Jet Propulsion Laboratory
California Institute of Technology

Cyber-Physical Systems

Cody Kinneer

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Jet Propulsion Laboratory, California Institute of Technology

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What are cyber-physical systems?

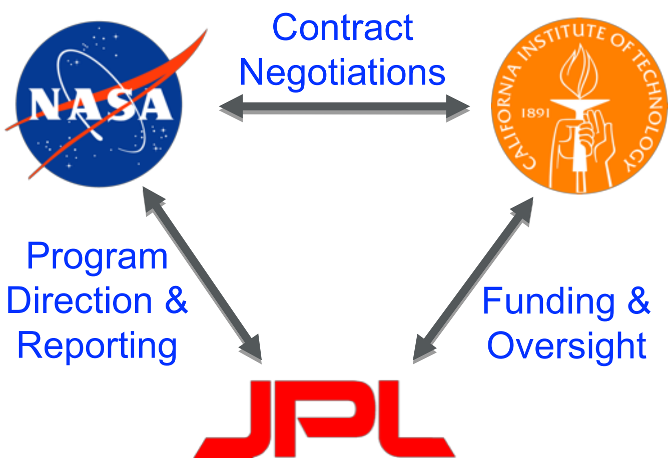
- Interaction with physics
- Changes in the environment
- Different kinds of requirements
- Modeling for performance / safety


UBER

The NASA Jet Propulsion Laboratory

Relationship to NASA and the California Institute of Technology

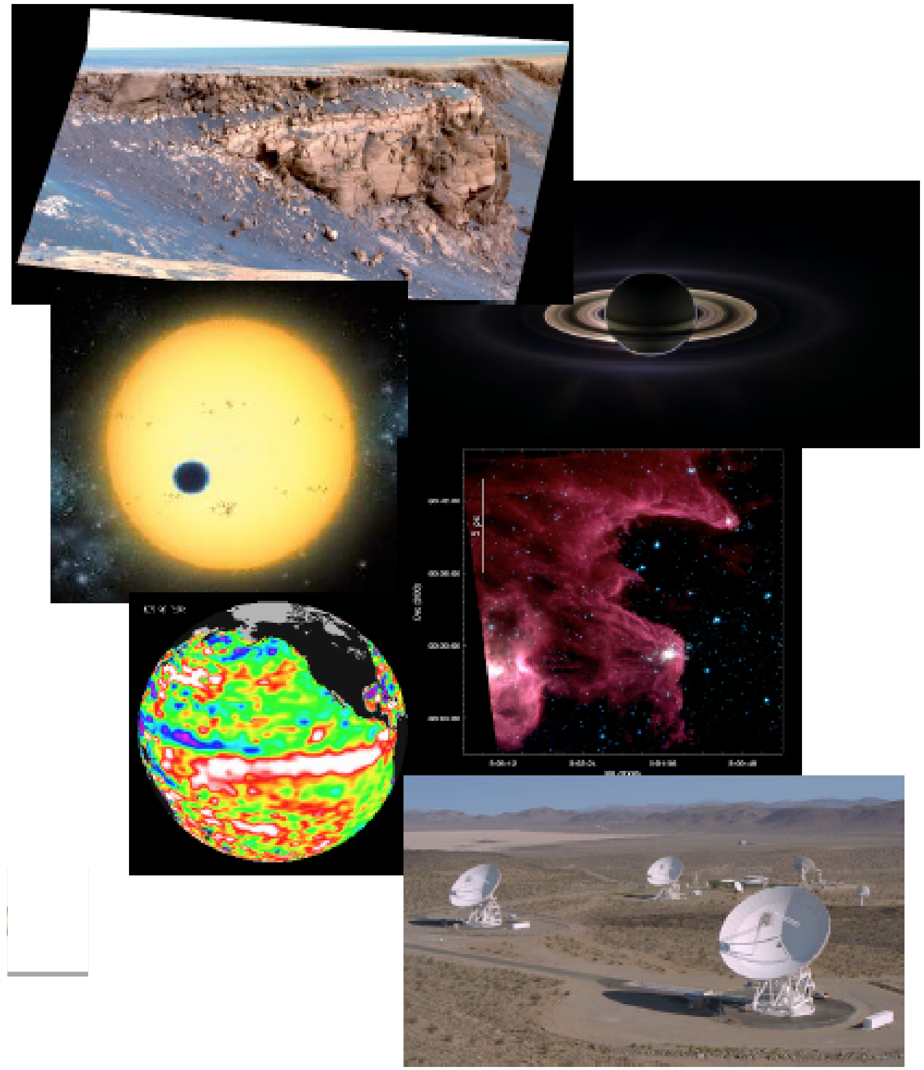
- Located in Pasadena, CA
- NASA-owned *"Federally-Funded Research and Development Center"*
- University-operated
- 5,000 employees



Source: Lin et al., 2011

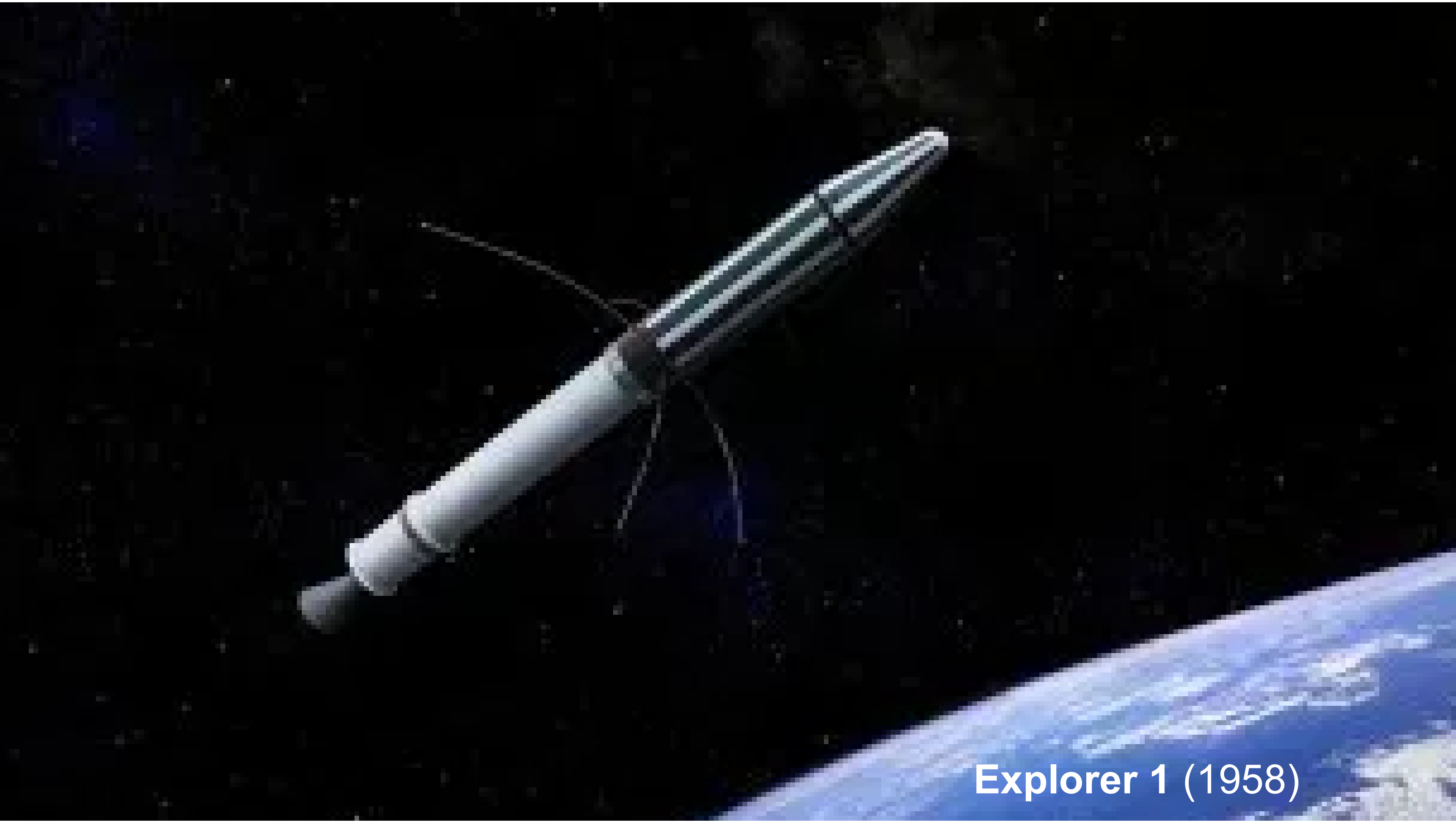
JPL's Mission is Robotic Space Exploration

