Presented at the 2012 SCEA/ISPA Joint Annual Conference and Training Workshop - www.iceaaonline.com

TECOLOTE RESEARCH, INC.
Bridging Engineering and Economics
Since 1973

Real Data, Real Uncertainty

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27 June 2012

Approved for Public Release

Outline

- CRUAMM Purpose
- CRUAMM Process
- Illustrative Result
- CRUAMM Final Report

The Purpose of CRUAMM

- **If you are provided a method without uncertainty information, rather than guess or using one of the AFCAA CRUH defaults, locate the method and its input in CRUAMM for a representative uncertainty distribution**
- **You can also use CRUAMM to cross check the uncertainty you derive from your data or your other sources**
- **CRUAMM does not supplant existing best practices**
  - If you have the data to build a CER, use it to develop the prediction interval for use in your model
  - If you are provided a CER complete with uncertainty information, use them in your model

Expressing Uncertainty

Given:

Cost Element $_{\text{Point Estimate}}$ = Your Methodology

Its uncertainty can then be expressed:

Cost Element $_{\text{Uncertainty}}$ = *f*(Your Methodology, Distribution Shape, Distribution Parameters)

With CRUAMM, its uncertainty can then be expressed:

Cost Element $_{\text{Uncertainty}}$ = Your Methodology * Unitized Distribution

Orders of Dispersion

- **First Order**
  - Amount of spread in a single parameter of a dataset
  - Example: cost elements, cost drivers
- **Second Order**
  - Amount of spread in a factor relationship
  - Example: Non Recurring as a factor of T1
- **Third Order**
  - Amount of spread in a the error term of a best fit equation
  - Example: Confidence interval of a CER derived from regression

CRUAMM

- **Fourth Order**
  - Prediction interval from a statistically derived CER
  - Example: CER prediction interval for a given independent variable

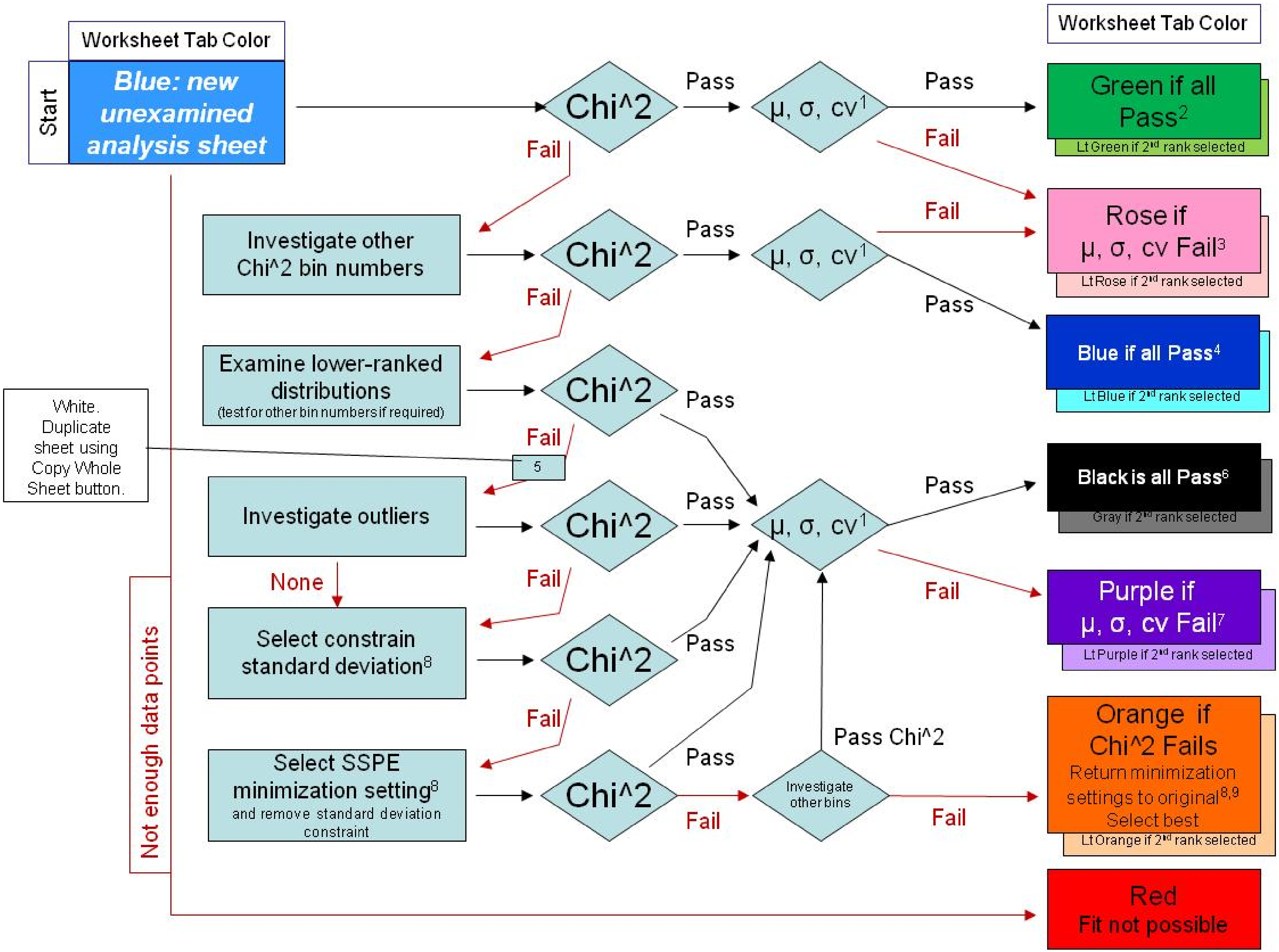
Distribution Fit Process

- **Collect and normalize the data**
  - Sort sample data in ascending order
  - Assign a cumulative percentile using the NIST[1] formula (different than Excel) but apply a “correction for continuity” [2] (0.5*ObsFreq+NumObsBelow)/ObsCount
  - Use the sample descriptive statistics to provide a starting point for fit parameters
- **Assess the difference between the sample and fit using either:**
  - Sum squared error (SSE) - highly influenced by very large sample points (as compared to mean)
  - Sum squared percent error (SSPE) - highly influenced by fitted points close to zero (divide by zero)
- **Use *Excel Solver or ACEIT CO$TAT to find the fit parameters that minimize SSE or SSPE**
  - Set optional constraints such as: Low>0, Low<LowestSamplePoint, High>HighestSamplePoint
- **Rank the fits using standard error of the estimate (SEE) or standard percent error (SPE)**
  - This is a preferred method to rank the fits (rather than SSE or SSPE directly) because it accounts for the degrees of freedom
  - Accounts for number of parameters required to uniquely define a distribution
    - 2 for Normal, lognormal , 3 for Triangular, 4 for Beta
  - Many tools do not account for the number of parameters as they are designed to address fits on hundreds or thousands of data points. The difference between 1000, 997 and 995 degrees of freedom (on 1000 data points) has no impact on SEE but for 10 data points, the difference between 10, 7 and 5 degrees of freedom can be dramatic.
- **Use a Goodness-of-Fit test (Chi^2) to determine significance of the fit**
  - Minimum SSE or SSPE alone does not necessarily mean the fit is meaningful
  - Other tests (K-S, AD) cannot be applied to every distribution. Only Chi^2 provides a p-value for any distribution

1. NIST= National Institute of Standards and Technology

2. From “Reliability and Information Functions for Percentile Ranks” Kim May and W. Alan Nicewander, Journal of Educational Measurement, Vol. 31, No. 4 (Winter, 1994), pp. 313-325

CRUAMM Results are Based on a Consistent Process for Evaluating Distribution Fits



