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NRO Cost Group Risk Process

- **Problem: NRO Cost Group (NCG) has had problems with its Monte Carlo cost risk analysis process, e.g.,**
  - Negative risk!
  - Traceability!!
  - Inability to answer key questions!!!
- **D/NCG did not want to continue using Monte Carlo simulation in its cost risk analysis.**

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- **Questions D/NCG *really* wanted to be able to answer:**
  - How much 'risk' is in the estimate?
    - ❖ *Translation*: How many dollars are in the recommended budget to guard against 'risky' events happening?
    - ❖ And, to which WBS elements are they allocated?
  - How 'risky' is the recommended budget?
    - ❖ *Translation*: If the budget is set at the estimate (or any other value), what is the likelihood of an overrun?
  - How much 'management reserve' is in the budget?
    - ❖ *Translation*: How many dollars are in the budget for management reserve, over and above dollars expected to be needed for acquisition and risky events?
- **NCG Objective:**
  - Develop a risk process we understand, that is acceptable community-wide, that answers these questions, and that we can readily describe to senior decision-makers.

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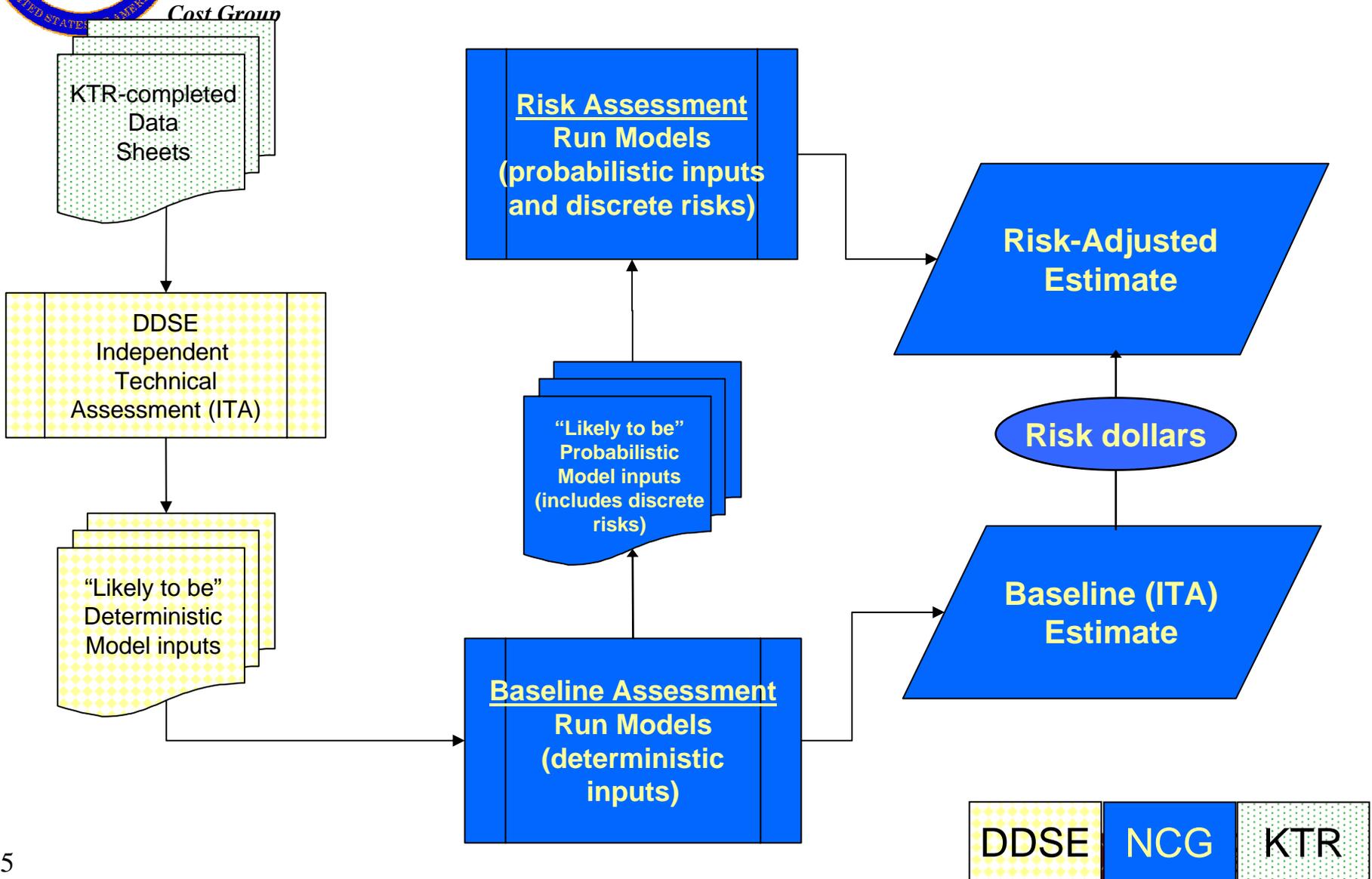
- **DDNRO requirements for ICE**
  - Provide an estimate for what the program is "likely to be" vice the program "as specified" by the SPO and contractors

- **Should include:**
  - Provision for normal problems, not "sunny day" estimates
  - Schedule growth
  - Requirements creep
  - Weight growth
  - Software code growth
  - Etc…

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National Reconnaissance Office

Risk Process Flowchart

Cost Group

KTR-completed Data Sheets

DDSE Independent Technical Assessment (ITA)

"Likely to be" Deterministic Model inputs

Risk Assessment Run Models (probabilistic inputs and discrete risks)

"Likely to be" Probabilistic Model inputs (includes discrete risks)

Baseline Assessment Run Models (deterministic inputs)

Risk-Adjusted Estimate

Risk dollars

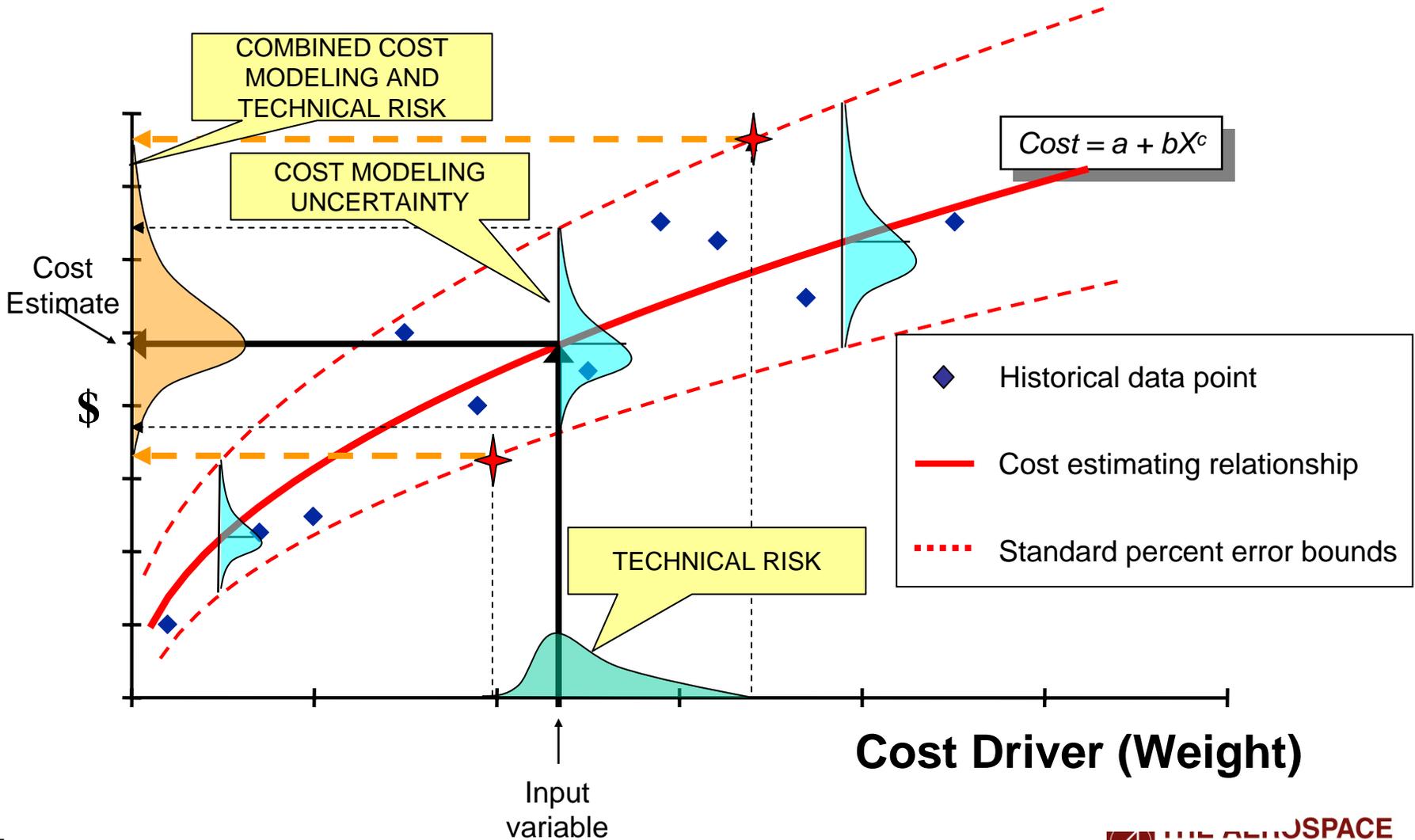**Baseline (ITA) Estimate**

DDSE | NCG | KTR

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Basic Risk Principles

- **Cost estimates usually involve many CERs**
  - Each of these CERs has uncertainty (standard error)
  - CER input variables have uncertainty (technical uncertainty)
- **Must combine CER uncertainty with technical uncertainty for many CERs in an estimate**
  - Usually cannot be done arithmetically; must use simulation to roll up costs derived from Monte Carlo samples
    - ❖ Add and multiply probability distributions rather than numbers
    - ❖ Statistically combining many uncertain, or randomly varying, numbers
  - Monte Carlo simulation
    - ❖ Take random sample from each CER and input parameter, add and multiply as necessary, then record total system cost as a single sample
    - ❖ Repeat the procedure thousands of times to develop a frequency histogram of the total system cost samples
    - ❖ This becomes the probability distribution of total system cost

