The Incremental Cost of One or More Copies:

Quantifying efficiencies from building spacecraft and instrument constellations

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A growing emphasis on multiple spacecraft

- **Mission architecture innovations**
  - Multi-point measurements (spatial and temporal distributions)
  - Constellations for continuous and/or persistent coverage
  - Formation flight for coordinated operations (e.g. interferometry)
- **Disaggregation and fractionation**
  - Resiliency of systems
  - Reliability of data collection and utility
  - Integrity of data collection and quality of service
- **Cost savings...? Intuitively…**
  - Distributed systems should be less expensive than monolithic ones
  - Smaller satellites should benefit from reduced development and production schedules

But how much do the copies cost?

Common Approaches

- **Bottoms-up estimate (BUE)**
  - Difficult to verify and validate
  - Very subjective
- **Learning curve**
  - Produces big numbers not substantiated by history
  - Does not scale well down to fewer than ten units
- **Cost-to-cost factor**
  - Warfield (1998) recommended 36% of the cost of the original unit per copy
  - Does this factor estimate APL copy costs?

We needed to test:

1. **Is cost-to-cost estimation valid?**
2. **If so, what factor is appropriate?**

Data collection and normalization

- **Spacecraft data are from**
  - STEREO (twin spacecraft launched in 2006)
  - Van Allen Probes (twin spacecraft launched in 2012)
- **Instrument data are from**
  - JEDI (three identical sensors launched on JPL's Juno spacecraft in 2011)
  - RBSPICE (two identical sensors launched on the Van Allen Probes in 2012)
- **For each constellation hardware was**
  - Built by the same team
  - For the same project
  - Without interruption in development or production
- **Cost data include**
  - Design, build, and subsystem-level integration
  - Normalized to single-year dollars using NASA new-start inflation index

Calculation of a cost to copy (CtoC) factor

- **Cost record rules (in order of preference)**
  1. Detailed WBS information where non-recurring engineering (NRE) and recurring engineering (RE) are broken out
  2. Timekeeping data at the employee level, based on guidance from PM, SE, and financial managers
  3. Costs prior to CDR were defined as NRE; costs post CDR were RE
- **Cost to copy factor**

$$CtoC = \frac{\frac{RE}{n}}{NRE + \frac{RE}{n}}$$

Where n = number of units contained in the costs

Spacecraft CtoC results – system level

	STEREO	Van Allen Probes
NRE as % of total	46%	48%
RE as % of total	54%	52%
Total number of units	2	2
Cost to Copy factor	41%	36%

- **The two results were surprisingly consistent**
  - Both constellations consisted of two spacecraft
  - STEREO's orbit is heliocentric, while VAP is in Earth-orbit
  - Spacecraft architectures differed substantially in RF and G&C subsystems
- **The results are also close to the Warfield and Roust factor of 36% (1998)**
- **These factors are dramatically lower than any conventional learning curve would predict!**

STEREO

- **Solar TErrestrial RElations Observatory**
  - Part of NASA's Solar Terrestrial Probes Program
  - Launched twin spacecraft in October, 2006, into offset orbits in order to capture 3D images of the sun
  - Mission studies coronal mass ejections in order to better understand space weather
  - Solar powered, 3-axis stabilized spacecraft with launch mass of about 642 kg each

Photo credit: JHU/APL

Van Allen Probes

- **Van Allen Probes**
  - Part of NASA's Living With a Star Program
  - Twin spacecraft launched August, 2012
  - Mission studies the radiation belts for better understanding of space weather
  - Solar powered