Illustrative Results for One Subsystem

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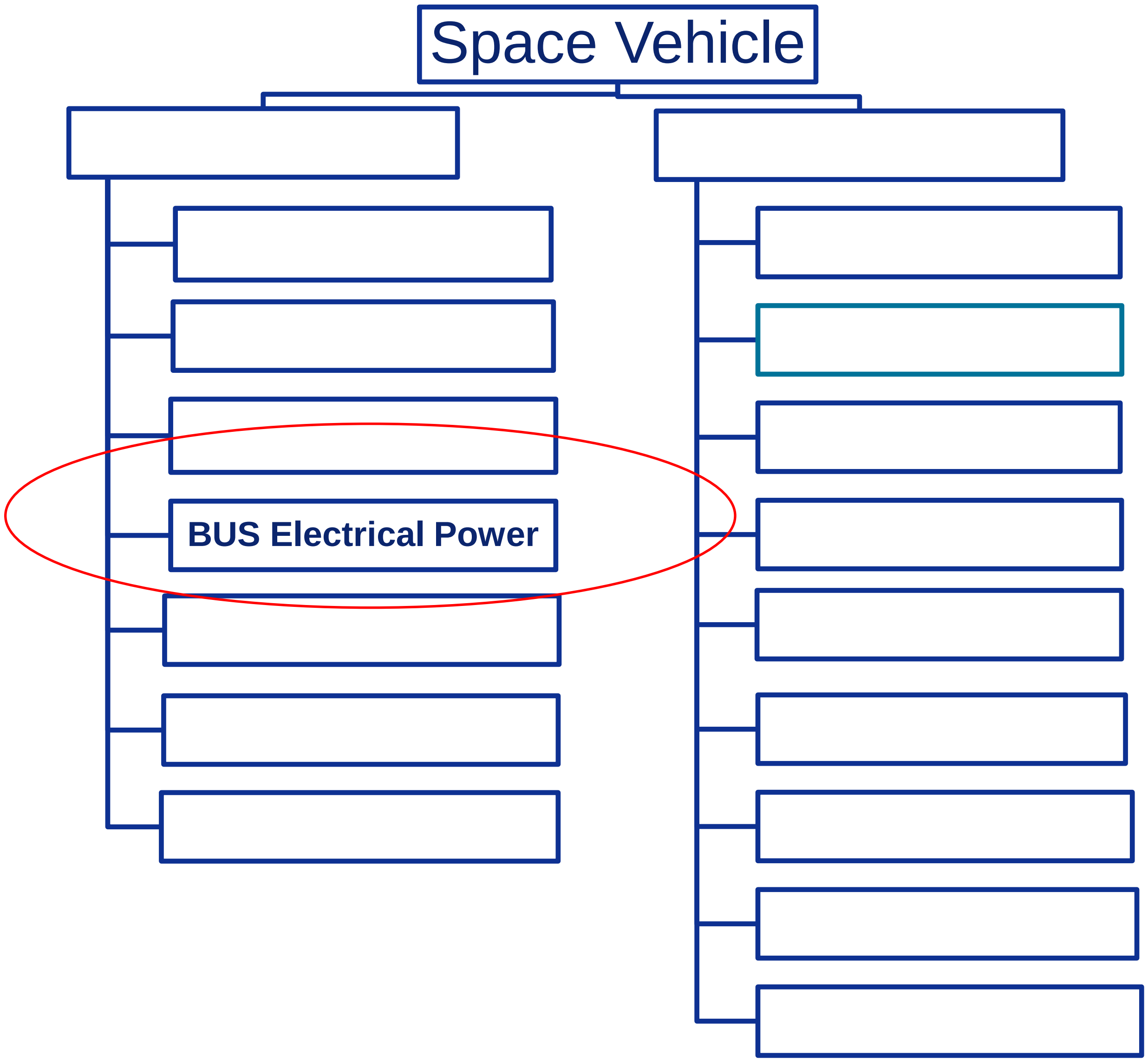
Space Vehicle
BUS Electrical Power

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Analyst Wants to Use the FireSat CER for EPS, but needs Uncertainty Guidance

- **Use CRUAMM to identify representative uncertainty for:**
  - the Electrical Power Subsystem CER
  - the EPS CER independent variable (EPS Weight)

WBS Description	Unique ID	CER	Point Estimate	Forecast (PE * Uncert)	Distribution	Uncertainty	Min	Max or Std Dev
Satellite			$298,647	$298,647		Mean or Mode		
Payload	RDPayload		$168,462	$168,462				
IR Sensor		356851 * PayloadDiam^0.562	$168,462	$168,462	Triangular	1	0.071	**1.9640**
Spacecraft Bus	RDSpBus		$15,096	$15,096				
Structure		157 * StrWgt^0.83	$2,787	$2,787	Triangular	1	0	1.9528
Thermal		394 * ThermWgt^0.635	$1,331	$1,331	Triangular	1	0	1.9528
Electrical Power System (EPS)		62.7 * EPSWgt	$2,865	$2,865		1		
Telemetry Tracking & Command (TT&C) and Command & Data Handling (C&DH)		545 * TTCWgt^0.761	$2,344	$2,344	Lognormal	1		0.2941
Attitude Determination & Control Sys		464 * ADCSWgt^0.867	$5,769	$5,769	Lognormal	1		0.4231
Int & Assy		989 + 0.215 * (RDPayload$ + RDSpBus)	$40,454	$40,454	Normal	1		**0.3544**
Program Level Costs		1.963 * (RDPayload$ + RDSpBus) ^0.841	$52,451	$52,451	Lognormal	1		**0.4609**
Ground Support Equip (GSE)		9.262 * (RDPayload$ + RDSpBus) ^0.642	$22,184	$22,184	Triangular	1	0	**3.1204**

Input Variable	Unique ID	CER	Point Estimate	Forecast	Distribution	Uncertainty	Min	Max or Std Dev
Payload Sensor diameter (m)	PayloadDiam		0.263	0.263	Lognormal	1		0.3000
Structure weight (kg)	StrWgt		32.000	32.000	Lognormal	1		0.5019
Thermal weight (kg)	ThermWgt		6.800	6.800	Triangular	1	0.261	2.7028
EPS weight (kg)	EPSWgt		45.700	45.700		1		
TT&D/DH weight (kg)	TTCWgt		6.800	6.800	Normal	1		0.1893
ADCS weight (kg)	ADCSWgt		18.300	18.300	Normal	1		0.3103
Spacecraft + Payload Weight (kg)	SpPyWgt		140.000	140.000	Lognormal	1		0.2307

All examples use fictitious data

Sample Extract From CRUAMM Public Domain Table

- **The "unitized" results are intended for public domain and are intended for use in "your" model**
  - uncertainty scales with "your" point estimate

See Previous Chart for Filter Information

		The Point Estimate is:		
Parameter	Filter	Mean	Median	Mode
T1 CER [1]	None	Lognormal (1.0000, 0.4512)	Lognormal (1.0971, 0.4950)	Lognormal (1.3204, 0.5958)
T1 CER [3]	None	Triangular (0.1552, 0.7265, 2.1183)	Triangular (0.1635, 0.7651, 2.2308)	Triangular (0.2137, 1.0000, 2.9158)
NR CER [3]	None	Triangular (0.5206, 0.7584, 1.7210)	Triangular (0.5418, 0.7892, 1.7911)	Triangular (0.6865, 1.0000, 2.2694)
Weight Growth [2]	None	Triangular (0.5568, 0.6370, 1.8062)	Triangular (0.5850, 0.6692, 1.8975)	Triangular (0.8742, 1.0000, 2.8357)
	>50% New	Triangular (0.5853, 0.7180, 1.6967)	Triangular (0.6092, 0.7474, 1.7662)	Triangular (0.8151, 1.0000, 2.3631)
	<50% New	Triangular (0.5043, 0.6168, 1.8789)	Triangular (0.5316, 0.6502, 1.9805)	Triangular (0.8176, 1.0000, 3.0461)
T1 / Weight [3]	Commercial	Triangular (0.3442, 0.6256, 2.0302)	Triangular (0.3649, 0.6631, 2.1520)	Triangular (0.5503, 1.0000, 3.2454)
	Government	Lognormal (1.0000, 0.7077)	Lognormal (1.2251, 0.8670)	Lognormal (1.8387, 1.3013)
NRE / Weight [3]	New	Triangular (0.0283, 0.1925, 2.7792)	Triangular (0.0316, 0.2155, 3.1103)	Triangular (0.1468, 1.0000, 14.4348)
	Modified	Lognormal (1.0000, 0.9282)	Lognormal (1.3644, 1.2663)	Lognormal (2.5397, 2.3573)
NRE / T1 [3]	New	Triangular (0.0000, 0.1905, 2.8095)	Triangular (0.0000, 0.2136, 3.1495)	Triangular (0.0000, 1.0000, 14.7445)
	Modified	Lognormal (1.0000, 1.3844)	Lognormal (1.7078, 2.3642)	Lognormal (4.9806, 6.8950)

These footnotes identify the data source for each fit on this particular chart:
1 – CRUAMM – AFCAA
2 – CRUAMM – NRO
3 – CRUAMM - USCM

For this example, the CER produces the mean and the weight input is assumed to be the mode.

All examples use fictitious data

WBS:	**Electrical Power**	**Cost Driver:**	**T1 CER ($K)**
CER:	220.0 + Bus Electrical Power Weight*13.0 + CCL * 6000.0	CCL = 0; If Commercial CCL= 1; If Government	
Dist Form:	Actual/Predicted		
Best Fit	Lognormal (Mean =1.1388, Std Dev = 0.6722)		
Dependent	753 – 4087 6$K	**Independent**	94 – 1969 lbs

Cost Risk and Uncertainty Analysis Data Report

Commodity	Space	**Dispersion**	Third
WBS	Residuals	**Units**	
Element	EPS	**Data Comment**	EPS T1 = 220 + EPS Weight(lbs) * 13 + CCL * 9000
Sub-Element	T1 Rec	**Phase**	
Category	EPSRecT1Residuals	**Comment**	
Filter and Fit Settings	Filter= NONE: , Fit = SSE on Value, Percentile = CoC, Using: CO$TAT Engine		
Fit Constraints	Force Min => 0: Nor TRI Beta | Force Include Sample Min/Max: TRI Beta		
Recommended Fit	Lognormal (Mean = 1.14, Std Dev = 0.67)		

