Small Satellite Cost Model

Version 98 INTRO

User's Guide

Prepared by:

The Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009-2957

15 June 1998

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THE AEROSPACE CORPORATION
El Segundo, California

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Prepared by:

N.Y. Lao
(310) 336-7876

T.J. Mosher
(310) 336-1203

J.M. Neff
(310) 336-1080

The Aerospace Corporation
P.O. Box 92957
Los Angeles, CA 90009

15 June 1998

Table of Contents

EXECUTIVE SUMMARY

Traditional weight-based parametric cost-estimating relationships (CERs) and other cost models derived from the experience of traditional large satellites are not appropriate for estimating costs of modern (post-1990) small satellites. This User's Guide, which accompanies version 98 INTRO of the Small Satellite Cost Model (SSCM), is the product of an on-going study of small satellites initiated in 1987 by The Aerospace Corporation. The system-level cost-estimating relationships implemented in this software provide the analyst with the ability to more credibly estimate costs of a modern small spacecraft.

The SSCM98 INTRO version CERs were derived from a database of twenty-eight modern small-satellite programs. These programs tend to be characterized by low cost, maximal use of existing components and off-the-shelf technology, and reduced program-management oversight and developmental effort.

Cost estimates, given in FY97 $K, are based on a variety of technical parameters, including weight, power, and performance characteristics. A multiplicative-error model is fit to the data, with the error of estimation expressed as a percentage of the estimate, rather than as a uniform dollar amount regardless of the size of the estimate. Fit quality of the CERs is measured by percentage standard error and Pearson's correlation squared between actuals and estimates.

I. INTRODUCTION

I.1 Background

In the late 1980s, a new satellite program paradigm emerged and opened up a new class of space applications. Low-profile, low-cost satellites, funded primarily by ARPA (the Department of Defense's Advanced Research Projects Agency), STP (the Air Force's Space Test Program) and university laboratories, were being built with maximal use of existing components and off-the-shelf technology and minimal non-recurring developmental effort.

In the early 1990s, the National Aeronautics and Space Administration (NASA) was faced with adopting a new design philosophy in the face of declining budgets caused by increased public fiscal scrutiny. Dan Goldin, NASA's administrator, called for space missions that are "faster, better, and cheaper", essentially asking engineers to do more for less. This environment has evoked a fundamental change in the method by which NASA spacecraft are procured. The prior approach where satellite programs were driven solely by performance characteristics to meet certain mission objectives, with cost and schedule as secondary concerns, is being reversed. Given new funding limitations and schedule constraints, designers are asked to respond with mission objectives that can be attained within rigid cost caps. It is especially challenging to enact the "faster, better, and cheaper" philosophy in the design of NASA science and planetary spacecraft due to their unique nature and sometimes challenging operating conditions. NASA appears to be showing increased interest in small spacecraft as evidenced by programs like the Small Explorer (SMEX) Program, the Earth System Science Pathfinder (ESSP) Program, the Midsize Explorer Program (MIDEX), and the Small Satellite Technology Initiative (SSTI).

In addition to NASA and the DoD, foreign defense and space agencies, such as CNES (Centre National d'Etudes Spatiales) and ESA (European Space Agency), have identified small spacecraft as a viable means for establishing a space program without incurring large development costs. Commercial developers of space systems have recently shown increased interest in small satellites by making major investments in mobile communications and remote sensing applications. Small satellites, because of their functional and operational characteristics and their comparatively low development and service costs, allow access to space by more customers and to the space business by more suppliers than the large space systems we have become accustomed to over the last 20-30 years.[1] Relatively low acquisition costs and short development timelines offer space-related capabilities previously reserved only for well-funded programs. Small satellites with sufficient power, pointing and tracking accuracy, on-board data compression, storage and processing capabilities, high-rate data downlinking, and associated ground segments for a variety of applications have been demonstrated. Use of available subsystem hardware and software, procured in a streamlined fashion, has also been demonstrated to be feasible and cost-effective.

Recent small-satellite studies at The Aerospace Corporation have shown that cost-reduction techniques employed on modern small-satellite programs result in system costs that are substantially lower than those estimated by traditional weight-based parametric cost-estimating relationships (CERs).[2] Cost models based on historical costs and technical parameters of traditional large satellites do not appear

[1] Thompson, D.W., "The Microspace Revolution", address given at the Langley Colloquium Series, NASA, December 1991.
[2] Abramson, R.L. and Bearden, D.A., *Cost Analysis Methodology for High-Performance Small Satellites*, SPIE (The International Society for Optical Engineering), International Symposium on Aerospace and Remote Sensing, Small Satellite Technology and Applications III, Orlando, FL, April 1993.

to be applicable[3,4]. Credible parametric cost estimates for small-satellite systems require CERs derived from a cost and technical data base of modern (post-1990) small satellites.

Since the release of the first version of SSCM in 1995, program managers have placed increased emphasis on improving the performance of space projects within tighter budgets and shorter development times. The reality that launch cost is typically a large percentage of a program's budget (as much as 30% in some cases), has led to a movement by government and industry toward smaller platforms in order to reduce overall cost. Furthermore, advanced technologies are increasingly being incorporated into small spacecraft to systematically reduce mass and increase performance in some cases with minimal insight into the impacts to cost and assumed risk. The small satellite community has received increased interest as budgets continue to tighten; dozens of small satellite missions are currently in the works, ranging from experimental to operational in nature in both government and commercial arenas. The need for a current, credible small spacecraft cost model remains as important as ever.

