Space System Cost Variance Overview

February, 2001

Donald MacKenzie

Bonnie Addison

Wyle Laboratories, Inc.

TOPICS

- **Objectives**
- **Definitions**
- **Box Production Variance**
- **Production Cost Probability Distributions**
- **Box Recurring Cost CER Variance**
- **Box Level Correlation**
- **Bus Subsystem Correlation**
- **Summary**

Objectives

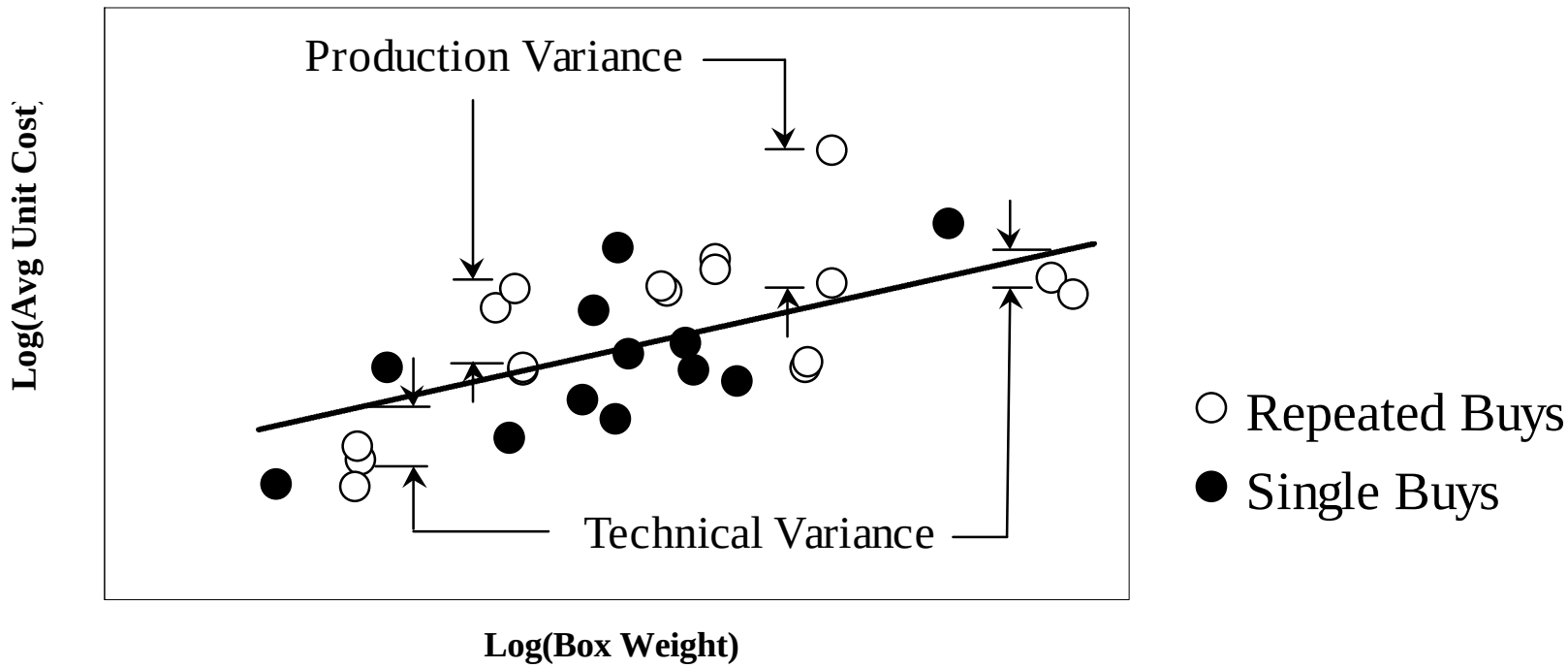
- **Characterize amount of variance and covariance in space hardware production**
  - Box unit costs
  - Recurring T1/Wt CERs
  - Box-to-box correlation
  - Subsystem-to subsystem correlation
- **Use information in risk analysis process**
  - Production cost risk (direct use)
  - Development cost (indirect)

wyle laboratories

Example Box Unit Production Costs

Space System Cost Variance and Estimating Uncertainty

Example Box AUC vs. Weight Data



Factors Contributing to Production Variance

- **Labor productivity variations**
- **Learning, loss of learning, accidents**
- **Economic fluctuations**
- **Inflation rates used to normalize may be too low**
  - DoD OSD indices vs. Space System Contractor indices
  - Production personnel average experience level (and salary) increases with time
- **Progressive schedule stretches and funding caps**
- **Bias in NR/R cost segregation**
  - Some boxes probably have embedded NR costs

Definitions

- **Average Unit Cost for N Type i boxes from Contract k**

  $AUC_{ik} = Rec_{ik}/N_{ik}$

- **AUC Coefficient of Variation for box Type i over M contracts**

  $COV_i = 100*StdDev(AUC_{ik})/Avg(AUC_{ik})$ (k=1…M)

  $= 100* \sigma_i / \mu_i$

- **Normalized AUC Residual for box Type i from Contract k**

  $R_{ik} = (AUC_{ik} - \mu_i) / \sigma_i$

Definitions (Con't)

- **Correlation Coefficient -- between box Type i and box Type j Average Unit Costs**

$$CC_{ij} = [Avg(AUC_{ik} \bullet AUC_{jk}) - \mu_i \bullet \mu_j)] / \sigma_i \bullet \sigma_j$$

- **Effective Correlation -- between Average Unit Costs for all box pairs in a sequence of M contracts**

$$EC = [StdDev_k(\Sigma_i AUC_{ik})^2 - \Sigma_i \sigma_i^2] / [(\Sigma_i \sigma_i)^2 - \Sigma_i \sigma_i^2]$$

Numerator = Total Covariance for all box pairs

Denominator = Maximum possible Covariance

Box Production Variance Analysis

Analysis Procedure

- **Collect box average unit costs and C/P ratios for contract sequence 1, 2 …M**
- **Screen box sequences to eliminate cases with design changes and/or unusually large C/P**
  - Substantial weight change
  - Non-zero percent new design
  - Max AUC / Min AUC > 4
- **Calculate sequence statistics**
  - Box AUC, COV, Normalized Residuals
  - Box-to-box Correlation Coefficients

wyle laboratories

Box and System COVs

Space System Cost Variance and Estimating Uncertainty

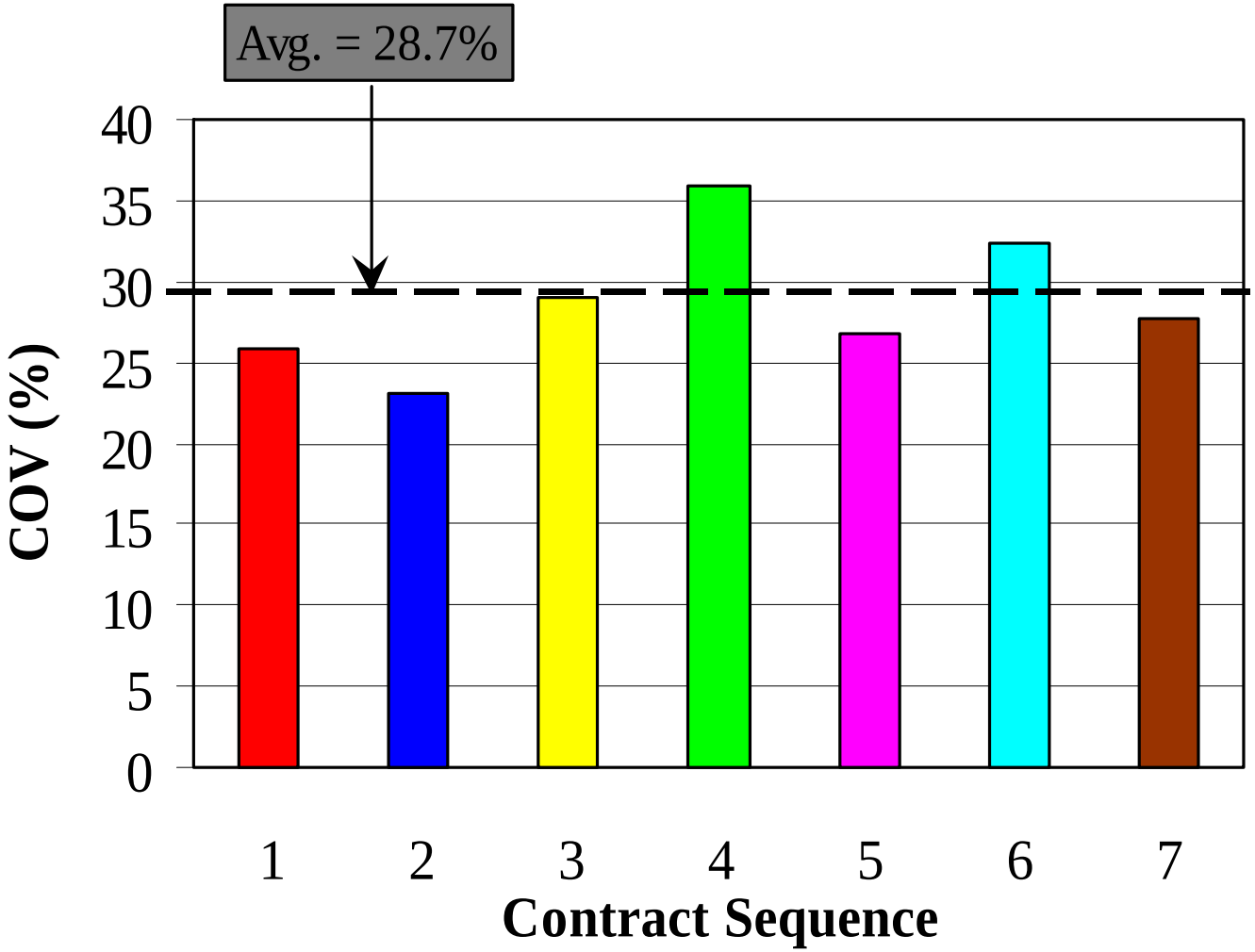
Box and System Production Coefficients of Variation

