Campaign-Level Dynamic Network Modelling for Spaceflight Logistics for the Flexible Path Concept

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[Part of the presented work was performed with
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Future In-Space Operations Colloquium
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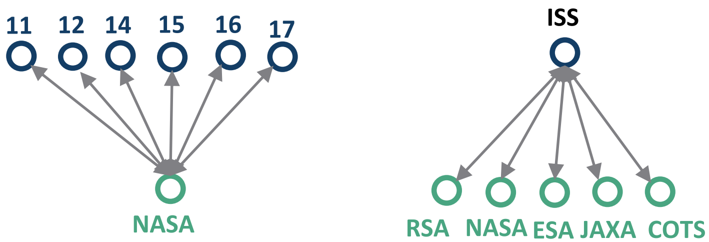
Outline

- Introduction
- Space Logistics Network Modeling
- Case Study: Impact Evaluation of ISRU for Mars Exploration
- Conclusion and Ongoing Research

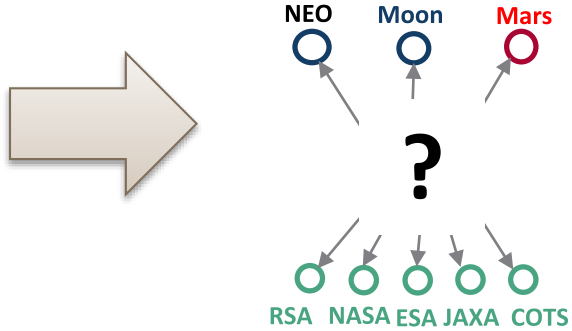
Background

Past/Current Space Programs | **Future Space Programs**



Apollo (Carry-along)

International Space Station (Resupply)



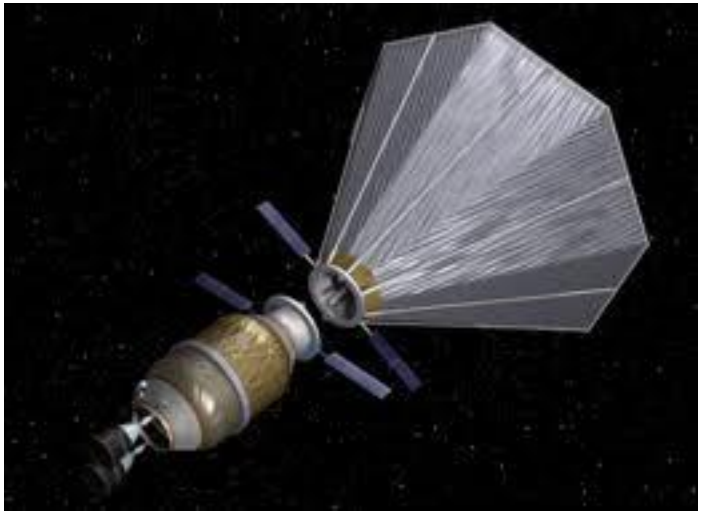
- **Logistics network becomes increasingly complex for future space exploration**
  - Pure carry-along or resupply does not work efficiently any more
- **New strategic logistics paradigm is required**
  - Combination of <u>Prepositioning</u>, <u>Carry-along</u>, and/or <u>Resupply</u>?
  - Effective use of logistics infrastructure such as <u>In-situ Resource Utilization (ISRU)</u> and <u>propellant depot</u>.
    - Propellant is the largest mass fraction for rockets (e.g. >90%).

Space Logistics Infrastructure

- **In-Situ Resource Utilization (ISRU)**
  - "Oil field" in space
  - Generate resource from the in-situ environment
    - E.g. Propellant, water, gas…
  - Location: Moon, Mars, …
  - Limitations: long construction period, large plant mass

- **Propellant depot**
  - "Gas station" in orbit
  - Store propellant/structure in space
  - Location: Lagrangian points, Low-Lunar Orbit, …
  - Limitations: Refilled by tanker from the Earth or ISRU, boiloff

<u>Are they effective and efficient at the campaign level?</u>



Credit: NASA,ULA

Research Objective

Objective: A campaign-level architecture/design optimization tool

- **Optimize multiple missions and their technology uses concurrently**
- **Capture trades for multiple technology options**
  - **ISRU (lunar, Martian), Propulsion (chemical, NTR, *SEP*), *3D-printing*, etc…**
- **Applicable for various destinations:**
  - **NEO, Mars, Moon, etc…**

This presentation will show one scenario for Mars exploration

- **Why Dynamic?**
  - Not much emphasis on system deployment phase, which is non-negligible in space exploration.
  - Interdependency between missions are also non-negligible
- **Why Network Modeling?**
  - LP-based Broad Tradespace Exploration

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Space Logistics

- **Space Logistics:**
  - The theory and practice of driving space system design for operability and managing the flows of materiel, services, and information needed throughout the system lifecycle (AIAA Space Logistics Committee)