I.2 Cost Estimating Methods

SSCM is a parametric cost model: a series of mathematical relationships that relate spacecraft cost to physical, technical, and performance parameters that are known to strongly influence spacecraft costs. The basis for these relationships is a data base of actual costs and technical parameters for thirty modern small satellites. Parametrics is one of three typical ways to estimate costs of future systems, the other two being engineering buildup and analogy. Selection of an approach depends on the scope of the effort estimated, the detail of technical design definition, the availability and appropriateness of usable historical costs, and the ability of the cost estimators[5]. Figure I-2 shows the program phase when the three cost estimation methods are often applied[6].

Parametric estimates, also called model based, "top-down", or Cost Estimating Relationship (CER) estimates, are based on mathematical expressions relating cost as a dependent variable to one or more spacecraft design parameters. The mathematical estimates are correlated using both regression analysis between data points for several existing developed systems that share physical or performance characteristics with the system to be estimated along with engineering judgment in those circumstances where pure statistics fall short. A typical example is the weight of the structures subsystem related to the structure subsystem's cost. An underlying assumption of the parametric approach is that the same forces that affected the cost of the systems that are used as data points also will affect the cost of the future system[4].

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[3] Bearden, D.A., et al, "Comparison of NEAR Costs with a Small-Spacecraft Cost Model", AIAA/USU Conference on Small Satellites, 16-19 September 1996.

[4] Bearden, D.A. and Lopez, A., "Cost Estimation of Small Satellites, A Practical Case: the MINISAT 01 Mission", AIAA/USU Conference on Small Satellites, 16-19 September 1996.

[5] Nguyen, P., Lozzi, N., Galang, W., Hu, S., Sjovold, A., Young, P., Book, S., Schmitz, J., *Unmanned Space Vehicle Cost Model*, 7th Edition, Space and Missile Systems Center, August, 1994.

[6] Blanchard, Benjamin S., Fabrycky, Wolter J., *System Engineering and Analysis*, Prentice Hall, 1990.

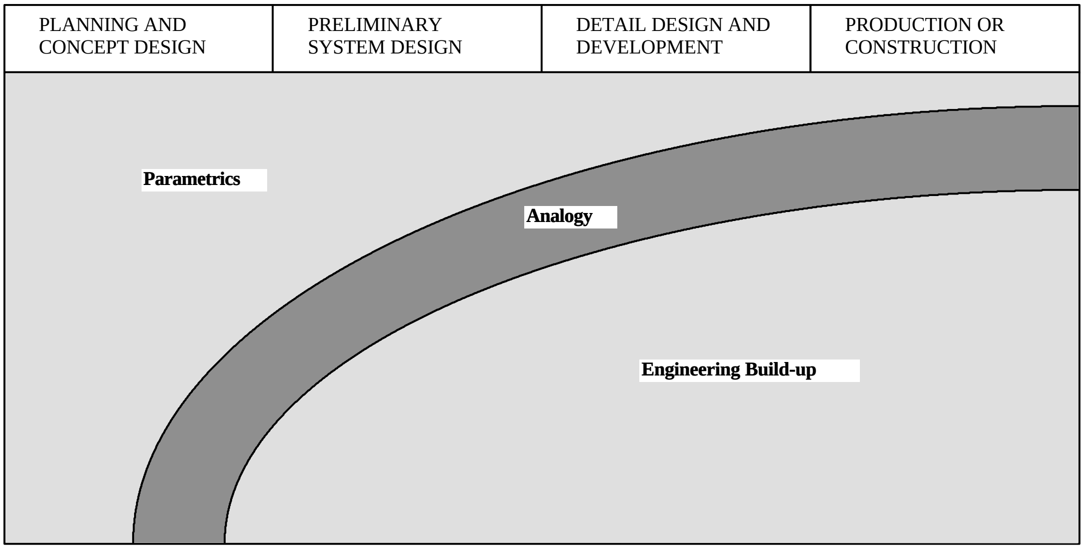

Figure I-2. Cost Estimation by Program Phase

Parametric methods can range from high level "rules of thumb" to lower level models that use a set of CERs for the structure, power, and thermal subsystems, etc. Parametrics have become a standard method of estimating early program costs, but the assumption of using the past to predict the future that underlies this method is continually debated by engineers, managers and cost analysts.

Analogous estimates are performed on the basis of comparison. Costs from one or more past programs that are very similar in complexity and objectives are used based on the analyst's judgment that those programs are representative of the program to be estimated. This cost data is then subjectively adjusted upward or downward to account for more or less complexity in the new program. This approach is used when there is sufficient knowledge of the program and when there are comparable historical spacecraft program cost data to make credible analogy comparisons. A basic premise of analogy costing is that no new system is actually totally new. In reality, most programs originate or evolve from already existing programs, representing simply a new combination of components or a modest evolution from past technologies. The advantage of this approach is the relative simplicity when applicable databases are accessible. The obvious disadvantages result from the difficulty of obtaining enough technical and program detailed cost data for both the program to be estimated and from the one to which the analogy is being made.

