Development of the Small Satellite Cost Model (SSCM) Edition 2002

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Abstract—The paradigm shift in the late 1980's from large satellites to small satellites required that new methodologies be developed to assess their cost. In 1991, The Aerospace Corporation (Aerospace) began to study small satellites to better understand the design principles that were being employed in their implementation. One of the outcomes of this work was the development of the Small Satellite Cost Model (SSCM). This model estimates subsystem- and system-level costs for satellites weighing less than 1000 kg using cost estimating relationships (CERs) derived from actual costs and technical parameters. This paper discusses the history and development of SSCM, with the primary focus on the changes implemented in the newest edition of the model. Future enhancements to the model will also be discussed.

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1. INTRODUCTION

In the past decade, developers of space systems have turned toward small satellites as vehicles for science and technology demonstration missions. Small satellites, because of their functional and operational characteristics and comparatively low development and service costs, provide access to space for more users than the large satellites prevalent over the last 20-30 years. [1] Relatively low acquisition costs and short development timelines offer space-related capabilities previously reserved only for highly-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 by NASA, the DoD, the Centre National d'Études Spatiales (CNES), and the European Space Agency (ESA). However, due to the desire to use less expensive small launch vehicles, 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.

Small satellite studies at The Aerospace Corporation have shown that cost-reduction techniques, including the use of commercial off-the-shelf hardware and software, employed on modern small satellite programs, result in system costs that are substantially lower than those estimated by traditional weight-based parametric CERs. [2] Cost models based on historical costs and technical parameters of traditional large satellites are not applicable to this class of missions. [3], [4] Credible parametric cost estimates for small satellite systems require CERs derived from a cost and technical database of modern (post-1990) small satellites. SSCM was developed in response to this shift towards small satellites.

2. HISTORY

Work on the development of CERs to estimate the costs of small satellites began in the early 1990's with funding from various DoD organizations. These early CERs only

estimated system-level costs of spacecraft and were based on a very limited database. The CERs continued to be refined and were eventually implemented in a standalone DOS-based PC program known as The Aerospace Corporation's Small Satellite Cost Model. These CERs estimated the total satellite bus cost as a function of spacecraft technical parameters (e.g. mass, power, pointing accuracy). In the mid-1990's, a new methodology for developing CERs was implemented with the introduction of the General-Error Regression Model (GERM). Additionally, work was begun on the first set of subsystem CERs.

At the same time, NASA began to seek better cost analysis methods and models specifically tailored to small satellite programs. This was motivated by NASA's need to respond to increasingly frequent questions regarding small satellite concepts and system analysis. In 1995, NASA's Lewis Research Center (now Glenn Research Center) and NASA Headquarters (HQ) Code BC funded the first phase of an activity at Aerospace to gather information regarding capabilities and costs of small satellites and to develop a set of subsystem-level small satellite CERs. This effort involved an examination of technical and economic issues related to designing, manufacturing and operating small satellites. Programs either already completed or launching in the next year were targeted for data collection, so that the technical and cost data obtained were as close to final as was feasible. A cost and technical survey was generated and distributed to each of these programs. The data that was collected consisted not only of mass, power, technical parameters, and cost for satellites, but also impacts on cost such as schedule difficulties, funding interruptions, requirements changes, and cost-sharing among multiple contractors. From this data, The Aerospace Corporation developed several stand-alone CERs that estimated recurring and non-recurring costs of small satellite subsystems. This model, along with other cost estimating tools and databases, provided the capability to estimate life-cycle costs for a variety of small mission concepts. The resulting form of the model, which used subsystem CERs to estimate the total cost of a small satellite, is the form that the model has to this day.

Two factors allowed Aerospace to gather the data needed to generate the CERs. First, contractors were assured that any proprietary information delivered would be treated in a restricted manner, used only for the purpose intended, and not released to organizations, agencies or individuals not associated with the study team. Second, any contractor that provided information on a satellite to be used in the generation of the CERs received the next edition of SSCM when development was finished.

In 1998, The Aerospace Corporation began funding SSCM development and upgrades through internal research and development funds, resulting in the release of an updated edition that same year. This edition was the first to include interplanetary spacecraft and incorporate NASA's technology readiness levels (TRLs) to generate risk-based estimates. Also, the model was moved from a DOS- to an Excel-based tool. Work on SSCM has continued, leading to the release of new editions in 2000 and 2002. SSCM Edition 2002 includes a number of changes, including a more powerful and flexible graphical user interface.

3. CER DEVELOPMENT

Before any new CERs could be generated for SSCM Edition 2002, the database had to be updated with data on satellites that had recently been completed or were nearing completion. After the data were properly categorized and normalized, the task of CER development was undertaken. This began by using a combination of statistics, sound engineering judgment, and often, common sense, to find which of the 70+ technical parameters within the database worked best for each subsystem. As an example, for the electrical power subsystem (EPS), the following cost drivers were initially considered: EPS mass, beginning-of-life power, solar array area, design life, battery capacity, payload power, and spacecraft power.