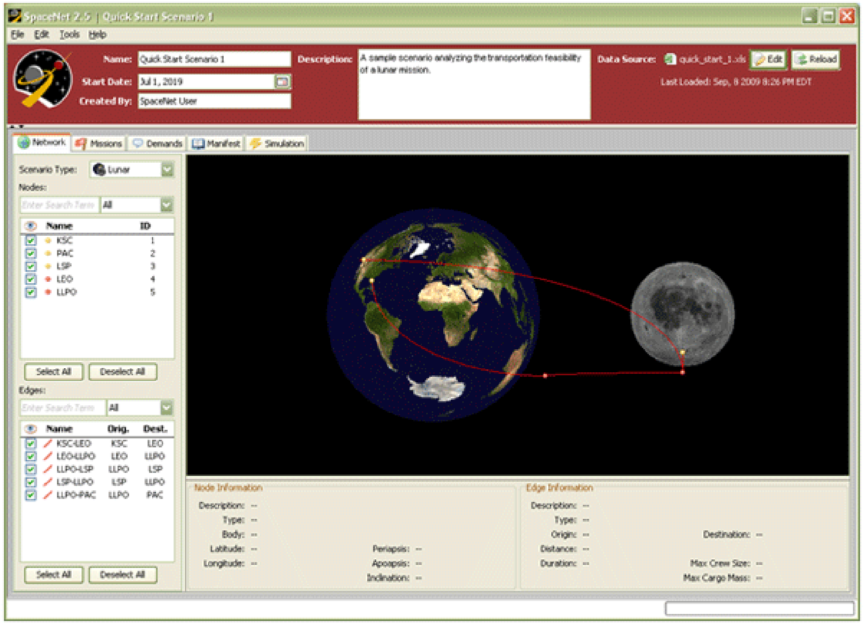
Credit: AIAA

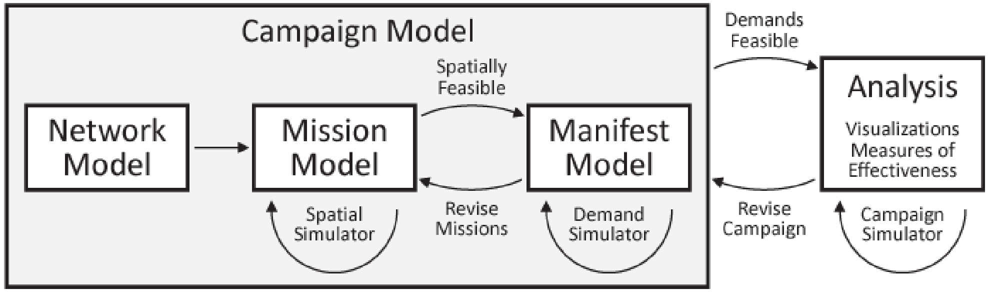
- **MIT Space Logistics Project:**
  - Terrestrial supply chain analogies
  - Space Logistics network analysis
  - Exploration demand-supply modeling with uncertainties
  - Interplanetary Supply Chain Architecture: Trade Studies

Credit: MIT

SpaceNet

- **SpaceNet 2.5r2 (de Weck et al.)**
  - A software modeling the space exploration logistics within a discrete event simulation environment
  - Perform demand analysis using a dynamic logistics model of a given mission sequence.
  - Simulate the full campaign to quantify Measures of Effectiveness (MOE)



