SSC13-IV-1

The Incremental Cost of One or More Copies – Quantifying Efficiencies from Building Spacecraft and Instrument Constellations

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ABSTRACT

Organizations struggle to estimate costs associated with generating small lots of instruments and spacecraft built as part of constellations. APL has experience building spacecraft constellations and instrument series, with a meticulous record of the associated historical costs available for research. To answer the question, "How much do the copies cost?" we explore the cost histories of STEREO, The Van Allen Probes, JEDI, and RBSPICE from APL experience. We generate a formula for estimating the cost of spacecraft and instrument copies from the historical record. We test the factor's predictive value and provide associated statistics. Finally, we explore how other organizations can adjust and adapt the APL formula for instrument/spacecraft copy costs to reflect their own experience for estimating the cost of producing small constellations of identical instruments or spacecraft.

INTRODUCTION

As NASA and DoD space program funding has experienced budget pressure over more recent decades, an emphasis has emerged on building smaller, less expensive spacecraft in constellations, rather than larger single-spacecraft systems. Intuitively, cost savings should be achievable when organizations can build multiple exact copies of spacecraft on a continuous production line using the same sets of resources for each. However, quantifying the cost savings associated with this approach is difficult. Learning curve theory is helpful to understand costs of the assembly of hundreds of copies, but it does not apply well for smaller lots of ten or fewer items. Furthermore, the historical accounting record rarely breaks out the cost of the individual units when multiple copies were produced. Warfield and Roust (1998) offered a factor of 36% to cover the cost of a spacecraft copy produced on the same assembly line as the original. In order to verify the applicability of this factor, and to estimate accurately the expected cost of producing a constellation of spacecraft or instruments, we demonstrate how APL's historical accounting record can be dissected, recurring and nonrecurring engineering (RE & NRE) broken out, and a reasonable range of cost to copy (CtoC) factors can be developed. We show how organizations can develop the corresponding factors from their own historical accounting record, and we offer solutions for organizations with insufficient accounting data to develop their own factors.

DATA COLLECTION AND NORMALIZATION

The data used to develop the CtoC factors for this paper came from accounting records for APL's STEREO spacecraft, the Van Allen Probes, the JEDI instrument flying on the Jet Propulsion Laboratory's Juno mission, and the RBSPICE instrument currently in use on the Van Allen Probes. There are two identical STEREO spacecraft, two identical Van Allen Probes, three identical JEDI instruments, and two identical RBSPICE instruments. In all instances, the first flight units and subsequent copies were built by the same team, for the same project, and without interruption in development or production. All internal data collected from accounting records was normalized into single-year dollars using NASA New Start Inflation Index. The CtoC factors developed for this paper exclusively look at the cost of developing multiple copies. This includes the cost to design, build, and integrate (at the subsystem level) the constellations of spacecraft or instruments.

Spacecraft Constellations

Cost data were collected for the design, development, and integration of spacecraft hardware subsystems up to delivery to Observatory Integration, Assembly, and Test. As discussed above, NASA New Start Inflation Index was used to normalize spend-year cost data into FY13$. The resulting collections of costs had, in some cases, sufficient detail in the work breakdown structure (WBS) to break out NRE from RE costs. However, analysts encountered problems when the WBS did not include this detail. From conversations with the program managers, lead engineers, and the financial leads of the programs, it was possible to set hierarchical rules for breaking out NRE and RE. First, where the WBS contained sufficient detail, and the cost record showed proper recording of the breakout, the data were considered clean and required no adjustment. Next, with guidance from subsystem leads and program managers, analysts used timekeeping data (recorded by individual workers) to reassign labor costs into appropriate proportions of NRE and RE. Finally, if insufficient insight was gained from the first two steps, costs prior to Critical Design Review (CDR) were considered NRE, and thirty days post-CDR costs were defined as RE. This allowed analysts to look at spacecraft costs in detail, down to the subsystem level, to see how CtoC compared across spacecraft subsystems, as well as at the spacecraft and project levels.

Instrument Constellations

After normalizing the data for development and fiscal year, WBS details along with program management (PM) inputs were used to distinguish between RE and NRE. RE was comprised of parts with the exception of the engineering model (EM) parts, the actual flight model (FM) costs associated with assembly of the instrument, and the internal harness costs. NRE included all design aspects of the instrument as well as the entirety of the engineering model and its parts. After discussions with the PMs, all of the program management and systems engineering costs were also categorized as NRE, based on judgment that the addition of a small number of identical copies would not increase the management necessary to complete the project. Several items within APL's WBS structure contained both NRE and RE costs. For these less straightforward items CDR was used to partition the data into RE and NRE. Again, all expenditures before CDR were considered NRE, and thirty days post-CDR costs were categorized as RE.