Engineering buildup estimates, commonly referred to as "grass roots" or "bottoms-up" estimates, are created by accumulating costs from the lowest level of detail. To get an estimate by this method the detailed spacecraft design, manufacturing, and procurement steps are laid out in great detail. Direct vendor bids are used for various components and detailed labor costs estimated. All of this data is compounded to get an estimate with the greatest amount of detail possible. Engineering buildup estimates are often used in the latter phases of a project when the design configuration is relatively stable. However, it is also often used when no historical costs are available and engineering judgment is the only source for basis of the estimate. In this case the validity of these costs rests in the credibility of the expert opinion applied and the fact that costs have been examined at a very low level. This method of estimating has the advantage of being individually tailored to a specific program and is traceable to a very detailed level. Balanced against these advantages are its requirements for volumes of information and documentation. It is also limited in cases where the design has not reached a very detailed level.

Flexibility is also a problem because with each major change in program configuration the estimate must be completely updated. Finally, engineering estimates can often be inflated or overly optimistic depending on the conservatism and experience of the source.

II. MODELING FRAMEWORK

II.1 Scope of SSCM

Several assumptions and ground rules further define the scope and limitations of the small-satellite model. Each of the following items should be carefully reviewed by the working cost estimator to ensure the small satellite program for which the estimate is being generated is consistent with the CER framework and that the CERs and model are not misapplied:

1. Estimates assume the cost of developing and producing one spacecraft, the phase known among DoD users as EMD (Engineering, Manufacturing, and Development), and among NASA users as Phases C/D. Phases A/B (concept development) and Phase E (operations) are not included. Also, the emphasis is on spacecraft (bus) costs; payload, launch vehicles, upper stages, and associated ground equipment are not included.
2. All costs estimated by CERs are contractor costs. Award fees and incentives are not included, nor are government costs. In the cases where a government agency acted as contractor (NASA GSFC, e.g.), effort was made to include civil services costs due to "contractor-like" activities.
3. CERs estimate costs in fiscal-year 1997 thousands of U.S. dollars (FY97$K). Underlying cost data were inflated to FY97$ using the latest available NASA inflation indices.
4. CERs are statistical fits to data derived from actual costs of recent small satellite programs. Use of CERs to estimate costs of future programs relies on the assumption that historical trends will accurately reflect future costs.
5. CERs estimate burdened costs including direct labor, material, overhead, and general and administrative costs.
6. Most programs in the data base rely on some degree of hardware commonality to previous units, but limited quantitative data were available. CERs therefore yield costs that represent an "average" amount of heritage, an "average" level of technology complexity, and an "average" amount of schedule delays and engineering changes. Cost estimates derived from the CERs should therefore be accompanied by a comprehensive cost-risk assessment to estimate potential effects of a level of complexity below or beyond average. SSCM98 INTRO does not include a cost-risk capability.
7. CERs were derived using a generalized error regression model (GERM) and assuming constant relative error. Implicit in this method is the assumption that cost-estimating error is a percentage of the estimated costs, rather than a particular dollar value independent of the estimate. Standard error of the estimate for each CER is therefore given as a percent. Refer to Section IV for more details on CER derivation techniques.

II.2 Computer Implementation

As with other recent versions of the Smallsat Cost Model, Version 98 INTRO is implemented as a Microsoft Excel workbook, consisting of a number of individual worksheets. These sheets are:

1. Title Sheet
2. Cost Input Sheet
3. Cost Estimate Sheet
4. List of Programs Sheet

The model has been designed to run on both PCs and Macintoshes running Excel 5.0 or greater. No additional software is needed.

II.3 Computer Operation

Upon loading the model (sscm98intro.xls), the title screen will automatically appear. Buttons at the bottom offer the user the option to "start," or to "exit." Pressing the "start" button will jump the user to the input sheet and present the user with a dialog box, which requests that a label (a word or phrase) be entered to identify the particular costing session. If that phrase is entered, it will be present on each printable sheet, and will become the default filename when the user chooses to save his inputs (Note: multiple word filenames are permitted under Windows 95, Windows NT, and the Mac OS, but not under Windows 3.1. Windows 3.1 users should limit their label to no more than 8 alphanumeric characters). Users may also choose to leave the session unlabeled, either by pressing OK with the edit box blank, or by pressing Cancel. The label dialog can also be bypassed by using Excel's index tabs instead of the start button. After entering a label (or canceling), the user is placed in the data input sheet.

Once all the input parameters have been supplied, the user can choose to either save his inputs (by pressing the "save inputs" button located at the top), or jump to either the cost estimate or cost risk sheets (again, by using the appropriate buttons at the top, or by using the Excel index tabs). If a cost driver is unknown, the user should make sure that the value is blank (by using the Delete key), or the cost estimate may be in error. The Cost Estimate sheet lists the estimated spacecraft bus cost, which is a combination of the estimates generated by each individual CER. The individual CER cost estimates are also listed. Note that the standard error of the estimate is listed for the combined cost estimate and for each individual CER. A graph plots the results of each CER along with the combined cost estimate. For detailed instructions on operating the model, refer to Section VI, Applying the Model.