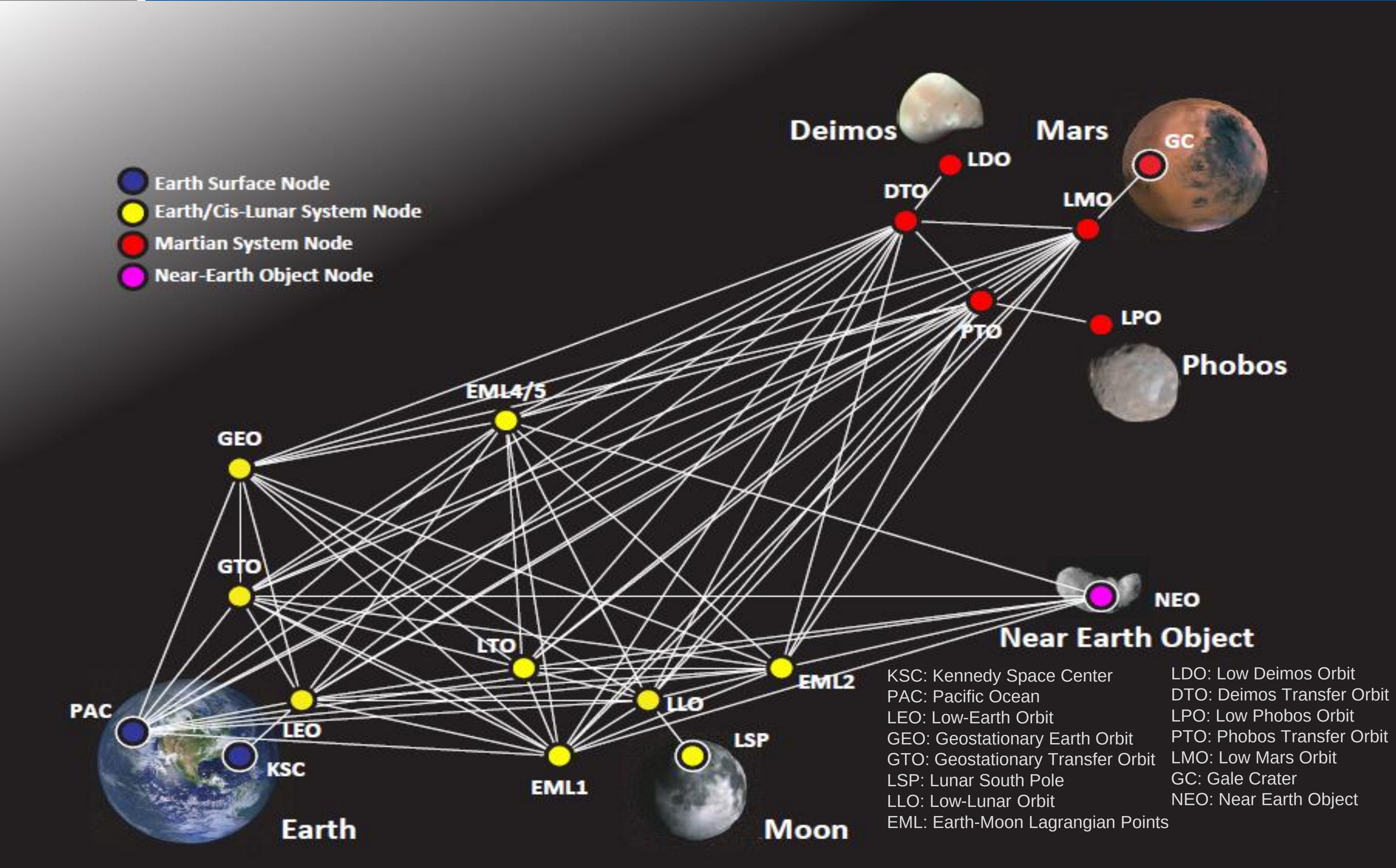


http://strategic.mit.edu/spacenet/

Literature on Space Architecture Optimization

Paper	Contribution	Dynamic	Campaign -Level	Optimization
Conventional	Point Design			
Rudat et al. Battat et al.	Exhaustive Space Architecture Tradespace Exploration	x		
Arney et al.	Graph-Theoretic Space Architecture Tradespace Exploration	x	x	
Taylor et al.	Dynamic Space Logistics Network Modeling using Heuristics	x		x
Ishimatsu et al.	Static Space Logistics Network Modeling using Generalized Multi-Commodity Flow		x	x
Ho et al.	Dynamic Space Logistics Network Modeling using Time-Expanded Generalized Multi-Commodity Flow	x	x	x

Network Modeling of Space Logistics



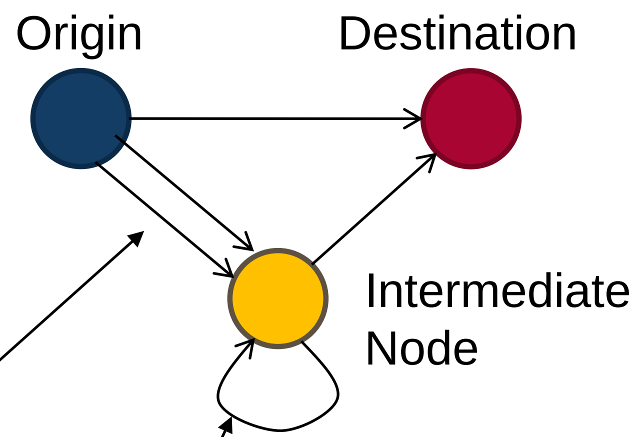
Generalized Multi-Commodity Network Flow (GMCNF)

- **Space logistics modeling by Static Generalized Multi-Commodity Flow (GMCNF) (Ishimatsu et al.)**
  - Generalized flow: Network with arcs that involve gain/loss.
  - Multi-commodity flow: Network with multiple commodities.
  - Generalized multi-commodity flow: Multi-commodity network with arcs that involve gain/loss, commodity type conversion, or both of them.

E.g. ISRU propellant generation

E.g. Propellant consumption

E.g. Food->Waste



- **Commodity: [payload, vehicle, propellant, food, water, waste, structure, crew, …]**

Multi-Graph for multiple transportation options (e.g. Nuclear Thermal Rocket vs. Chemical Rocket; Pareto optimal trajectories along TOF - ΔV trade)

Self-loops: Resource generation/consumption at nodes

GMCNF Formulation (Ishimatsu et al.)

$$\boldsymbol{x}_{ij}^{\pm} = \begin{bmatrix} x_{ij1}^{\pm} \\ \vdots \\ x_{ijK}^{\pm} \end{bmatrix}$$: Commodity in/outflow

Minimize:

$$\mathcal{J} = \sum_{(i,j)\in\mathcal{A}} \boldsymbol{c}_{ij}^{+\,T} \boldsymbol{x}_{ij}^{+}$$

subject to:

$$\sum_{j:(i,j)\in\mathcal{A}} \boldsymbol{x}_{ij}^{+} - \sum_{j:(j,i)\in\mathcal{A}} \boldsymbol{x}_{ji}^{-} \leq \boldsymbol{b}_i \quad \forall\, i \in \mathcal{N}$$ Mass balance

$$\boldsymbol{x}_{ij}^{-} = \boldsymbol{B}_{ij} \boldsymbol{x}_{ij}^{+} \quad \forall\,(i,j) \in \mathcal{A}$$ Flow Transformation

$$\boldsymbol{C}_{ij}^{+} \boldsymbol{x}_{ij}^{+} \leq \boldsymbol{p}_{ij}^{+} \quad \forall\,(i,j) \in \mathcal{A}$$ Flow Concurrency

$$\boldsymbol{x}_{ij}^{\pm} \geq \boldsymbol{0}_{K\times 1} \quad \forall\,(i,j) \in \mathcal{A}$$ Flow bound

Linear Programming formulation -> Computationally efficient!

