Integrated Estimating Relationships

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Abstract

The development of NASA's phasing model and its accuracy metric enabled additional research to be conducted on the integrated relationships between cost estimating, schedule estimating, and mission phasing. NASA's Office of Evaluation (OE) Cost Analysis Division (CAD) initiated a review in order to better understand and quantify the cost and schedule impacts of budget constraint issues, insight on how phasing affects cost and schedule, and more adequately plan for missions.

Using the same 37-mission database as the phasing model, schedule and cost models were also developed to form an integrated set of 3 estimating relationships and each mission's corresponding residual errors. The correlated residuals formed a trivariate distribution that enabled conditional probabilities (confidence levels) and conditional expectations (means) to be evaluated. From this analysis, a suite of tools was developed to empower decision makers to quantify the health of their program and to understand cost, schedule, and phasing trade-offs.

This paper describes the overall study, the resulting equations, and general finding when using multiple models. This provides analysts an effective way to assess changes in one dimension (e.g., phasing) and it's impact on another dimension (e.g., schedule).

Agenda

This Research Funded by NASA/OE/CAD

- Phasing, Cost, and Schedule Models
- Integrated Estimating Relationships
- Application Examples
  - Programmatic health check
  - Dual-conditioned case: Schedule probability
  - Single-condition case: Joint confidence in schedule and cost

2013: NASA's Phasing Estimating Relationship (PER)

Phasing models based on CADRe

- Project-level (excluding launch)
- Spacecraft-level

Phasing "drivers" affect amount of front/back-loading

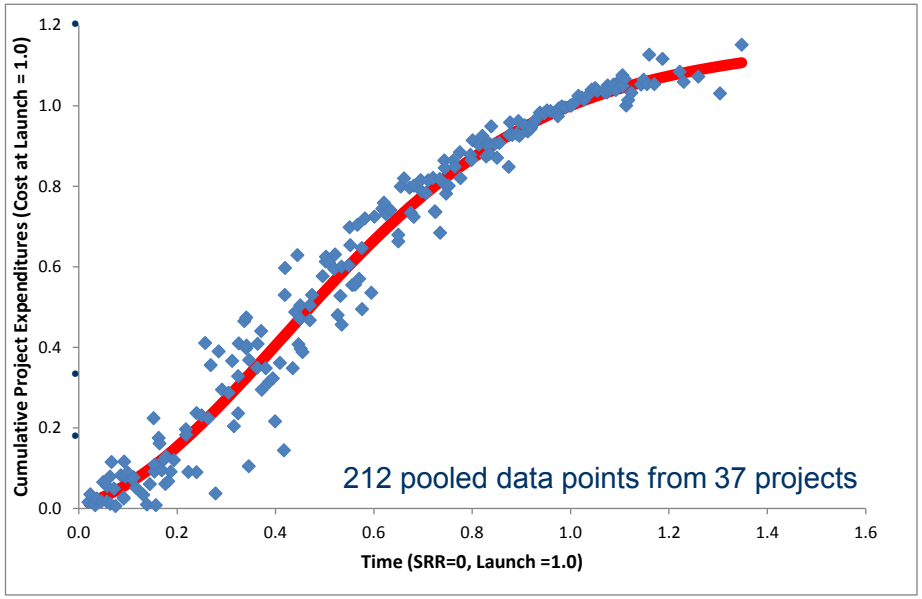
- AO vs. Directed mission
  Total project cost
- Significant GFE (foreign payload)
- Time to PDR

Useful accuracy metrics

- For project evaluation, budget defense
- For cost, schedule trades

Available to NASA, industry

Charts:
http://www.nasa.gov/offices/ooe/Symposium.html
Toolkit: Charles.D.Hunt@nasa.gov