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



Source: Nichols & Lin, 2014

You Might Know Some of These…



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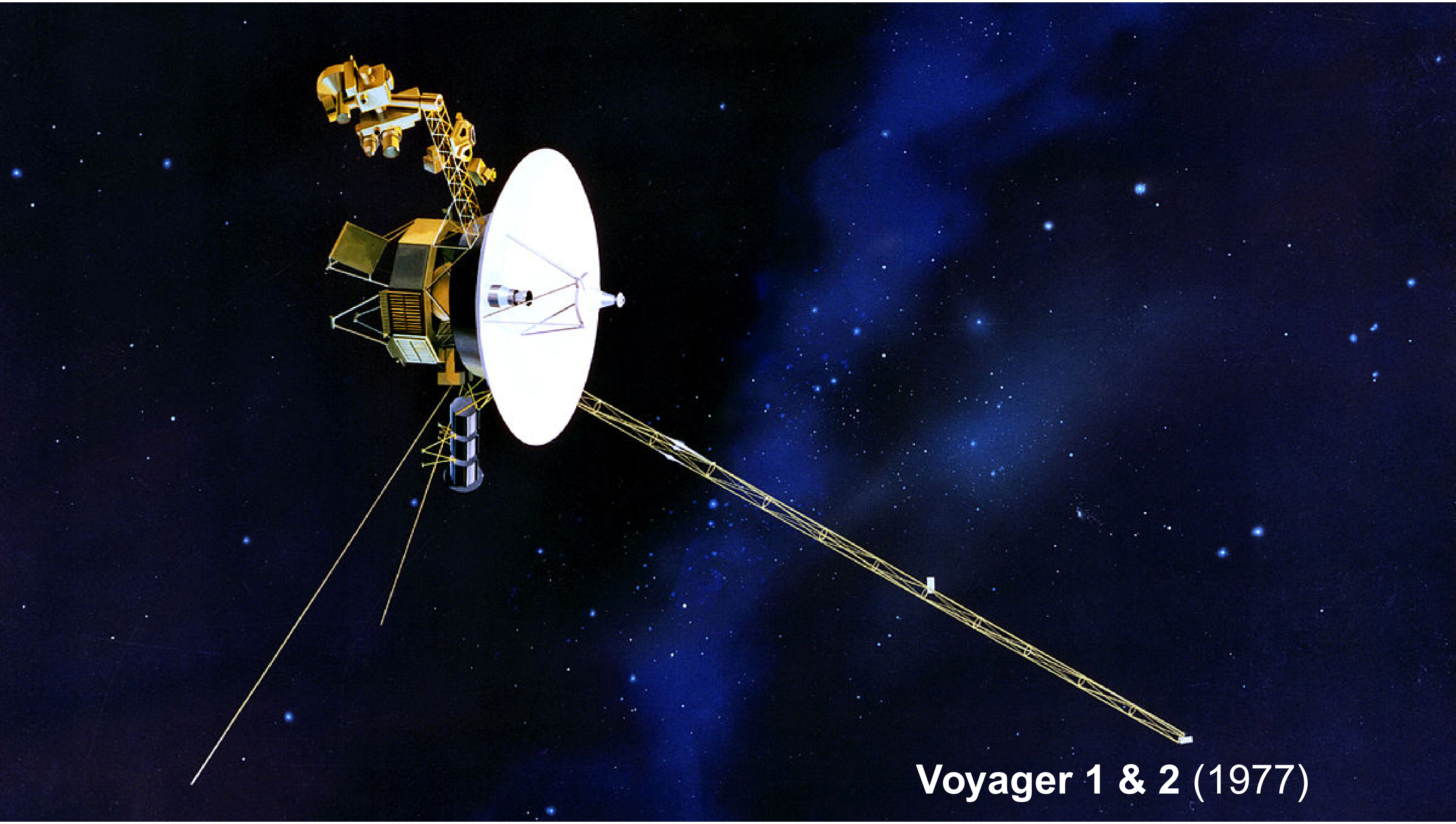
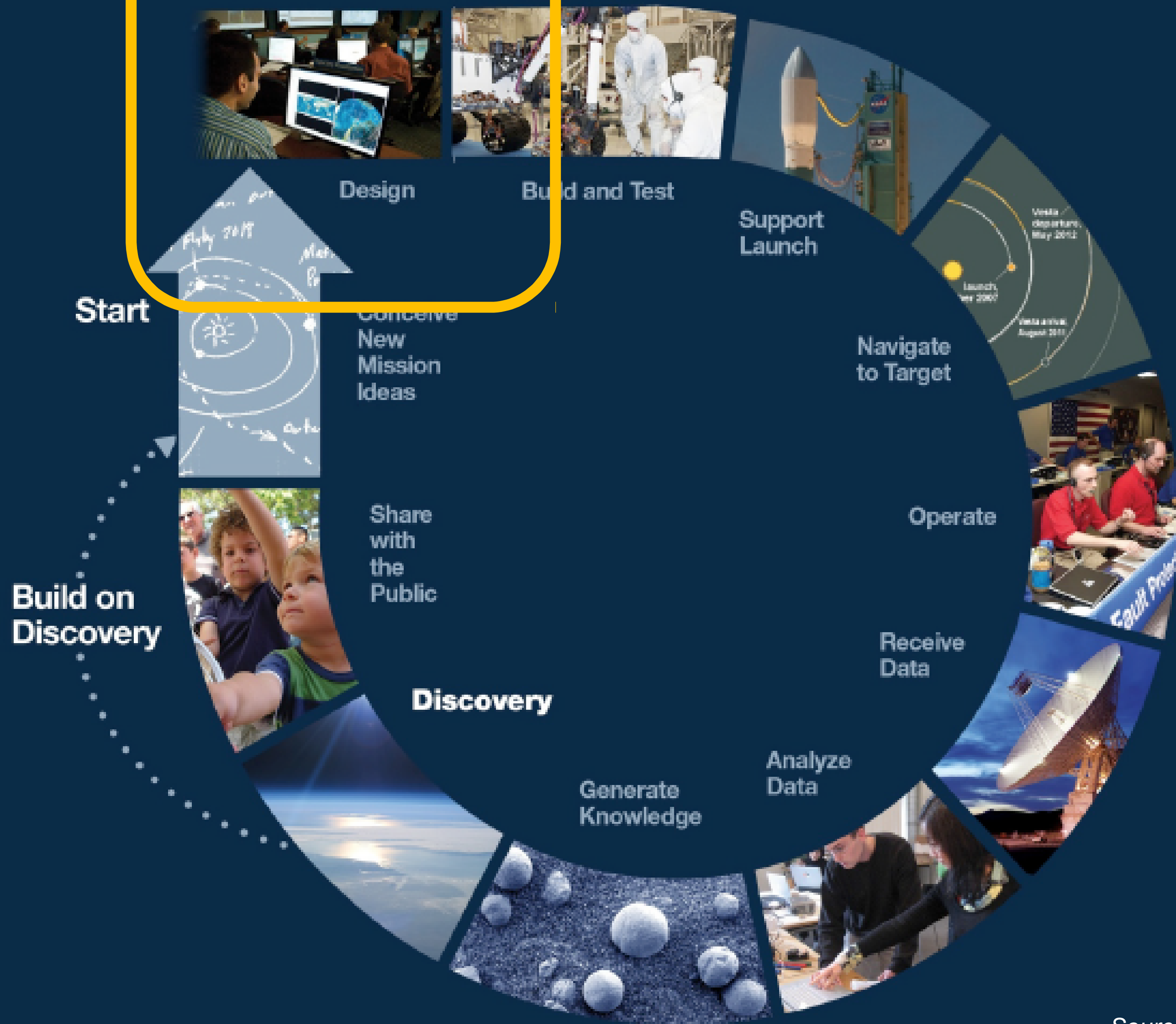