Examples of B-matrix and C-matrix

$\boldsymbol{B}_{ij}^{(1)}$: Propulsive Burn (propellant mass fraction ϕ_{ij})

$$\boldsymbol{x}_{ij}^{-} = \begin{bmatrix} \text{payload} \\ \text{crew} \\ \text{propellant} \\ \text{consumables} \\ \text{waste} \end{bmatrix}_{ij}^{-} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -\phi & -\phi & 1-\phi & -\phi & -\phi \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_{ij} \begin{bmatrix} \text{payload} \\ \text{crew} \\ \text{propellant} \\ \text{consumables} \\ \text{waste} \end{bmatrix}_{ij}^{+} = \boldsymbol{B}_{ij}\boldsymbol{x}_{ij}^{+}$$

$\boldsymbol{B}_{ij}^{(2)}$: Consumables (at a rate of c) into Waste (a rate of w)

$$\boldsymbol{x}_{ij}^{-} = \begin{bmatrix} \text{payload} \\ \text{crew} \\ \text{propellant} \\ \text{consumables} \\ \text{waste} \end{bmatrix}_{ij}^{-} = \exp\left(\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & -c & 0 & 0 & 0 \\ 0 & w & 0 & 0 & 0 \end{bmatrix}_{ij} \Delta t_{ij} \right) \begin{bmatrix} \text{payload} \\ \text{crew} \\ \text{propellant} \\ \text{consumables} \\ \text{waste} \end{bmatrix}_{ij}^{+} = \boldsymbol{B}_{ij}\boldsymbol{x}_{ij}^{+}$$

$\boldsymbol{C}_{ij}^{+}$: Structure Mass (inert mass fraction f_{inert})

$$\eta \equiv \frac{f_{inert}}{1-f_{inert}}$$

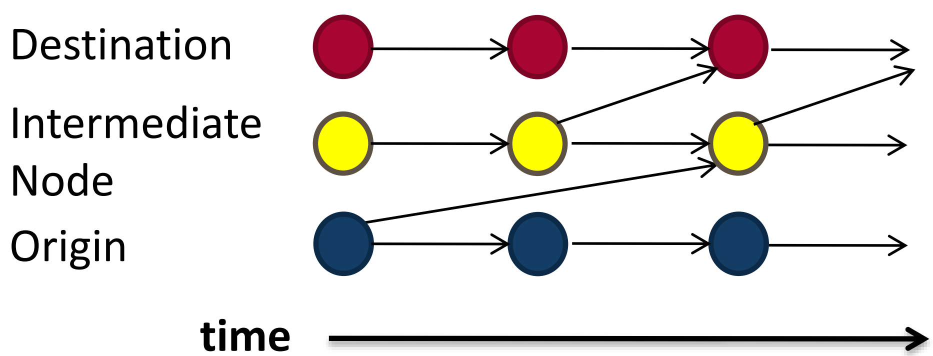
$$\boldsymbol{C}_{ij}^{+}\boldsymbol{x}_{ij}^{+} = \begin{bmatrix} 0 & \eta & -1 \end{bmatrix}_{ij}^{+} \begin{bmatrix} \text{payload} \\ \text{propellant} \\ \text{structure} \end{bmatrix}_{ij}^{+} \leq 0$$

Time-Expanded Network

- **Limitation of Static modeling: No time dimension**
  - Not considering time ordering of events
  - Not considering time windows for transportation/supply/demand
  - Not considering interdependencies between the missions

  ⇒ **Can provide unrealistic solutions**
- **Dynamic Generalized Multi-commodity Flow**
  - Time-expanded network: Expanding nodes to time dimension
  - Static network is an lower and overoptimistic bound of full time-expanded network

What is a good time step?