RESULTS

Spacecraft Analysis Result

Results from the analysis are given in Table 1 below. At the spacecraft system level, CtoC for STEREO was 41%. A breakdown by subsystem of the CtoC provides insight into the components of this overall factor, as shown for STEREO in Table 2. Although some results were surprising, much of the analysis was intuitively appealing. For example, STEREO's harness, which had a straightforward design and high TRL, had a high CtoC factor of 58%, while the avionics subsystem required significantly more NRE, with a CtoC of 27%.

Table 1: Spacecraft System Level Results

	STEREO	Van Allen Probes
NRE	46%	48%
RE	54%	52%
Total Number of Units	2	2
CtoC Factor	41%	36%

Table 2: STEREO Subsystem Level Results

Subsystem	NRE	RE	CtoC
Guidance & Control	30%	70%	54%
Power (incl. PDU)	52%	48%	31%
Harness	27%	73%	58%
Mechanical/Structural	39%	61%	43%
Thermal	40%	60%	43%
RF/Communications	26%	74%	59%
C&DH (IEM)	58%	42%	27%
Propulsion	47%	53%	36%
Flight Parts Qual	63%	37%	23%

The Van Allen Probes demonstrated CtoC at the spacecraft level of 36%. At the subsystem level, this factor ranged from 16% – 78%, reflecting expected patterns as well. Table 3 shows the Van Allen Probes' CtoC factors by subsystem.

Table 3: Van Allen Probes Subsystem Level Results

Subsystem	NRE	RE	CtoC
Guidance & Control	59%	41%	26%
Power (incl. PDU)	63%	27%	23%
Harness	53%	47%	34%
Mechanical/Structural	51%	49%	33%
Thermal	73%	27%	16%
RF/Communications	58%	42%	27%
C&DH (IEM)	31%	69%	52%
Propulsion	12%	88%	78%
Flight Parts Qual	30%	70%	54%

Instrument Analysis Results

Results from the analysis are provided in Table 4 below. The JEDI instrument constellation demonstrated a CtoC of 28% of the cost to develop the first unit. RBSPICE has a CtoC factor of 45%. This difference may be attributable to a couple of factors. First, the JEDI and RBSPICE instruments were very similar to one another and had the benefit of almost concurrent builds (RBSPICE was completed approximately eight months after JEDI). Some NRE could have been shared between the two projects. This may artificially decrease the CtoC factor for JEDI and increase the CtoC factor for RBSPICE. Furthermore, RBSPICE consisted of a two-instrument constellation, while JEDI had three copies. The lower cost of a single copy of JEDI relative to a single copy of RBSPICE may reflect a learning curve of sorts.

Table 4: Instrument System Level Results

	JEDI	RBSPICE	JEDI & RBSPICE
NRE	46%	38%	43%
RE	54%	62%	57%
Total Number of Units	3	2	5
CtoC Factor	28%	45%	21%

This warranted further exploration, so analysts approached the question as if the two projects, JEDI and RBSPICE, had been conducted as a single project, where five identical copies of the instrument were produced. This generated a CtoC factor of 21% (see Figure 1). This result seems to support the idea that a learning curve can be developed for small constellations of instruments.

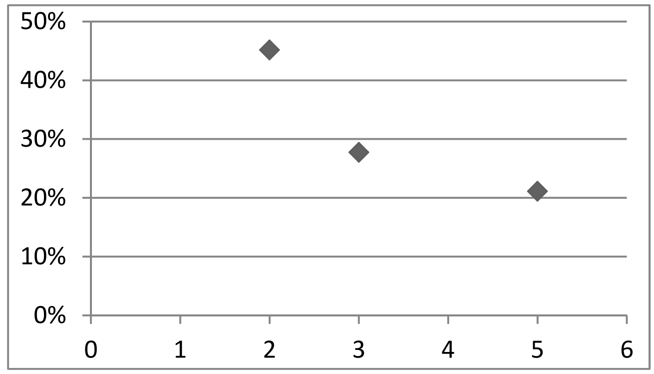

Figure 1: Instrument CtoC Factors vs. Total Number of Instruments

NASA guidelines set forth in the Handbook for Cost Estimating direct the reader to the Air Force's Learning Curve Guidelines for the aerospace industry, which recommend a learning curve efficiency of 85%. Although a cost model based on these guidelines generates higher costs for the second and third units than the historical record shows, by the time five units are in production, the 85% learning curve factor begins to approach the costs demonstrated in APL's accounting records. We are unable to test whether the learning curve remains valid for larger lots, or whether it eventually begins to undershoot the cost of the copies. It is beyond the scope of this paper to develop an alternative learning equation to estimate the cost differences as more and more identical copies are made within a constellation, but it warrants further study.