You Might Know Some of These…

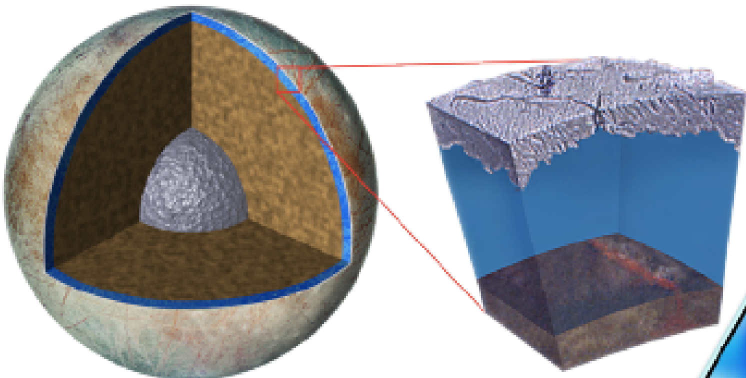
The JPL Product Lifecycle



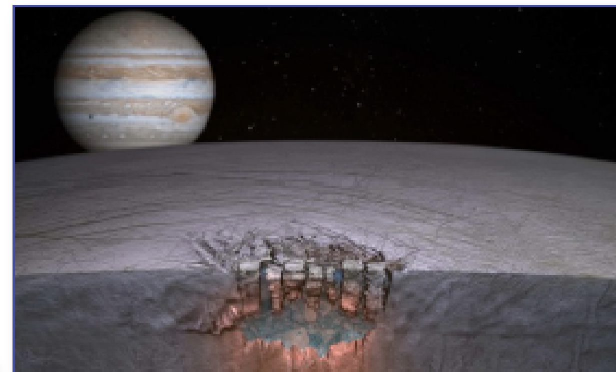
Source: *Nichols & Lin, 2014*

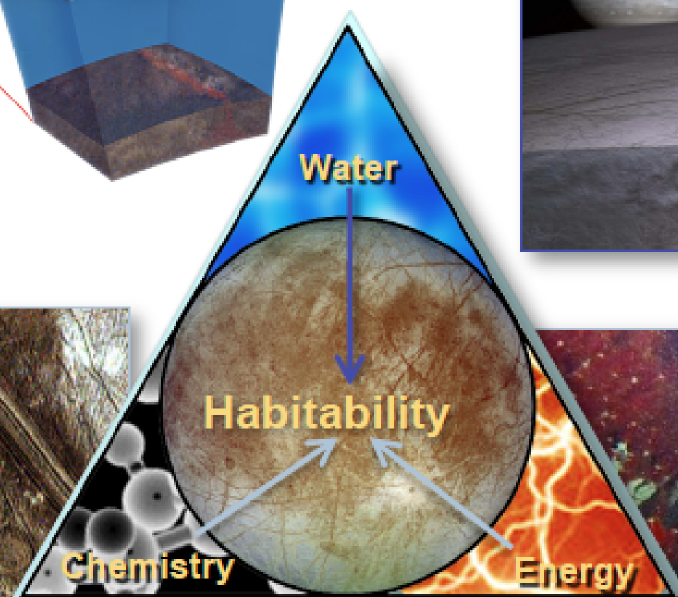
Planned Mission to Jupiter’s Moon Europa

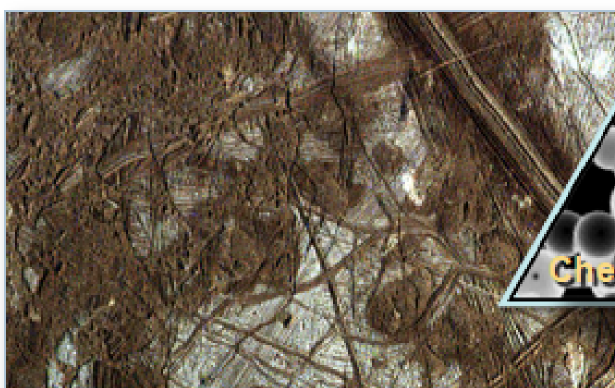
Looking for the Ingredients of Life



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

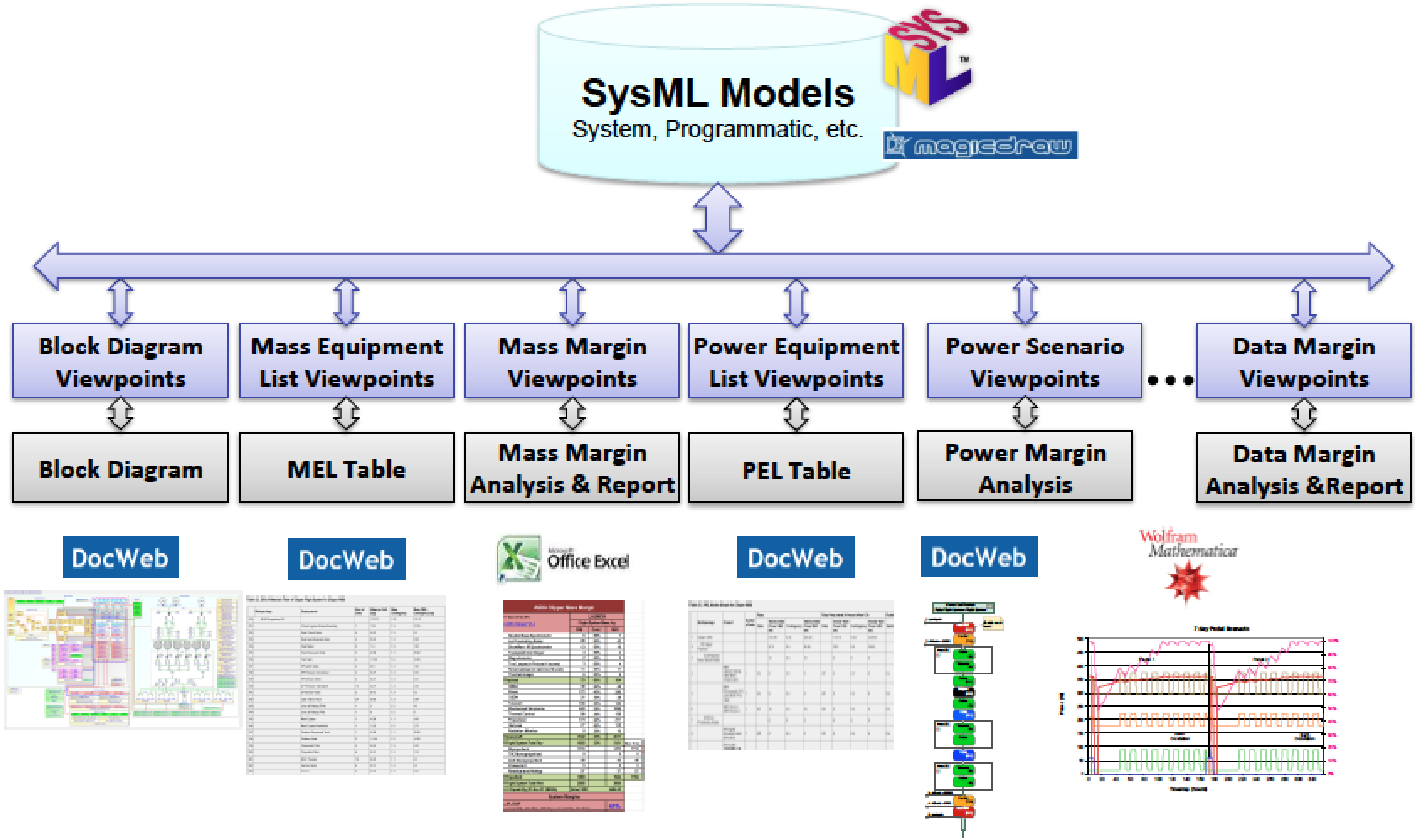
- Managing multiple architectural alternatives
- Reliably determining whether design concepts “close” on key technical resources
- Ensuring correctness and consistency of multiple, disconnected engineering reports
- Managing design changes before a full design exists

MBSE has been instrumental in addressing these challenges

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

Source: Nichols & Lin, 2014

Europa System Model Framework



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

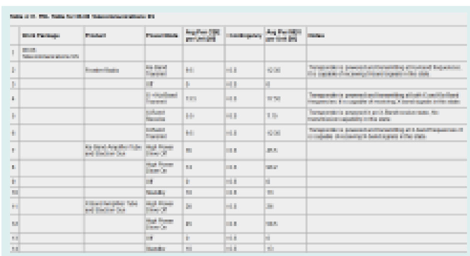
Source: Nichols & Lin, 2014

Integrated Power / Energy Analysis

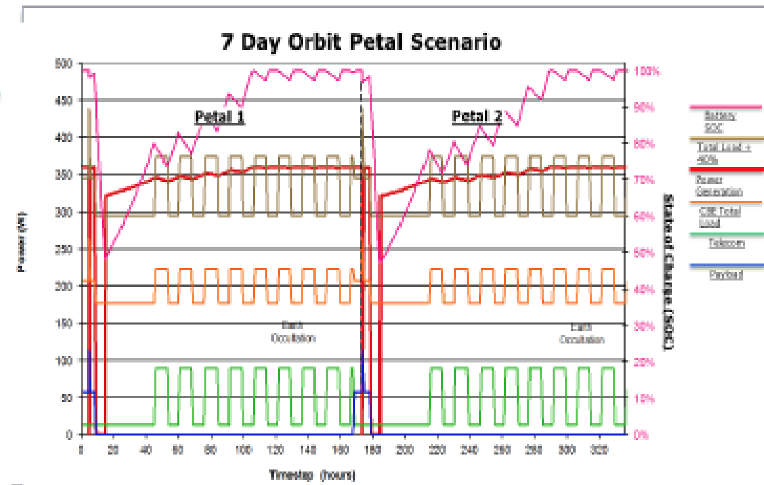
System Model:
- Equipment List
- Demand vs Mode
- Scenario Definitions