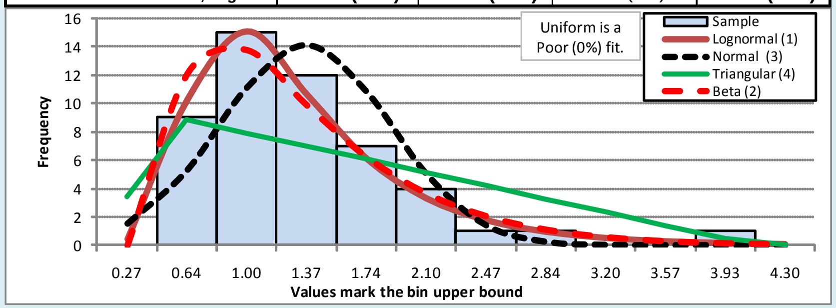
Dataset Statistics and Fitted Distributions

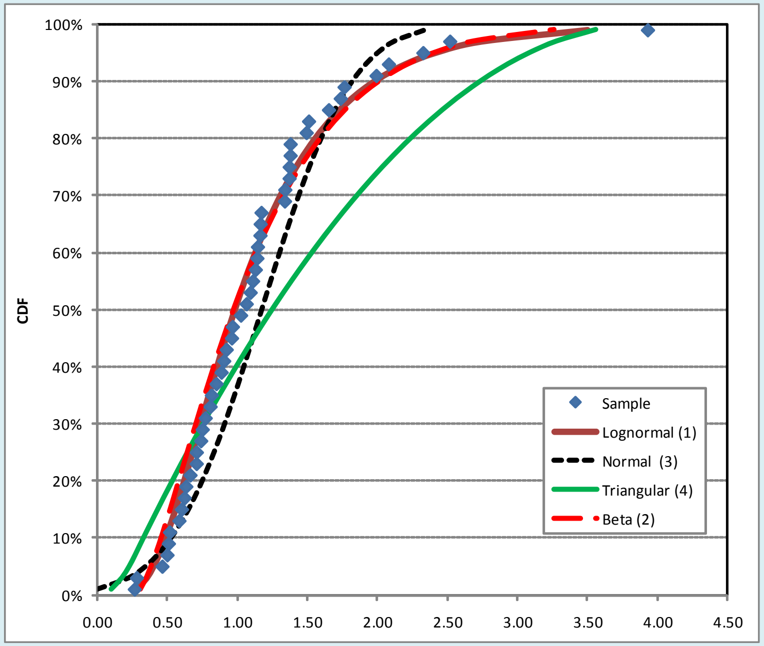
Sample

Can be used to define a CDF directly

Percentile	Value
0%	0.2623
5%	0.4677
10%	0.5174
15%	**0.6067**
20%	0.6529
25%	0.7129
30%	0.7658
35%	0.8204
40%	0.8993
45%	0.9642
50%	**1.0493**
55%	1.1147
60%	1.1475
65%	1.1692
70%	1.3436
75%	1.3760
80%	1.4403
85%	**1.6569**
90%	1.8824
95%	2.3306
100%	3.9345

	Sample	Lognormal	Normal	Triangular	Beta
Mean	1.1408	1.1388	1.1760	1.4015	1.1320
StdDev	0.6413	0.6722	0.5055	0.8972	0.6526
CV	0.562	0.590	0.430	0.640	0.576
Min	0.2701			0.0000	0.2701
Mode		0.7272	1.1760	0.2701	0.6171
Max	3.9345			3.9345	17.2398
Data Count	50			**Alpha**	1.605
				Beta	30.000
	Rank	**1**	**3**	4	**2**
	Standard Error of Estimate	0.0945	0.2744	0.4729	0.1341
	SEE / Fit Mean	8.3%	23.3%	33.7%	11.8%
	Chi^2 Fit test 9 Bins, Sig 0.05	**Good (63%)**	**Good (27%)**	Poor (0%)	**Good (21%)**





All examples use fictitious data

CRUAMM Commodity Appendix

Not intended for public domain.

CRUAMM appendix contains data points.

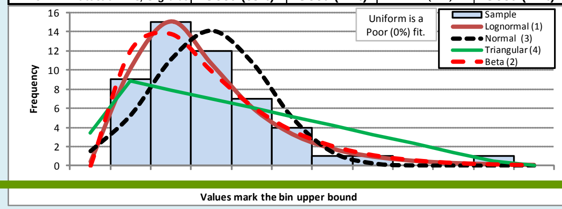
Cost Risk and Uncertainty Analysis Data Report

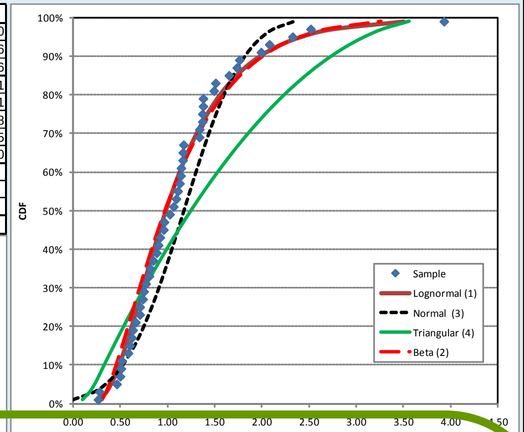
Commodity	Space	**Dispersion**	Third
WBS	Residuals	**Units**	
Element	EPS	**Data Comment**	EPS T1 = 220 + EPS Weight(lbs) * 13 + CCL * 9000
Sub-Element	T1 Rec	**Phase**	
Category	EPSRecT1Residuals	**Comment**	
Filter and Fit Settings	Filter= NONE: , Fit = SSE on Value, Percentile = CoC, Using: CO$TAT Engine		
Fit Constraints	Force Min => 0: Nor TRI Beta | Force Include Sample Min/Max: TRI Beta		
Recommended Fit	Lognormal (Mean = 1.14, Std Dev = 0.67)		

Dataset Statistics and Fitted Distributions

Sample	
Can be used to define a CDF directly	
Percentile	**Value**
0%	0.2623
5%	0.4677
10%	0.5174
15%	**0.6067**
20%	0.6529
25%	0.7129
30%	0.7658
35%	0.8204
40%	0.8993
45%	0.9642
50%	**1.0493**
55%	1.1147
60%	1.1475
65%	1.1692
70%	1.3436
75%	1.3760
80%	1.4403
85%	**1.6569**
90%	1.8824
95%	2.3306
100%	3.9345

	Sample	Lognormal	Normal	Triangular	Beta
Mean	1.1408	1.1388	1.1760	1.4015	1.1320
StdDev	0.6413	0.6722	0.5055	0.8972	0.6526
CV	0.562	0.590	0.430	0.640	0.576
Min	0.2701			0.0000	0.2701
Mode		0.7272	1.1760	0.2701	0.6171
Max	3.9345			3.9345	17.2398
Data Count	50			**Alpha**	1.605
				Beta	30.000
	Rank	**1**	**3**	4	**2**
Standard Error of Estimate		0.0945	0.2744	0.4729	0.1341
	SEE / Fit Mean	8.3%	23.3%	33.7%	11.8%
Chi^2 Fit test 9 Bins, Sig 0.05		**Good (63%)**	**Good (27%)**	Poor (0%)	**Good (21%)**





Dataset

Source	Space CERs Faux Data
Dataset Comments	Update

		Min	Max	CV	Units
CER 1st Var	EPST1	753.000	40864.000	0.838	0.000
CER 2nd Var	Wt	94.154	1969.846	0.622	0.000

Observation	EPSRecT1Residuals	EPST1	Wt
Project Name 1	0.2701	1,719.0000	472.6923
Project Name 2	0.5035	1,809.0000	259.4615
Project Name 3	1.1339	31,849.0000	1,451.3077
Project Name 4	1.7411	40,864.0000	1,096.1538
Project Name 5	1.4974	25,500.0000	1,293.0000
Project Name 6	0.9265	4,259.0000	336.6923
Project Name 7	0.4677	4,273.0000	685.9231
Project Name 8	0.2855	1,324.0000	339.7692
Project Name 9	0.9704	6,532.0000	500.8462
Project Name 10	0.6067	8,253.0000	1,029.4615
Project Name 11	0.7123	5,901.0000	620.3846
Project Name 12	0.9084	6,538.0000	536.6923
Project Name 13	0.6269	5,626.0000	673.3846
Project Name 14	1.3755	22,891.0000	1,263.2308
Project Name 15	1.3447	24,238.0000	1,369.6154
Project Name 16	1.5143	14,674.0000	728.4615
Project Name 17	1.1147	13,079.0000	885.6154
Project Name 18	2.0847	11,937.0000	423.5385
Project Name 19	0.7551	4,536.0000	445.1538
Project Name 20	1.1692	6,421.0000	405.5385
Project Name 21	1.3760	11,349.0000	617.5385
Project Name 22	1.1673	11,031.0000	710.0000
Project Name 23	3.9345	8,656.0000	152.3077
Project Name 24	1.7682	35,147.0000	1,512.0769
Project Name 25	1.3423	1,956.0000	95.1538