Overall, the results demonstrated that the factor given in the Warfield paper (1998) holds, approximately, for APL's experience building multiple copies of spacecraft and instruments. There are insufficient data available to explore whether spacecraft copies and instrument copies have different cost factor distributions. However, the subsystem-level spacecraft cost factors show that it is worthwhile to take design-specific detail into account wherever possible.

APL's recent cost record was detailed enough to generate this analysis and its results. However, organizing and adjusting the data was non-trivial, and many organizations may find that their data lack sufficient detail to calculate and verify the CtoC factor that best reflects their cost experience. A method for solving that problem is provided in the next section.

HOW-TO

This section lays out a step-by-step approach to approximating an organization-specific CtoC factor, given an accurate accounting record at a reasonable level of detail. We discuss how to handle an unwieldy data record, and we offer an approach that can be used for cost estimates even when no historical factors are available, as long as NRE and RE are broken out. We recommend that data be collected only from projects with continuous builds.

Once historical costs have been collected and normalized into single-year dollars, rules for breaking out NRE vs. RE should be established. If participants in the historical programs are available for discussion, a few conversations can help a great deal in establishing these rules. If detailed time-keeping records are available, these can be dissected with the right information to ascertain when NRE work was being performed, and when RE work started, based on which individuals were logging hours on the project at any given time. If all else fails, a point-in-time can be chosen as the cut-off between NRE and RE, based on the project schedule, for example. This should be evaluated carefully by subsystem for anomalies. The project may have logged its CDR on a specific date, but one or more subsystems may have completed NRE work before or after that date; adjustments should be made accordingly.

The CtoC factor can be calculated as follows:

$$\mathrm{TotalCost} = \mathrm{NRE} + \mathrm{RE} \tag{1}$$

$$N = Total\ number\ of\ units\ contained\ in\ the\ costs$$

$$\mathrm{CtoC} = \frac{\frac{\mathrm{RE}}{\mathrm{N}}}{\mathrm{NRE}+\frac{\mathrm{RE}}{\mathrm{N}}} \tag{2}$$

Each organization with a reasonably detailed cost history should thus be able to generate its own validated CtoC factor for use in cost estimates and proposals. If historical data are insufficient or unavailable, the above equation can be used for a cost estimate where NRE and RE are broken out.

But what if the CtoC factors from different projects give different results (as demonstrated by APL's own data), and differences in project details don't explain the range? Furthermore, how can cost analysts use historical CtoC data to inform a cost estimate even when few data points are available, and they may or may not reflect attributes of the estimated project that contribute to NRE costs, such as TRL? We next show how to account for the uncertainty associated with the CtoC factor in the cost estimating process.

ACCOUNTING FOR CTOC UNCERTAINTY

Project managers and other stakeholders may need to understand the risk associated with the estimated cost of a project using an organizational CtoC factor. Furthermore, cost evaluating organizations may be wary of a CtoC factor that is significantly different from what they expect to see. Using risk analysis and Monte Carlo simulation techniques, cost analysts can quantify and report the amount of uncertainty around their CtoC factor.

APL's range of CtoC factors was fairly consistent. The average CtoC factor at the system level is 37.5%, with a standard deviation of 7.3%. As expected, an F test to determine whether spacecraft have a different mean CtoC factor than instruments yielded an insignificant p-value. This was no surprise, since the averages are 38.5% and 36.5% respectively, and there are only two data points for each grouping. At the subsystem level, spacecraft CtoC factors varied widely, however, with an average of 39% and a standard deviation of 16%. This suggests that it makes sense to model spacecraft copies differently from instrument copies, if subsystem-level design data are available.

The range of CtoC factors generated from the historical data can be used to create a reasonable range around the expected CtoC factor. Some valid approaches include:

1. Discrete uniform: treat each derived factor as an equally probable result.
2. Continuous uniform: use the maximum and minimum derived factors to get a range, from which any contained point is equally probable.
3. Continuous data-driven cumulative density function: rank-order the factors from smallest to largest and fit a curve

Analysts could also work with triangular, beta, etc. The available data points could be treated as a subset where the maximum and minimum define, for example, the 30th and 70th percentiles of the distribution, etc. Some general rules are that the CtoC factor distribution should be bounded at 0 and 1, since it cannot possibly be negative, and it does not make sense to assume that an identical copy of a unit would ever cost more than its original when produced within the same time frame by the same team of engineers. Subsystems or instruments that require a great deal of technology development can be modeled well with expected CtoC factors at the low end of the reasonable range to capture the expectation of large NRE costs. Bear in mind however, that this will result in understated total development costs if the baseline cost estimate for the first unit does not include enough NRE. This also does not hold when the instrument or subsystem contains expensive materials and components that drive up the ratio of RE to NRE. Cost estimates, particularly those derived parametrically, should be carefully scrutinized and adjusted where necessary to account for issues such as TRL. Subsystems or instruments consisting largely of commercial off the shelf (COTS) or build-to-print (BTP) components are more likely to have higher CtoC factors, reflecting their low NRE costs.