As a starting point for CER generation, one-variable linear and non-linear CERs were considered, taking note of statistical outliers and identifying whether apparent discrepancies were attributable to numerical errors or possibly non-traditional ways of accounting for costs. Then, multi-variable CERs were examined using non-correlated cost drivers whenever possible. For example, little is gained by regressing against both beginning-of-life power and end-of-life power, since the two are highly correlated. With the increase in information in the database, CERs with more than two variables could be explored. A significant amount of time was spent on this endeavor, since it was thought that CER quality would be greatly improved with higher-order forms. In several instances, this proved to be the case. General-error regression was used to compare the standard errors of each potential CER, allowing selection between the better of the one, two, and higher-order variable CERs. Three-dimensional graphics tools assisted in the development of these CERs, allowing visualization of the shapes of the functions against the input data, and helping in the determination of appropriate functional forms as well.

In the cases where it made engineering sense, the data for a particular subsystem was divided into separate categories to account for fundamentally different subsystem design types. An example of this is the attitude determination and control system (ADCS) subsystem, where spin-stabilized and 3-axis designs are significantly different and driven by different design parameters. By segregating the data for the different types of designs, the cost drivers for each type could be better explored, leading to more appropriate CERs.

Statistical Approach

The small satellite subsystem CER development effort takes advantage of developments in regression techniques applied to cost analysis. In regression, models are classified as one

of two types: additive-error or multiplicative-error. In the simple linear case the model can be expressed 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 error model in (1) is known as an additive-error model, since the error is an additive term. The error model in (2) is known as a multiplicative-error model, since the error term is a multiplicative factor.

Analogous examples for a common nonlinear situation are

$$y = ax^b + \varepsilon \qquad (3)$$

or

$$y = ax^b \varepsilon \qquad (4)$$

where y is true cost, x a cost-driver, ax^b is the 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 often not valid. A case in point is where the actual costs change by an order of magnitude or more as a function of the inputs, in which case the random error should be considered proportional to the cost. In such an instance, a multiplicative-error model can be assumed, where the error is proportional to the y-value, so that larger costs lead to larger dollar value errors.

The discussion to follow only focuses on multiplicative error, since that is the formulation used to derive the subsystem CERs for SSCM. The statistical framework is the equation

$$y = f(x)\varepsilon \qquad (5)$$

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 is found to be appropriate. In theory, there is no limit to the number of forms that can be used; in practice, however, the forms are often "limited" to a smaller set 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,

$$\varepsilon_i = \frac{y_i}{f(x_i)} \qquad (6)$$

where $\varepsilon_i = 1$ for all i would indicate no prediction error. Here, 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:

$$\sum_{i=1}^{n} (\varepsilon_i - 1)^2 = \sum_{i=1}^{n} \left[\frac{y_i}{f(x_i)} - 1 \right]^2 = \sum_{i=1}^{n} \left[\frac{y_i - f(x_i)}{f(x_i)} \right]^2 \qquad (7)$$

where x_i and y_i are the observed values. This minimization is achieved via numerical computation, yet some care must be exercised to ensure that one obtains the global minimum when employing such methods. This problem has been mitigated 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). [5]

Once the regression has been carried out, there are a number of ways to assess the quality of the CER:

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 the SEE is

$$SEE = \sqrt{\frac{1}{n-m} \sum_{i=1}^{n} \left(\frac{y_i}{f(x_i)} - 1 \right)^2} \qquad (8)$$

where n is the number of observed values, and m is the number of parameters being estimated (not the number of independent variables). The SEE quantifies the accuracy to which the cost model represents its own underlying data under the various uncertainties.

Average Percentage Bias: The algebraic sum (positives and negatives included) of all percentage errors made in estimating points of the data averaged over the number of points; bias measures how well percentage over-estimates and under-estimates are balanced.

Pearson's Correlation Squared: R^2 value measures the amount of correlation between estimates and corresponding

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database actuals, that is, the extent of linearity in the relationship between the two quantities.

Even within the GERM framework, there are two schools of thought on which types of CERs to derive: minimum percentage error (MPE) or minimum unbiased percentage error (MUPE). All things being equal, an unbiased estimator is preferred over a biased one. Unfortunately, in general, a CER cannot be optimized with respect to two different criteria (SEE <u>and</u> bias, for example), and so SSCM's CERs cannot be optimal with respect to all three above statistical criteria. In choosing to derive MUPE CERs for SSCM, zero bias was considered preferable to lower standard error, allowing the model to calculate an unbiased estimate of the entire spacecraft bus.