III. DATA BASE

III.1 Data-Gathering Activity

Aerospace devised a plan to conduct research and collect data to support development of a parametric cost model based entirely on modern small-satellite cost and technical data. The goal was to allow credible subsystem-level cost analysis of potential small-satellite missions without first requiring a detailed design. Achieving this goal depended on relating cost to weight, power, performance parameters and other cost-driving technical characteristics. Programs either already completed or awaiting launch in the next year were targeted. The task plan for data acquisition and subsequent CER formulation can be described as follows:

- Data Identification
  - Assess current data-base applicability
  - Identify new data needs
  - Generate survey form
- Data Acquisition
  - Follow-up on existing industry and government relationships
  - Acquire relevant NASA-specific data
  - Survey additional contractors as identified
- Data Normalization
  - Assess subsystem-level design and integration procedures
  - Represent data in FY97$
  - Identify and include hidden costs (e.g., civil service labor)
  - Separate engineering model costs from development costs
  - Calibrate cost data based on special circumstances
  - Identify system-level costs
- CER Formulation and Development
  - Postulate candidate functional forms
  - Perform regressions
  - Identify correlations
  - Generate multiple-parameter CERs

Three of the four tasks listed above involve interaction with data. Whenever appropriate, data acquired previously by The Aerospace Corporation were utilized. To supplement the existing data base with subsystem-level cost data and NASA-specific data, an updated cost and technical survey sheet was generated and distributed to organizations and contractors involved in the small-satellite industry. Contractors who build small satellites or provide small-satellite services (e.g. components, launchers, etc.) were surveyed and interviewed to gather information on the state of the industry as a whole, as well as data on specific programs. As an FFRDC (Federally-Funded Research and Development Center), The Aerospace Corporation enjoys a special relationship with the U.S. government, and as such, is in a unique position to receive and merge proprietary data from several private companies into special-purpose data bases to support government space-acquisition goals. Contractors are assured that any proprietary information delivered will be treated in a restricted manner, used only for the purpose intended, and not released to third parties without the express written consent of the contractor. The information is used exclusively for analysis purposes directly related to cost-model development. Only composite information depicted in a generalized manner may be delivered as part of this report, and the data base itself remains proprietary. In some cases, formal non-disclosure agreements between the companies and The Aerospace Corporation were necessary to facilitate delivery of proprietary data.

Technical survey elements are listed in Figure III-1. Technical data elements include programmatic, weight-based, and performance-based parameters for the satellite in general and each of the major subsystems. Some details on payload specifications are included; however, emphasis was placed on obtaining data for spacecraft bus and bus subsystem characteristics.

In addition to technical data, the following subsystem costs were requested for the following elements:

- Propulsion
- Thermal Control
- Attitude Control
- Structures
- Command & Data Handling
- Telecommunications (TT&C)
- Electric Power
- Spacecraft Software
- Spacecraft Integration, Assembly, Test
- Program Management/System Engineering
- Launch and Orbital Operations Support

Nonrecurring (development) and Recurring (unit production) costs were collected whenever available. Information concerning particular program circumstances (e.g., schedule delay, redesign) that may affect the cost figures were also noted.

GENERAL	**ELECTRIC POWER SUBSYSTEM (EPS)**
User Agency/Contact	EPS Mass (kg)
Acquisition Agency/Contact	Power BOL/EOL/Average (Watts)
Contractor Name/Contact	Payload/Spacecraft Power (Watts)
Principal Subcontractors	Solar Cell Type/Area (m^2)
Contact Name/Telephone Number	Battery Type (NiCd, NiH2, etc.)/Number of Cells
Mission Type	Total Battery Capacity/DOD (A-Hr/%)
Launch Vehicle/Upper Stage	EPS Heritage (% old design)/Previous Units
Project Schedule	EPS RDT&E TRL
First/Last Launch	
Development/Production Quantity	**ATTITUDE CONTROL SUBSYSTEM (ACS)**
Satellite Dry/Wet Mass (kg)	ACS Mass (kg)
Spacecraft Bus Dry/Wet Mass (kg)	Stabilization Type
Design Life/Goal/Actual Life (months)	Attitude Knowledge (deg)
Orbital Parameters (Alt, Incl, etc.)	Pointing Accuracy (deg)
Spacecraft Heritage (% old design)/Previous Units	Sensors (Number, Type)
Spacecraft RDT&E TRL	ACS Heritage (% old design)/Previous Units
	ACS RDT&E TRL
STRUCTURES AND MECHANISM	
Structures Mass (kg)	**PAYLOAD(S)**
Material	Description
Percentage Advanced Composites (%)	Specifications (Performance, Power, etc.)
Dimensions/Shape	Payload Mass (kg)
Volume ($inches^3$)	
Structures Heritage (% old design)/Previous Units	**COMMAND AND DATA HANDLING (C&DH)**
Structures RDT&E TRL	C&DH Subsystem Mass (kg)
	Flight Software (lines of code/language/% reuse)
TELECOMMUNICATIONS (TT&C)	Ground Software (lines of code/language/ % reuse)
Telecommunications Mass (kg)	Memory (e.g. recorders) (Mbytes)
Uplink Band/Downlink Band	Data Transfer Rate (Mbps)
Bandwidth (KHz)	Data Processor (type, throughput)
Uplink/Downlink Data Rates (Kbps)	Data Management Heritage (% old design)/Previous Units
Main Processor (Memory-Mbytes, CPU)	Data Management RDT&E TRL
Telecomm. Heritage (% old design)/Previous Units	
Telecommunications RDT&E TRL	**PROPULSION**
	Propulsion Dry Mass (kg)
THERMAL CONTROL	Thrusters (quantity, thrust, etc.)
Thermal Subsystem Mass (kg)	Propellant/Oxidizer (type, weight)
Type (Active, Passive)	Total Impulse (ft. per sec.)
Thermal Heritage (% old design)/Previous Units	Propulsion Heritage (% old design)/Previous Units
Thermal RDT&E TRL	Propulsion RDT&E TRL

Figure III-1. Small satellite technical survey elements including system-level and subsystem-level parameters.

