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Critique of Cost-Risk Analysis and Frankenstein Spacecraft Designs: A Proposed Solution

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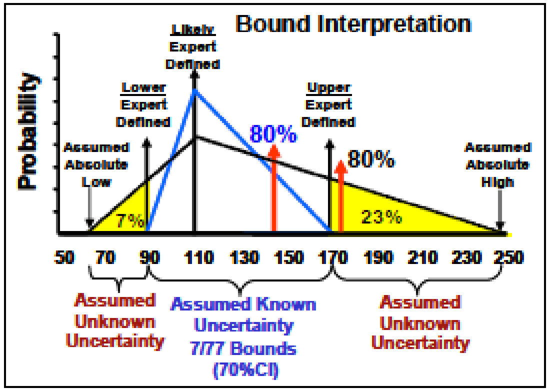
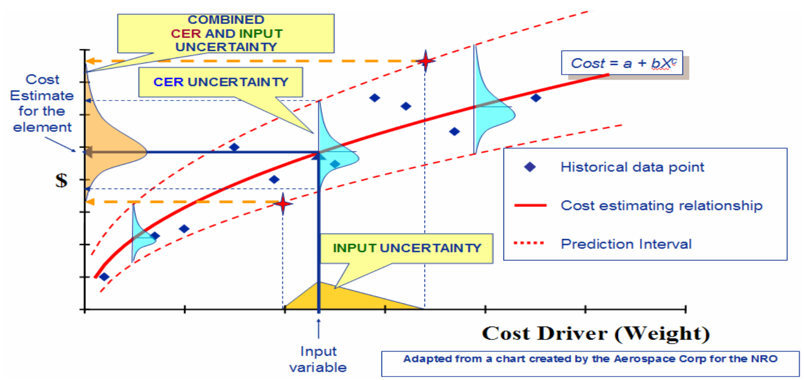
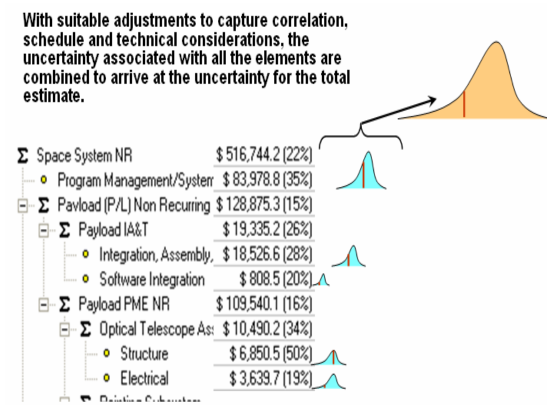
Eric Plumer, NASA CAD HQ
Mohamed Elghefari, Pasadena Applied Physics

Cost-Risk Analysis "Best Practice"

	CBE Mass	CBE Mass w/Contingency	CBE Power	CBE Power w/Contingency
Payload Total	**105 kg**	**139 kg**	**110 W**	**140 W**
Spacecraft (Dry)	**235 kg**	**268 kg**	**182 W**	**205 W**
Structures & Mechanisms	85 kg	97 kg	0 W	0 W
Thermal	9 kg	11 kg	15 W	19 W
Propulsion Dry Mass	12 kg	12 kg	1 W	1 W
Attitude Determination Subsystem	7 kg	8 kg	16 W	17 W
Attitude Control Subsystem	14 kg	15 kg	36 W	39 W
Electrical Power Subsystem	79 kg	90 kg	21 W	30 W
Communications	10 kg	10 kg	18 W	19 W
Command and Data Handling	20 kg	24 kg	75 W	81 W
Propellant & Pressurant	**65 kg**	**65 kg**		
Spacecraft Propellant & Pressurant	65 kg	65 kg		
Total (Dry)	**405 kg**	**472 kg**	**292 W**	**345 W**
Total (Wet)	**470 kg**	**537 kg**	**292 W**	**345 W**
LV Capability	755 kg	755 kg		
Launch Mass Margin	**61%**	**41%**		







To give a sense of "confidence" in a point estimate, cost analysts are expected to generate "credible" probabilistic distributions of potential costs that capture uncertainties associated with cost estimating methodology and cost drivers and account for correlation between cost elements

Cost-Risk Analysis "Best Practice" Mathematically

- Each simulation trial results in a set of values for spacecraft subsystems masses, subsystems power loads, and corresponding set of values for subsystems costs

$$M_{SC}^{i} = \{m_j^i\} = \{m_{Str}^i, m_{Th}^i, m_{Propulsion}^i, m_{EPS}^i, m_{ADS}^i, m_{ACS}^i, m_{Com}^i, m_{CDH}^i\}$$
$$P_{SC}^{i} = \{p_j^i\} = \{p_{Str}^i, p_{Th}^i, p_{Propulsion}^i, p_{EPS}^i, p_{ADS}^i, p_{ACS}^i, p_{Com}^i, p_{CDH}^i\}$$
$$\varepsilon_{SC}^{i} = \{\varepsilon_j^i\} = \{\varepsilon_{Str}^i, \varepsilon_{Th}^i, \varepsilon_{Propulsion}^i, \varepsilon_{EPS}^i, \varepsilon_{ADS}^i, \varepsilon_{ACS}^i, \varepsilon_{Com}^i, \varepsilon_{CDH}^i\}$$
$$X_{SC}^{i} = \{X_j^i\} = \{X_{Str}^i, X_{Th}^i, X_{Propulsion}^i, X_{EPS}^i, X_{ADS}^i, X_{ACS}^i, X_{Com}^i, X_{CDH}^i\}$$

- The total "simulated" spacecraft system dry mass, power requirement, and cost estimate are

$$M_{SC\,Total}^{i} = \sum_{j=1}^{8} m_j^i \qquad P_{SC\,Total}^{i} = \sum_{j=1}^{8} p_j^i \qquad X_{SC\,Total}^{i} = \sum_{j=1}^{8} X_j^i$$

