Jet Propulsion Laboratory
California Institute of Technology

Model-based Systems Engineering at the Jet Propulsion Laboratory: Past, Present, and Future

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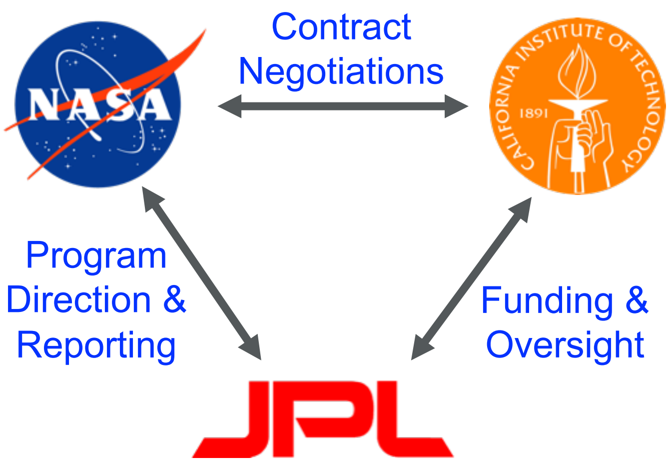
The NASA Jet Propulsion Laboratory

Relationship to NASA and the California Institute of Technology

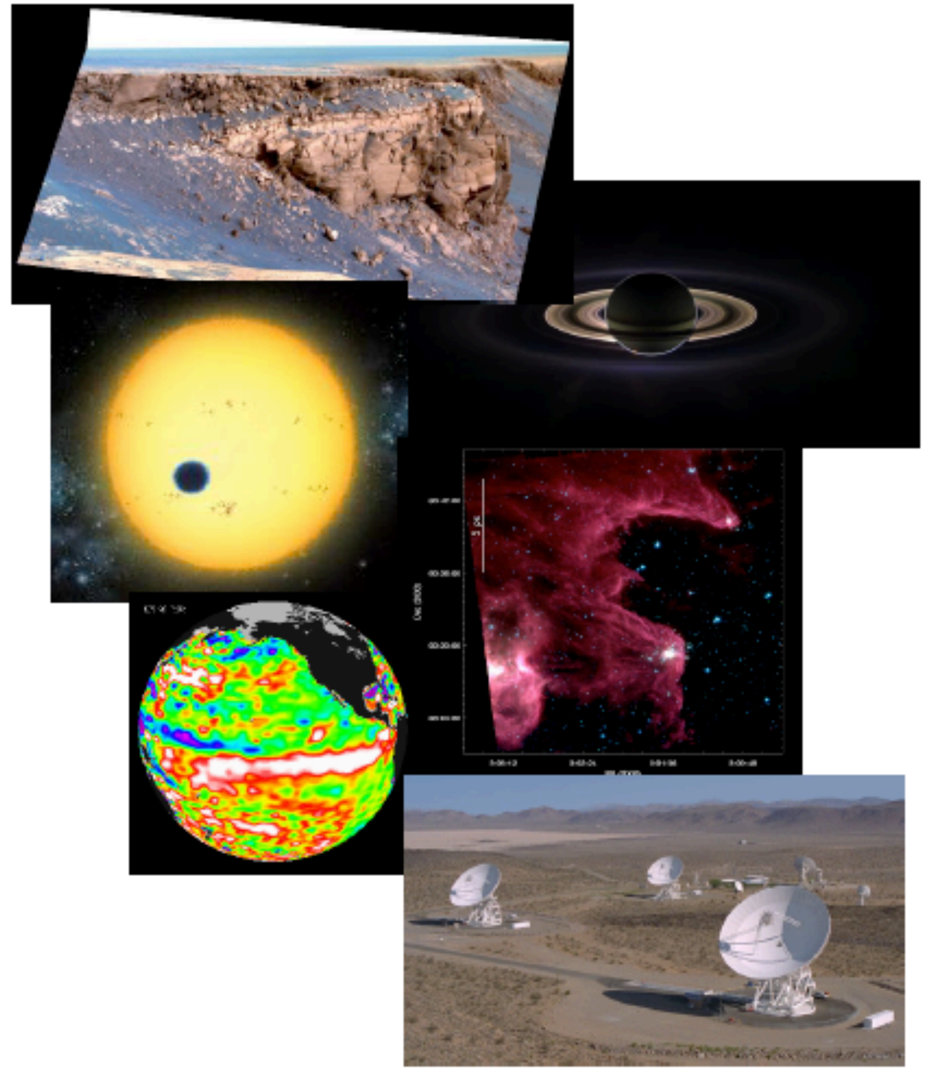
- Located in Pasadena, CA
- NASA-owned *”Federally-Funded Research and Development Center”*
- University-operated
- 5,000 employees



Source: Lin et al., 2011

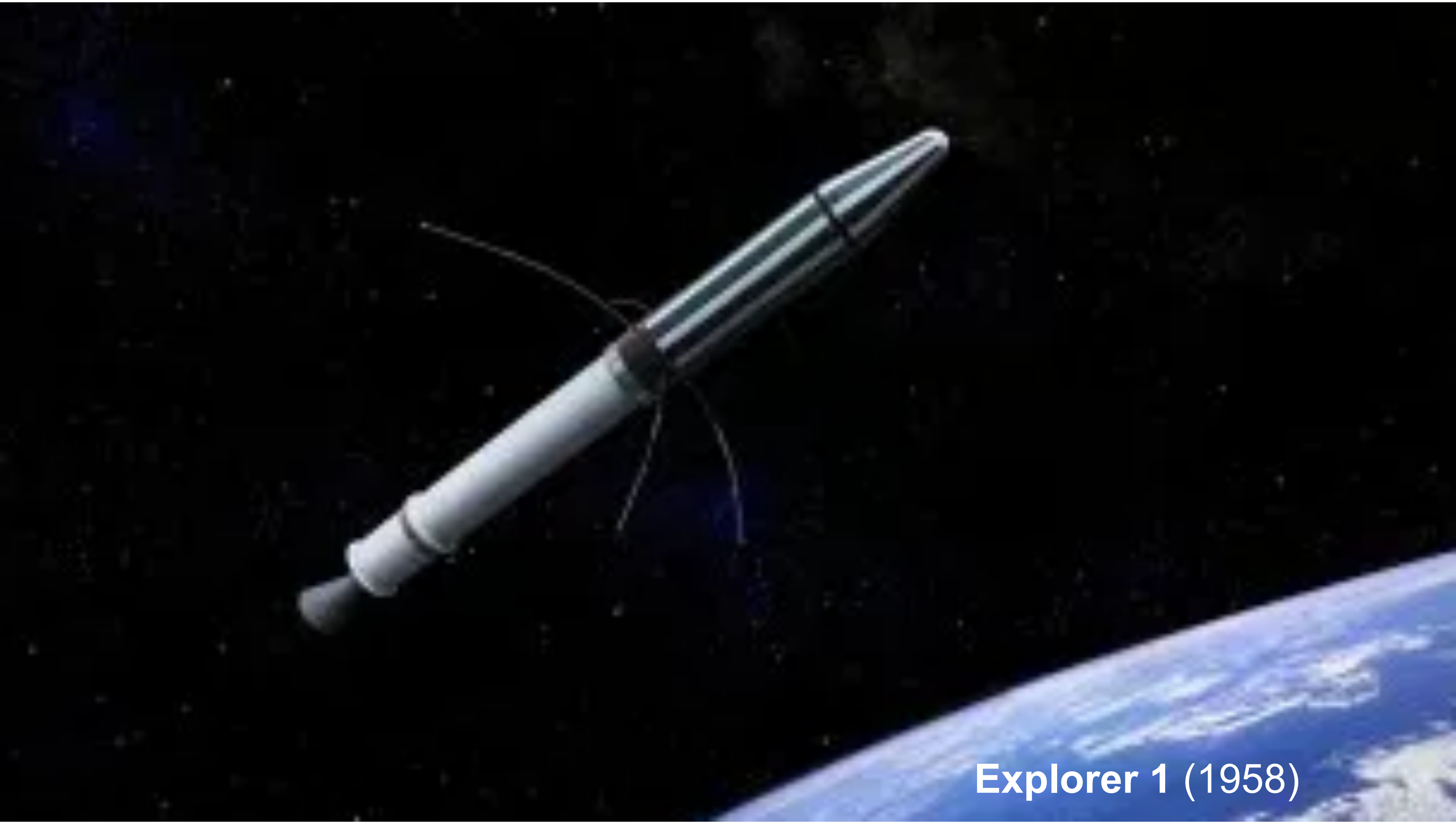
JPL's Mission is Robotic Space Exploration

- Mars
- Solar System
- Exoplanets
- Astrophysics
- Earth Science
- Interplanetary Network



Source: Nichols & Lin, 2014

You Might Know Some of These…



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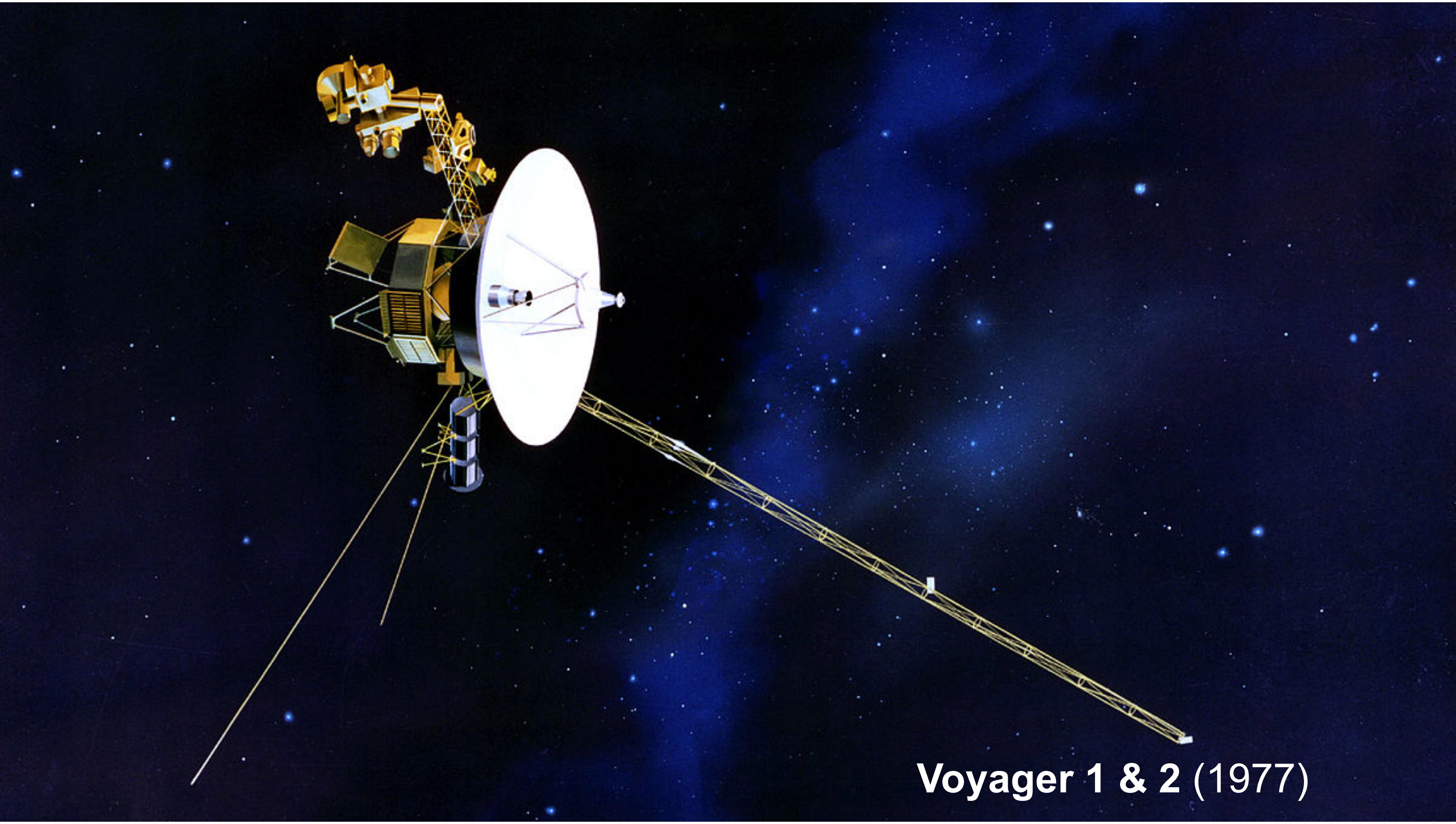
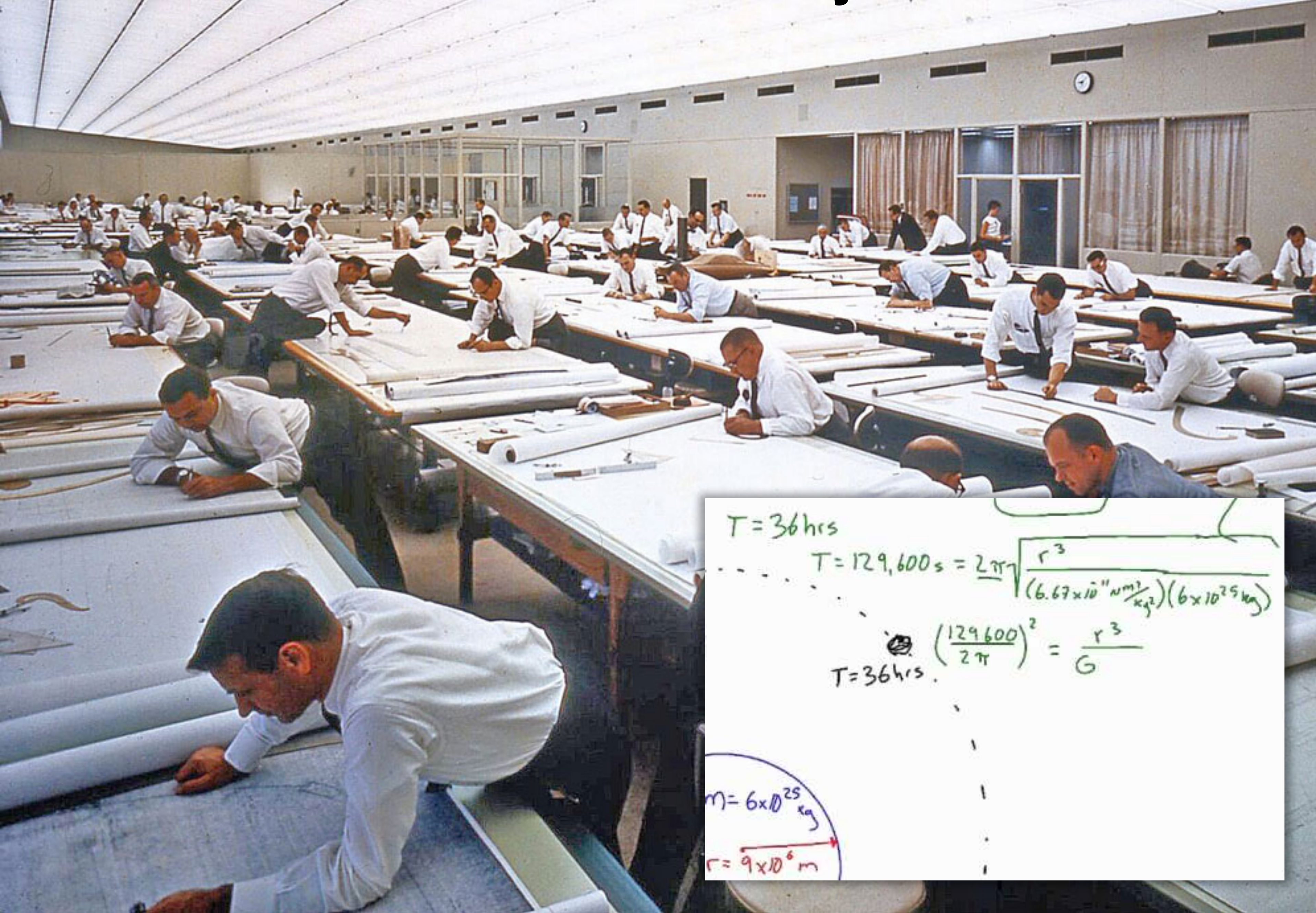


You Might Know Some of These…

We’ve Always Used Models…



Our Motivation for Adopting MBSE

Why Change a Running System?