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COMBINED COST MODELING AND TECHNICAL RISK

COST MODELING UNCERTAINTY

$Cost = a + bX^c$

Cost Estimate

$

Historical data point

Cost estimating relationship

Standard percent error bounds

TECHNICAL RISK

Cost Driver (Weight)

Input variable

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Probability Density Function

Lognormal Cost Distribution
Mean = $120M
Std. Dev = $35M

- 50th percentile $115M
- Mean $120M
- 80th percentile $146M
- 5th percentile $72M
- 95th percentile $184M

Y-axis: **Probability Density**

X-axis: **$M** (40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250)

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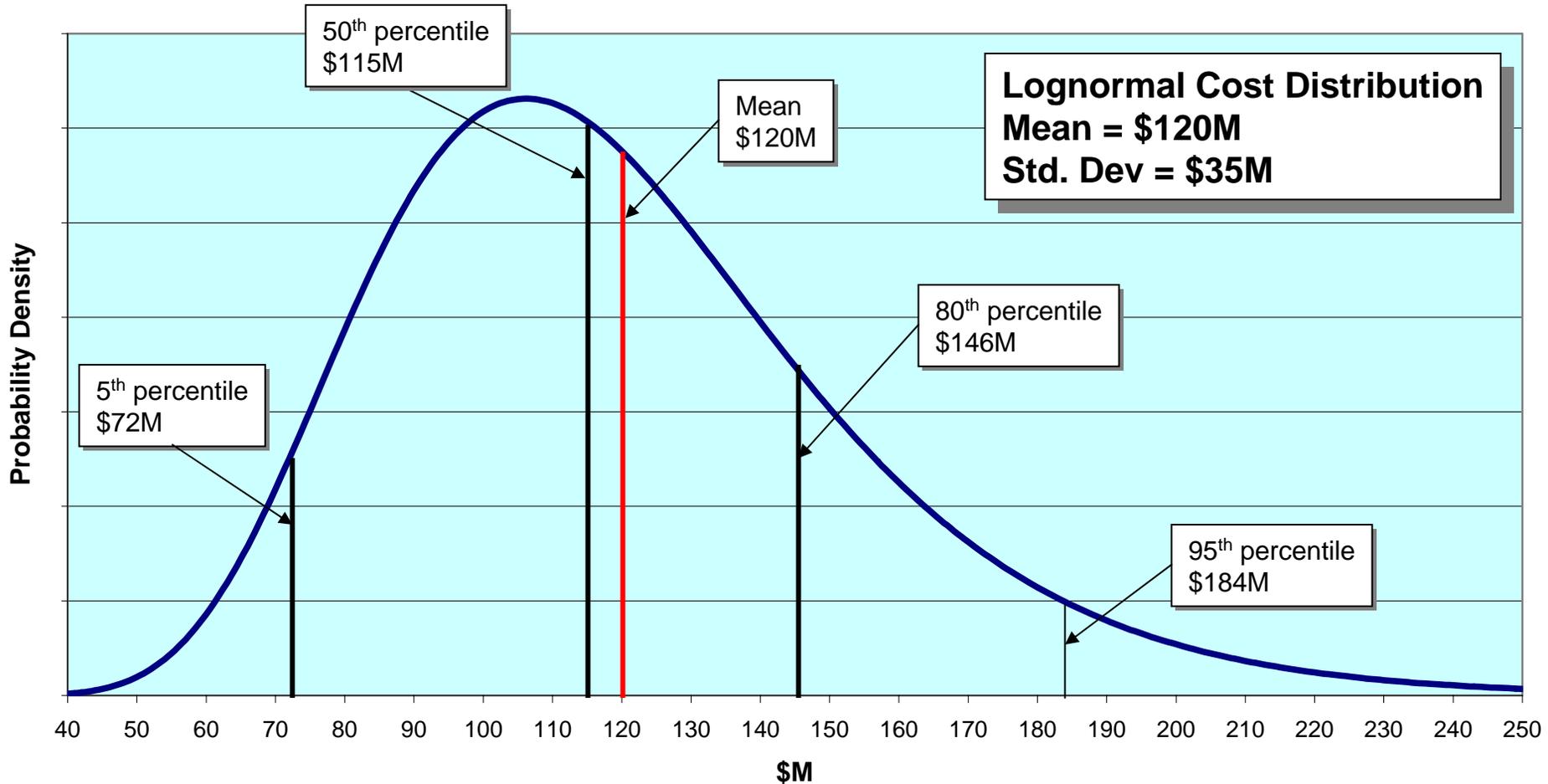
Cumulative Distribution Function (CDF), or S-Curve

Cost Group

95th percentile
$184M

80th percentile
$146M

50th percentile
$115M

Mean
$120M
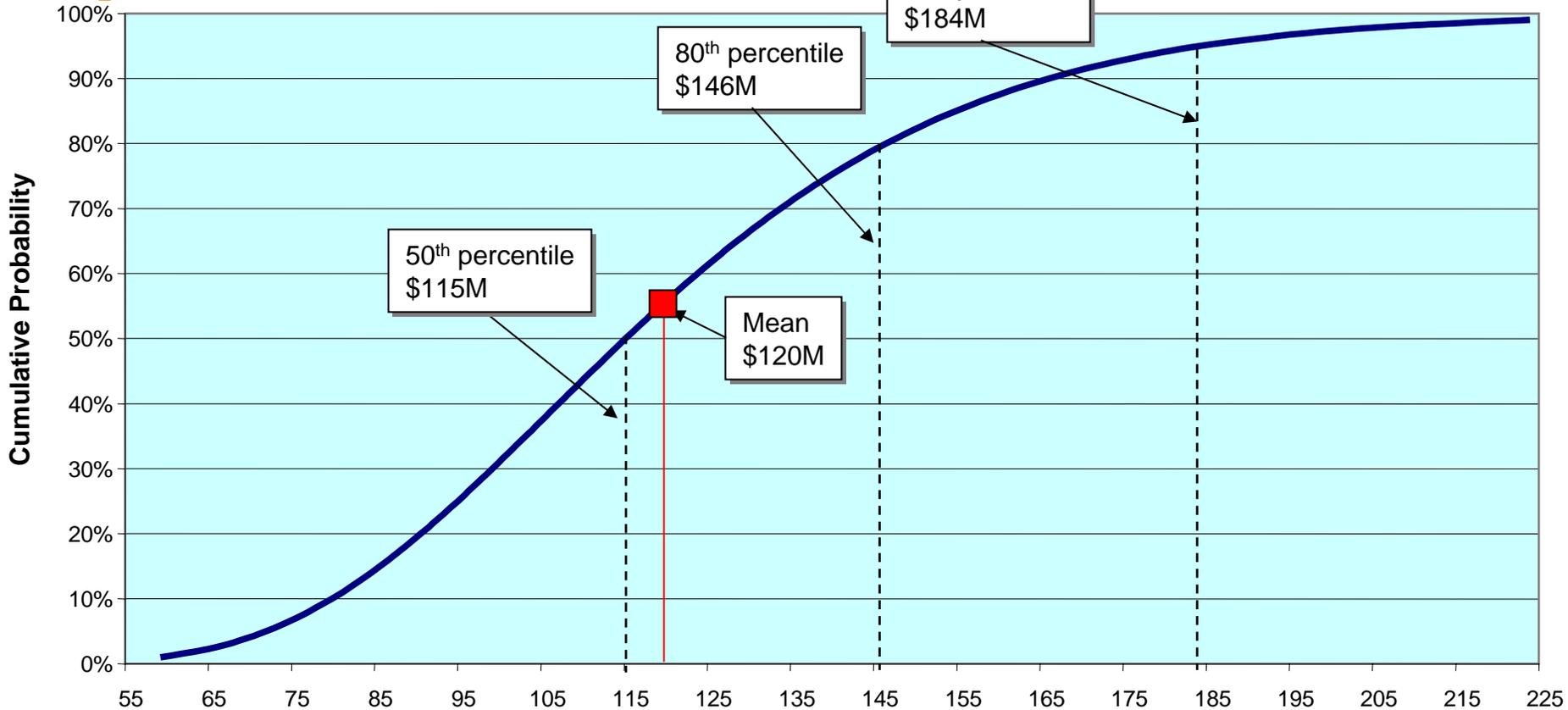
50% probability of cost coming in at or below $115M
45% probability of cost coming in between $115M and $184M
20% probability of cost exceeding $146M
5% probability of cost exceeding $184M

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The NCG Risk Process

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Basic Principles

- **Step 1: Define "likely-to-be" program.**
  - Using deterministic inputs from the Independent Technical Assessment (ITA).
- **Step 2: Quantify the probability distributions describing the modeling uncertainty of all CERs, cost factors, and other estimating methods.**
  - Specifically, the type of distribution (normal, triangular, lognormal, beta, etc.)
  - The mean and variance of the distribution
- **Step 3: Quantify the correlation between all WBS elements that are estimated using CERs and other methods.**
  - If unknown, assess whether NO correlation, MILD correlation, or HIGH correlation, for example:
    - ❖ NONE: $\rho = 0$, MILD: $\rho = \pm0.2$, HIGH: $\rho = \pm 0.6$
  - Correlation affects the overall cost variance

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- **Step 4: Set up and run the cost estimate in a Monte Carlo framework (e.g., Crystal Ball, @RISK), resulting in a "baseline" estimate.**
  - This will provide a probability distribution of the cost based on cost estimating model uncertainty only.
  - Report the MEAN as the *baseline* expected cost.