Observation	EPSRecT1Residuals	EPST1	Wt
Project Name 26	1.6569	4,752.0000	203.6923
Project Name 27	1.1752	3,710.0000	225.9231
Project Name 28	2.3306	6,563.0000	199.6923
Project Name 29	0.8902	2,911.0000	234.6154
Project Name 30	0.9642	23,086.0000	1,132.6154
Project Name 31	1.0694	10,534.0000	740.7692
Project Name 32	1.0976	9,269.0000	632.6923
Project Name 33	1.0292	13,398.0000	984.4615
Project Name 34	0.7764	8,886.0000	863.4615
Project Name 35	0.8204	9,394.0000	863.9231
Project Name 36	1.1495	12,276.0000	804.5385
Project Name 37	0.8113	15,444.0000	1,447.3077
Project Name 38	1.1454	11,492.0000	754.8462
Project Name 39	0.6379	4,682.0000	547.6923
Project Name 40	2.5223	4,124.0000	108.8462
Project Name 41	0.5215	753.0000	94.1538
Project Name 42	1.9965	4,001.0000	137.2308
Project Name 43	1.3829	35,011.0000	1,238.3077
Project Name 44	0.8539	14,477.0000	1,287.1538
Project Name 45	0.6678	9,281.0000	1,052.0769
Project Name 46	1.3832	35,724.0000	1,969.8462
Project Name 47	0.5888	11,283.0000	1,457.2308
Project Name 48	0.5134	7,164.0000	1,056.4615
Project Name 49	0.7439	10,302.0000	1,048.3077
Project Name 50	0.7123	24,820.0000	1,968.9231

All examples use fictitious data

Using CRUAMM To Define Uncertainty

- **Notional model, no correlation applied (functional only), not representative of a properly correlated result**
- **CRUAMM used to identify representative uncertainty for:**
  - the Electrical Power Subsystem CER
  - the EPS CER independent variable (EPS Weight)

WBS Description	Unique ID	CER	Point Estimate	Forecast (PE * Uncert)	Distribution	Uncertainty	Min	Max or Std Dev
Satellite			$298,647	$298,647				
Payload	RDPayload		$168,462	$168,462				
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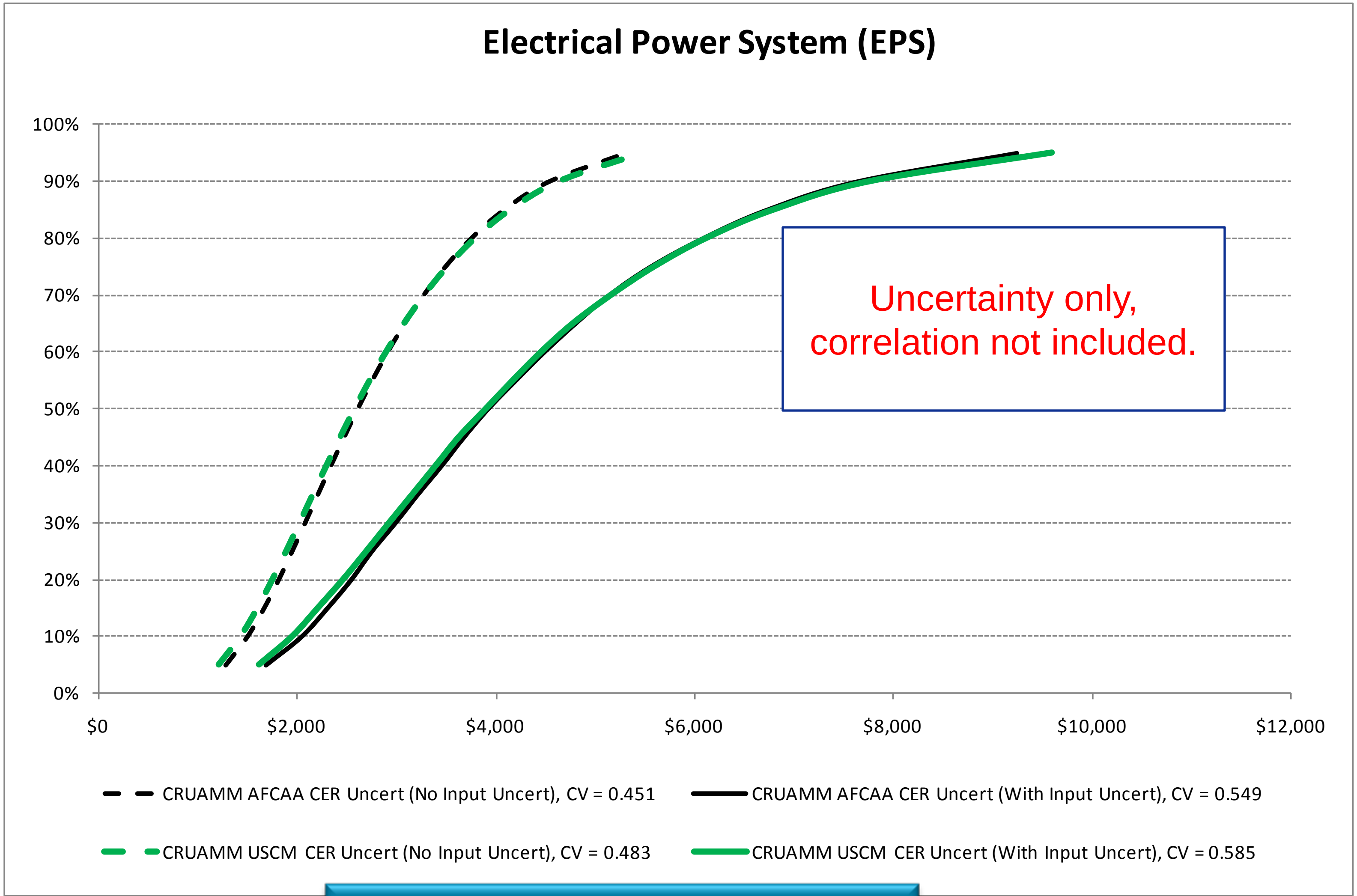
Thermal weight (kg)	ThermWgt		6.800	6.800	Triangular	1	0.261	2.7028
EPS weight (kg)	EPSWgt		45.700	45.700	**Triangular**	**1**	**0.8742**	**2.8357**
TT&D/DH weight (kg)	TTCWgt		6.800	6.800	Normal	1		0.1893
ADCS weight (kg)	ADCSWgt		18.300	18.300	Normal	1		0.3103
Spacecraft + Payload Weight (kg)	SpPyWgt		140.000	140.000	Lognormal	1		0.2307

All examples use fictitious data

Compare Spacecraft Bus EPS FireSat CER Uncertainty Derived from Fitting AFCAA or USCM CER Residuals

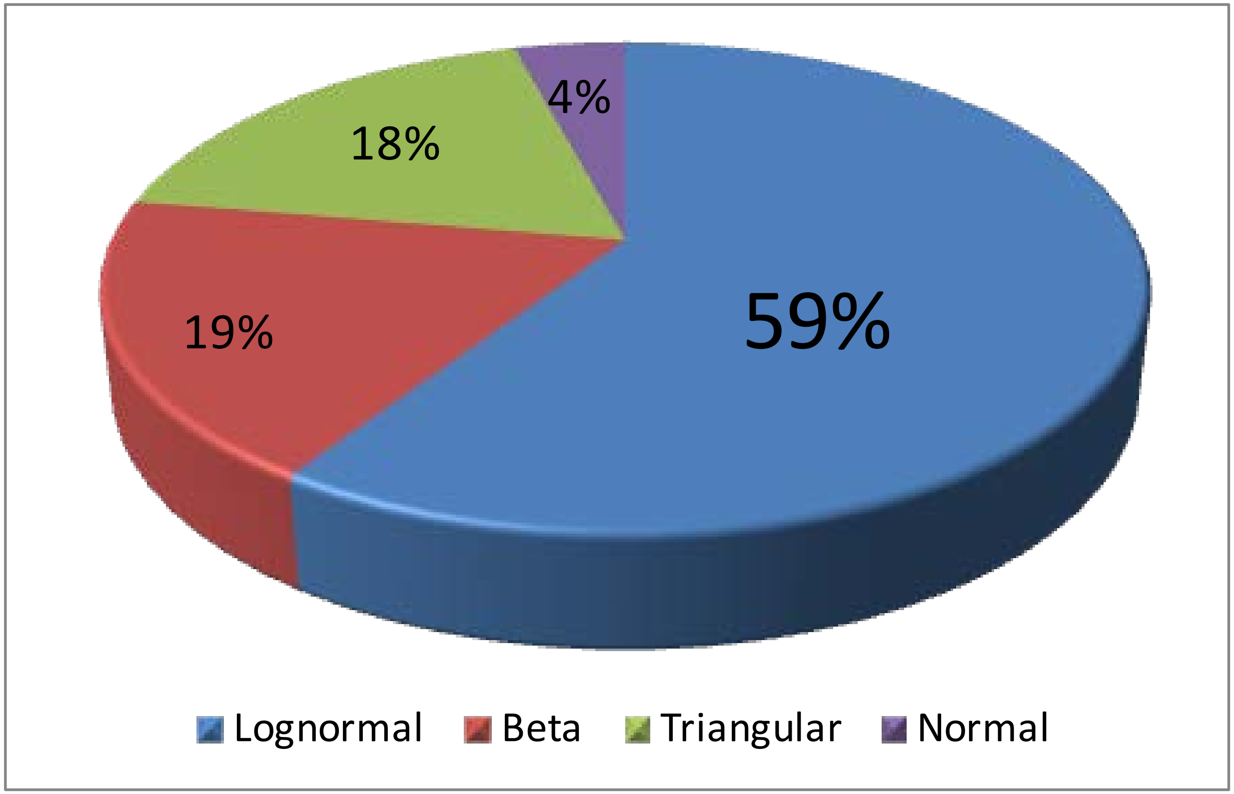
- **Dotted lines are result using CER uncertainty only**
- **Solid lines are result using CER plus Input uncertainty**



