Jet Propulsion Laboratory
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Model-Transformation-Based Computational Design Synthesis for Mission Architecture Optimization

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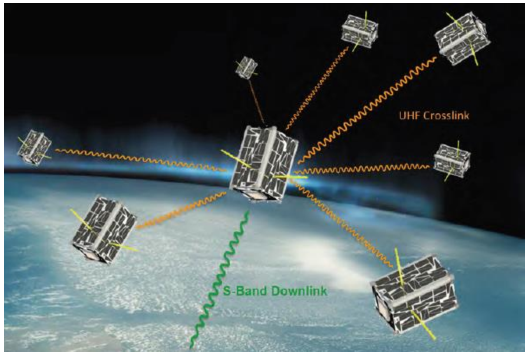
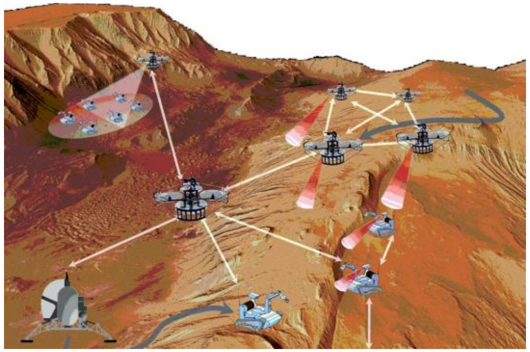
Networked Constellations of Spacecraft

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





Motivating Case Study

Spacecraft-Based Radio Interferometry

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

Radio interferometers:

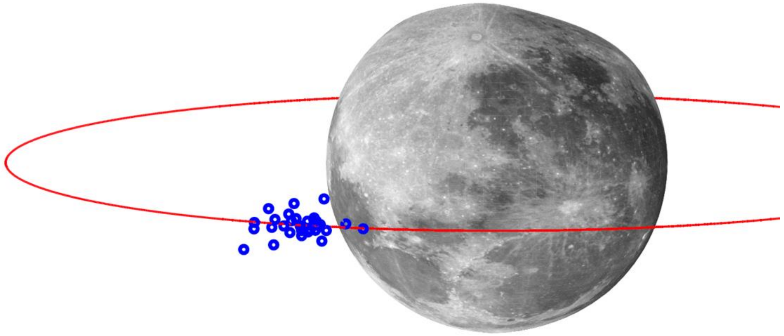
- Radio telescopes consisting of multiple antennas
- Achieve the same angular resolution as that of a single telescope with the same aperture

➔ Typically ground-based

Want to do this in space:

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

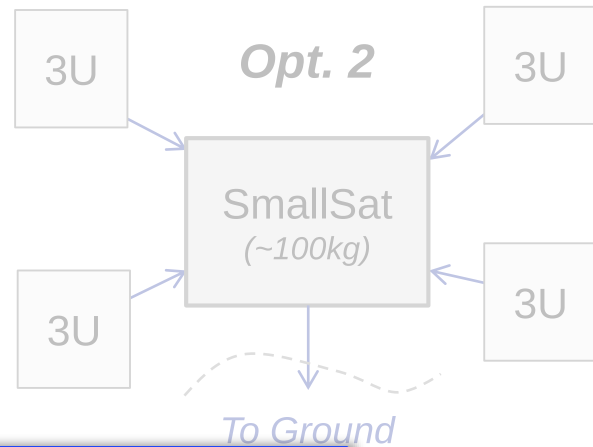
➔ CubeSats or SmallSats are promising enablers for this



Which Architecture is Optimal?

Opt. 1

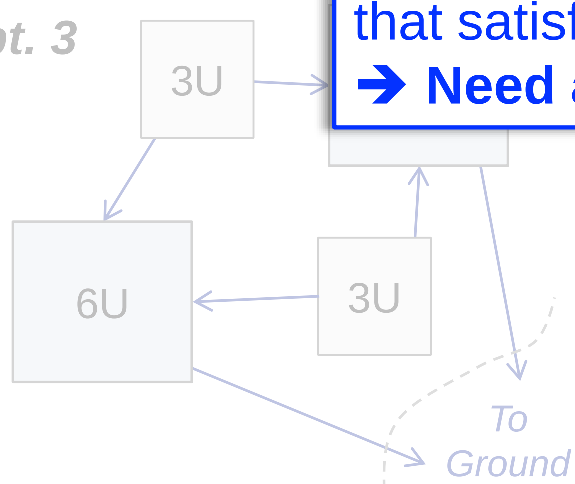
Same functionality, different qualities / performance
➔ **Examine trade-offs**



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

...ery large data ...Earth

Opt. 3



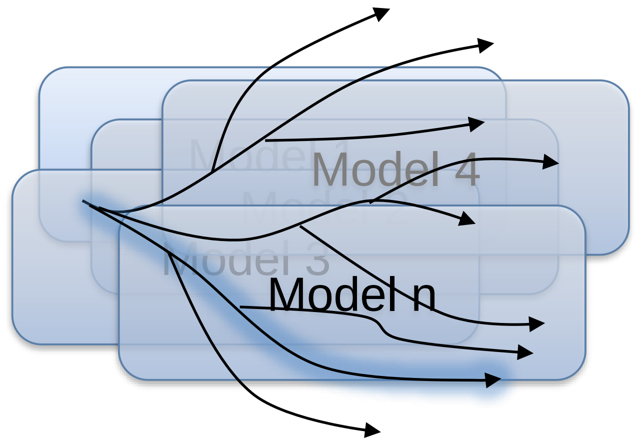
- ...any spacecraft?
- Are all equipped with interferometry payloa...
- Who c...
- What frequency bands? Multi-hop?
- …
- Optimal w.r.t. cost? Science value?