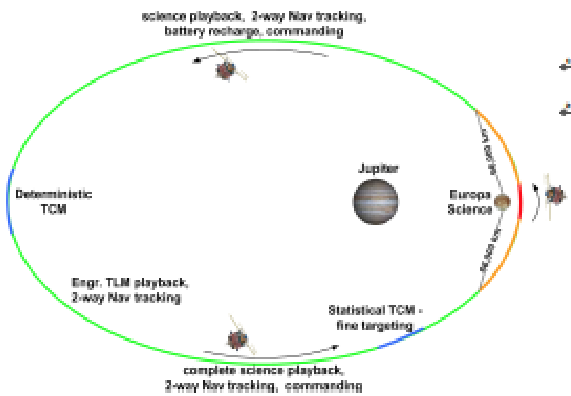
Subsystem Power Models
- Power Source Models
- Battery Models
- Load Profile Simulation

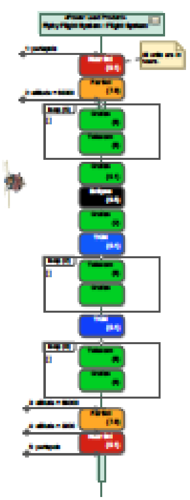
Integrated Power/Energy Analysis



Power Profile Analysis







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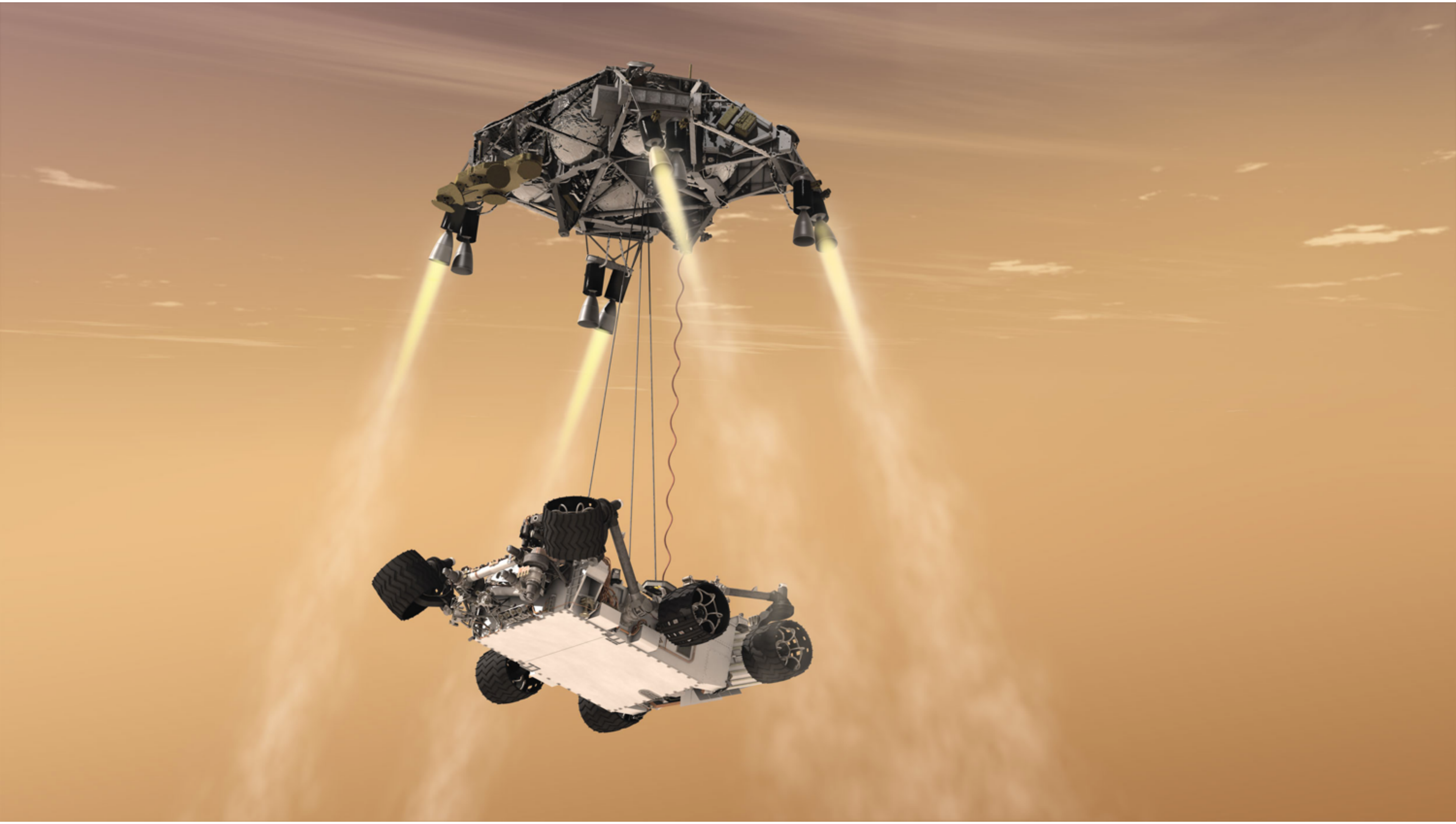
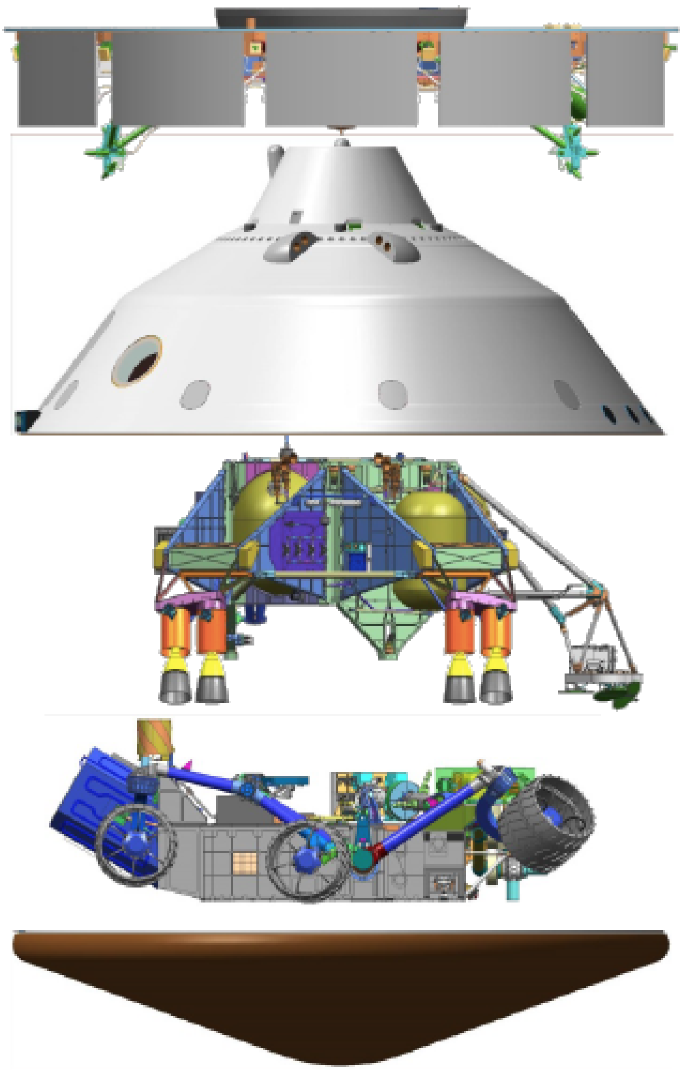
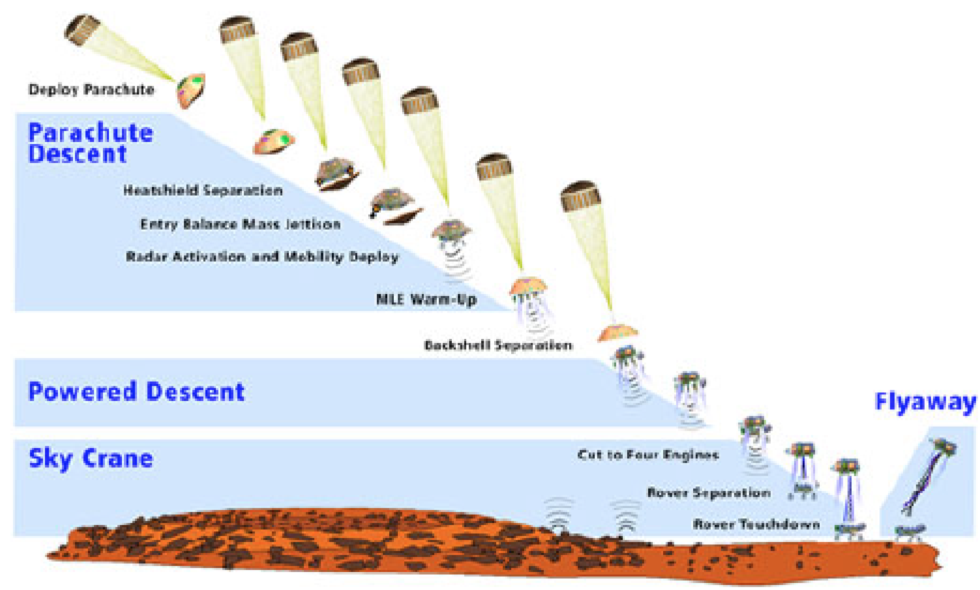


