ICEAA 2024
MAY 14-16 - MINNEAPOLIS

Data-Driven Constellation Architecture Design Using Integrated Models (MOD02)

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Background and Motivation

Traditional early-phase satellite design and evaluation methodology

- Fast-paced, linear flowing
- Minimal maturation iterations due to aggressive schedules and lean budgets
- Cost evaluations assessed near the end of the design phase

Issues

1. Design concepts are often predicated on previous programs or designs which may have limited applicability to the mission.
2. Few design iterations are performed, resulting in potentially non-optimal concepts for cost and the required mission performance.
3. Design teams have low flexibility with regards to proposed concepts; opposing drastic change in response to aggressive deadlines.
4. Chronological separation of the technical design from the cost assessment results in low transparency or complete loss of insight into the cost implications of early design decisions.

New early-phase satellite design and evaluation methodology

- Data-driven parametric surrogate modeling that links performance requirements to cost

Advantages

1. Captures downstream impacts to cost from design choices
2. Allows for optimal ranges of design parameters that minimize cost while maximizing performance
3. Enables on-the-fly “what-if” analyses
4. Can help inform requirements development

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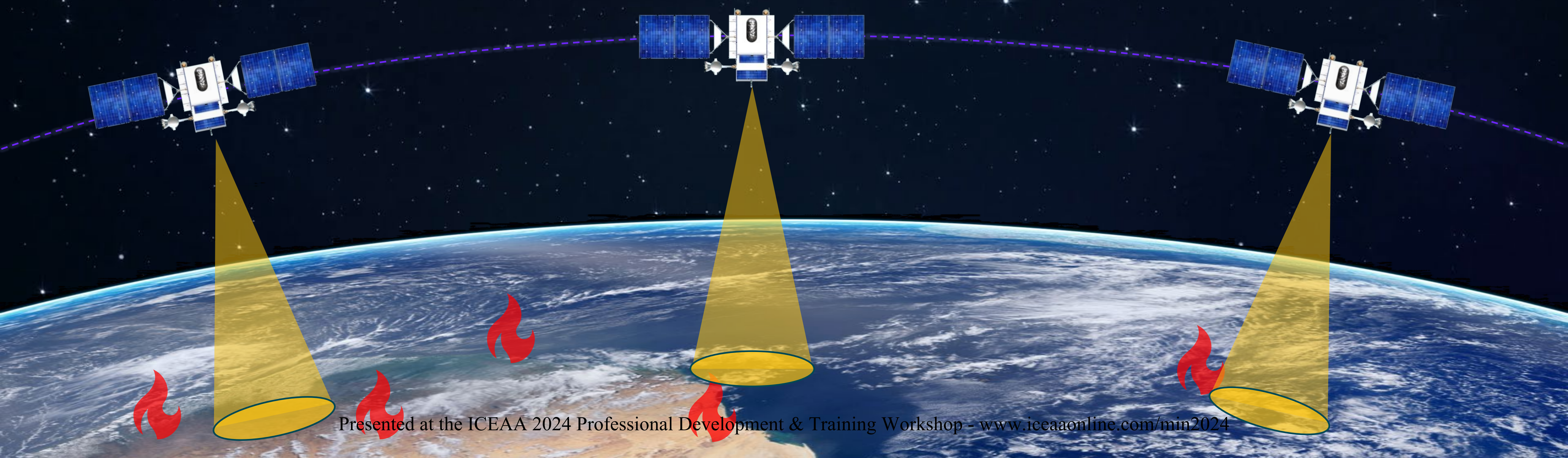
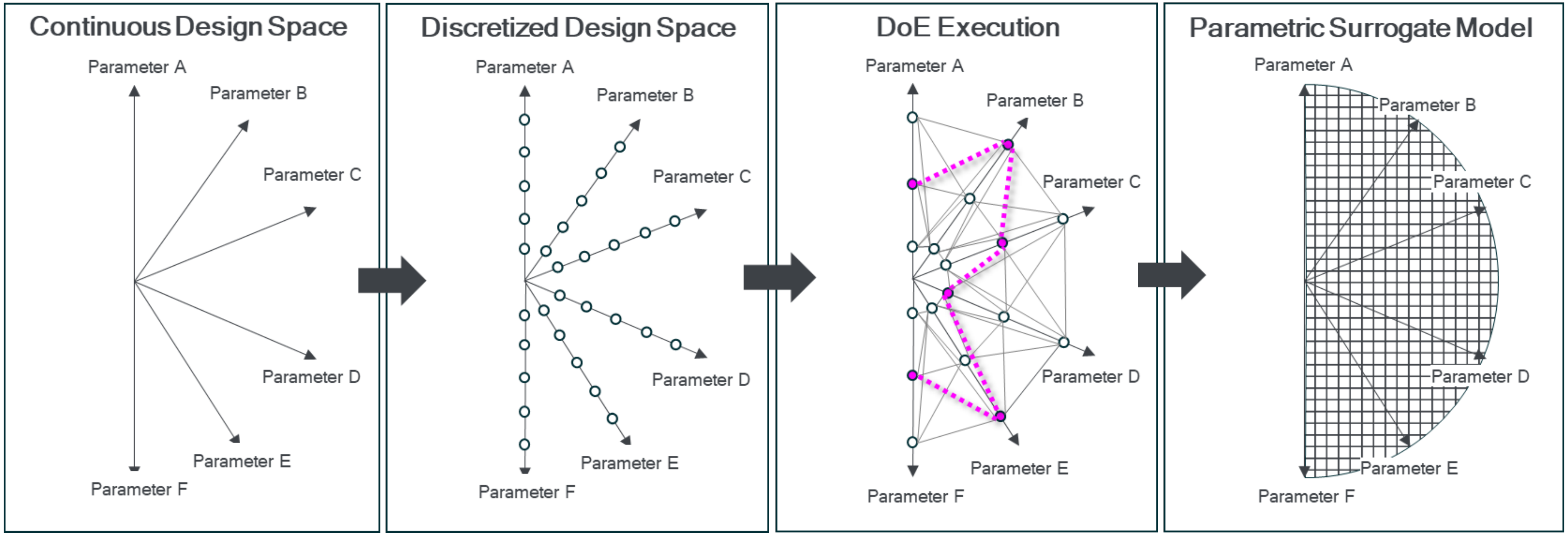
Example Mission: SPACE-BASED FIRE MONITORING AND DETECTION

