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UNCLASSIFIED
SE/IT/PM Factor Development Using Trend Analysis
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Abstract

Systems Engineering (SE), Integration and Test (I&T), and Program Management (PM) costs have traditionally been difficult items to estimate at any point in a program. Cost Estimating Relationships (CERs) are often used in practice to predict the ultimate SE/IT/PM cost. The utility of a CER naturally lessens as a program matures since CERs do not typically account for known performance to date. Many people view SE/IT/PM activities as a level of effort and estimate them as a function of time, which is dependent on predicted schedule, but does not account for program performance to date. Widely-used methods that do take the actual performance into account include earned value, staffing-level methods, and fixed-percentage extrapolation. Each of these methods has weaknesses that can be avoided using the presented technique.

This paper presents an alternative to common estimating methods, using both historical data on similar programs and actual performance on the current program to project final costs. It builds on concepts first applied by an NRO contractor in 2004 for a space system program. This method examines the historical trend of cumulative SE/IT/PM versus percentage of time complete. SE/IT/PM is typically influenced by the prime mission product or the sum of hardware and software. The trend shows a high percentage SE/IT/PM at the beginning, followed by a lower, constant percentage, finally concluding with a graded rise. This is referred to as the “bathtub effect.” Preliminary analysis demonstrated a consistent shape of the curve confirmed by several historical programs. Variations on this concept are explored, as well as possible applications of risk.

Estimating relationships are shown for multiple levels of SE/IT/PM, including Space Systems, Space Segment and Ground Segment. It is important to note that while the study was performed using space system data, the method could easily be applied to any Government program cost estimate. Challenges for future research are also identified, most prominently the need for more time-phased data. With the addition of future data, it appears this method can offer the potential for more realistic estimates of SE/IT/PM costs given known information to date.

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Background

Many different methods are employed to estimate SE/IT/PM at all Work Breakdown Structure (WBS) levels. Some of the inherent flaws in these methods make estimating SE/IT/PM for an in-process program difficult. The strengths and weaknesses of some of the major methods are presented in this section.

Parametric

Parametric equations are typically used early in the program to estimate cost based on completed analogous programs. A linear regression with a single variable of the data would result in a factor being applied to a base. For example, SE/IT/PM could be estimated as 25% of a hardware cost estimate. This method is useful in the beginning stages of a program, but once program actuals are collected, they cannot be factored in to the parametric CER. That same 25% factor would be applied even if the program were charging 50% SE/IT/PM as a factor of hardware charges.

Earned Value

Earned Value is used to calculate an Estimate At Complete (EAC), based on the spent dollars, work complete, and work scheduled. This method is useful for making adjustments to predicted values using program actuals. This method is the most similar to the proposed time-phased approach. Earned Value stops short of looking at trends with respect to percent time complete. Instead, the cost or schedule performance indicators would likely be used as a factor to adjust the SE/IT/PM estimate.

Staffing Level

Staffing-level estimates are sometimes used to predict program costs. The staffing can be analyzed with the predicted schedule to determine a suitable ramp-up and ramp-down in personnel. These estimates are useful because they can be adjusted when actual staffing data are collected. One weakness of this method is that it is difficult in practice to mathematically derive a predicted staffing level from other program actuals. Rayleigh and Weibull curves are used to predict staffing from a total resource estimate. Once the program is in progress there are no simple ways to predict the shape of the rest of the curve.

Level of Effort as a Function of Time

Another staffing-level estimating method is Level of Effort (LOE) with respect to time. Unlike the Staffing-Level approach, LOE is dependent on actuals to date. One common approach is to take current program staffing, and adjust the ramp-down to coincide with the current predicted schedule. This method does not necessarily use historical data when determining the ramp-down or shape of the curve and may be difficult to defend.

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Fixed-Percentage Extrapolation

Fixed-percentage extrapolation uses the current SE/IT/PM percentage and applies that percentage to the remainder of the program. This method is simple to apply, but as our research demonstrates, it is not very effective. The basis of the research is that the percentage will form a "bathtub" shape due to the relationship of SE/IT/PM staffing versus procurement spending.

Basic Principles and Ideas

This paper presents a time-trend approach to SE/IT/PM that addresses the variability of the SE/IT/PM percentage over the program schedule. With more data and research, this method could complement many of the existing methods. This method examines the historical trend of cumulative SE/IT/PM versus percentage of time complete. SE/IT/PM is typically influenced by the prime mission product or the sum of hardware and software. The trend shows a high percentage of SE/IT/PM at the beginning, followed by a lower percentage, concluding with a graded rise. This is considered the "bathtub effect."

The primary assumption that drives the analysis for this time trend method is that SE/IT/PM factors follow similar trends among analogous programs. Figure 1 shows three actual space segment-level SE/IT/PM trend lines and a consolidation of the three programs. The y-axis represents cumulative SE/IT/PM percentages over the life of each program (scaled for comparison) while the x-axis represents the percent time complete in the program (A program 4 years into a 10-year schedule is assumed to be 40% complete). Schedule estimating relationships should be used to determine a realistic total program schedule. The general relationship for SE/IT/PM at Space Segment and Space System levels behaves consistently. At the beginning of a program, the majority of resources are devoted to Program Management and Systems Engineering. Conversely, little is initially charged to production. As production levels increase, SE/IT/PM becomes a smaller percentage of the hardware/software base cost and hits a minimum when around 30% - 40% of the schedule is complete. Finally, more Integration and Testing is performed and the cumulative SE/IT/PM ratio increases again.

