5, GPS 13-40, I-4, IDCSP, NATO-3, OSO-I, P-72-2, P-78, TACSAT, and TDRSS 1-6. The independent variable beginning-of-life power has an average of 904 watts with a range of 40 to 2,400 watts. The recurring cost for first unit LOOS has an average of \$3.1 million and a range of \$0.2 million to \$8.6

million in FY 1992 dollars. Figure IV-11 shows a scatter plot of the actual versus predicted costs from Equation (IV-11).

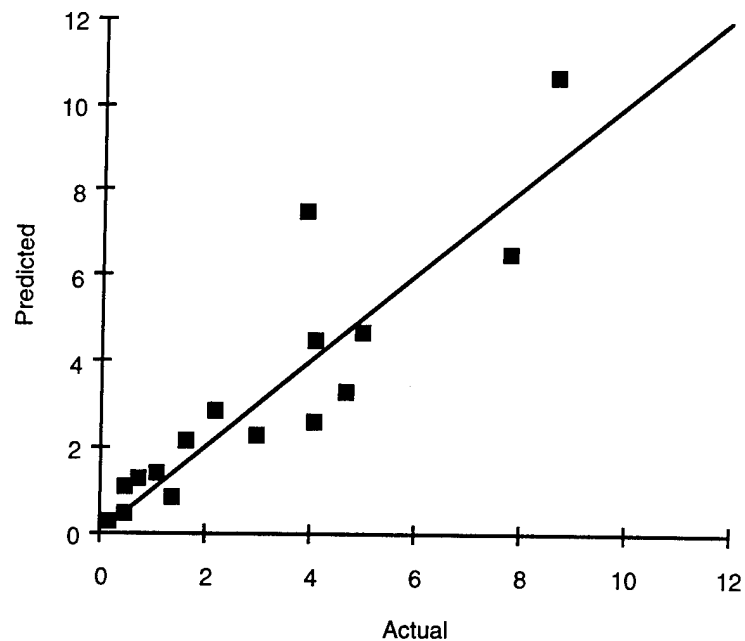


Figure IV-11. Actual and Predicted Recurring Launch and Orbital Operations Support Cost (Millions of FY 1992 Dollars)

Observation of the CER shows that for every 1-percent increase in beginning-of-life power, the cost increases by 0.92 percent. Once again, increased BOLP implies a larger, more complex satellite. If the spacecraft is a new design, the cost increases by a factor of 2.19. For new spacecraft or a new generation of spacecraft, the test and integration activities become quite detailed. Integrating operations activities and a new ground system or a major ground-system upgrade requires much lead time, which is typically driven by software development. A spacecraft's complexity not only drives team size but also requires team members with specific skills [13, p. 495]. A newly designed spacecraft is also more expensive because no learning has been accomplished. Prelaunch planning, launch and ascent support, and initial on-orbit operations must be performed with no prior experience. These reasons justify the use of new design as an estimator for recurring LOOS costs.

H. SUMMARY

This chapter contains the CERs we developed for the following categories of program costs: hardware engineering, integration and assembly, system engineering, system test and evaluation, aerospace ground equipment, and launch operations and orbital

support. In most cases, CERs for both nonrecurring and recurring costs are included. In the next chapter, we summarize the results from this chapter as well as the previous chapter.

V. SUMMARY OF RESULTS

In conjunction with weight, we found numerous non-weight physical and performance parameters and also indicator variables—variables with a value of either 0 or 1 to indicate whether a feature is present or not, also called programmatic cost drivers—to be good predictors of spacecraft costs. Table V-1 lists the subsystem-level cost drivers by subsystem and Table V-2 list the program-level cost drivers by function.

We used the CERs in support of the OSD Technical Support Group in the fall of 1993 to evaluate several space-based surveillance options. The systems estimated were down-sized DSP, Follow-On Early Warning System Multi-Spectral Satellite and DSP-C (Competitive). The model was able to differentiate among the different designs and capabilities of these satellites and provided estimates that made engineering sense.

We found that augmenting the performance and physical characteristic variables with programmatic cost drivers enhanced the capability of the models. By accounting for the different missions and acquisition strategies of the satellites in the database, we were able to produce models that can be used to estimate a wider range of satellite programs.