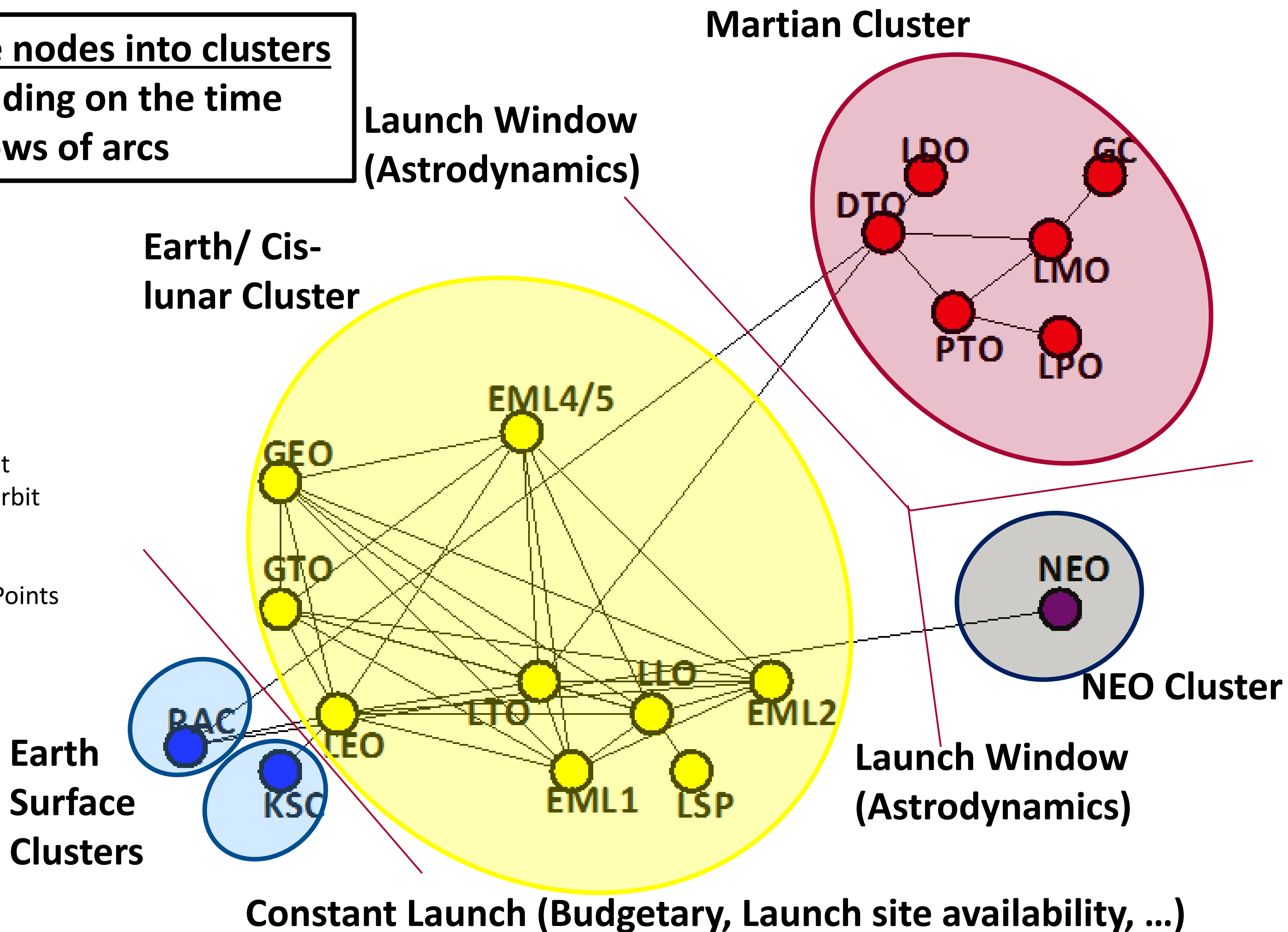


Proposed Cluster-Based Time-Expanded Network

Basic Ideas: Only "important" timings matter in time-window critical systems!

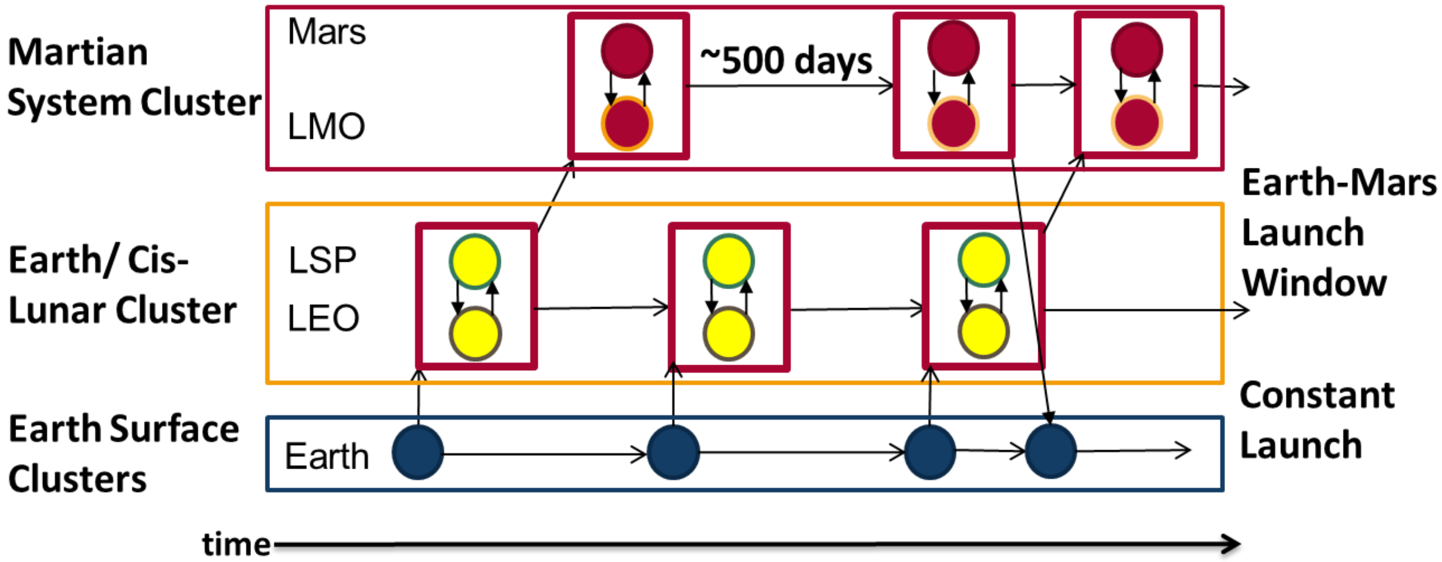
1. **Divide nodes into clusters depending on the time windows of arcs**