Functional allocation is key
➔ **Synthesis problem**

Mission Architecture Trade Space Exploration

Mechanized Exploration

Abstraction of Domain



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

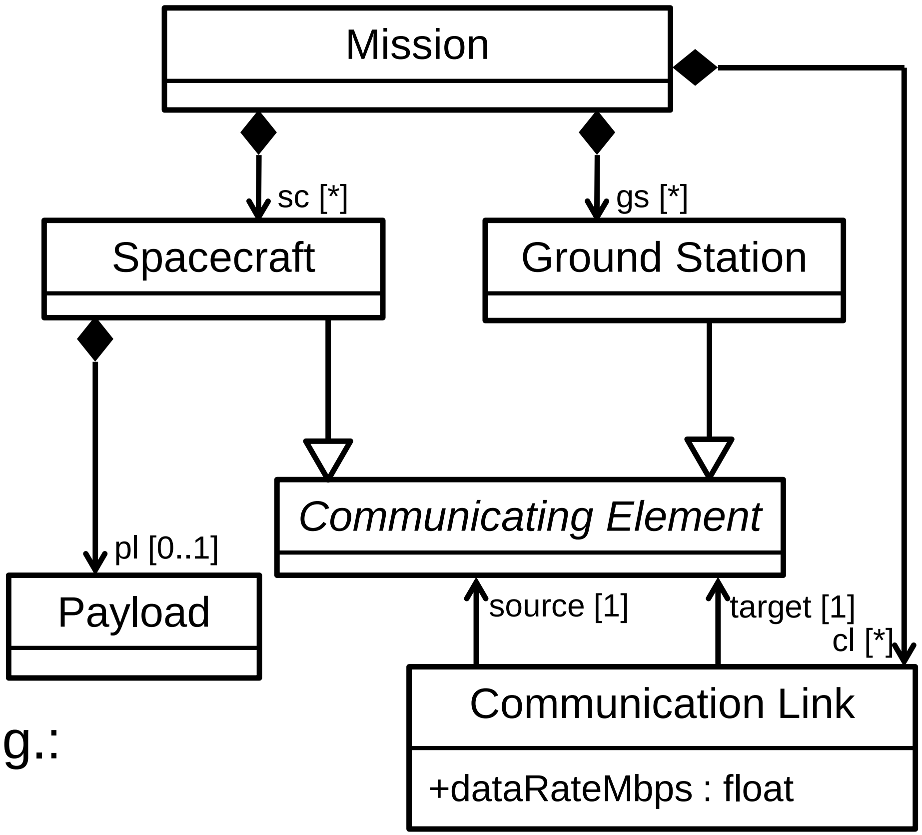
Problem Description

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 (meta-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"

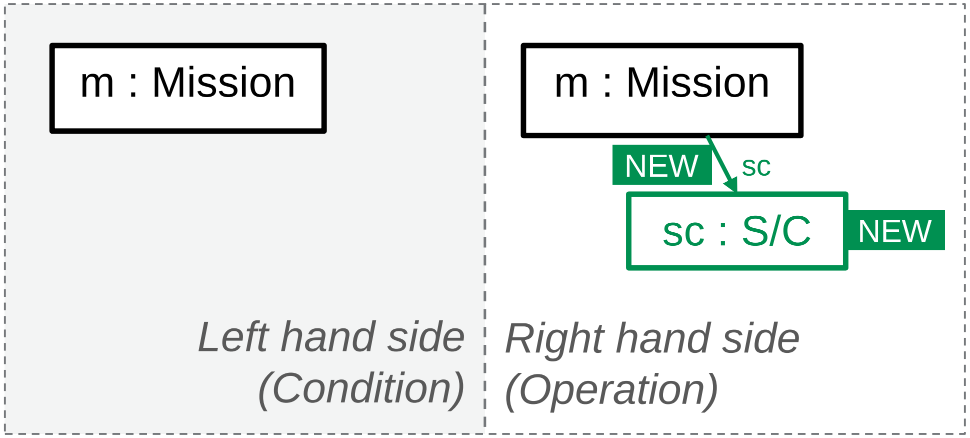
  "All spacecraft must (transitively) be connected to at least one ground station through a communication link"

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

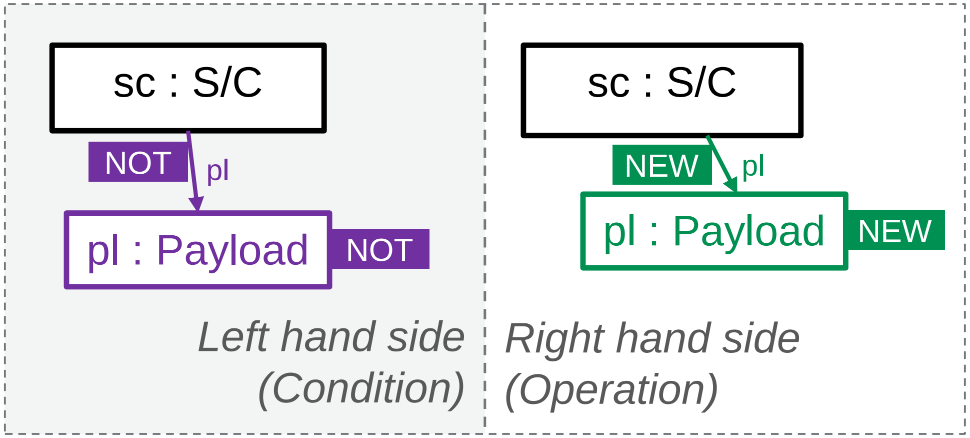
Model-Transformation-Based Exploration

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)