- Strengthen quality of formulation products by allowing for exploration of a more comprehensive option space
- More, integrated engineering analysis and less paper management
- Validation of systems early and often
- Improve quality of communication and understanding among system and subsystem engineers
- Achieve greater design re-use
- Reduce number of product and mission defects in the face of growing complexity, and increase productive / reduce cost

Source: Nichols & Lin, 2014

Status of MBSE Adoption at JPL

- Developing a MBSE infrastructure consisting of:
  - Foundational elements including ontologies, domain-specific languages + tools and recurring modeling patterns
  - Software tooling, consisting of interoperable solutions for a comprehensive modeling approach and document generation
  - Community of practice for education and sharing of experience

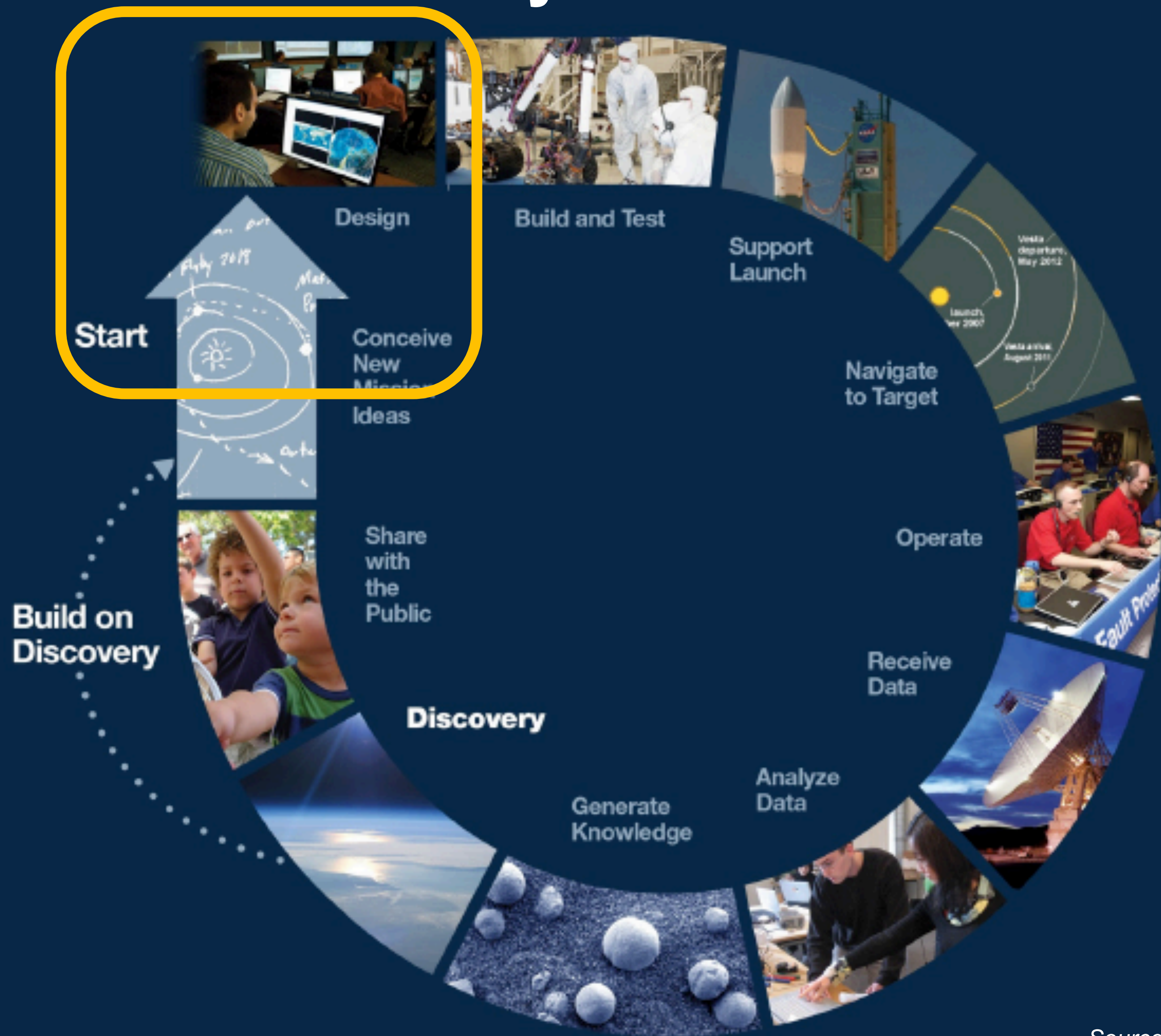
- Application of MBSE to real project systems engineering problems across a wide landscape of project types, activities and lifecycle phases

- Research & technology development for exploring novel concepts and advancing the state of current practice

Source: Nichols & Lin, 2014

Applications of MBSE

The JPL Product Lifecycle

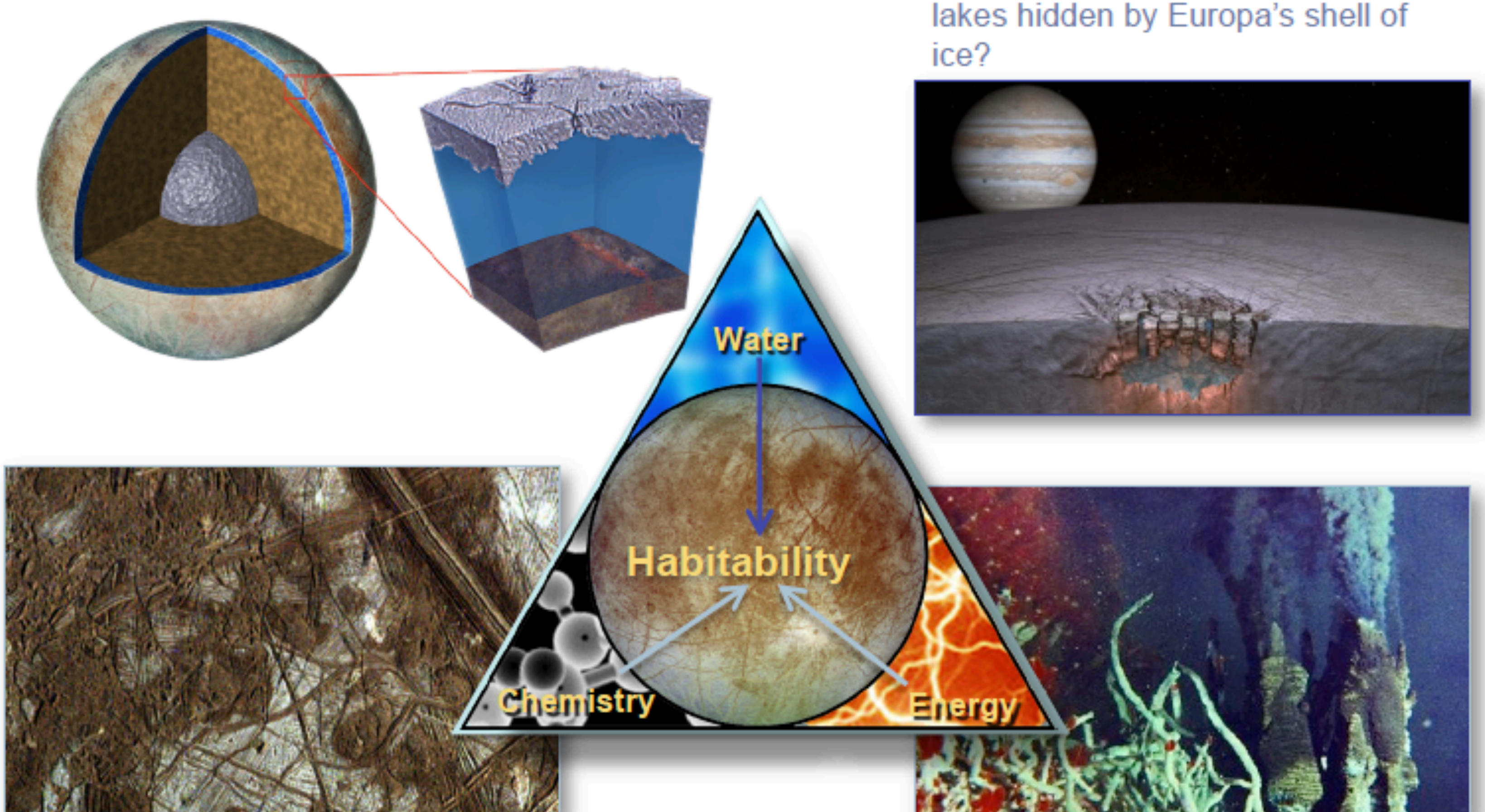


Source: Nichols & Lin, 2014

Planned Mission to Jupiter's Moon Europa

Looking for the Ingredients of Life

Water: Are a global ocean and lakes hidden by Europa's shell of ice?



Chemistry: Do red surface deposits contain organics from below?

Energy: Can surface oxidants provide energy for metabolism?

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Source: Nichols & Lin, 2014

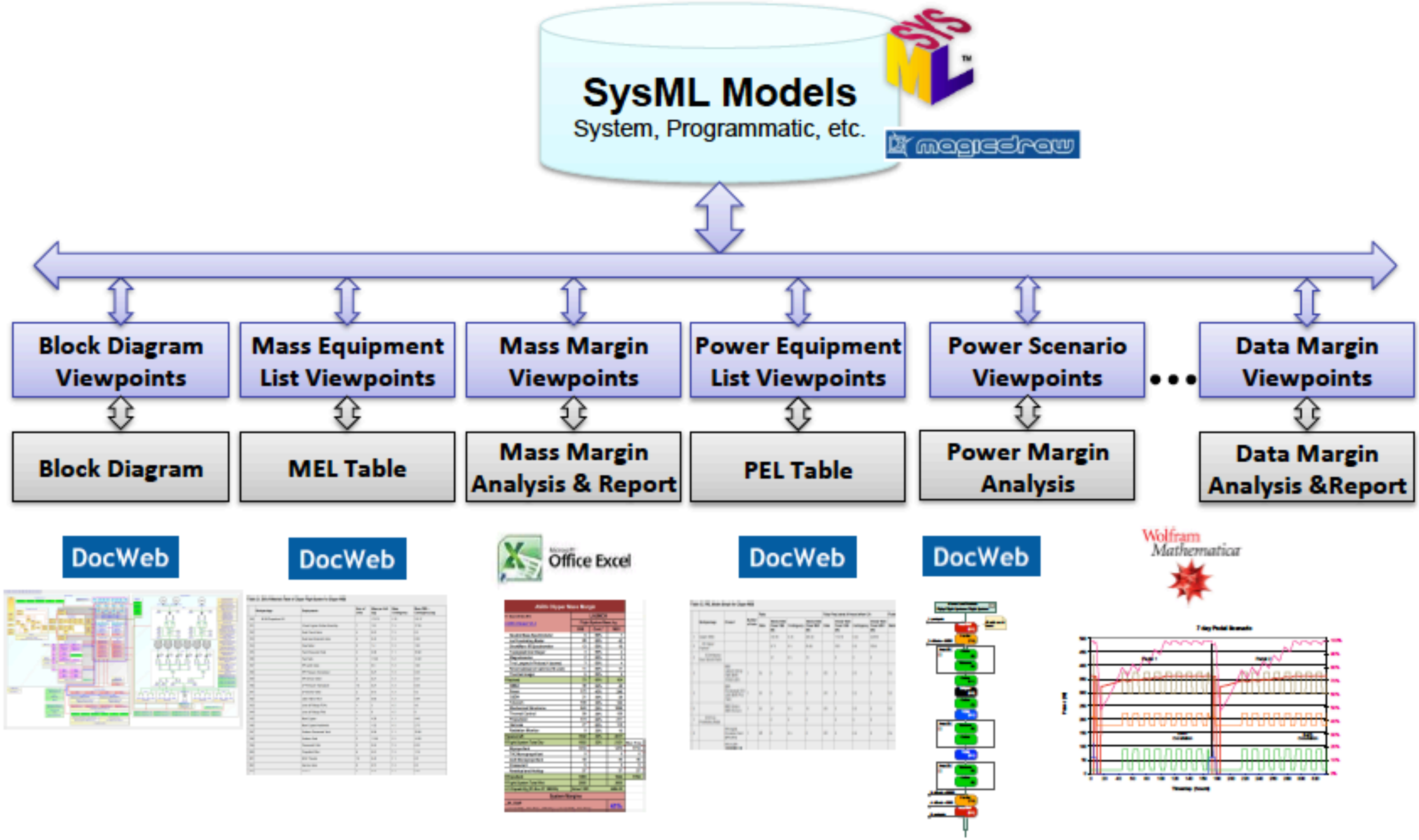
Systems Engineering Challenges During Early Project Phases

- Managing multiple architectural alternatives
- Reliably determining whether design concepts "close" on key technical resources
- Ensuring correctness and consistency of multiple, disconnected engineering reports
- Managing design changes before a full design exists