Contract Sequence	No. of Contracts	No. of Boxes		Avg. Box AUC COV (%)	"System" AUC COV (%)		
		All	Selected		2-Box	3-Box	4-Box
1	4	44	34	25.9	3.2	27.3	26.1
2	4	41	40	23.0	5.5	13.4	2.4
3	3	62	52	29.1	19.2	29.2	--
4	2	25	20	36.0	32.3	--	--
5	2	64	53	26.7	6.5	--	--
6	2	32	27	32.4	0.8	--	--
7	2	42	35	27.7	6.6	--	--
Total	19	310	261	--	--	--	--
Average	--	44.3	37.3	28.7	10.6	23.3	14.3

wyle laboratories

Average Box COVs by Sequence

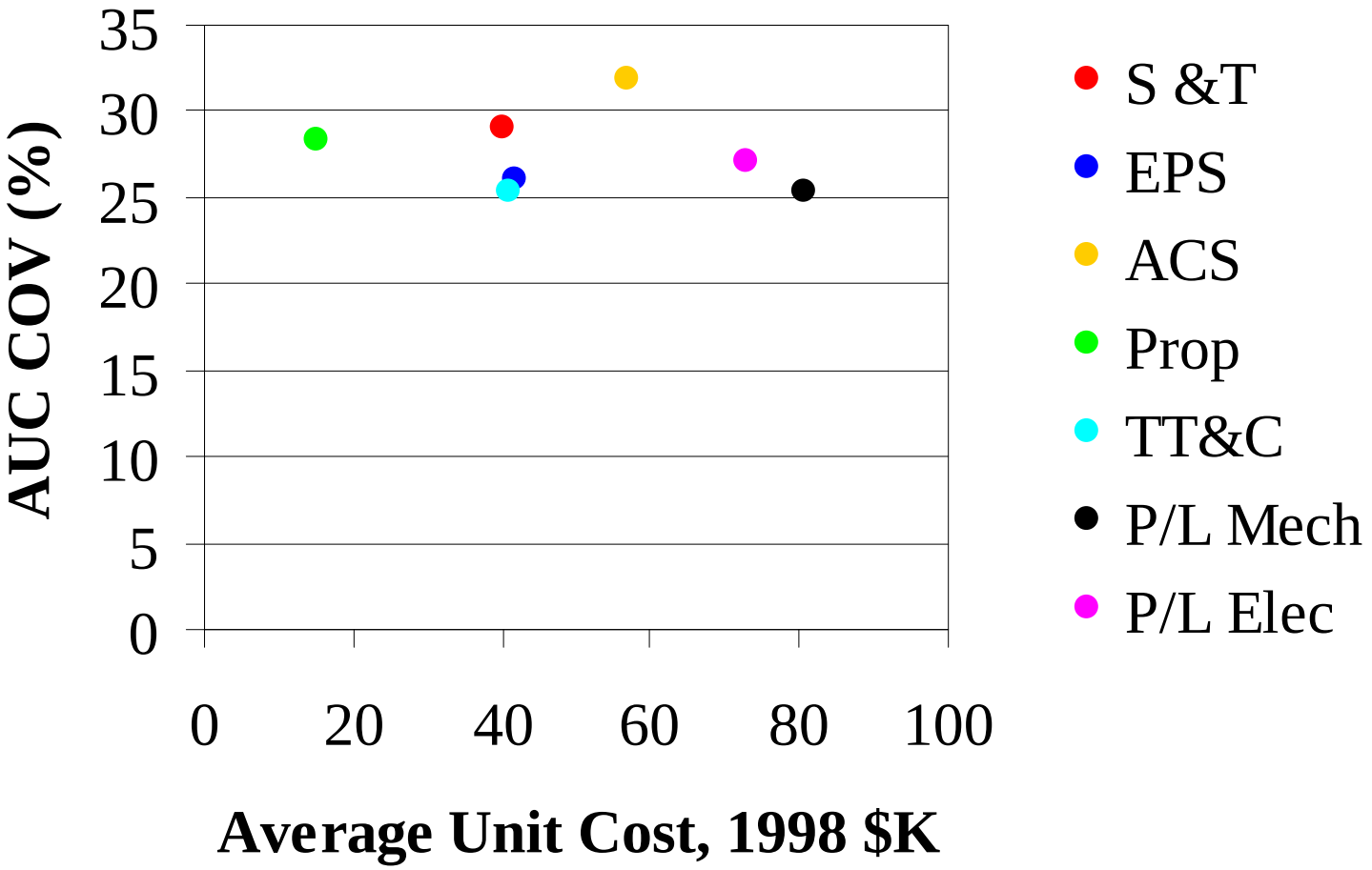
Space System Cost Variance and Estimating Uncertainty



wyle laboratories

Average Box COVs by Type

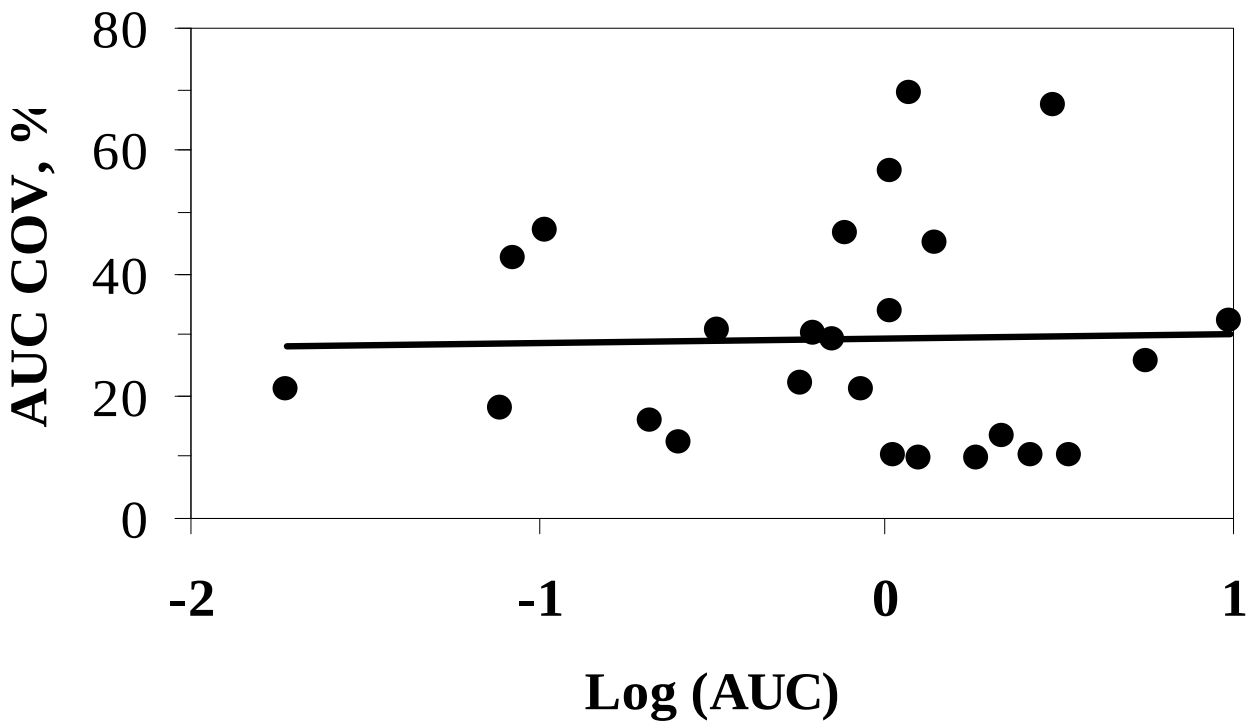
Space System Cost Variance and Estimating Uncertainty



Structures & Thermal Box COV vs. Log(AUC)

Space System Cost Variance and Estimating Uncertainty

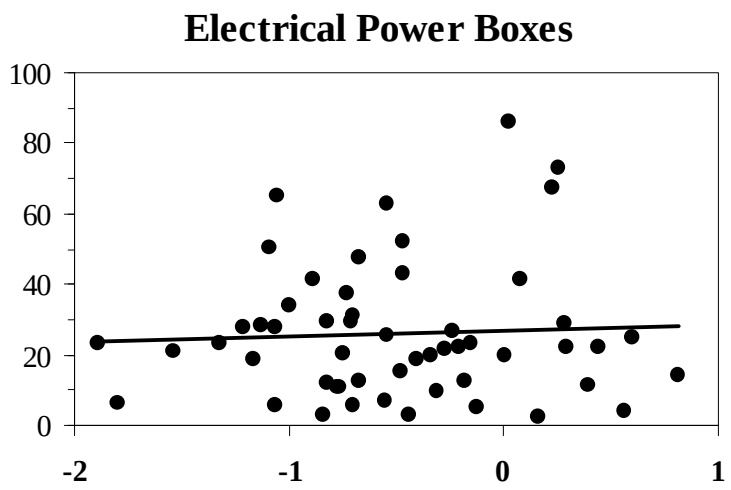
Structures & Thermal Subsystem Boxes
AUC COV vs. Log(AUC Average Cost)

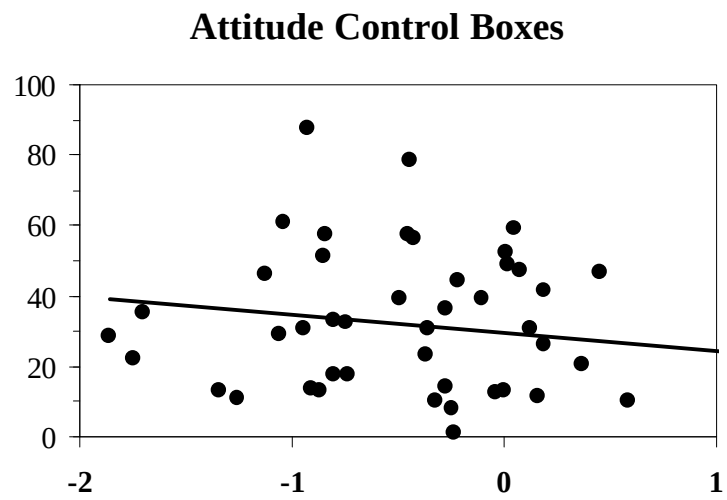


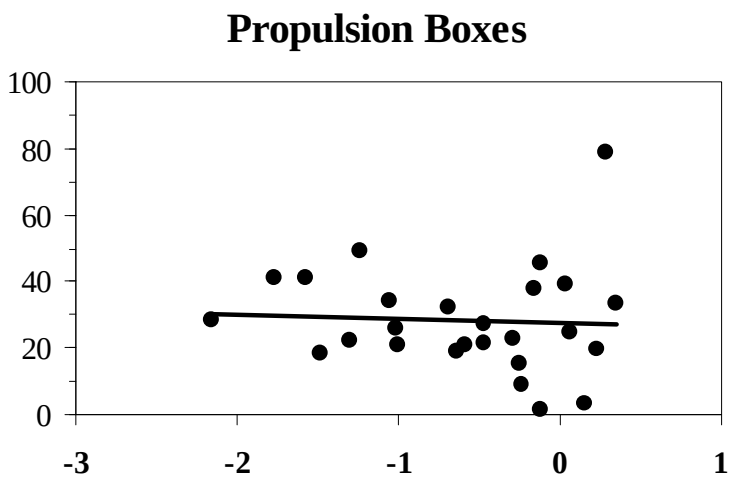
wyle laboratories

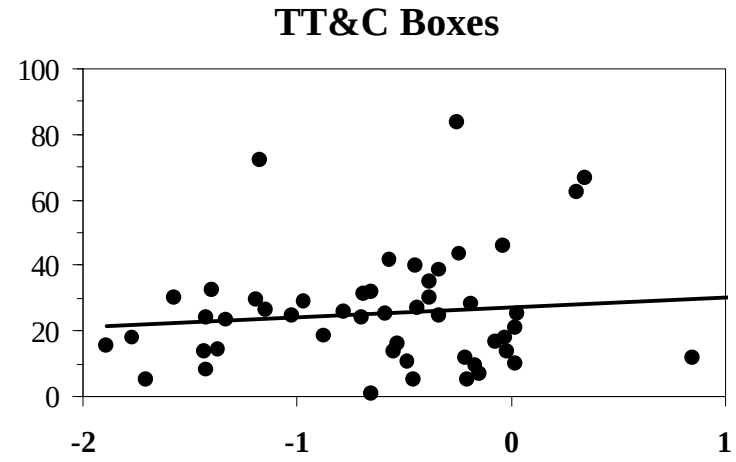
Box COV vs. Log(AUC) - Other Bus Subsystems