- Suppose that a three-year remote sensing mission is required at a **competitive cost** to help firefighters monitor potential fire risk locations and locate active fires across the continental United States at a maximum **revisit rate of 6 hours**.
- This mission requires that each vehicle be capable of **monitoring at least 30 separate locations per day** with an image resolution less than or equal to **8 meters per pixel** through smoke for a duration of no less than **2 seconds per location**.



Parametric Surrogate Model Creation



1. Ascertain design-space influencing independent parameters constituting the **Continuous Design Space**
2. Subdivide the parameters in the continuous design space to create a **Discretized Design Space**
3. Minimize number of samples/simulations while maximizing design space coverage with a **Design of Experiments**
4. Model full design space using a **Parametric Surrogate Model** built using regressions or machine learning techniques

Parametric Surrogate Model Creation

Question	Requirement	Influencing Factor
What does the customer want to observe?	Fires through smoke 8m resolution per pixel	Sensor Phenomenology
How often does the customer want to observe it?	Every 6 hours	Altitude
How much of it does the customer want to observe?	30 per vehicle per day 2s duration	Vehicle Agility Number of Vehicles and their Spacing
How much will it cost?	Competitive Cost	Factors driving cost are not easily ascertained

Informs which parameters are necessary for a DoE

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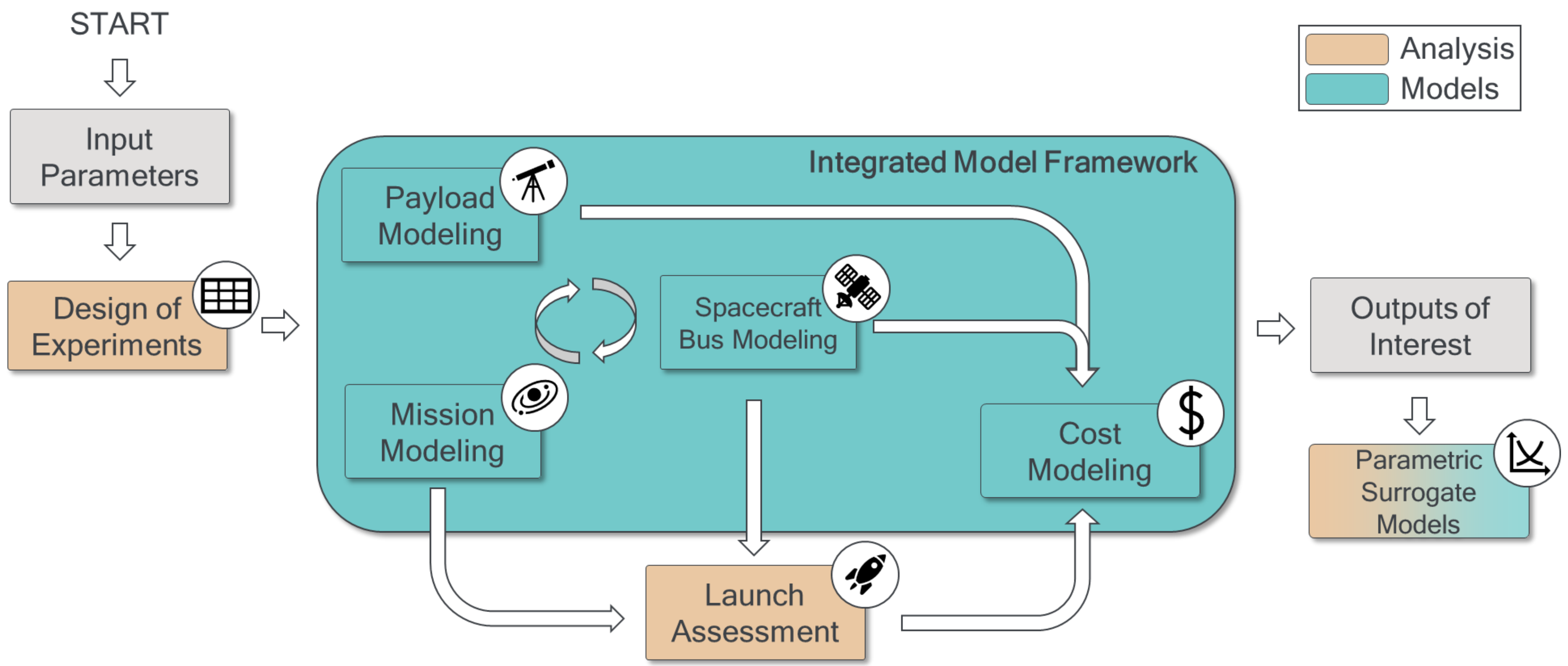
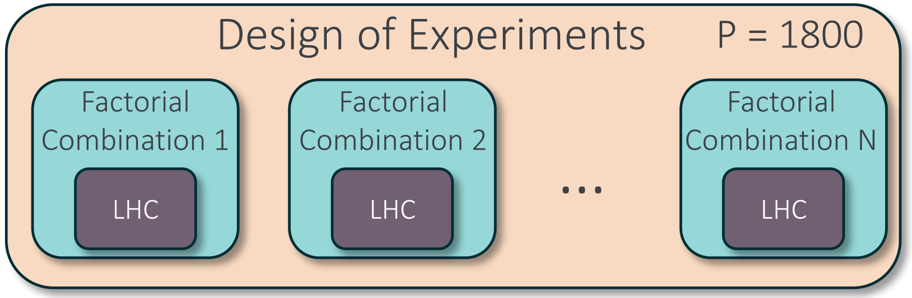
Analysis Flow