All examples use fictitious data

Relative Frequency of Distribution Shapes

- **Over 1400 fitted distributions**
  - Lognormal Dominates
  - Normal is Notably Rare
- **"Regardless … the uncertainty … may be modeled with a lognormal distribution."** **Air Force Handbook for Cost Uncertainty and Risk Analysis July 2007**



CRUAMM Final Report

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Bridging Engineering and Economics Since 1973

CR-1501/1

Cost Risk and Uncertainty Analysis Metrics Manual (CRUAMM)

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TABLE OF CONTENTS

Sample CRUAMM Public Domain Document Table (Listed by Commodity and WBS Element)

- **Results for a single WBS element from a specific commodity**
- **Colors identify different orders of dispersion (Orange= 1st, Yellow= 2nd, Green= 3rd)**
- **Green typically has the lowest CV and are associated with CER residuals**
- **Orange typically has the highest CV and are associated with raw data**

		Numerator		Denominator		Sample	Fitted	My Point Estimate is the:		
Dataset	Count	Label	Range	Label	Range	CV	CV	Mean	Median	Mode
Metrics from CER Dataset										
NR CER, All	11	NR	2477.38 - 11424.26	Weight	86.96 - 621.13	0.271	0.259	Triangular (0.5206, 0.7584, 1.7210)	Triangular (0.5418, 0.7892, 1.7911)	Triangular (0.6865, 1.0000, 2.2694)
NR Cost per Lb, NR CER Datapoints, All	12	NR	2477.38 - 11424.26	Weight	86.96 - 621.13	0.463	0.445	Triangular (0.0709, 0.7294, 2.1997)	Triangular (0.0746, 0.7680, 2.3160)	Triangular (0.0972, 1.0000, 3.0157)
NR Typical Cost, NR CER Datapoints, All	12					0.486	0.463	Triangular (0.2965, 0.3942, 2.3093)	Triangular (0.3215, 0.4275, 2.5040)	Triangular (0.7521, 1.0000, 5.8576)
T1 CER, All	44	NR	0 - 20222.18	Weight	10.92 - 621.13	0.421	0.412	Triangular (0.1552, 0.7265, 2.1183)	Triangular (0.1635, 0.7651, 2.2308)	Triangular (0.2137, 1.0000, 2.9158)
T1 Cost per Lb, Commercial	10	T1	1839.7 - 13567.79	Weight	66.9 - 525.5	0.387	0.369	Triangular (0.3442, 0.6256, 2.0302)	Triangular (0.3649, 0.6631, 2.1520)	Triangular (0.5503, 1.0000, 3.2454)
T1 Cost per Lb, Government	34	T1	319.1 - 17861.82	Weight	10.92 - 621.13	0.673	0.708	Lognormal (1.0000, 0.7077)	Lognormal (1.2251, 0.8670)	Lognormal (1.8387, 1.3013)
T1 Typical Cost, Commercial	10					0.642	0.717	Lognormal (1.0000, 0.7168)	Lognormal (1.2304, 0.8819)	Lognormal (1.8625, 1.3350)
T1 Typical Cost, Government	34					1.065	1.011	Lognormal (1.0000, 1.0110)	Lognormal (1.4220, 1.4376)	Lognormal (2.8754, 2.9070)
Metrics from Entire Dataset										
NR to T1 Ratio, New Design	20	NR	184.22 - 20222.18	T1	319.1 - 17450.68	0.707	0.641	Triangular (0.0000, 0.1905, 2.8095)	Triangular (0.0000, 0.2136, 3.1495)	Triangular (0.0000, 1.0000, 14.7445)
NR to T1 Ratio, Modified Design	17	NR	138.54 - 7416.68	T1	765.54 - 17861.82	1.060	1.384	Lognormal (1.0000, 1.3844)	Lognormal (1.7078, 2.3642)	Lognormal (4.9806, 6.8950)
NR Cost per Lb, New Design	20	NR	184.22 - 20222.18	Weight	10.92 - 621.13	0.647	0.630	Triangular (0.0283, 0.1925, 2.7792)	Triangular (0.0316, 0.2155, 3.1103)	Triangular (0.1468, 1.0000, 14.4348)
NR Cost per Lb, Modified Design	17	NR	138.54 - 7416.68	Weight	33.35 - 596.76	0.849	0.928	Lognormal (1.0000, 0.9282)	Lognormal (1.3644, 1.2663)	Lognormal (2.5397, 2.3573)
T1 Cost per Lb, New Design	20	T1	319.1 - 17450.68	Weight	10.92 - 621.13	0.752	0.818	Lognormal (1.0000, 0.8182)	Lognormal (1.2921, 1.0572)	Lognormal (2.1571, 1.7650)
T1 Cost per Lb, Modified Design	17	T1	765.54 - 17861.82	Weight	33.35 - 596.76	0.464	0.452	Triangular (0.3180, 0.4049, 2.2772)	Triangular (0.3445, 0.4387, 2.4674)	Triangular (0.7853, 1.0000, 5.6243)
NR Cost per Lb, All	45	NR	1.24 - 20222.18	Weight	10.92 - 621.13	1.062	1.055	Beta (0.0003, 5.4745, 0.5514, 2.4678)	Beta (0.0004, 8.8015, 0.5514, 2.4678)	Beta (, , 0.5514, 2.4678)
T1 Cost per Lb, All	50	T1	34.88 - 17861.82	Weight	10.92 - 621.13	0.622	0.638	Lognormal (1.0000, 0.6376)	Lognormal (1.1860, 0.7562)	Lognormal (1.6681, 1.0636)
NR Typical Cost, New Design	20					0.985	0.995	Lognormal (1.0000, 0.9950)	Lognormal (1.4107, 1.4036)	Lognormal (2.8072, 2.7931)
NR Typical Cost, Modified Design	17					1.089	1.264	Lognormal (1.0000, 1.2639)	Lognormal (1.6117, 2.0370)	Lognormal (4.1863, 5.2911)
Recurring Typical Cost, New Design	20					1.003	0.937	Beta (0.0527, 3.5826, 0.4797, 1.3079)	Beta (0.0776, 5.2727, 0.4797, 1.3079)	Beta (, , 0.4797, 1.3079)
Recurring Typical Cost, Modified Design	17					1.023	1.213	Lognormal (1.0000, 1.2127)	Lognormal (1.5719, 1.9063)	Lognormal (3.8836, 4.7098)
T1 Typical Cost, Modified Design	20					1.121	1.085	Lognormal (1.0000, 1.0855)	Lognormal (1.4759, 1.6021)	Lognormal (3.2150, 3.4899)
T1 Typical Cost, Modified Design	17					1.002	1.183	Lognormal (1.0000, 1.1832)	Lognormal (1.5491, 1.8329)	Lognormal (3.7177, 4.3986)
NR Typical Cost, All	43					1.189	1.205	Beta (0.0005, 4.5342, 0.3160, 1.1173)	Beta (0.0011, 10.2913, 0.3160, 1.1173)	Beta (, , 0.3160, 1.1173)
Recurring Typical Cost, All	51					1.017	1.028	Beta (0.0029, 4.2807, 0.4890, 1.6092)	Beta (0.0047, 6.8080, 0.4890, 1.6092)	Beta (, , 0.4890, 1.6092)
T1 Typical Cost, All	51					1.080	1.104	Lognormal (1.0000, 1.1044)	Lognormal (1.4899, 1.6454)	Lognormal (3.3071, 3.6524)
Cost Driver Metrics from CER Dataset										
Weight, NR CER Datapoints, All	12					0.735	0.732	Beta (0.3092, 2.2084, 0.2024, 0.3540)	Beta (0.4636, 3.3113, 0.2024, 0.3540)	Beta (, , 0.2024, 0.3540)
Weight, T1 CER Datapoints, Commercial	10					0.375	0.358	Normal (1.0000, 0.3585)	Normal (1.0000, 0.3585)	Normal (1.0000, 0.3585)
Weight, T1 CER Datapoints, Government	34					0.780	0.692	Triangular (0.0000, 0.0429, 2.9571)	Triangular (0.0000, 0.0487, 3.3544)	Triangular (0.0000, 1.0000, 68.9146)
Cost Driver Metrics from Entire Dataset										
Weight, All	50					0.684	0.670	Triangular (0.0000, 0.1062, 2.8938)	Triangular (0.0000, 0.1199, 3.2677)	Triangular (0.0000, 1.0000, 27.2524)

All examples use fictitious data

Benefits of the CRUAMM Project

- **Tools to systematically store normalized data and perform fits**
  - Underlying math and assumptions are “open” for scrutiny and validation
  - Every algorithm is supported by authoritative references
  - Validated to generate results very close to other commercial tools
- **Standard process to elicit consistent fit analysis across a variety of analysts**
  - In particular, the analysis flow chart is a critical and compelling product from this effort
- **Over 2000 fits provides a rich source of data to analyze for trends**
  - One example was the dominance of lognormal across all fits
  - Should examine subsets of the data for trends (e.g., T1 or weight)