4. COST RISK

Technology and Heritage

One of several dilemmas in cost-estimation is the uncertainty inherent in parametric models, which includes such things as uncertainty associated with hardware design, inflation, labor rates, contractor accounting practices and overhead rates. In the case of parametric cost models utilizing general-error regression, and with SSCM in particular, general cost-estimating uncertainty is quantified by the SEE.

Cost growth due to unforeseen technical difficulties has greater potential to cause costing uncertainty than any other single influence. Technical difficulties are related to a program's attempt to inject new technologies with limited or no flight demonstration into the design of the spacecraft. Twelve major NASA programs initiated after 1977 and completed before 1993 experienced an average cost growth of 77%, with eight of them citing technical complexities as a major risk driver. [6] Unfortunately, quantification of technical risk is not nearly as straightforward as quantifying general cost-estimating uncertainty.

The level of design reuse (i.e. heritage) in a particular subsystem also impacts the amount of cost risk inherent in building that subsystem. Heritage is not the same as

technology insertion; a system can exist where a previously developed design is utilized, but new technologies are also incorporated. A common example is an existing ADCS design that incorporates a new star tracker into a standard interface.

A simple scheme for adjusting the cost estimate based on technical risk and heritage has been implemented for SSCM Edition 2002. This scheme uses a triangular cost probability distribution for each subsystem, where the most likely cost is the output of the CER, and the upper and lower limits are user-defined (Figure 1). By identifying the lowest possible cost for the subsystem (e.g. 10% below the most likely estimate), as well as the highest possible cost (e.g. 150% greater than the most likely estimate), an appropriate distribution is calculated. A subsystem with very low design maturity and no flight heritage must have a much larger upper bound than a subsystem that has flight heritage and is very mature. This scheme allows modification of the cost risk parameters for each subsystem to properly take into account the cost uncertainty due to technology development and heritage. Future enhancements to this methodology will focus on mechanisms for adjusting costs based on the average heritage and technology development of the missions in the SSCM database.

Cost-Probability Distribution

Two sources of risk for each cost element have been defined: general cost-estimating uncertainty and uncertainty due to design implementation. General cost-estimating uncertainty is quantified by the SEE, while uncertainty due to design implementation is quantified by a triangular distribution defined by A, B, and M. These two sources of cost risk are merged into one cost-probability distribution that has a mean equal to the mean of the triangular distribution

$$Mean_{ss} = \frac{1}{3}(A + B + M) \qquad (9)$$

and a variance that is equal to the sum of the variances from both sources of uncertainty.
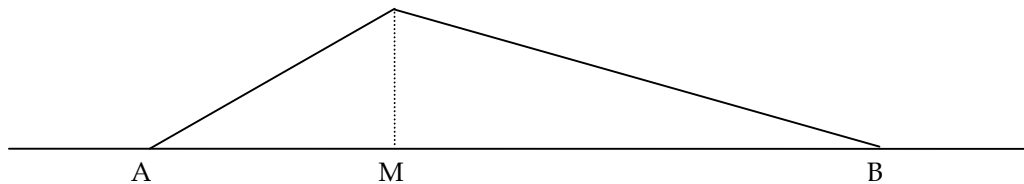

Figure 1 – Example of triangular distribution defined by the lower bound, A, upper bound, B, and the "most likely" estimate, M, derived from the CER. Depending on the inputs, the triangle can have any shape, including a right triangle (A = M or M = B), isosceles (M – A = B – M), or even a single point (A = M = B).

$$Var_{ss} = SEE^2 + \frac{1}{18}(A^2 + B^2 + M^2 - AB - AM - BM)$$

$$(10)$$

The system-level variance is also affected by the correlation of the errors in individual subsystems. Cross-correlation coefficients are needed to accurately capture the statistical effects of adding uncertainties. [7], [8] Correlation coefficients can be calculated in two ways: linear (Pearson's product-moment) correlation and rank (Spearman's) correlation. [9] Pearson's product-moment correlation is a measure of the linearity between two random variables and Spearman's rank correlation is a measure of the monotonicity between two random variables. In SSCM, linear correlation coefficients are derived and used because the sum of random variables depends on Pearson's product-moment correlation and not Spearman's rank correlation.

Correlation coefficients are generated for the relationship between each subsystem- and system-level element. The coefficients are calculated using

$$\rho_{xy} = \frac{\sum_{i=1}^{n}(x_i - x_m)(y_i - y_m)}{\sqrt{\sum_{i=1}^{n}(x_i - x_m)\sum_{i=1}^{n}(y_i - y_m)}} \quad (11)$$

where ρ_{xy} is the correlation coefficient between two elements, x and y are errors from each element, and x_m and y_m are the average errors from each element. Correlation coefficients range in value from –1 to +1. A coefficient of either –1 or +1 denotes that two subsystems are perfectly correlated; the error in one subsystem will be directly reflected in the error of the subsystem to which it is correlated.