- **Step 5: Now incorporate technical uncertainty and discrete risks.**
  - Step 5a: Set up a new estimate which also contains any "discrete risk" events that are to be guarded against.
    - ❖ Quantify appropriate modeling uncertainties and correlations, as in Steps 2 and 3, for these discrete risks.
  - Step 5b: Define the probability distributions for all CER input variables.
   - ❖ Also may need to quantify correlation between CER input variables.

- **Step 6: Re-run the Monte Carlo simulation with random CER input variables and discrete risk events, resulting in a final "risk-adjusted" estimate.**
  - Results in a new *risk-adjusted* cost probability distribution.
  - Wider and shifted to the right.

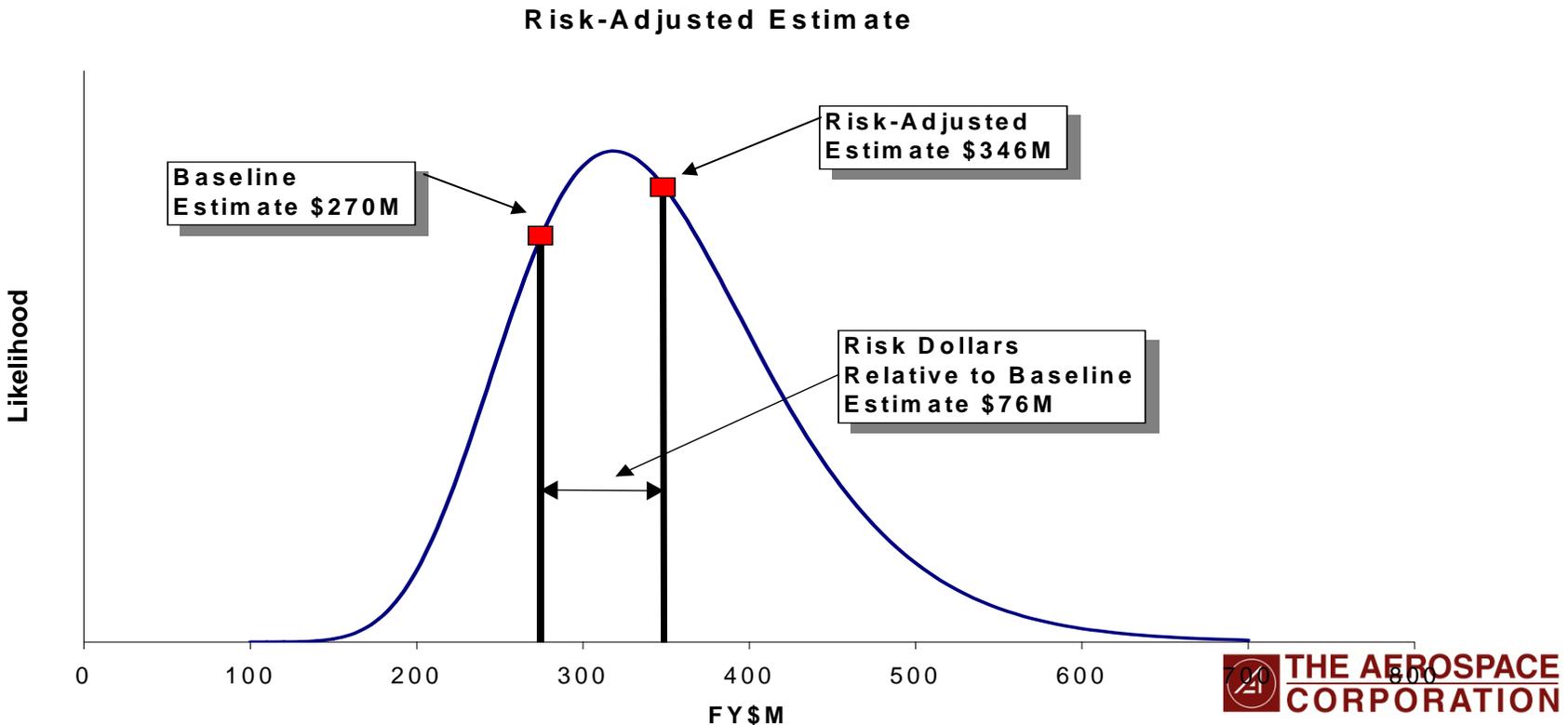**Baseline vs. Risk-Adjusted Estimates**

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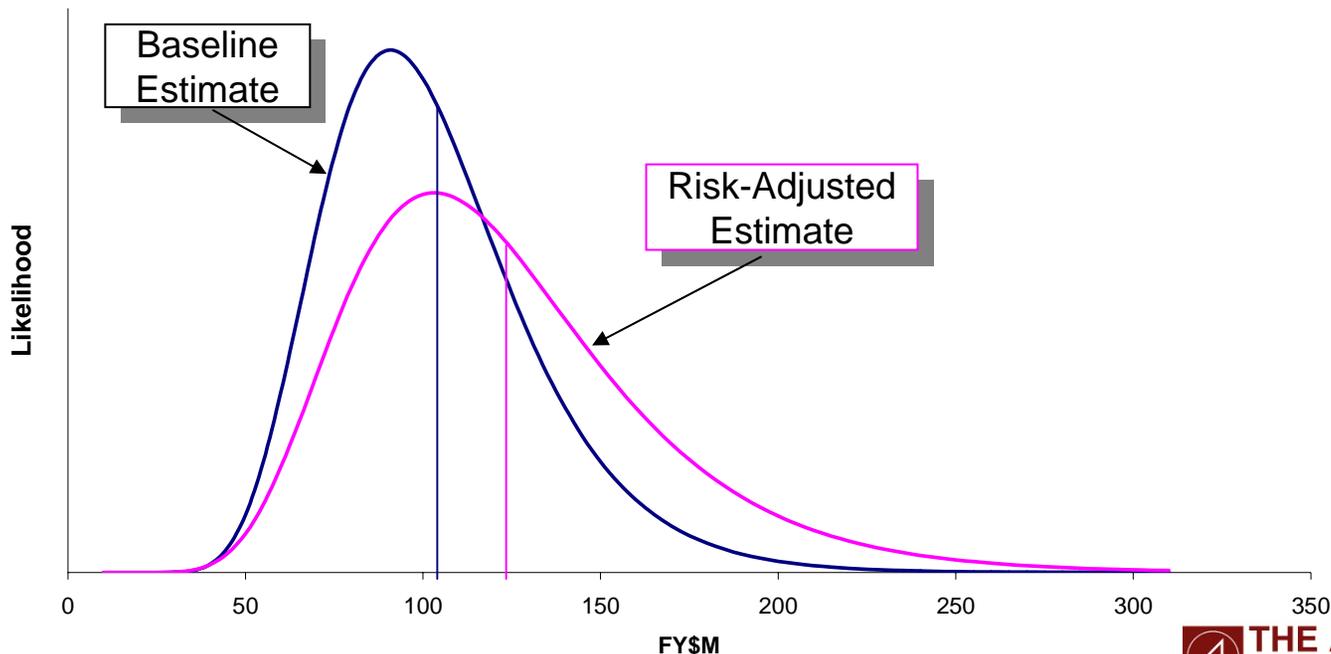
- ## Step 7: Assess "risk dollars."
  - Difference between the "risk-adjusted" *mean* and the "baseline" *mean* represents the estimate of "risk dollars."
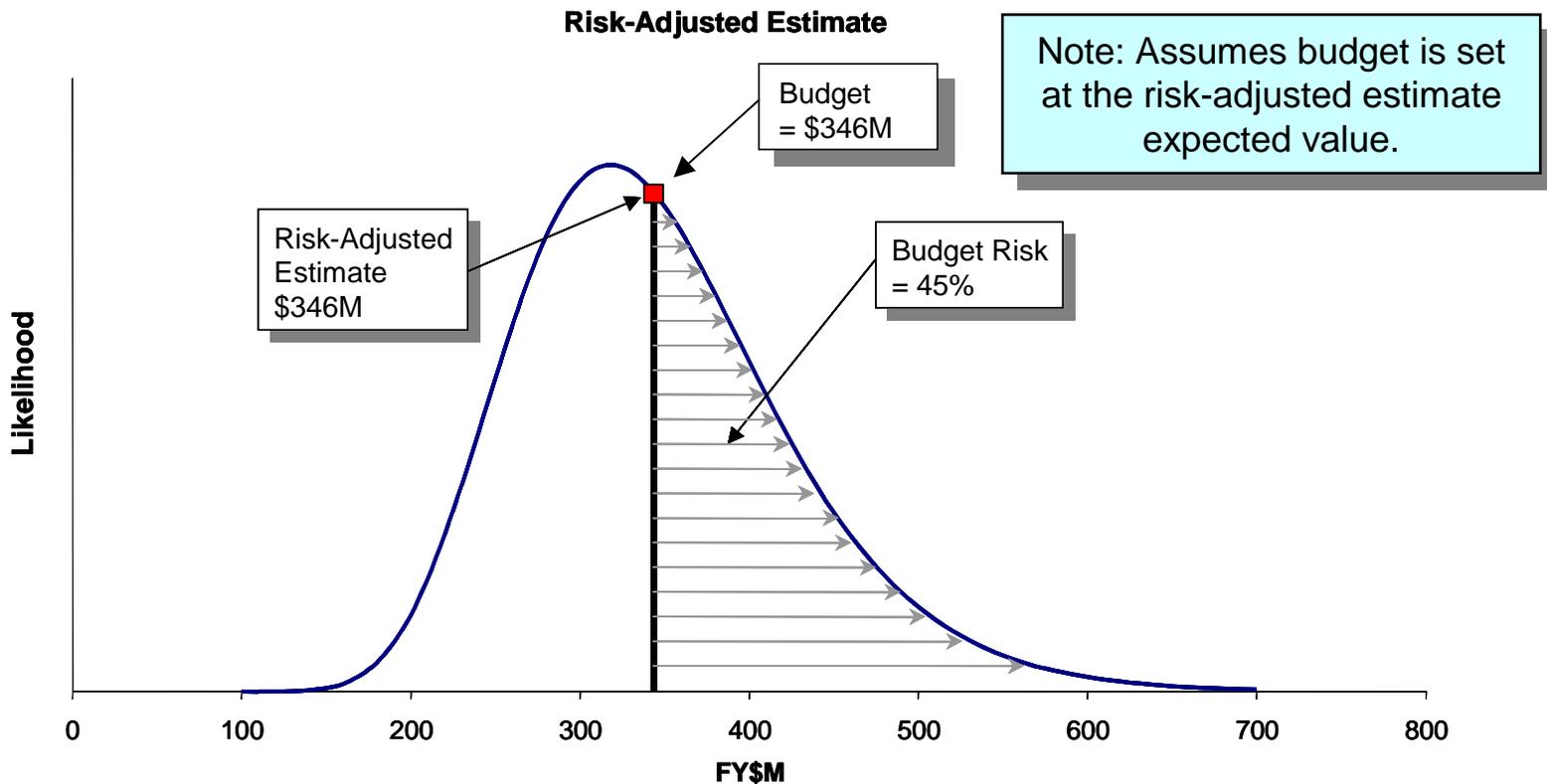 - Risk dollars can be allocated downward to any level of WBS using a variety of simple approaches.