MBSE has been instrumental in addressing these challenges

Source: Nichols & Lin, 2014

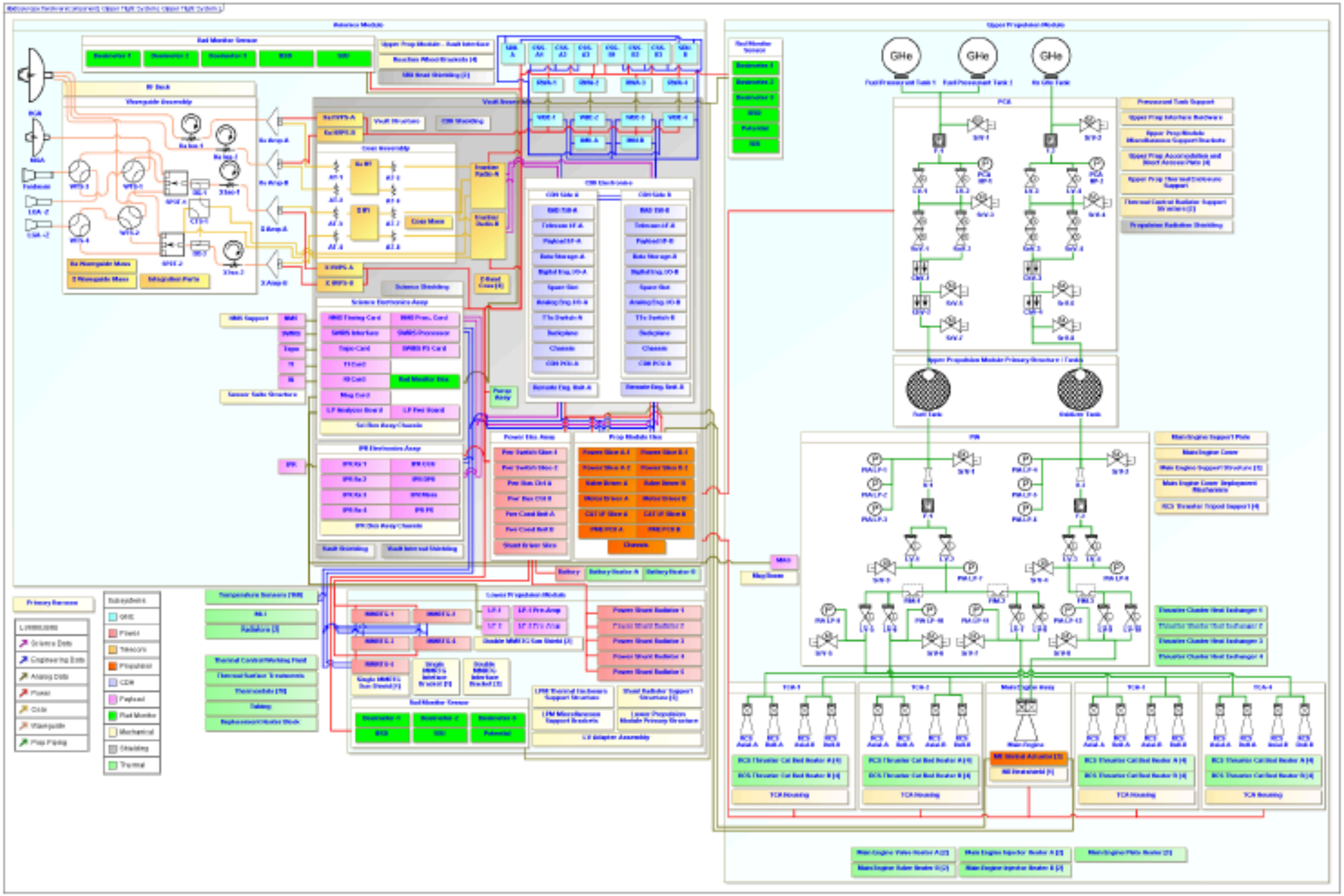
Europa System Model Framework



Pre-Decisional Information -- For Planning and Discussion Purposes Only

Source: Nichols & Lin, 2014

More Meaningful System Diagrams



Pre-Decisional Information -- For Planning and Discussion Purposes Only

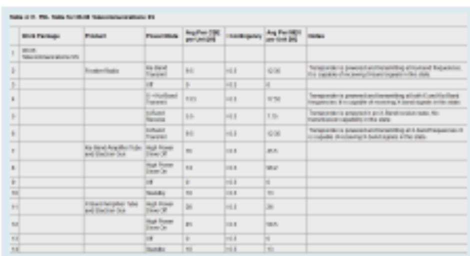
Source: Nichols & Lin, 2014

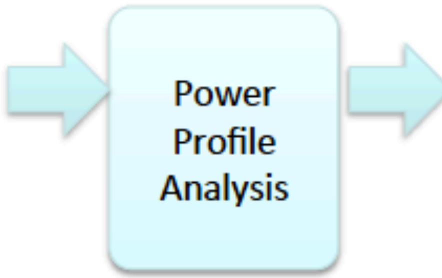
Integrated Power / Energy Analysis

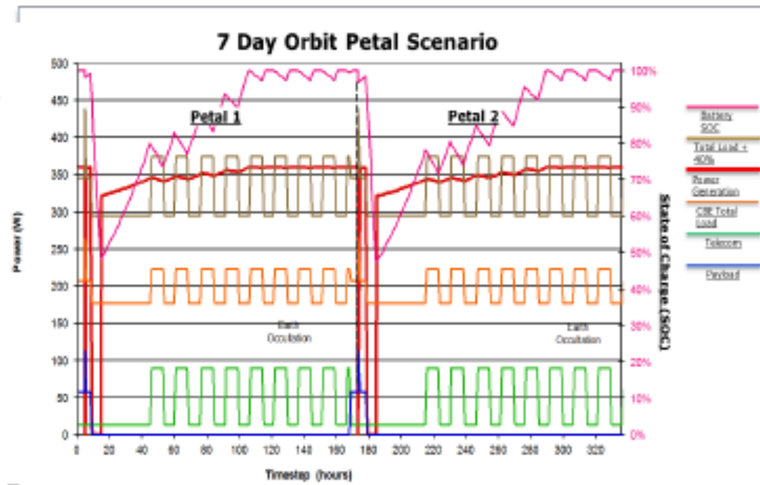
System Model:
- Equipment List
- Demand vs Mode
- Scenario Definitions

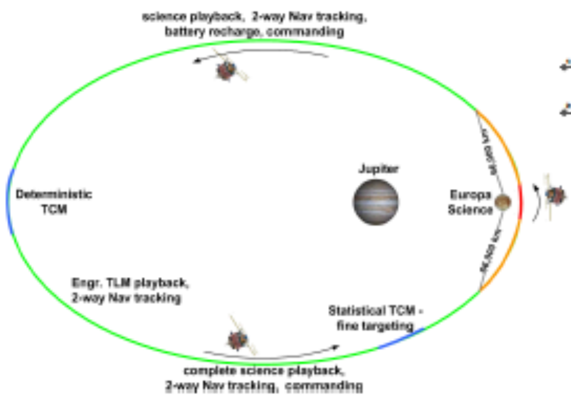
Subsystem Power Models
- Power Source Models
- Battery Models
- Load Profile Simulation

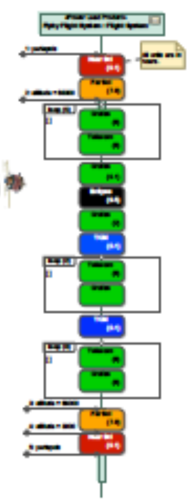
Integrated Power/Energy Analysis











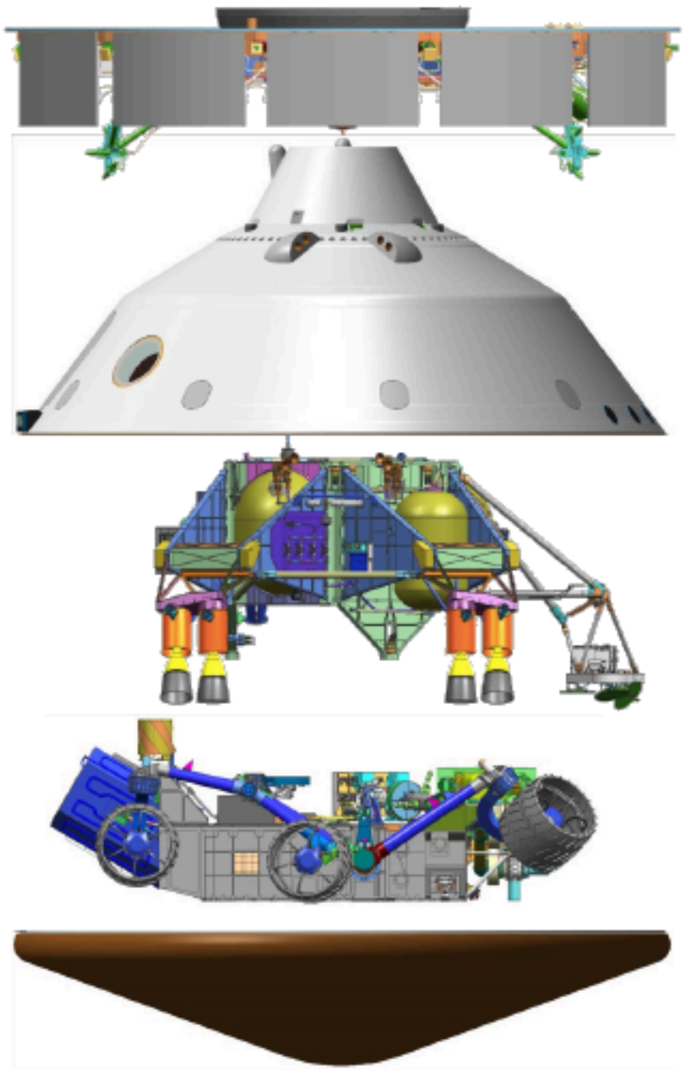
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Source: Nichols & Lin, 2014

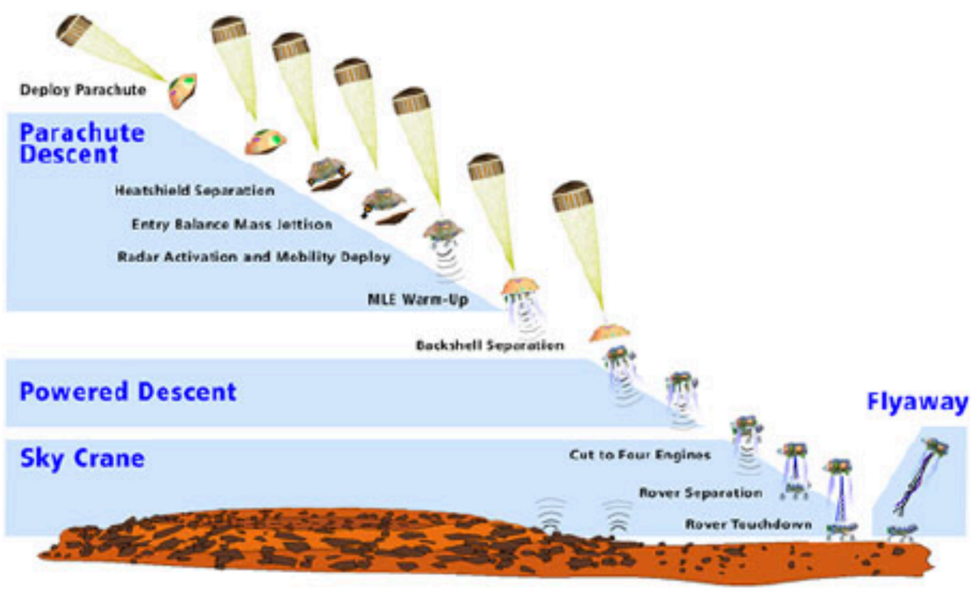
Mars 2020 – MBSE Applications

Source: Nichols & Lin, 2014

Mars 2020 - Coping with Complexity



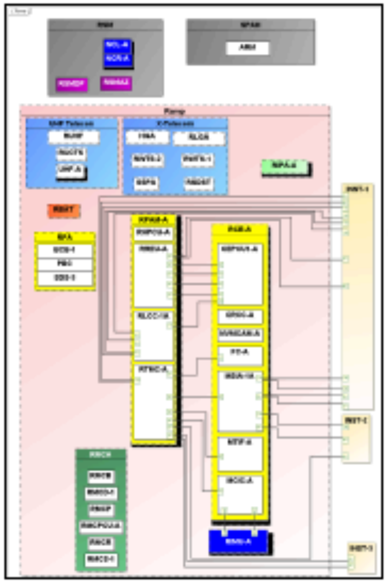
- Mars 2020: follow-on to MSL
- Challenge: engineer inherently complex mission and system at lower cost, and changes to payload instruments



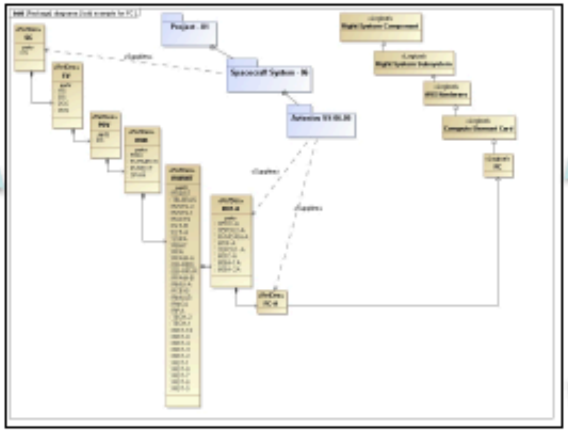
Source: Nichols & Lin, 2014

Example System Modeling (Derived) Products

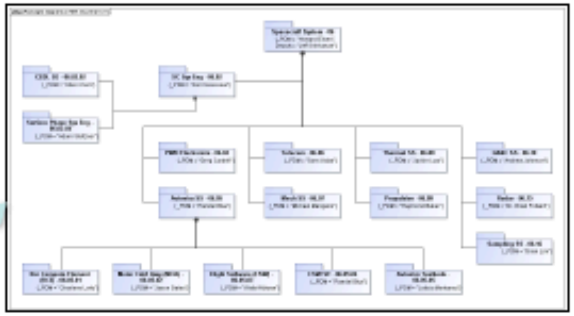
System Block Diagrams and Interfaces



Physical Decomposition, Logical Decomposition, and WBS



Org Chart



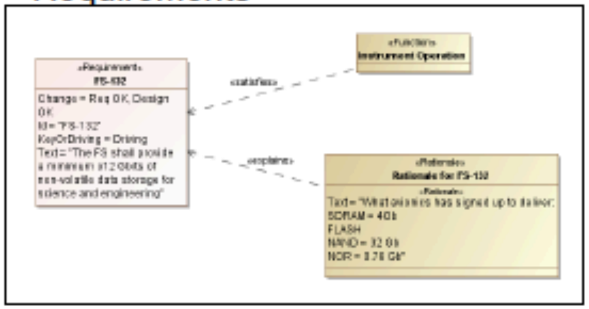
Linking information to core components (Reference Designators)

Resource Tracking (e.g., subset of web-accessible MEL)

Flight System	Flight Quantity	CBE (kg)	MEV (kg)	Contingency (Percent)	Contingency Level	CBE All Count (kg)	MEV All Count (kg)
Flight System	1	915.06	942.27	2.97	N/A	915.06	942.27
RPS	1	44.79	45.68	2.00	N/A	44.79	45.68
RTG	1	44.79	45.68	2.00	N/A	44.79	45.68
_PAYLOAD	1	72.23	73.73	2.04	N/A	72.23	73.73
Thermal	1	41.14	41.96	2.00	N/A	41.14	41.96
RVRTSTAT	12	0.01	0.01	2.00	N/A	0.16	0.16
RIPA	1	14.58	14.87	2.00	N/A	14.58	14.87
RVRTHRM	1	17.28	17.63	2.00	N/A	17.28	17.63
CHBSFL	1	0.90	0.91	2.00	N/A	0.90	0.91
RVRPRT	192	0.00	0.00	2.00	N/A	0.28	0.29