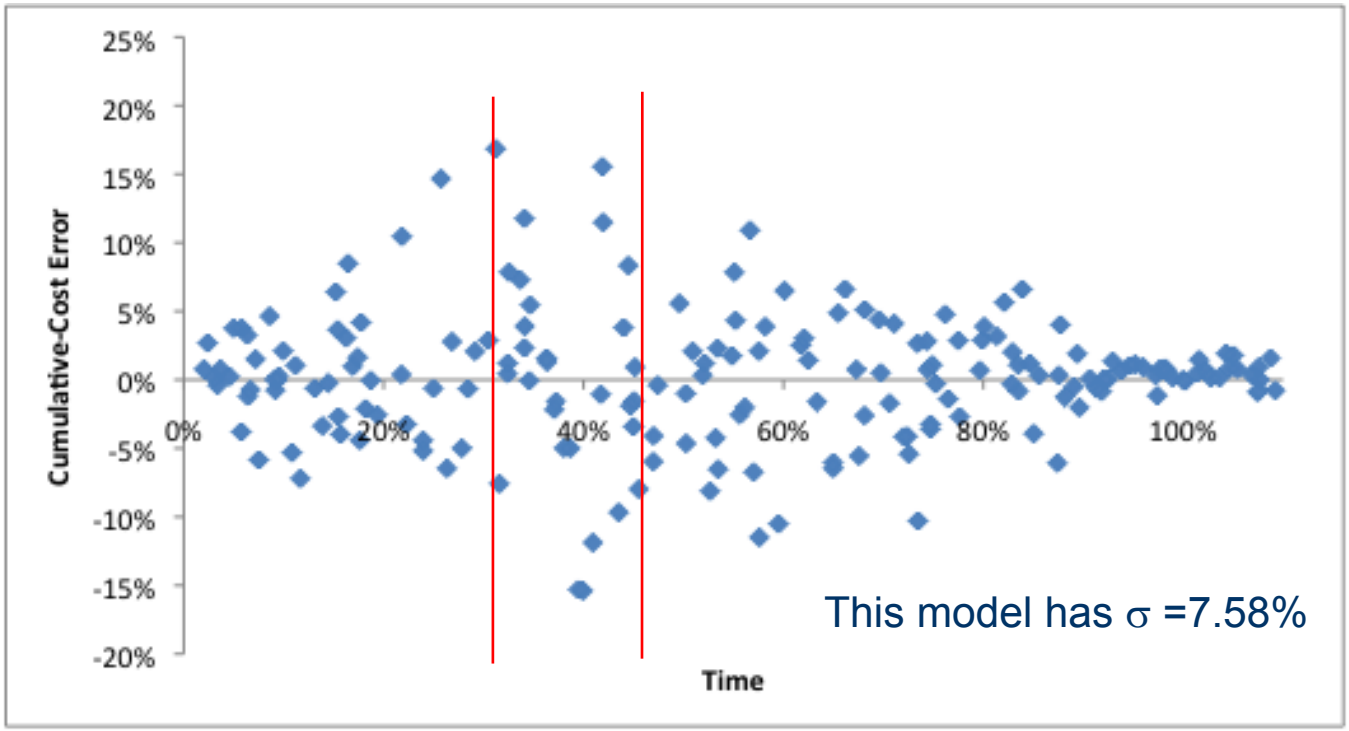


$$E\ t = d\left[Rt + 1 - e^{-\alpha(t-\gamma)^{\beta}}\right]$$

$$d = \frac{TOTAL\ COST}{R+1-e^{-\alpha(1-\gamma)^{\beta}}}$$

PER Residuals

- Each project has one residual per year, 4 to 10 total
- One residual from each @ ~40% time is used
- Indicates front or back-loading through critical early years



PER quantifies how front or back-loaded a project profile is

- Historical profiles (actuals)
- Proposed/planned profiles

Unanswered Questions

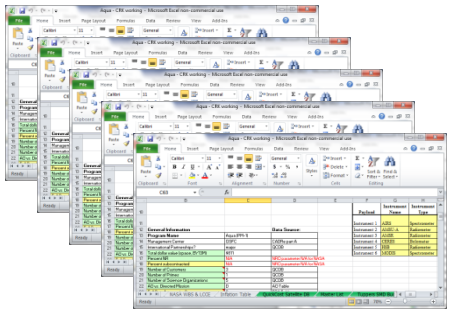
- **PER alone cannot answer some key questions:**
  - ✓ How realistic is a project's phasing/cost/schedule combination?
  - ✓ How likely is the schedule target, given the cost cap and phasing profile?
  - ✓ What is the joint confidence in meeting cost and schedule given a phasing profile?

- **PER is one of three estimating relationships we need**
  1. Phasing estimating relationship (PER)
  2. Cost estimating relationship (CER)
  3. Schedule estimating relationship (SER)

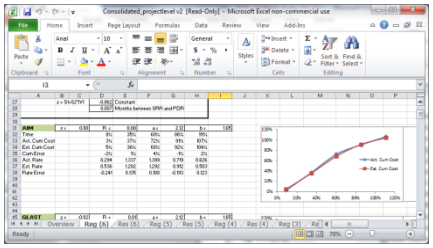
Dataset and Normalizations

- CADRe technical and cost data on 37 projects
- Normalization workbook created for each project
  - All sources identified and/or linked
- First tab in each workbook brought into regression book

AIM	MAP
GLAST/Fermi	Mars Odyssey
IBEX	MER
Contour	MGS
Stardust	TIMED
Dawn	Mars Pathfinder
Genesis	Kepler
THEMIS	OCO
CLOUDSAT	MSL
GALEX	Juno
GRACE	NuSTAR
LRO	SDO
MRO	COBE
New Horizons	ICEsat
Phoenix	TRMM
SIRTF	NEAR
STEREO	Aqua (PM-1)
GRAIL	Aura (Chem-1)
Glory	