Space System Cost Variance and Estimating Uncertainty





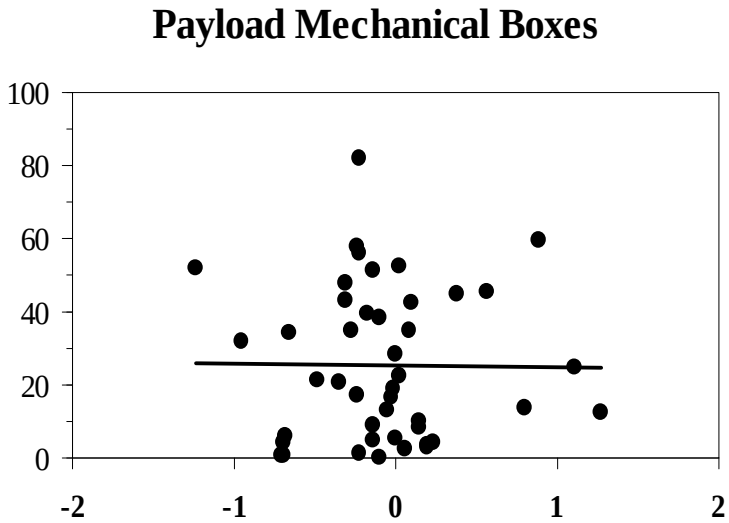


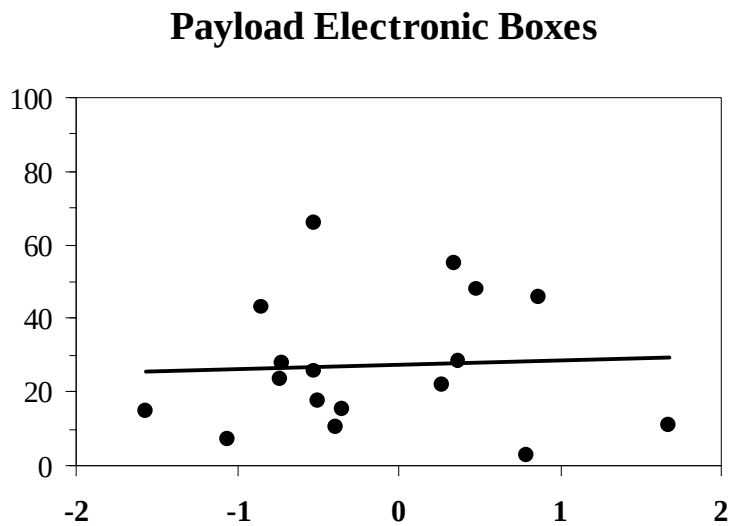


wyle laboratories

Box COV vs. Log(AUC) - Payload Boxes

Space System Cost Variance and Estimating Uncertainty

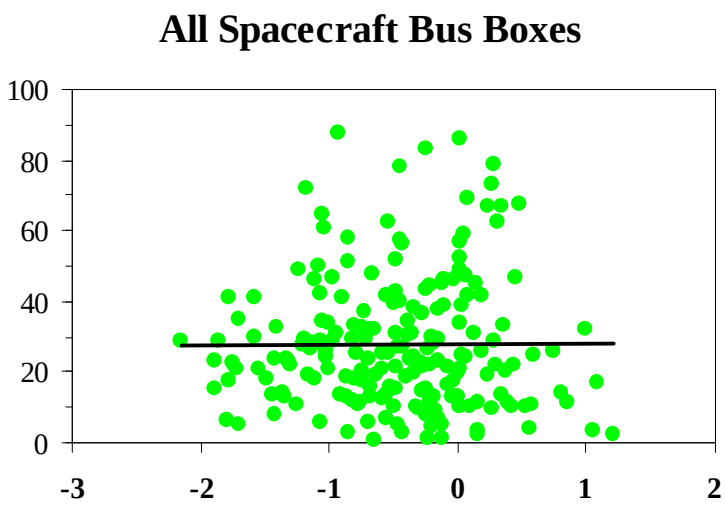


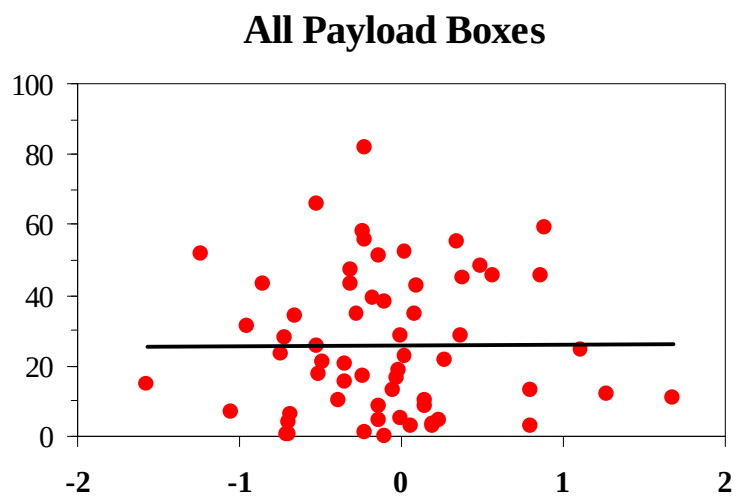


wyle laboratories

Box COV vs. Log(AUC) - All Bus, P/L Boxes

Space System Cost Variance and Estimating Uncertainty

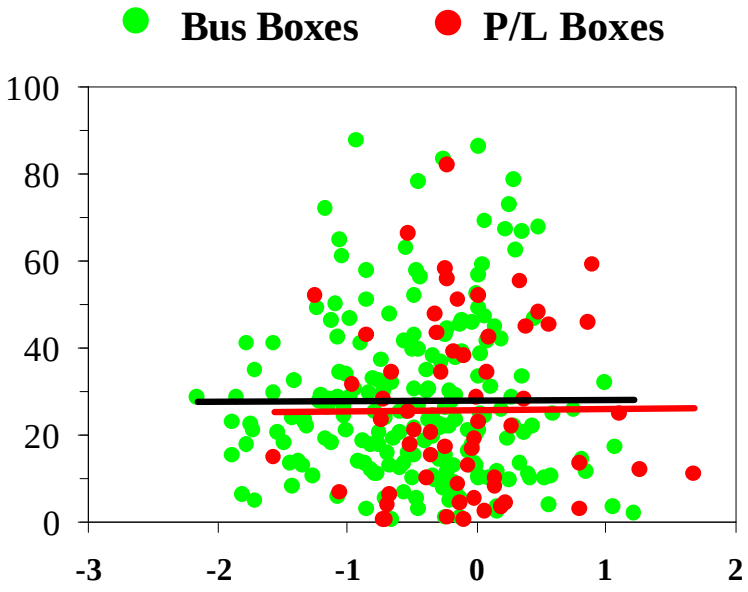


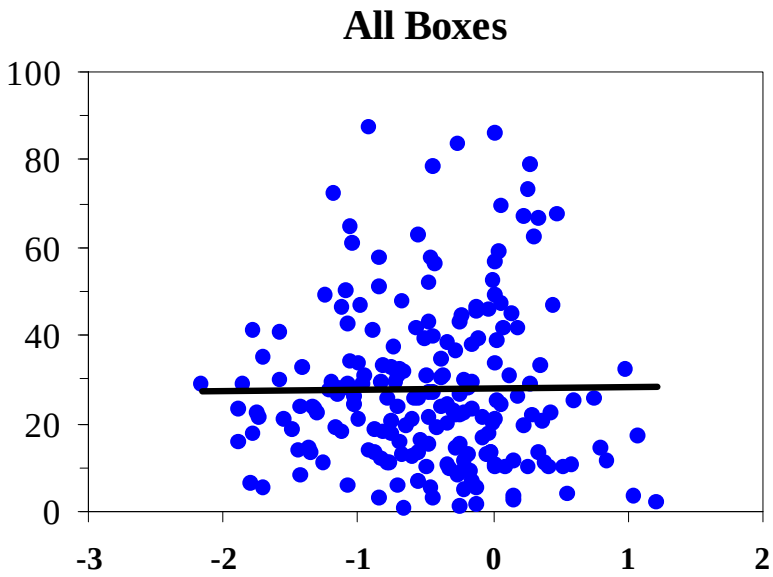


wyle laboratories

Box COV vs. Log(AUC) - All Boxes

Space System Cost Variance and Estimating Uncertainty

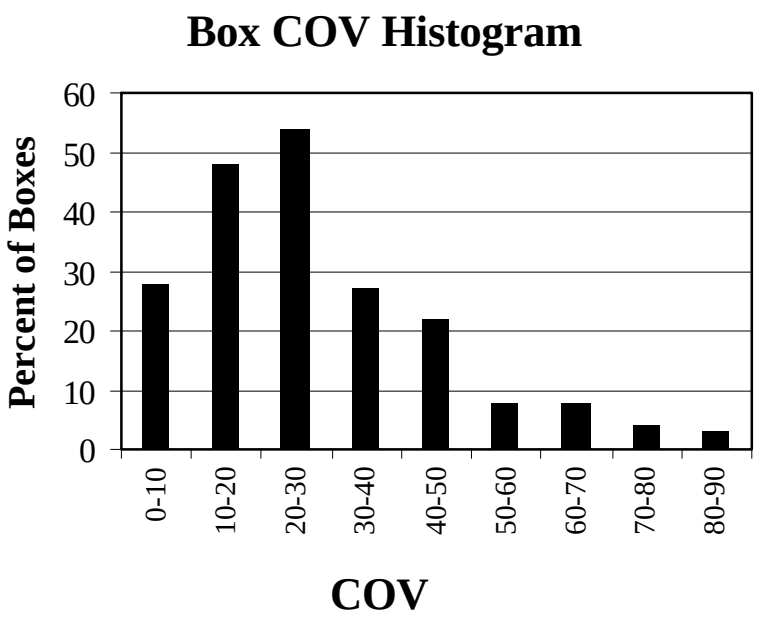


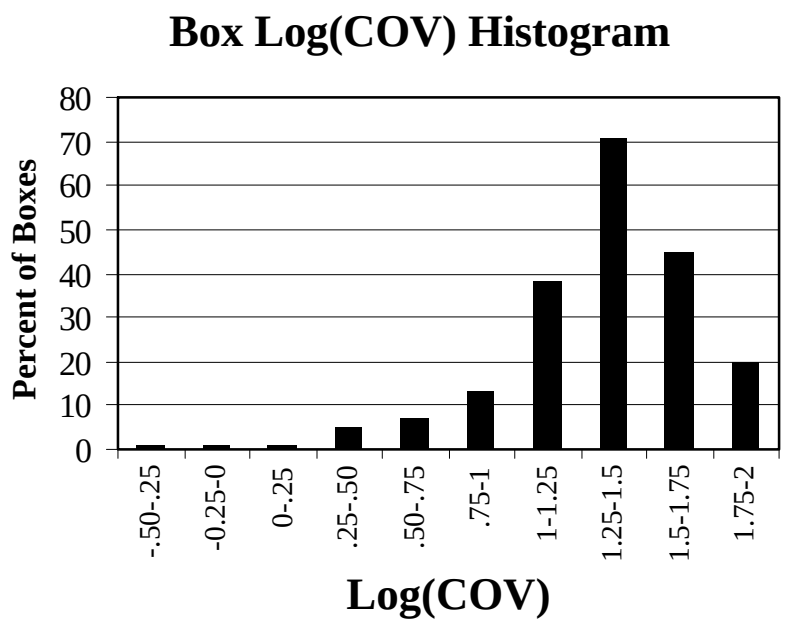


wyle laboratories

Box COV Distributions

Space System Cost Variance and Estimating Uncertainty



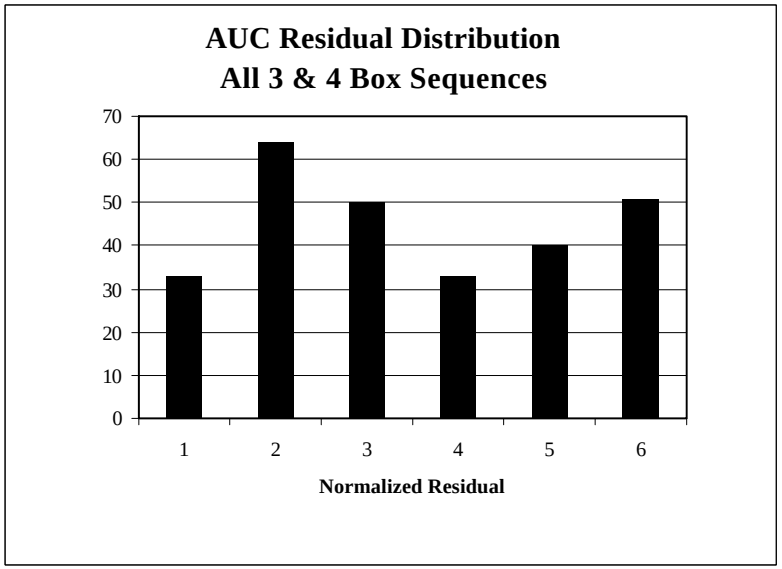