Risk-Adjusted Estimate

Baseline Estimate $270M

Risk-Adjusted Estimate $346M

Risk Dollars Relative to Baseline Estimate $76M

Likelihood

FY$M

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Basic Principles

Cost Group

- ## Step 8: Assess "budget risk."
  - Area under the PDF to the right of the budget represents budget risk.

Risk-Adjusted Estimate

Budget = $346M

Note: Assumes budget is set at the risk-adjusted estimate expected value.

Risk-Adjusted Estimate $346M

Budget Risk = 45%

Likelihood

0   100   200   300   400   500   600   700   800
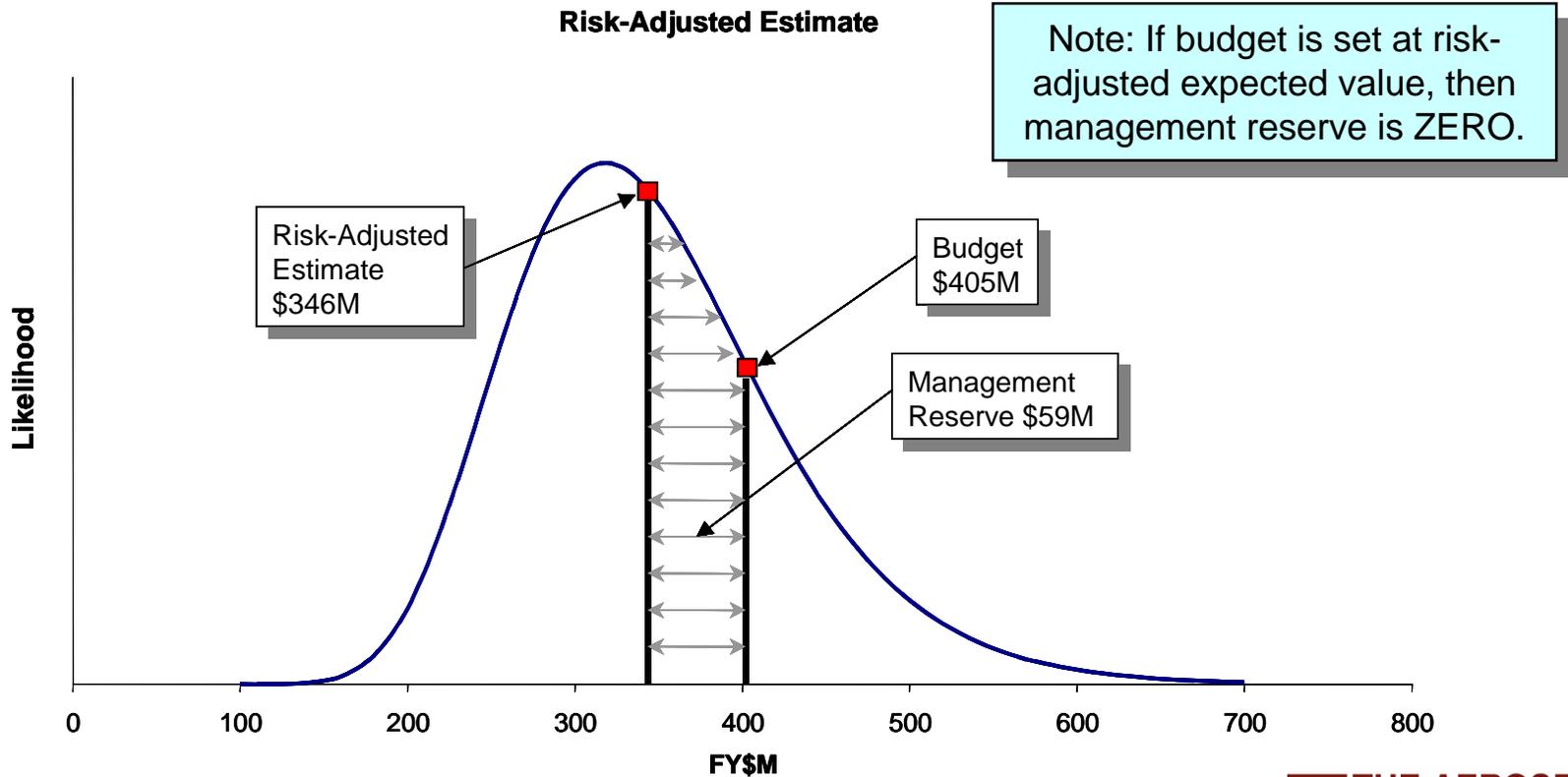
FY$M

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Basic Principles

Cost Group

- ## **Step 9: Assess "management reserve."**
  - Difference between mean of risk-adjusted estimate and budget represents management reserve.

Risk-Adjusted Estimate

Note: If budget is set at risk-adjusted expected value, then management reserve is ZERO.

Risk-Adjusted Estimate $346M

Budget $405M

Management Reserve $59M

Likelihood

0   100   200   300   400   500   600   700   800

FY$M

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- The following example demonstrates the procedure.
- First, an estimate will be produced using the deterministic "roll-up" procedure.
- Second, the "baseline" cost estimate resulting from the ITA will be developed using Monte Carlo simulation.
- Third, the "risk-adjusted" cost estimate will be developed, again using Monte Carlo simulation.

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The Deterministic Roll-Up Procedure

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- In the deterministic roll-up procedure, we simply insert the input variables into the CER equations and evaluate the result.

- In this example, we take neither CER modeling uncertainty nor input variable uncertainty into consideration.

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WBS
 1.1 Bus
 1.2 Software
 1.3 Payload
Total

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Example Space System CERs

•Bus

- – Expected Cost (FY00$) = 87,450(Bus Weight)$^{0.79}$
- – Standard Percent Error (SPE) = 34%

•Software

- – Expected Cost (FY00$) = 435,216(KSLOC)$^{0.83}$
- – SPE = 46%

•Payload

- – Expected Cost (FY00$)

  = 3,568,510(Payload aperture)$^{0.84}$(Number of prisms)$^{0.95}$
- – SPE = 25%

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- **Input variables may differ depending on who is providing them. In this case the trend is…KTR<PM<ITA.**

- **For this example, we will use the ITA (likely-to-be) inputs.**

Input Variables	KTR	PM	ITA
Bus Weight (lbs)	1000	1100	1500
Software KSLOC	100	150	250
Payload aperture (m)	1	1	1
Payload number of prisms	2	3	10

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Example Deterministic Roll-Up Cost Estimate

WBS	Mean Estimate (FY00$)		
	KTR	PM	ITA
Bus	$ 20,500,281	$ 22,103,448	$ 28,240,469
Software	$ 19,893,209	$ 27,852,270	$ 42,559,357
Payload	$ 6,893,907	$ 10,133,328	$ 31,804,379
Total	**$ 47,287,397**	**$ 60,089,047**	**$ 102,604,205**

Note the lack of any information
about cost uncertainty

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Monte Carlo Simulation of Baseline Cost Estimate

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- In the next example, we *statistically* combine the probability distributions of the CERs.

- Since the CERs in this example produce MEANs, then the mean of the total estimate is equal to the deterministic roll-up.