$$X_j^i = f_j(m_j^i p_j^i,) * \varepsilon_{ij}$$

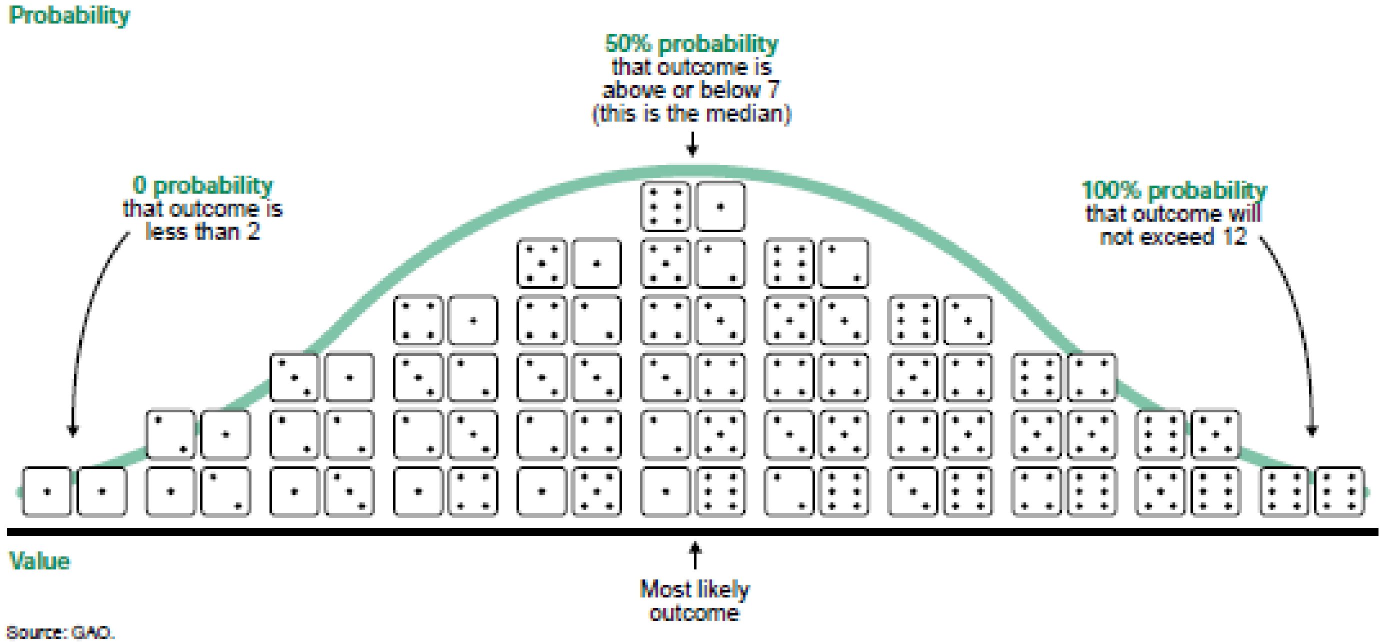
- The probability of occurrence of each simulation outcome

$$\forall\, i, f\left(M_{SC}^i, P_{SC}^i, \varepsilon_{SC}^i, X_{SC}^i\right) = \frac{1}{n} \neq 0$$

- The Cumulative Density Function

$$F\left(M_{SC}^i, P_{SC}^i, \varepsilon_{SC}^i, X_{SC}^i\right) = \sum_{X_{SC}^k \leq X_{SC}^i} f\left(M_{SC}^k, P_{SC}^k, \varepsilon_{SC}^k, X_{SC}^k\right)$$

Probability Distribution to Model Uncertainty



Probability theory is based on concept of event and sample space

- Event: value of dice roll
- Sample space: all possible value outcomes associated with rolling a pair of dice
  - 36 possible outcomes
  - Normalization condition is met: $\int_{-\infty}^{+\infty} f(s)ds = \int_{2}^{12} f(s)ds = 1$

Probability theory is based on the concepts of event and sample space which must be defined before one can attempt to model uncertainty using probability distribution

What's the Meaning of a Measurement or Event in Cost Estimating Experiment?

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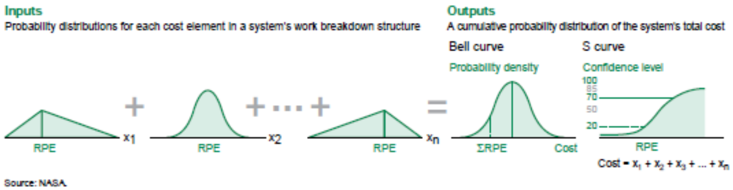
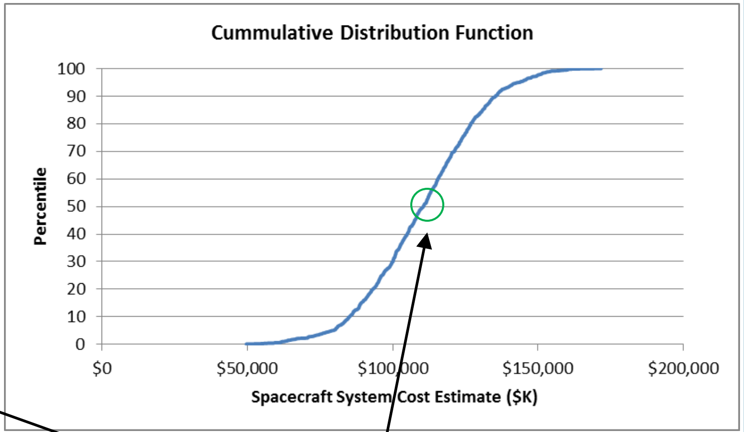
What is the "ensemble" or "sample space " of your experiment?

$$
\begin{array}{ccccccc}
m^1_{Str} & m^2_{Str} & m^3_{Str} & \cdots & m^i_{Str} & \cdots & m^n_{Str} \\
m^1_{Th} & m^2_{Th} & m^3_{Th} & \cdots & m^i_{Th} & \cdots & m^n_{Th} \\
m^1_{Propulsion} & m^2_{Propulsion} & m^3_{Propulsion} & \cdots & m^i_{Propulsion} & \cdots & m^n_{Propulsion} \\
m^1_{EPS} & m^2_{EPS} & m^3_{EPS} & \cdots & m^i_{EPS} & \cdots & m^n_{EPS} \\
m^1_{ADS} & m^2_{ADS} & m^3_{ADS} & \cdots & m^i_{ADS} & \cdots & m^n_{ADS} \\
m^1_{ACS} & m^2_{ACS} & m^3_{ACS} & \cdots & m^i_{ACS} & \cdots & m^n_{ACS} \\
m^1_{Com} & m^2_{Com} & m^3_{Com} & \cdots & m^i_{Com} & \cdots & m^n_{Com} \\
m^1_{C\&DH} & m^2_{C\&DH} & m^3_{C\&DH} & \cdots & m^i_{C\&DH} & \cdots & m^n_{C\&DH} \\
p^1_{Str} & p^2_{Str} & p^3_{Str} & \cdots & p^i_{Str} & \cdots & p^n_{Str} \\
p^1_{Th} & p^2_{Th} & p^3_{Th} & \cdots & p^i_{Th} & \cdots & p^n_{Th} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
p^1_{Com} & p^2_{Com} & p^3_{Com} & \cdots & p^i_{Com} & \cdots & p^n_{Com} \\
p^1_{C\&DH} & p^2_{C\&DH} & p^3_{C\&DH} & \cdots & p^i_{C\&DH} & \cdots & p^n_{C\&DH} \\
\varepsilon^1_{Str} & \varepsilon^2_{Str} & \varepsilon^3_{Str} & \cdots & \varepsilon^i_{Str} & \cdots & \varepsilon^n_{Str} \\
\varepsilon^1_{Th} & \varepsilon^2_{Th} & \varepsilon^3_{Th} & \cdots & \varepsilon^i_{Th} & \cdots & \varepsilon^n_{Th} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\varepsilon^1_{Com} & \varepsilon^2_{Com} & \varepsilon^3_{Com} & \cdots & \varepsilon^i_{Com} & \cdots & \varepsilon^n_{Com} \\
\varepsilon^1_{C\&DH} & \varepsilon^2_{C\&DH} & \varepsilon^3_{C\&DH} & \cdots & \varepsilon^i_{C\&DH} & \cdots & \varepsilon^n_{C\&DH} \\
X^1_{Str} & X^2_{Str} & X^3_{Str} & \cdots & X^i_{Str} & \cdots & X^n_{Str} \\
X^1_{Th} & X^2_{Th} & X^3_{Th} & \cdots & X^i_{Th} & \cdots & X^n_{Th} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
X^1_{Com} & X^2_{Com} & X^3_{Com} & \cdots & X^i_{Com} & \cdots & X^n_{Com} \\
X^1_{C\&DH} & X^2_{C\&DH} & X^3_{C\&DH} & \cdots & X^i_{C\&DH} & \cdots & X^n_{C\&DH}
\end{array}
$$





outcome of experiment = Spacecraft point design and associated cost

Points that make up the s-curve represent not only possible spacecraft cost outcomes but spacecraft design outcomes as well!