KSC: Kennedy Space Center
PAC: Pacific Ocean
LEO: Low-Earth Orbit
GEO: Geostationary Earth Orbit
GTO: Geostationary Transfer Orbit
LSP: Lunar South Pole
LLO: Low-Lunar Orbit
EML: Earth-Moon Lagrangian Points
LDO: Low Deimos Orbit
DTO: Deimos Transfer Orbit
LPO: Low Phobos Orbit
PTO: Phobos Transfer Orbit
LMO: Low Mars Orbit
GC: Gale Crater
NEO: Near Earth Object



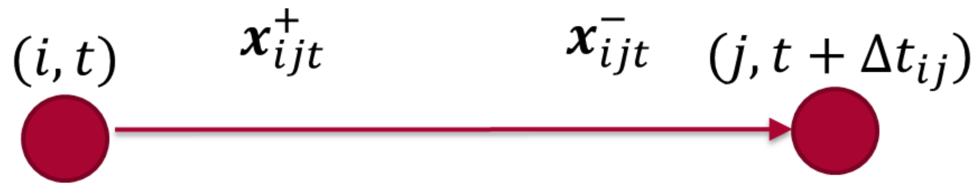
Proposed Cluster-Based Time-Expanded Network

1. Divide nodes into clusters depending on the time windows of arcs
2. Draw cluster-scale time-expanded network for clusters only at open windows
3. Allow a round trip within the cluster at each time window



- Useful for time window critical system.
- Computationally efficient and provides a good approximation of a realistic solution.

Dynamic GMCNF formulation



$\{0 \ldots T\}$: Time steps (integers)
W_{ij} : Time windows for Arc (i,j)
$\boldsymbol{x}_{ijt}^{\pm}$: Commodity in/outflow

Minimize:

$$\mathcal{J} = \sum_{(i,j)\in\mathcal{A}} \sum_{t\in\{0\ldots T-1\}} \boldsymbol{c}_{ij}^{+\,T} \boldsymbol{x}_{ijt}^{+}$$

subject to:

$$\sum_{j:(i,j)\in\mathcal{A}} \boldsymbol{x}_{ijt}^{+} - \sum_{j:(j,i)\in\mathcal{A}} \boldsymbol{x}_{ji(t-\Delta t_{ji})}^{-} \leq \boldsymbol{b}_{it} \quad \forall t \in \{0 \ldots T-1\} \ \forall\, i \in \mathcal{N}$$

Mass balance

$$\boldsymbol{x}_{ijt}^{-} = \boldsymbol{B}_{ij} \boldsymbol{x}_{ijt}^{+} \quad \forall t \in W_{ij} \ \forall\, (i,j) \in \mathcal{A}$$

Flow Transformation

$$\boldsymbol{C}_{ij}^{+} \boldsymbol{x}_{ijt}^{+} \leq \boldsymbol{p}_{ij}^{+} \quad \forall t \in W_{ij} \ \forall\, (i,j) \in \mathcal{A}$$

Flow Concurrency

$$\begin{cases} \boldsymbol{x}_{ijt}^{\pm} \geq \boldsymbol{0}_{K\times 1} & if\ t \in W_{ij} \\ \boldsymbol{x}_{ijt}^{\pm} = \boldsymbol{0}_{K\times 1} & otherwise \end{cases} \quad \forall t \in \{0 \ldots T-1\} \ \forall\, (i,j) \in \mathcal{A}$$

Flow bound

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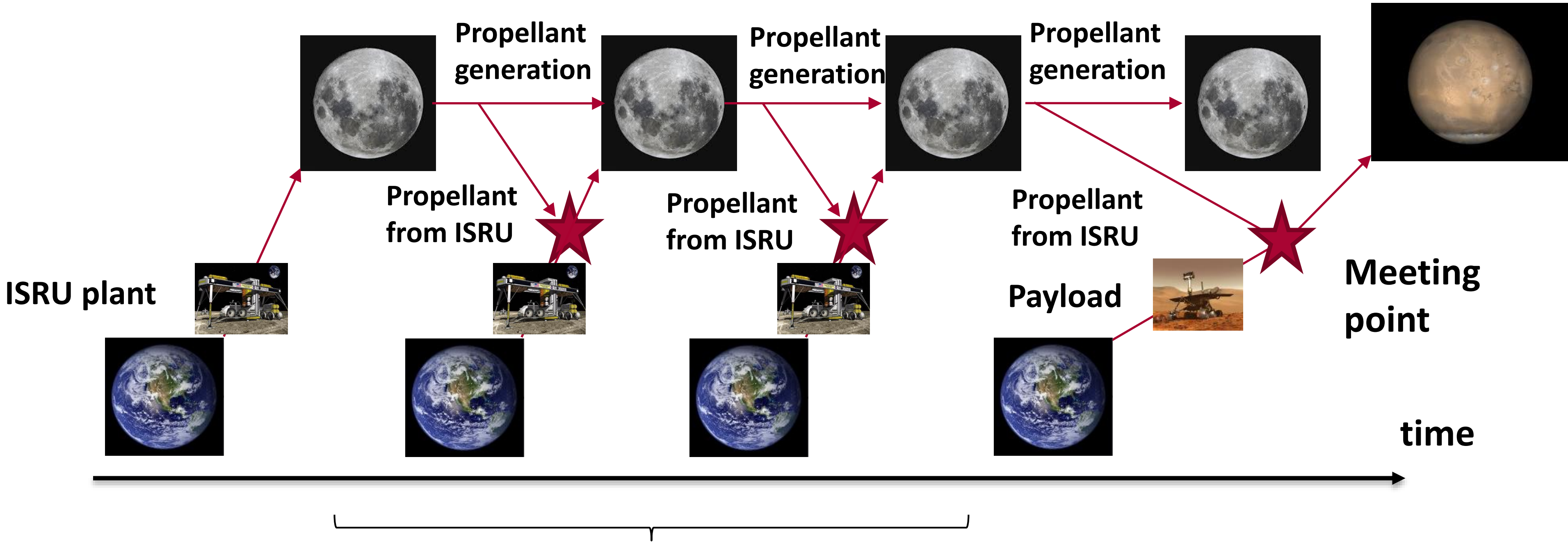
Assumptions for Case Study