Mars 2020 - Coping with Complexity



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



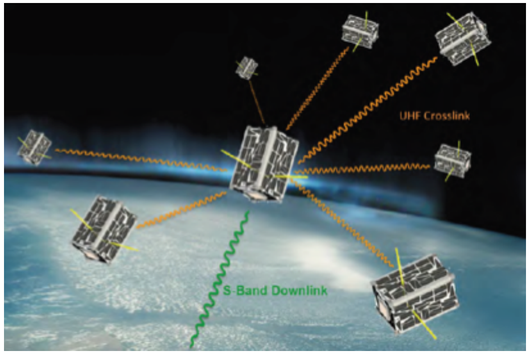
Source: Nichols & Lin, 2014

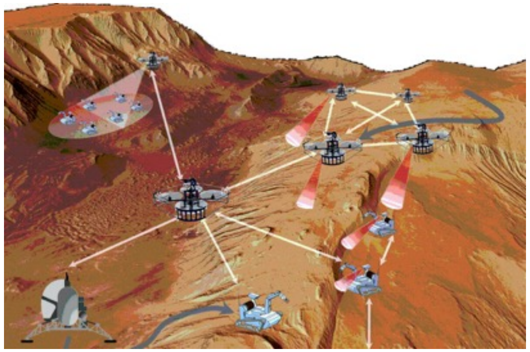
Networked Constellations of Spacecraft

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:

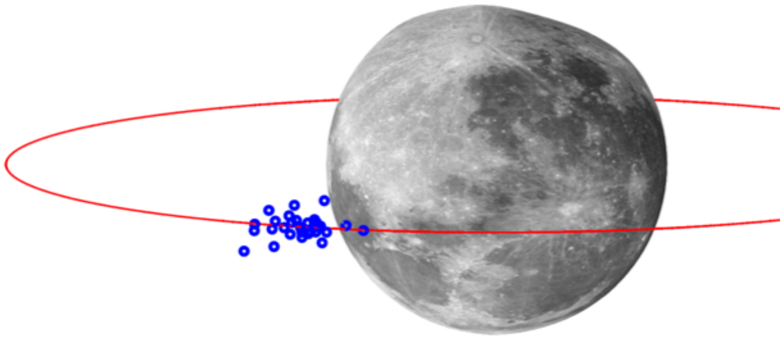
- Radio telescopes consisting of multiple antennas
- Achieve the same angular resolution as that of a single telescope with the same aperture

➔ Typically ground-based

Want to do this in space:

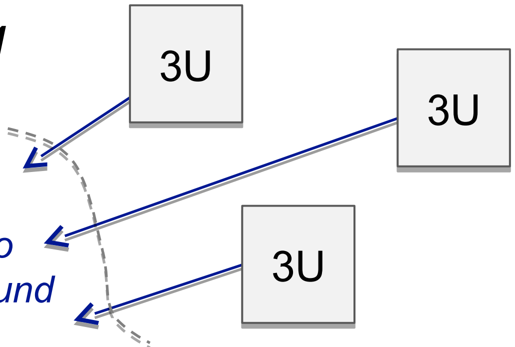
- Frequencies < 30Mhz blocked by ionosphere
- Cluster of spacecraft (3 – 50) functioning as telescopes in LLO

➔ CubeSats or SmallSats are promising enablers for this

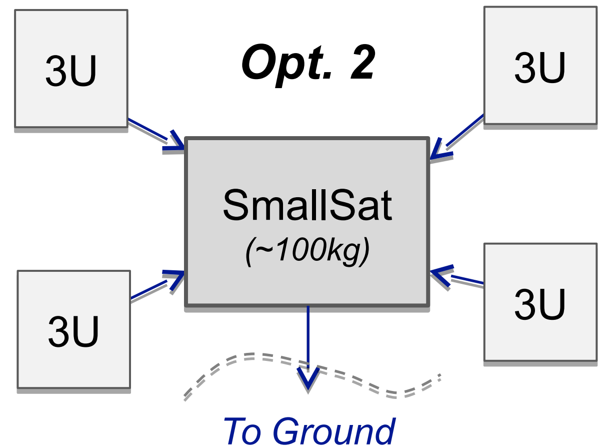


Which Architecture is Optimal?

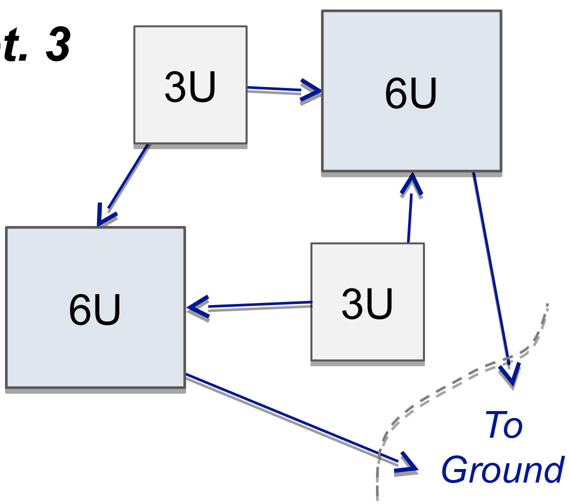
Opt. 1



Opt. 2



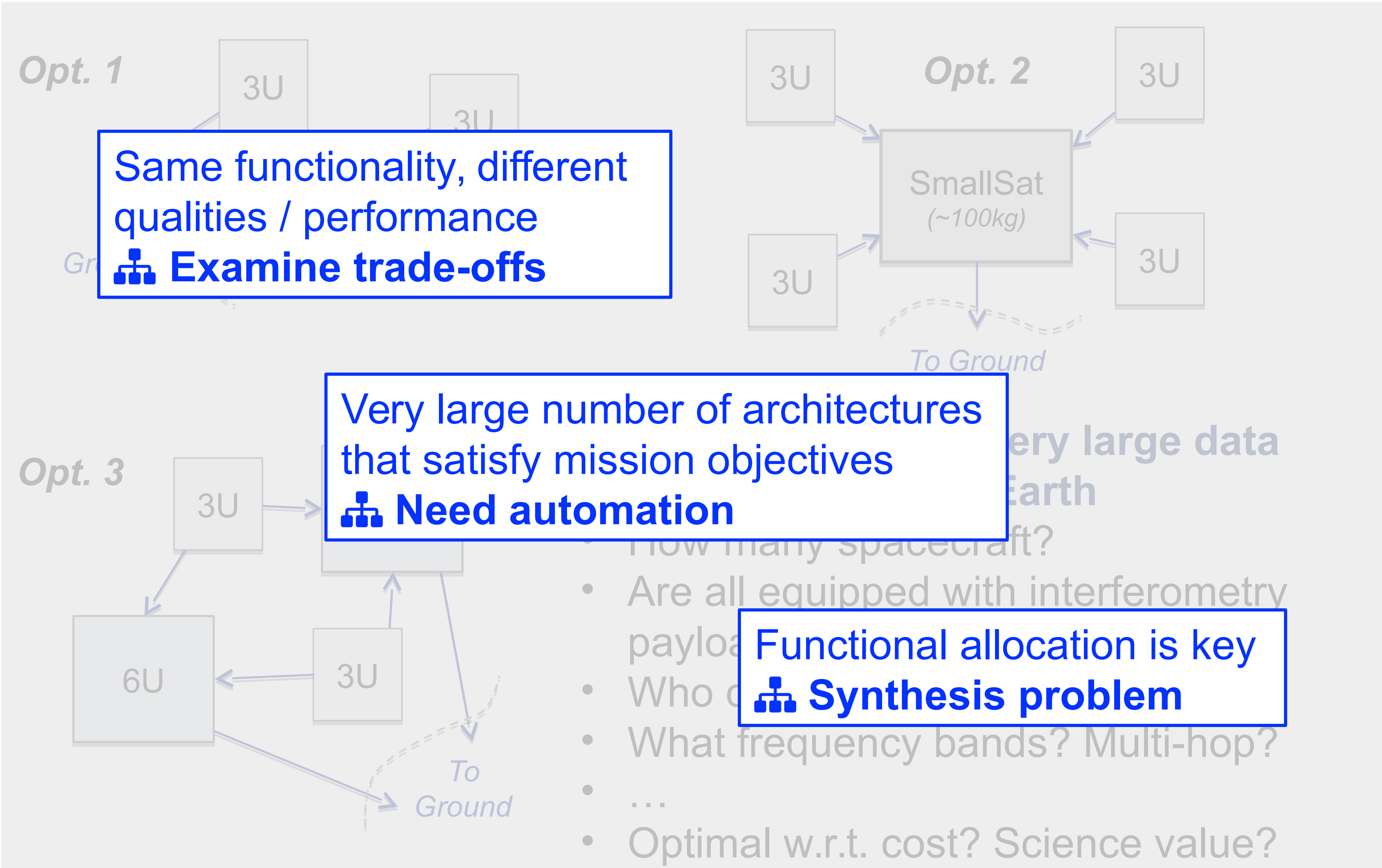
Opt. 3



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?