There is a Problem….

- Technical design parameters of spacecraft subsystems are *interdependent*, *analytically* and *implicitly* related to one another via key physical relationships
- These key physical relationships are generally not upheld when cost analysts perform cost-risk simulations
- The generated spacecraft point designs (i.e., simulated sets of CER input variables) based on subjective statistics may be neither technically feasible nor buildable (i.e., "Frankenstein" designs)
- Yet all simulation design outcomes are assigned non-zero probability of occurrence and, consequently, the resulting spacecraft system cost CDF is invalid
- The resulting cost-risk assessment may be too high or too low

Design parameters of spacecraft subsystems are related to one another via key physical relationships which are generally NOT upheld in cost-risk simulations

Cost-Risk Analysis "Best Practice" Violates Laws of Physics….

- Rocket equation:

$$m_{prop} = M^{i}_{SC\,Total}\,[e^{\left({}^{\Delta V}/_{I_{sp}g}\right)} - 1],$$

- Solar array sizing equation:

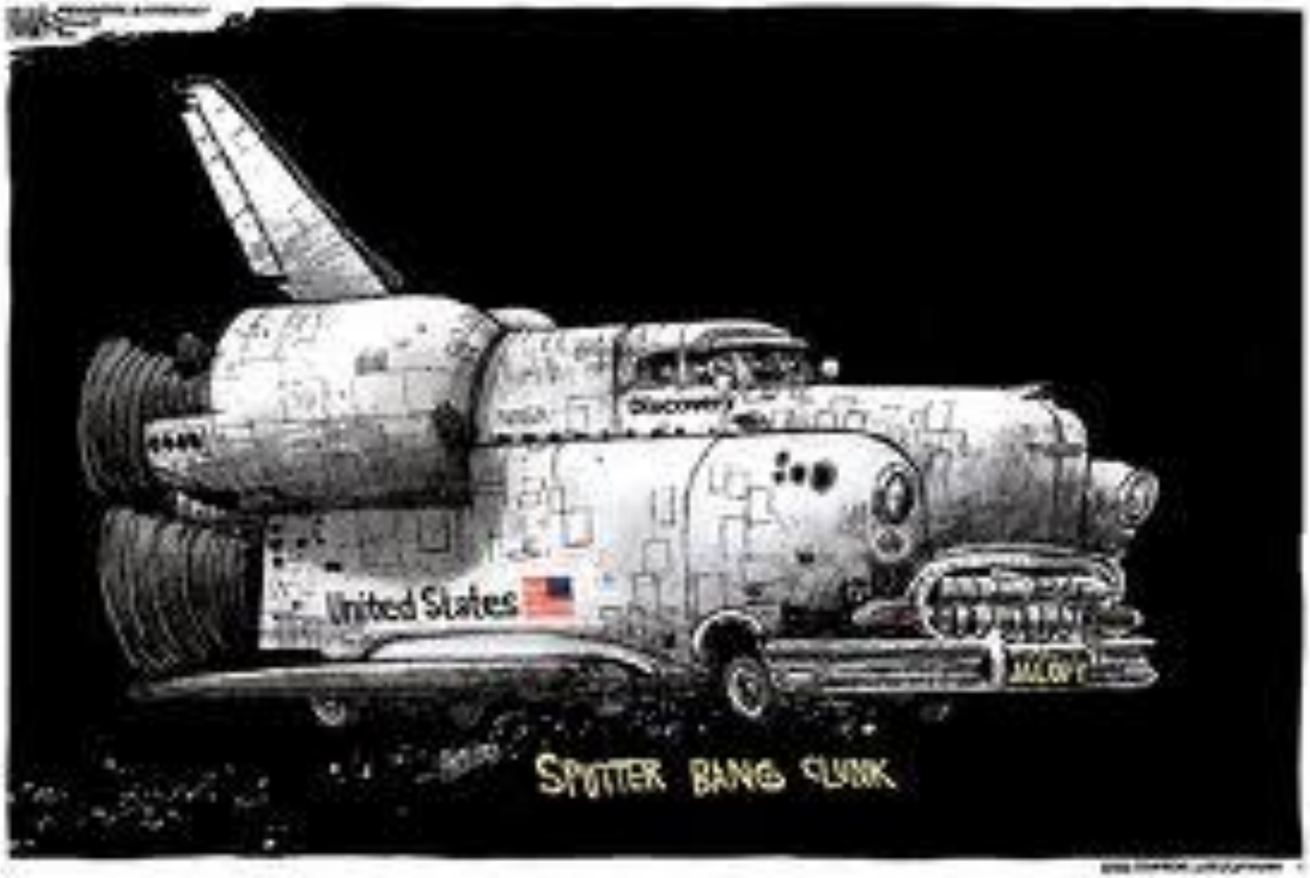
$$A = \frac{P_{EOL}}{F_S\, f_p\, \varepsilon_{BOL}(1.0 - \delta_{los})[1.0 - \gamma_T(t_0 - t_{REF})]\cos(\alpha)\,(1.0 - \beta)^T},$$

- Stefan-Boltzmann law:

$$A = \frac{Q}{\sigma T^4},$$

Some of the randomly generated spacecraft point designs based on subjective statistics are not technically feasible, buildable, or flyable. Yet they are assigned non-zero probability of occurrence and consequently cost-risk assessment is invalid

The Problem Pictorially…



Points on S-curve may represent cost of a Frankenstein spacecraft Design!

NASA's Data Collection to Support Analysis Work

The Importance of NASA Data Collection

Data Collection and Tool Provision are essential to improving NASA-wide cost analysis capabilities. Funding these capabilities is a top priority of the Cost Analysis Division

Cost & Schedule Estimating Policy	Decision Support	Estimating Analysis Capabilities
Identification	Identify/Analyze Cost & Schedule-Related Issues	Tool Provision
Development	Support Agency-level Studies	Best Practices
Implementation	Advise Agency Leadership	Data Collection/Dissemination
Communication		Research and Capability Enhancements
Track and Measure		Community Outreach & Enhancement
		Analysis Support

<u>Data Collection</u>

- **The Cost Analysis Data Requirement (CADRe)** – the 'flight recorder' for <u>all</u> major NASA programs and projects provides data that is the foundational life blood of NASA's cost analysis capabilities.

- CADRe data collected temporally at six major project milestones supports analysis and decision making for all major NASA acquisitions, and provides the basis for the Agency's external commitments, but depends on the ONCE database to make the data accessible.
- NASA's programmatic performance has been improving over the last decade, enabled by CADRe data, and continued collection of this essential temporal data is. high priority and must continue.