The variance from the correlation coefficients is added to the variance for the CER and design implementation uncertainty to generate the variance for the total spacecraft and system according to [10]

$$Var_t = \sum_{i=1}^{n} Var_{ss} + 2\sum_{k=2}^{n}\sum_{j=1}^{k-1} \rho_{jk}\sigma_j\sigma_k \quad (12)$$

where ρ_{jk} is the correlation coefficient between elements j and k, and σ_j and σ_k are the standard deviations for elements j and k calculated from the original variance equation. The first term represents the sum of the element variances, while the second term is the covariance calculated from the correlation coefficients.

With the total system variance calculated, a cost-probability distribution can be generated. Research by The Aerospace Corporation and the MITRE Corporation has shown that this distribution may be accurately approximated by a lognormal distribution. [11] This approximation technique, known as Formal Risk Assessment (FRISK), allows confidence percentiles to be computed without Monte Carlo simulation. The end product of cost risk assessment in this framework is a total spacecraft cost-probability distribution, from which mean, standard deviation, percentiles, and other descriptive statistics can be read.

Error Estimation Outside the Range of Validity

Parametric cost models have certain advantages and disadvantages, as do all cost estimation techniques. One of the disadvantages of such models is that the CERs can only be reliably applied to inputs that fall within the range of the data used to create the CERs, which is termed the "range of validity." As a variable strays further from the range of validity, it would be expected that the CER estimate would be less reliable. For example, if a subsystem CER is based on subsystem mass and the mass range within the database is 5 kg to 50 kg, an estimate for a subsystem weighing 55 kg would be seen as more reliable than one weighing 80 kg.

Applying CERs outside the range of validity makes two assumptions: (1) the CER remains valid beyond the data range; and (2) the SEE does not change outside the data range. The first assumption is not all that unreasonable, based on some studies done with data points outside the SSCM database. An in-depth analysis was made with one of the early SSCM editions using the planetary spacecraft NEAR (Near Earth Asteroid Rendezvous), which went beyond the SSCM database range in several cases, and provided decent correlation between the model results and the actual spacecraft costs. [3] Furthermore, in the absence of additional information, there is little reason to doubt the CER trend in the vicinity of the data range, although the trend may be less certain further away from the range of validity. However, the second assumption is questionable at best and unreasonable at worst, as the uncertainty should increase as the input deviates further from the database range. The SEE is a statistical measure whose value is based on the underlying data. By the very nature of the problem, there is no way to analytically compute a new value outside the range of validity. Further, the SEE is a measure of cost-estimating uncertainty, not CER-applicability uncertainty. The problem here is one of data-insufficiency, since there is simply not enough data available to make an analytical estimate of the behavior of the variance outside the range of the database.

In the current edition, the SEE is not adjusted outside the range of validity of the input data. Thus, the user needs to take great care to examine cases where the input data is outside the range of validity, and make a sound engineering decision about whether the CER remains applicable. Research is on-going at The Aerospace Corporation into new methods for addressing this problem by estimating the SEE based on the spread of the input data, but they are not sufficiently mature for implementation in this edition of SSCM.

5. FUNDING PROFILE

To aid in project planning and milestone development, a new funding profile function has been added to SSCM. This function spreads the total development cost to generate a funding profile for the spacecraft for the formulation (Phase B) and implementation (Phases C and D) phases. Phase B starts with the authority to proceed (ATP) and Phase D ends at launch plus 30 days. This profile can be used as a tool to look at various ways to spread costs. It is only meant to be a guideline in planning program spending since it spreads only the spacecraft portion of the total project costs and does not account for other programmatic issues such as yearly funding caps.

The funding profile is generated using the equation [12]

$$F(S) = A\big[10 + S\big((15-4S)S - 20\big)\big]S^2$$
$$+ B\big[10 + S\big((6S-15)\big]S^3$$
$$+ \big[1-(A+B)\big](5-4S)S^4 \qquad (13)$$

where F(S) represents the fraction of the funding spent up to time S, S is the fraction of development time elapsed, and A and B are coefficients based on the desired rate of spending.

The coefficients A and B are selected based on the desired spreading of the costs, based on the percentage expenditure of costs at the schedule midpoint. Figure 2 shows examples of front-loaded spending, evenly distributed spending, and back-loaded spending.