Design Input	Lower Range	Upper Range	DoE Type
Altitude (km)	450	800	LHC
Number of Constellation Planes	4	11	Factorial
Number of Satellites per Plane	2	6	Factorial
Slew Rate (deg/s)	0.5	4.0	LHC
Ground Sample Distance (m)	3.0	30.0	LHC



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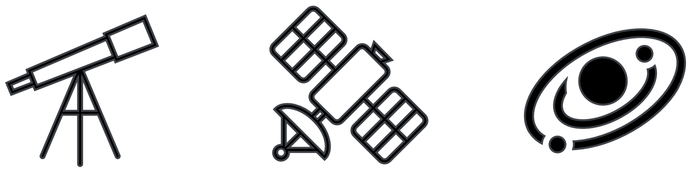
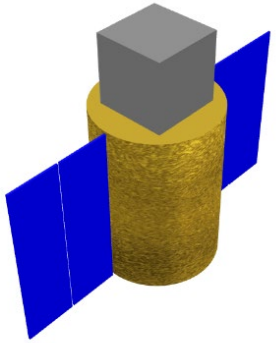
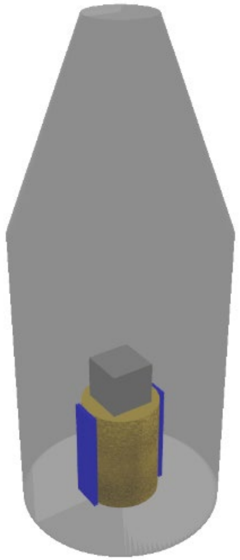
Engineering Models



- Mission, Payload, and Bus interdependencies must be modeled to accurately capture downstream impacts to design choices
- *MOSAIC* is a unified mission and space vehicle modeling framework
  - ✓ Cross-model communication
  - ✓ Configurable and customizable
  - ✓ Validated against historic flight and study designs
  - ❑ *Mission Modeling:*
    - ❑ Orbit propagation, target collection scheduling, vehicle maneuver dynamics
    - ❑ Varying payload phenomenology modeling
  - ❑ *Space Vehicle Modeling*:
    - ❑ Rapid, iterative, physics-first methods
    - ❑ SME-developed subsystem and system sizing routines
    - ❑ Historic design choices and regressions
  - ⚐ Cannot estimate cost without dedicated cost modeling capabilities





Cost Modeling

- Analysis of Alternatives (AoAs) have unique challenges for cost estimators
- *Parametric Estimating* is appropriate methodology commonly used in early lifecycle phases
  - ✓ Adapt well to changing design parameters
  - ✓ Offer statistical results with insights into quality & uncertainty
  - Relevant and reliable historical data is required
  - More cases & changes to design parameters → the more inputs needed for modeling
- Cost Estimating Relationships (CERs) can be highly effective, IF…
  - ❑ Relevant CERs are available to cover the WBS scope of the mission
  - ❑ Reliable input values can be provided for independent variables in CERs

We need great CERs + We need great design tool to develop input variables

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BALLER | CER Development and Integration Process

Data Normalization → **Regression Analysis** → **Integration with MOSAIC**

1. **Develop** a Standard WBS
2. **Map** SWBS to all historical programs' cost
3. **Normalize** cost data
   - *Allocate NRE vs RE charges*
   - *Adjust costs to a common base-year*
4. **Identify** candidate variables for data collection
   - *leverage industry cost group insights*
5. **Collect and review** technical and programmatic data
   - Map to SWBS to ease regression analysis
6. **Organize** and consolidate data to support efficient regression analysis

1. **Explore** the data: assess correlations of independent variables
   - to each other, and to cost
2. **Review** preliminary data analysis with technical SMEs
   - revisit tech data as required
3. **Perform regression** analysis and develop CERs
4. **Review** preliminary CERs with technical SMEs
   - revisit previous steps as necessary
5. **Publish and document** CERs once validation

1. **Review** CERs and assess all independent variables
2. **Develop** engineering model output analogs or relationships to CER inputs
3. **Insert** CERs into engineering models
4. **Validate** engineering model integrated CER predictions against CER expected predictions