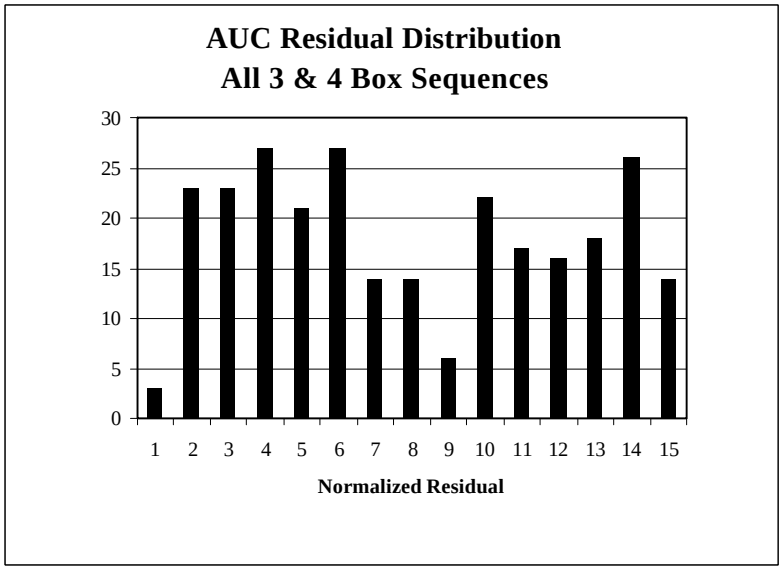
Production Cost Probability Distributions

wyle laboratories

Box AUC Residual Distribution

Space System Cost Variance and Estimating Uncertainty



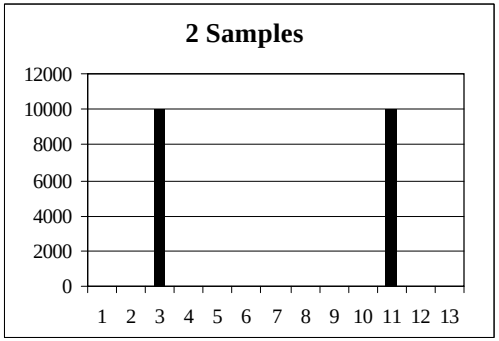


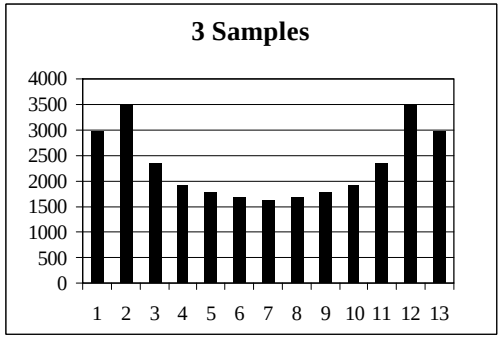
wyle laboratories

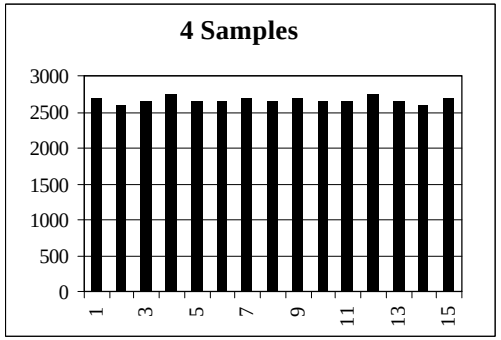
Sampling From Normal Distributions

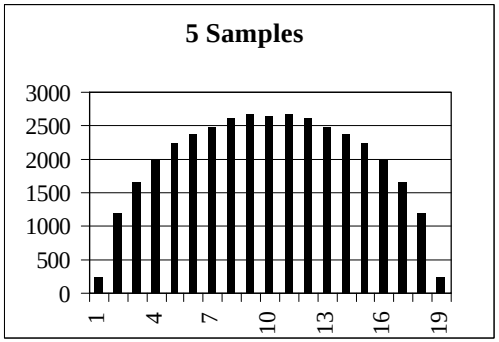
Space System Cost Variance and Estimating Uncertainty

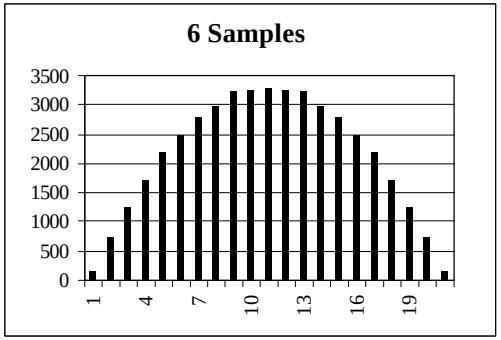
Exact Normalized Residual Distributions -- N Samples from a Normal Distribution

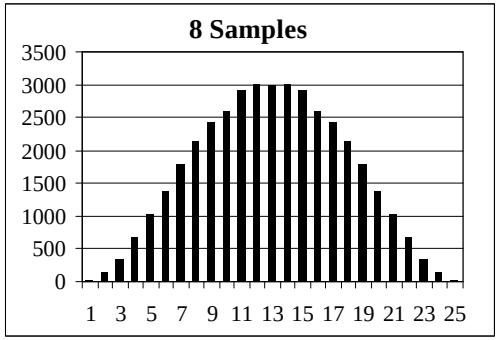










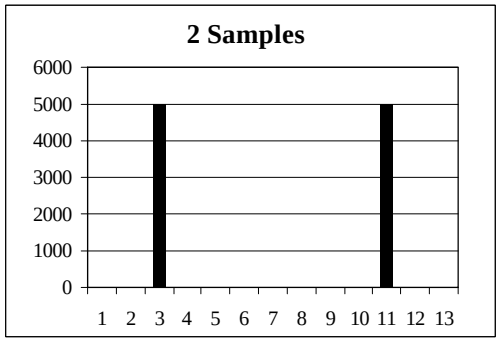


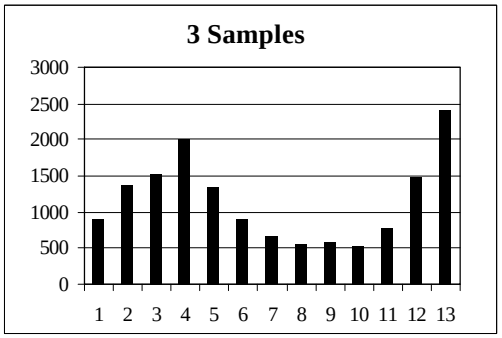
wyle laboratories

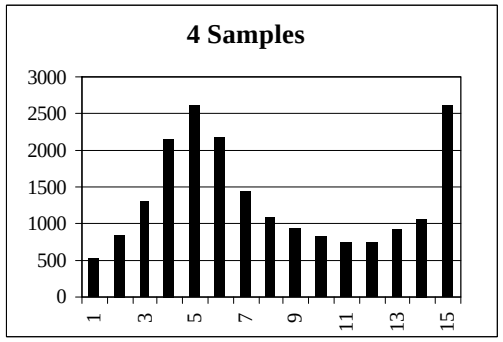
Sampling From Lognormal Distributions

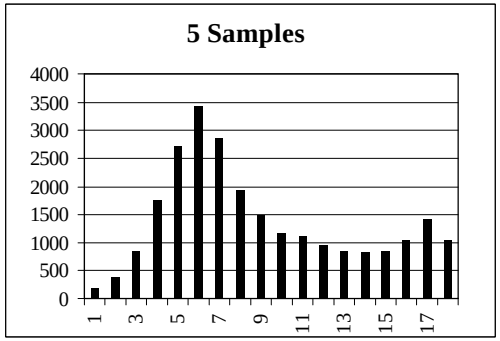
Space System Cost Variance and Estimating Uncertainty