<u>Provides Basis for Tool Provision</u>

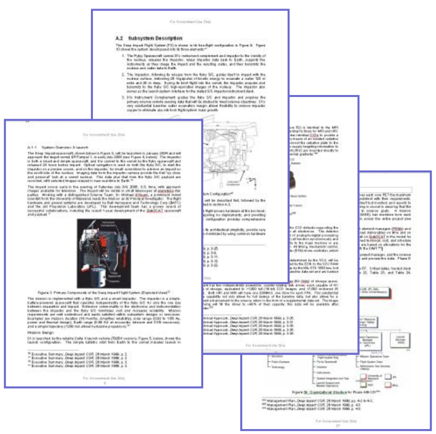
- CAD funds key <u>workhorse</u> estimating tools that are used NASA-wide by the agency's cost analysis community and essential for all cost analysis done at the Centers.
- Included are NASA-developed tools (NAFCOM/PCEC and NICM) and commercially available tools (e.g. PRICE, JACS, POLARIS, SEER).
- CAD standardizes tool use and maximizes efficiency for NASA through agency-wide licenses.
- Cost analysis capabilities across the agency would be crippled without these tools.

Cost Analysis Data Requirement (CADRe)

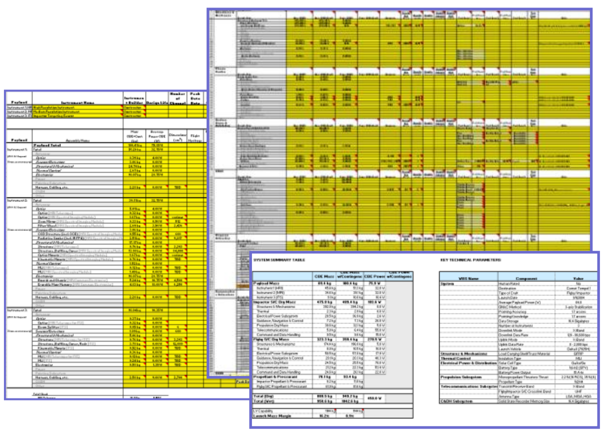
- **A three-part document:**
  - Part A: Describes a NASA project at each milestone (SRR, PDR, CDR, SIR, Launch and End of Mission), and describes significant changes that have occurred.
  - Part B: Contains standardized templates to capture key technical parameters that are considered to drive cost (Mass, Power, Data Rates).
  - Part C: Captures the NASA project's Cost Estimate and actual life cycle costs within the project's and a NASA Cost Estimating Work Breakdown Structures (WBS).

CADRe

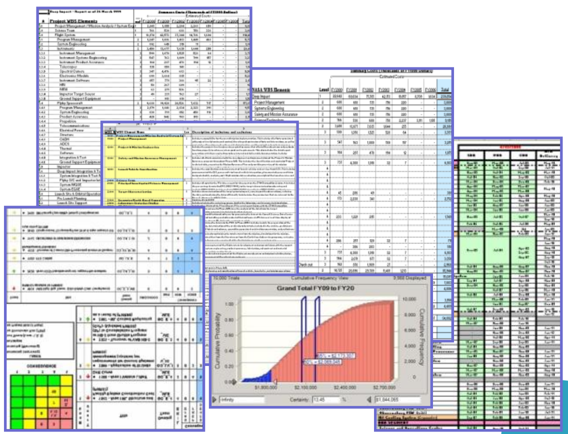
Part A: Descriptive Information



Part B: Technical Data



Part C: Life Cycle Cost Estimate



- Note: THE "LAUNCH" CADRes for a mission captures the final costs and as-built mass, and power data. The SRR, PDR, CDR CADRes contain Current Best Estimates.

When Are CADRes Required?

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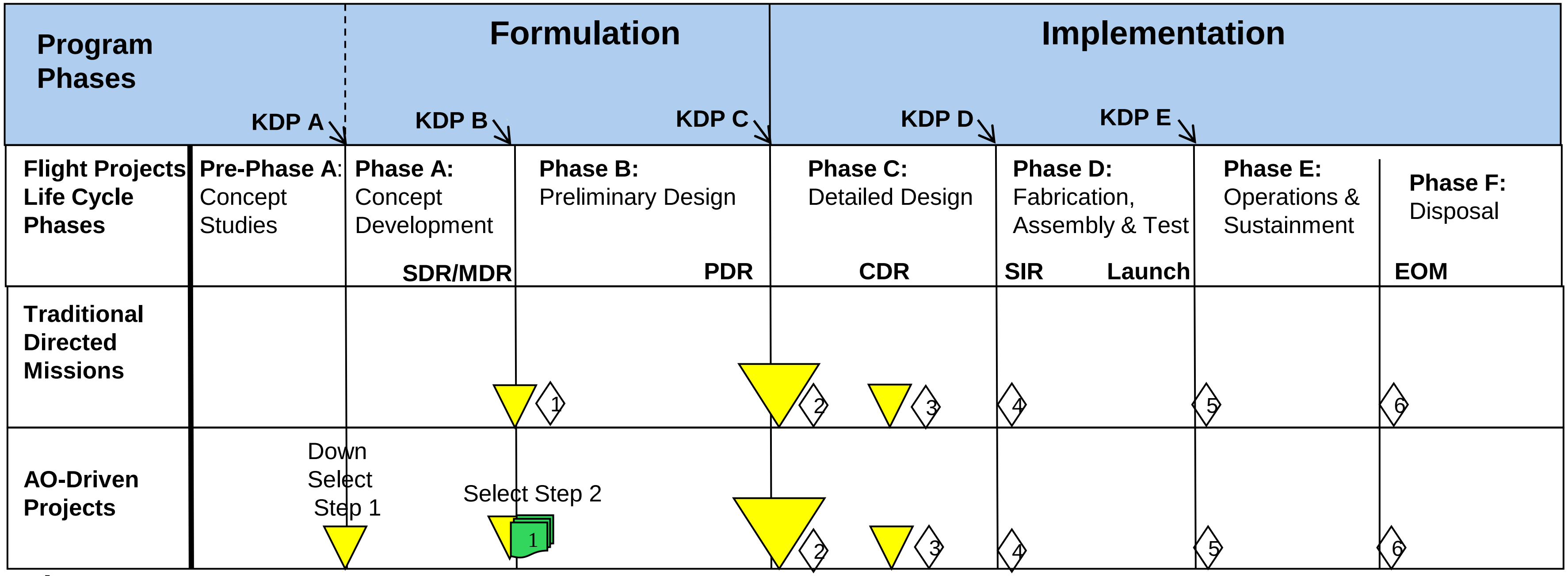
CADRe is updated at each indicated milestone starting with SDR/MDR



Legend

Key Decision Point (KDP)

1 All parts of CADRe due 30-45 days after KDP B

1 CADRe delivered; based on Concept Study Report (CSR) and winning proposal

2 All parts of CADRe due 30-45 days after KDP C using PDR material

3 Update as necessary 30-45 days after CDR using CDR material

4 Update as necessary 30-45 days after KDP D using SIR material

5 CADRe, All Parts due 90 days after launch, based on as built or as deployed configuration

6 CADRe, update Part C only after the end of decommissioning and disposal

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CADRe Customers (Beneficiaries)

