Space Logistics and Mission Design

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Space Systems Optimization Group

Space Systems Optimization Group (Ho Research Group)

- **Established at UIUC in 2016; moved to Georgia Tech in 2019.**
- **Current members: 1 PostDoc, 11 Ph.D. students, 3 master's students; 5 undergrad students.**
- **Former members (PostDocs, RAs, Ph.D./M.S. graduates) are currently:**
    - **4 university professors** at Univ. of Michigan, Princeton University, Stevens Institute of Technology, and West Virginia University, respectively.
    - **10+ in industry**, including Boeing, Airbus, Northrop Grumman, Blue Origin, APL, Collins Aerospace, CU Aerospace, etc.
- **Sponsors include:**

Space Systems Optimization Group

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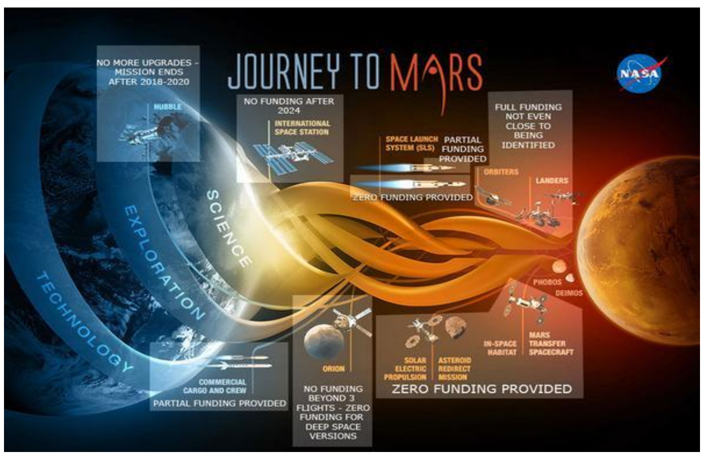
SSOG

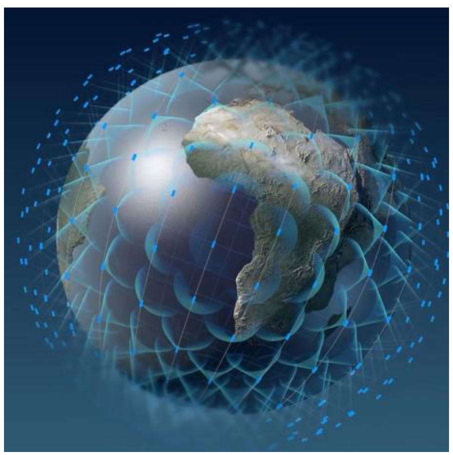
Mission: To create <u>optimization models and methods</u> to tackle <u>complex space mission design and systems engineering challenges.</u>

- **Explore the intersection of optimization and space systems**
- **Pioneer the *logistics-driven* modeling and optimization in space mission design**