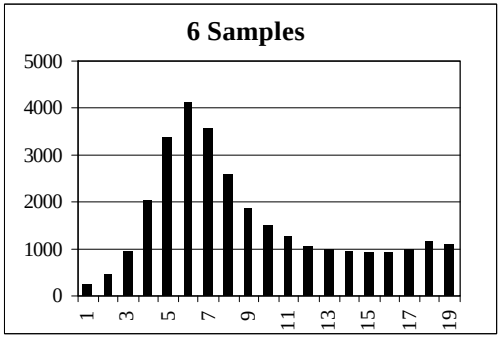
Exact Normalized Residual Distributions -- N Samples from a Lognormal Distribution

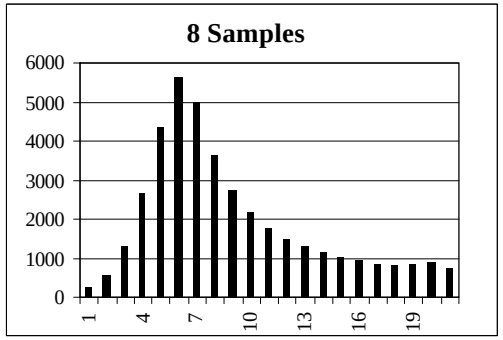








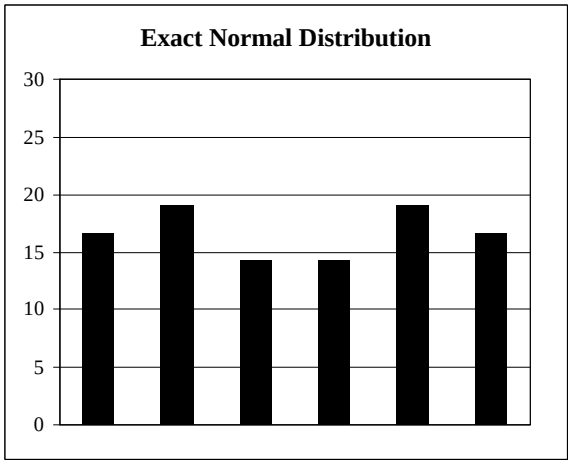


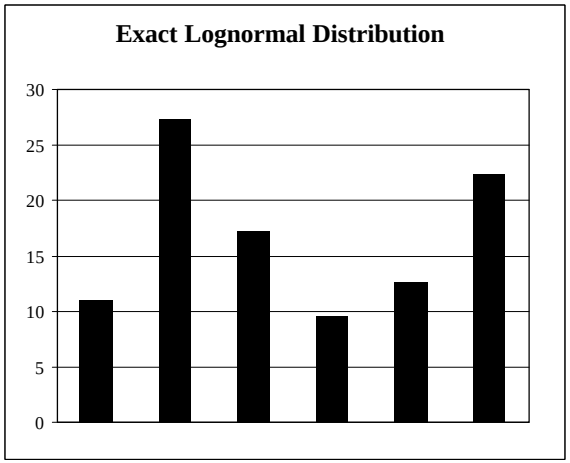


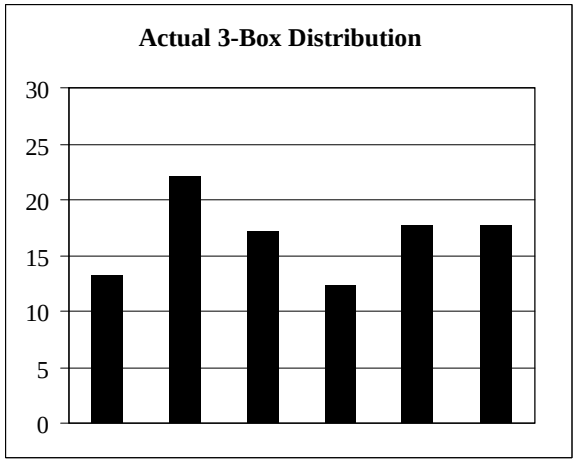
wyle laboratories

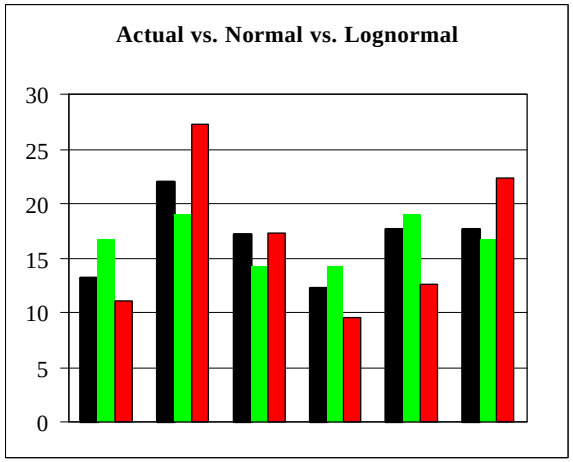
3-Box Residual Comparison - 6 Bins

Space System Cost Variance and Estimating Uncertainty









Average Absolute Bin Errors

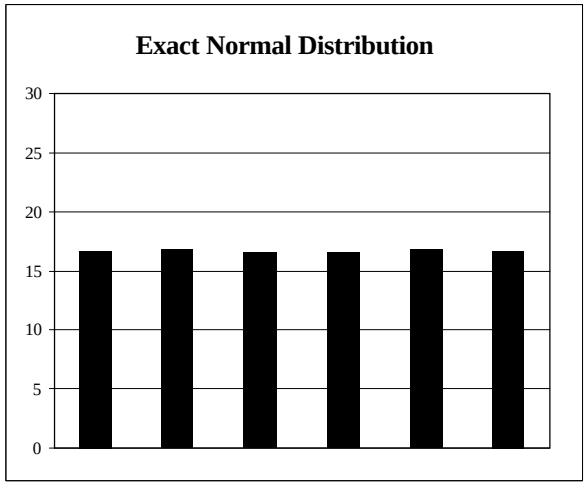
Normal = 2.29

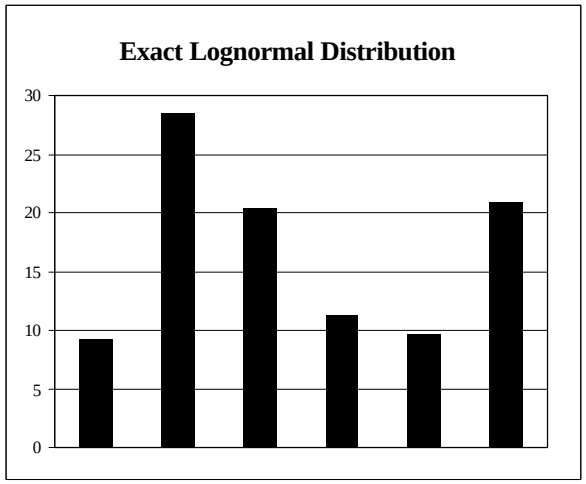
Lognormal = 3.35

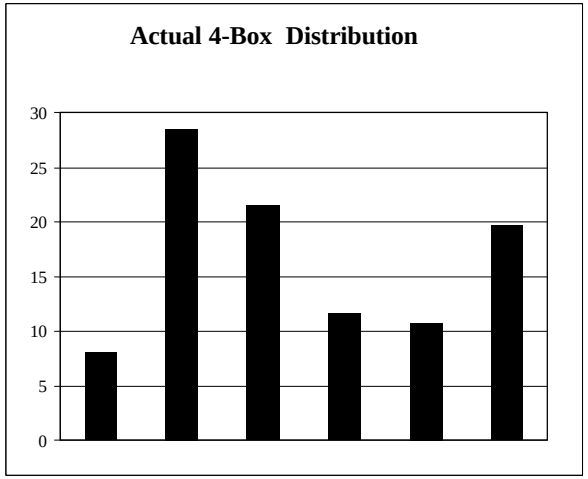
wyle laboratories

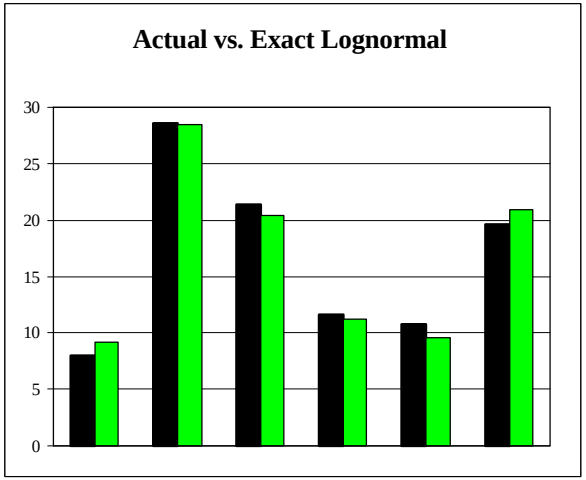
4-Box Residual Comparison - 6 Bins

Space System Cost Variance and Estimating Uncertainty