Internal NASA Customers

SMD — Various SMD Cost Studies and Analysis of Projects

SOMA — Reviewing AO proposals

SID — Portfolio Modeling; Rapid Cost/Schedule Assessing

GSFC — Flight Projects, RAO, Explorers Office, Integrated Design Center,

IPAO — Historical Data, Assessment support

MSFC — Cost Model Development and Calibrations

LaRC — Cost research, Used by TMCO Panel for AO reviews

APL — Cost Engineering Trades

JPL — TEAM X Cost Engineering Trades

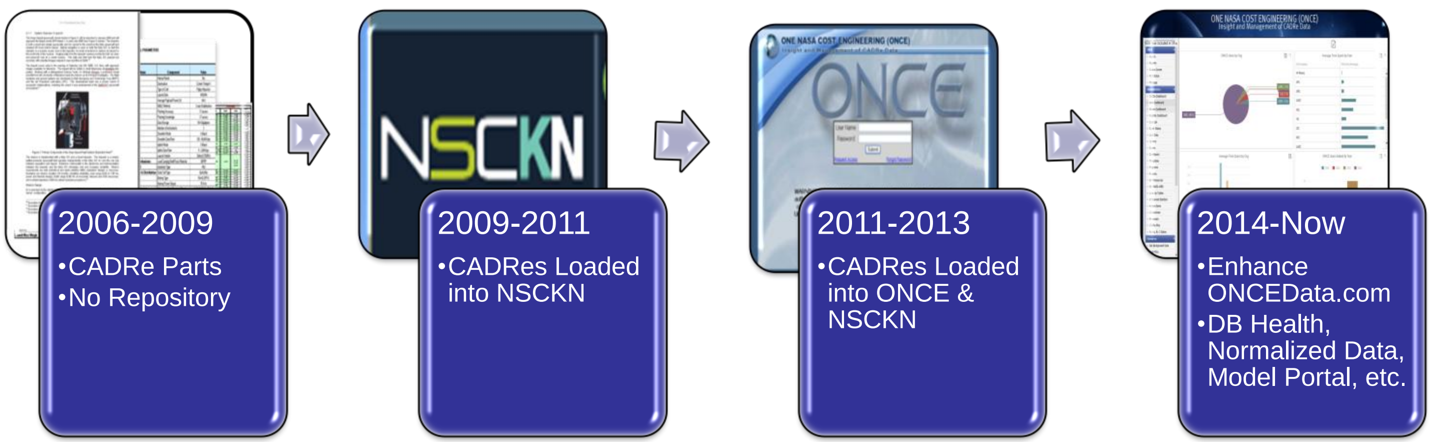
CAD — Cost/Schedule Improvement, Policy Improvement, JCL Improvement
Model Calibration, Research and Tool Development

External NASA Customers

Air Force
GAO
NRO
NOAA
OMB
DNI

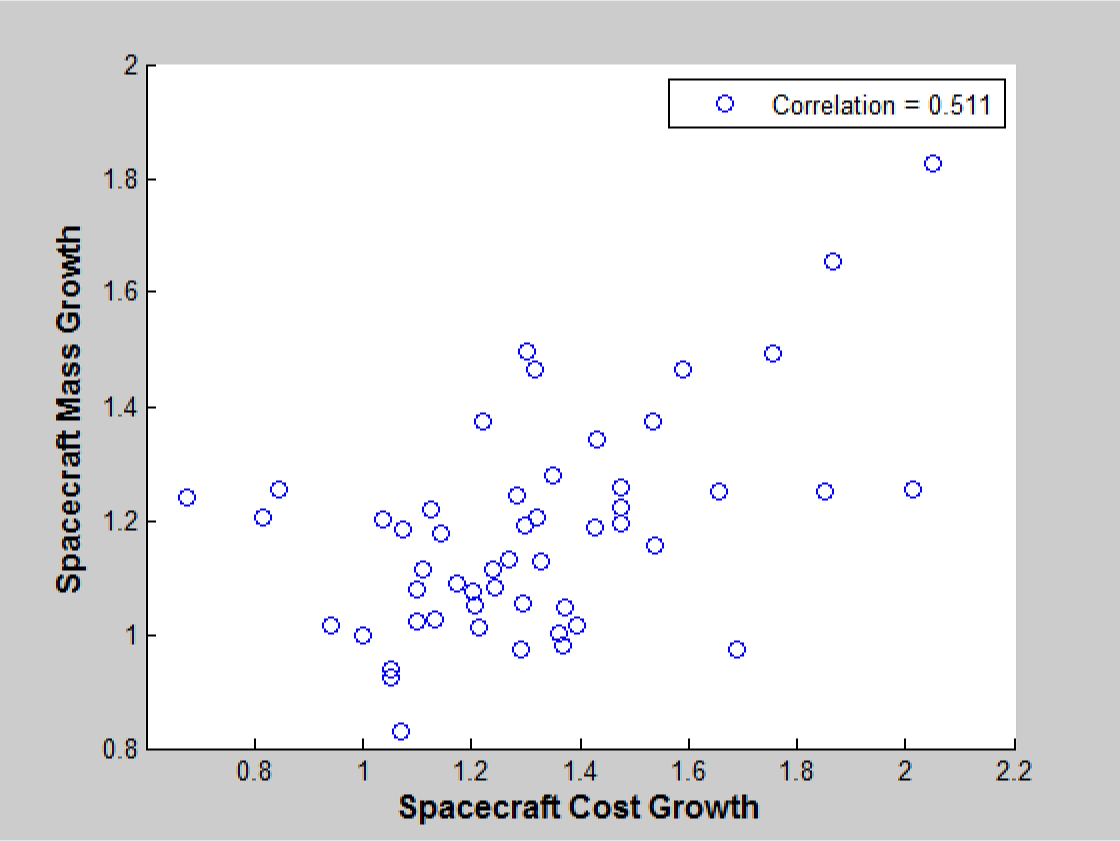
What is One NASA Cost Engineering Database?

- Cloud Compliant Database that automates the Search and Retrieval of CADRe Data
  - Active Server Pages utilizing: Microsoft SQL Server 2005 database; .NET framework; VB.Net; C#; Javascript; VBScript
- ONCE is a powerful tool for searching CADRe data across multiple NASA projects
- Able to simultaneously pull data across multiple projects, milestones, and tech data fields (mass, power, etc)
- Easy navigation to any desired CADRe, able to produce customized reports.
- Filtering features in ONCE provide an easy way to obtain the information needed quickly
- After retrieving the desired data, it is easy export to excel or nearly any statistical package to perform regression analysis
  - ONCE helps order and access the CADRe (flight recorder) data, transforming it into useful information.



ONCE has evolved over last several years.

One Solution: Spacecraft Probabilistic Cost Growth Model



Growth in cost drivers (i.e. spacecraft mass) can be captured by applying appropriate spacecraft cost growth factor

Spacecraft Probabilistic Cost Growth Model in a Nutshell

- Model does not require cost driver uncertainty input
- Requires only two parameters:
  - Current Best Estimate(CBE) of spacecraft system cost
  - CBE maturity relative to project milestones, which is reasonably objective
- Based on historical analogous systems (available in NASA CADRe database)
- Predicts spacecraft system cost growth (or shrinkage)
- Produces cost growth factor distribution result (embodies uncertainty) that recognizes the   possibility of growth or shrinkage of cost driver (i.e. spacecraft design parameters)

Provides probabilistic cost growth adjustment to spacecraft cost CBE

Study Dataset

NASA Project	CSR/SRR	PDR	CDR
CONTOUR	N/A	X	X
MESSENGER	X	X	X
New Horizons	X	X	X
STEREO	X	X	X
AIM	X	X	X
AQUA	X	X	X
CHIPSat	X	X	N/A
EO-1	X	N/A	X
GLAST	X	X	X
IBEX	X	X	X
LRO	N/A	X	X
RHESSI	X	X	X
SWAS	X	X	X
Terra	X	X	X
TRACE	X	N/A	N/A
TRMM	X	X	X
CloudSat	X	X	X
MRO	X	X	X
Spitzer	X	X	X