Project Norm. Workbooks
- Traceable to CADRe and other data sources



Consolidated Workbook
- All data needed for regressions

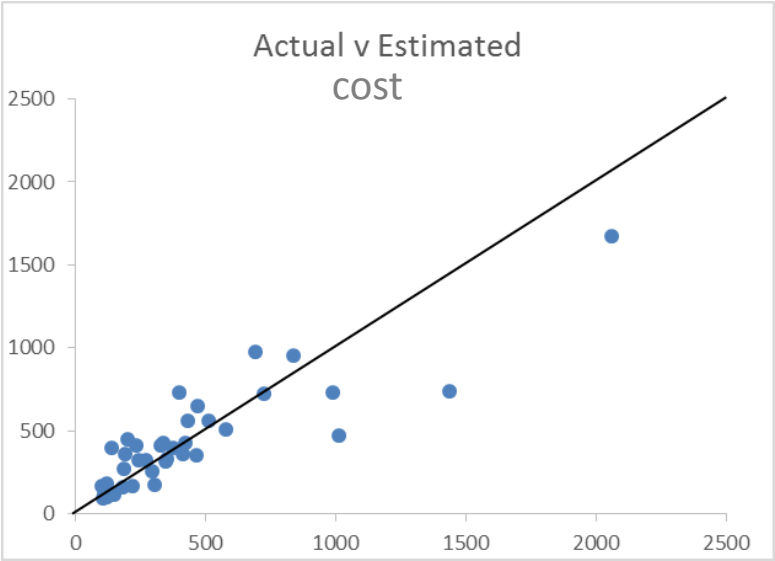
New SER and CER

- **Same n=37 database as PER… yields full set of correlated residuals**
- **Regressions in Excel**
  - Primary method is Zero-bias Minimum percent error (ZMPE)
  - Secondary is Log Transformed Ordinary Least Squares (LOLS)
- **Goal: Reasonable models that form basis for proof of concept**

PER Drivers	SER Drivers	CER Drivers
Total Mission Cost	Payload Mass	Spacecraft Mass
Months from SRR to PDR	Months from SRR to PDR	Percent New Design
GFE Hardware	Earth Orbiting or Interplanetary	Earth Orbiting or Interplanetary
AO or Directed	AO or Directed	AO or Directed

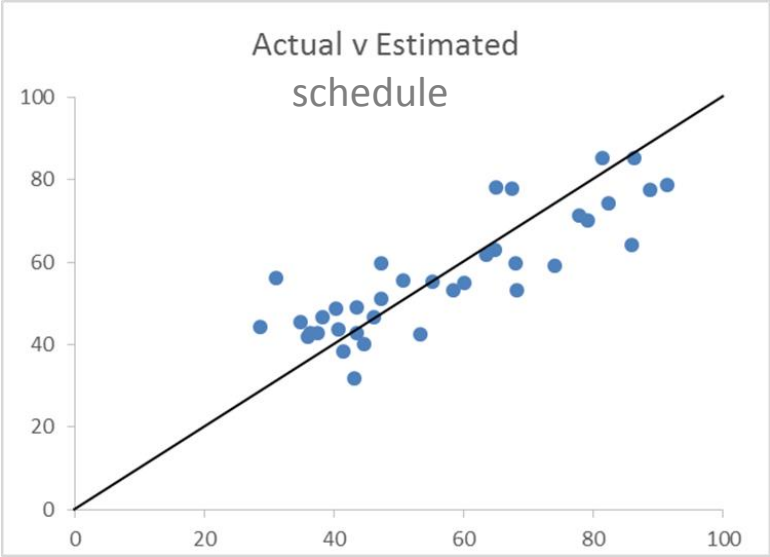
CER and SER

Project Cost (SRR-to Launch, BY13$M) =
44.5*(mass)^.46 * (%ND)^.69 * .60^(EO) * .63^(AO)



SPE of Estimate	41.66%
R-squared	0.74
Bias	0.00%

Months from SRR to Launch =
31*(payload mass)^.118 + .84*(SRRtoPDR) + 4.8*EO -11.0*AO



SPE of Estimate	41.66%
R-squared	0.74
Bias	0.00%

Reasonable models… Others can be used

A Trivariate Distribution

- Cost, Schedule, and Phasing models built from same dataset
- Residual errors (actual / estimated) form a trivariate distribution
- All analysis is based on these residuals
  - "Costly" means higher than the CER
  - "Front-loaded" is relative to the PER
  - "Long duration" means longer than the SER

Regression Residual Errors		
Phasing	SER	CER
1.0320	0.9202	1.1605
1.0037	0.8637	0.7648
1.1795	0.8729	1.2294
0.9639	0.8177	0.3567
0.9173	0.7664	0.6887
1.0546	1.2543	0.7962
0.9657	0.9300	0.7571
0.9935	1.0174	1.3136
1.0807	1.2533	1.1628
0.9198	1.0963	0.6045
0.9501	1.0267	0.9328
1.0495	0.9835	0.9816
0.9499	0.8825	1.1293
0.9139	1.1155	1.1413
0.9941	0.8263	1.0873
0.9080	1.3396	2.1564
0.9867	1.0920	0.7244
0.8868	1.0784	1.7514
0.9875	1.1293	1.0550
0.9652	1.0917	0.8362
0.9909	0.8473	1.3272
0.8563	0.8547	0.8754
0.8578	0.5491	0.5739
0.9723	1.0138	0.4486
0.8293	1.3506	0.7992
0.9838	1.0277	0.9121
0.8875	1.1378	1.3131
1.0261	1.2807	1.2326
0.9822	0.9104	1.0065
1.1198	0.7888	0.6737
0.9978	1.1084	0.7098
1.0232	1.1453	0.9510
0.9678	0.9983	1.1560
0.9663	0.9562	0.5503
1.1202	0.6440	0.5375
1.0166	0.8312	1.9506
0.9661	1.1612	1.3526