SSCM generates an estimate for Phases C and D of the spacecraft development, yet the funding profile spreads costs over Phases B, C, and D. Therefore, the SSCM estimate must be augmented to account for the amount of funding spent in Phase B. According to the NASA Systems Engineering Handbook, the costs in Phase B should typically be between six and 10 percent of the development costs. [13] Based on this, SSCM adds 10 percent to the Phase C/D estimate prior to generating the funding profile.
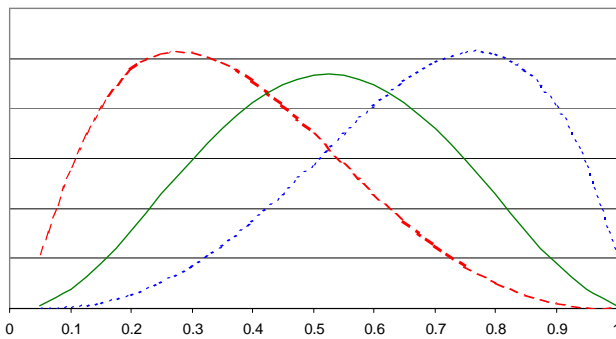

Figure 2 – Various funding profiles; dashed line represents front-loaded (e.g. engineering), solid line represents evenly distributed (e.g. manufacturing), and dotted line (e.g. flight testing) represents back-loaded.

6. MODEL APPLICATION

SSCM Edition 2002 is implemented in Excel as a standalone workbook. The workbook is backed up by Visual Basic for Applications modules to perform many of the functions of the model. Inside the workbook are worksheets that display the results of the model, including five user worksheets and three information worksheets. The user worksheets are Inputs, Cost Estimate, Cost Risk, Funding Profile, and Inflation Factors, and the information worksheets are Glossary, Drivers, and CERs.

Inputs

The **Inputs** worksheet shown in Figure 3 lists all the spacecraft characteristics that can be used to generate a cost estimate. Some parameters listed on the Inputs worksheet are only required under certain conditions, defined by the choices made in the drop-down boxes. There is also a Notes space to track decisions or comments about the inputs.

The information in the Range area is used to identify input values that are outside the range of the CERs, as shown in Figure 4. Each CER was generated from a specific data set

Figure 3 – Inputs Area. The inputs for the parameters used in the CERs (left-hand column) are entered in the center column, and notes on each input can be placed in the right-hand column.

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time	45.5%	22	12	66	
Maximum Distance from Sun		1		2.7	
Design Life		6	24	96	
Satellite Wet Mass		179.2	800	877	
Satellite Dry Mass		224.8		658.3	
BOL Power		150	1010	1000	1.0%
Solar Array Area		1.47		14.6	
Structure Mass		19.96		236	
Pointing Control		0.7		5	
Pointing Knowledge		0.0005	0.01	1.5	
Propulsion Subsystem Dry Mass		9	40	118.2	
C&DH Subsystem Dry Mass		9.3	20	31.85	
Transmit Power		5		18.1	
Downlink Datarate		31.5	1000	2290	
Thermal Subsystem Mass		2.7	8	11.2	

Figure 4 – Range Area. Displays information on whether an input for a parameter is within the valid range for the CER, is not being used, has not yet been entered, or is outside the range of validity.

and is only intended to be valid within this range. Many parameters that will be used to generate SSCM estimates will not fall within their respective ranges, and it is up to the user to determine whether the CERs are valid for the input data. The Range area consists of Minimum and Maximum columns that show the lower and upper limits for each cost driver. Included with these values are the inputs for those drivers and a comparison of the input values to the valid data ranges for the CERs. This area also clues the user as to whether all the necessary parameters to generate an estimate have been supplied.

Cost Estimate

The **Cost Estimate** sheet displays the results of the cost model for the given inputs, including a table of the cost estimate broken out by subsystem, and two graphs that provide detailed information on the estimate.

The cost estimate table (Figure 5) shows the estimated cost for each subsystem. Non-recurring and recurring costs are presented, as well as the development and first unit total.

The subsystem costs are summed into a Spacecraft Bus subtotal, which is added to the system-level programmatic costs to create the Spacecraft Development & First Unit total. The Range area displays messages if one of the input parameters for a particular subsystem is out of range.

Two additional columns display how the total costs are split by subsystem. The Sub-level column shows how the Spacecraft Bus costs are divided among each subsystem, while the System-level column shows how the Spacecraft Development & First Unit costs are divided among the spacecraft bus and system-level programmatics. These data are also presented in graphic form below the cost estimate table, as shown in Figure 6.

Cost Risk

The **Cost Risk** sheet is where the subsystem estimates from the Cost Estimate sheet are rolled-up via the FRISK methodology. The cost risk table shown in Figure 7 has separate areas to input the high and low percentages, the triangular probability distribution of the user-defined cost risk and the combined mean and standard error of the estimate (see Section 4. Cost Risk).

The Most Likely column is the result of the CER for that particular subsystem. The shape of the triangular probability distribution is determined by the high and low percentages defined on this sheet.

The Mean is the risk-impacted mean of the triangular distribution, while the Standard Error includes both the variance from the CER and the variance from the triangular distribution. The means are summed, and the standard errors are combined along with cross-correlation terms (see Section 4) to create a system-level mean and standard error, respectively. The cost probability distribution is displayed below the cost summary in graphical and tabular format, as shown in Figure 8.