Campaign-Level Space Exploration Mission Design

On-Orbit Servicing, Assembly, and Manufacturing



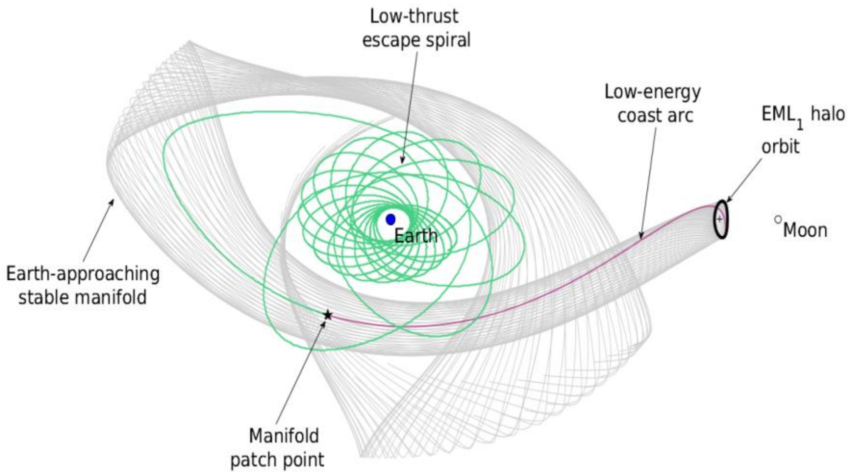
SmallSat Constellation

Credit: NASA, DARPA, OneWeb

Motivation

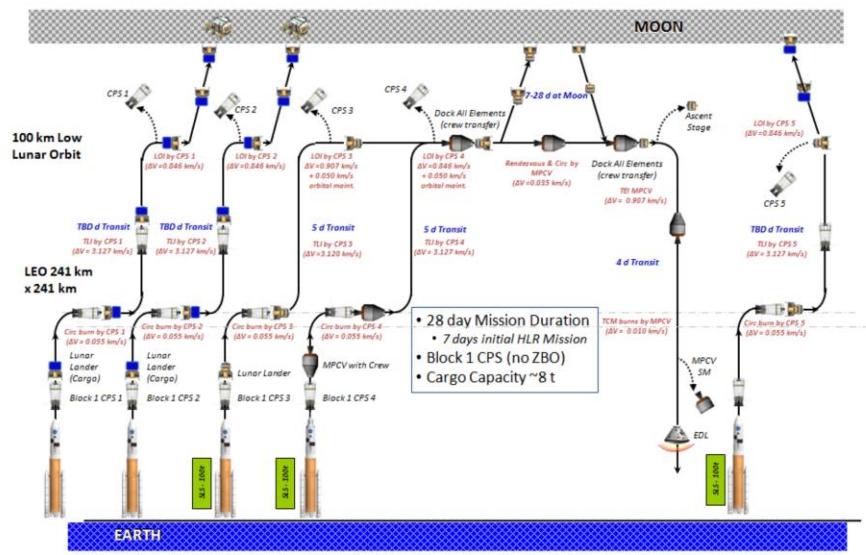
Conventional Space Research

- Focus on astrodynamics/orbital design of **a single mission/spacecraft** (e.g., Hayabusa).
- Multi-mission campaign designs are often performed manually.
- Worked well for conventional stand-alone missions.



Need for New Research

- Focus on rigorous campaign-level optimization and coordination of **multiple space missions/spacecraft**.
- Responds to the timely needs given the **growing complexity of space missions and technologies** (e.g., on-orbit satellite refueling and servicing)



Credit: NASA

Space Logistics

Space Logistics: The theory and practice of driving space system design for operability and supportability, and of managing the flow of material, services, and information needed throughout a space system lifecycle (AIAA Space Logistics Technical Committee)