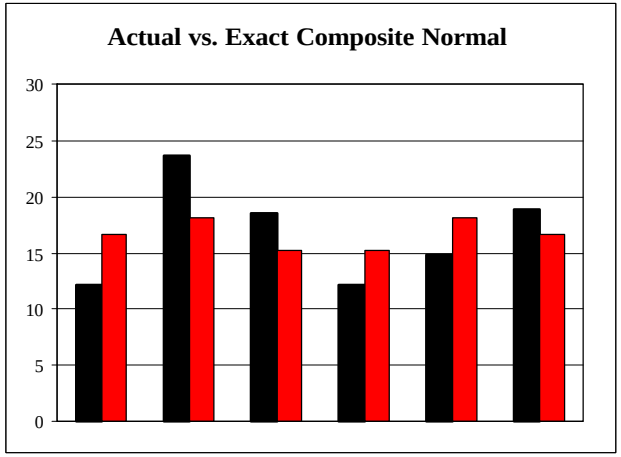


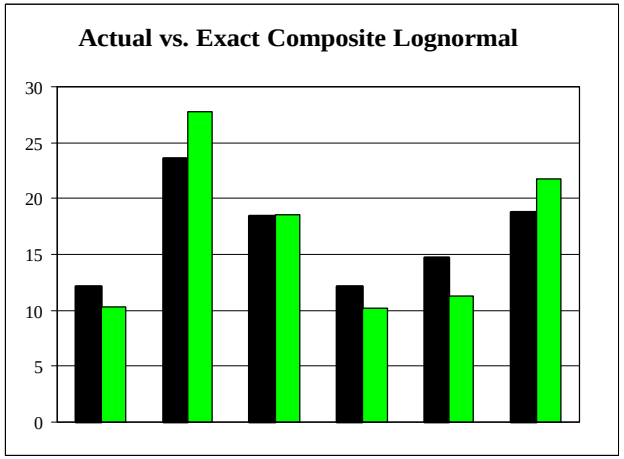
Avg Abs Bin Error = 1.3 percent

wyle laboratories

Composite Box AUC Distributions

Space System Cost Variance and Estimating Uncertainty

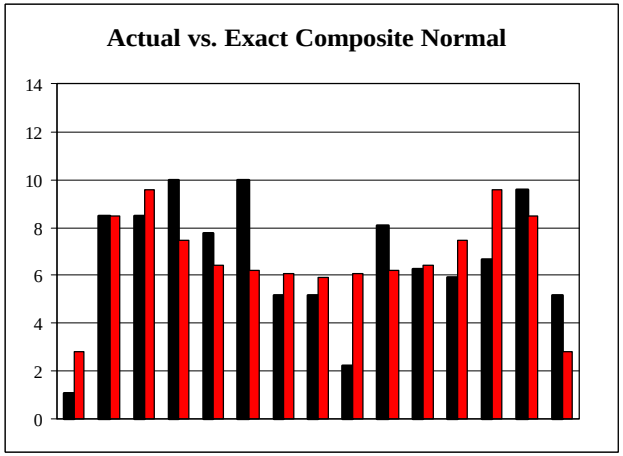


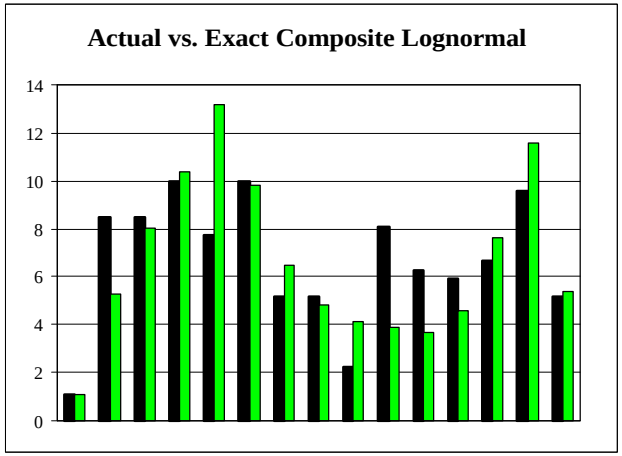


Average Absolute Bin Errors

Normal = 3.63

Lognormal = 2.42





Average Absolute Bin Errors

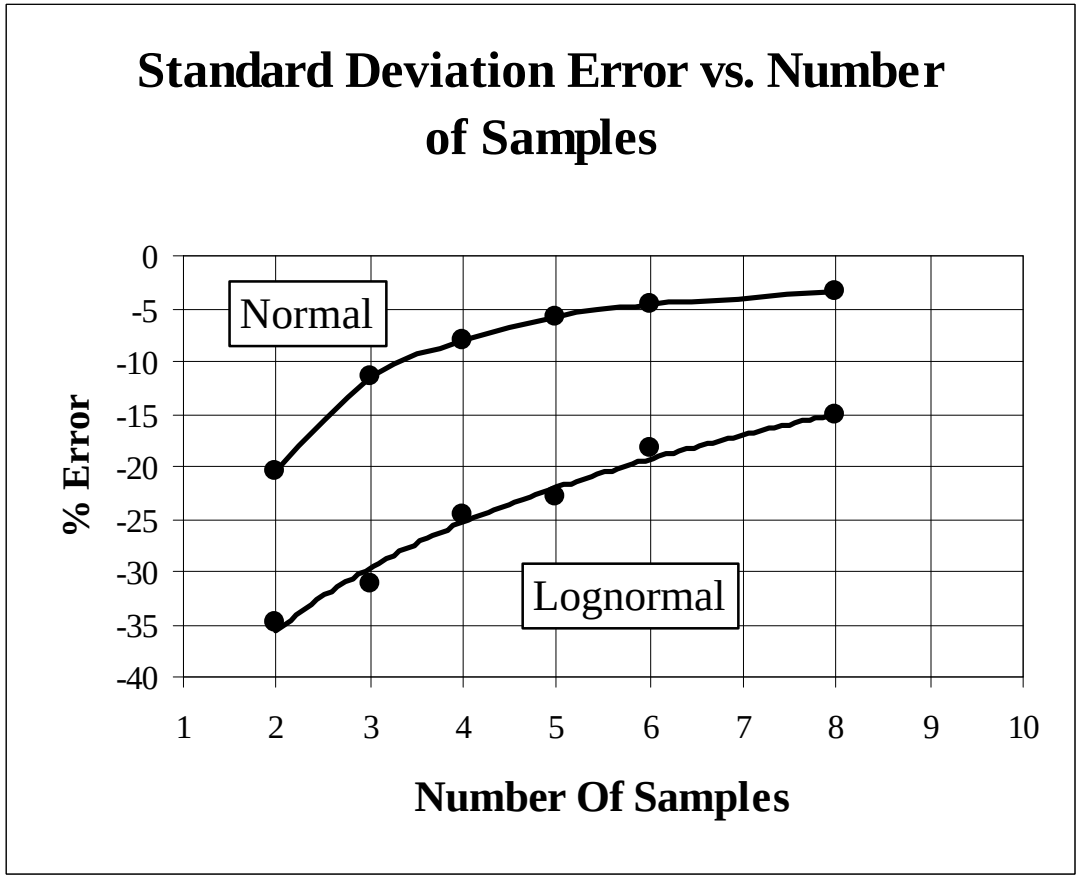
Normal = 1.73

Lognormal = 1.65

wyle laboratories

COV Statistical Sampling Bias

Space System Cost Variance and Estimating Uncertainty



wyle laboratories

Corrected AUC COVs

Space System Cost Variance and Estimating Uncertainty

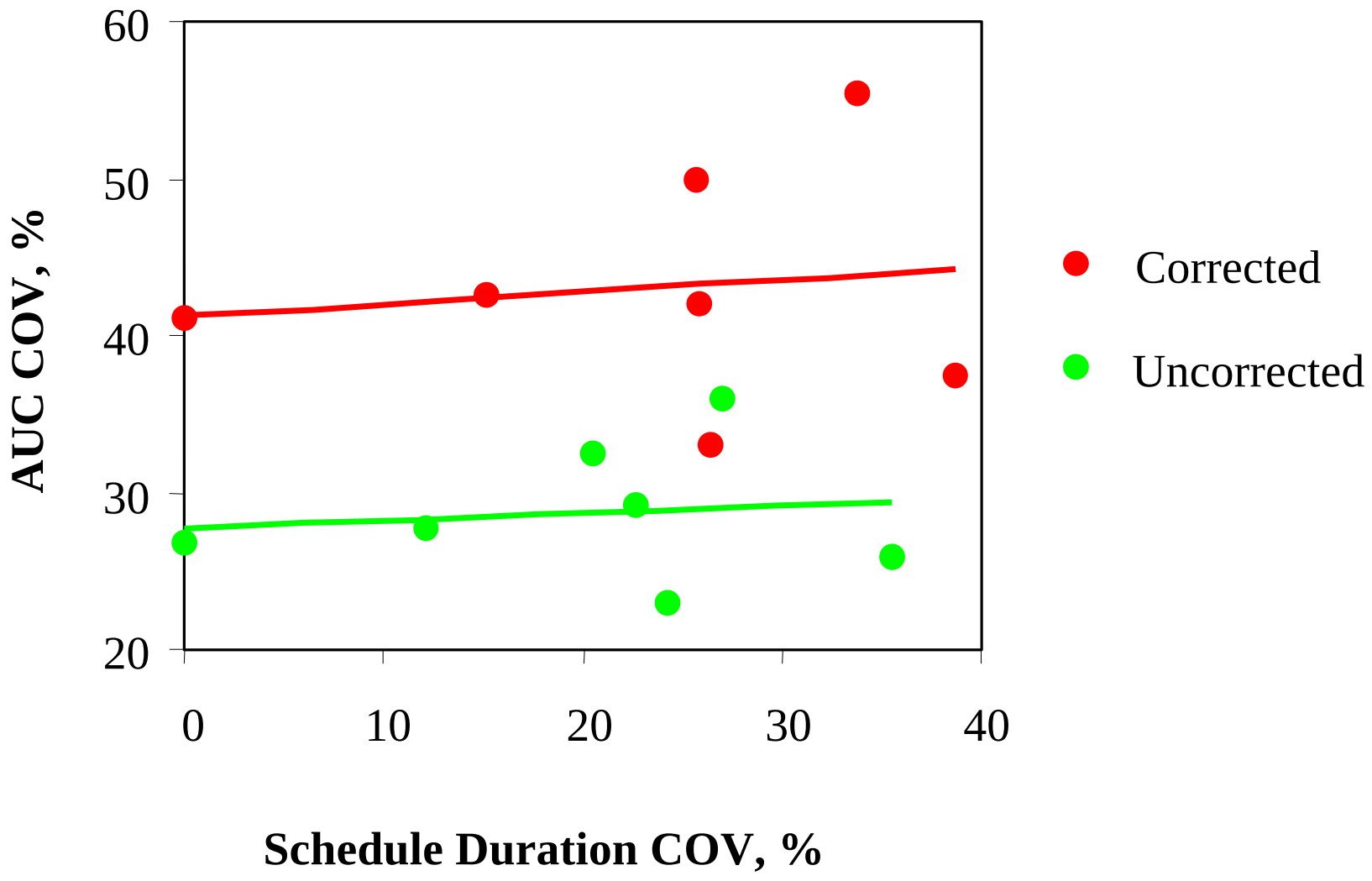
Correction of Box Coefficients of Variation for Sampling Biases (Approximate)