III.2 List of Programs

Figure III-2 lists the program, sponsor, contractor, launch date and function of the small satellites that make up the subsystem-level data base. Earth-orbiting missions and planetary programs are each listed in alphabetical order by contractor name.

PROGRAM	SPONSOR	CONTRACTOR	LAUNCH	FUNCTION
ALEXIS	DOE	AEROASTRO	Apr-93	X-RAY MAPPING
DARPASAT	DARPA/AF	BALL AEROSPACE	Dec-93	CLASSIFIED
LOSAT-X	SDIO	BALL AEROSPACE	Jul-91	SENSOR EXPERIMENTS
CRO	SDIO	DSI (CTA)	Apr-91	CHEMICAL RELEASE
PEGSAT	NASA/DARPA	DSI (CTA)	Apr-90	CHEMICAL RELEASE
GLOMR I	DARPA	DSI (CTA)	Nov-85	MESSAGE RELAY
POGS/SSR	ONR	DSI (CTA)	Apr-90	GEOMAGNETIC SURVEY
REX	STP	DSI (CTA)	Jun-91	RADIATION STUDIES
TEX	ONR	DSI (CTA)	Apr-90	COMMUNICATIONS
SCE	ONR	DSI (CTA)	Apr-90	COMMUNICATIONS
RADCAL	STP	DSI (CTA)	Jun-93	RADAR CALIBRATION
MICROSAT	DARPA/Army	DSI (CTA)	Nov-91	COMMUNICATIONS
MACSAT	DARPA/ONR	DSI (CTA)	May-90	COMMUNICATIONS
SAMPEX	NASA	GSFC	Jul-92	PHYSICS EXPERIMENT
APEX	STP	OSC	Aug-94	POWER EXPERIMENTS
SEASTAR (ORBVIEW 2)	NASA	OSC	Aug-97	OCEAN COLOR
MICROLAB	NASA	OSC	Mar-95	LIGHTNING MAPPER
ORBCOMM-X	OSC	OSC	Jul-91	COMMUNICATIONS
HEALTHSAT II	SATELLIFE	SSTL	Sep-93	COMMUNICATIONS
S80/T	CNES	SSTL	Aug-92	COMMUNICATIONS
MSTI-1	SDIO	SPECTRUM/JPL	Nov-92	SENSOR EXPERIMENTS
MSTI-2	SDIO	SPECTRUM	May-94	SENSOR EXPERIMENTS
FREJA	SNSB	SSC	Oct-92	FIELD/PLASMA MEASUREMENT
STEP 0	STP	TRW/CTA	Mar-94	AUTONOMY EXPERIMENTS
STEP 1	STP	TRW/CTA	Jun-94	ATMOSPHERIC PHYSICS
STEP 2	STP	TRW/CTA	May-94	CLASSIFIED
STEP 3	STP	TRW/CTA	Jul-95	SCIENCE/COMM EXPERIMENT
BREM-SAT	DARA	U. OF BREMEN	Feb-94	SCIENCE EXPERIMENT

Figure III-2. Small satellite programs, sponsors, contractors, first launch and functions that make up the system-level data base.

IV. DERIVATION OF CERS

IV.1 Selection of CER Cost Drivers and CER Development

After cost data were properly categorized and normalized, the task of CER development was undertaken. For each of the subsystems, we considered a subset of the more than 70 technical parameters collected on each of the small satellites in our data base. Choosing the subset involved a combination of statistics, sound engineering judgment, and, often, common sense. For example, in the derivation of the CER for the electrical power subsystem (EPS), we initially considered the following cost drivers: EPS mass, beginning-of-life power, solar array area, design life, battery capacity, payload power, and spacecraft power. As a first step we considered one-variable CERs (linear and non-linear, as appropriate), taking note of statistical outliers and following up to ascertain whether or not apparent discrepancies were attributable to numerical errors or possibly non-traditional ways of accounting for certain costs.

Then we examined multi-variable CERs, using non-correlated cost drivers whenever possible (for example, one would gain little by regressing against both beginning-of-life power and end-of-life power, since the two are highly correlated). Three-dimensional visualization graphics tools assisted in development of these CERs, allowing us to see the shapes of the function against the data points, and helping in the determination of appropriate functional forms as well. Again, outliers were treated individually and assessed for accuracy and validity. Because general-error regression permits direct comparison of standard errors, we were always able to pick between the better of the one, two, and higher-order variable CERs. Unlike earlier versions of SSCM, a significant amount of time was spent experimenting with and developing two- and three-variable CERs. Due to the increased sample size for this version, we were able to greatly improve CER quality in one instance by addition of a third variable. Results of the CER development effort are detailed in Section V.

IV.2 Statistical Approach

The small-satellite subsystem CER development effort takes advantage of fairly recent developments in regression techniques applied to cost analysis.

In regression, we classify models as one of two types: additive-error or multiplicative-error. In the simple linear case, for example, we can express the model in one of two ways:

$$y = a + bx + \varepsilon \qquad (1)$$

or

$$y = (a + bx) * \varepsilon , \qquad (2)$$

where y is the true cost, x is a cost-driving parameter, $a + bx$ is the estimated cost, and ε is the (random) error of estimation (a and b are referred to as "coefficients" of the model). The first type of error model (1) is known as an additive-error model, since the error is an additive term. The second type (2) is known as a multiplicative-error model, since the error term is a multiplicative factor.