- **Objective:** Minimize Initial Mass to Low-Earth-Orbit (IMLEO)
- **Variables: 21 types of commodities over each arc**
  - **Payload:** Equipment/Habitat; Samples
  - **Human:** Crew; Returning Crew
  - **Consumables:** Hydrogen; Oxygen; Methane; Water; Food; Waste
  - **Tanks:** Hydrogen Tank; Oxygen Tank; Methane Tank; Water Tank
  - **Other Inert Mass (excluding Tank):** Crew Vehicle; LOX/LH2 Inert; Nuclear Thermal Rockets (NTR) Inert; LOX/LCH4 Inert
  - **Entry Structure:** Aeroshell/TPS
  - **ISRU:** Oxygen ISRU; Water ISRU; Methane ISRU
- **Propulsion Options:**
  - LOX/LH2; NTR; LOX/LCH4 for Mars ascent/descent
  - All with aerocapture option when applicable
- **Boil-Off:**
  - LH2: 0.127%/day; LOX: 0.016%/day
- **Lunar and Martian ISRU:**
  - 10 [kg/plant kg/year] for soil-based ISRU (Hydrogen Reduction/Molten Regolith Electrolysis/Water Ice Extraction)
  - 10 [kg/plant kg/year] for atmosphere-based ISRU (Sabatier Reaction)

Concept of Bootstrapping ISRU deployment

- **<u>Bootstrapping ISRU deployment:</u>** developed by Koki Ho's PhD thesis at MIT; research continues at UIUC.
  - Deploy ISRU in stages with frequent cis-lunar missions
  - Utilize propellant generated by ISRU for further ISRU deployment



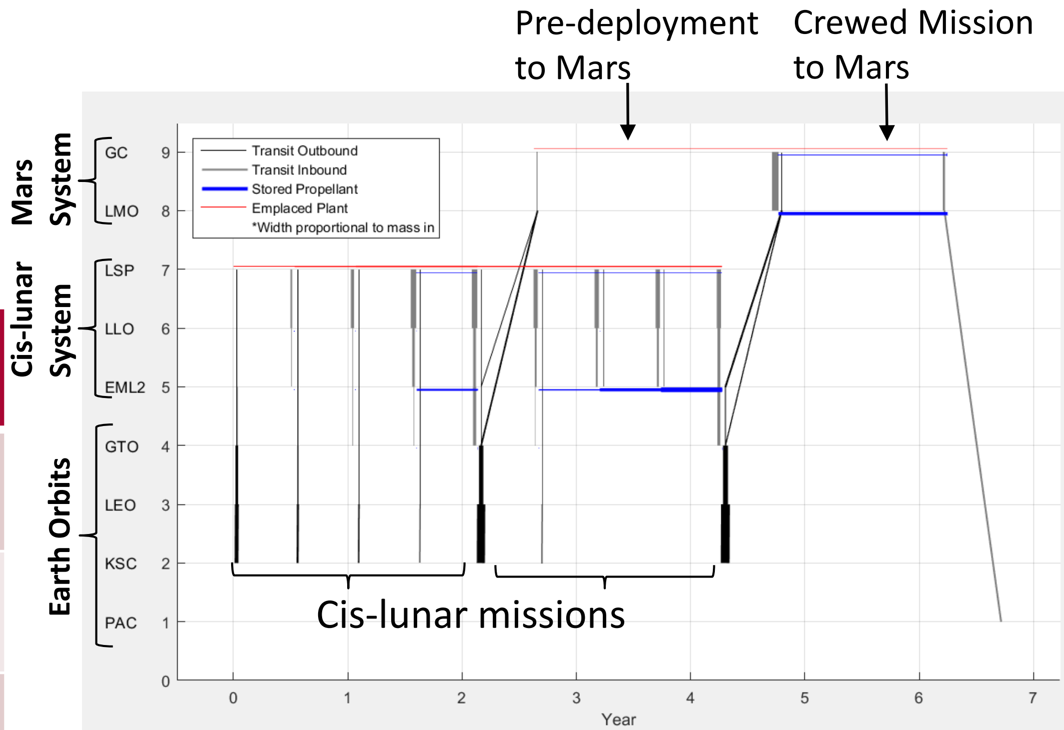
- Each cis-lunar mission is a **<u>round trip between Moon and Earth orbits</u>**.
- **<u>Frequency of the cis-lunar missions</u>** is a key parameter.