	Estimate (FY02$K)				% of	% of	
	Non-rec	Rec	Total	Std Error	Sub-level	Sys-level	Range
Spacecraft Bus Subsystems							
ADCS	3,072	2,513	**5,585**	1,407	17.9%		
Propulsion	3,191	3,191	**6,383**	1,991	20.5%		
Power	3,486	4,814	**8,299**	2,606	26.6%		BOL power is 1.0% high
TT&C*	1,464	1,586	**3,049**	2,484	9.8%		
C&DH*	1,586	1,718	**3,303**		10.6%		
Structure	2,173	1,851	**4,023**	1,002	12.9%		
Thermal	295	252	**547**	235	1.8%		
Spacecraft Bus	**15,266**	**15,924**	**31,190**	**4,468**	**100%**	**77.5%**	
IA&T*	673	1,146	**1,820**	1,515		4.5%	Development time is 59.1% low
PM/SE*	893	1,520	**2,412**			6.0%	Development time is 59.1% low
LOOS	0	4,797	**4,797**	2,024		11.9%	
S/C Development & First Unit	**16,832**	**23,387**	**40,219**	**5,134**		**100%**	

*TT&C/C&DH and IA&T/PM/SE costs are generated from a single CER for each pair and standard error is presented as such. Splits presented are based on database data.

Figure 5 – Cost Estimate Table. The section to the left includes details on the estimate for the spacecraft generated by the CERs including non-recurring/recurring costs, total costs, and percentage distributions at the subsystem-level and system-level. The section to the right highlights inputs that are out of the valid range of the CERs for each estimate.
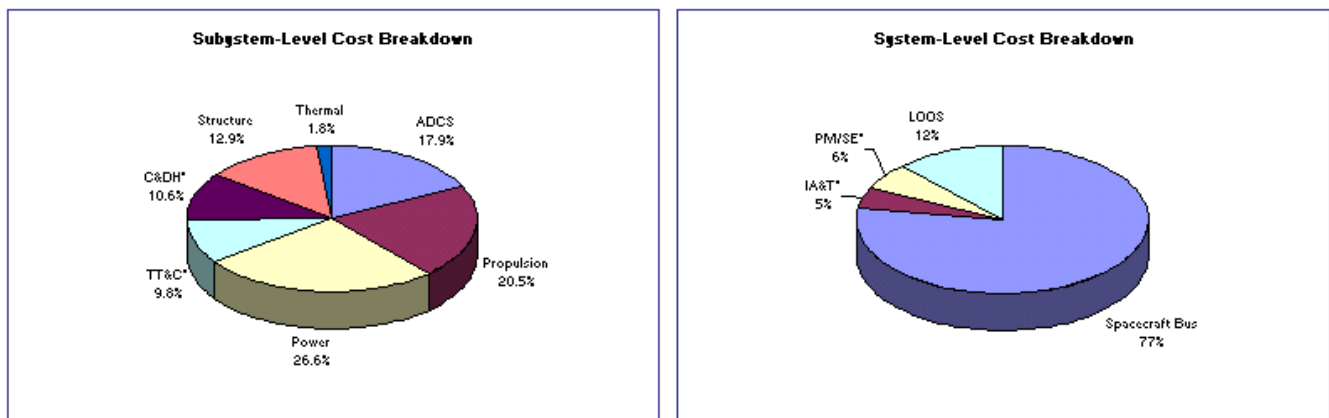
Figure 6 – Cost Breakdown Plots. The chart on the right shows the subsystem-level cost breakdown. The chart on the right shows the system-level cost breakdown.

	Percentages		Distribution Points			Estimate (FY02$K)	
	Low	High	Low	Most Likely	High	Mean	Std Error
Spacecraft Bus Subsystems							
ADCS	10%	40%	5,026	5,585	7,819	**6,143**	1,662
Propulsion	10%	10%	5,745	6,383	7,021	**6,383**	2,008
Power	20%	50%	6,639	8,299	12,449	**9,129**	3,116
TT&C/C&DH	0%	150%	6,352	6,352	15,881	**9,528**	4,350
Structure	5%	35%	3,822	4,023	5,431	**4,426**	1,159
Thermal	5%	45%	520	547	793	**620**	274
Spacecraft Bus			28,104	31,190	49,394	36,229	6,613
IA&T/PM/SE	0%	50%	4,232	4,232	6,348	**4,937**	1,837
LOOS	0%	20%	4,797	4,797	5,757	**5,117**	2,171
S/C Development & First Unit			37,134	40,219	61,499	46,284	7,484