19 Earth-Orbiting and Deep Space Missions Obtained from NASA CADRe Database

Model Development Approach

1) Developed spacecraft system cost change database

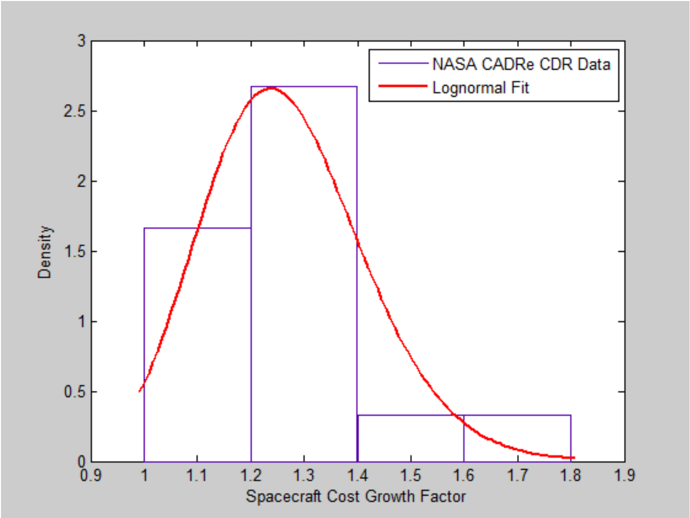
2) Performed exploratory analysis to uncover appropriate fit distribution

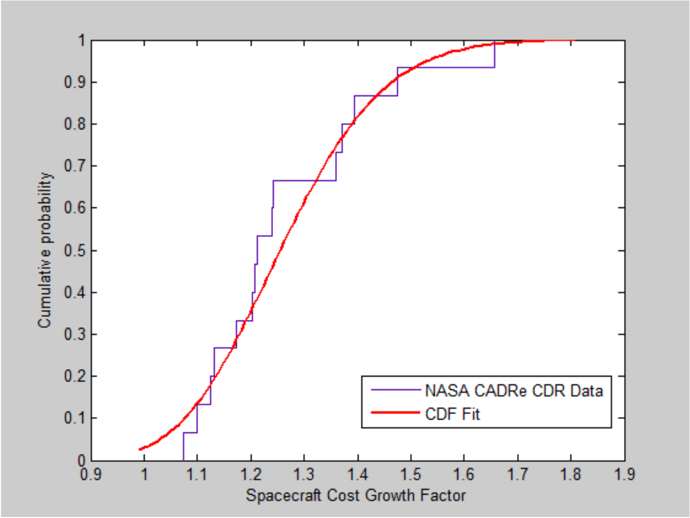
3) Fit lognormal PDF to our spacecraft system cost growth data

4) Developed Empirical Cumulative Distribution Functions (ECDF) of spacecraft cost Growth Factor (GF) for various project milestones

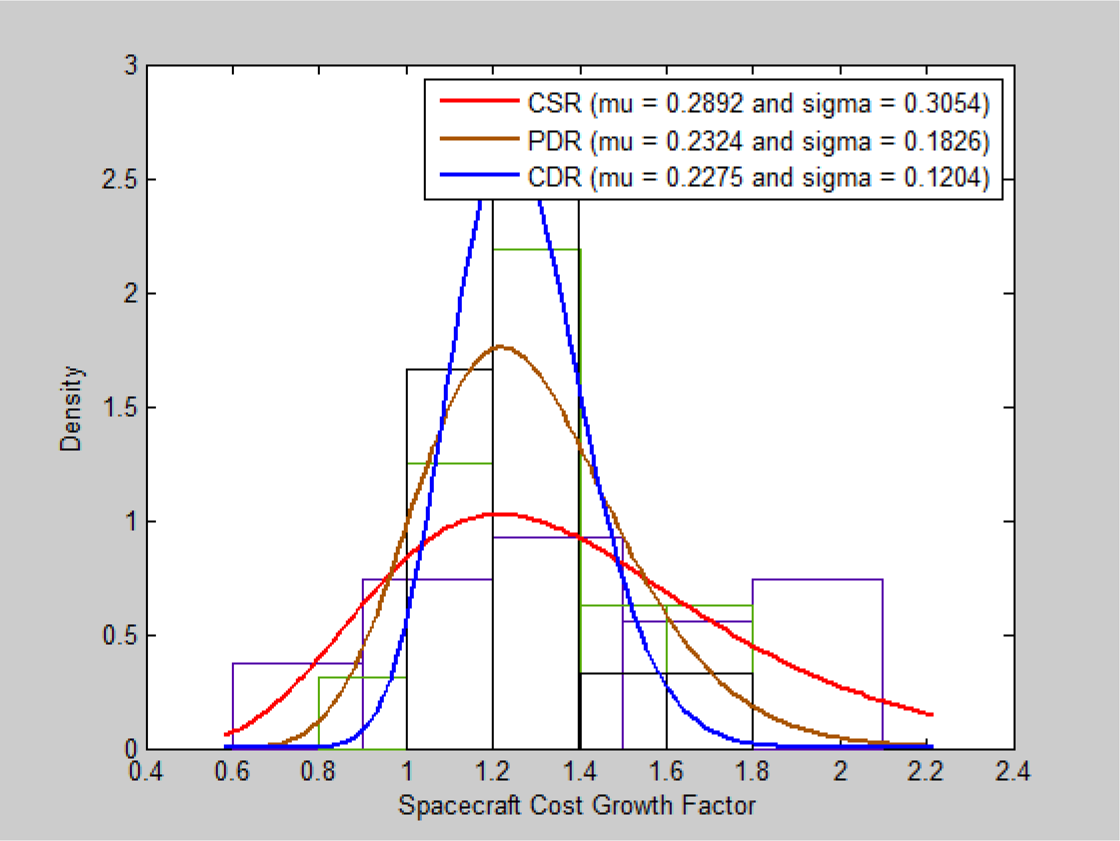
$$SC\ Cost\ Change_{MS} = \frac{SC\ Cost_{Launch} - SC\ Cost\ EAC_{MS}}{SC\ Cost\ EAC_{MS}}, \quad where\ MS = CSR, PDR, CDR,$$

$$SC\ Cost\ GF_{MS} = 1 + SC\ Cost\ Change_{MS}.$$





Spacecraft Probabilistic Cost Growth Model



$$f(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{\frac{-(\ln x - \mu)^2}{2\sigma^2}\right\} \;\; ; \;\; x > 0.$$

Decreasing mean growth factor and growth factor uncertainty (decreasing CV) as estimate relative maturity increases

Methodology: Spacecraft System Cost Growth Adjusted S-Curve

1. Determine spacecraft subsystem cost drivers (mass or other key technical parameters) and obtain their CBE values
2. Plug these values in the appropriate spacecraft subsystem CERs, ignoring their contingency values
3. Develop cost probability distributions of spacecraft subsystems to model uncertainty associated with the cost methodology only
4. Account for correlation between costs of various spacecraft subsystems
5. Perform simulation, use the "rollup procedure" and generate the overall spacecraft system cost distribution.
6. Select the appropriate spacecraft cost growth factor distribution based on where in the mission development life cycle the spacecraft cost CBE is being generated.
7. Adjust the resulting spacecraft cost probability distribution by combining it with the selected spacecraft cost growth factor distribution
8. Use the resulting cost probability distribution to assess the percentile or "confidence" level associated with a point estimate
9. Recommend sufficient cost reserves to achieve the percentile or level of "confidence" acceptable to the project or organization
10. Allocate, phase, and convert a risk-adjusted cost estimate to then-year dollars

Conclusions

- Cost analysts need to understand that while spacecraft design parameters are not typically known with sufficient precision, their uncertainties should NOT be modeled with subjective distributions
  - Let's not abuse theory of probability! Know what you are simulating, define your event and sample space
- Spacecraft subsystem design parameters are analytically and implicitly related by physical and engineering relationships
- One suggested solution is probabilistic growth cost model which embodies cost driver uncertainty
- System-of-systems cost models should ensure the validity of their input vectors
- Be wary of traditional cost estimate S-curve, it's just a measure of an individual's belief
- We will always lack the normalization condition unless we find a way to apply Quantum Field Theory in cost-risk analysis!!!