Subset of patterns are extended from institutionally-and Europa derived patterns

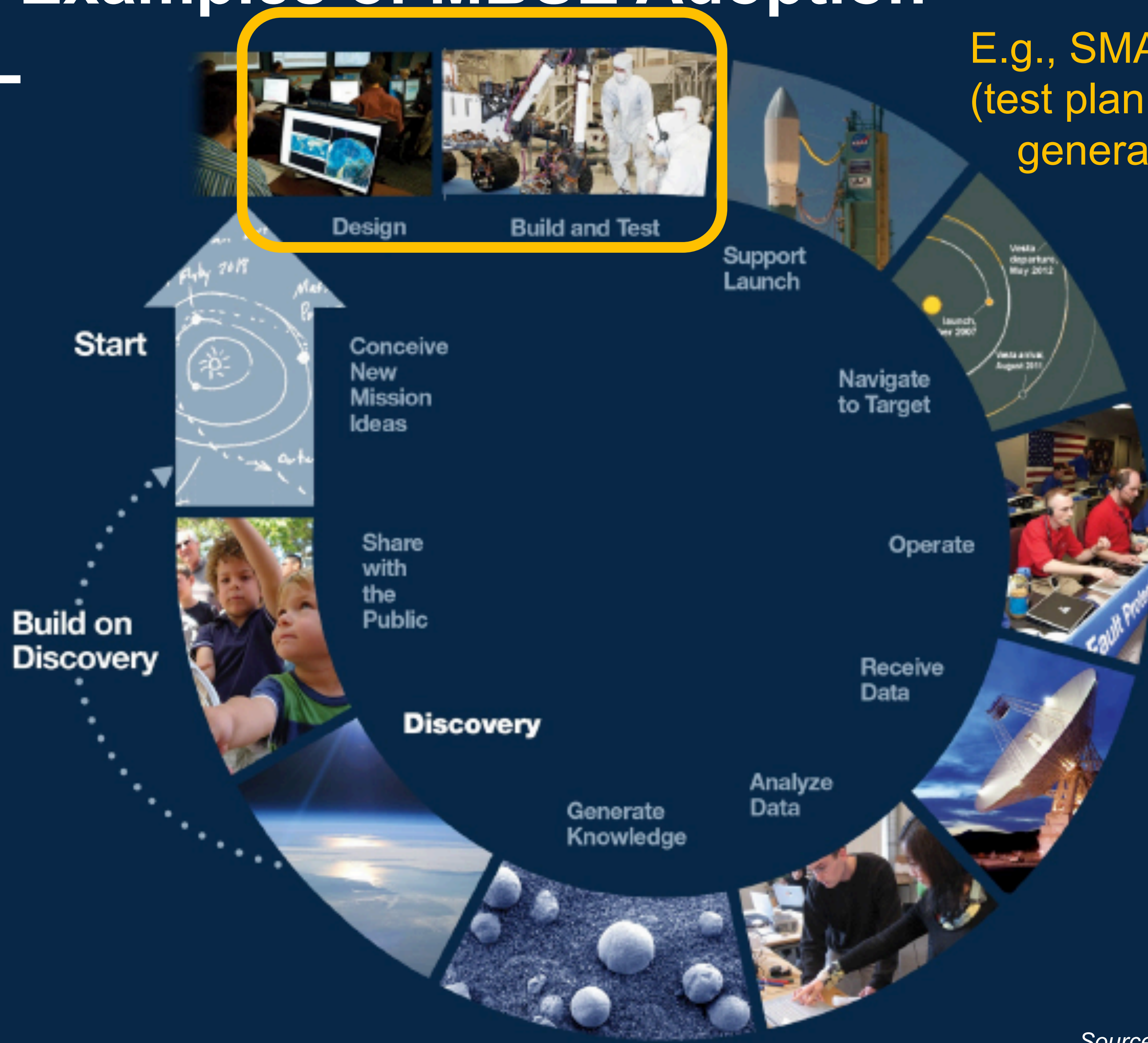
Assessment of Key & Driving Requirements



System model provides integrated, consistent, and broadly-accessible design information and change assessment

Source: Nichols & Lin, 2014

Other Examples of MBSE Adoption at JPL

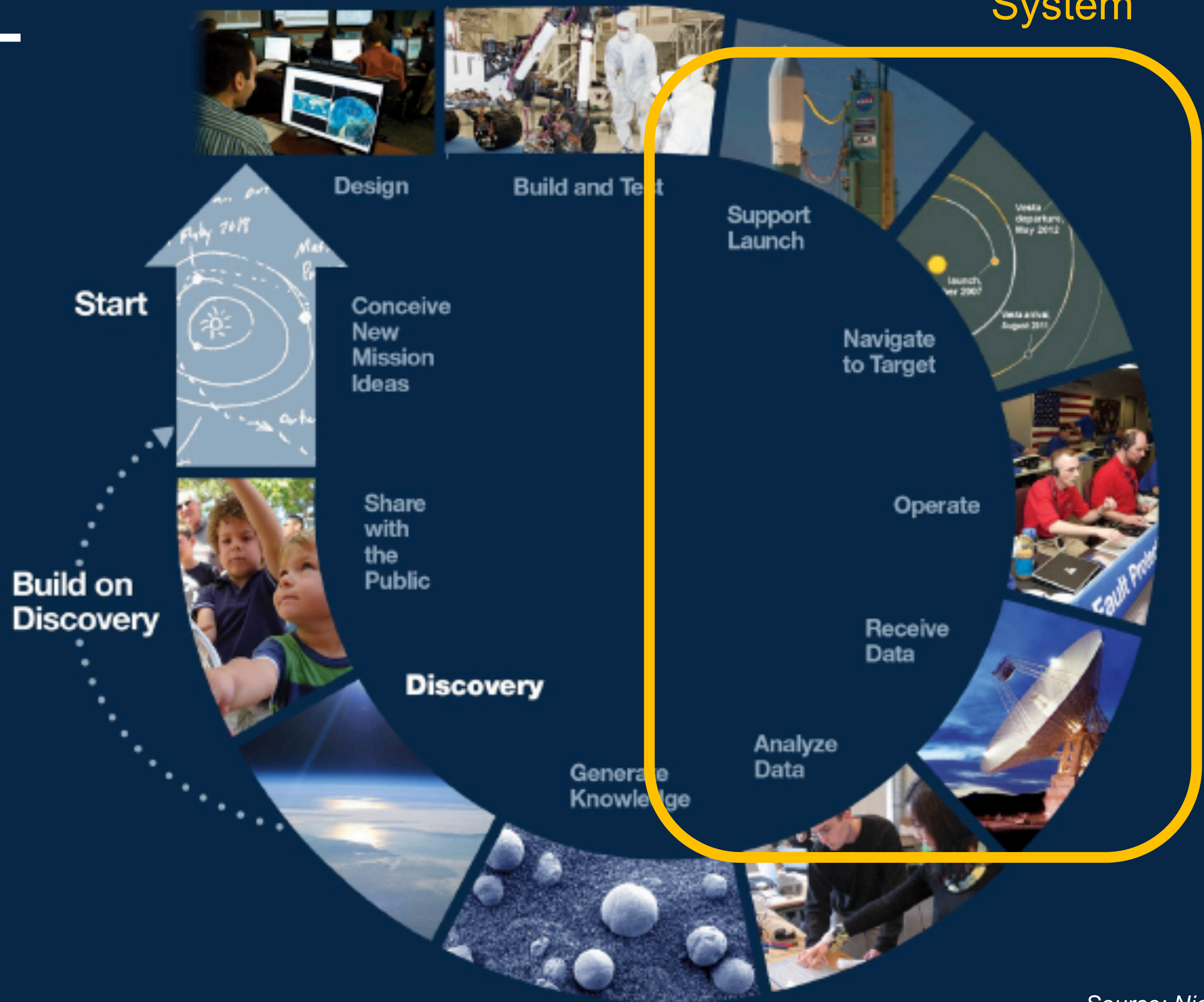


E.g., SMAP: V&V (test plan and code generation)

Source: Nichols & Lin, 2014

Other Examples of MBSE Adoption at JPL

E.g., Advanced Multi-Mission Operations System



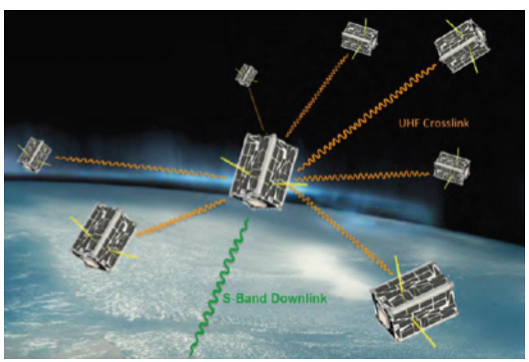
Source: Nichols & Lin, 2014

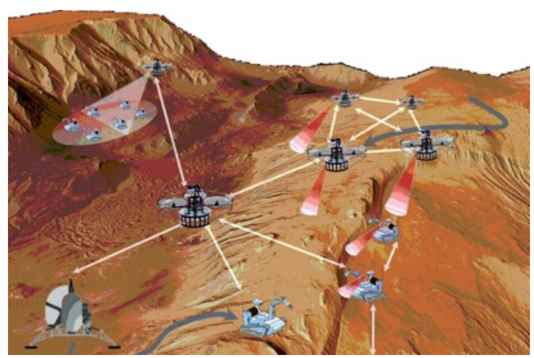
Research & Technology Development

Networked Constellations of Spacecraft

JPL Interplanetary Network Initiative

- Small spacecraft may enable the development of innovative low-cost networks and multi-asset science missions
- Goal of initiative is to develop new technologies that support novel mission concept proposals & influence Decadal Survey
  - New approaches to communication, system design, and operations required
  - Our task's work focuses on design and trade space exploration





Artist's Concepts

Example Motivating Case

Spacecraft-Based Radio Interferometry

Source: http://www.passmyexams.co.uk/GCSE/physics/images/radio-telescopes-outdoors.jpg

Radio interferometers:

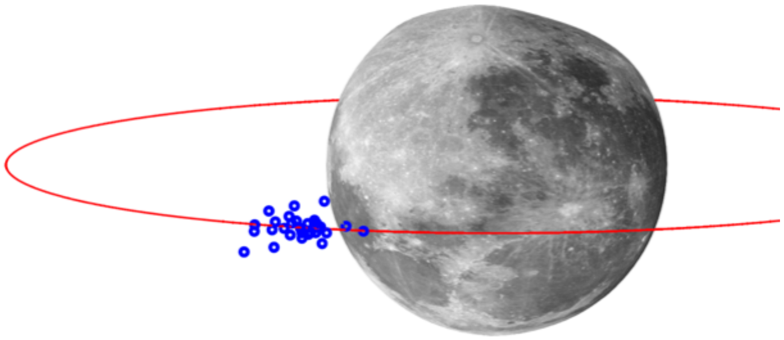
- Radio telescopes consisting of multiple antennas
- Achieve the same angular resolution as that of a single telescope with the same aperture

➔ Typically ground-based

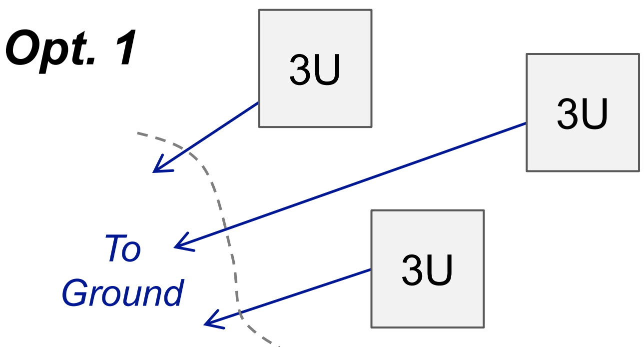
Want to do this in space:

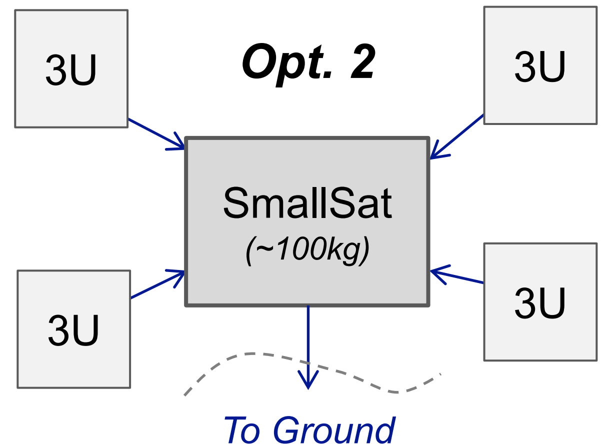
- Frequencies < 30Mhz blocked by ionosphere
- Cluster of spacecraft (3 – 50) functioning as telescopes in LLO

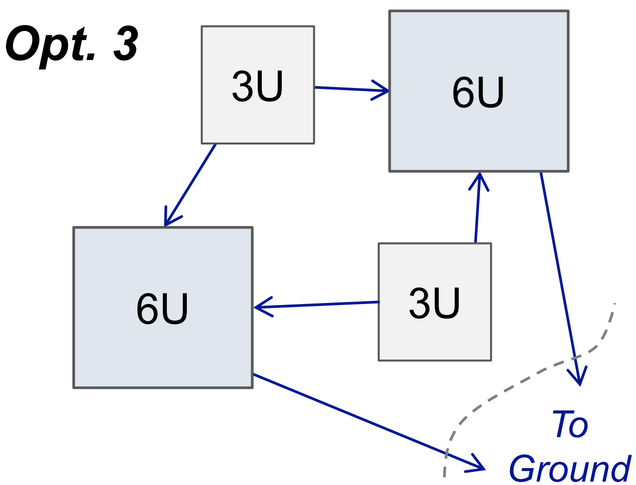
➔ CubeSats or SmallSats are promising enablers for this



Which Architecture is Optimal?



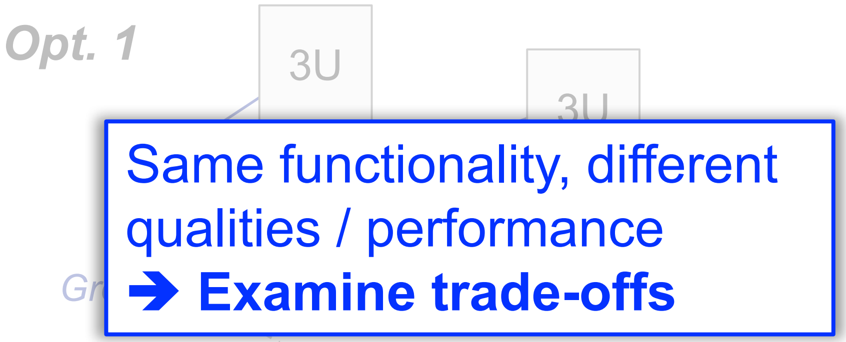




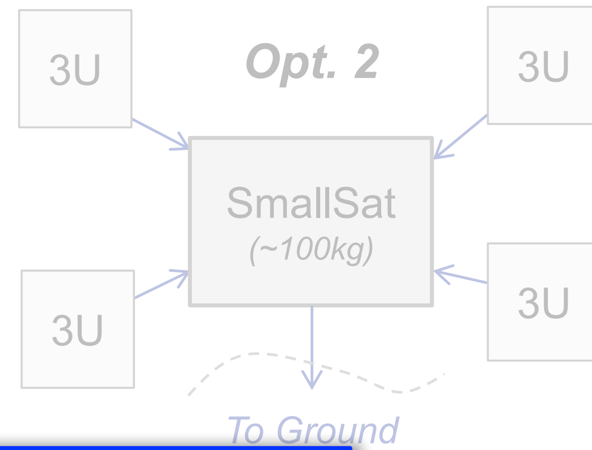
Challenge: transmit very large data volume from LLO to Earth

- How many spacecraft?
- Are all equipped with interferometry payload? Are some just relays?
- Who communicates with Earth?
- What frequency bands? Multi-hop?
- …
- Optimal w.r.t. cost? Science value?