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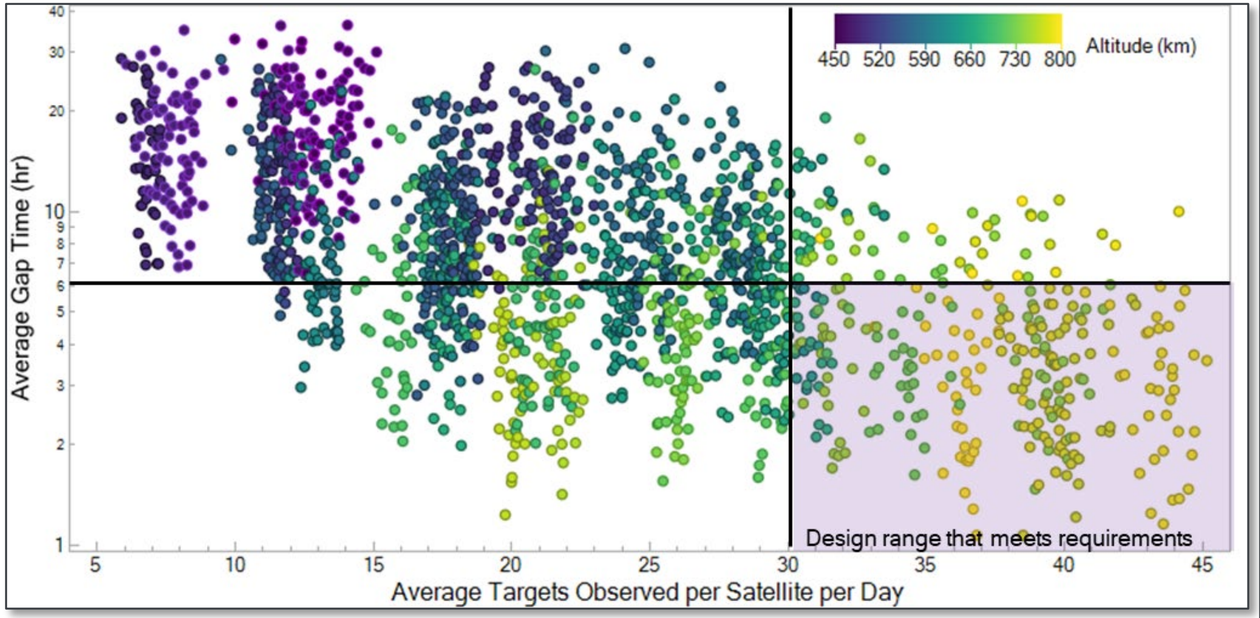
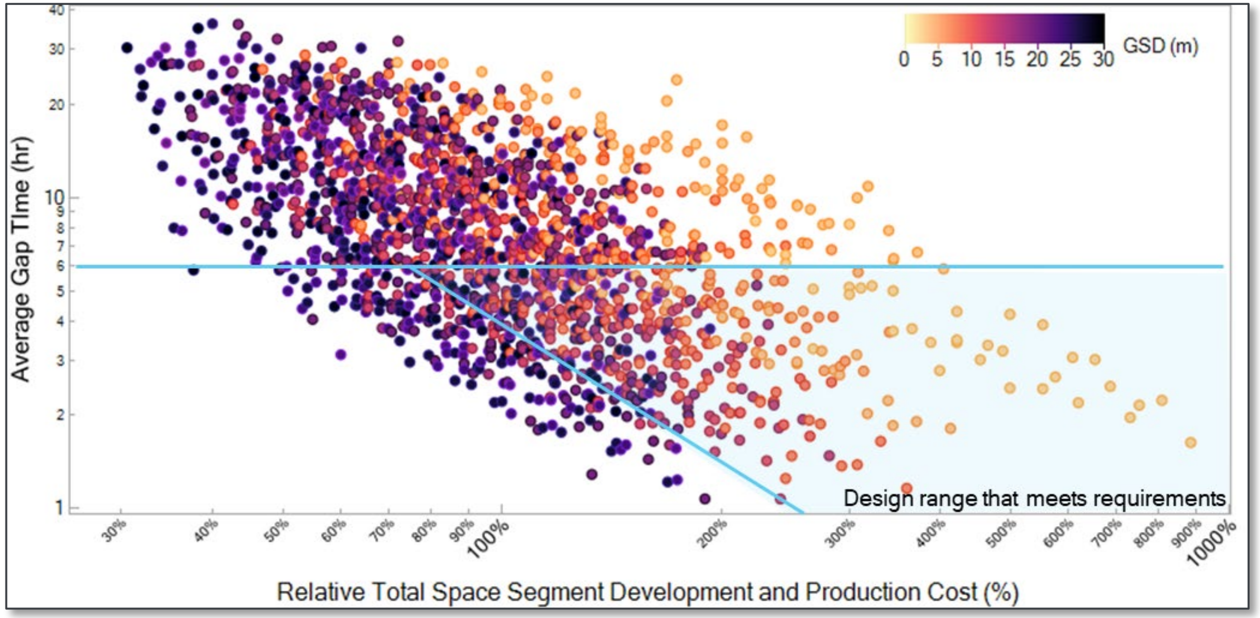
Data Exploration