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Questions?

Backup Slides

Spacecraft Cost and Mass Growth Dataset and Summary Statistics at MS-CSR

CSR		
Mission	**SC Cost GF**	**SC Mass GF**
MESSENGER	187%	166%
New Horizons	185%	125%
STEREO	154%	116%
AIM	137%	98%
CHIPSat	105%	93%
IBEX	159%	146%
RHESSI	147%	122%
SWAS	153%	137%
TERRA	143%	119%
CLOUDSAT	201%	126%
MRO	132%	146%
SPITZER	130%	150%
AQUA	82%	121%
EO-1	205%	183%
GLAST	111%	111%
TRACE	68%	124%
TRMM	100%	100%
WIRE	107%	83%
Observations	**18**	**18**
Mean	**139%**	**126%**
Median	**140%**	**123%**
STDEV	**39.52%**	**25.61%**
Min	**68%**	**83%**
Max	**205%**	**183%**

Spacecraft Cost and Mass Growth Dataset and Summary Statistics at MS-PDR

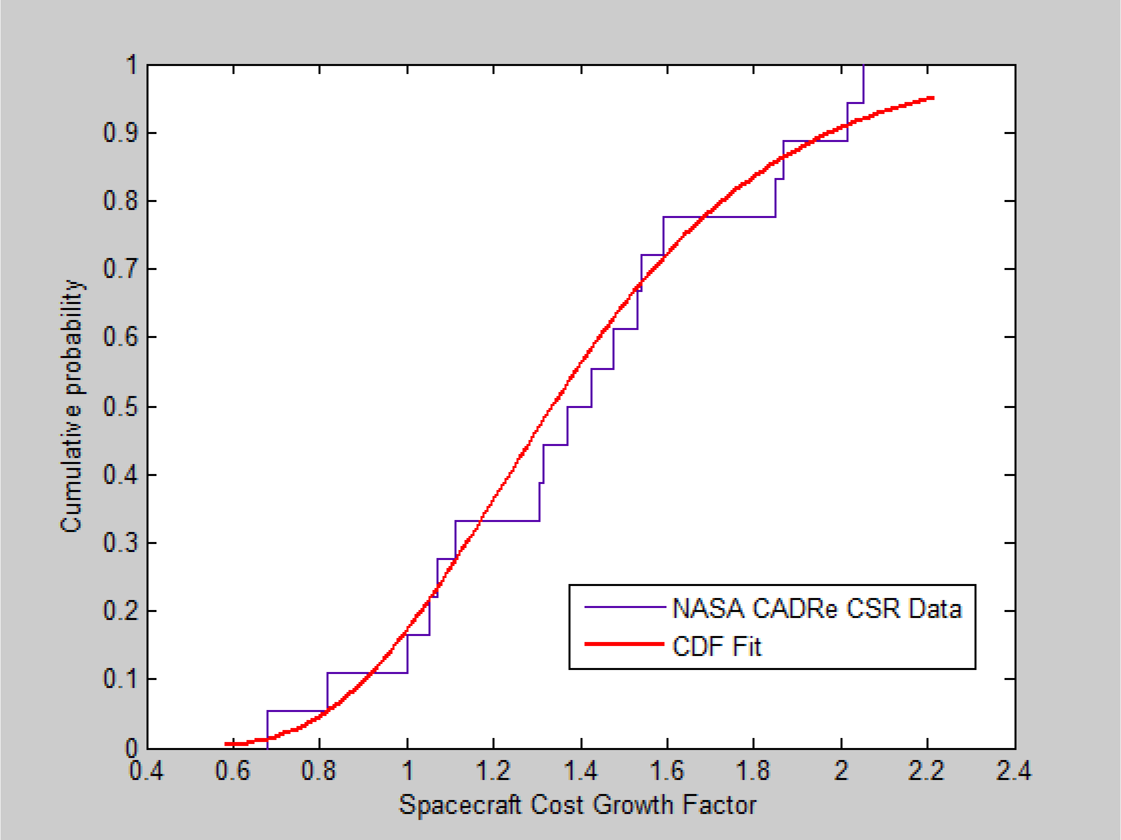
PDR		
Mission	**SC Cost GF**	**SC Mass GF**
COUNTOUR	94%	101%
MESSENGER	135%	128%
New Horizons	122%	137%
STEREO	132%	121%
AIM	129%	97%
AQUA	104%	120%
CHIPSat	84%	125%
GLAST	130%	119%
IBEX	143%	134%
LRO	127%	113%
RHESSI	147%	126%
SWAS	110%	102%
TERRA	129%	105%
TRMM	115%	118%
CLOUDSAT	169%	97%
MRO	128%	124%
SPITZER	175%	149%
Observations	**17**	**17**
Mean	**128%**	**119%**
Median	**129%**	**120%**
STDEV	**23.43%**	**14.63%**
Min	**84%**	**97%**
Max	**175%**	**149%**

Spacecraft Cost and Mass Growth Dataset and Summary Statistics at MS-CDR

CDR		
Mission	**SC Cost GF**	**SC Mass GF**
COUNTOUR	105%	94%
MESSENGER	133%	113%
New Horizons	107%	119%
STEREO	124%	112%
AIM	139%	101%
AQUA	121%	105%
EO-1	137%	105%
GLAST	110%	108%
IBEX	112%	122%
LRO	120%	108%
RHESSI	147%	120%
SWAS	121%	101%
TERRA	113%	102%
TRMM	117%	109%
CLOUDSAT	136%	100%
MRO	124%	108%
SPITZER	166%	125%
Observations	**17**	**17**
Mean	**126%**	**109%**
Median	**121%**	**108%**
STDEV	**15.91%**	**8.45%**
Min	**105%**	**94%**
Max	**166%**	**125%**