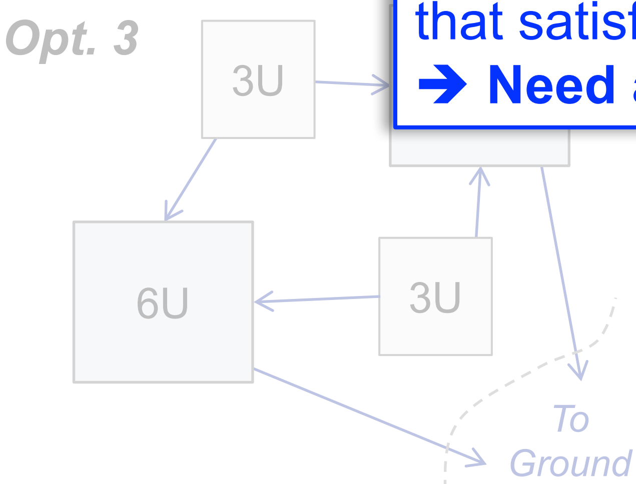
Which Architecture is Optimal?



Same functionality, different qualities / performance
➔ **Examine trade-offs**



Very large number of architectures that satisfy mission objectives
➔ **Need automation**



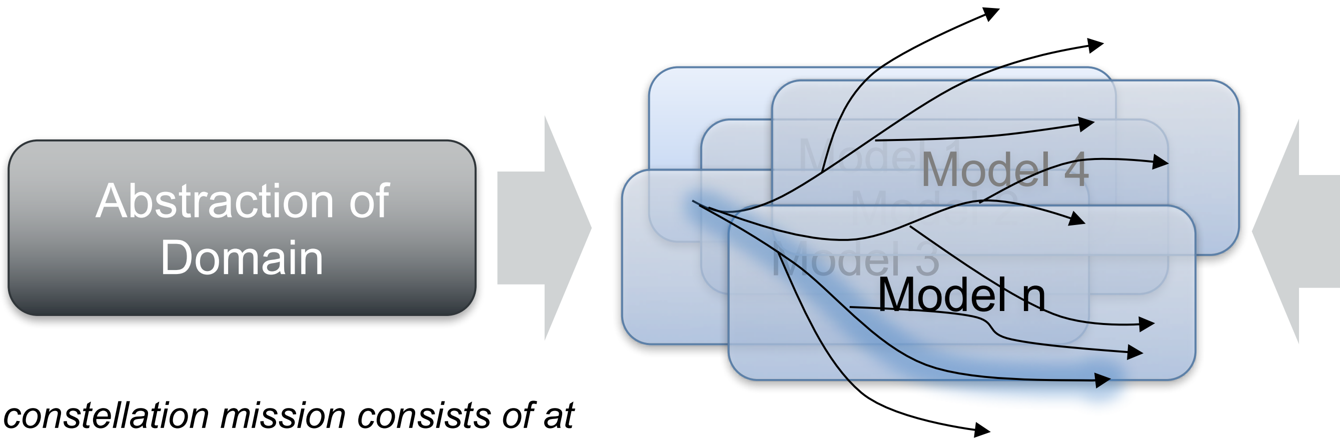
ery large data
Earth

- How many spacecraft?
- Are all equipped with interferometry payloa
- Who c
- What frequency bands? Multi-hop?
- …
- Optimal w.r.t. cost? Science value?

Functional allocation is key
➔ **Synthesis problem**

Mission Architecture Trade Space Exploration

Mechanized Exploration



Which interferometry missions are optimal with respect to cost & scientific benefit?

"A constellation mission consists of at least 2 spacecraft and at most 100"

"A spacecraft can, but does not have to contain the interferometry payload"

"Operation of the interferometry payload operation requires power"

Solution Generation Search

Models in domain

"Constellation mission A with 3 spacecraft, one of which has a

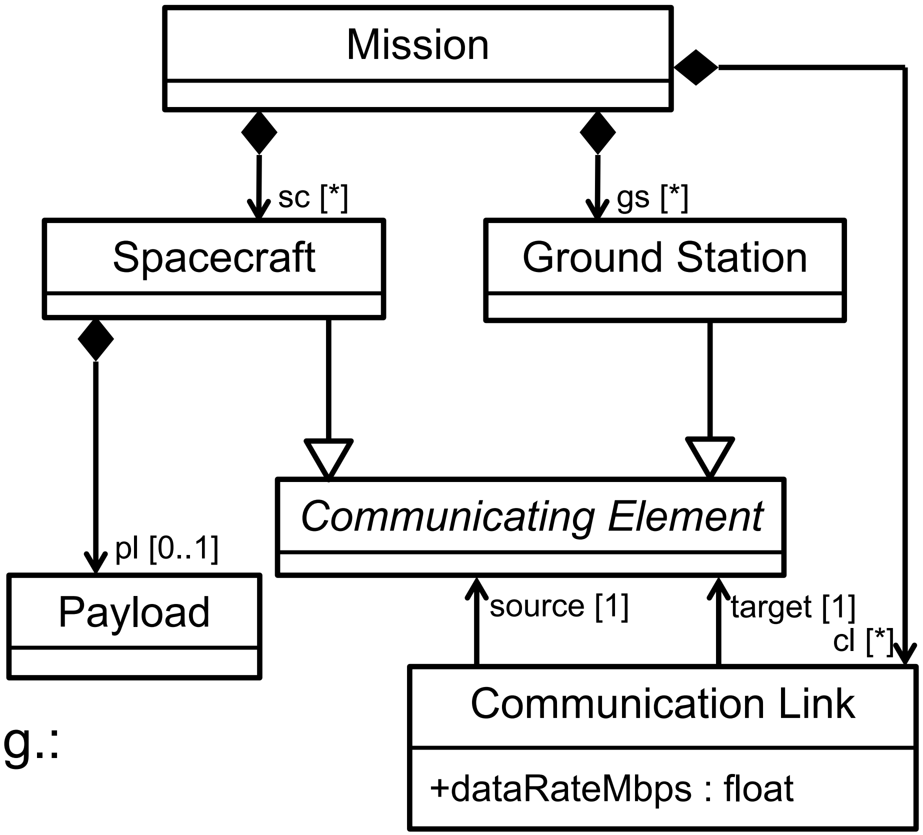
Problem Description

Which models in the domain are we looking for?

In practice, too many possible solutions to generate & compare all
➔ **View as a search problem**

Domain Model & Well-Formedness Constraints

- Domain model
  - Concepts
  - Associations / relations
  - Attributes
  - ➔ Describes a **universe of discourse**: many models in domain
  - ➔ Describes structural part of the problem



- Typically annotated with addl. well-formedness constraints, e.g.:

  "No communication loops may exist"

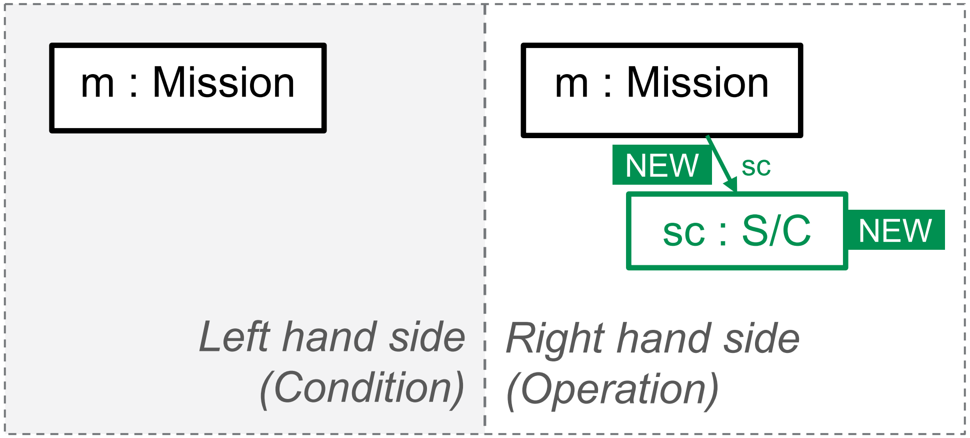
  "All spacecraft must (transitively) be connected to at least one ground station through a communication link"

Any model in the domain is a (structurally) valid solution

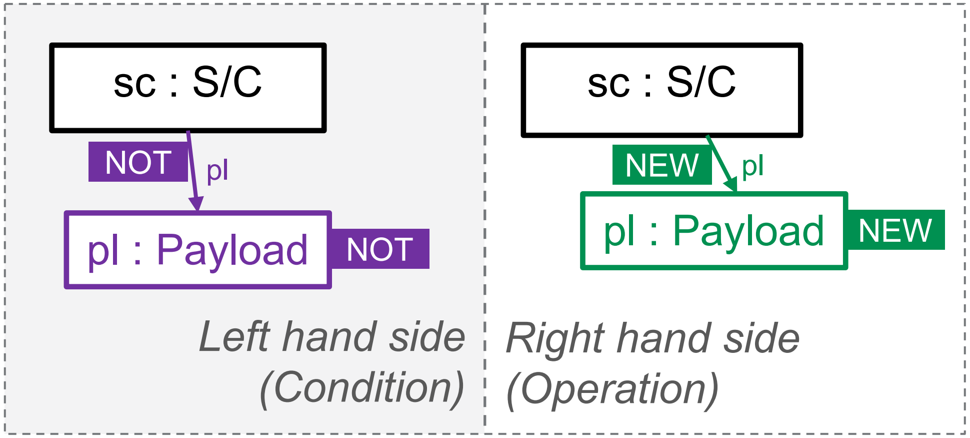
Model-Transformation-Based Exploration

Model Transformation Rules as Enablers for Evolving Solutions

- Transformation Rules
  - **LHS**: Condition for match in input model (e.g., *"find an element of type Mission"*)
  - **RHS**: Operation to be performed (e.g., *"create a new element of type S/C (Spacecraft) and attach it to the matched mission"*)
- Here: *endogenous* transformations
  - Source and target meta-models are the same
- Used for generating models in domain (~design rules)



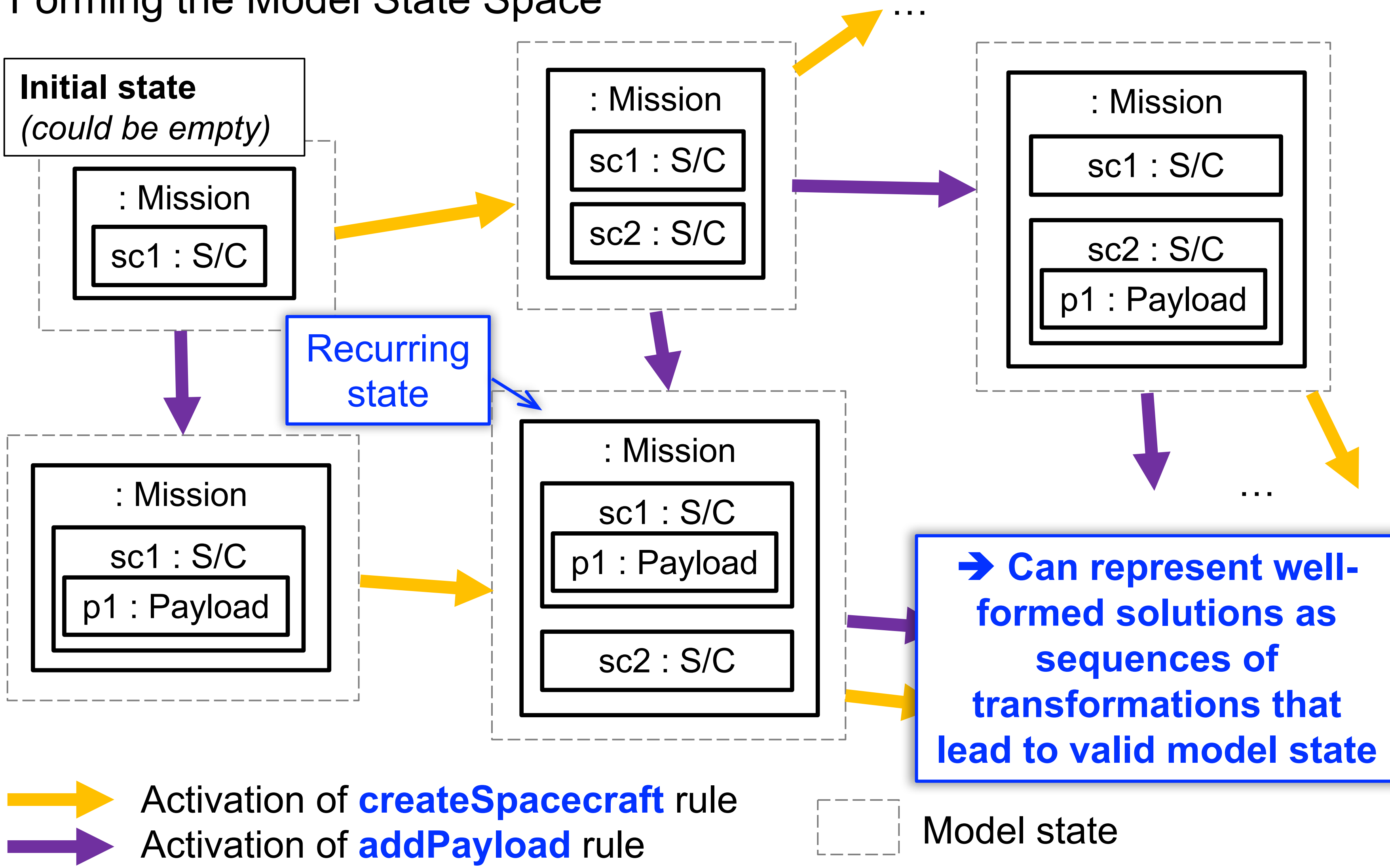
Rule "createSpacecraft"



Rule "addPayload"

Model-Transformation-Based Exploration

Forming the Model State Space



Driving Exploration Towards Optima

Using Evolutionary Algorithms to find Pareto-Optimal Solutions

Crossover

Individual x:	**Add Spacecraft**	**Add X-Band Comm**	**Add Spacecraft**	**Add Comm Link**	***fitness=0.6***
(Selection from population)					*(Obj. Fct. Values)*
Individual y:	**Add Spacecraft**	**Add Ka-Band Comm**	**Add Payload**	**Add Spacecraft**	***fitness=0.5***

Here, individuals are **sequences of transformation rule activations**
→ Each genome in population is a variable with set of trafo rules as range