Results

Analysis

- 3 cases are considered depending on the frequency of cis-lunar missions

Cis-lunar missions freq	IMF=0.1 IMLEO	IMF=0.2 IMLEO
(1) 780 days (all-up)	813 MT (no ISRU)	1180 MT (no ISRU)
(2) 390 days (bootstrapping)	769 MT	1050 MT
(3) 195 days (bootstrapping)	662 MT	861 MT



Findings

- With all-up strategy , lunar ISRU **does NOT** pay off.
- With bootstrapping strategy, lunar ISRU **does** pay off.
- More frequent cis-lunar missions (i.e. more reuses of vehicles) => lower IMLEO.
- The quantitative results depend on various assumptions (e.g. ISRU productivity, IMF).

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Conclusion and Ongoing Research

Objective: A campaign-level architecture/design optimization tool

Strength

- Architecture-level global optimization and sensitivity analysis
  - Provide technology investment portfolio over time
- General methodology applicable for different missions/campaigns
- Low computational effort (~1 min for Mars case on a desktop computer)

Limitation

- Linearization effects can result in a relatively low fidelity reusable vehicle/ISRU model (e.g. vehicle as a "flow")

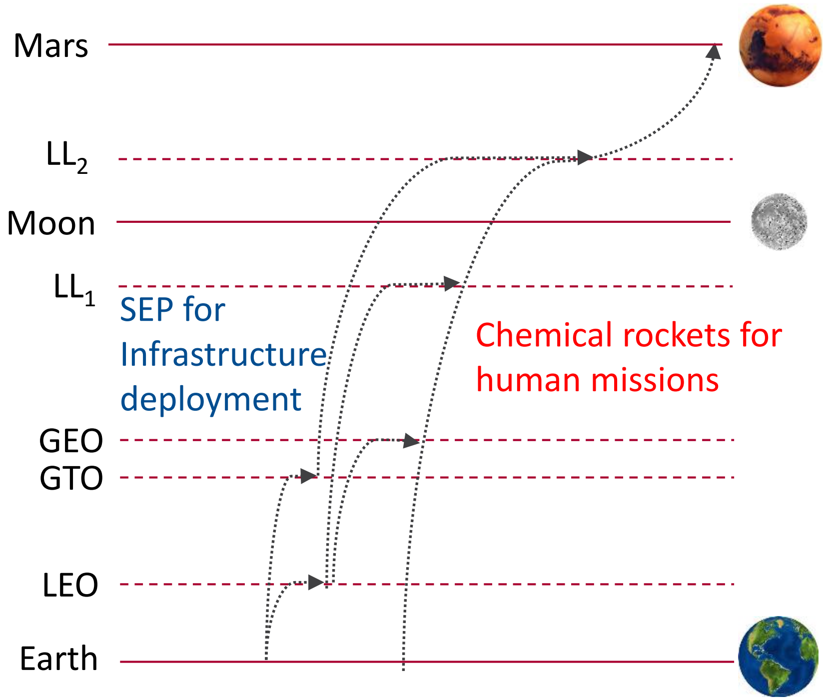
Ongoing Research at UIUC: 3 presentations for AIAA Space 2016:

- **SEP trajectory design** and **its campaign-level trade with chemical rockets/ISRU/depot uses**
- Integration with **higher-fidelity vehicle model** using mixed-integer nonlinear programming
- Design and Optimization for **on-orbit repair/refuel system** with 3D printing using stochastic model and queueing theory

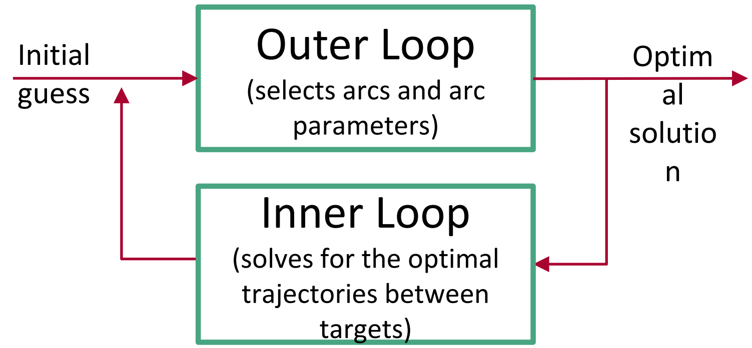
$\Rightarrow$Towards **Campaign-Level Astrodynamics and Mission Design**

Ongoing Research Example: Incorporating SEP into space logistics models

How can low-thrust technologies (like SEP) best aid beyond-LEO space operations that involve multi-mission campaigns?



Case study with possible waystations and sample paths



- Inner loop will provide solutions to the low-thrust and impulsive high-thrust trajectory problem, providing a value of the objective function (usually, mass or time): *cost of travelling on an arc using provided thruster type*
- Outer loop will perturb the state vector that is input to the inner loop: *parameters of each arc*