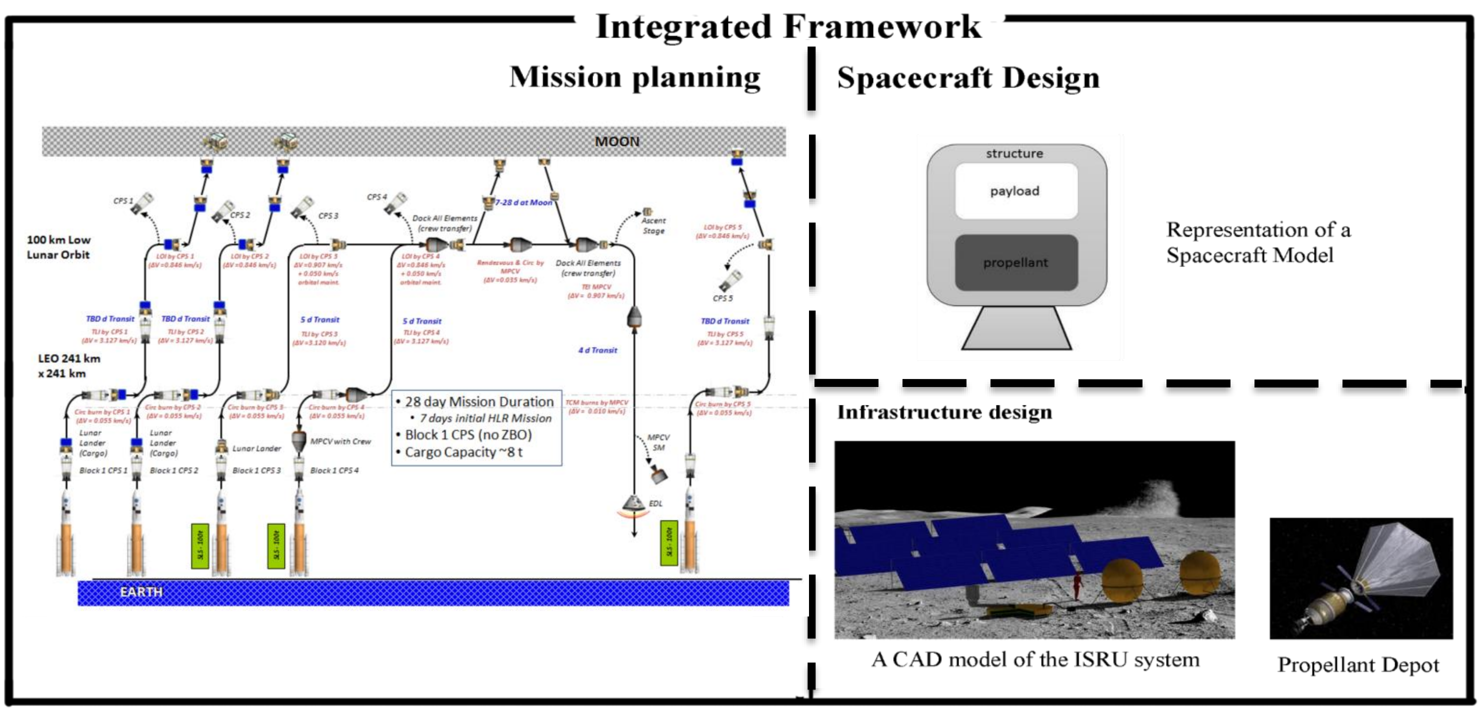
Credit: AIAA, STEAM

Space Logistics Research Example 1: Campaign-Level Space Mission Design

Motivation: The entire architecture of a complex multi-mission space campaign needs to be optimized, including:

- Commodity transportation flow for payload, propellant, consumables, etc.
- Sizing (or choice) of spacecraft/infrastructure for each leg of the mission
- Mission timelines and sequences over the entire campaign

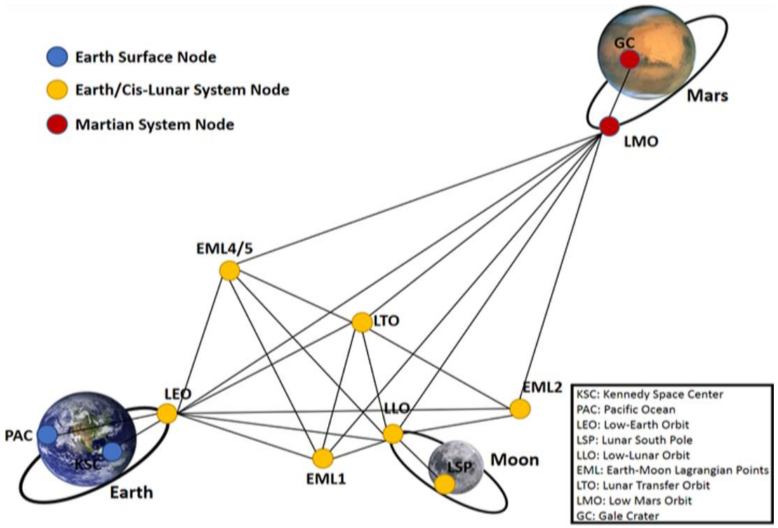
⇒ Need a rigorous and efficient method for **integrated campaign mission planning and spacecraft/infrastructure design.**

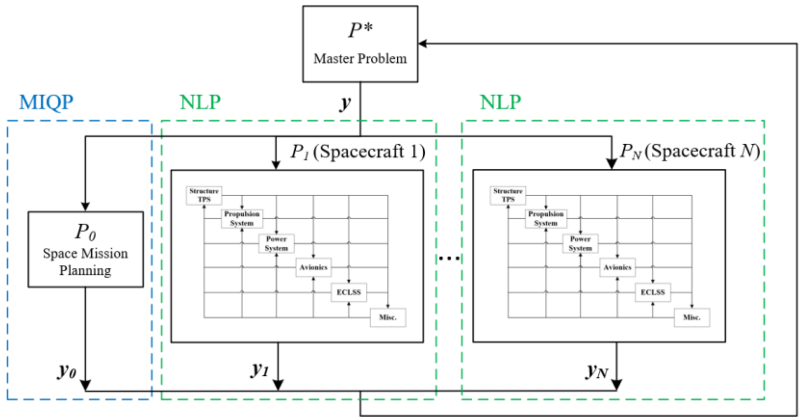


Space Logistics Research Example 1: Campaign-Level Space Mission Design

Approach:

1. Develop a dynamic generalized network model for space traffic management, inspired by terrestrial logistics approaches.
2. Develop a piece-wise linear approximation for nonlinear vehicle models so that the entire problem can be approximated efficiently (**Approximate Solution**).
3. Leveraging the unique structure of the problem, develop a decomposition-based optimization framework that solves the entire problem using Augmented Lagrangian Coordination (**Optimal Solution**).