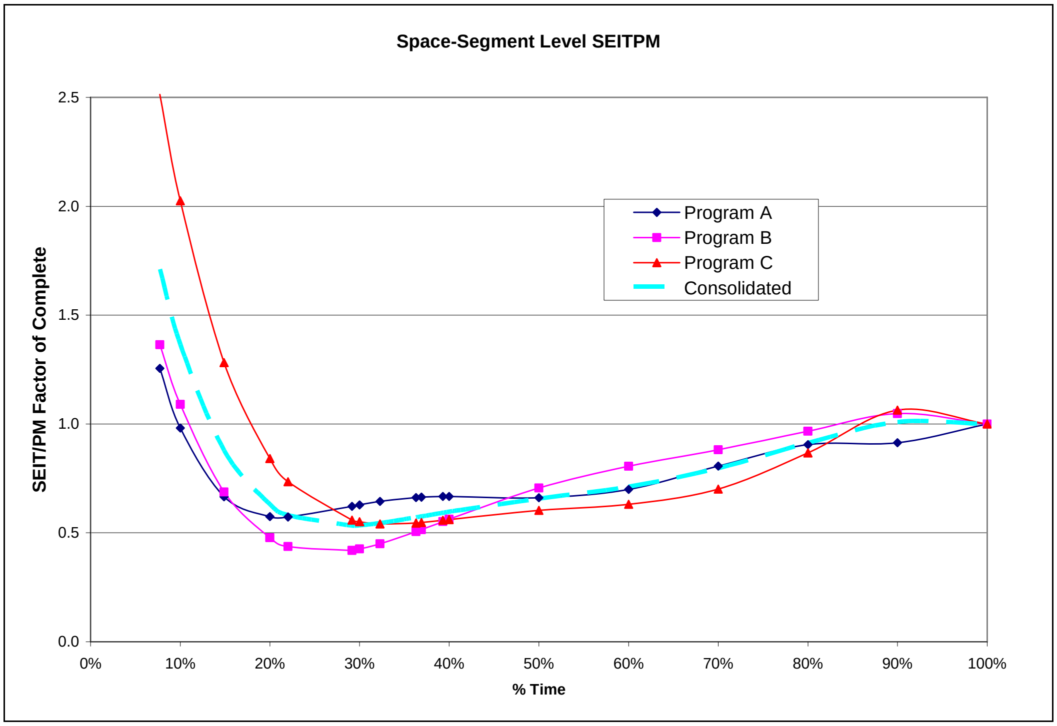

Figure 1. Example of Space Segment SE/IT/PM Trends for Three Programs. Note that all programs follow a nearly identical trend.

Methods

Table 1 and Figure 2 display Space System SE/IT/PM data for one program and an associated formula for its trend line. Table 1 shows the cumulative SE/IT/PM ratio at various points in the program timeline. The Factor of Complete (FC) represents the current cumulative SE/IT/PM ratio as a percentage of the final cumulative SE/IT/PM rate.

% Complete	Cumulative SEIT/PM Ratio	Factor of Complete
10%	6.9%	0.80
20%	4.4%	0.51
30%	3.4%	0.40
40%	3.2%	0.37
50%	3.5%	0.41
60%	4.2%	0.49
70%	5.3%	0.62
80%	6.7%	0.78
90%	8.0%	0.93
100%	8.6%	1.00

Table 1. Sample SE/IT/PM data

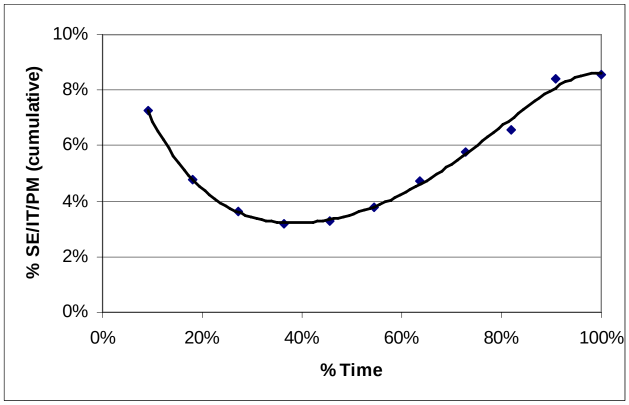

Figure 2. Sample SE/IT/PM resulting trend line

FC and trend curves will be used to predict SE/IT/PM at any point in the program.

Once trend lines are established for all data available, the FC can be analyzed. The implementation used in estimating thus far is based on the assumption that trends of all programs should carry equivalent weight in determining the final estimate. That is, a SE/IT/PM ratio trend from a higher cost program will not influence the estimate any more than another SE/IT/PM ratio trend based on available data. Based on this assumption, we calculated the consolidated trend curve by establishing a normalized scale for all time trends. All trend lines are scaled to intersect at 100% time and 100% FC (See Figure 1). The consolidated curve is an average of these three curves. The estimate is a point where the consolidated trend curve intersects with 100% complete after being scaled to the latest data point available. The general scaling calculation is shown below.

$$\text{Cumulative SE/IT/PM (\% complete)} = \frac{\text{SE/IT/PM ratio @ current \% complete}}{\text{Mean FC @ current \% complete}} * (\text{Mean FC for x\% complete})$$

Table 2. FC for 3 programs presented with associated Means and Standard Deviations.