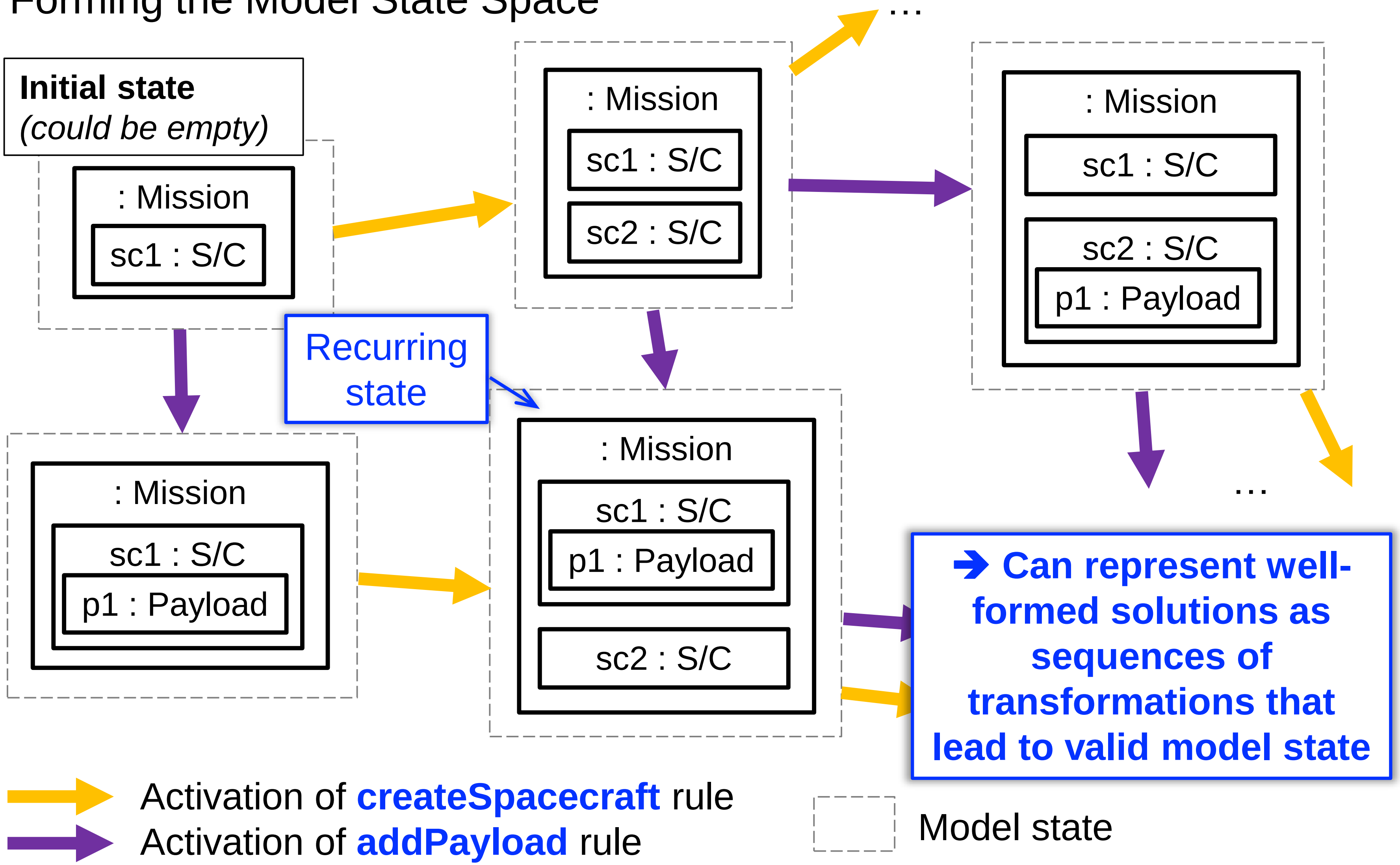
Rule "createSpacecraft"



Rule "addPayload"

Model-Transformation-Based Exploration

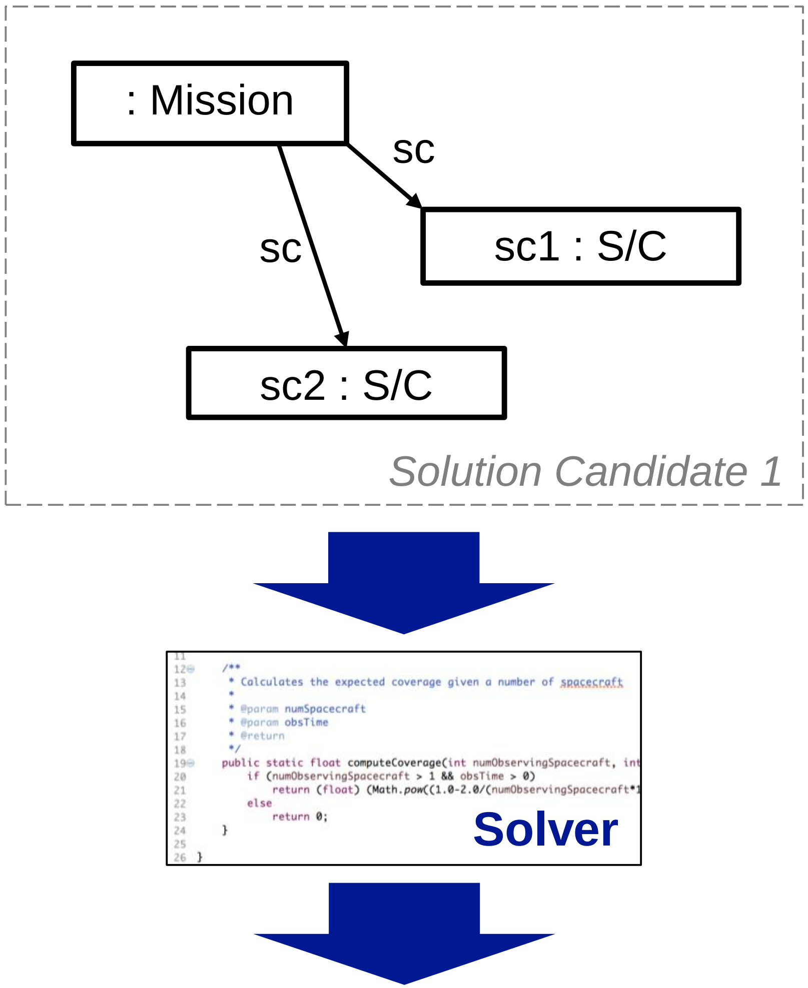
Forming the Model State Space



Evaluating the Objectives

- Evaluating objectives requires analysis of the candidate solution *(interpretation by a solver)*
  - Determine performance and determine values for measures of effectiveness
  - Determine objective function values

- Analyses defined at level of domain: part of formal interpretation of models within domain



"Scientific value of candidate 1 is 0.34"

Driving Exploration Towards Optima

Using Evolutionary Algorithms to find Pareto-Optimal Solutions

Crossover

Individual x:

(Selection from population)