CRUAMM Provides a Source of Real Uncertainty Derived from Real Data

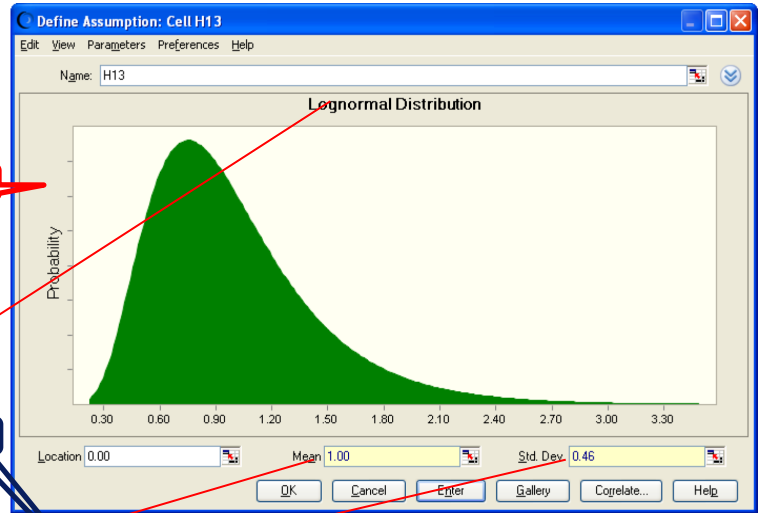
FireSat Spacecraft Bus Backup

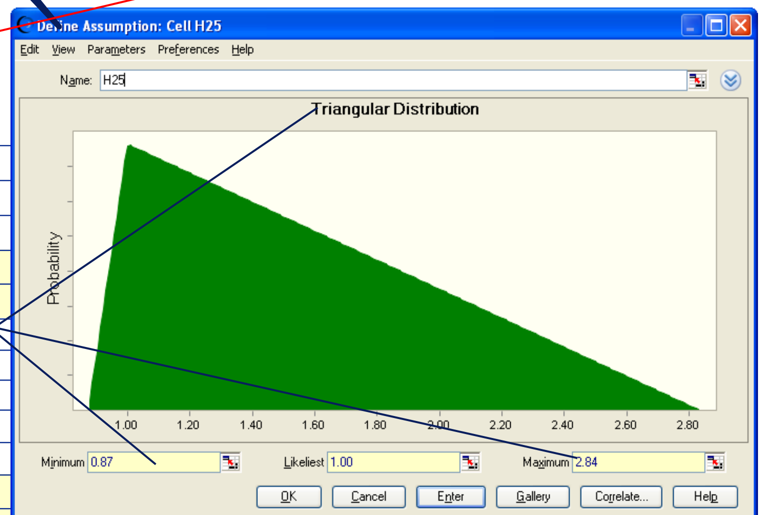
Approved for Public Release

Detail of Assigning CRUAMM Unitized Results Into a Crystal Ball Model

WBS Description	Unique ID	CER	Point Estimate	Forecast (PE * Uncert)	Distribution	Uncertainty	Min	Max or Std Dev
Satellite			$298,647	$298,647				
Payload	RDPayload		$168,462	$168,462				
IR Sensor		356851 * PayloadDiam^0.562	$168,462	$168,462	Triangular	1	0.071	**1.9640**
Spacecraft Bus	RDSpBus		$15,096	$15,096				
Structure		157 * StrWgt^0.83	$2,787	$2,787	Triangular	1	0	1.9528
Thermal		394 * ThermWgt^0.635	$1,331	$1,331	Triangular	1	0	[illegible]
Electrical Power System (EPS)		62.7 * EPSWgt	$2,865	$2,865	**Lognormal**	**1**		**0.4512**
Telemetry Tracking & Command (TT&C) and Command & Data Handling (C&DH)		545 * TTCWgt^0.761	$2,344	$2,344	Lognormal	1		0.2941
Attitude Determination & Control Sys		464 * ADCSWgt^0.867	$5,769	$5,769	Lognormal	1		0.4231
Int & Assy		989 + 0.215 * (RDPayload$ + RDSpBus)	$40,454	$40,454	Normal	1		**0.3544**
Program Level Costs		1.963 * (RDPayload$ + RDSpBus) ^0.841	$52,451	$52,451	Lognormal	1		**0.4609**
Ground Support Equip (GSE)		9.262 * (RDPayload$ + RDSpBus) ^0.642	$22,184	$22,184	Triangular	1	0	**3.1204**

Input Variable	Unique ID	CER	Point Estimate	Forecast		Mean		Std Dev
Payload Sensor diameter (m)	PayloadDiam		0.263	0.263	Lognormal	1		0.3000
Structure weight (kg)	StrWgt		32.000	32.000	Lognormal	1		0.5019
Thermal weight (kg)	ThermWgt		6.800	6.800	Triangular	1	0.261	[illegible]
EPS weight (kg)	EPSWgt		45.700	45.700	**Triangular**	**1**	**0.8742**	**2.8357**
TT&D/DH weight (kg)	TTCWgt		6.800	6.800	Normal	1		[illegible]
ADCS weight (kg)	ADCSWgt		18.300	18.300	Normal	1		[illegible]
Spacecraft + Payload Weight (kg)	SpPyWgt		140.000	140.000	Lognormal	1		0.2307