New: **Add Ka-Band Comm** ***fitness=0.8***

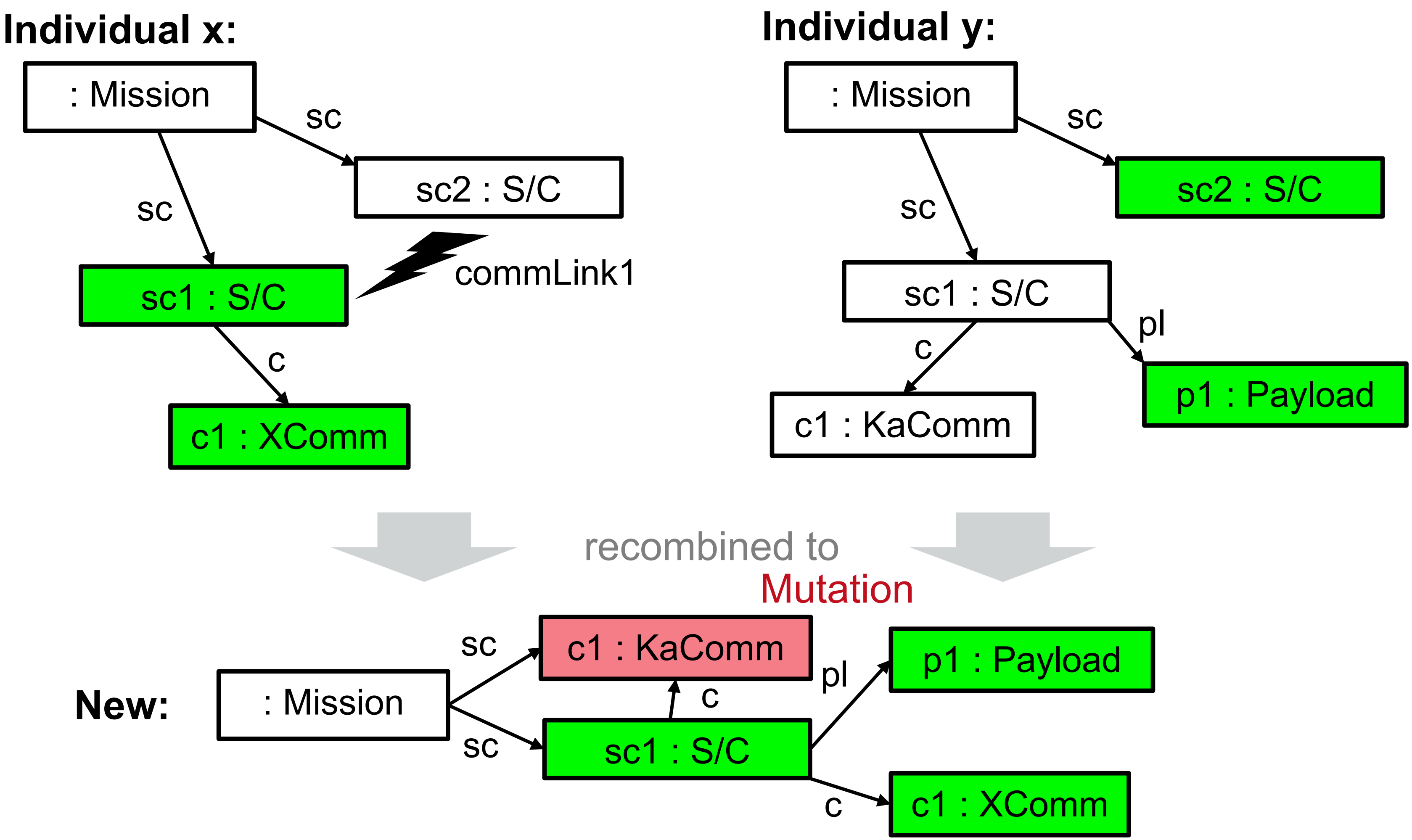
(Recombined individual in next generation)

Mutation

Could also be a "placeholder" transformation (= rule "do nothing")

Driving Exploration Towards Optima

Models Resulting from Executing Transformations



Implementation

Open Source Technologies Used in Implementation

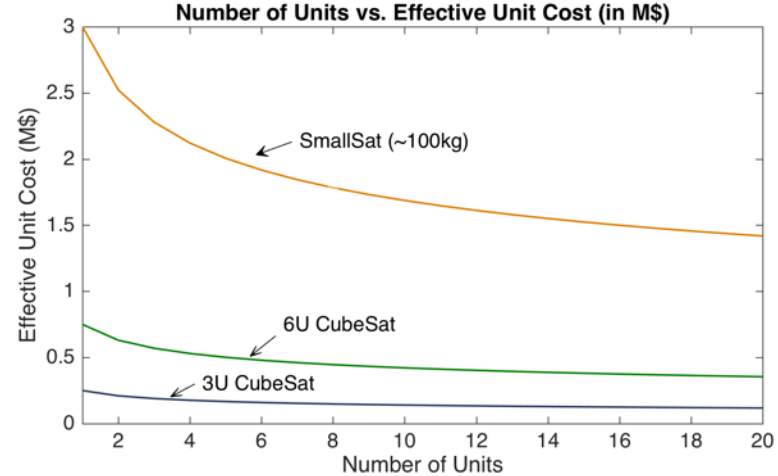
- Representation of Domain
  ➔ Ecore / Eclipse EMF + OCL
- Exploration Rules
  ➔ Henshin (or Viatra)
- Analyses / Fitness Functions
  ➔ Java
- Optimization Using Genetic Algorithms
  ➔ MOMoT, MOEA (or Viatra DSE)

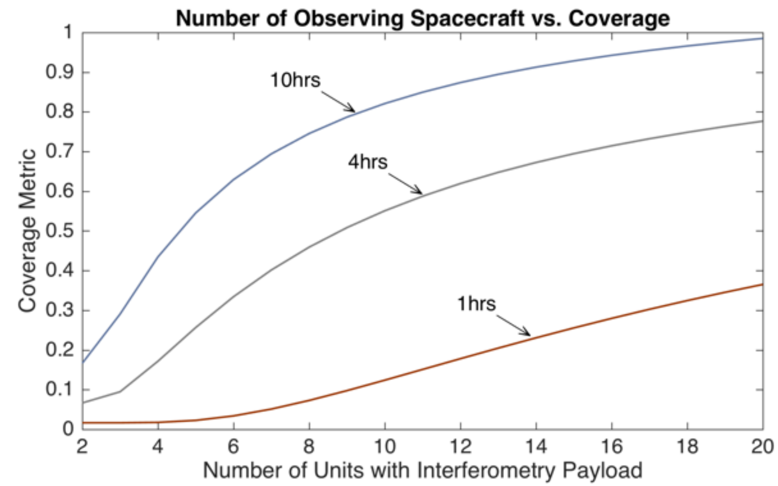
Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

Application to Case Study

- Three objectives:
  - Minimize cost
  - Maximize coverage (measure of scientific benefit)
  - Minimize mission time
- Typical link budget for data rates
- Data collection & transfer model
- Abstracted away orbit design through coverage model
- Experiment setup:
  - 16 transformation rules
  - 180 variables per individual
  - NSGA-II with population size 1000, and 1000 generations
  - 30 runs, 20 minutes each*

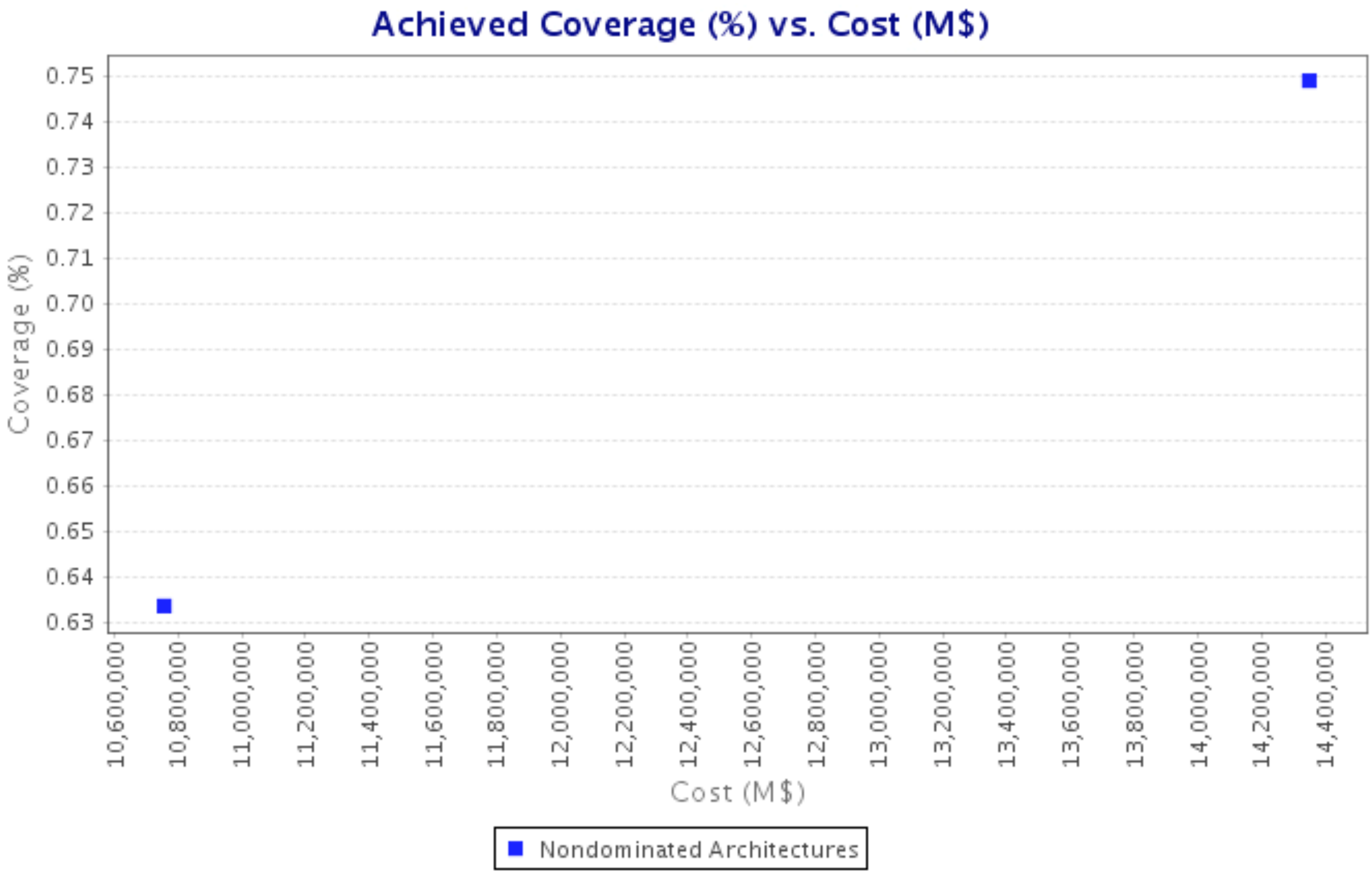
* 8 core Intel i7 @ 2.7Ghz, 16GB DDR3 RAM





<u>Fictitious</u> cost model (top) and coverage model (bottom)

Evolution of Population (Algorithm: NSGA-II)



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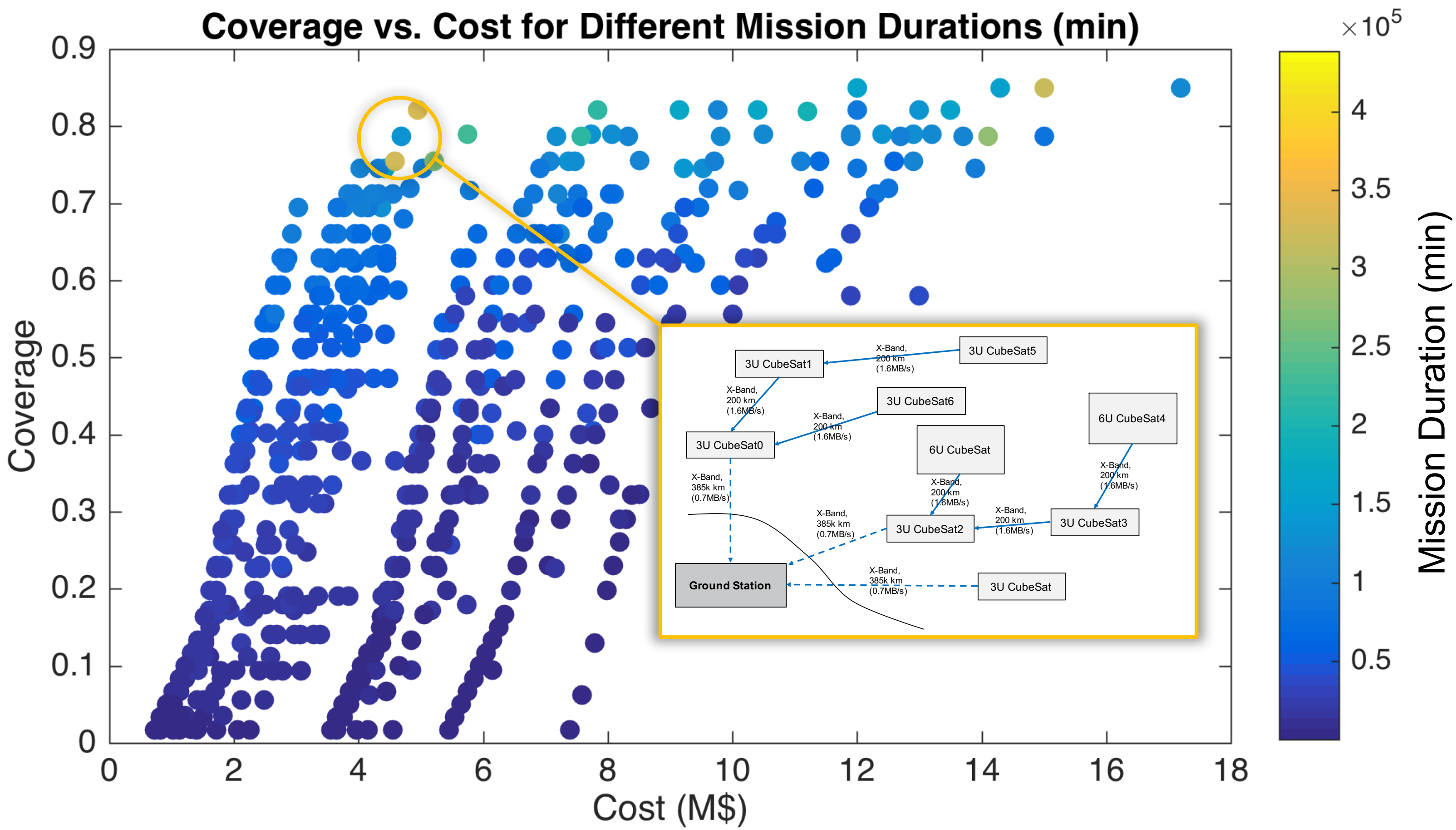
Results from Application to Case Study