Analysts leery of the historical accounting record may also choose to regard their organizational data points as "updates" to a distribution centered around the Warfield guideline of 35%. This allows for a hybrid approach, where industry standards are combined with internal data. If, for example, an analyst discovers that the accounting record produces CtoC factors consistently higher than the Warfield guideline, but there is concern that the data understate total NRE relative to the cost estimate at hand, the analyst may choose to model cost risk using the Warfield factor as the mode of a right-skewed Beta distribution that includes the organization's historical data in its tail. As subsequent cost data become available to be included in the analysis, analysts can determine whether the original data are, in fact, representative.

Once an appropriate probability density function has been found to describe the distribution of the organization-specific CtoC factor, this level of uncertainty can be built into a Monte Carlo cost simulation. Sensitivity analysis, where the simulation is run once without any variability in the CtoC factor, and once with CtoC uncertainty included, will allow the analyst to compare results to quantify how the overall cost distribution changes due to uncertainty in CtoC. This, in turn, can help the project to determine how risky the cost estimate for a constellation of satellites or instruments is. For NASA projects, this is useful to gain perspective on the amount by which unallocated future expenditures (UFE) should be increased to cover the risk that the cost of multiple spacecraft or instrument copies will be higher than expected. For DoD projects, the CtoC uncertainty must be included in any analysis in order to avoid understating total cost risk.

CONCLUSION AND WAY FORWARD

The goal of this study was to determine the applicability of a CtoC factor published in a 1998 paper by Warfield and Roust to APL's experience building constellations of instruments and spacecraft. Although four available data points would seem anemic in most industries, this was a solid foundation for APL's specialized experience in the aerospace industry. The data points ranged from 27% to 45%, as shown in the summary Table 5. This range would suggest that the Warfield and Roust factor was and remains a good approximation for an APL CtoC factor. The results were surprisingly consistent across spacecraft and instruments.

Table 5: Summary Results

	JEDI	RBSPICE	STEREO	Van Allen Probes
NRE	46%	38%	42%	47%
RE	54%	62%	58%	53%
N	3	2	2	2
CtoC Factor	28%	45%	41%	36%

In spite of its simple goal, the study revealed some interesting facts about spacecraft subsystem-level CtoC factors that have led to process improvements for APL's cost estimating approaches. We are now able to apply well-reasoned CtoC factors at the subsystem level, rather than estimating total CtoC at the spacecraft level. This allows us to use factors that reflect the engineering specifications of the estimated system, including TRL, the extent of radiation shielding, availability of materials, etc. The ability to model at the subsystem level helps us to understand the underlying reasons for differences in CtoC factors from different projects in the accounting record. Furthermore, the stratification of CtoC factors for both spacecraft and instruments in the historical record has allowed us to improve the way we model CtoC cost risk.

The study also pointed out areas where further investigation is required. All of the data points used for this study are from NASA programs, even though APL has examples of constellations built for DoD programs as well. Analysts determined that the cost data are insufficiently detailed to generate a reliable estimation of NRE and RE using the existing accounting record. However, this is worth the effort to investigate, and further analysis is planned to assess whether APL's DoD constellations have similar CtoC factors to APL's NASA constellations. Specifically, there may be some bifurcation of results when low-cost, risk-tolerant system designs are considered, such as those emerging in the cube- and nanosatellite class, due in part to commoditization of subsystems and other mass-manufacturing techniques. Similarly, the numbers by which envisioned constellations might be produced could also have an impact on current predictive models. Correspondingly, APL investigations into alternate space mission classes, such as "Express" associated with 20-50 kg vehicles, and other launch enablers, have already indicated potential disruptive cost economies (Apland et al. 2012). Another area where further study is warranted is whether a type of learning curve can be used to describe cost savings incrementally by unit for small lots. The current approach assumes that, for a small constellation of spacecraft or instruments, no learning takes place after the first unit is built. However the JEDI and RBSPICE data seemed to suggest that each additional unit was progressively less expensive than the last, which points toward a learning curve. Since traditional learning curves are a poor fit to describe the data, more investigation is required.

REFERENCES

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LIST OF ACRONYMS

1. BTP: Build to print
2. CDR: Critical Design Review
3. COTS: Commercial off the shelf
4. CtoC: Cost to Copy
5. EM: Engineering Model
6. FM: Flight Model
7. NRE: Non-recurring engineering
8. PM: Program Management
9. RE: Recurring engineering
10. TRL: Technology Readiness Level
11. UFE: Unallocated Future Expenditures
12. WBS: Work Breakdown Structure

BIOGRAPHIES

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