Conditional Expectation

- Expected value of one variable conditioned on the other two
- Estimated by ordinary least-squares regression

Dual-Condition Expectations

$$E(S \mid C,P) = .151\varepsilon_C - .342\varepsilon_P + 1.184$$
$$E(C \mid S,P) = .700\varepsilon_S + .020\varepsilon_P + .281$$
$$E(P \mid C,S) = .001\varepsilon_C - .0627\varepsilon_P + 1.042$$
$$\text{where } \varepsilon_n = \frac{\text{actual } n}{\text{estimated } n}$$

Single-Condition Expectations

$$E(C \mid S) = .699\varepsilon_S + .302$$
$$E(C \mid P) = -.246\varepsilon_P + 1.241$$
$$E(S \mid P) = -.380\varepsilon_P + 1.371$$
$$E(S \mid C) = .154\varepsilon_C + 0.845$$
$$E(P \mid C) = -.009\varepsilon_C + 0.989$$
$$E(P \mid S) = -.0619\varepsilon_S + 1.041$$
$$\text{where } \varepsilon_n = \frac{\text{actual } n}{\text{estimated } n}$$

- Same results also obtained by assuming normality and computing the conditional means
  - i.e., using the population regression equation

Multivariate Normal Distribution

- $\mathbf{X} = (X_1, X_2, X_3)$ is a 3-dimensional random vector (e.g., SER, PER, CER)
  - The expected vector of $\mathbf{X}$ is μ
  - The variance-covariance matrix is $\Sigma = \mathrm{Cov}(X_i, X_j)$, i, j = 1, ..., 3

- Partitioning:
  - Say $\mathbf{X}_1$ is a subvector of $\mathbf{X}$ with dimension 1 (e.g., SER)
  - Then $\mathbf{X}_2$ is the remainder of $\mathbf{X}$ with dimension 2 (e.g., PER, CER)

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \end{bmatrix} \qquad \boldsymbol{\mu} = \begin{bmatrix} \boldsymbol{\mu}_1 \\ \boldsymbol{\mu}_2 \end{bmatrix} \qquad \boldsymbol{\Sigma} = \begin{bmatrix} \boldsymbol{\Sigma}_{11} & \boldsymbol{\Sigma}_{12} \\ \boldsymbol{\Sigma}_{21} & \boldsymbol{\Sigma}_{22} \end{bmatrix}$$

  - The conditional distribution of $\mathbf{X}_1$ given $\mathbf{X}_2$ is distributed as

$$\mathbf{X}_1 \,|\mathbf{X}_2 \sim N_m(\mu_1, + \Sigma_{12}\Sigma_{22}^{-1} (\mathbf{X}_2 - \mu_2), \Sigma_{11} - \Sigma_{12}\, \Sigma_{22}^{-1}\Sigma_{12}')$$

- Conditional mean and variance are known exactly for the normal case.
  - Basis for a "programmatic health check" tool
  - Similar solutions worked out for one or more lognormal distributions

Programmatic Health Check

- **Programmatic Family Health Check**
  - Assess how "in family" the project is based on PER, SER, CER
    - Green if within 1 standard deviation
    - Red if outside 1 standard deviation
  - Each evaluation is conditional
    - For example, is schedule within 1σ given the phasing and cost conditions?

Programmatic Health Check		Standard deviation of marginal distributions		
	Project Baseline	Upper (+1σ)	Lower (-1σ)	
Phasing	5%	4%	-10%	RED
SER	18%	14%	-20%	RED
CER	-4%	50%	-24%	GREEN

Residuals computed by comparing baseline plan to SER, PER, CER results.

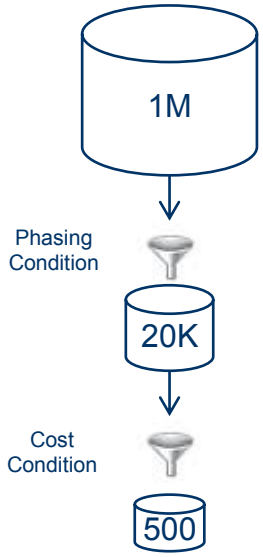
Upper and lower standard deviation of marginal distributions.