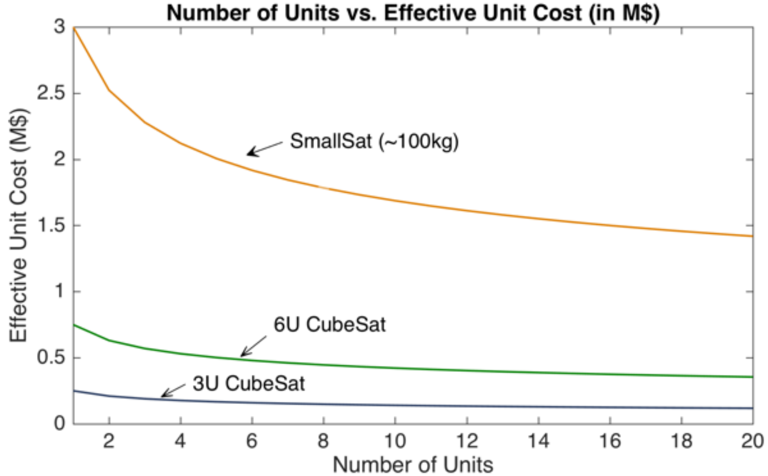
Same functionality, different qualities / performance
Examine trade-offs

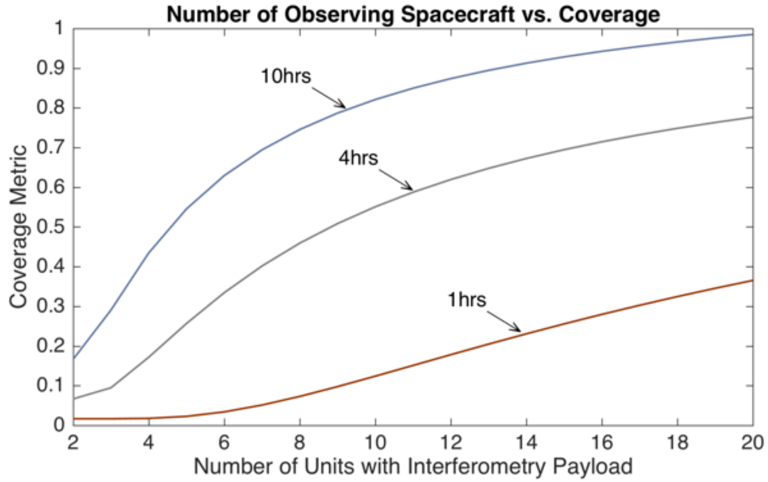
Very large number of architectures that satisfy mission objectives
Need automation

Functional allocation is key
Synthesis problem

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*

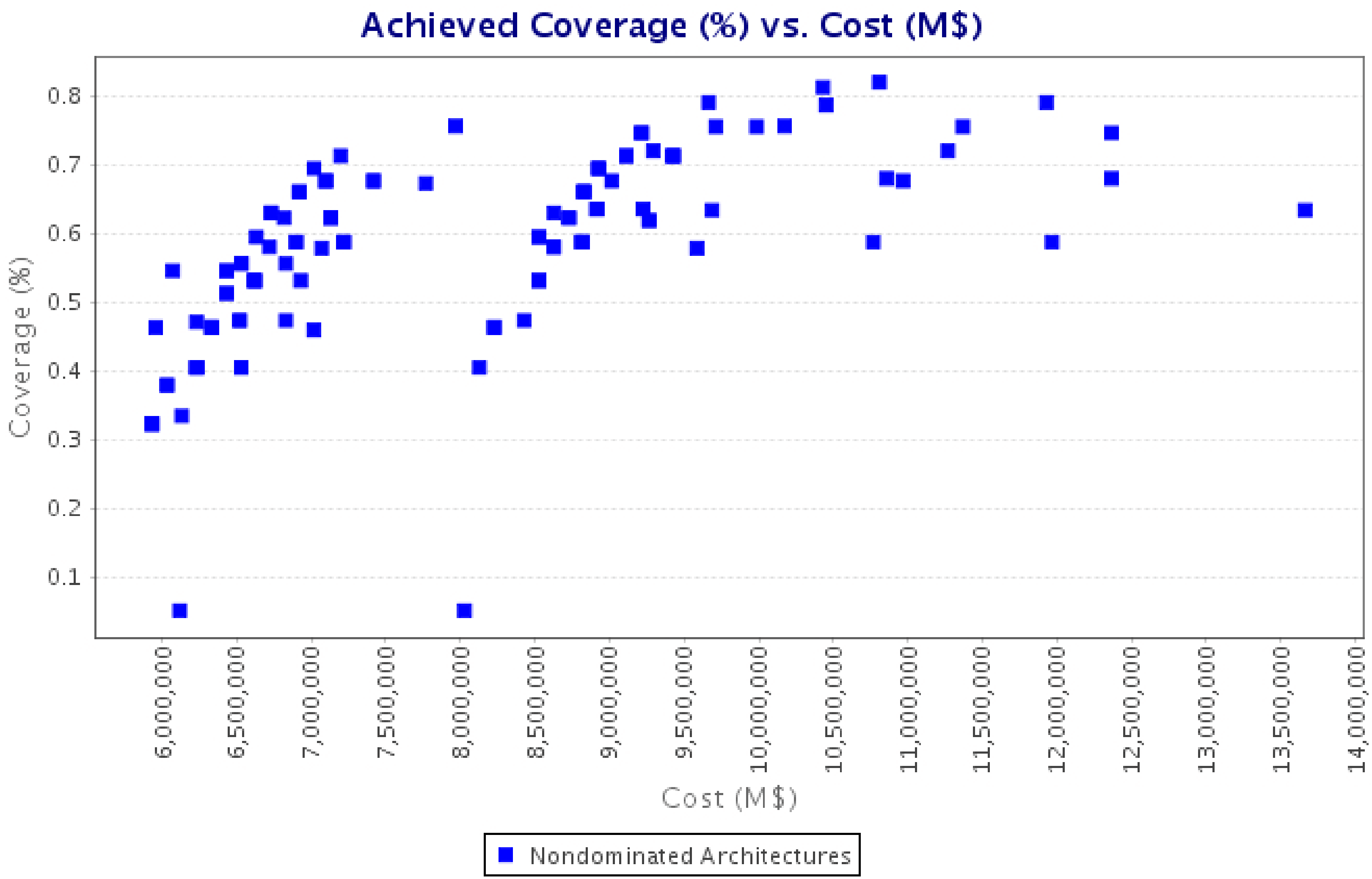




Fictitious cost model (top) and coverage model (bottom)

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

Evolution of Population (Algorithm: NSGA-II)