Add Spacecraft	Add X-Band Comm	Add Spacecraft	Add Comm Link	*fitness=0.6*

(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*

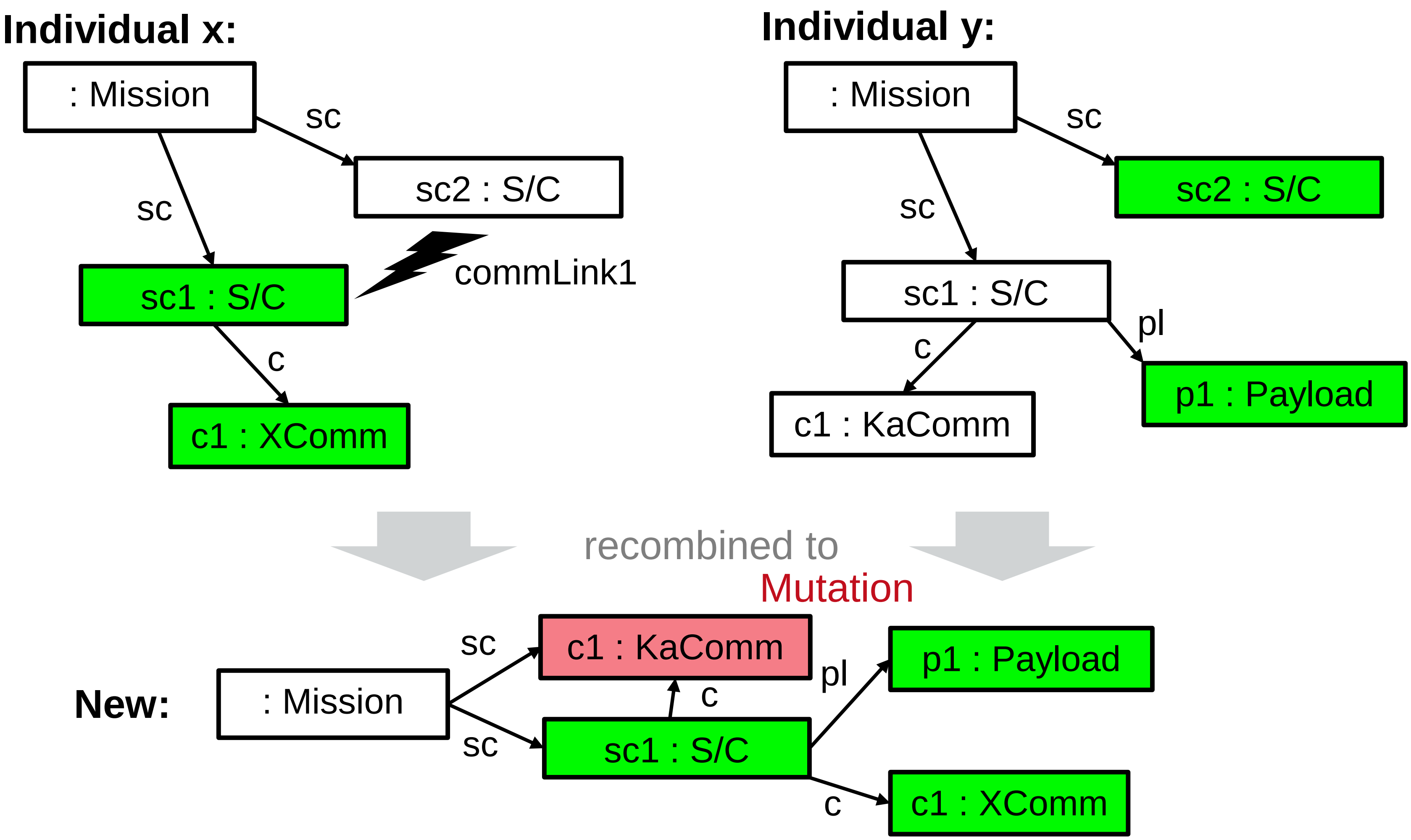
(Recombined individual in next generation)

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

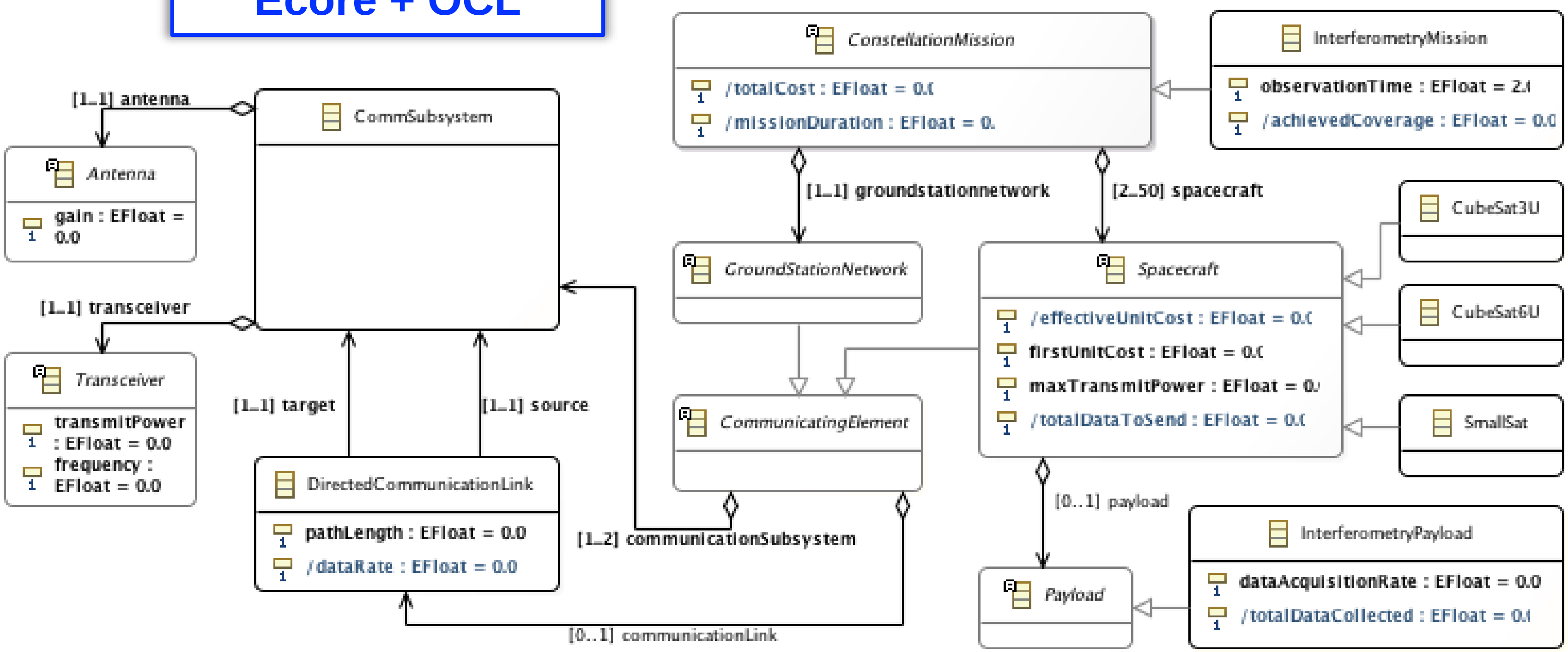
- Analyses / Fitness Functions
  ➔ Java

- Optimization Using Genetic Algorithms
  ➔ MOMoT, MOEA

Application to Case Study

Representation of Domain (Excerpt)