Visualization of Trade Space



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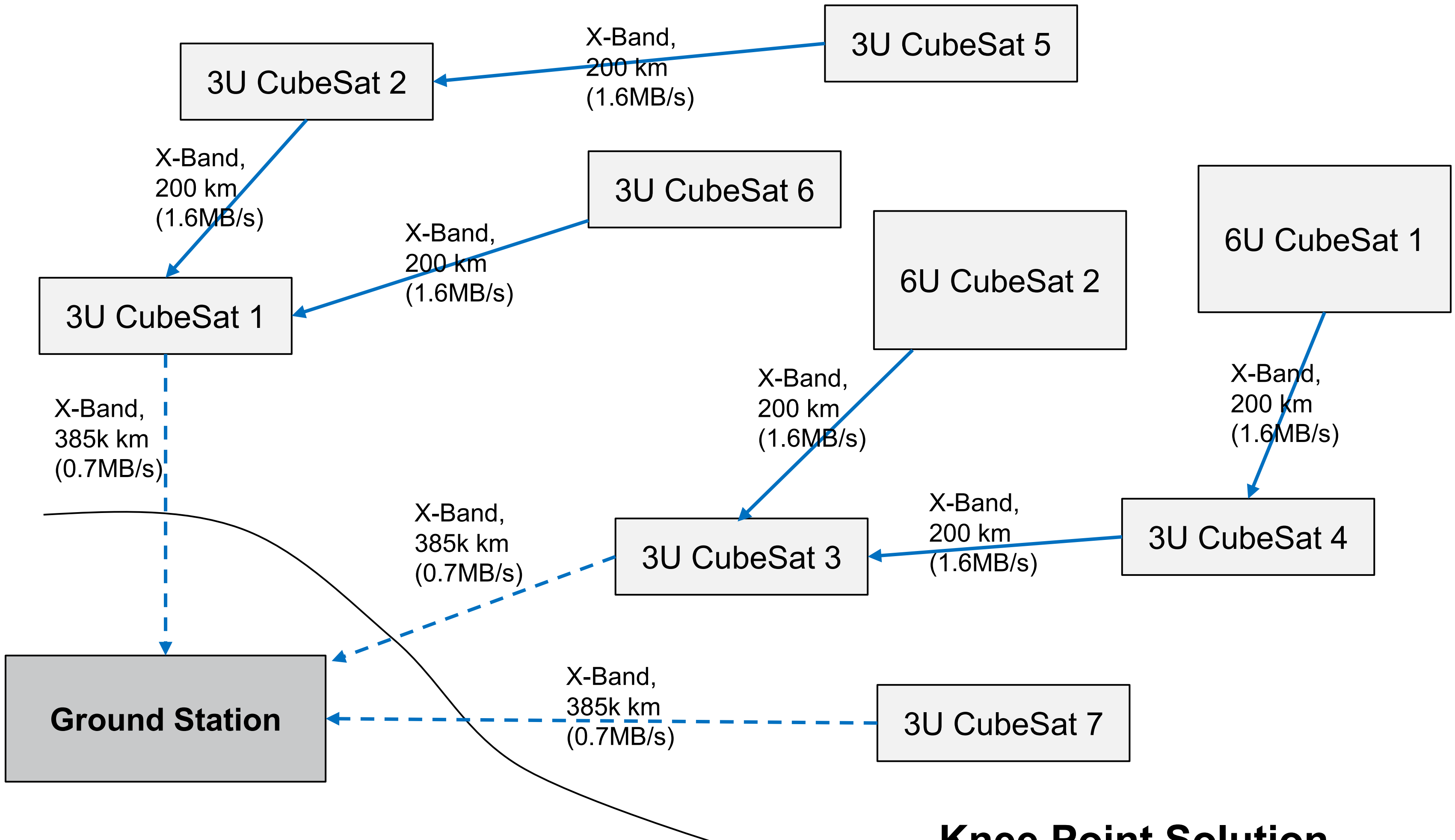
Results from Application to Case Study

"Knee Point" Solution

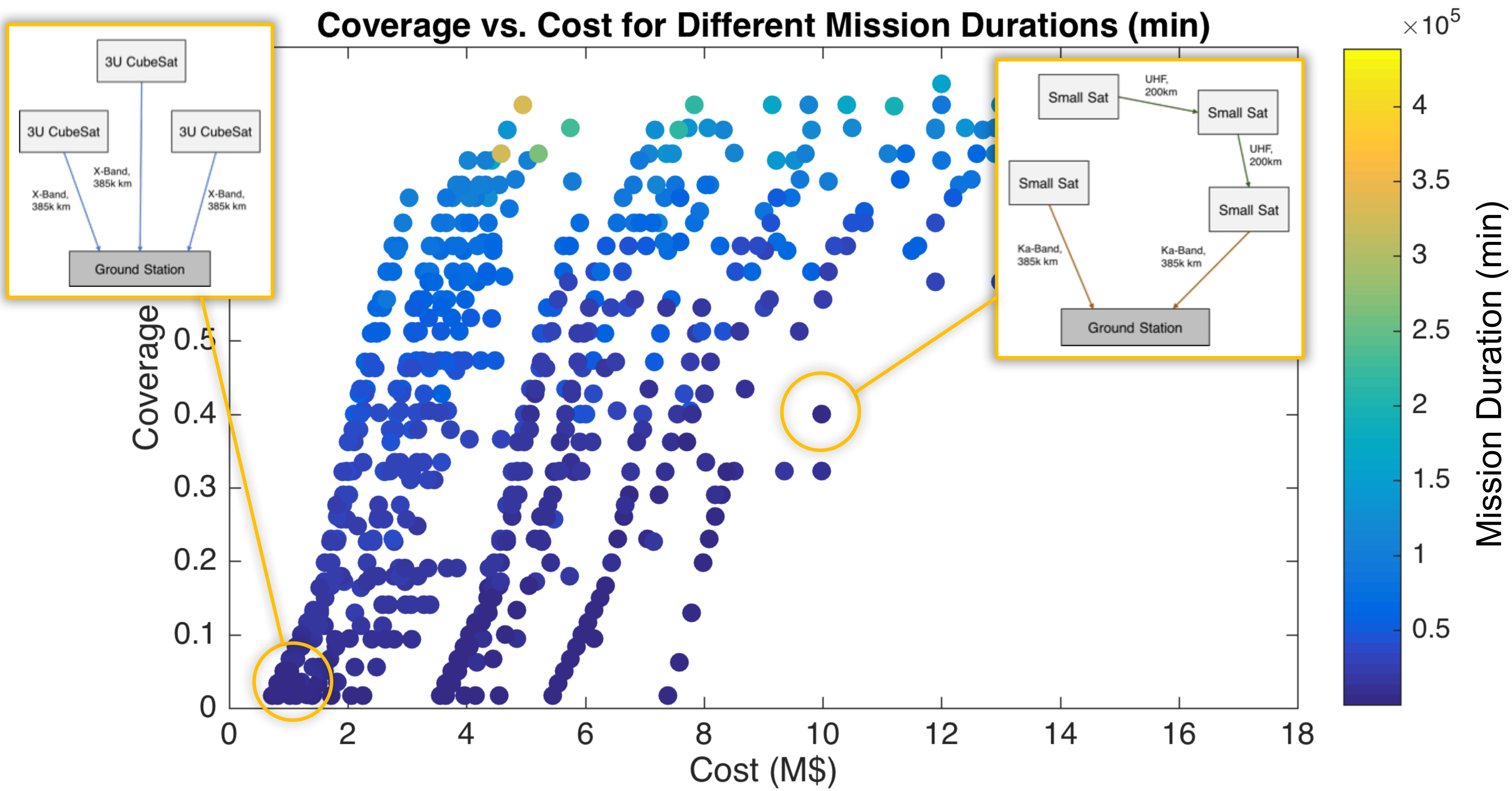


Knee Point Solution

$4.7M, ~0.79 coverage (10h observation)

Results from Application to Case Study

Visualization of Trade Space



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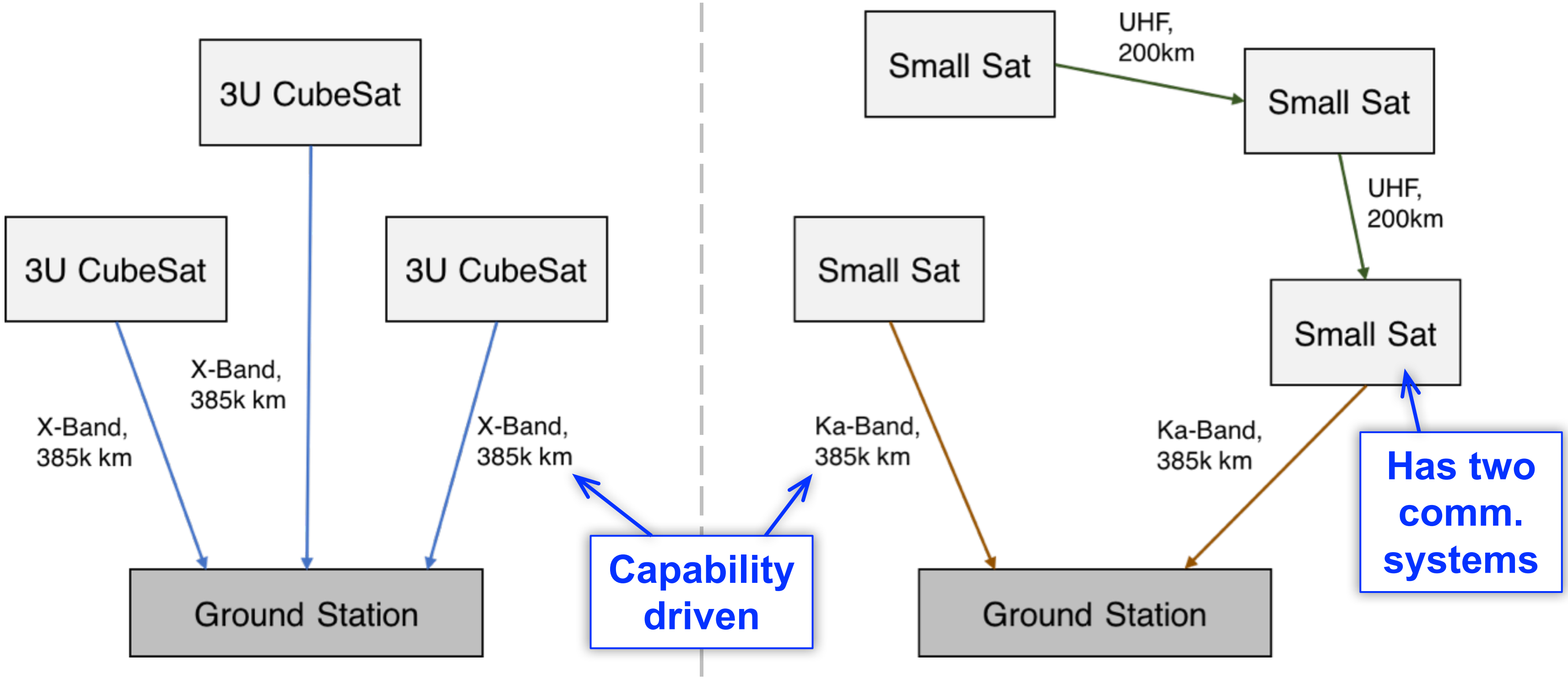
Results from Application to Case Study

Examples of Pareto-Optimal (Nondominated) Solutions



Candidate Solution #1
$1M, ~0.02 coverage

Candidate Solution #2
$10M, ~0.4 coverage

Similar mission duration, but #1 has much longer downlink time

Summary & Conclusions

- MBSE enhances communication, and improves productivity and quality
  - More complete transmission of concepts and rationale
  - More complete exploration of design space
  - Ability to study multiple distinct mission concepts for the same resources as it would have previously cost to study just one
  - Information is kept consistent and up-to-date
  - Requirements validation and design verification can be done often and early

- MBSE helps manage complexity and promotes reuse of design information and institutional knowledge

References

[1] C. Lin, D. Nichols, H. Stone, S. Jenkins, T. Bayer, D. Dvorak: *Experiences Deploying MBSE at NASA JPL*. Frontiers in Model-based Systems Engineering Workshop, Georgia Institute of Technology, Atlanta, Georgia, USA, April 2011.

[2] Dave Nichols and Chi Lin: *The Application of MBSE at JPL Through the Life Cycle*. INCOSE International Workshop, January 2014.

[3] S.J.I. Herzig, S. Mandutianu, H. Kim, S. Hernandez, T. Imken: *Model-Transformation-Based Computational Design Synthesis for Mission Architecture Optimization*. AIAA / IEEE Aerospace, March 2017.

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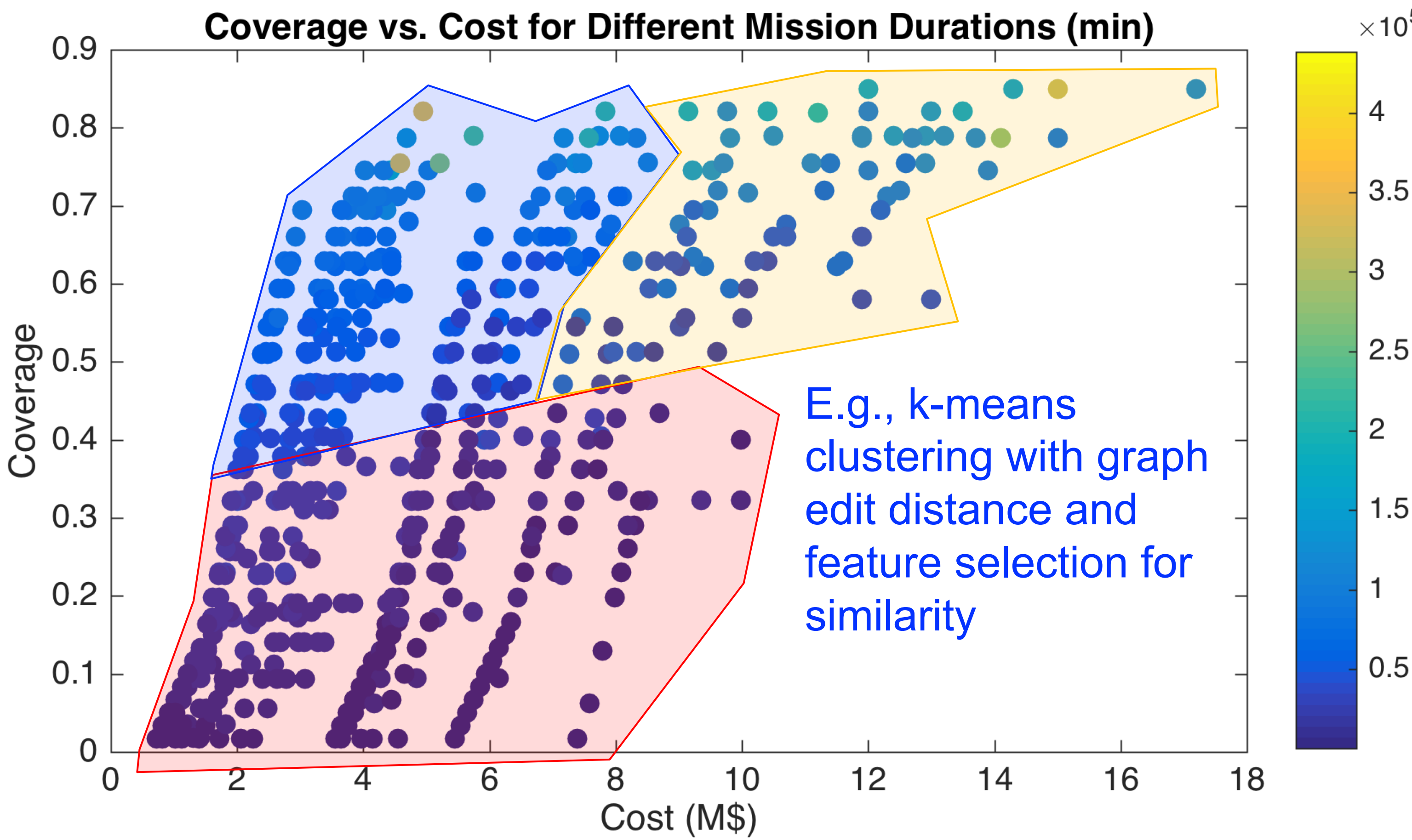
Backup Slides

What's Next?