Analogous examples for a common nonlinear situation are

$$y = ax^{b} + \varepsilon \text{ ,} \qquad \text{(additive-error)}$$

or

$$y = ax^{b}\varepsilon \qquad \text{(multiplicative-error)}$$

where y is true cost, x a cost-driver, ax^b is estimated cost, and ε the error of estimation.

In an additive-error model, each observed value of cost is assumed to be a function of cost-driving parameters plus a random error term that does not depend on the parameters. Unfortunately, this assumption is not often valid. A case in point is where the values of actual costs change by an order of magnitude or more as a function of the parameters, in which case the random error is more realistically considered to be proportional to the magnitude of the cost, thereby effectively depending on the parameters. In such a case, it is often more realistic to assume a multiplicative-error model. In a multiplicative-error model, the error is proportional to the y-value, so that the larger the cost, the larger the dollar value of error is permitted to be.

We focus only on multiplicative error, since that is the formulation used to derive the subsystem CERs. Our statistical framework is the equation

$$y = f(x)*\varepsilon \text{ ,}$$

where y is the true cost, x is a cost-driving parameter, $f(x)$ is the estimated cost, and ε is the proportional error of estimation. Here, $f(x)$ can take on *any* functional form, linear or non-linear, single or multivariate, that we find appropriate (in theory, there is no limit to the number of forms that can be used; in practice, however, we are often "limited" to a smaller subset of possibilities, due to the nature or shape of the data).

In the multiplicative-error model, one sample observation y_i corresponds to each x_i, and the error term ε_i equals the ratio of y_i to $f(x_i)$. Thus,

$$\varepsilon_i = \frac{y_i}{f(x_i)}$$

where $\varepsilon_i = 1$ for all i would indicate no prediction error. In this case, the least-squares problem is to find the coefficients (of f) that minimize the sum of squared relative deviations (errors) from the predictions. That is, once the functional form is chosen, the calculation consists of minimizing the sum of squared *percentage* errors:

$$\text{minimize} \quad \sum (e_i - 1)^2 = \sum \left[\frac{y_i}{f(x_i)} - 1 \right]^2 = \sum \left[\frac{y_i - f(x_i)}{f(x_i)} \right]^2$$

where the x_i and y_i are the observed values. This minimization is achieved via numerical computation; this is the only minor drawback of the method -- some care must be exercised to ensure that one obtains the global minimum when employing such methods. We have mitigated this problem by developing and employing several powerful mathematical tools to assist in the minimization process. This form of regression has been termed "General Error Regression", and the model "General Error Regression Model" (GERM).

Once the regression has been performed, there are a number of ways to assess the quality of the CER; the following terms and definitions are used for each of the CERs presented in Section V:

Standard Error of Estimate (SEE): The root-mean-square (RMS) of all percentage errors made in estimating points of the data (a "one-sigma" number that can be used to bound the actual cost within an interval about the estimate). Note that this number is a *percentage*, rather than, say, a dollar value. The formula for SEE is

$$SEE = \sqrt{\frac{1}{n-m} \sum \left(\frac{y_i}{f(x_i)} - 1 \right)^2}$$

where n is the number of observed values, and m is the number of parameters being estimated (not the number of independent variables).

Pearson's Correlation Squared: R^2 value measures the amount of correlation between estimates and corresponding data base actuals, that is, the extent of linearity in the relationship between the two quantities.

V. COST ESTIMATING RELATIONSHIPS

CERs for small satellites are listed in Table V-1.[7] Standard error and Pearson's correlation squared between actuals and estimates are listed for each CER. The range of underlying data for each CER driver is listed also.

Table V-1. Cost Estimating Relationships for Small Satellites

CER (FY97 $M)	Std Err (%)	R^2	Drivers	Min	Max
y = 6.86*(X1^0.160)*(X2^-0.356)	29.6	0.73	X1 = EOL Power (W)	5	500
			X2 = Pointing Accuracy (deg)	0.05	5
y = 0.745*(X1^0.554)*(X2^0.0363)	35.7	0.81	X1 = TT&C/C&DH Mass (kg)	3	30
			X2 = Payload Power (W)	10	120
y = 1.53*(X1^0.0107)*(X2^0.509)* (1.0096^X3)	35.7	0.75	X1 = Downlink Data Rate (kbps)	1	2,000
			X2 = Average Power (W)	5	200
			X3 = Prop. Subsystem Dry Mass (kg)	0	35
y = 0.681*(X1^0.661) - 1.51*X2^0.289	37.2	0.89	X1 = Satellite Bus Dry Mass (kg)	20	400
			X2 = Pointing Accuracy (deg)	0.05	5
y = 4.55*(X1^0.255)*1.99^X2	38.5	0.73	X1 = Solar Array Area (m^2)	0.3	10
			X2 = ACS Type (1=3-axis,0=other)	0	1
y = 0.602*X1^0.839	37.1	0.85	X1 = Power Subsystem Mass (kg)	7	70

[7] D.A. Bearden, R. Boudreault, J.R. Wertz, "Cost Modeling," in *Reducing Space Mission Cost*. Torrance, CA: Microcosm Press, 1996.