- Average gap time and average targets observed have an exponential decay relationship
- Both performances metrics improve with altitude increases
- **If increasing altitude leads to better mission performance, what is the impact to cost?**



- Cost trends strongly with average gap time
- GSD has little no bearing on average gap time but shifts cost to the right
- Optimal cost range for requirements likely between 80% and 100% relative total cost
- **How does cost trend with GSD?**

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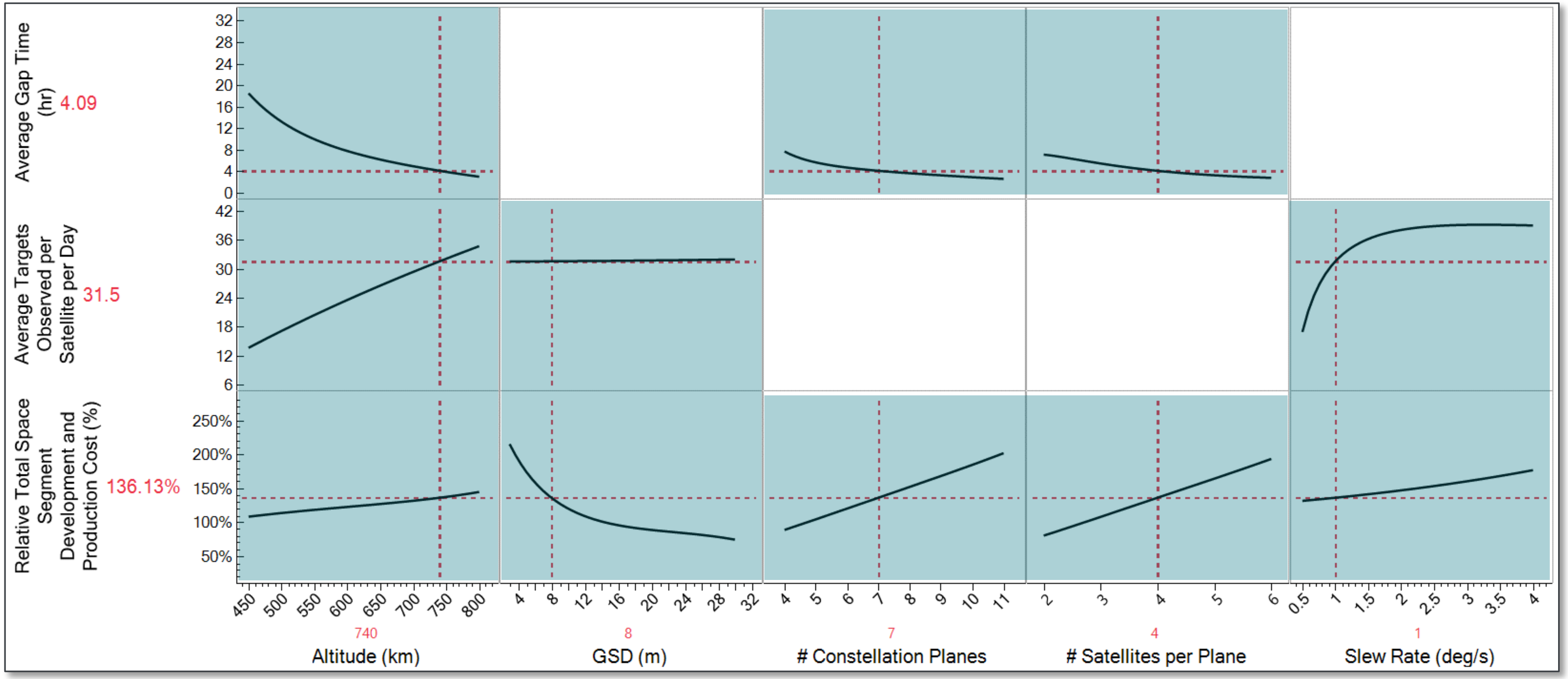
Surrogate Model