Table V-1. Subsystem-Level Cost Drivers

Subsystem	Cost Drivers
<i>Structure</i>	
Nonrecurring Engineering	Prototype, Structure Weight
Nonrecurring Manufacturing	Aluminum Content, Extended Launch Vehicle Deployment, Science Mission, Solar Array Area
Recurring Manufacturing	Aluminum Content, Solar Array Area
<i>Thermal Control</i>	
Nonrecurring Engineering	Thermal Control Weight, Beginning-of-Life Power
Nonrecurring Manufacturing	Design Life, Steady State Low Temperature, Prototype
Recurring Manufacturing	Thermal Control Weight, Spacecraft Weight, NASA Mission
<i>Attitude Determination and Control</i>	
Nonrecurring Engineering	Sensor Weight, Design Life, Spin Stabilization, Design Newness
Nonrecurring Manufacturing	Prototype, Sensor Weight, ACS Weight
Recurring Manufacturing	Spin Stabilization, Low Earth Orbit, Sensor Weight, ACS Weight
<i>Reaction Control/Propulsion</i>	
Nonrecurring Engineering	Spacecraft Weight, Spin Stabilization, NASA Mission, Communications Mission
Nonrecurring Manufacturing	Geosynchronous Orbit, Three-axis Stabilization, RCS Weight, Engine/Thrusters Included
Recurring Manufacturing	RCS Weight, Design Life, Engine/Thrusters Included
<i>Electrical Power Supply</i>	
Nonrecurring Engineering	Design Life, EPS Beginning-of-Life Power
Nonrecurring Manufacturing	EPS Beginning-of-Life Power, Design Newness
Recurring Manufacturing	EPS End-of-Life Power
<i>Telemetry, Tracking, and Control</i>	
Nonrecurring Engineering	Number of Channels
Nonrecurring Manufacturing	Design Life, Prototype, TTC Power Required, TTC Subsystem Weight
Recurring Manufacturing	Number of Channels, Design Newness, Low Earth Orbit
<i>Communications Payload</i>	
Nonrecurring Engineering	Design Life, Communications Subsystem Weight, Number of Channels
Nonrecurring Manufacturing	Communications Subsystem Weight
Recurring Engineering	Antijamming Capability, Communications Subsystem Weight, Modified (Follow-on Acquisition)
Recurring Manufacturing	Number of Channels, Antijamming Capability

Table V-2. Program-Level Cost Drivers

Function	Cost Drivers
<i>Hardware Engineering</i>	
Recurring	Beginning-of-Life Power, Communications Mission, Prototype, Design Newness, Surveillance Mission
<i>Integration and Assembly</i>	
Nonrecurring	Prototype, Production Lot Quantity, Science Mission, Nuclear Hardening, Design Life
Recurring	Spacecraft Weight, Design Newness, Modified (Follow-on Acquisition), Beginning-of-Life Power
<i>Program Management and Data</i>	
Nonrecurring	Spacecraft Weight, Prototype, Communications Mission, Production Lot Quantity
Recurring	Spacecraft Weight, Beginning-of-Life Power
<i>System Engineering</i>	
Nonrecurring	Operational (versus Experimental), Communications Missions, Spacecraft Weight, Modified (Follow-on Acquisition)
Recurring	Spacecraft Weight, Beginning-of-Life Power, Operational (versus Experimental), Prototype, Modified (Follow-on Acquisition), Nuclear Hardening
<i>System Test and Evaluation</i>	
Nonrecurring	Production Quantity, Operational (versus Experimental), Beginning-of-Life Power, Modified (Follow-on Acquisition)
Recurring	Nuclear Hardening, Spacecraft Weight
<i>Aerospace Ground Equipment</i>	
Nonrecurring	Design Newness, Spacecraft Weight, Design Life
<i>Launch Operations and Orbital Support</i>	
Recurring	Design Newness, Beginning-of-Life Power

REFERENCES

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- [1] United States Air Force, Space Systems Division. "Unmanned Space Vehicle Cost Model, Sixth Edition." SD-TR-88-97, November 1988.
- [2] United States Air Force, Space Division. "Unmanned Spacecraft Cost Model, Fifth Edition," June 1981.
- [3] Planning Research Corporation. "NASA Cost Model (NASCOM)." PRC D-2337, October 1990.
- [4] United States Air Force, Space and Missile Systems Center, "Unmanned Space Vehicle Cost Model," Seventh Edition, August 1994.
- [5] Frazier, Thomas P., Bruce N. Angier, James Bui, T. Keith Blankenship, Stephen R. Shyman, and John Horak. "Cost-Estimating Relationships for Space-Based Systems." Institute for Defense Analyses, Paper P-2513, April 1991.
- [6] Bui, James, and Neang Om. "Estimating Software Development Costs and Schedules for Space Systems." Institute for Defense Analyses, Paper P-2830, May 1994.
- [7] Goldberger, A. S. *Topics in Regression Analysis*. London: The MacMillan Company, 1968, pp. 120-123.
- [8] Bui, James, Peter Kysar, and James Roth. "Estimating the Costs of Nuclear-Radiation-Hardened Military Satellites (U)." Institute for Defense Analyses, Paper P-2857, SECRET/RD, November 1994.
- [9] Chetty, P. R. K. *Satellite Technology and Its Applications*, Blue Ridge Summit, PA: Tab Books, Inc., 1988.
- [10] Draper, N. R., and H. Smith. *Applied Regression Analysis*. New York: John Wiley and Sons, Inc., 1966, p. 20.
- [11] Kmenta, Jan. *Elements of Econometrics*, New York: The Macmillan Company, 1971.
- [12] Fortescue, Peter W., and John P. W. Stark, "Spacecraft Systems Engineering," Department of Aeronautics and Astronautics, University of Southampton, UK: John Wiley and Sons, chap. 11.
- [13] Wertz, James R., and Wiley L. Larson (editors), *Space Mission Analysis and Design*, Space Technology Library, 1991.
- [14] Agrawal, Brij N., *Design of Geosynchronous Spacecraft*, New Jersey: Prentice-Hall, Inc., 1986.
- [15] Fuhs, Allen E., *An Analysts Guide to Military Space*, to be published by American Institute of Aeronautics and Astronautics, January 1992.
- [16] USCM7 WBS, Appendix E. Defense Support Program Block 1 (DSP-1), Spacecraft 18-22 Data Package, Tecolote Research, Inc., May 19, 1992.
- [17] Ford Aerospace and Communications Corporation, "Spacecraft System Familiarization," SCF Course N. 213, February 1983.