VI. APPLYING THE MODEL

VI.1 FREJA Example

Below we will present an example of applying SSCM98 INTRO to the cost estimation of the FREJA spacecraft. FREJA was built and operated by the Swedish Space Corporation on behalf of the Swedish government and the Federal Republic of Germany. FREJA was launched in October of 1992 to make high resolution measurements of the upper ionosphere and lower magnetosphere of the aurora. All the data required for input into SSCM is obtainable from public sources[8]. FREJA is included in the SSCM database.

VI.2 Cost Input Sheet

The first step in performing the cost estimate is to gather and enter the required input data into SSCM's Cost Input sheet. Inputs are typed into the orange-shaded cells, or selected from the drop-down boxes for the grey-shaded cells. Figure VI-1 is a screen capture of the input sheet with the appropriate FREJA parameters filled in. In the case of FREJA, the far right column is empty. However, had the data provided been outside of the range of the underlying data for a particular CER, this column would contain an out-of-bounds warning.

THE AEROSPACE CORPORATION SSCM98 INTRO

Cost Input Data

Retrieve Inputs | Save Inputs | Estimate | List of Programs | Print sheet

Freja

Cost Driver (Units)	Value	Valid Range		
		Low	High	Outside range
End-of-Life Power (W)	130.	5	500	
Pointing Accuracy (degrees)	5.	0.05	5	
TT&C/C&DH Subsystem Mass (kg)	18.6	3	30	
Payload Power (W)	66.	10	120	
Downlink Data Rate (kbps)	524.	1	2,000	
On-orbit Average Power (W)	91.	5	200	
Propulsion Subsystem Dry Mass (kg)	15.	0	35	
Satellite Dry Mass (kg)	214.	20	400	
Solar Array Area (m^2)	2.	0.3	10	
ACS Type — GG/Spin Stabilized	1			
Power Subsystem Mass (kg)	40.6	7	70	

Note: If a cost driver is unknown, be certain that the value is blank (use the Delete key), or the cost estimate may be in error.

Legend

- required input
- do not change!
- do not change!

Figure VI-1. Cost Input Sheet for FREJA

[8] "FREJA Facts: The Management, Design, Development, Launch, and Early Operations of the FREJA Satellite," Swedish Space Corporation.

VI.3 Cost Estimate Sheet

The Cost Estimate sheet lists a total estimated spacecraft bus cost and standard error. This total bus cost is a combination of the bus cost estimates from each of the CERs. Each individual CER estimate is also listed. No user input or interaction is allowed on this sheet; it is simply a report sheet where the user can take a first look at the system cost estimates, and make adjustments (by going back to the input sheet) as necessary. The total estimate and the results of each CER appear on a graph at the bottom of the sheet. The total bus cost estimate of $14.6M (FY97) is within one standard error of the actual bus cost, which was $9.4M (FY97). The actual bus cost does not include the value of several items which were donated to the FREJA program, including an antenna deployment mechanism, solar panels, a sun sensor, and a nutation damper. This is an illustration of the principle that cost estimates need to be interpreted in light of engineering judgment and the special circumstances of individual programs.

THE AEROSPACE CORPORATION SSCM98 INTRO

Inputs | List of Programs | Print sheet

Cost Estimate

Freja

Estimated Spacecraft Bus Co:	14.6	(FY97 $M)
Standard Error of Estimate	5.2	(FY97 $M)

CER	Individual CER Estimates Drivers	Estimate (FY97$M)	Std Error (FY97$M)
(1)	EOL Power, Pointing Accuracy	8.4	2.5
(2)	TTC/CDH Subsystem Mass, Payload Power	17.2	6.1
(3)	Downlink Data Rate, Average On-orbit Power, Propulsion Subsystem Dry Mass	18.6	6.7
(4)	Satellite Dry Mass, Pointing Accuracy	21.3	7.9
(5)	Solar Array Area, ACS Type	10.8	4.2
(6)	Power Subsystem Mass	14.3	5.3

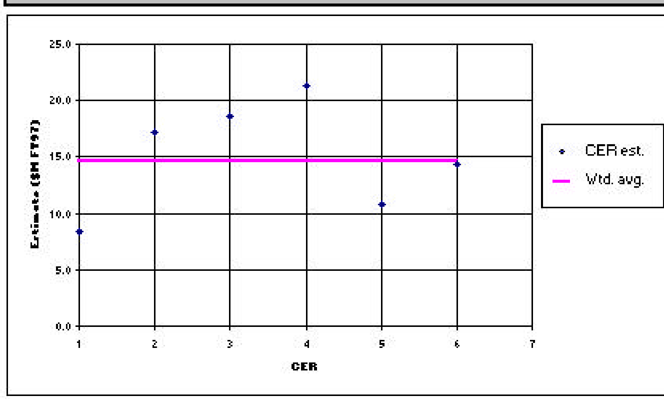

Figure VI-2. Cost Estimate Sheet for FREJA

VII. SUMMARY

Traditional cost-estimating models based on historical data from large civil and military programs appear to overestimate costs of today's small satellites. Over the past 10 years, several low-profile, low-cost satellites have been procured by NASA, ARPA, STP, and BMDO. These programs have often succeeded in dramatically reducing nonrecurring development costs by making use of existing hardware and off-the-shelf components and by reducing contractor oversight and reporting requirements. In an attempt to credibly estimate costs of such programs, Aerospace has developed a set of system-level cost-estimating relationships based entirely on actual cost, physical, and performance parameters of twenty-eight modern small satellites.