Contract Sequence	Avg. Box AUC COV (%)	No. of Samples with N Boxes				Weighted Correction Factors Normal Distribution				Weighted Correction Factors Lognormal Distribution				Corrected AUC COVs	
		2	3	4	Tot	2	3	4	Tot	2	3	4	Tot	Normal	Lognormal
		Raw Factors >>				1.25	1.14	1.09		1.54	1.41	1.35			
1	25.9	16	5	13	34	0.59	0.17	0.42	1.17	0.72	0.21	0.52	1.45	30.3	37.5
2	23.0	14	11	15	40	0.44	0.31	0.41	1.16	0.54	0.39	0.51	1.43	26.6	32.9
3	29.1	15	37		52	0.36	0.81		1.17	0.44	1.00		1.45	34.0	42.1
4	36.0	20			20	1.25			1.25	1.54			1.54	45.0	55.4
5	26.7	53			53	1.25			1.25	1.54			1.54	33.4	41.1
6	32.4	27			27	1.25			1.25	1.54			1.54	40.5	49.8
7	27.7	35			35	1.25			1.25	1.54			1.54	34.6	42.6
Total	--	180	53	28	261										
Average	28.7					0.86	0.23	0.12	1.21	1.06	0.29	0.14	1.49	33.9	41.8

wyle laboratories

AUC COV vs. Schedule COV

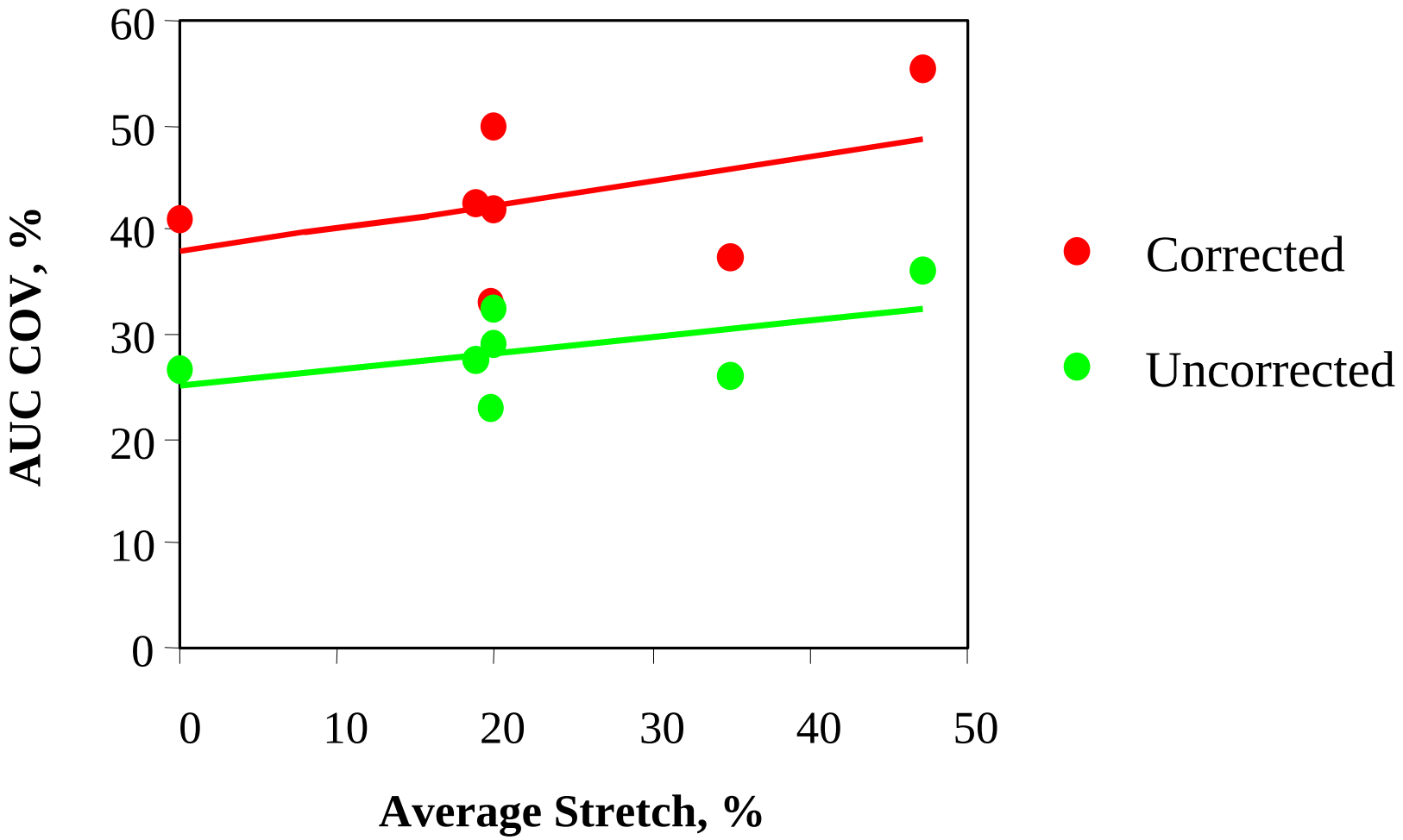
Space System Cost Variance and Estimating Uncertainty



wyle laboratories

AUC COV vs. Average Schedule Stretch

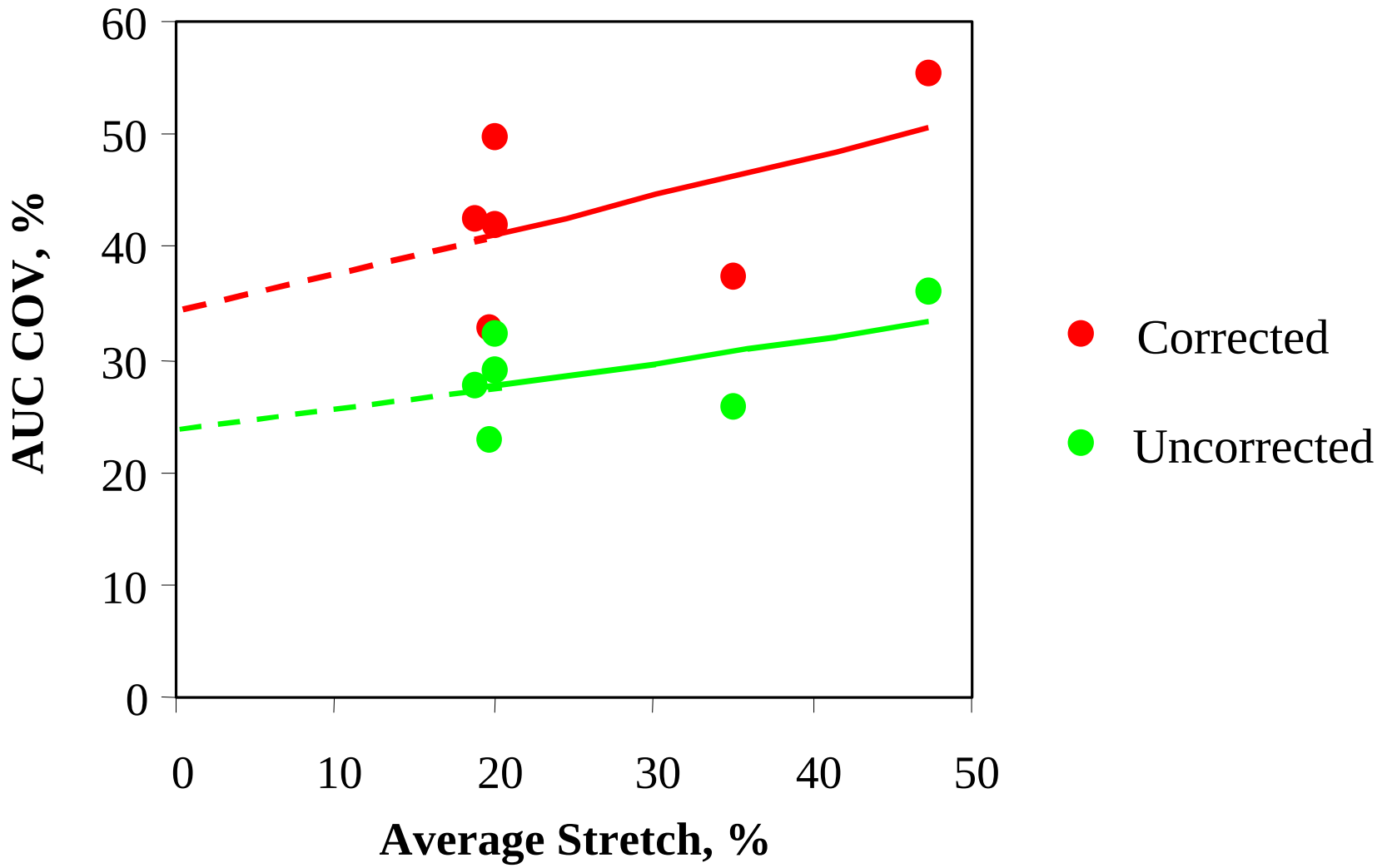
Space System Cost Variance and Estimating Uncertainty