Higher altitudes improve performance at a higher rate than they increase cost

Number of planes and vehicles per plane increase cost at a higher rate than they improve performance



GSD increases cost exponentially with gentle changes in performance

Slew Rate improves performance at a faster rate than it increase cost only up to a certain point

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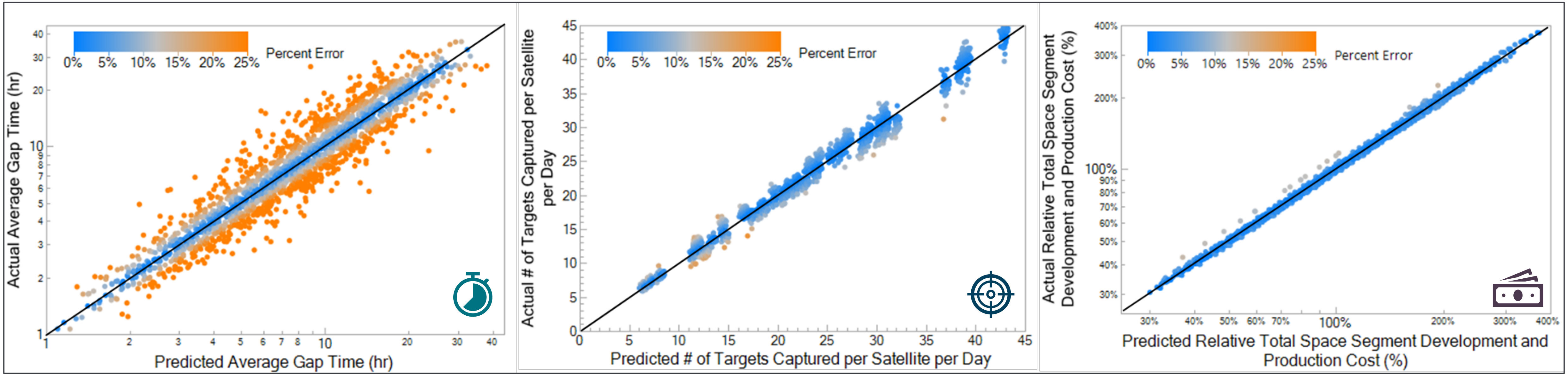
Surrogate Model Validation

- R^2 values indicate surrogate models fit data well
- RMSPE values provide better error estimates for all data ranges than RMSE
- Linearity in models demonstrates surrogate model is performing well in comparison to truth data

Goodness of Fit Metrics

Parametric Surrogate Model	R^2	RMSE	RMSPE
Average Gap Time (hr)	0.90	2.42	23.8%
Average Number of Target Observations per Vehicle per Day	0.97	1.52	6.5%
Relative Total Space Segment Development and Production Cost (%)	0.99	5.60	3.5%