Figure 7 – Cost Risk Table. The user inputs sets a triangular distribution for the cost risk of each subsystem by setting the lowest and highest possible cost as a percentage of the CER estimate. The mean and standard error for each subsystem are calculated and used to generate system-level values for use in the cost probability distribution.
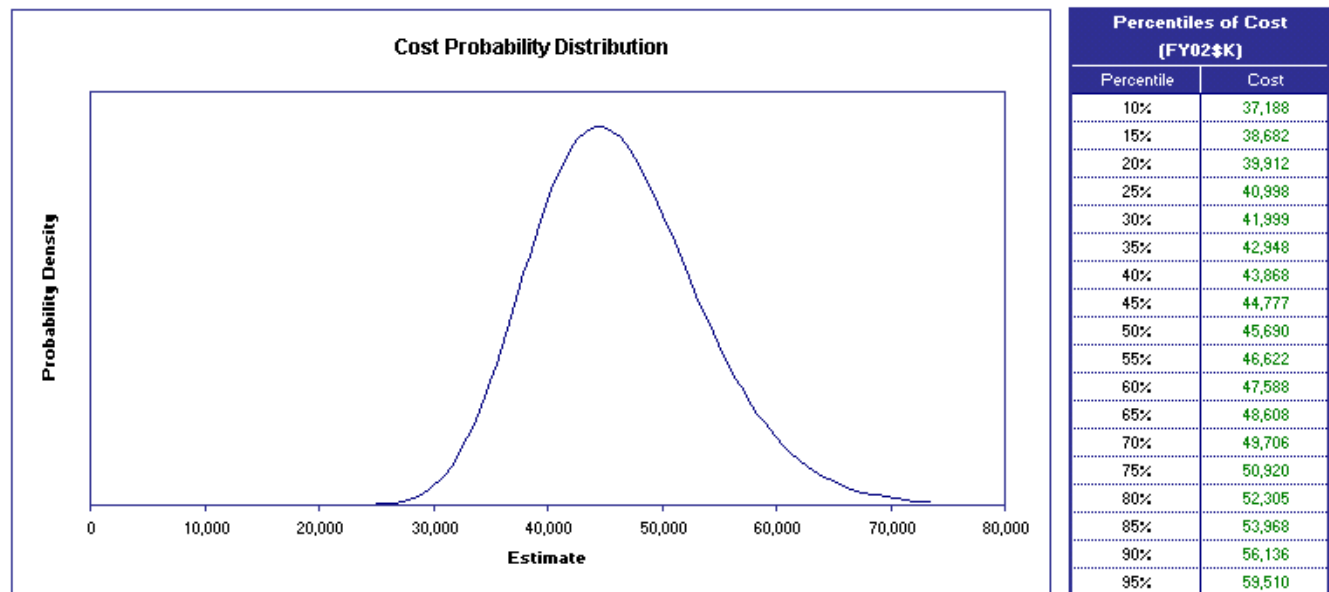

Percentiles of Cost (FY02$K)	
Percentile	Cost
10%	37,188
15%	38,682
20%	39,912
25%	40,998
30%	41,999
35%	42,948
40%	43,868
45%	44,777
50%	45,690
55%	46,622
60%	47,588
65%	48,608
70%	49,706
75%	50,920
80%	52,305
85%	53,968
90%	56,136
95%	59,510

Figure 8 – Cost Risk Plot. The graph on the left shows the cost probability distribution function as a lognormal distribution. The table on the right shows cumulative probability.

Launch Date (mm/yyyy)	Dec-06
Funding Spent at Schedule Midpoint (%)	60
Basis for Funding Profile	◉ Constant Year ○ Real Year

Milestone	Date
Development Start	May-06
Development End	Jan-07

Funding Profile (FY02$K)	FY06	FY07
Yearly Funding	30,527	13,714
Cummulative Funding	30,527	44,241

Figure 9 – Funding Profile Inputs Outputs. The top section shows the Funding Profile inputs. The middle section shows the calculated start and end points of the spacecraft development period. The bottom section shows the yearly and cumulative funding by fiscal year.

It should be noted that the model has a great amount of flexibility in adjusting the estimate based on the user's understanding of the subsystem technology readiness, subsystem heritage, and the cost risk methodology.

Funding Profile

The **Funding Profile** worksheet generates the monthly spending levels for the development of the spacecraft based on the development time, model estimate, and several user-defined inputs (Figure 9). The funding profile spreads costs from the beginning of Phase B (ATP) to the end of Phase D (launch plus 30 days). These inputs are the launch date and the percentage of funding spent at the schedule midpoint – a measure of how the funding will be distributed. The development start date is calculated based on the development time defined on the Inputs worksheet along with the launch date. Then, based on the choice of constant or real-year dollars, monthly and cumulative plots of funding are generated (Figure 10). These costs are summarized by fiscal year in the Funding Profile table.

The total cost that is distributed in this function is the Spacecraft Development & First Unit total from the Cost

Estimate sheet. Future editions of SSCM will plot a user-selected percentage from the Cost Risk sheet.