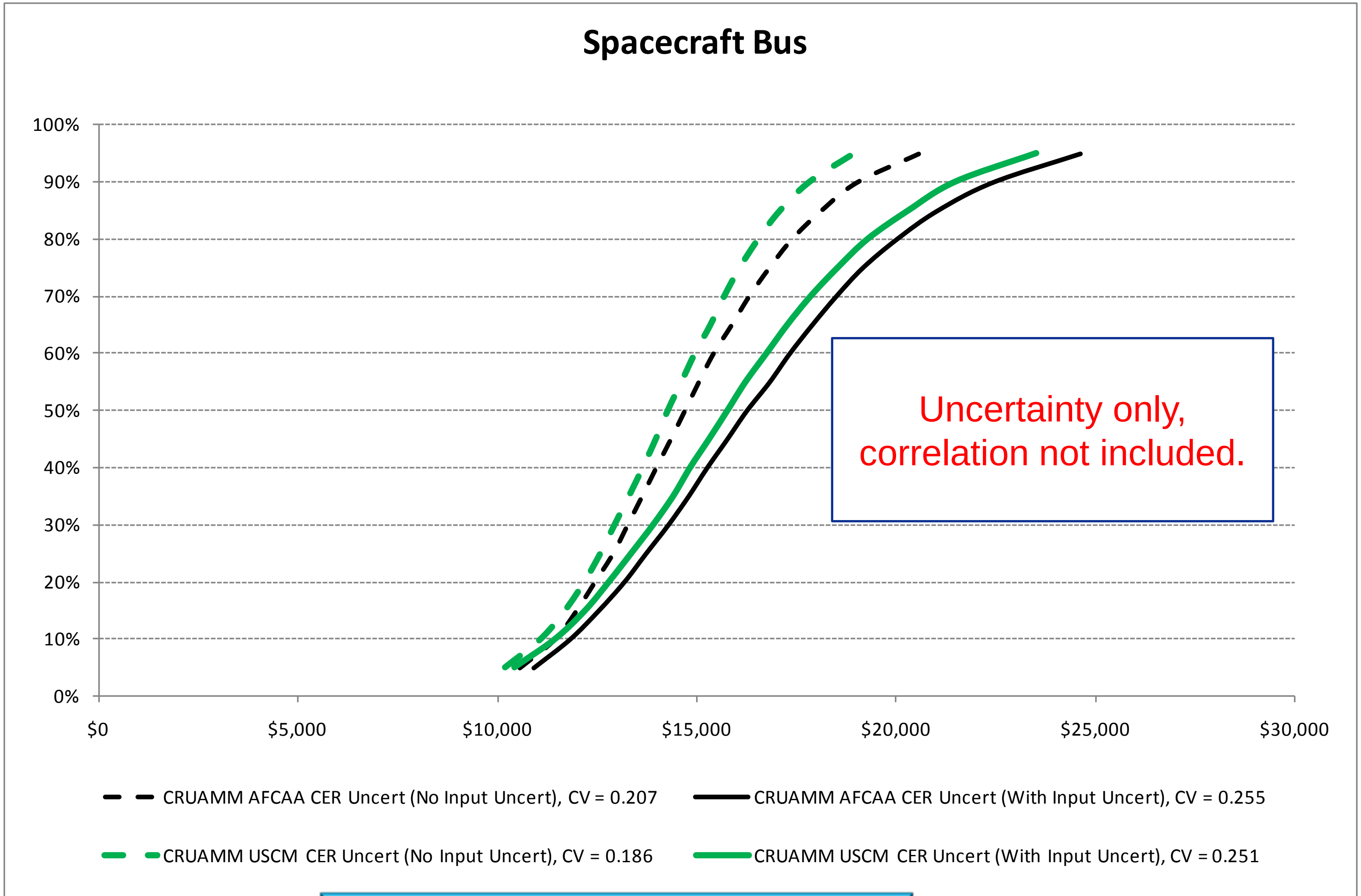




Parameter	Mean	Median	Mode
T1 CER [1]	Lognormal (1.0000, 0.4512)	Lognormal (1.0971, 0.4950)	Lognormal (1.3204, 0.5958)
NR CER [1]			
T1 CER [3]	Triangular (0.1552, 0.7265, 2.1183)	Triangular (0.1635, 0.7651, 2.2308)	Triangular (0.2137, 1.0000, 2.9158)
NR CER [3]	Triangular (0.5206, 0.7584, 1.7210)	Triangular (0.5418, 0.7892, 1.7911)	Triangular (0.6865, 1.0000, 2.2694)
Weight Growth [2]	Triangular (0.5568, 0.6370, 1.8062)	Triangular (0.5850, 0.6692, 1.8975)	Triangular (0.8742, 1.0000, 2.8357)
	Triangular (0.5853, 0.7180, 1.6967)	Triangular (0.6092, 0.7474, 1.7662)	Triangular (0.8151, 1.0000, 2.3631)
	Triangular (0.5043, 0.6168, 1.8789)	Triangular (0.5316, 0.6502, 1.9805)	Triangular (0.8176, 1.0000, 3.0461)
T1 / Weight [3]	Triangular (0.3442, 0.6256, 2.0302)	Triangular (0.3649, 0.6631, 2.1520)	Triangular (0.5503, 1.0000, 3.2454)
	Lognormal (1.0000, 0.7077)	Lognormal (1.2251, 0.8670)	Lognormal (1.8387, 1.3013)
NRE / Weight [3]	Triangular (0.0283, 0.1925, 2.7792)	Triangular (0.0316, 0.2155, 3.1103)	Triangular (0.1468, 1.0000, 14.4348)
	Lognormal (1.0000, 0.9282)	Lognormal (1.3644, 1.2663)	Lognormal (2.5397, 2.3573)
NRE / T1 [3]	Triangular (0.0000, 0.1905, 2.8095)	Triangular (0.0000, 0.2136, 3.1495)	Triangular (0.0000, 1.0000, 14.7445)
	Lognormal (1.0000, 1.3844)	Lognormal (1.7078, 2.3642)	Lognormal (4.9806, 6.8950)

Compare Spacecraft Bus AFCAA and USCM Uncertainty Results

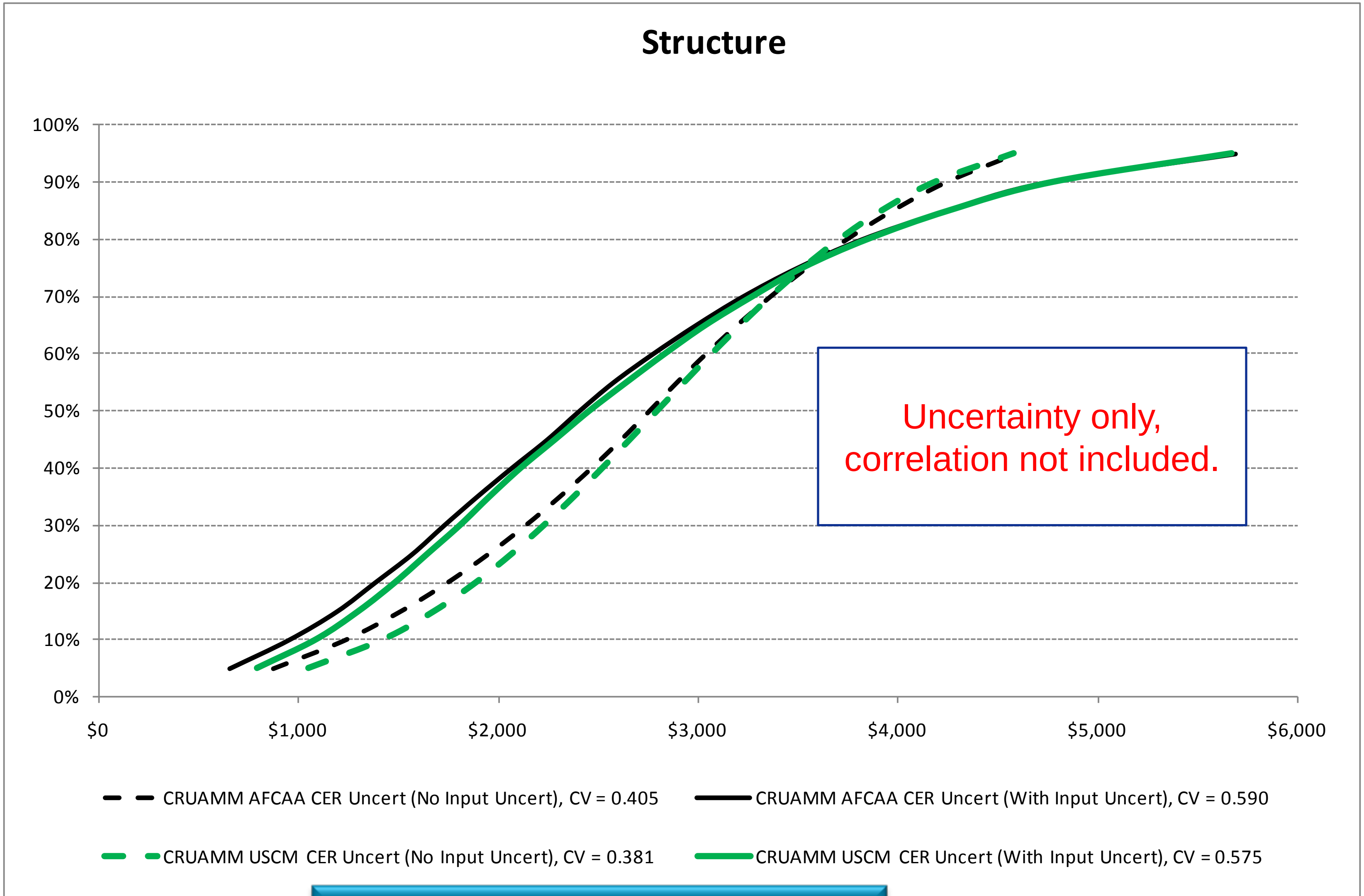
- Dotted lines are result using CER uncertainty only
- Solid lines are result using CER plus Input uncertainty



All examples use fictitious data

Compare Spacecraft Bus Structure AFCAA and USCM Uncertainty Results

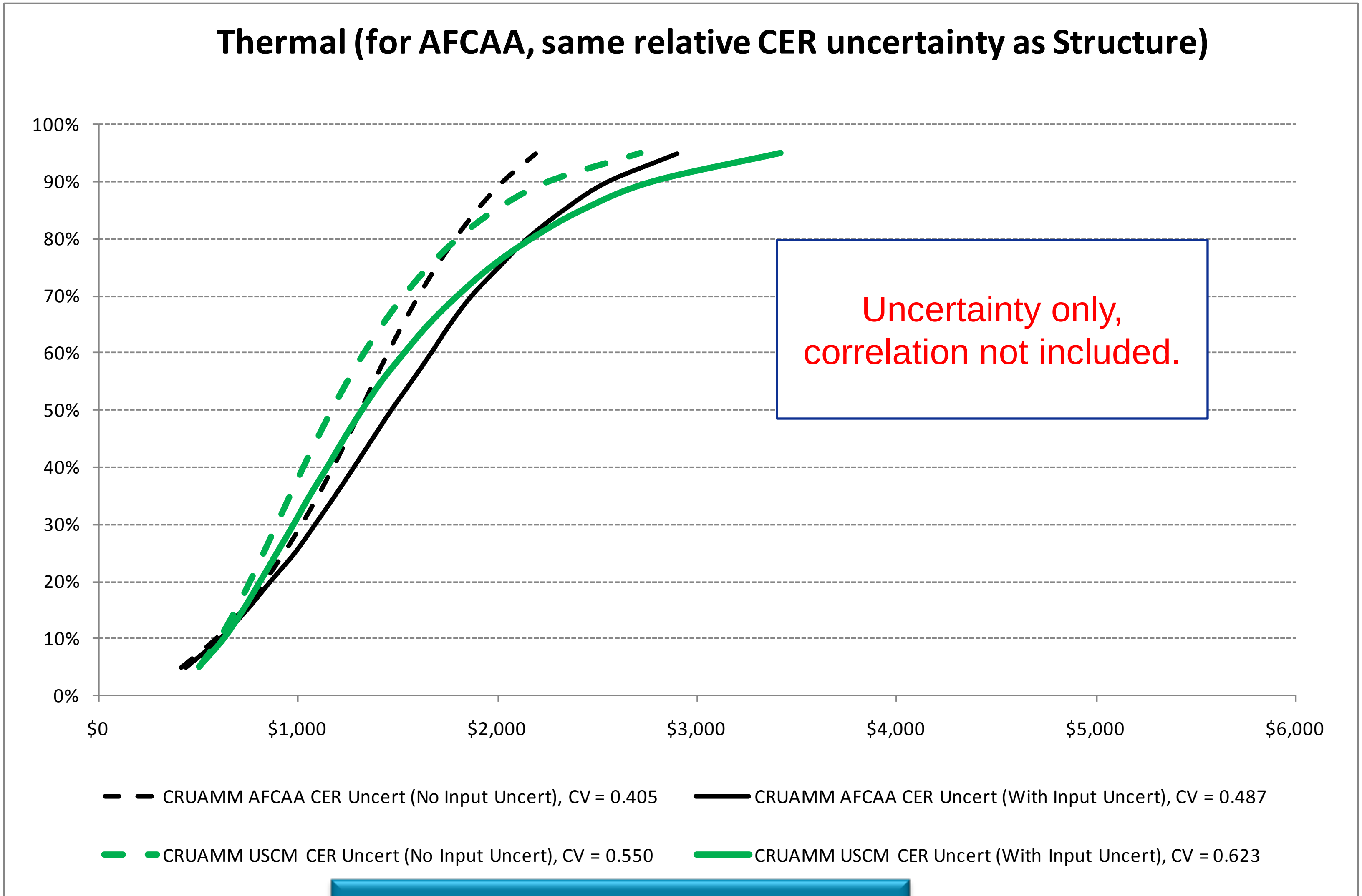
- Dotted lines are result using CER uncertainty only
- Solid lines are result using CER plus the same Input uncertainty