Photo credit: JHU/APL

Spacecraft CtoC results – subsystem level

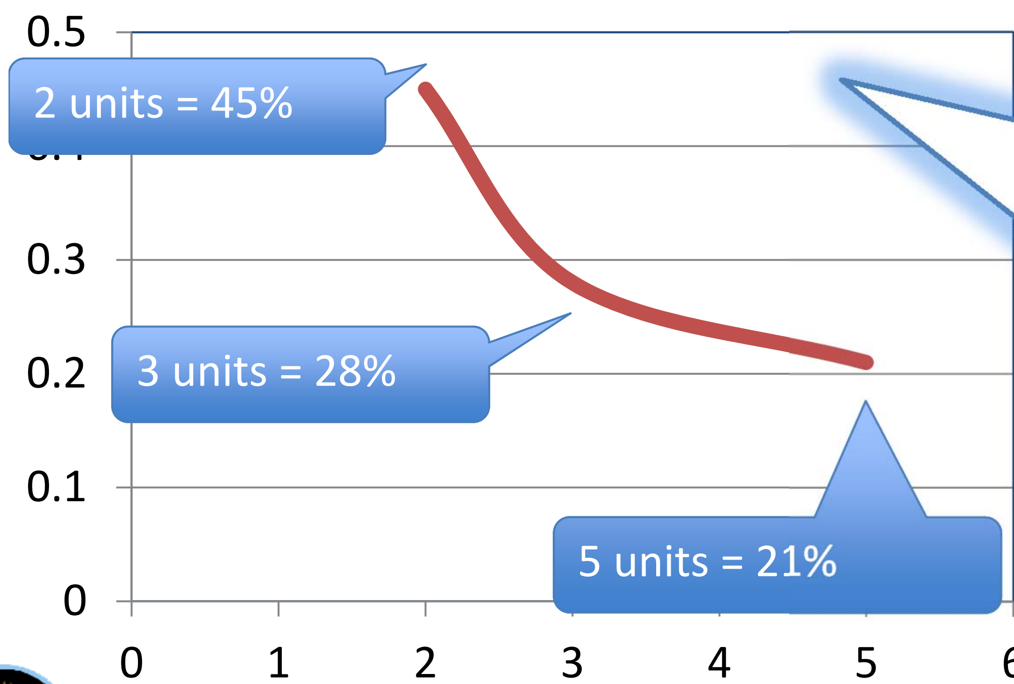
Cost to Copy factor (% of original unit cost)

	STEREO	Van Allen Probes	Average
Guidance and Control	54	26	40
Power (incl. PDU)	31	23	27
Harness	58	34	46
Mechanical/Structural	43	33	38
Thermal	43	16	30
RF/Communications	59	27	43
C&DH (IEM)	27	52	40
Propulsion	36	78	57
Flight Parts Qualification	23	54	39

Why is the variation greater at the subsystem level?

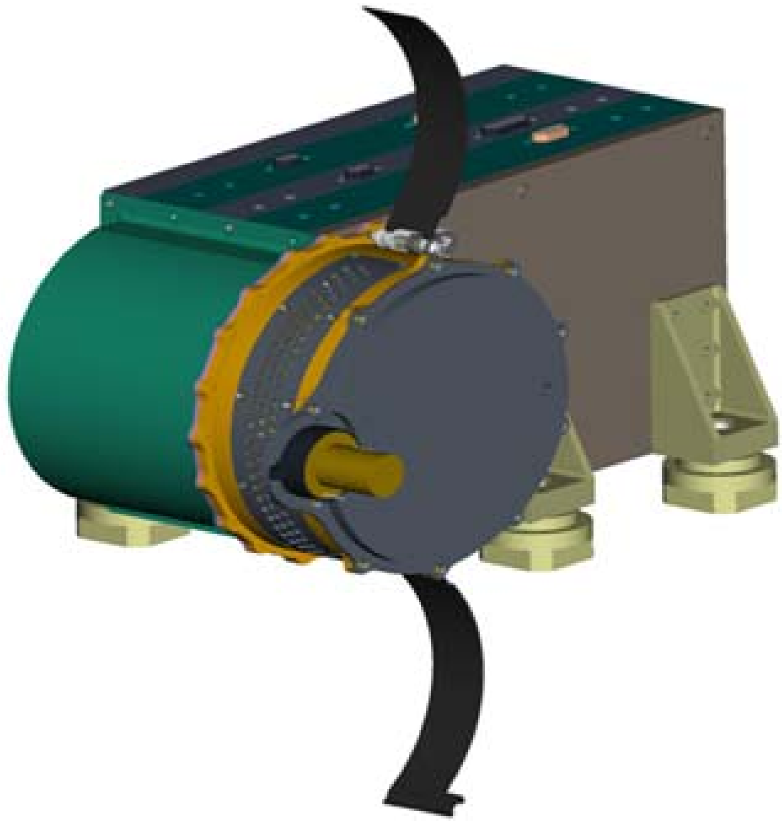
Instrument CtoC results – system level

	RBSPICE (%) (2 copies)	JEDI (%) (3 copies)	JEDI + RBSPICE (%) (5 copies)
Total number of units	2	3	5
Cost to Copy factor	45	28	21



Before normalization for system-level wraps costs (PM, SE, S&MA), the CtoC for the five sensors together was 21%, lower than the range with 2 or 3 copies. Could this be something akin to a learning curve?