Notional "Health Check" result

Conditional Probabilities: More Utility

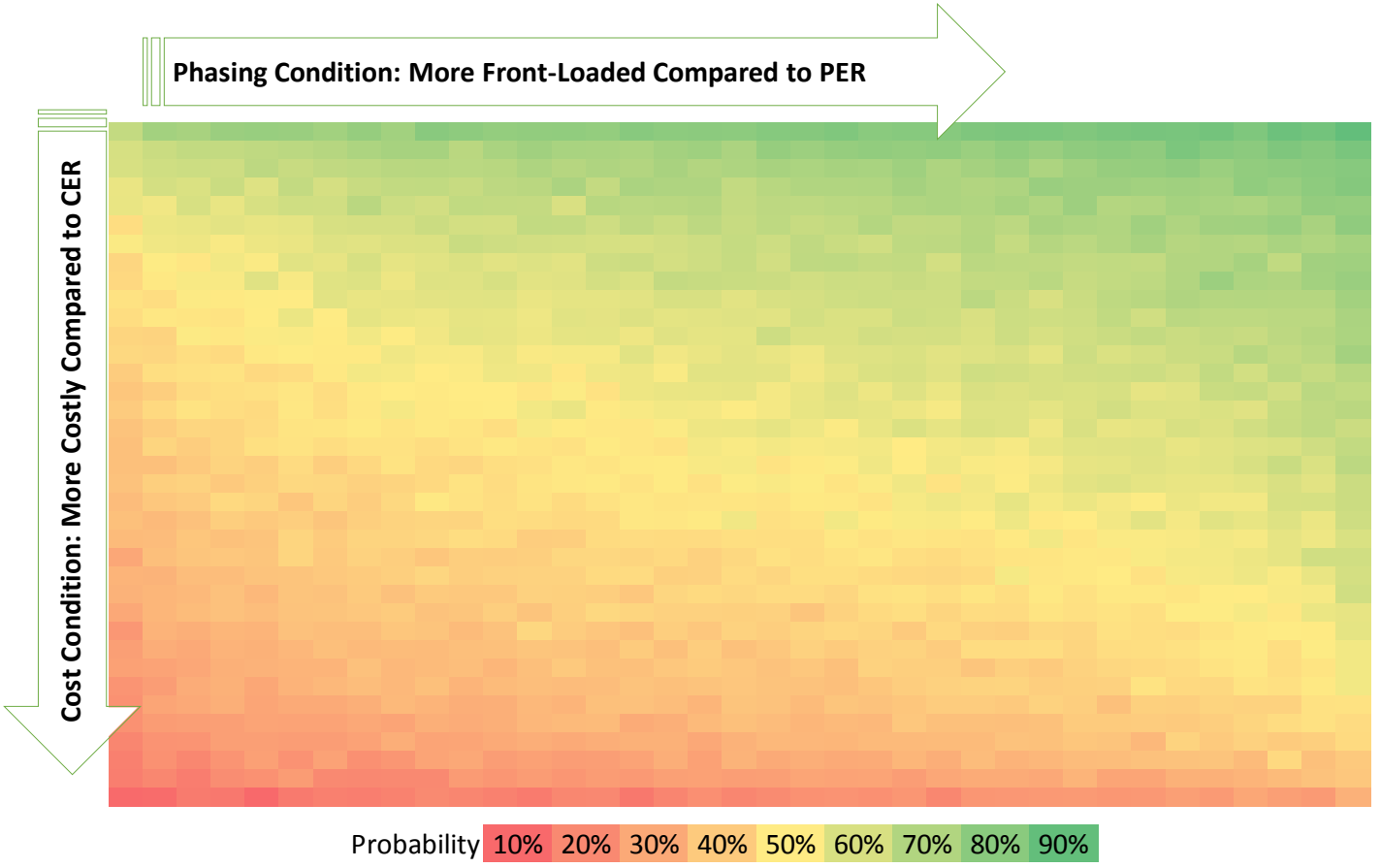
- **Confidence level in one variable, conditioned on the other two**
- **By simulation:** (no distributional assumption needed)
  - Sample directly from correlated residuals
  - Create large database (1M samples)
  - Filter & count outcomes that satisfy any combination of input conditions

Example:
Given my project's budget profile & cost estimate, what is the probability it will be ready for launch by the need date?



What % are below target launch date?

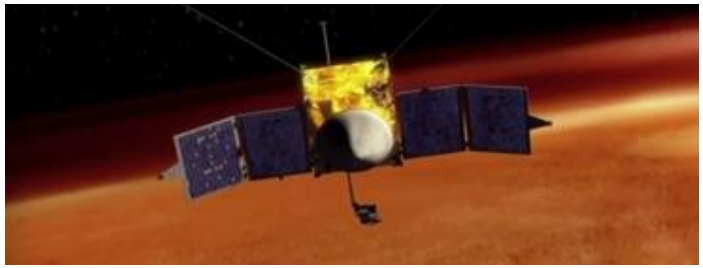
Conditional Probability Result



Probability that schedule will be shorter than target

Example: MAVEN at SRR

- **Mars Atmosphere and Volatile Evolution Mission**
  - GSFC-led project
  - Lockheed Martin spacecraft
  - Fixed launch: 20-day launch window
- **From the SRR CADRe:**
  - Planned cost: 33% above the CER: ε_c=1.33
  - Planned schedule: 51 months, which is 5.4% above the SER: ε_s=1.054
  - Planned budget profile: -2.6% back-loaded: ε_p=.974



Given SRR plans (phasing and total budgeted cost) what is the confidence that this schedule will be met?