- However, the probability distribution of the total estimate reflects the uncertainty due only to cost modeling uncertainty.
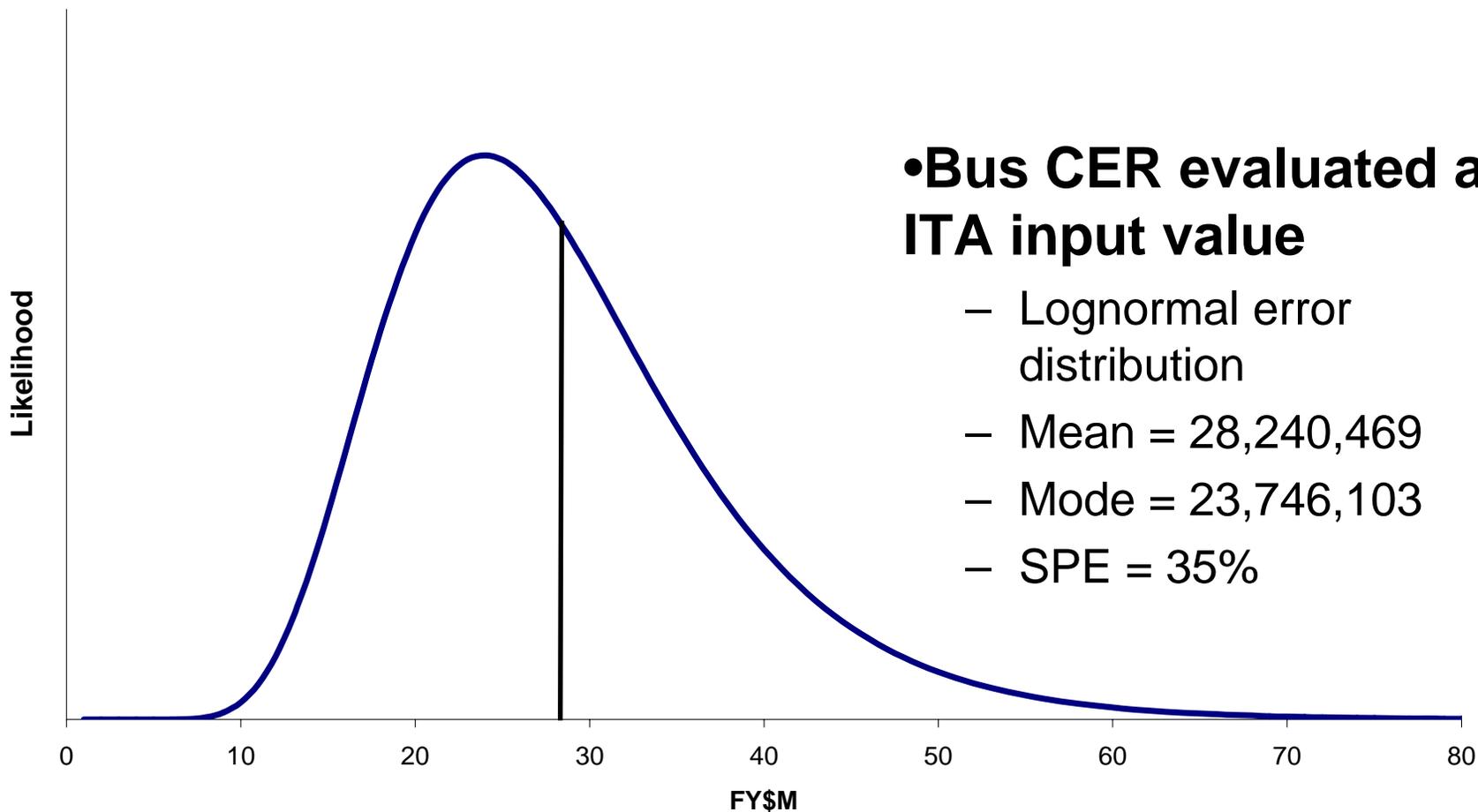
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Input Variables	ITA
Bus Weight (lbs)	1500
Software KSLOC	250
Payload aperture (m)	1
Payload number of prisms	10

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Example CER Uncertainties

- **Bus CER evaluated at ITA input value**
  - Lognormal error distribution
  - Mean = 28,240,469
  - Mode = 23,746,103
  - SPE = 35%

Example CER Uncertainties

- **Software CER evaluated at ITA input value**
  - Lognormal error distribution
  - Mean = 42,559,357
  - Mode = 31,912,155
  - SPE = 46%

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Example CER Uncertainties

Cost Group

- **Payload CER evaluated at ITA input value**
  - Lognormal error distribution
  - Mean = 31,804,379
  - Mode = 29,039,790
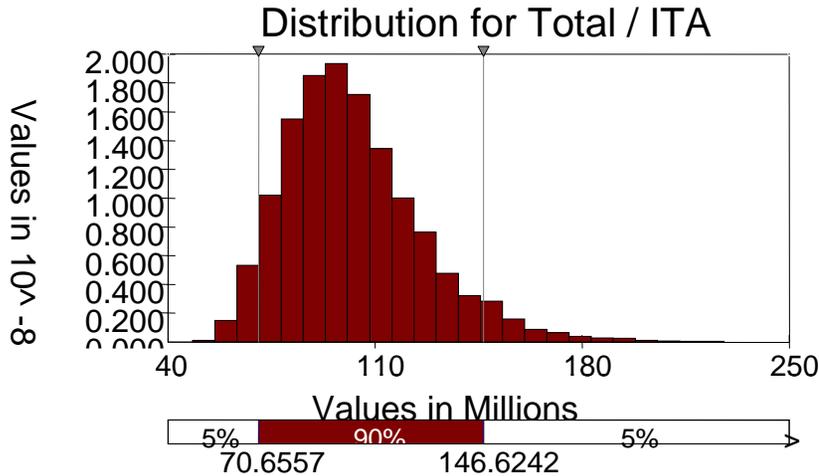 - SPE = 25%

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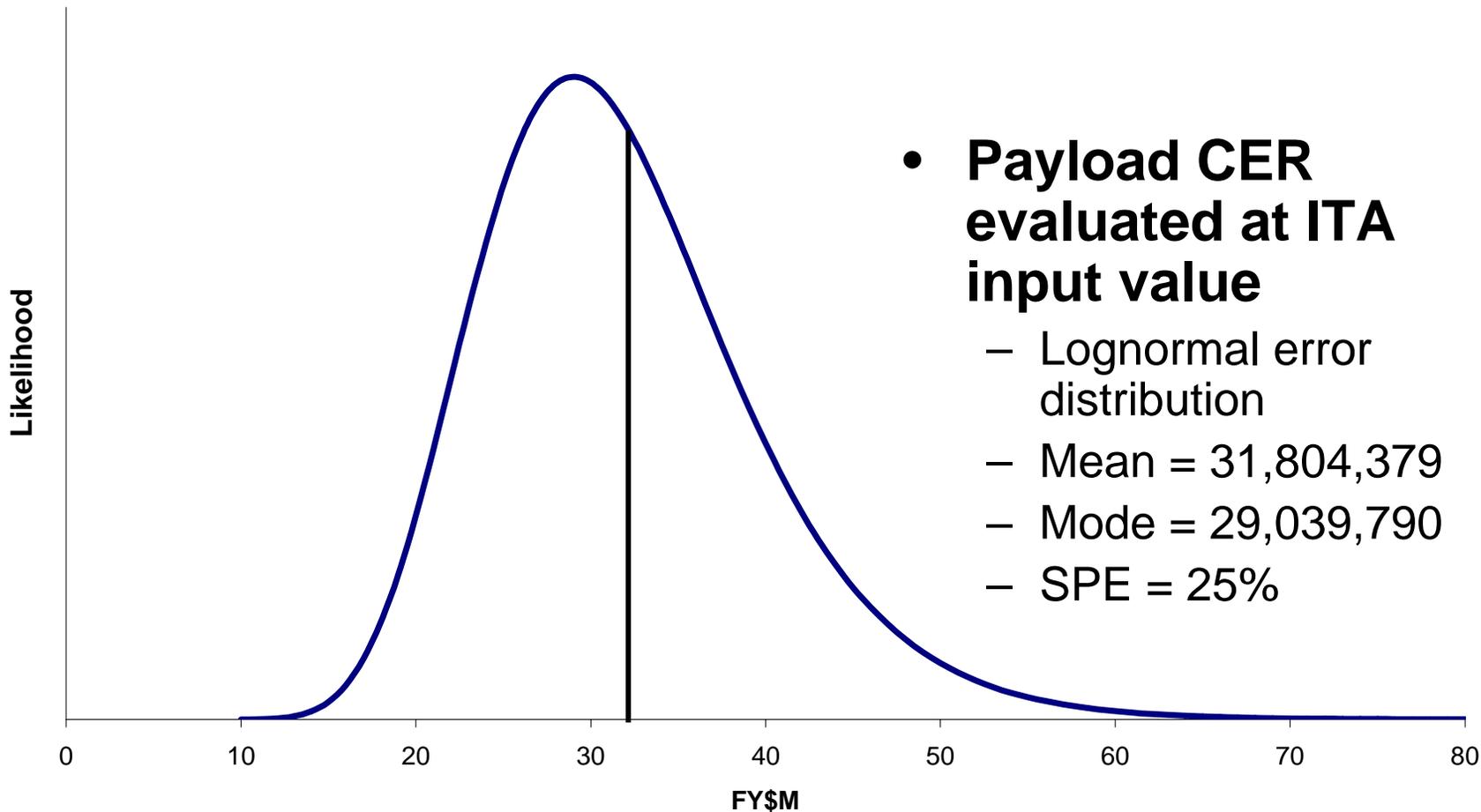
- **Correlation between WBS elements estimated using CERs must be quantified in order to properly assess the total cost distribution.**

CER Correlations	Bus	Software	Payload
Bus	1.00	0.40	0.60
Software		1.00	0.40
Payload			1.00