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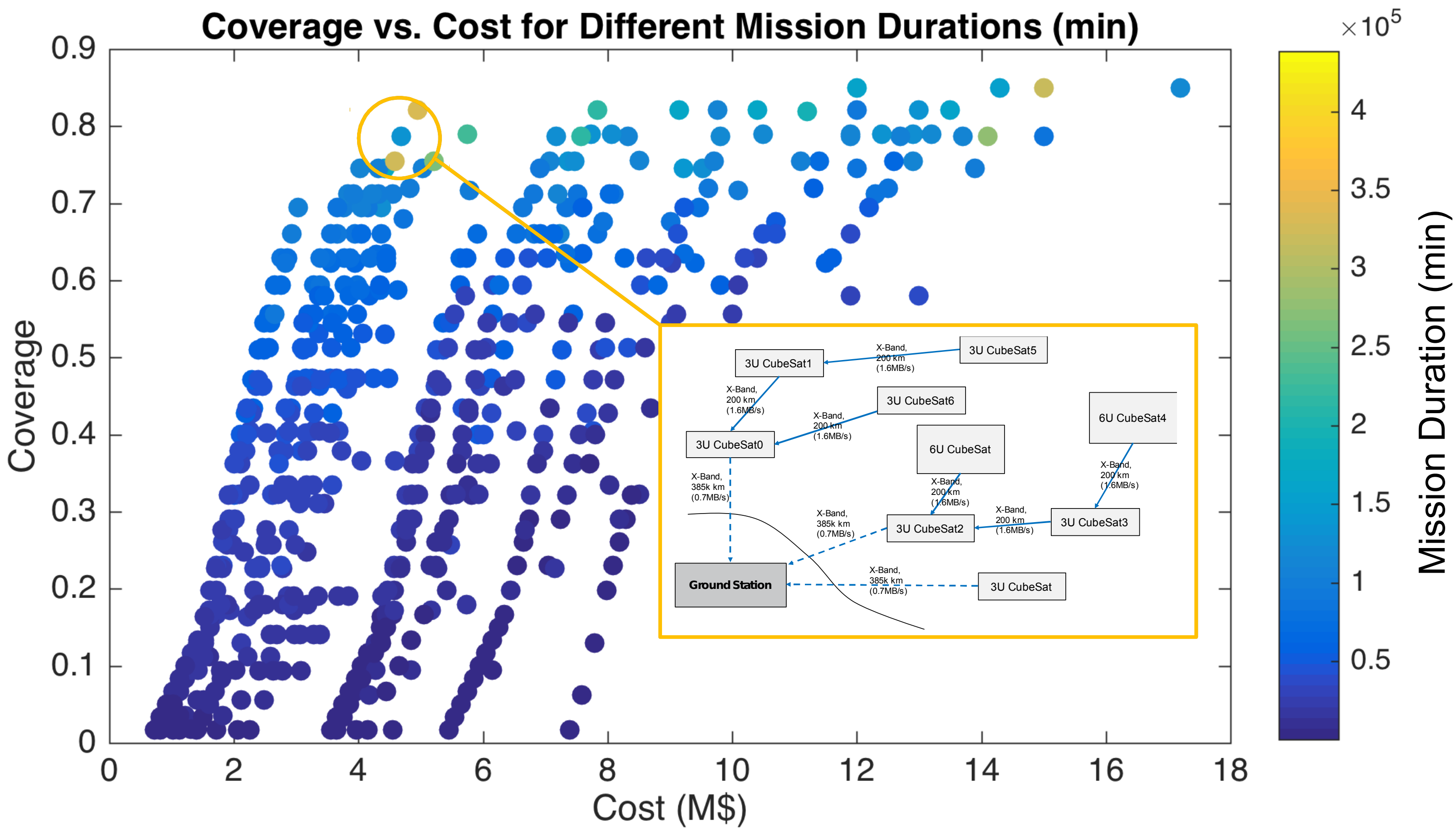
Results from Application to Case Study

Visualization of Trade Space



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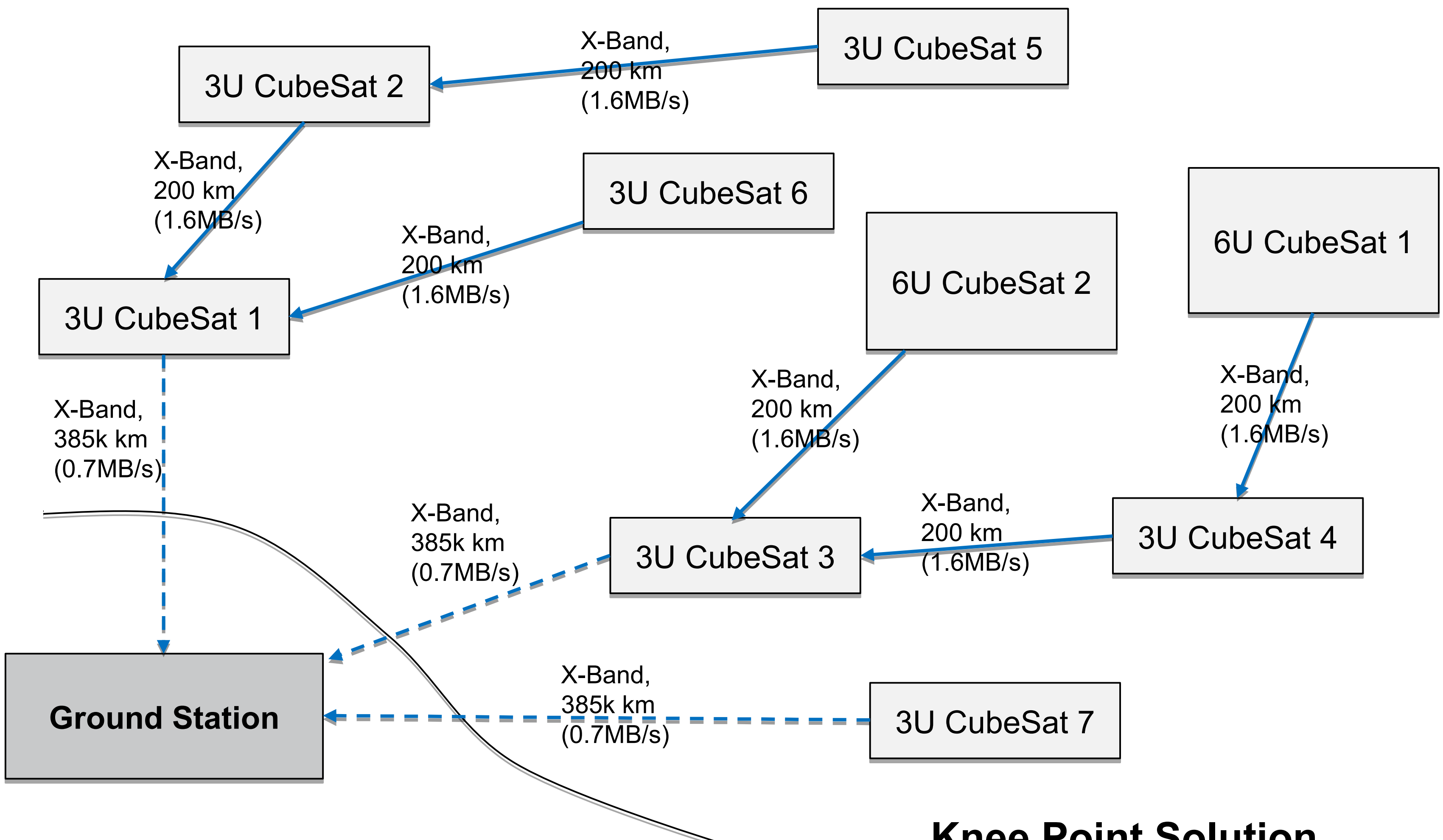
Results from Application to Case Study