- [18] The Analytic Science Corporation (TASC), gen. ed., AFSC Cost Estimating Handbook Series, Vol. 6, "Space Handbook," by M. Koscielski et al., El Segundo: Tecolote Research, Inc., December 1987.

ABBREVIATIONS

ABBREVIATIONS

ACS	attitude control system
AE	Atmospheric Explorer
ATS	Applications Technology Satellite
BMDO	Ballistic Missile Defense Organization
CER	cost-estimating relationship
COMSAT	communications satellite
CRRES	Combined Radiation Release Experiment Satellite
DISA	Defense Information Systems Agency
DMSP	Defense Meteorological Support Program
DoD	Department of Defense
DSCS	Defense Satellite Communications System
DSP	Defense Support Program
EMD	engineering and manufacturing development
EOL	end of life
EPS	electrical power supply
F	Fahrenheit
FLTSATCOM	Fleet Satellite Communications System
GPS	Global Positioning System
GRO	Gamma Ray Observatory
I&A	integration and assembly
IDA	Institute for Defense Analyses
IDCSP	Initial Defense Communications Satellite Program
INTELSAT	Intelligence Satellite
LOOS	launch operations and orbital support
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications Network or NASA Cost Model*
OSO	Orbiting Solar Observatory
PM&D	program management and data
RCS	reaction control system
SDIO	Strategic Defense Initiative Organization
SE	system engineering

SMC	Space and Missile Systems Center
TACSAT	Tactical Communications Satellite
TC	thermal control
TCS	thermal control system
TDRSS	Tracking and Data Relay Satellite System
TT&C	telemetry, tracking, and command
USCM5	Unmanned Spacecraft Cost Model, Fifth Edition
USCM6	Unmanned Space Vehicle Cost Model, Sixth Edition
WBS	work breakdown structure

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22204-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE February 1996	3. REPORT TYPE AND DATES COVERED Final Report, Sep 1992-Feb 1996	
4. TITLE AND SUBTITLE Functional Cost-Estimating Relationships for Spacecraft			5. FUNDING NUMBERS DASW01 94 C 0054 T-R2-597.13	
6. AUTHOR(S) James Bui, Neang I. Om, James K. Roth, Melissa L. Corso, Jennifer A. Titus				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Institute for Defense Analyses 1801 N. Beauregard Street Alexandria, VA 22311-1772			8. PERFORMING ORGANIZATION REPORT NUMBER IDA Paper P-3020	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) BMDO/POE The Pentagon, Room 1E1037 Washington, DC 20301			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12A. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12B. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The costs to acquire space-based missile defense systems are often reviewed by DoD. Issues are raised concerning the cost models used to generate cost estimates for space-based missile defense systems. The Ballistic Missile Defense Organization questions the use of traditional weight-based spacecraft cost models developed by the Air Force Space and Missile Systems Center. The concern is motivated by changes in satellite designs of future systems where smaller but more capable spacecraft are being built. Using weight-based cost models yields lower cost estimates, although the spacecraft are more capable. IDA developed spacecraft functional (engineering and manufacturing) cost-estimating relationships (CERs) at the spacecraft subsystem level using performance and physical characteristics that are not primarily weight-based. We developed nonrecurring (design, development, and test) and recurring (production) CERs for the spacecraft bus, including ground support equipment, and for communications payloads. The CERs show that programmatic aspects, which reflect the requirements and acquisition environments that the satellites were acquired under, have considerable influence on satellite costs.				
14. SUBJECT TERMS Ballistic Missile Defense System; Space Based Systems; Spacecraft; Cost Models; Cost Estimating Relationships (CERs)			15. NUMBER OF PAGES 80	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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