Example Space System Baseline Cost Estimate
(Based on ITA)
Cost Group

Distribution for Total / ITA

Values in 10^-8

Values in Millions

5% | 90% | 5%
70.6557 — 146.6242

Distribution for Total / ITA

Values in Millions

5% | 90% | 5%
61.6001 — 157.4489

Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 37,005,204	5%	$ 61,600,060
Maximum	$ 260,807,568	10%	$ 68,869,344
Mean	$ 102,601,197	15%	$ 73,239,408
Std Dev	$ 29,781,151	20%	$ 77,270,168
Variance	8.86917E+14	25%	$ 80,880,104
Skewness	0.891075203	30%	$ 84,569,976
Kurtosis	4.306213614	35%	$ 87,982,064
Median	$ 98,602,912	40%	$ 91,568,056
Mode	$ 124,873,288	45%	$ 95,080,008
		50%	$ 98,602,912
		55%	$ 102,403,448
		60%	$ 106,082,536
		65%	$ 109,934,520
		70%	$ 114,261,336
		75%	$ 119,015,656
		80%	$ 125,274,904
		85%	$ 132,768,368
		90%	$ 142,145,376
		95%	$ 157,448,896
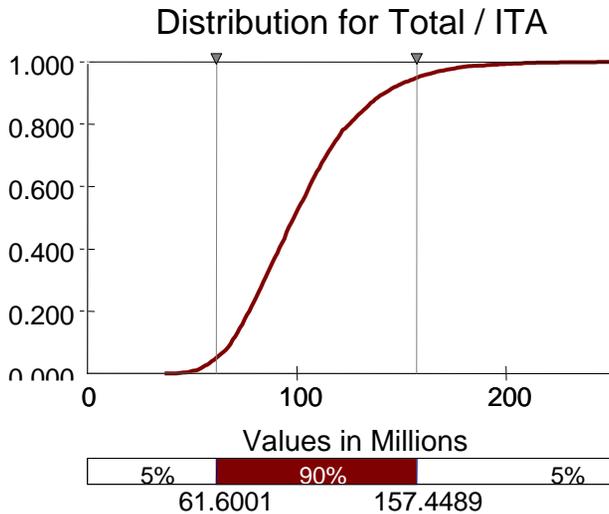
- The Baseline cost estimate reflects CER modeling uncertainty only. CER inputs are "most likely" values based on ITA.
- This is the estimate for a program that has only "normal" risk.
- The "expected value" or MEAN is $102.6M, and the standard deviation is $29.8M.

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Monte Carlo Simulation of Risk-Adjusted Cost Estimate

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Risk-Adjusted Cost Estimate

- In the risk-adjusted cost estimate, we now combine discrete risk events and the uncertainty of the input distributions with the uncertainty of the CERs.

- Since the input distributions tend to be right-skewed, the expected cost tends to be larger than the baseline estimate.

- In addition, the risk-adjusted cost distribution tends to be wider than the baseline estimate.

- The difference between the expected cost of the risk-adjusted estimate and the expected cost of the baseline estimate is, by definition, the amount of *RISK dollars* included in the risk-adjusted estimate.

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- Following an assessment of the bus weight, it is determined that bus weight may be modeled with a Beta distribution whose 10th percentile is 1300 lbs, most likely value is 1500 lbs, and 90th percentile is 2500 lbs.
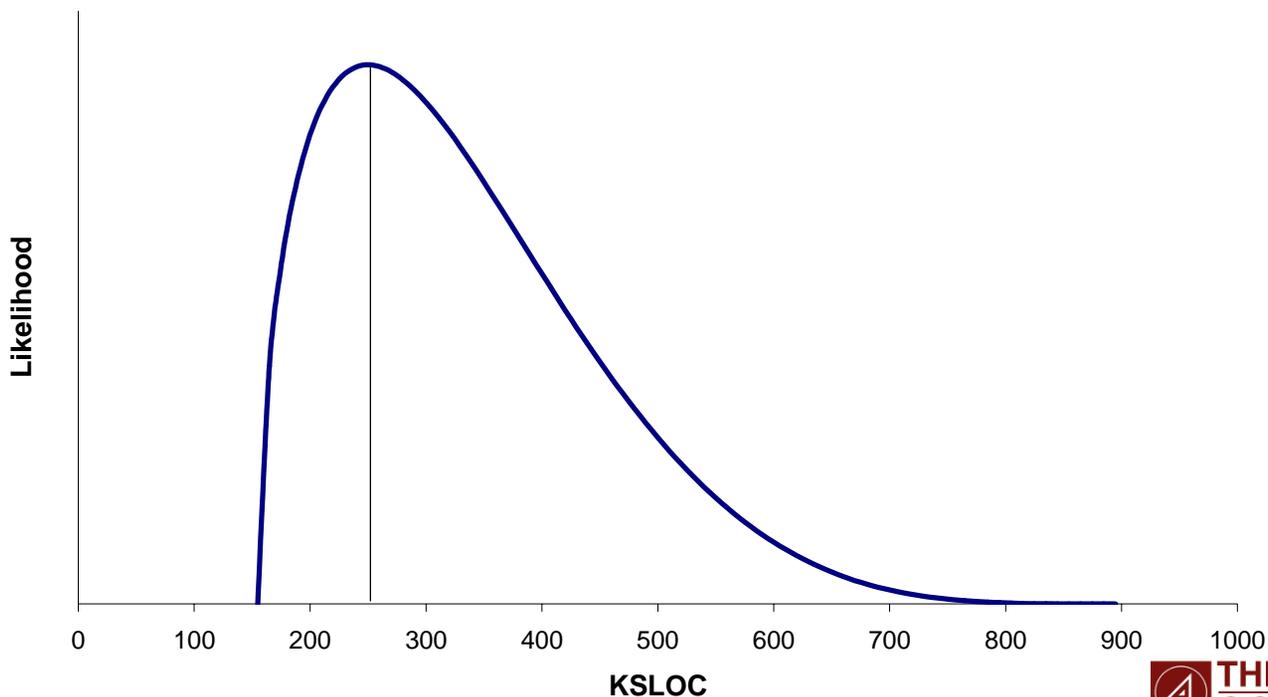
- Similarly, it is determined that KSLOC may be modeled with a Beta distribution whose 10th percentile is 200 KSLOC, most likely value is 250 KSLOC, and 90th percentile is 500 KSLOC.
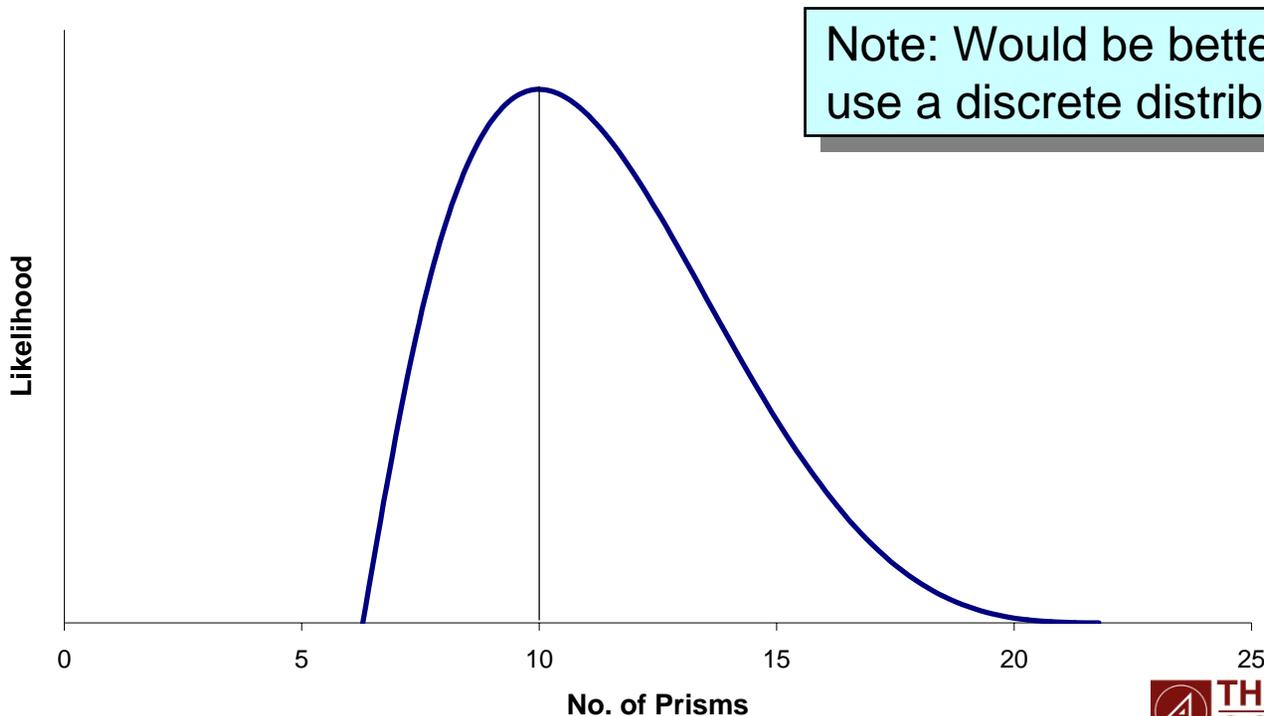
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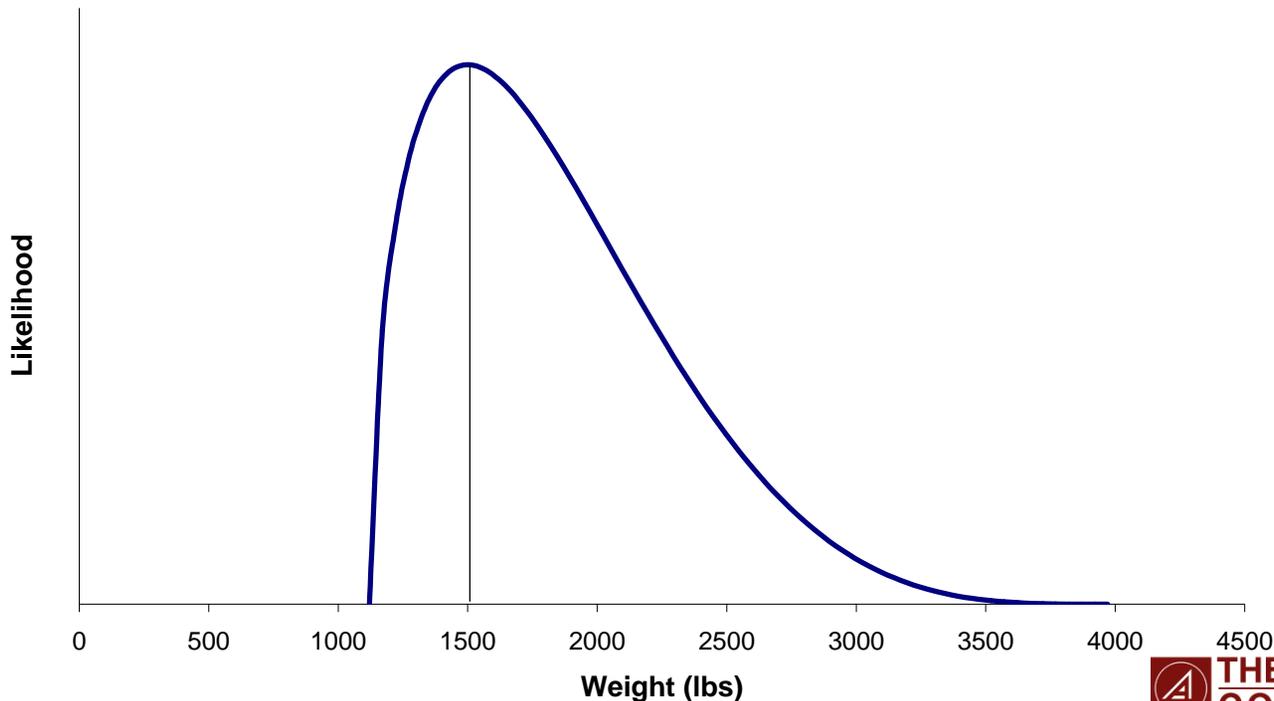
Example Risk-Adjusted Prism Input Assumptions