	Factor of Complete (FC)				
% Complete	**Program A**	**Program B**	**Program C**	**Mean**	**Std Dev**
10%	**1.04**	**0.80**	**1.84**	**1.23**	**0.543**
20%	**1.03**	**0.51**	**0.95**	**0.83**	**0.275**
30%	**0.83**	**0.40**	**0.66**	**0.63**	**0.217**
33%	***0.77***	***0.38***	***0.63***	**0.60**	**0.198**
40%	**0.68**	**0.37**	**0.65**	**0.57**	**0.169**
50%	**0.67**	**0.41**	**0.73**	**0.60**	**0.171**
60%	**0.75**	**0.49**	**0.83**	**0.69**	**0.176**
70%	**0.86**	**0.62**	**0.91**	**0.80**	**0.155**
80%	**0.92**	**0.78**	**0.98**	**0.89**	**0.105**
90%	**0.93**	**0.93**	**1.03**	**0.96**	**0.060**
100%	**1.00**	**1.00**	**1.00**	**1.00**	**0.000**

NOTE: Italics denotes data used for Example below.

Figure 3 shows the standard deviation from Table 2 plotted against percent time complete. Note that the inflection points on the plot are around 20% and 70% complete. This is intuitively true because there is a lot of change before CDR at 20% complete and before IOC at 70% complete.

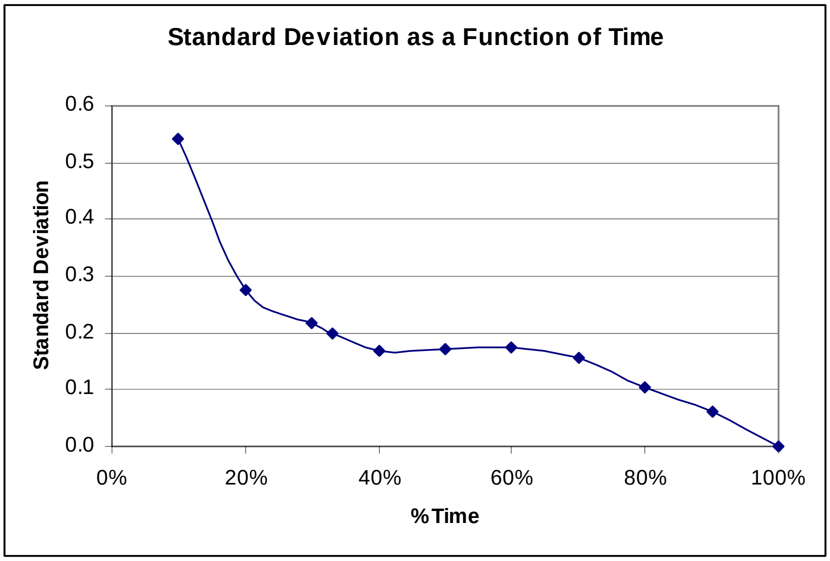

Figure 3. Standard deviation as a function of time.
Note the inflection points around 20% and 70% complete.

Cost risk associated with the trend method can be determined using the standard deviation of the factors to complete for the percent time being estimated from. Table 2 contrasts the mean and standard deviation for the three programs' data for System Level SE/IT/PM. The trend of the standard deviation shows that as the program progresses, the variance of the FC goes to zero. This shows that the later in time that a program is, the more confidence one can have in an estimate using this method. The method for applying the cost modeling risk is similar to the application of cost modeling risk in other settings. Given the small number of data points, we cannot accurately predict the shape of the probability distribution of the FC.

Example

Using schedule analysis, it has been determined that Program A was 33% complete in terms of time from Authority to Proceed (ATP) to the predicted launch date. The cumulative System level SE/IT/PM of this program has been calculated to be 8.4% from Cost Performance Report (CPR) data at this particular time. The program manager is interested in estimating the final SE/IT/PM ratio for the program. As shown in Table 2, the mean FC at 33% time is 0.60. This means that 8.4% is, on average, 60% of the final cumulative system level SE/IT/PM factor for the program. The calculation for Program A's expected cumulative SE/IT/PM factor at the end of the program is shown below.

$(0.084) / (0.6) * (1.00) = 0.14$

The mean estimate for this program's system level SE/IT/PM percentage at the end of the program is 14%.

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Figure 4 shows the consolidated trend line for system level SE/IT/PM scaled to this program for multiple points in time using the same method. Given that the current cumulative SE/IT/PM factor is 8.4% at 33% time complete, program actuals to date closely replicate the shape of the historical data.

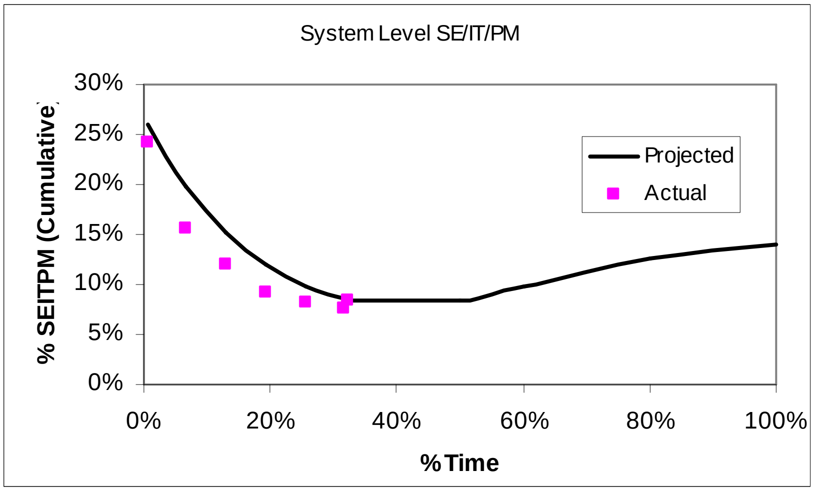

Figure 4. Example problem demonstrating a program at 33% complete charging 8.4% SE/IT/PM. The prediction using this method is 14% SE/IT/PM.