Domain model in Ecore + OCL



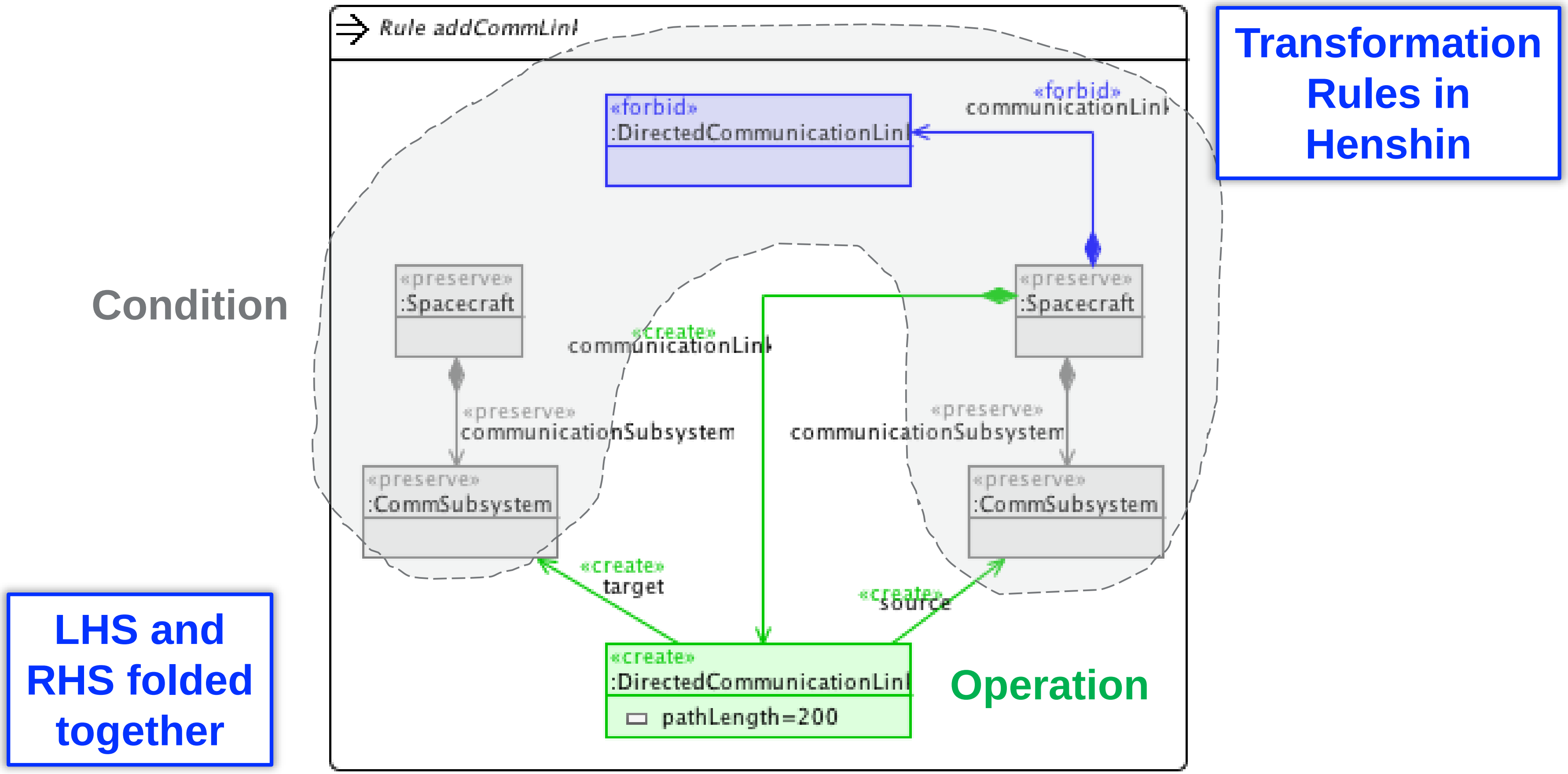
20 concepts, 9 associations, 15 attributes / parameters

> 48^{10} possible models

Too many for exhaustive search

Application to Case Study

Transformation Rule Example (Henshin Syntax): Add Comm. Link

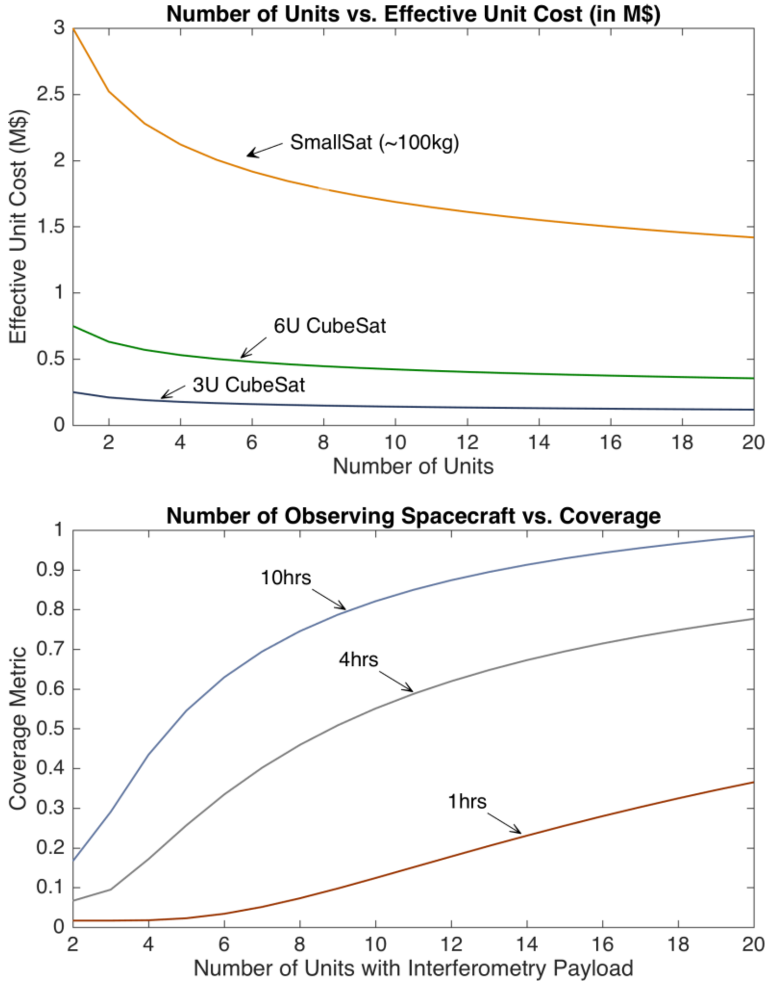


In Prose: *"Find 2 distinct spacecraft instances, and add a communication link between them"*