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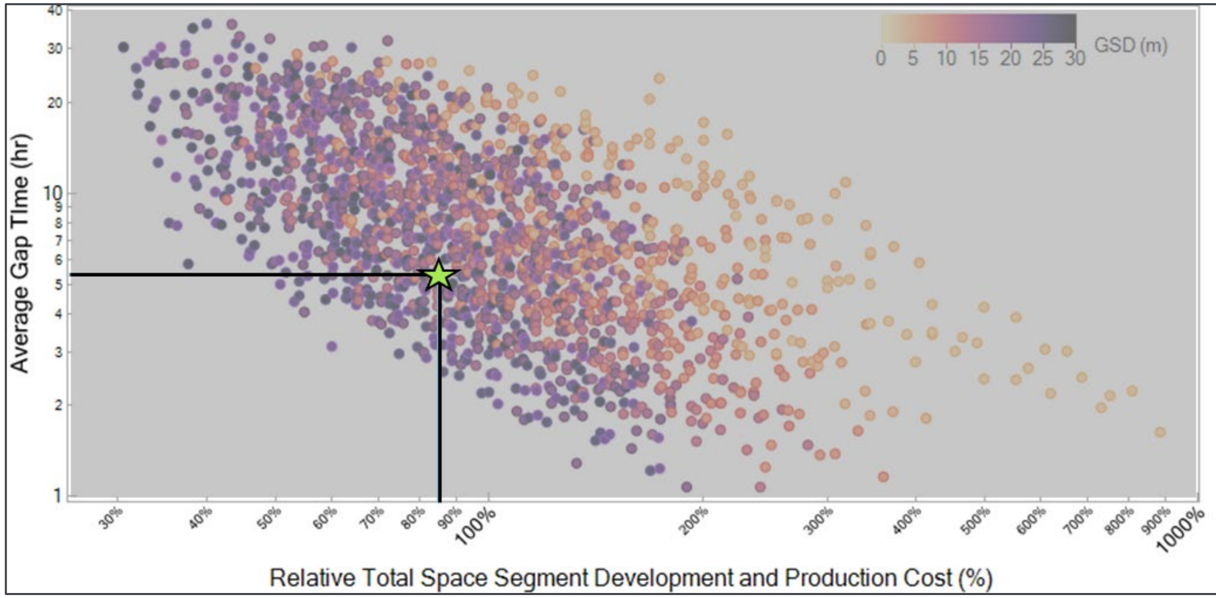
Results

Design Parameters	Concept 1	Concept 2	Concept 3	Concept 4
Altitude (km)	780	790	772	745
Number of Constellation Planes	6	4	4	5
Number of Satellites per Plane	3	4	5	4
Total Number of Vehicles	18	16	20	20
Slew Rate (deg/s)	0.80	0.75	0.80	1.00
Ground Sample Distance (m)	8.0	8.0	8.0	8.0
Parametric Surrogate Model Prediction				
Gap Time (hours)	5.01	5.93	5.50	5.52
Average Number of Target Observations per Vehicle per Day	31	31	30	30
Relative Total Space Segment Development and Production Cost (%)	98.3	91.6	105.2	104.8
Simulation Model Actual				
Gap Time (hours)	5.51	5.50	4.57	4.64
Average Number of Target Observations per Vehicle per Day	30	30	30	30
Relative Total Space Segment Development and Production Cost (%)	98.3	88.0	1.01	1.00
Predicted Vs. Actual				
Gap Time Error	9.07%	7.82%	20.35%	18.97%
Target Observation Error	3.33%	3.33%	0.00%	0.00%
Cost Error	0.27%	3.93%	3.99%	4.55%

- Errors between predicted values and actual results are all within model RMSPE calculated
- **Concept 2** is identified and verified as most cost-effective solution that meets requirements
- **Concept 1** vs **Concept 4** suggests additional launch with higher altitudes **(1)** may be similar in cost to two additional vehicles at lower altitude **(4)**



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Conclusion

- Accelerating complexity within the space mission architecture landscape necessitates the development of next generation of capabilities that can forecast the downstream impacts to cost and performance from design choices
- Capabilities presented here provide architects, engineers, stakeholders and customers the ability to project where ideal costs should lie given certain design requirements
- Program and Study design phases can begin from more meaningful starting points focusing on maximizing performance while minimizing costs