Concept Exploration

Many derivations were explored to build upon the original SE/IT/PM trend estimating method.

As mentioned previously, the trend analysis approach to SE/IT/PM can be easily applied at multiple WBS levels and elements. For a space program, these levels include Space System, Space (Mission Payload and Bus subsystems), and Ground. A different shape for each level was expected, but the data appeared to be consistent within each level. Figures 5, 6, and 7 show the shapes of the three levels of SE/IT/PM. It should be noted that the early stages of the program have a very small base, so the historical data are generally inconsistent before 20% complete. We have eliminated these points with small SE/IT/PM cost bases from Figures 6 and 7.

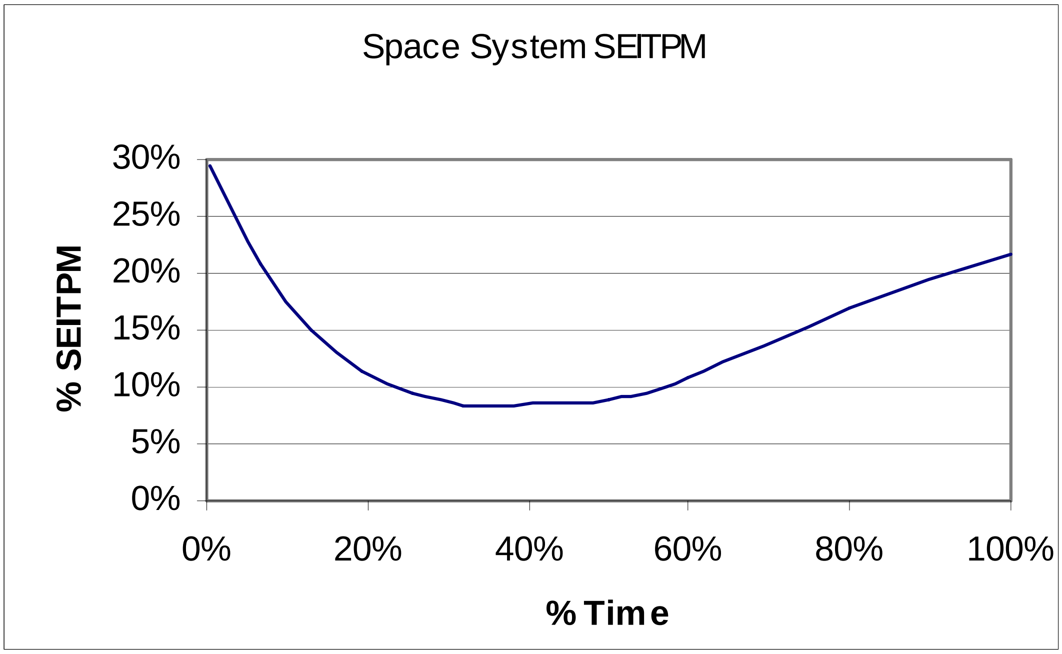

Figure 5. Space System SE/IT/PM curves.

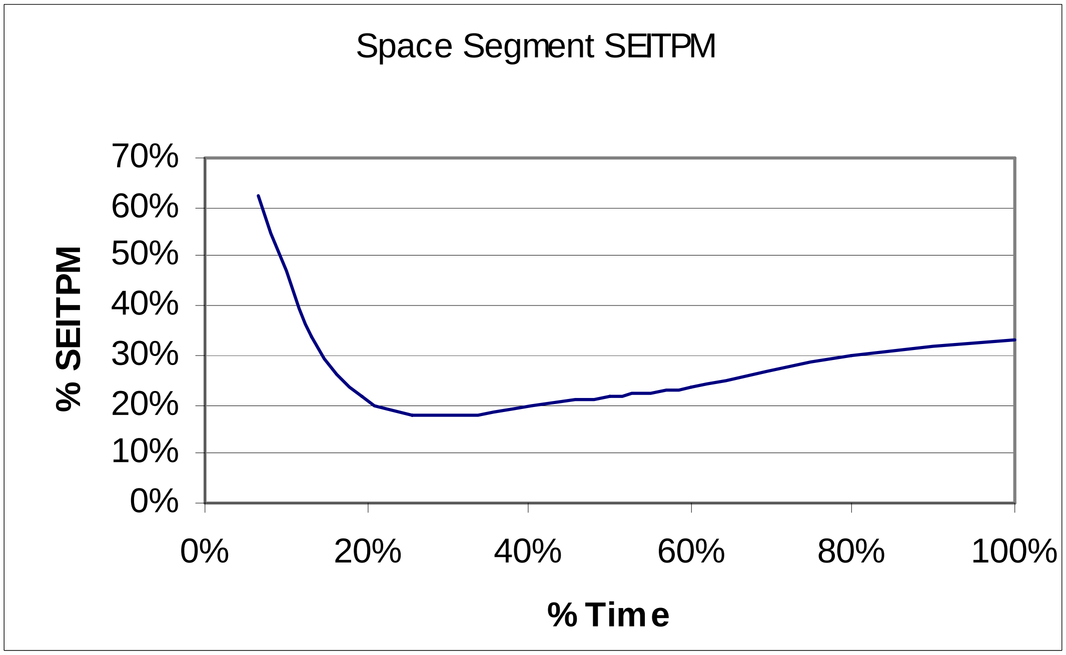

Figure 6. Space Segment SE/IT/PM curves.