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, 7 minutes each*

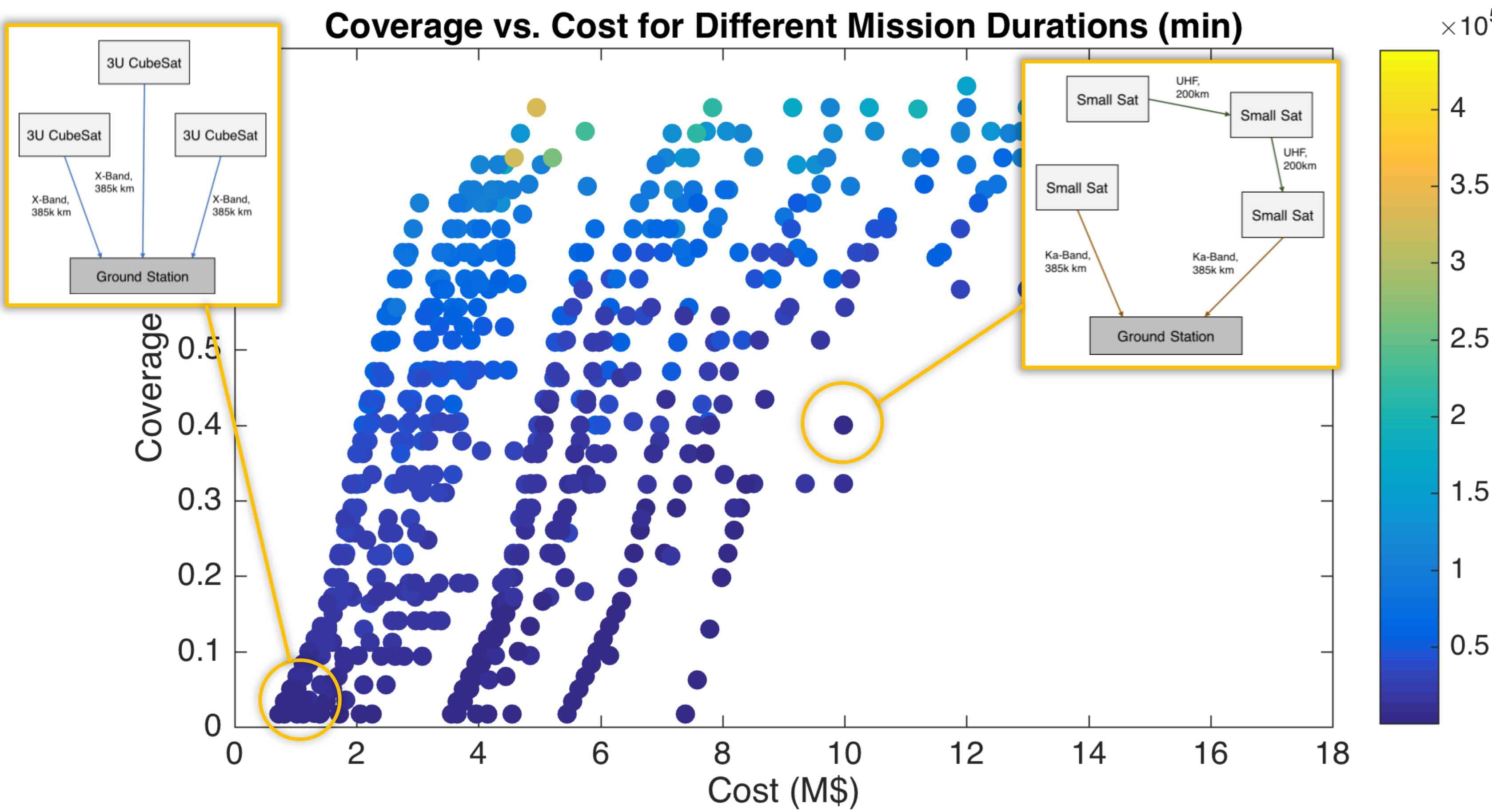
* 8 core Intel i7 @ 2.7Ghz, 16GB DDR3 RAM