Cost Group

- Likewise, it is determined that the number of prisms may be modeled with a Beta distribution whose 10th percentile is 8 prisms, most likely value is 10 prisms, and 90th percentile is 15 prisms.

Note: Would be better to use a discrete distribution.

Likelihood

No. of Prisms

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Example Input Correlation Coefficients

- Correlation between CER input variables must also be quantified in order to properly assess the total cost distribution.

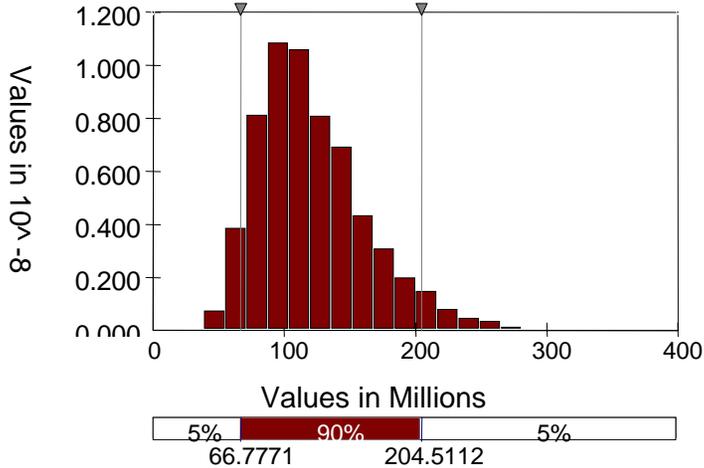| Input Correlations	Bus Wt	KSLOC	Prisms
Bus Wt	1.00	0.20	0.20
KSLOC		1.00	0.20
Prisms			1.00

Example Risk-Adjusted Cost Estimate

Cost Group

Distribution for Total / Risk-Adj

Values in 10^-8

Values in Millions

5%	90%	5%
66.7771		204.5112

Distribution for Total / Risk-Ad

Values in Millions

5%	90%	5%
66.7771		204.5112
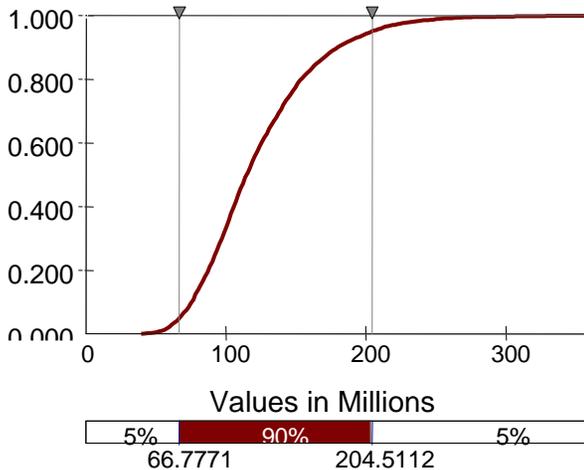
Summary Statistics			
Statistic	**Value**	**%tile**	**Value**
Minimum	$ 39,292,000	5%	$ 66,777,080
Maximum	$ 378,416,512	10%	$ 75,468,920
Mean	$ 122,612,321	15%	$ 81,322,864
Std Dev	$ 42,826,304	20%	$ 87,264,360
Variance	1.83409E+15	25%	$ 92,348,656
Skewness	1.108478562	30%	$ 96,908,376
Kurtosis	5.066359855	35%	$ 101,319,544
Median	$ 114,693,208	40%	$ 105,615,768
Mode	$ 110,262,928	45%	$ 110,020,008
		50%	$ 114,693,208
		55%	$ 119,863,880
		60%	$ 125,394,872
		65%	$ 131,426,760
		70%	$ 138,357,552
		75%	$ 145,406,560
		80%	$ 153,461,696
		85%	$ 164,604,624
		90%	$ 179,641,392
		95%	$ 204,511,232

- **The risk-adjusted cost estimate contains both CER modeling uncertainty and technical uncertainty.**
- **The "expected value" or MEAN is $122.6M, and the standard deviation is $42.8M.**
- **The difference between the expected value of this estimate and the baseline estimate is $20M.**
- **Therefore, this estimate contains $20M "risk dollars."**

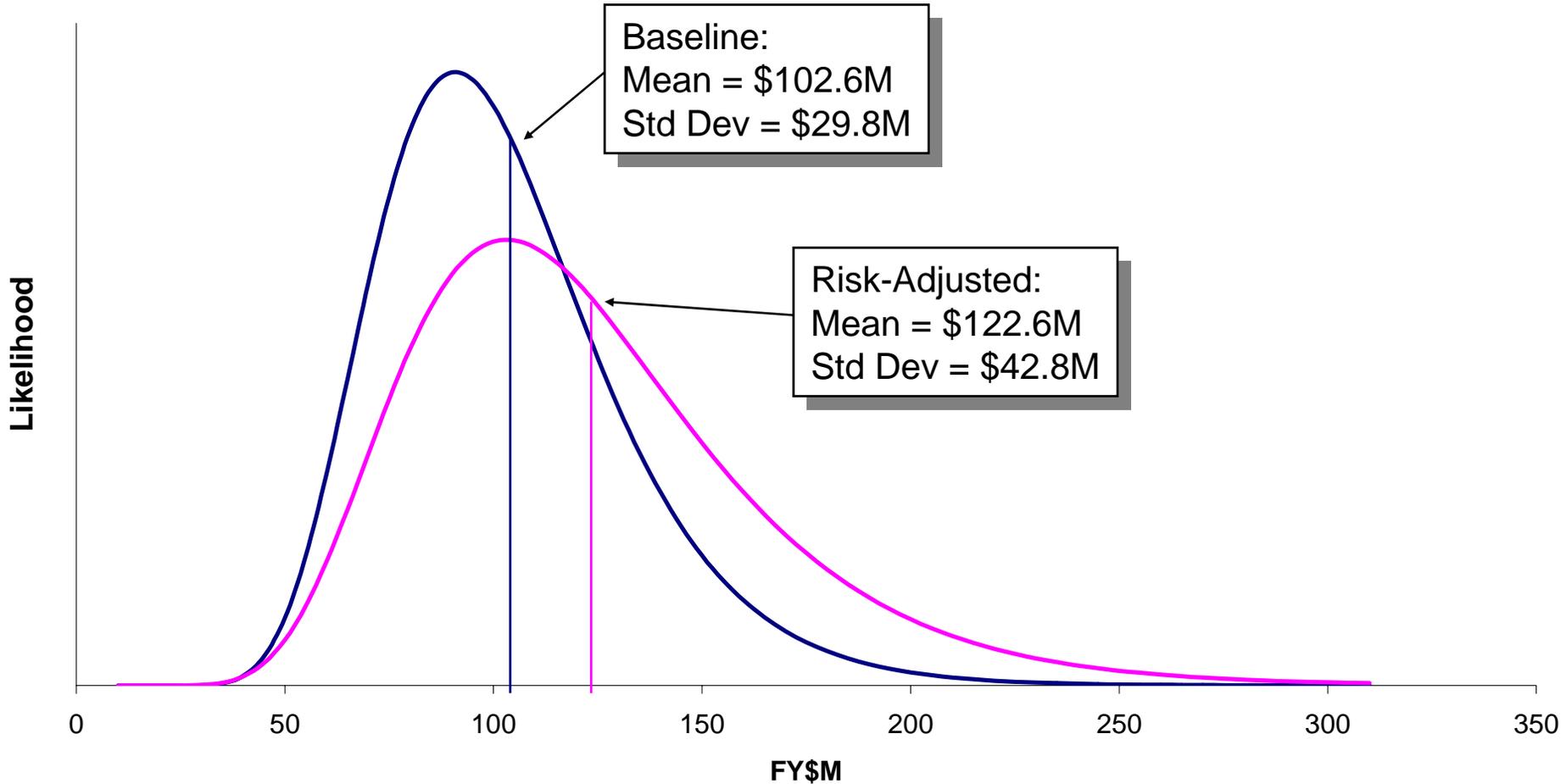**THE AEROSPACE CORPORATION**

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Example Risk-Adjusted Cost Estimate