"Knee Point" Solution

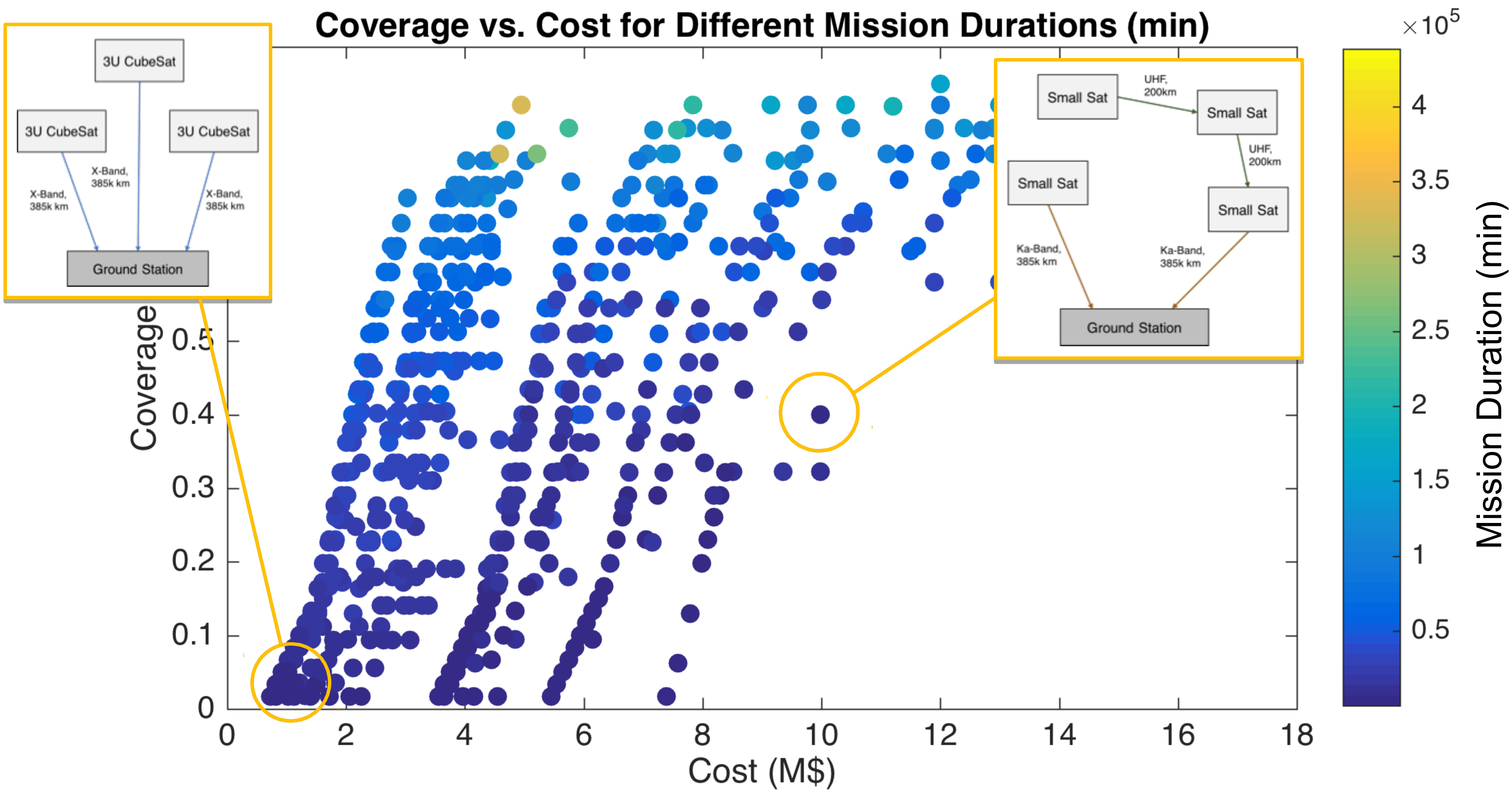


Knee Point Solution

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

Results from Application to Case Study

Visualization of Trade Space



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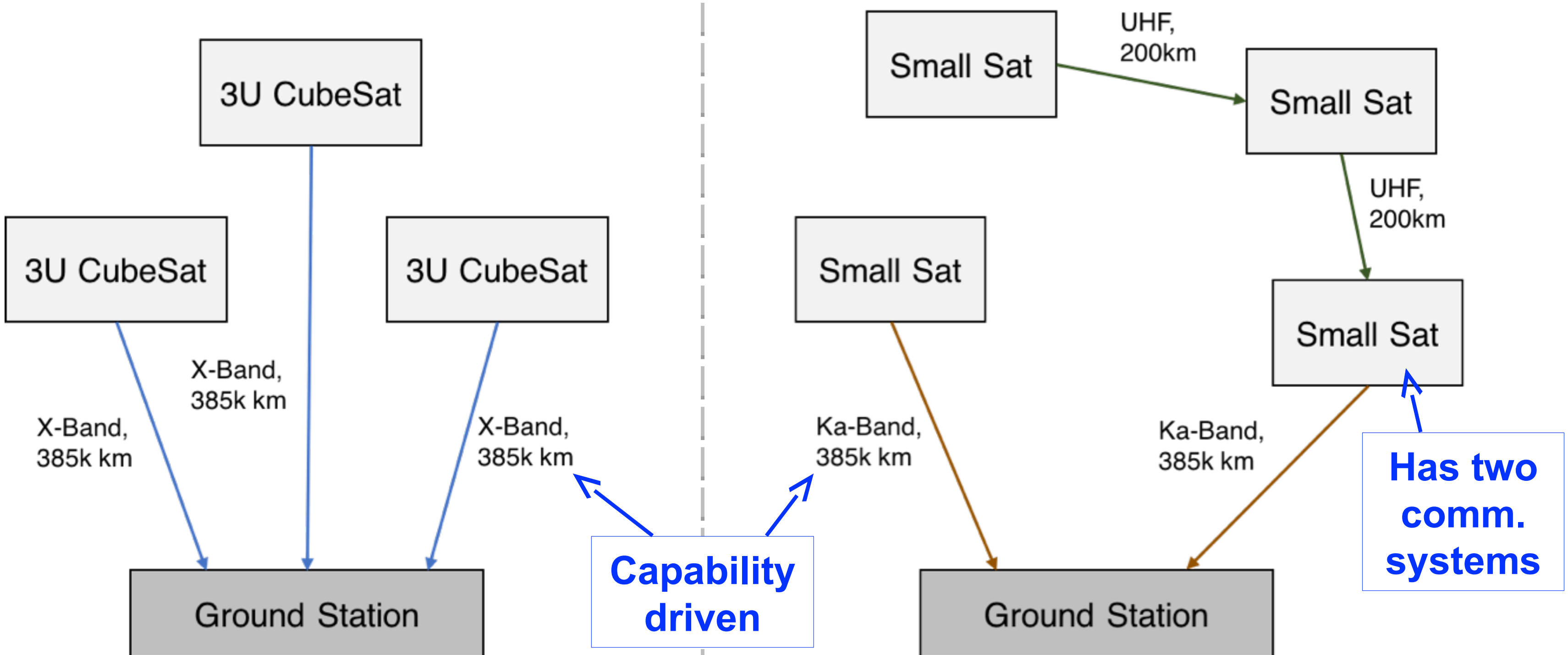
Results from Application to Case Study

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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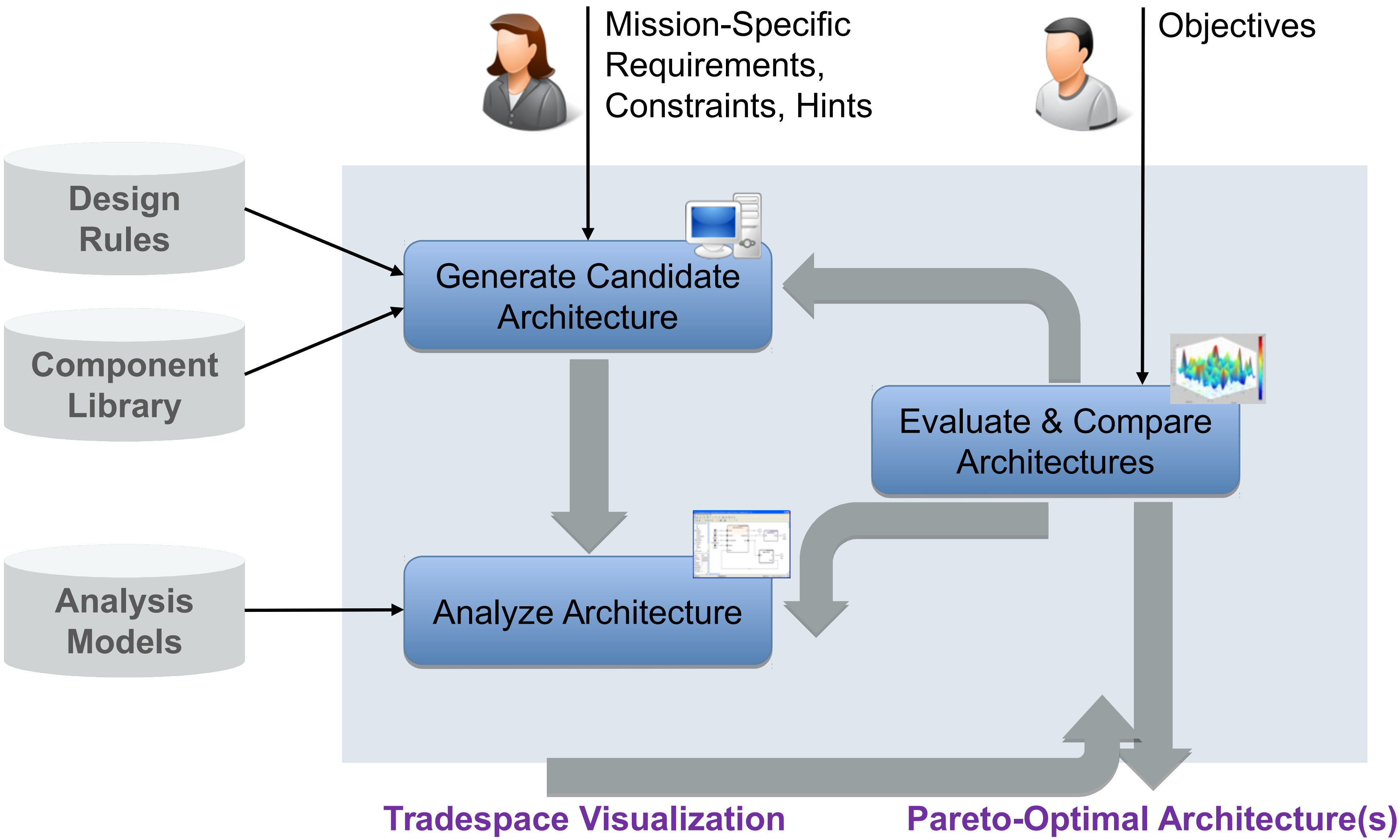
Backup Slides

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

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

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

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/)