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

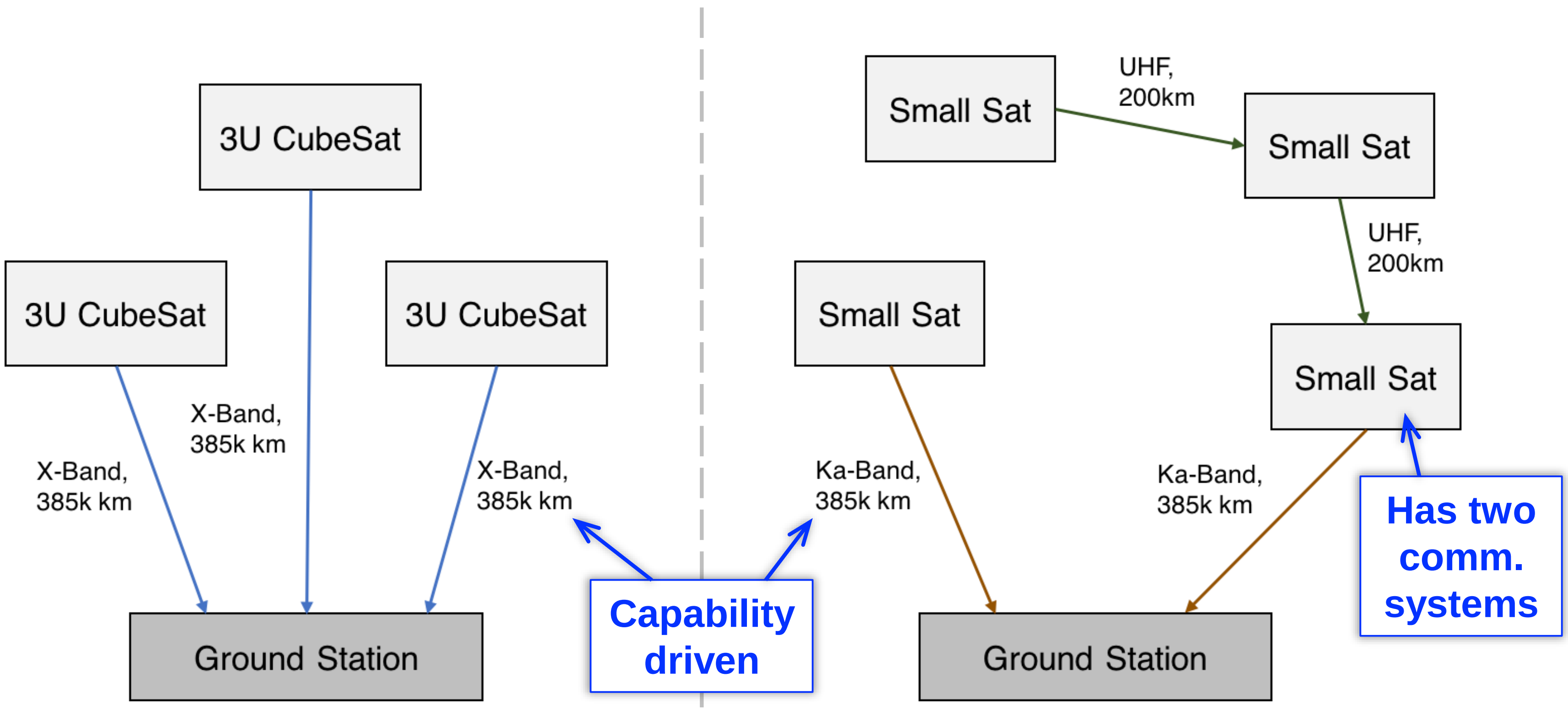
Results from Application to Case Study

Visualization of Trade Space



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

Conclusions

- Demonstrated method for solving highly complex synthesis problems and going beyond parametric trade space exploration
  - Generate diverse set of alternatives in a reasonable timeframe
  - Solutions generated based on abstract, description of problem
  - Enables designers to focus on **analysis**, and consider more options
- The generated candidate solutions can help spark creativity, but don’t replace a designer
  - Method meant to ***support*** designers and the creative process
  - Many solutions sensible to experts; however, some may required slight modification or additional local search → many constraints required
- Good performance for relatively limited problems, but should investigate methods for subdividing problem further in future work

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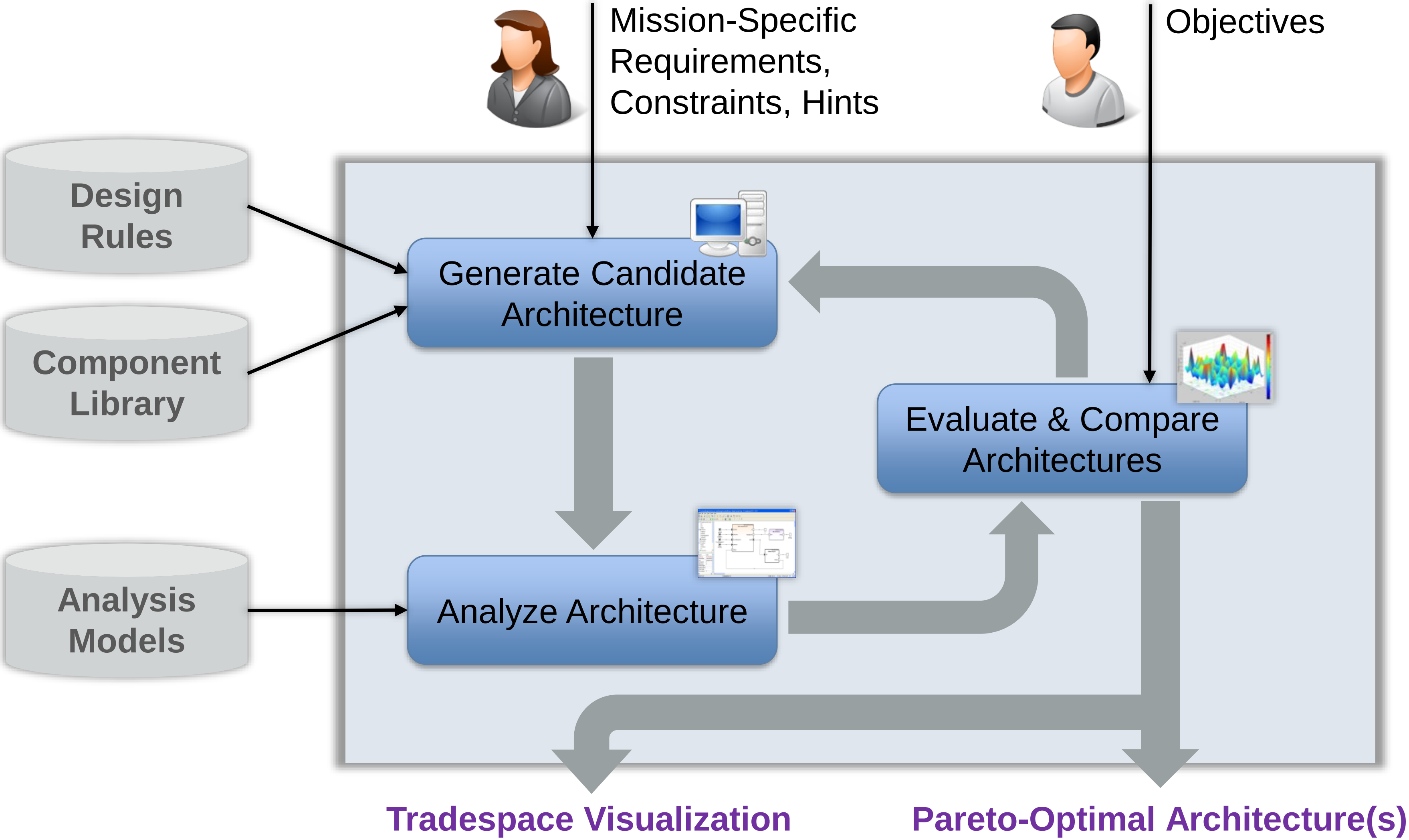
Backup Slides