RBSPICE and JEDI



- **Ion Composition Experiment**
  - Understand the effects of radiation belt storms on radiation electrons and ions
  - Better understand the solar cycles
  - The RBSPICE instrument differs slightly from the JEDI instrument mostly due to spacecraft interface

Photo credit: JHU/APL

Incremental copy costs – a learning cliff

- **The instrument data require normalization because**
  - Jedi and RBSPICE were five copies of the same sensor built by the same production team in the same time frame
  - Since the sensors were built for different programs, each required its own team of program managers and systems engineers

Before adjustment, the combination of JEDI and RBSPICE yields a ratio of RE to NRE that is too low because much NRE is doubled between the two projects.

- **After adjustment to include "level of effort" labor costs only once, the CtoC factor for RBSPICE and JEDI combined as a single project is**

34%

For small lots, there is little evidence of learning after the second unit is built

Accounting for uncertainty

- **Uncertainty in the range may reflect**
  - Amount of technology development
  - Level of complexity
  - Approach to cost accounting
  - The ratio of materials costs to labor costs
  - Manifested project risks
  - Other factors…
- **Cost risk analysis must account for two sources of uncertainty in the cost of a duplicate unit**
  - The cost risk of the original copy
  - The uncertainty of the cost required to duplicate the original

Historical data provide a *subset* of possible outcomes.
Cost risk analysis must include this uncertainty

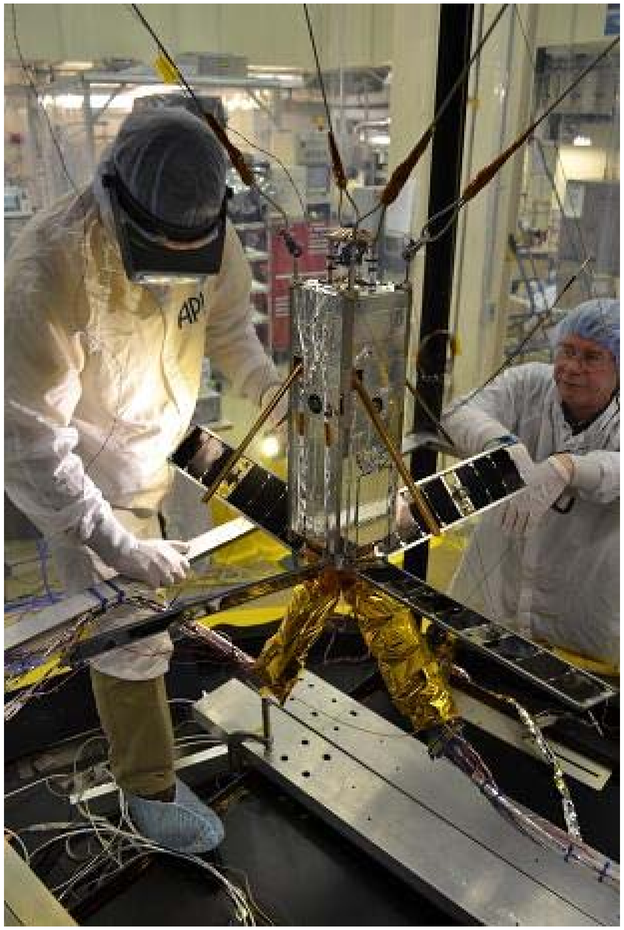
Study Results and Way Forward

- **The Warfield factor of 36% is a good CtoC approximation for APL**
  - Spacecraft average CtoC was 38%
  - Instrument composite CtoC was 34%

- **The study gave us a starting point for understanding CtoC uncertainty – we have begun to apply what we've learned in cost estimates**

- **Further research is required to understand**
  - Do DoD programs' CtoC factors differ from NASA programs'?
  - Do CtoC factors shift for low-cost, risk-tolerant systems, such as nanosats?
  - For constellations with more than a handful of units, can we observe a learning curve, or a different type of learning pattern?

Multi-mission Bus Demonstration



MBD is a nanosatellite designed to be modular, inexpensive, and multi-purpose. Further research is required to determine whether its copy cost would differ from APL's historical experience.

Photo credit: JHU/APL

Thank you for your attention!

Questions?