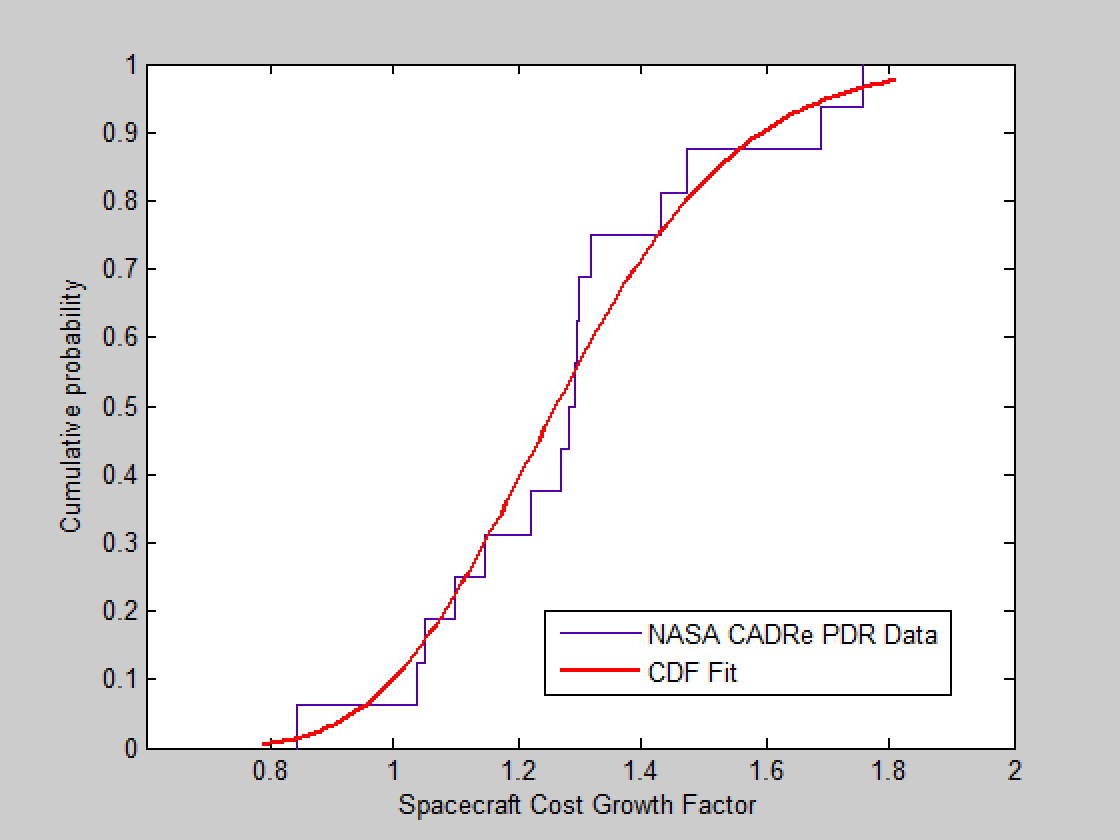
Empirical Cumulative Distribution Function of Spacecraft Cost Growth Factor

CSR	
%ile	SC Cost GF
5%	0.68
11%	0.82
21%	1.05
26%	1.07
32%	1.11
37%	1.30
42%	1.32
47%	1.37
53%	1.43
58%	1.47
63%	1.53
74%	1.54
79%	1.59
89%	1.87
95%	2.01



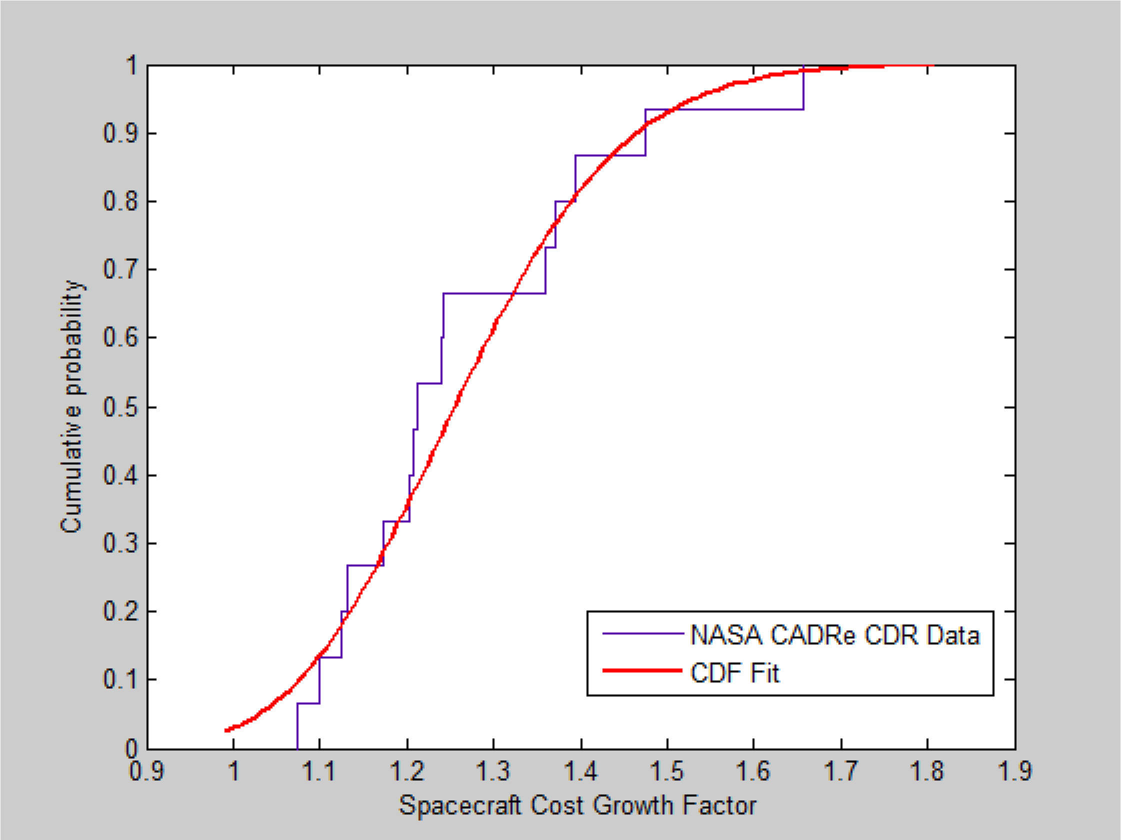
Empirical Cumulative Distribution Function of Spacecraft Cost Growth Factor

PDR	
%ile	SC Cost GF
6%	0.84
13%	1.04
19%	1.10
25%	1.15
31%	1.22
38%	1.27
44%	1.28
50%	1.29
56%	1.29
63%	1.30
69%	1.32
75%	1.35
81%	1.43
88%	1.47
94%	1.69



Empirical Cumulative Distribution Function of Spacecraft Cost Growth Factor

CDR	
%ile	SC Cost GF
6%	1.07
13%	1.10
19%	1.12
25%	1.13
31%	1.17
38%	1.20
44%	1.21
50%	1.21
56%	1.24
63%	1.24
69%	1.33
75%	1.36
81%	1.37
88%	1.39
94%	1.47



Value Added Benefits of CADRe for Projects and Research

Before CADRe:

– NASA had <u>no</u> repository of historical project programmatic, schedule, cost, and technical data.

– Programmatic history of NASA projects were not captured systematically.

– Cost Estimates were developed <u>without</u> understanding past history, so quality of cost estimates suffered.

– Cost Research efforts were limited and inconclusive without meaningful data.

– In family checks against other completed projects was difficult and not readily performed with any consistency.

– When cost data was collected, the data was not made available for other project estimating exercises.

With CADRe:

– NASA now has a generous repository of specific Cost, Technical, Schedule data to support cost estimating for future projects.

– NASA can now better evaluate future AO proposals to help determine which proposals are in family with history and better explain reasons for differences.

– Helps NASA PM record in a formal agency document key events that occurred during the project (both internal & external).

– Helps PMs understand relevant heritage and previous risk postures, and schedule durations when building their own baselines.

– CADRe allows for performing advanced cost research which was not possible previously (ie, Optimum Cost Phasing, Expl of Change, Dashboard Sheets).