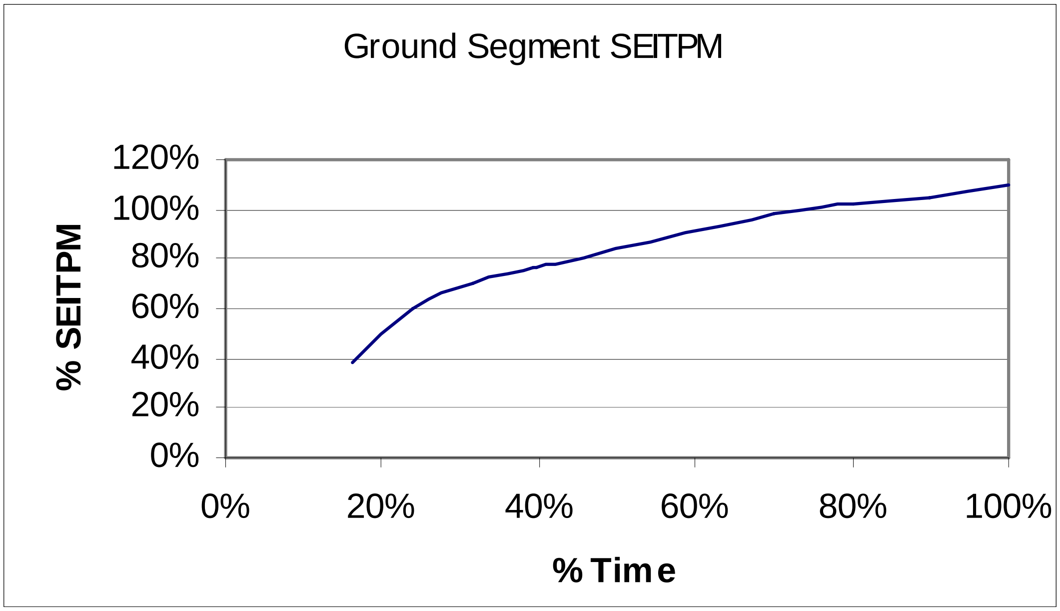

Figure 7. Ground SE/IT/PM curves.
Note the difference from the other curves before 20% complete.

The Ground SE/IT/PM curve shown in Figure 7 is different from the other two. We assumed that this is justifiable because the ground is mostly software development for space programs. Software development would require less program management at the beginning of the program, and more systems architecture and software coding. While more data would be necessary to fully explain this trend, little value should be given to percentages before 20% complete, and the uncharacteristic trend is very early in the program. Later stages are consistent with the other two curves.

Method Development

As more data were gathered, it became apparent that two distinct relationships could be inferred. First, as discussed in the previous two paragraphs, was the shape of the curve. The second relationship was whether the model should be additive or multiplicative.

Method 1. Percentage increase to completion.

One possible interpretation of the data would be to find a percent increase to completion for all data points in the set. A trend line could be inferred by the data which would show what factor must be multiplied by the current percent complete to predict the final. Since this approach is *multiplicative*, the resulting prediction can vary widely given slight variations in percent complete. Figure 8 shows the multiplicative method compared to an in-progress program. Note the exponential increase in percent SE/IT/PM from the most current point. The general form of the multiplicative approach is presented below.

$$\text{Cumulative SE/IT/PM (\% complete)} = \frac{\text{SE/IT/PM ratio @ current \% complete}}{\text{Mean FC @ current \% complete}} * (\text{Mean FC for x\% complete})$$

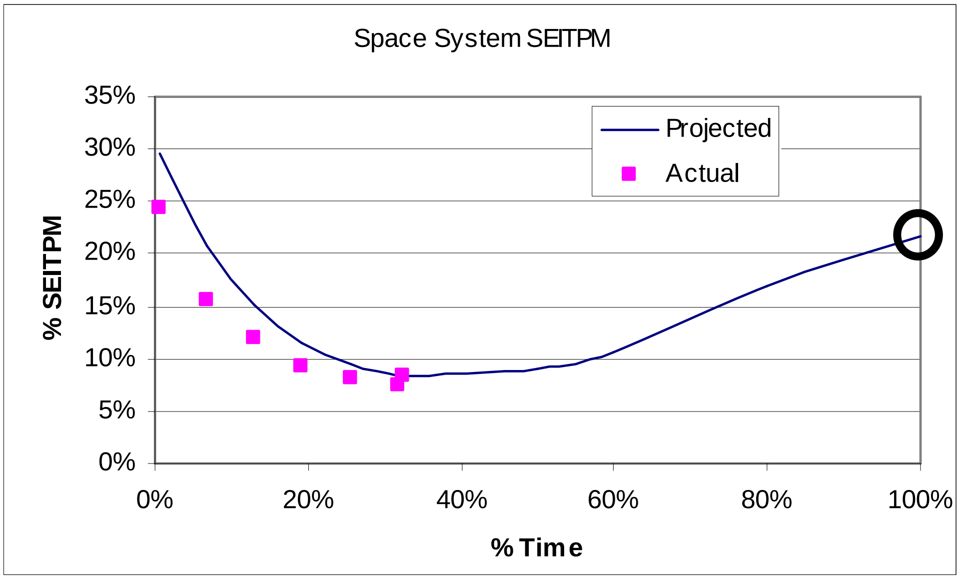

Figure 8. Percent complete versus percent increase to completion.