CERs were derived using a generalized error regression model and assuming constant relative error. Implicit in this method is the assumption that cost-estimating error is a percentage of the estimated costs, rather than a particular dollar value independent of the estimate. Cost drivers and CER function forms were chosen based on engineering judgment and statistical quality of regression results, the latter measured primarily by standard error and Pearson's correlation squared.

Small-satellite subsystem CERs presented in this report constitute a major advancement over what has been available previously in the area of credible estimating capabilities for small satellites. Incorporation of these CERs within a system design/cost-engineering tool or in a stand-alone cost model will support rapid turnaround, credible concept evaluation and technology trade studies. While useful as it stands, this project should also be considered as work in progress. Several recent and on-going small-satellite programs are being targeted for inclusion in future CER-development efforts.

Aerospace has also developed a more capable Pro version of this cost model, which is available to organizations who provide the SSCM team with cost and technical data on a regular basis. SSCM 98 Pro includes an ability to estimate cost at the subsystem level and provides a limited cost-risk analysis capability. Interested parties should contact the following Aerospace representative to get more details about the Pro version or to request additional copies of the Intro version:

Sharon Robinson
Administrative Services, M1-036
2350 E. El Segundo Blvd
El Segundo CA 90245

Phone 310-336-0384
Fax 310-336-5706

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APPENDIX A. REFERENCES

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APPENDIX B. AEROSPACE CORPORATION STUDY TEAM

D.A. Bearden, Systems Engineering Division	(310) 336-5852
N.Y. Lao, Space Architecture Department	(310) 336-7876
T.J. Mosher, Space Architecture Department	(310) 336-1203
J.J. Muhle, Space Architecture Department	(310) 336-2672
J.M. Neff, Space Architecture Department	(310) 336-1080
E.L. Burgess, Technology Projects Department	(703) 808-1209

Office Support

I.S. Newman, Space Architecture Department	(310) 336-4383

Administrative Contact

Sharon Robinson, Administrative Services	(310) 336-0384

APPENDIX C. ACRONYMS

ADCS	Attitude Determination and Control System
Al	Aluminum
ALEXIS	Array of Low-Energy X-ray Imaging Spectrometers
APEX	Advanced Photovoltaic and Electronics Experiment
ARPA	Advanced Research Projects Agency (formerly DARPA)
BMDO	Ballistic Missile Defense Organization
BOL	Beginning of Life
CER	Cost Estimating Relationship
C&DH	Command and Data Handling
CPU	Central Processing Unit
CRO	Chemical Release Observation
DARPA	Defense Advanced Research Projects Agency
DSI	Defense Systems, Inc. (renamed CTA Space Systems)
DOD	Department of Defense *or* depth of discharge
DOE	Department of Energy
EAC	Estimates at Completion
EOL	End of Life
EPS	Electrical Power Subsystem
FAST	Fast Auroral Snapshot Explorer
FRISK	Formal Risk Analysis
FSK	Frequency Shift Keying
GaAs	Gallium Arsenide
G&A	General and Administrative
GERM	General Error Regression Method
GLOMR	Global Low-Orbiting Message Relay
GN&C	Guidance, Navigation and Control
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HETE	High Energy Transient Experiment
IA&T	Integration, Assembly, and Test
IMU	Inertial Measurement Unit
I_{sp}	Specific Impulse
JPL	Jet Propulsion Laboratory

Kbps	Kilobits per second
LANL	Los Alamos National Laboratory
LEO	Low Earth Orbit
LeRC	Lewis Research Center
LOOS	Launch and Orbital Operations Support
LOSAT-X	Low-Orbit Satellite Experiment
MACSAT	Multiple-Access Communications Satellite
MB	Megabyte
MPE	Minimum Percentage Error
MSTI	Miniature Sensor Technology Integration
MTS	Member of the Technical Staff
MUPE	Minimum Unbiased Percentage Error
N_2H_4	Hydrazine
NASA	National Aeronautics and Space Administration
NEAR	Near Earth Asteroid Rendezvous
NiCd	Nickel Cadmium
NiH_2	Nickel Hydrogen
NRL	Naval Research Laboratory
ONR	Office of Naval Research
OSC	Orbital Sciences Corporation
PDR	Preliminary Design Review
POGS/SSR	Polar-Orbit Geomagnetic Survey/Solid-State Recorder
RADCAL	Radar Calibration
RDT&E	Research, Development, Test and Engineering
REX	Radiation Experiment
Re/NR	Recurring/Non-Recurring
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SMEX	Small Explorer
SDIO	Strategic Defense Initiative Organization
SEE	Standard Error of the Estimate
Si	Silicon
SSCM	Small Spacecraft Cost Model
SSTI	Small Spacecraft Technology Initiative
STEP	Space Test Experiments Platform
STP	Space Test Program
STS	Space Transportation System (Shuttle)
SWAS	Submillimeter Wave Astronomy Satellite
TBD	To Be Determined
TOMS-EP	Total Ozone Mapping Spectrometer - Earth Probe
TRL	Technology Readiness Level

TT&C	Telemetry, Tracking and Communications
UHF/VHF	Ultra-High Frequency/Very-High Frequency
USAF	United States Air Force
W	Watt
WBS	Work Breakdown Structure
ZPB	Zero Percentage Bias