MAVEN Schedule Confidence (@SRR)

Probability that schedule will be below 51 months, given cost and phasing conditions

Phasing Condition: More Front-Loaded Compared to PER

Cost Condition: More costly compared to CER

73%	80%	79%	81%	82%	82%	80%	82%	80%	85%	84%	83%	83%	83%	83%	85%	84%	85%	84%	86%	86%	87%	85%	86%	[illegible]	87%	88%	88%	87%	88%	89%	89%	90%	87%	91%	90%	93%
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42%	43%	44%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	53%	55%	54%	55%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	59%	57%	59%	59%	58%	60%	60%	62%	62%	70%
39%	43%	45%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	52%	52%	52%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55%	58%	57%	58%	56%	60%	60%	62%	59%	64%	65%
34%	43%	41%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	51%	49%	52%	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	52%	51%	54%	54%	57%	56%	55%	58%	59%	60%	60%	65%
36%	41%	39%	43%	42%	44%	46%	45%	45%	45%	46%	46%	48%	48%	46%	50%	46%	51%	47%	45[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55%	55%	56%	53%	56%	56%	57%	59%	59%	56%	60%	63%
37%	38%	39%	42%	42%	43%	43%	47%	44%	45%	46%	44%	46%	50%	47%	47%	49%	50%	49%	47%	[illegible]	[illegible]	[illegible]	[illegible]	51%	48%	51%	50%	52%	54%	54%	55%	57%	59%	56%	58%	63%
33%	36%	40%	42%	39%	43%	44%	46%	44%	47%	43%	45%	46%	45%	46%	47%	47%	48%	49%	48%	[illegible]	[illegible]	[illegible]	51%	52%	53%	53%	51%	52%	52%	57%	55%	54%	58%	57%	59%	63%
32%	38%	40%	41%	38%	40%	40%	41%	44%	43%	41%	41%	44%	43%	47%	47%	46%	43%	48%	47%	45%	[illegible]	48%	50%	50%	49%	52%	51%	47%	52%	51%	53%	52%	52%	57%	57%
32%	35%	36%	36%	38%	37%	38%	39%	38%	41%	40%	41%	44%	45%	45%	40%	41%	45%	47%	45%	44%	[illegible]	44%	49%	47%	47%	46%	47%	50%	50%	51%	50%	51%	53%	55%	57%	55%
29%	33%	33%	36%	36%	36%	36%	37%	41%	38%	38%	40%	41%	40%	41%	42%	42%	39%	42%	44%	44%	44%	45%	45%	45%	45%	47%	47%	48%	48%	44%	53%	50%	52%	50%	51%	55%
27%	32%	29%	33%	37%	32%	37%	32%	34%	38%	39%	36%	37%	36%	36%	37%	41%	37%	43%	40%	41%	40%	40%	44%	41%	45%	43%	44%	45%	46%	47%	47%	48%	45%	54%	47%	50%
26%	29%	26%	31%	32%	35%	30%	29%	29%	29%	35%	34%	35%	34%	35%	34%	37%	37%	36%	36%	38%	38%	38%	36%	39%	40%	40%	39%	43%	38%	38%	42%	42%	43%	45%	47%	49%
20%	21%	25%	24%	19%	25%	27%	26%	27%	30%	28%	27%	25%	29%	29%	24%	28%	31%	29%	30%	32%	33%	32%	34%	29%	33%	34%	34%	35%	34%	34%	36%	35%	39%	37%	35%	42%