Method 2. Percentage change from present to future.

Another interpretation of the data is *additive*, rather than *multiplicative*. In this method, the data are used as firm points, instead of the percent increase to complete in Method 1. The trend from those data is subsequently shifted up or down to find the current actuals. Figure 9 demonstrates how a composite curve shape was applied to a program in progress. The program is currently spending around 9% cumulative SE/IT/PM and can be expected to have spent 14% at complete. The form of the additive method is presented below.

$$\text{Cumulative SE/IT/PM} = \Delta(\text{Current to historical @ current \%complete}) + \text{Historical SE/IT/PM @ final}$$

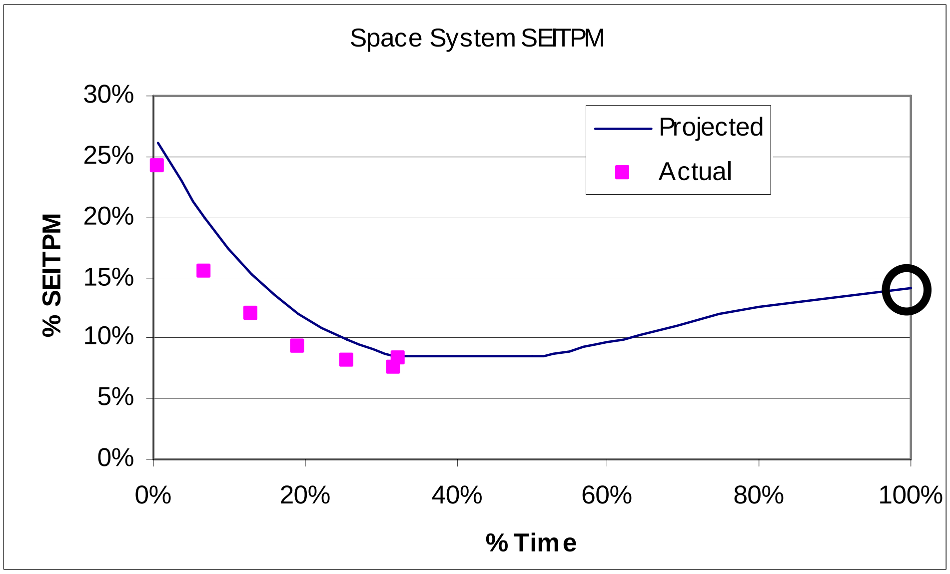

Figure 9. Percent change from present to future.

A comparison of Figures 10 and 11 demonstrates that the additive method, Method 2, more accurately captures the data trend. Method 1 results in a wide variation at complete, whereas Method 2 appears more consistent. Method 1 varies by over **10%**, while Method 2 varies by only **4%**.

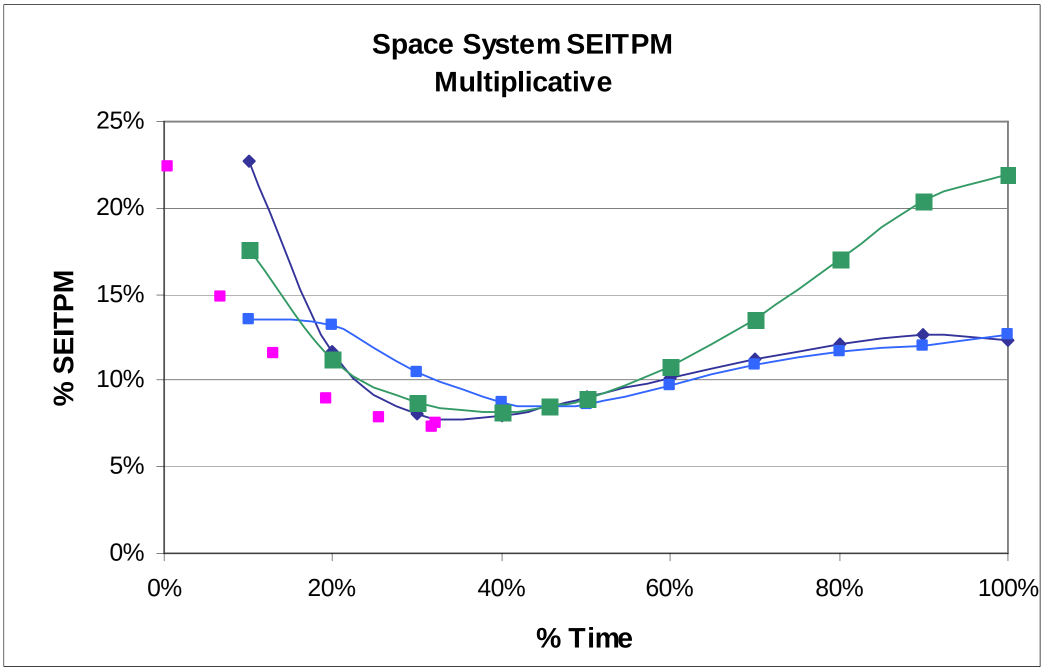

Figure 10. Relationship of datasets using Method 1. All points are scaled through 45% complete to demonstrate the effect of different prediction methods for an in-process program.