wyle laboratories

AUC COV vs. Average Schedule Stretch

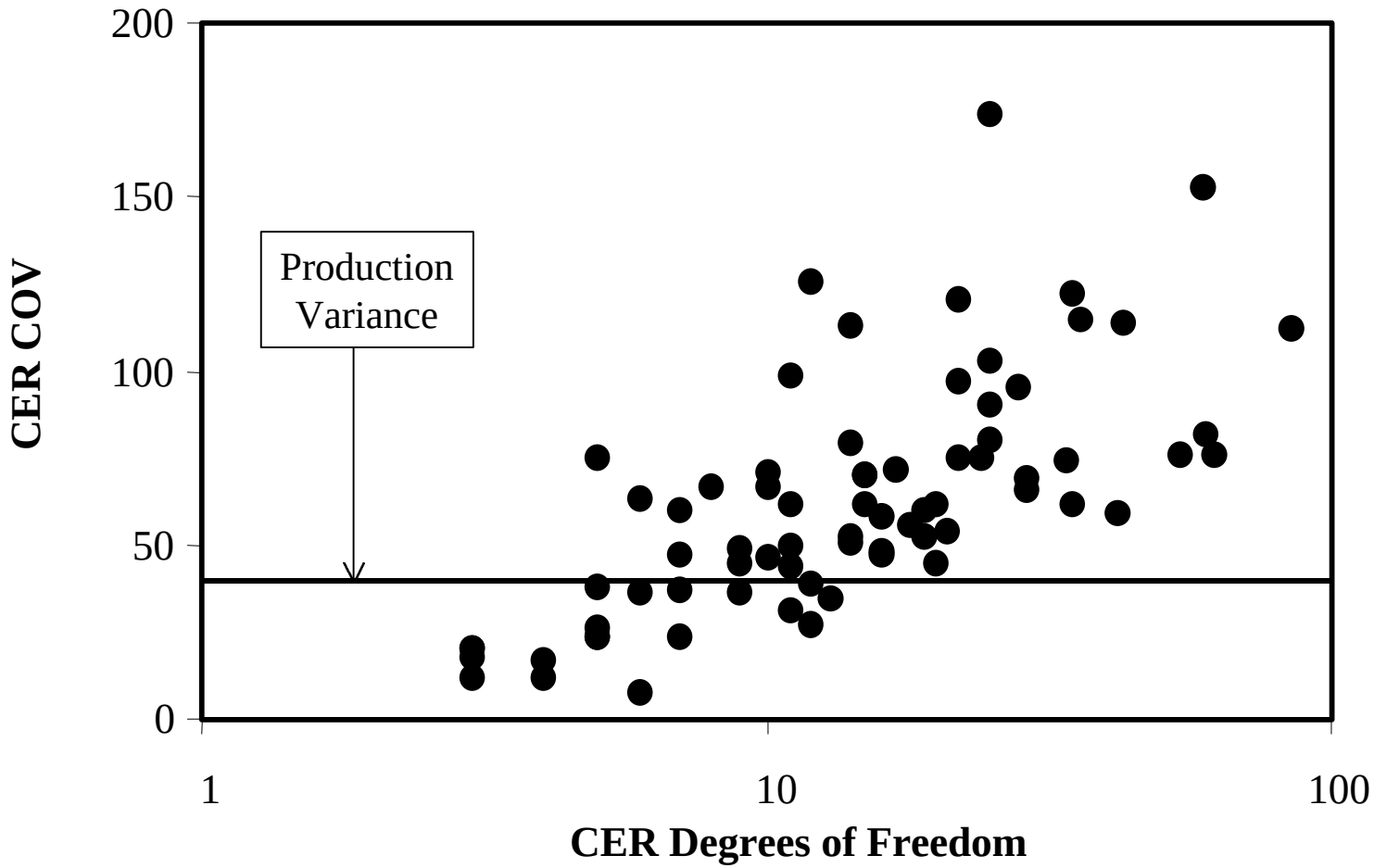
Space System Cost Variance and Estimating Uncertainty



wyle laboratories

CER COVs vs. Degrees of Freedom

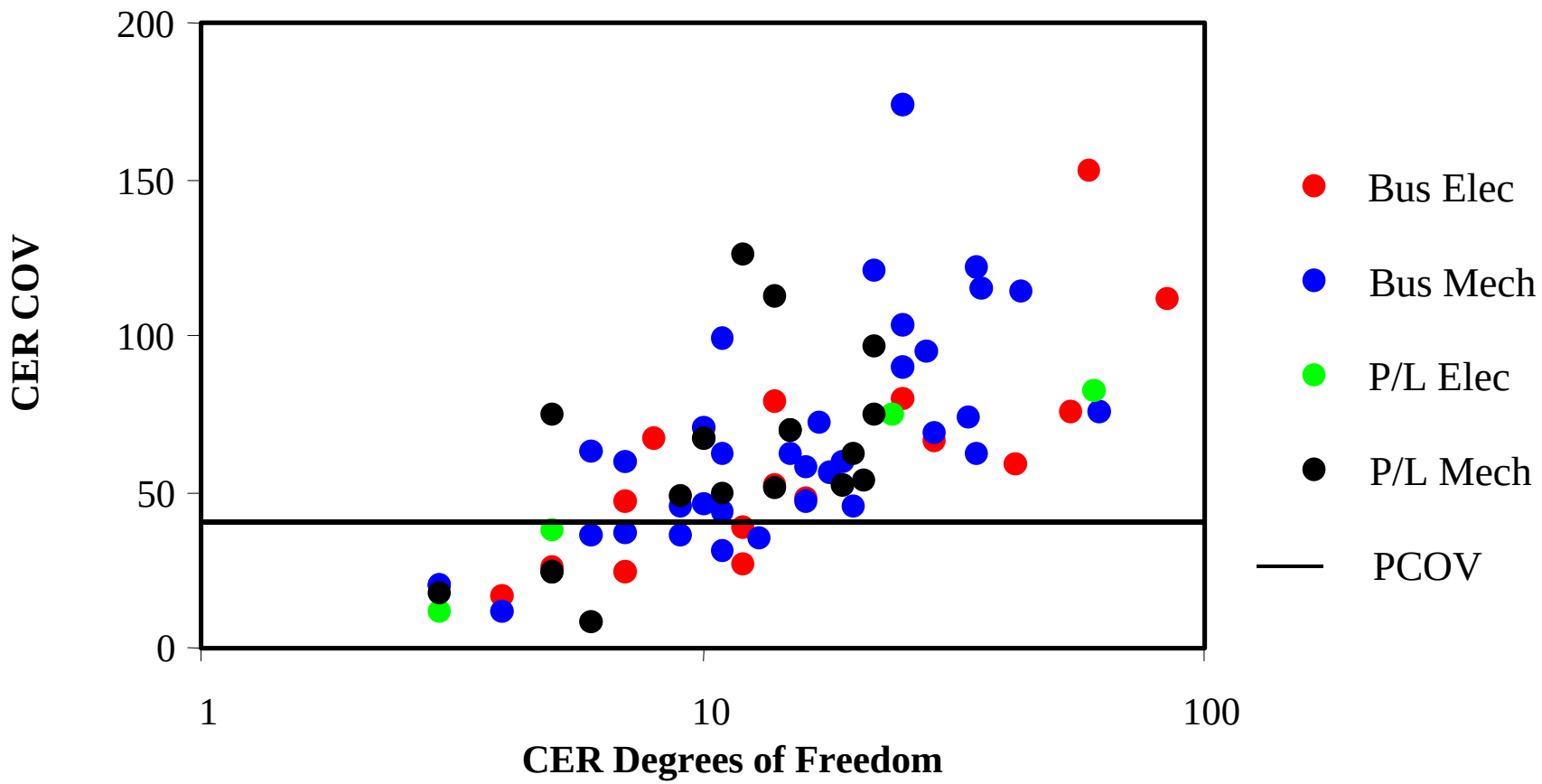
Space System Cost Variance and Estimating Uncertainty



wyle laboratories

CER COVs vs. DOF -- BY Equipment Class

Space System Cost Variance and Estimating Uncertainty



Observations and Conclusions

- **Production COV (PCOV) is in the 35-40 percent range across seven contract sequences**
- **PCOV appears to be fairly constant across space programs, box types and box sizes**
- **Production costs are probably lognormally distributed, or at least highly skewed**
- **20-30 percent of PCOV appears to be caused by schedule stretch**
- **Recurring cost (T1) COVs for CERs with 20-100 DOF are consistent with Production Variance**
- **CERs with less than 20 DOF underestimate COV -- COV should be adjusted for risk analyses**

Correlation Analysis

wyle laboratories

Box Production Cost Correlation

Space System Cost Variance and Estimating Uncertainty

Box Production Cost Correlation Levels

Contract Seq.	No. Boxes	Avg. Box AUC COV (%)	Avg. Correl. Coefficients			Effective Correlation		
			2-Box	3-Box	4-Box	2-Box	3-Box	4-Box
1	34	25.9	-0.03	0.27	0.32	-0.09	0.49	0.51
2	40	23.0	-0.03	-0.03	-0.04	-0.10	0.10	-0.11
3	52	29.1	-0.02	-0.03	--	0.36	0.39	--
4	20	36.0	0.46	--	--	0.89	--	--
5	53	26.7	0.01	--	--	-0.03	--	--
6	27	32.4	0.08	--	--	-0.14	--	--
7	35	27.7	0.11	--	--	0.08	--	--
Average	37.3	28.7	0.08	0.07	0.14	0.14	0.33	0.20
			0.02	(W/O Seq. 4)		0.01	(W/O Seq. 4)	
No. Cases	261		250	81	28	250	81	28

wyle laboratories

Bus Subsystem AUC Correlation

Space System Cost Variance and Estimating Uncertainty

Subsystem AUC CER Residual Correlation Levels

Subsystem	S&T	EPS	ACS	Prop	TT&C	Avg.
S&T	1.00	0.54	0.16	0.24	-0.08	0.22
EPS	0.54	1.00	0.42	0.07	0.49	0.38
ACS	0.16	0.42	1.00	-0.09	0.47	0.24
Prop	0.24	0.07	-0.09	1.00	0.10	0.08
TT&C	-0.08	0.49	0.47	0.10	1.00	0.25
Avg.	0.22	0.38	0.24	0.08	0.25	0.23
Avg. W/O Prop	0.21	0.48	0.35	N/A	0.29	0.33

Conclusions -- Production Correlation

- **Average box correlation is usually positive**
- **Larger boxes tend to display higher average correlation levels than small boxes**
- **Typical box production correlation is 0.15-0.20**
- **Bus subsystem correlation is about 0.20-0.40**
- **Propulsion correlation is much lower than correlation associated with other bus subsystems**
- **Reasonable assumptions are 0.15 for box level estimating and 0.30 for subsystem level estimating, although higher values might be justified**

System Level Estimating Uncertainty

wyle laboratories

System Production Cost COVs

Space System Cost Variance and Estimating Uncertainty

Example System Production Cost COV Values

No. Boxes	Box COV (%)	Correlation Coefficient	System COV (%)	No. Boxes	Box COV (%)	Correlation Coefficient	System COV (%)
20	30	0.10	11.4	20	30	0.20	14.7
50	30	0.10	10.3	50	30	0.20	13.9
100	30	0.10	9.9	100	30	0.20	13.7
200	30	0.10	9.7	200	30	0.20	13.5
20	50	0.10	19.0	20	50	0.20	24.5
50	50	0.10	17.2	50	50	0.20	23.2
100	50	0.10	16.5	100	50	0.20	22.8
200	50	0.10	16.2	200	50	0.20	22.6
20	70	0.10	26.7	20	70	0.20	34.3
50	70	0.10	24.0	50	70	0.20	32.5
100	70	0.10	23.1	100	70	0.20	31.9
200	70	0.10	22.6	200	70	0.20	31.6

Summary and Conclusions

- **Follow-on system production cost estimates should have COVs in the 10-15% range**
- **Production cost estimates for new systems should have COVs in the 15-30% range**
- **COVs for system development cost estimates should be in the 25-50% range, depending on the amount of design heritage and overall development challenge**
- **Forecasting is a risky business -- especially about the future!**