IEEE Aerospace 2017 Presentation on *“Model-Transformation-Based Computational Design Synthesis for Mission Architecture Optimization”*

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

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

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

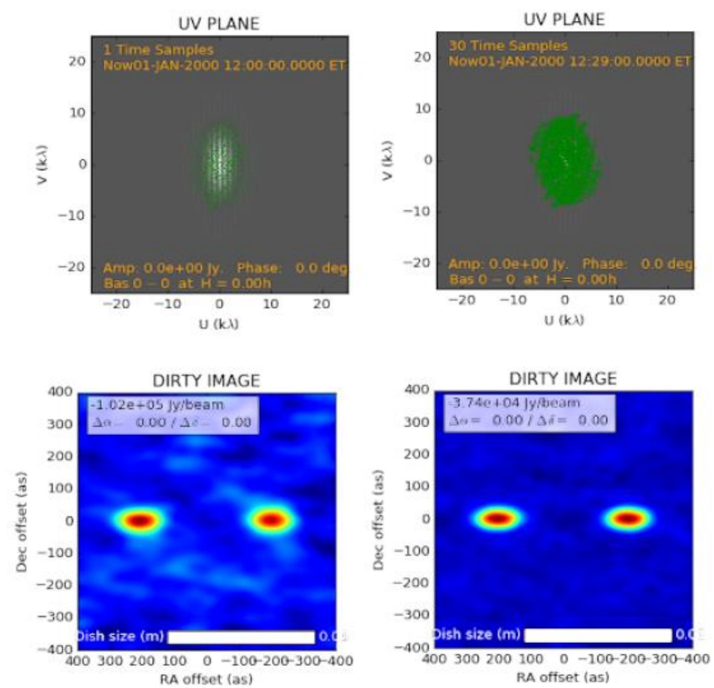
Application to Case Study

Coverage

- Simple coverage calculation

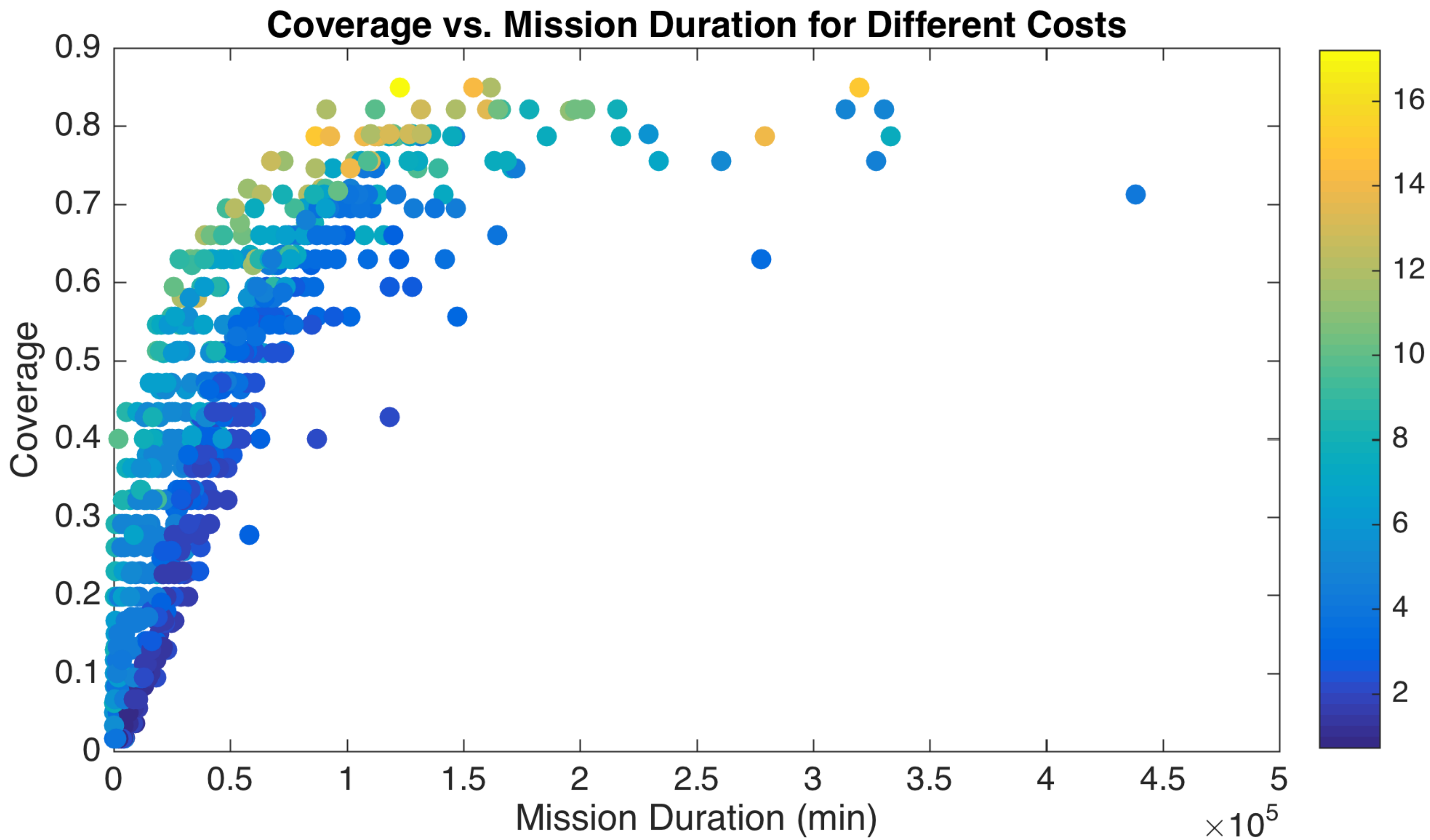
$$cov = (1 - \frac{2}{n_{obs}})^{1+9(1/t_{obs})} + 0.05\frac{t_{obs}}{3} \qquad (1)$$

- 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



Results from Application to Case Study

Cost vs. Mission Duration