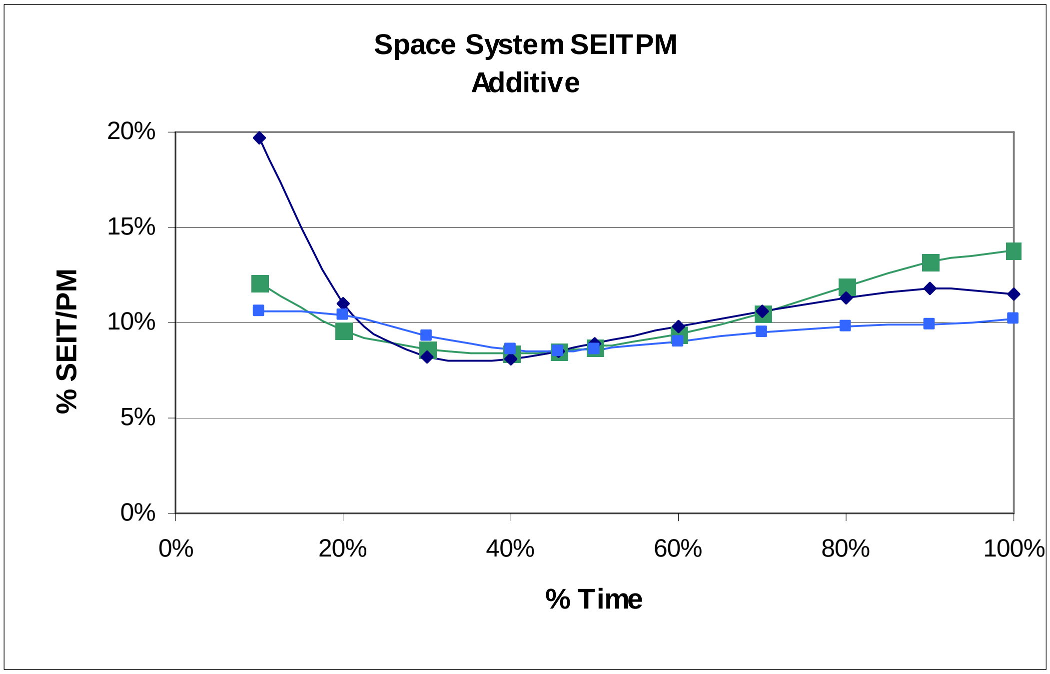

Figure 11. Relationship of datasets using Method 2. All points are scaled through 45% complete to demonstrate the effect of different prediction methods for an in-process program.

Method 3. 40% steady-state hypothesis.

After several methods were investigated, it became apparent that after 40% complete, the trend for percent cumulative SE/IT/PM becomes linear, and has a lower standard error. Intuitively this makes sense, as there is much more cumulative data and it becomes more difficult to change the percentage of SE/IT/PM. Figure 12 demonstrates the linear relationship and presents the corresponding R^2 values. Since the shape of the curve is of primary importance to this paper, a high R^2 is more informative than for a standard linear regression. The 3 sample datasets have R^2 values between 0.93 and 0.98.

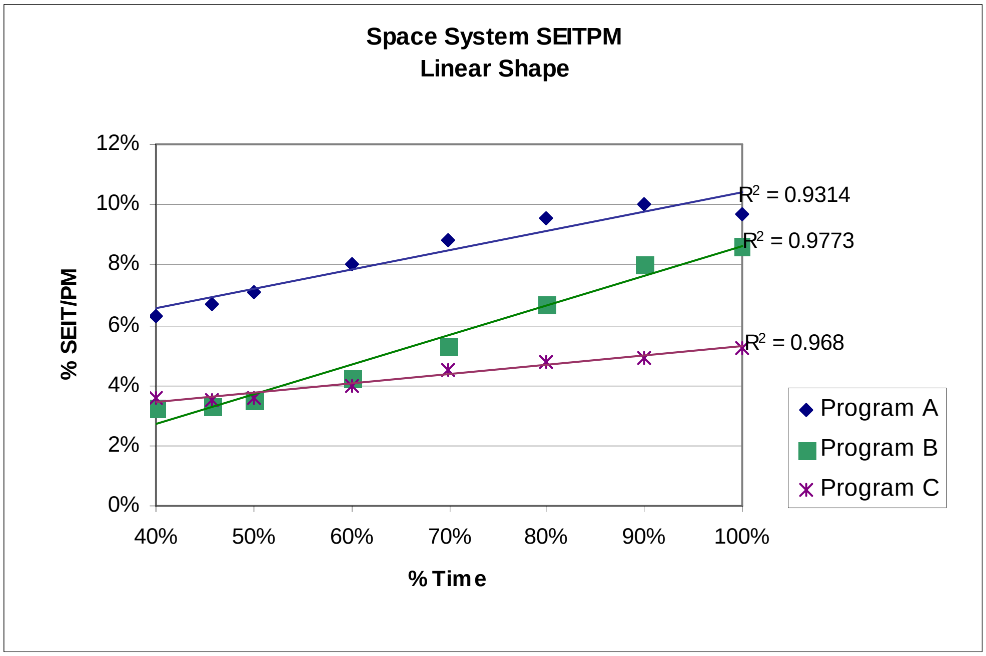

Figure 12. Linearity of SE/IT/PM data after 40% completion.
R^2 values from the last 40% of all datasets demonstrate linearity.