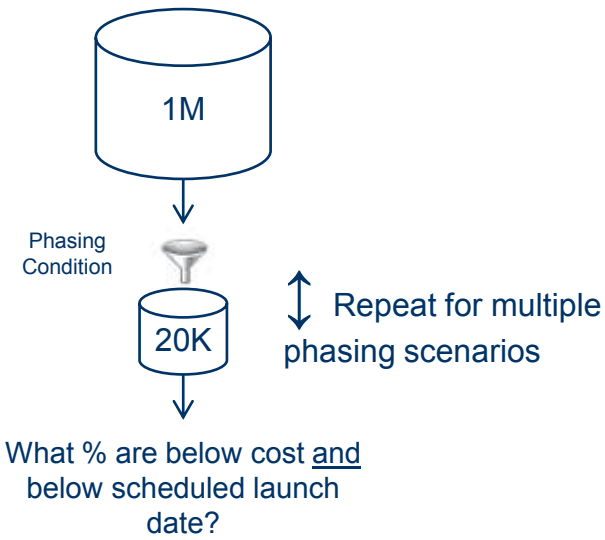
MAVEN SRR Plan falls in this region

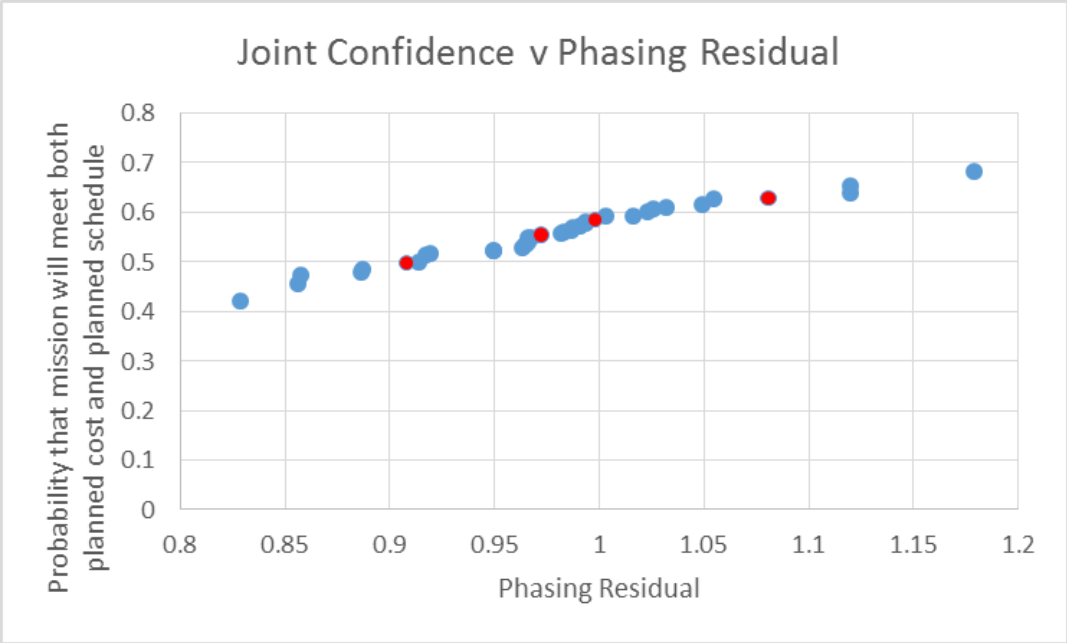
Lowering cost and increasing front-loading would increase schedule confidence

Probability	10%	20%	30%	40%	50%	60%	70%	80%	90%

Another Application: Joint Confidence Level

- Probability of meeting cost & schedule, conditioned on phasing
- By simulation: Similar process

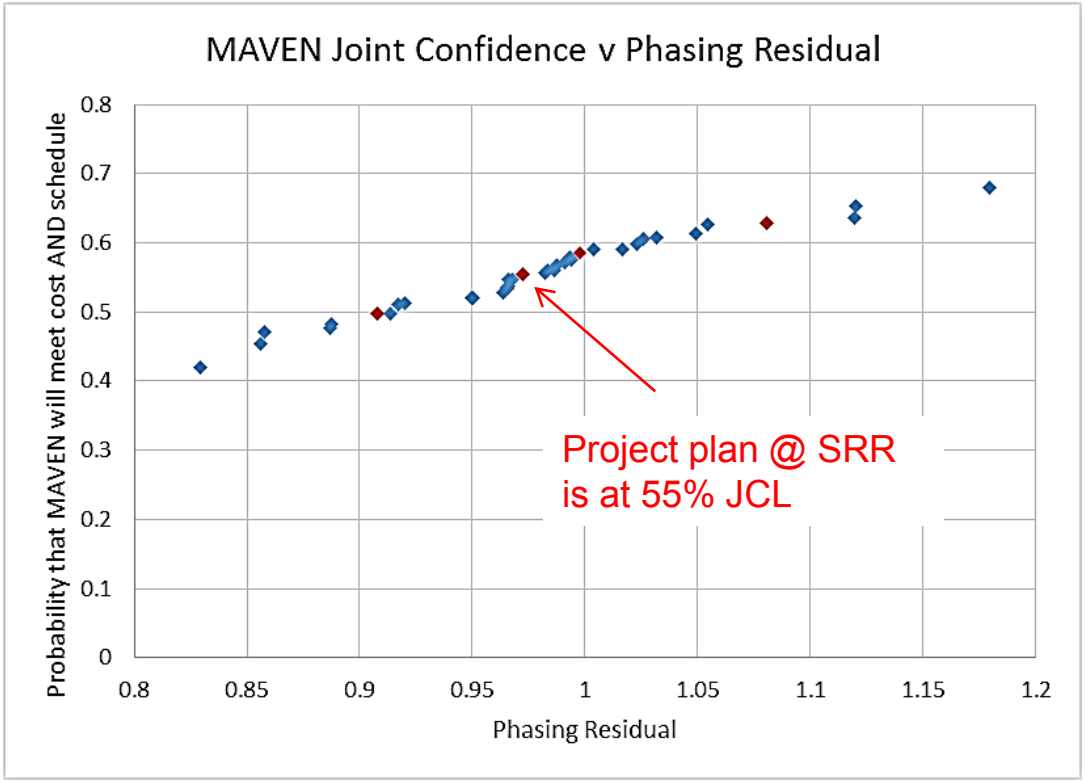




Joint Confidence Example: MAVEN @ SRR

- Both cost and schedule conditions are used when calculating JCL
- Joint confidence levels vs. phasing condition:

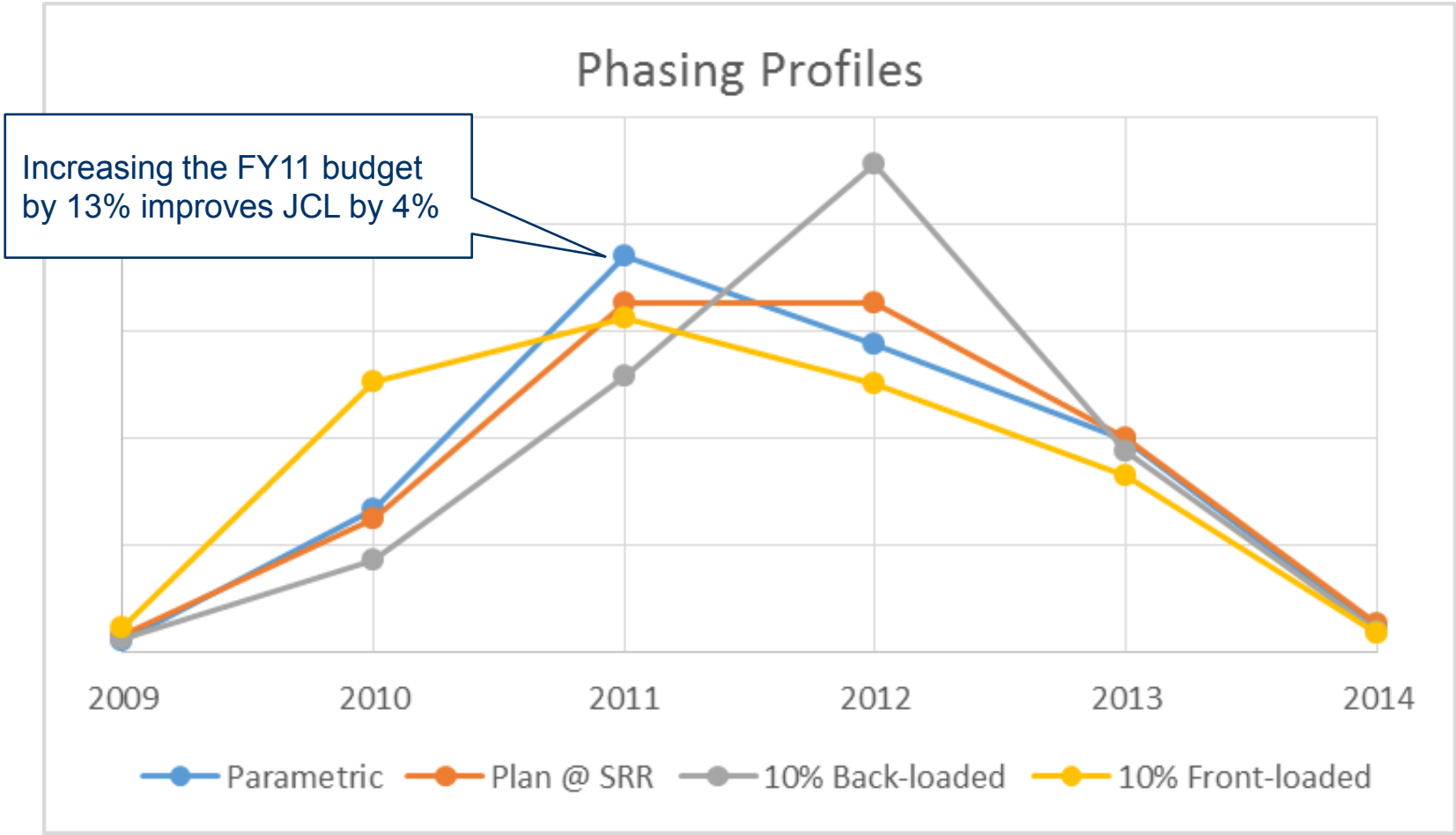
Phasing	Joint Confidence
Front-loaded by 10%	63%
Baseline PER	59%
SRR Plan (2.8 % back-loaded)	55%
Back-loaded by 10%	50%



Phasing adjustments can swing joint cost-schedule confidence from 42% to 68%

MAVEN "What-if" Profiles

- Changes in mission front-loadedness can noticeably affect JCL



Key Findings

- **Phasing affects schedule, which affects cost, but there is no evidence from this study that phasing alone drives cost.**

- **Conditional probabilities are useful models**
  - Trivariate conditional model has several uses
    - Single or dual conditions
    - Joint confidence level
    - Conditional expectations and S-curves
  - Changes in cost or schedule confidence level are clear in results
  - Several scenarios show this utility

- **These integrated estimating relationships are not generally useful for optimization problems**
  - Conditional expectation results are linear
  - Some have low statistical significance
  - No minima exist except at boundary conditions

Conclusion

- **Integrated Estimating Relationships quantify cost/schedule/phasing trade-offs**
  - Enabled by NASA's phasing model and its accuracy metric
  - Trivariate conditional model has several uses
    - Single or dual conditions
    - Joint confidence level
    - Conditional expectations and S-curves

- **This is a proof of concept**
  - Other cost, schedule, phasing models can be used
  - Requires database of correlated residuals (the trivariate distribution)

Thank You