- **The expected value of the risk-adjusted cost estimate ($122.6M) is $20M higher than the expected value of the baseline cost estimate ($102.6M).**

- **The interpretation is that the risk-adjusted cost estimate contains $20M risk dollars.**

- **Additionally, the $20M can be allocated into each WBS element by subtracting corresponding means as follows:**
  - Bus: $6.6M risk dollars
  - Software: $10.0M risk dollars
  - Payload: $3.4M risk dollars

- **Moreover, the standard deviation of the risk-adjusted estimate is about $43M while the baseline ITA estimate has a standard deviation of about $30M, indicating that the risk-adjusted cost estimate has a wider distribution.**

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Baseline vs. Risk-Adjusted Estimates

Baseline:
Mean = $102.6M
Std Dev = $29.8M

Risk-Adjusted:
Mean = $122.6M
Std Dev = $42.8M

Likelihood

FY$M

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The "S-Curve"

Cost Group

Cumulative Distribution Function

50th percentile $114.7M

Baseline Estimate Mean $102.6M

Risk-adjusted Estimate Mean $122.6M

80th percentile $153.5M

Cumulative Probability

FY00$M

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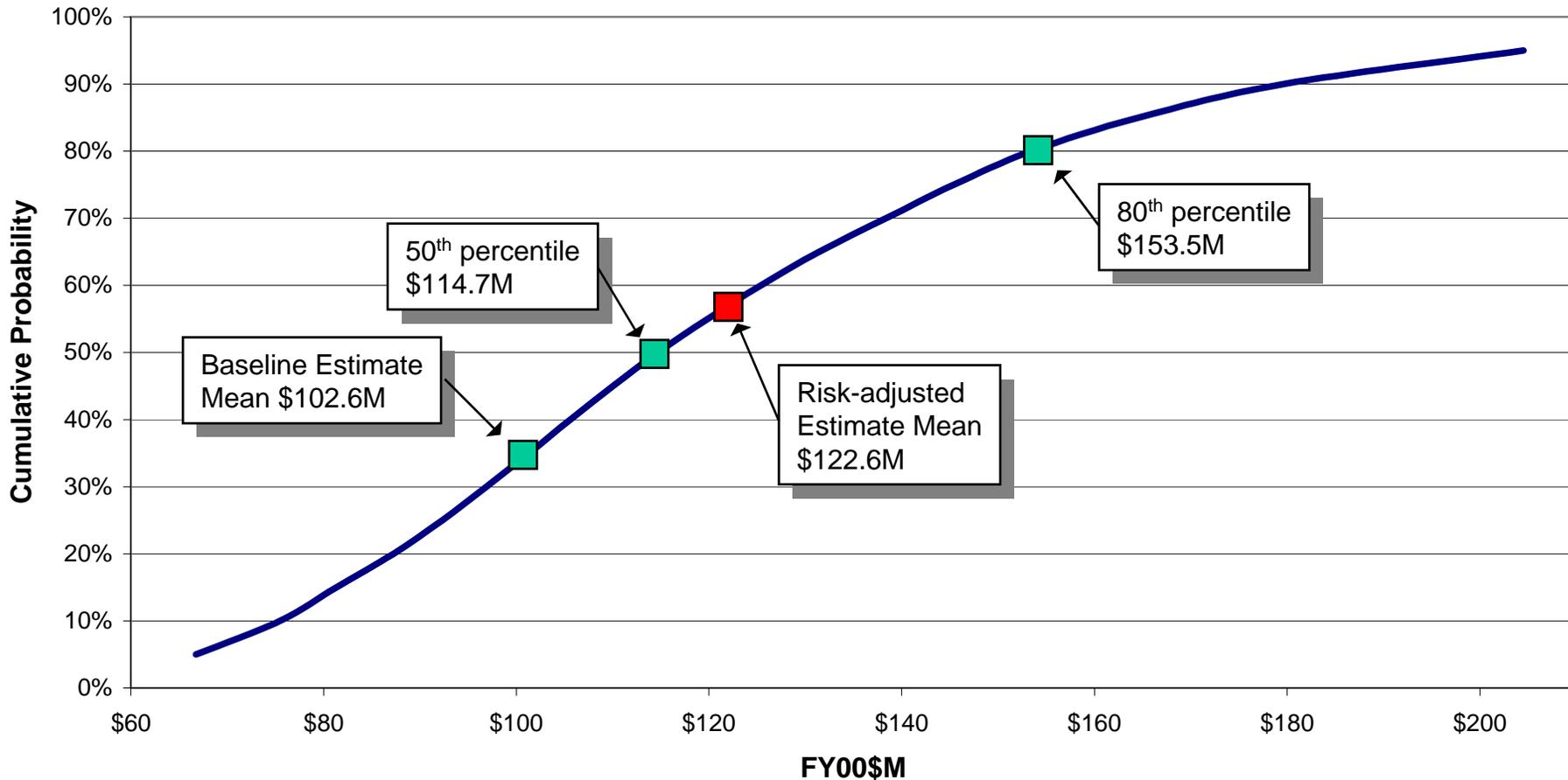
- **This is impossible to answer precisely.**
- **Decision-makers and cost analysts should always think of a cost estimate as a *probability distribution*, NOT as a *deterministic number*.**
- **The best we can provide is the *probability distribution* – If we think we can be any more precise, we're fooling ourselves.**
- ***It is up to the decision-maker to decide where he/she wants to set the budget.***
- **The probability distribution provides a quantitative basis for making this determination.**
  - Low budget = high probability of overrun
  - High budget = low probability of overrun

A Possible Narrative

Cost Group

- ***Decision-Maker:*** "So, what's your estimate, and how many 'risk dollars' are in it?"

- ***Estimator:*** "Sir, our *mean* estimate is $122.6M. It is located at the 57.5th percentile of our bottom line cost risk probability distribution, and contains $20M 'risk dollars' dedicated specifically for risk events over and above 'normal' estimating uncertainty. Moreover, we've allocated that $20M risk dollars downward to the major WBS elements. $6.6M is earmarked for bus weight growth, $10M is apportioned for software code growth, and $3.4M is allocated for risk in the number of prisms needed. But really, sir, the decision is up to you. You've seen the cost probability distribution, where would *you* like to set the budget?"

- ***Decision-Maker:*** "Great job! You deserve a raise! Let's be prudent and set our budget at, say, the 65th percentile of your estimate."

- ***Estimator:*** "Good thinking, sir. Let's see…the 65th percentile is $131.4M, therefore, in addition to $20M risk dollars, you'll have an additional $8.8M of *management reserve* in the budget, *and* you'll only have a 35% chance of a budget overrun."

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Potential Risk Variables

Cost Group

Space

Weight and Weight Growth

Quantities (eng/qual/refurb units, spares)

% Unique, % New

% Subcontract

Pixels, aperture diameter, wafer size

Wavelength, operating temp

Chip yield, ROIC redesign

Power consumed (electronics)

TWTA power, efficiency

Frequency, gain

Design life

Design Difficulty Rating

Manufacturing and Test Difficulty

Cost Improvement Percentage

Labor Rates

SEIT/PM Factors

Percent New/Reuse/Mod SLOC

S/W Team Experience and Capability

Ground

Hardware Quantities

Throughput capacity, requirements

Storage capacity, requirements

Software Productivity

S/W Development Tools

Programming Language

Software Requirements Volatility

Code Security Requirements

S/W Team Organizational Structure

Communication Interfaces

Memory Constraints

CPU Time Constraints

Real Time Code amount

Reliability

Required Level of Reusability

Application Complexity

Operating System

Team Experience

Software Requirements Volatility

Software Interface Complexity

COTS Hardware Price Distribution

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•Negative risk?

– It COULD happen! But, using this methodology, "negative risk," that is, occasions when the "risk-adjusted" estimate is less than the "baseline" estimate, will only occur when favorable outcomes are more likely than unfavorable outcomes.

•Traceability?

– Risk dollars can be traced to the CER input distributions.

•Inability to answer key questions?

– This methodology enables NCG to *quantify* and *explain*:
  - ❖ Risk dollars
  - ❖ Budget risk
  - ❖ Management reserve

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- **Definitions associated with cost risk.**
- **Basic risk principles.**
- **The NCG Risk Process.**
- **Example.**
- **Risk dollars.**
- **Budget risk.**
- **Management reserve.**
- **A possible narrative.**
- **Potential risk variables.**
- **Implementation issues.**
- **Conclusions**

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