Sources of Error

Location of Inflection Points

Not all expected curve shapes will match program actuals. It is desired to have the inflection point of the current program data match that of the expected curve fit. Regression statistics are not necessarily the answer here, although the Method of Least Squares may help. The problem with blindly applying statistical methods to this case is that since the data are cumulative, newer data points are more valuable than earlier data; especially with points before around 15-20% complete. This problem will be further addressed in "Future Work."

Schedule Estimate

Another challenge when using this method is that percent complete is very subjective. Data normalization compensated for schedule slips by using a percentage, but it is impossible to predict the exact schedule for a program in process. Though a small percentage off may be inconsequential, a long schedule slip could adversely impact the interpretation of cumulative percent SE/IT/PM.

Schedule slips were not explored in the study. There could be a SE/IT/PM percentage impact, as one would expect the heads for both SE/IT/PM and the base to stay at full strength for a longer period of time. An increase in SE/IT/PM percentage would generally be expected. This method would ideally capture schedule slip better than a headcount method, since the percentage method estimates the same headcount percentage on a larger base.

Future Work

More Time-Phased Data

The primary challenge of future work on this subject is to collect and analyze more time-phased data. The responsiveness of this method to the challenges presented above is the key to determining the usefulness of the method for cost estimating.

Risk or Inflection Bounds

One concept that should be explored further to strengthen the method is to provide prediction bounds. The shape of the expected curve may be difficult to align with the actuals to date with any degree of precision. The problem is natural in the early stages of a program, as a small base makes large fluctuations in % SE/IT/PM possible. When estimating the effect of an imperfect fit, a natural inclination would be to simply run the curve through the most current point. The top curve-fit in Figure 13 shows a current-point fit. Another possibility is to bound the problem by selecting two points through which to draw trend lines, as shown in Figure 13. The statistics behind prediction bounds are not explored in this paper, only suggested as a path of future research.

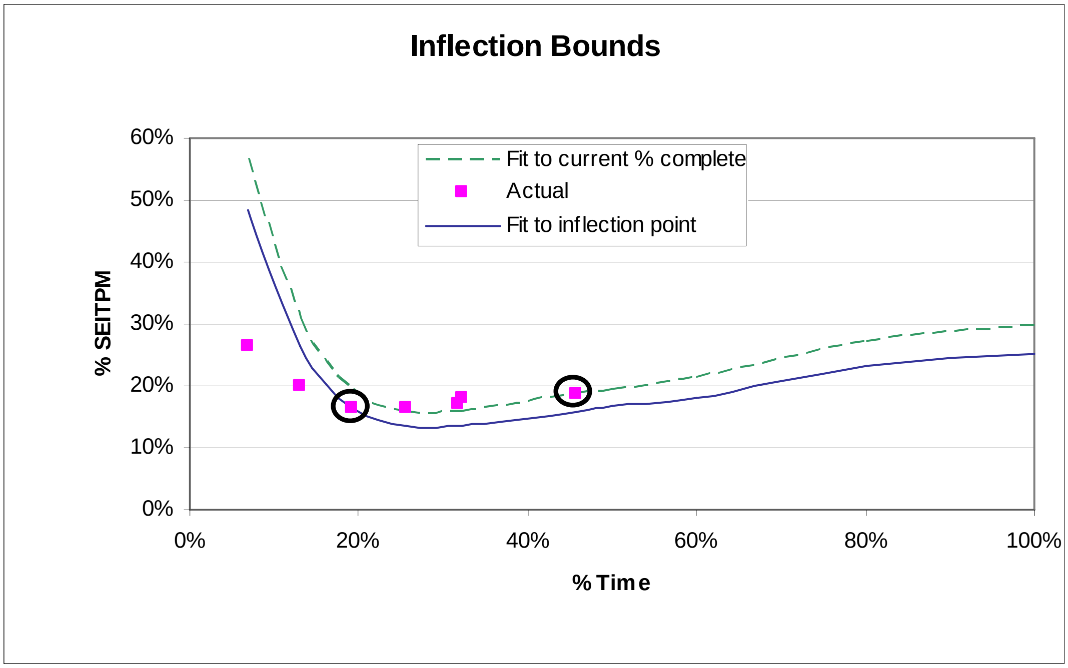

Figure 13. 2-point risk boundaries are a possible future research path.

Conclusion

The trend-analysis method of estimating SE/IT/PM costs could be a viable option for future estimates. More time-phased data is essential for deciding which of the proposed methods best represents the expected costs.

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Credits

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References

Our work was influenced by research performed by Duke O'Brien.

Acronyms

ATP	Authority to Proceed
CER	Cost Estimating Relationship
EVM	Earned Value Management
FC	Factor of Complete
HW	Hardware
ICE	Independent Cost Estimate
IT	Integration and Testing
I&T	Integration and Testing
NCG	NRO Cost Group
NRO	National Reconnaissance Office
PM	Program Management
SE	Systems Engineering
SER	Schedule Estimating Relationship
SW	Software
WBS	Work Breakdown Structure