All examples use fictitious data

Compare Spacecraft Bus Thermal
AFCAA and USCM Uncertainty Results

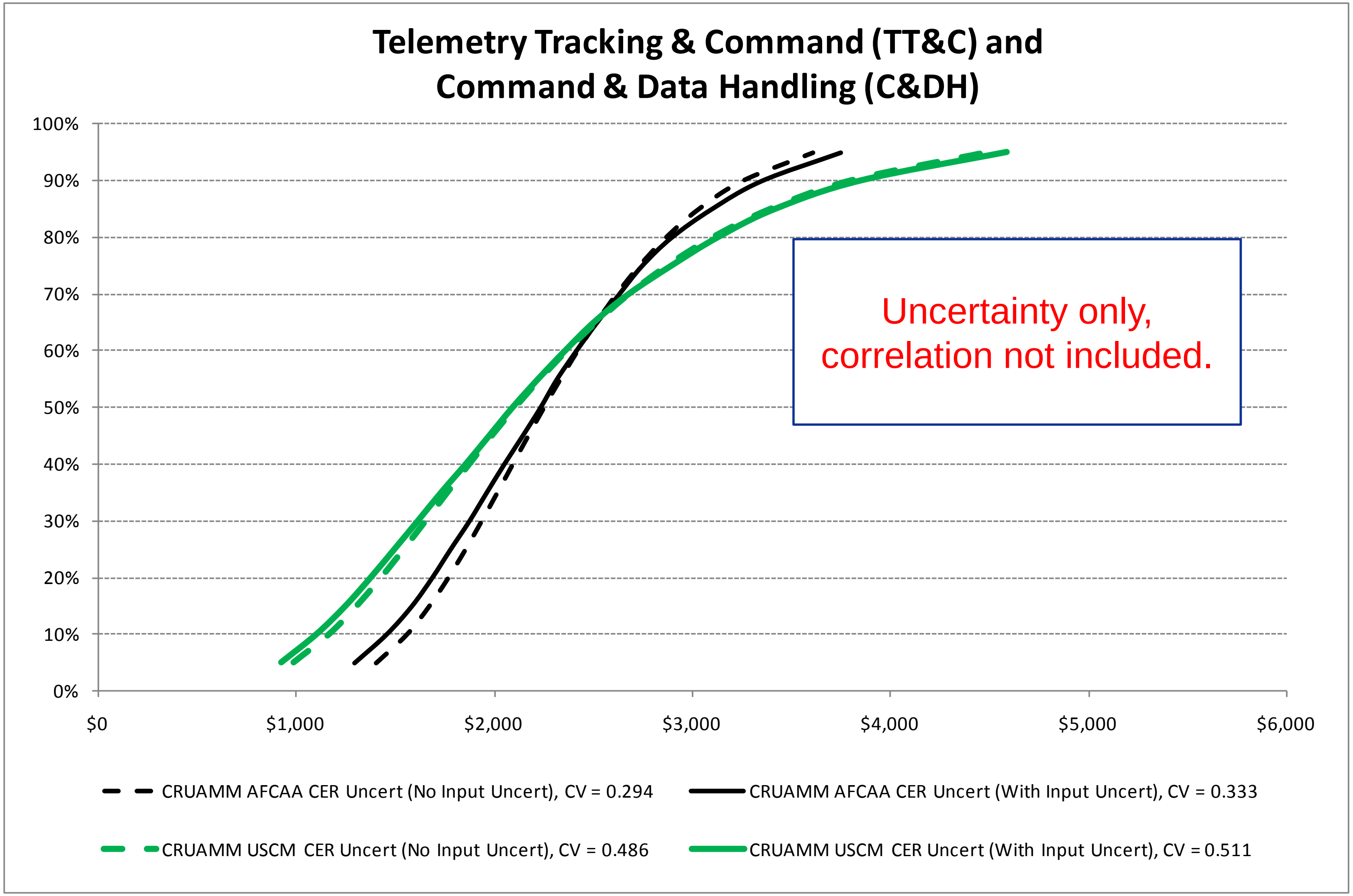
- Dotted lines are result using CER uncertainty only
- Solid lines are result using CER plus the same Input uncertainty



All examples use fictitious data

Compare Spacecraft Bus TT&C
AFCAA and USCM Uncertainty Results

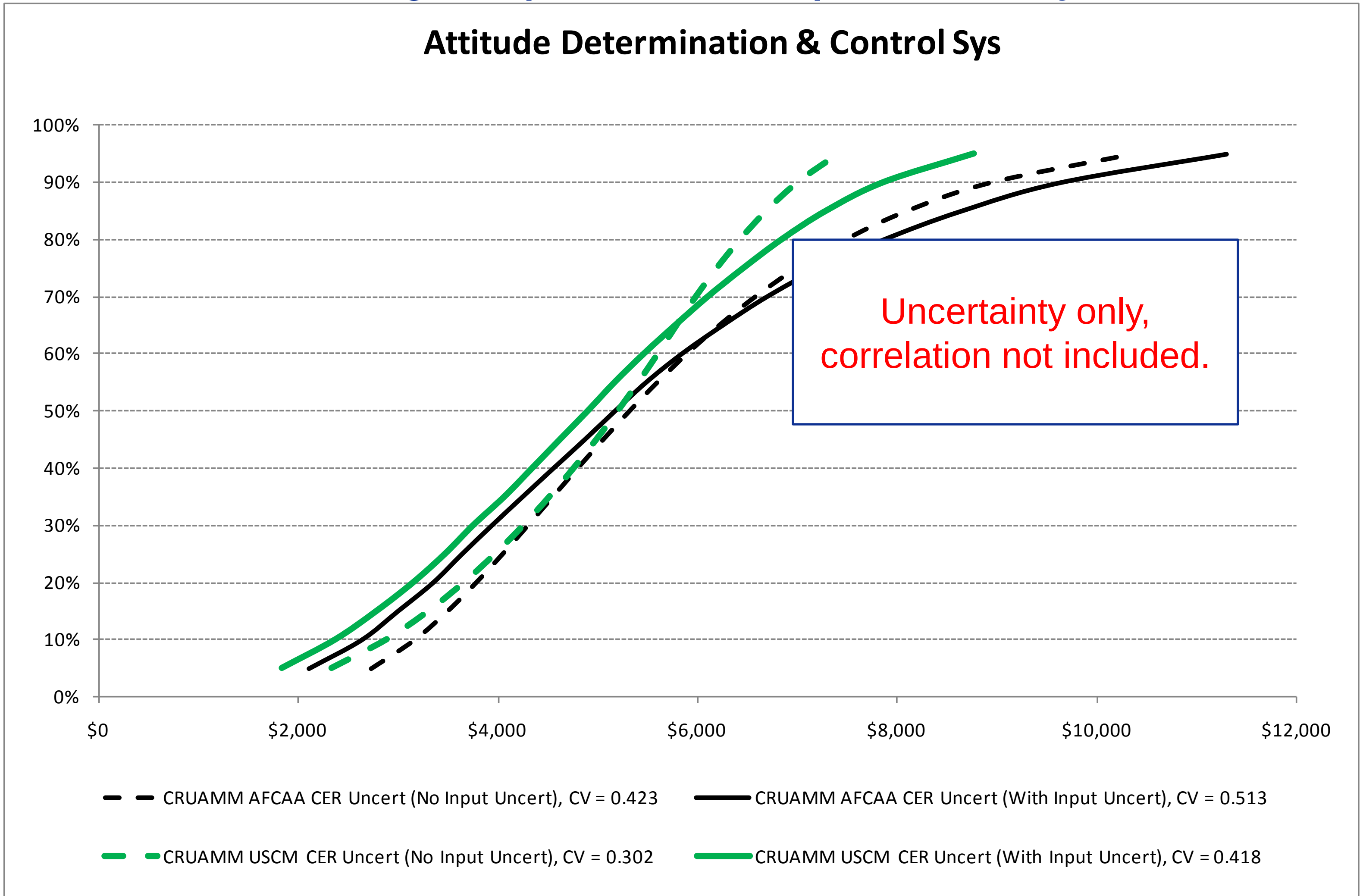
- Dotted lines are result using CER uncertainty only
- Solid lines are result using CER plus the same Input uncertainty



All examples use fictitious data

Compare Spacecraft Bus ADC AFCAA and USCM Uncertainty Results

- Dotted lines are result using CER uncertainty only
- Solid lines are result using CER plus the same Input uncertainty



All examples use fictitious data

References

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