Inflation Factors

The **Inflation Factors** worksheet defines the inflation factors that will be used to convert from the FY02 base to some other constant year dollars or to real year dollars, as shown in Figure 11. This sheet contains NASA and Air Force values for inflation from 1992 to 2002, along with each organization's projected inflation from 2003 to 2022. [14], [15] In addition, a customizable field offers the capability to input a set of user-defined inflation factors.

Information

The model also provides three sheets that provide additional information about the cost estimating methodology. The **Glossary** worksheet describes what hardware is estimated by each subsystem- level and system-level CER. The **Drivers** worksheet shows the cost drivers for each CER. The **CERs** worksheet shows the exact form for each CER.

7. CONCLUSION

Traditional cost-estimating models based on historical data from large civil and military programs overestimate costs of modern small satellites. Over the past 15 years, several low-profile, low-cost satellites have been procured by NASA, the DoD, CNES, and ESA. 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, The Aerospace Corporation has developed a set of subsystem-level cost-estimating relationships based entirely on actual costs, and physical and performance parameters of 35 modern small satellites.

CERs were derived using a generalized error regression model and assuming constant relative error. Implicit in this
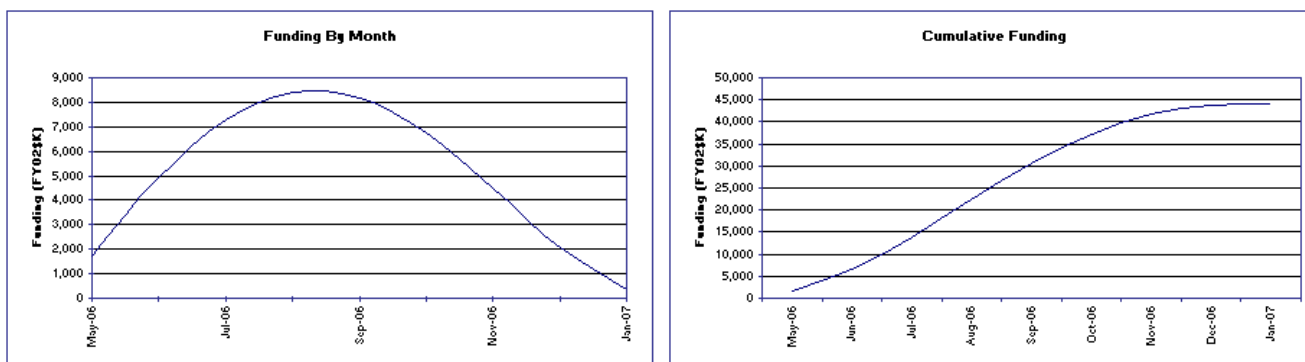

Figure 10 – Funding Profile Plots. The plot on the left shows the funding required per month, while the plot on the right shows the cumulative funding for Phases B, C, and D. The y-axis label indicates if the funding profile is in constant year or real year dollars.

Year	NASA	Air Force	Custom
1992	5.20%	2.80%	0%
1993	4.17%	2.70%	0%
1994	3.10%	2.00%	0%
1995	2.60%	1.90%	0%
1996	2.50%	2.00%	0%
1997	1.40%	2.10%	0%
1998	1.08%	0.70%	0%
1999	2.02%	0.80%	0%
2000	3.30%	1.00%	0%
2001	3.10%	1.50%	0%
2002	2.60%	1.50%	0%
2003	3.10%	1.50%	0%
2004	3.10%	2.00%	0%
2005	3.10%	2.00%	0%
2006	3.10%	2.00%	0%
2007	3.10%	2.00%	0%
2008	3.10%	2.00%	0%
2009	3.10%	2.00%	0%
2010	3.10%	2.00%	0%
2011	3.10%	2.00%	0%
2012	3.10%	2.00%	0%
2013	3.10%	2.00%	0%
2014	3.10%	2.00%	0%
2015	3.10%	2.00%	0%
2016	3.10%	2.00%	0%
2017	3.10%	2.00%	0%
2018	3.10%	2.00%	0%
2019	3.10%	2.00%	0%
2020	3.10%	2.00%	0%
2021	3.10%	2.00%	0%
2022	3.10%	2.00%	0%

Figure 11 – Inflation Factors. The user can use NASA or Air Force standard inflation factors or input user-defined values.

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 with the latter measured primarily by standard error and Pearson's correlation squared.

A cost risk methodology allows the user to define the cost probability distribution for each subsystem. A funding profile spreads the estimated costs over Phases B, C, and D to give the user an idea of what the potential funding obligations will be for the spacecraft over the course of the development.

While quite useful as it stands, this model should also be considered as a work in progress. Several recent small satellite programs are being targeted for inclusion in future CER development efforts, and several enhancements are already in work for the next edition of SSCM.

8. FURTHER INFORMATION

For more information on SSCM, or to learn how to obtain a copy of SSCM, visit the SSCM website at http://www.aero.org/software/sscm/ or send an email to SSCM@aero.org.

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10. ACKNOWLEDGEMENTS

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