Clustering of Similar Architectures



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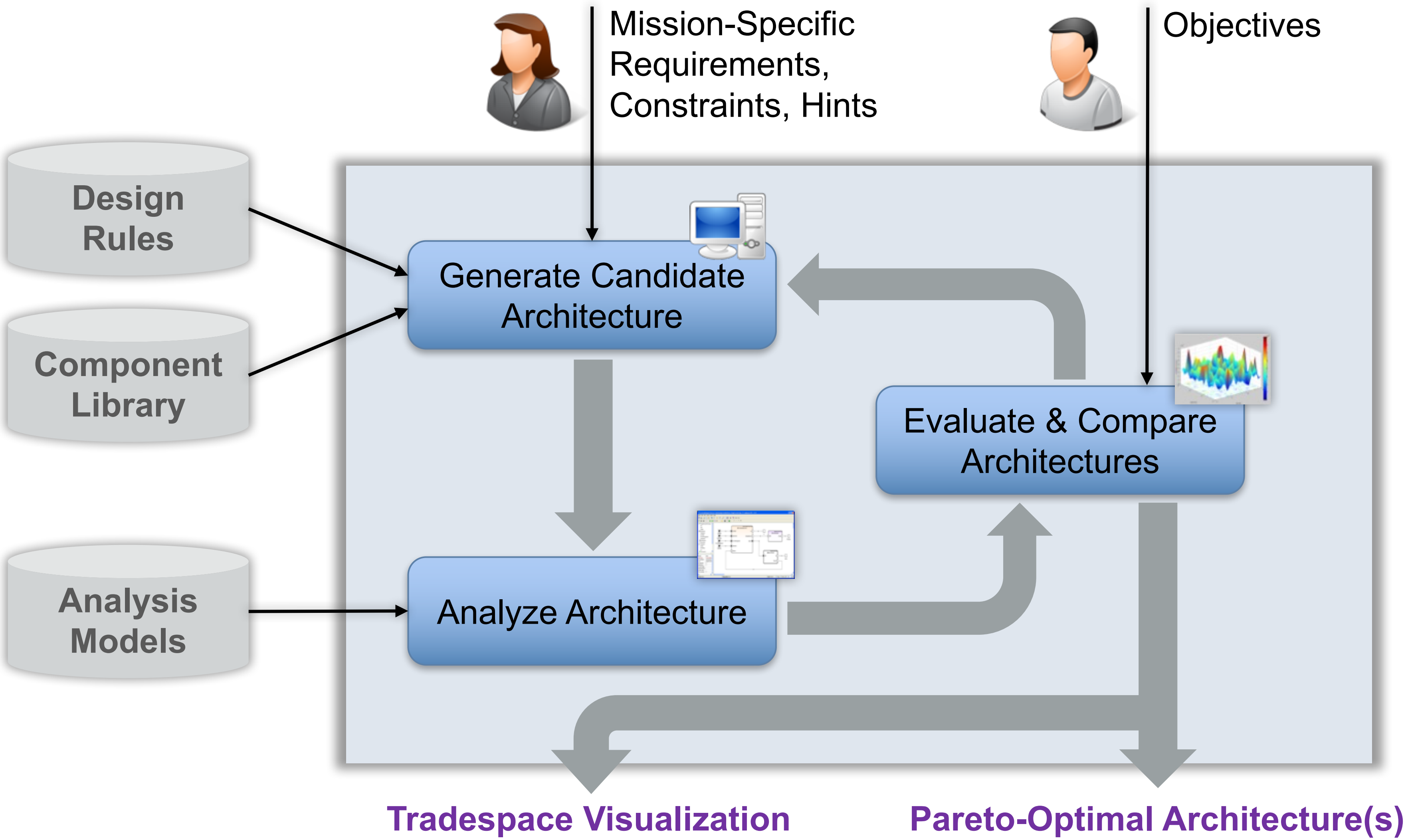
Framework

CDS for Mission Architecture Design



Application to Case Study

Link Calculations

- Derived from standard link budget, assuming above average noise due to expected interference from Moon

Table 1. Computed communication rates. 385k km case assumes 72 dBi receive antenna gain for X-band, and 85 dBi for Ka-band (similar to DSN).

Transmitter Configuration	200 km	385k km
UHF, 3 W, 1 dBi	5 Mbps	-
X-Band, 5 W, 10 dBi	1.6 Mbps	0.7 Mbps
Ka-Band, 15 W, 25 dBi	220 Mbps	80 Mbps

Application to Case Study

Cost Calculations

- Cost per spacecraft calculation incorporates a learning curve
- Assuming $ 100,000 per hour of observation to estimate observation and data processing cost

$$c_i = c_{base,type(i)} \cdot n_{type(i)}^{-0.25} + c_{conf,i} \quad (5)$$

$$c_{total} = \sum_{i=1}^{n_{sc}} c_i + 100,000 t_{obs} \quad (6)$$

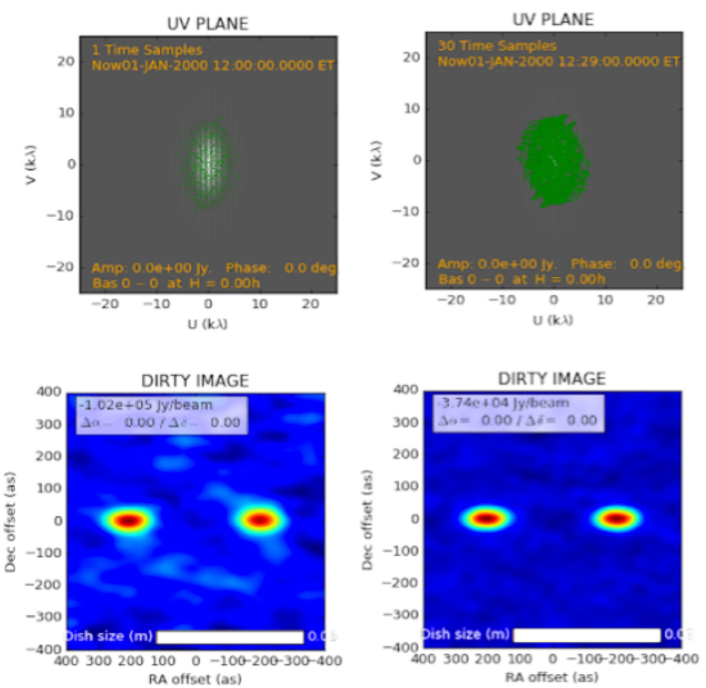
Application to Case Study

Coverage

- Simple coverage calculation

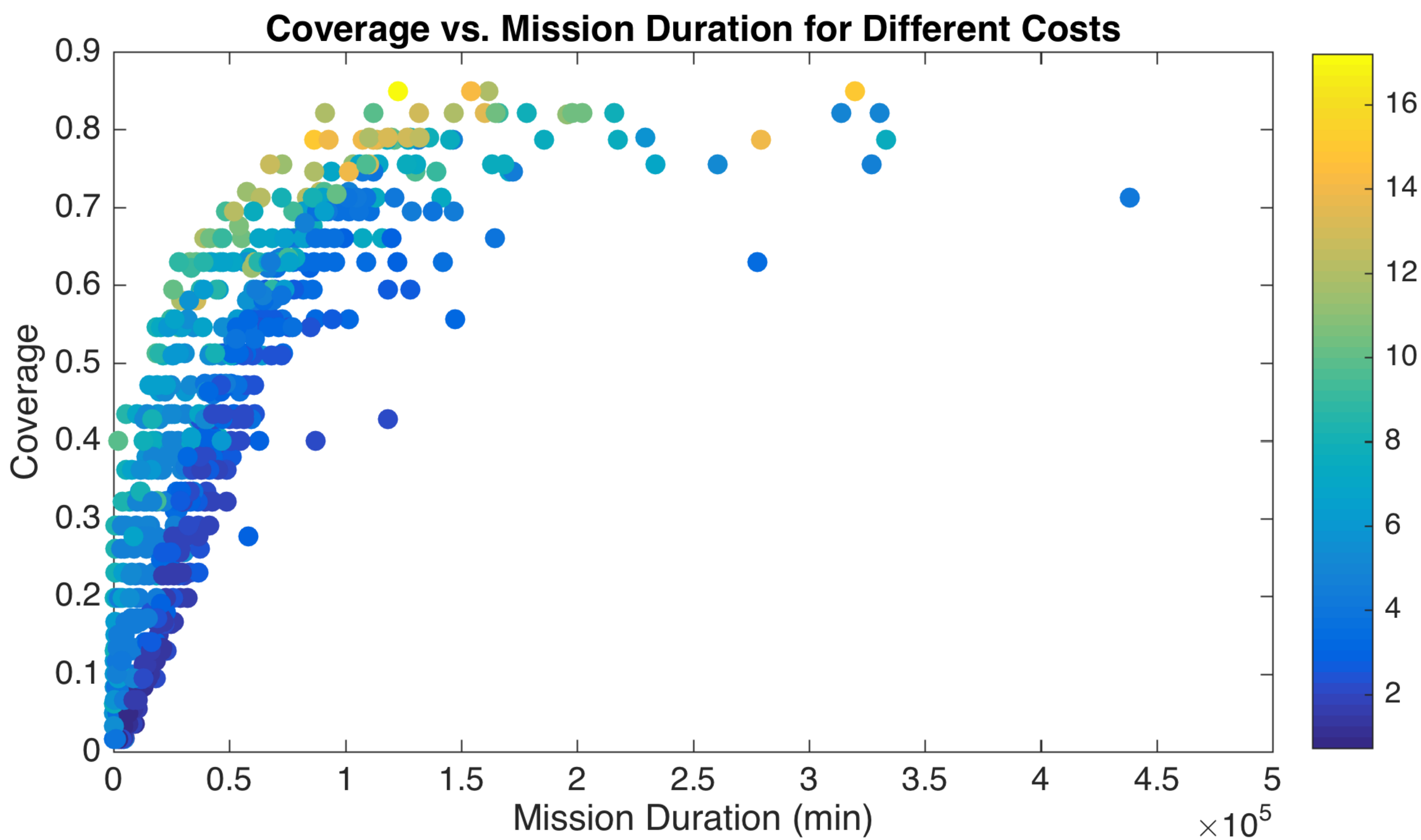
$$cov = \left(1 - \frac{2}{n_{obs}}\right)^{1+9(1/t_{obs})} + 0.05\frac{t_{obs}}{3} \qquad (1)$$

- Surrogate model that reflects trends observed from more sophisticated telescope array simulation performed by Alexander Hegedus (https://github.com/alexhege/Orbital-APSYNSIM/)



Results from Application to Case Study

Coverage vs. Mission Duration



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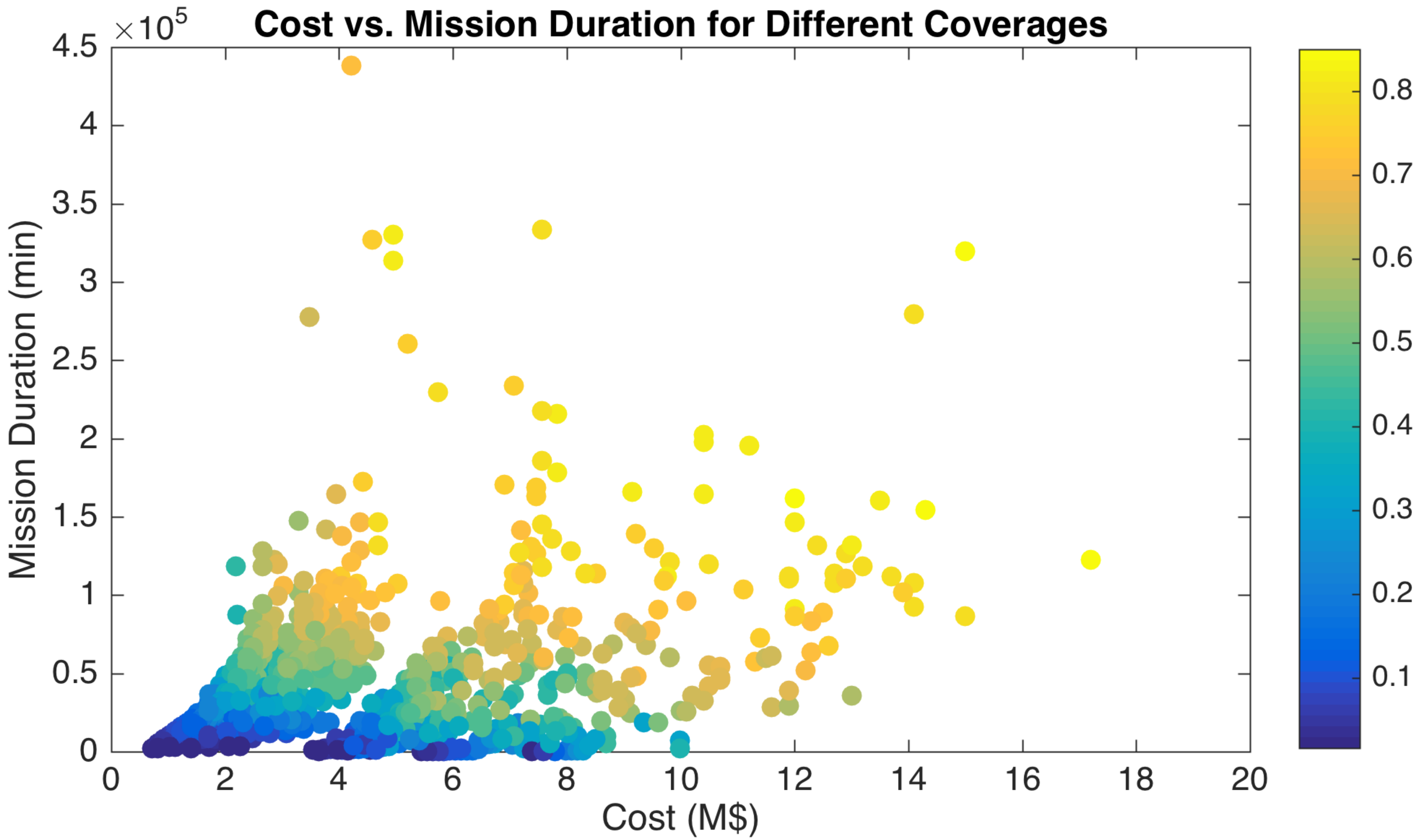
Results from Application to Case Study

Cost vs. Mission Duration



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