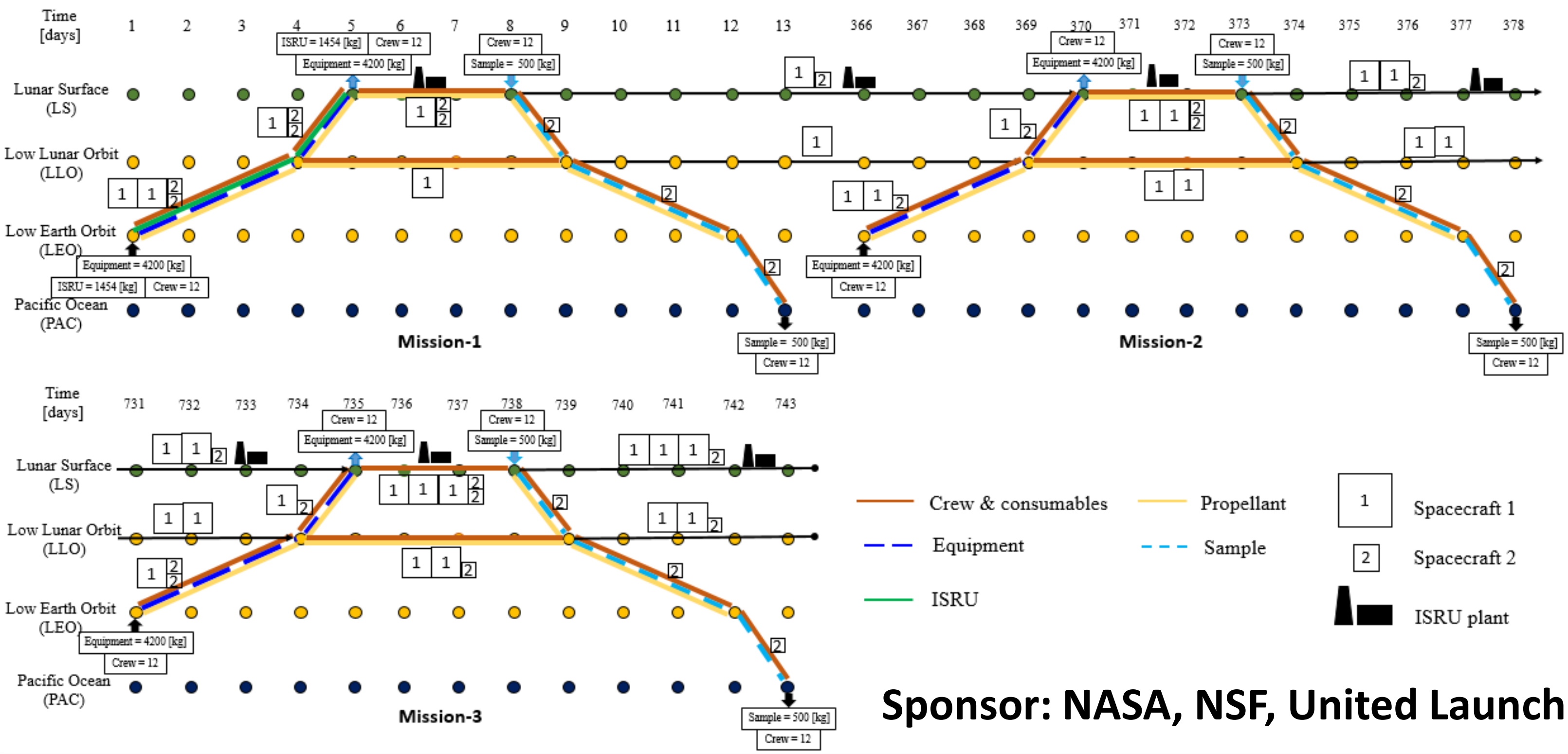


* H. Chen and K. Ho, "Integrated Space Logistics Mission Planning and Spacecraft Design with Mixed-Integer Nonlinear Programming," *Journal of Spacecraft and Rockets*, Vol. 55, No. 2, pp. 365-381, 2018.

** M. Isaji, Y. Takubo, and K. Ho, "Multidisciplinary Design Optimization Approach to Integrated Space Mission Planning and Spacecraft Design," *Journal of Spacecraft and Rockets*, Vol. 59, No. 5, pp. 1660-1670, 2022.

Space Logistics Research Example 1: Campaign-Level Space Mission Design

3-Mission Lunar Exploration (Approximate Soln. ~320s on a desktop computer)



Sponsor: NASA, NSF, United Launch Alliance

Developed tool provides <u>an effective decision support tool for *automated* space campaign design and analysis</u> considering the deployment and utilization of the infrastructure elements, e.g., ISRU, depots, etc.

* H. Chen and K. Ho, “Integrated Space Logistics Mission Planning and Spacecraft Design with Mixed-Integer Nonlinear Programming,” *Journal of Spacecraft and Rockets*, Vol. 55, No. 2, pp. 365-381, 2018.

Space Logistics Research Example 2: Analysis of On-Orbit Servicing Architecture

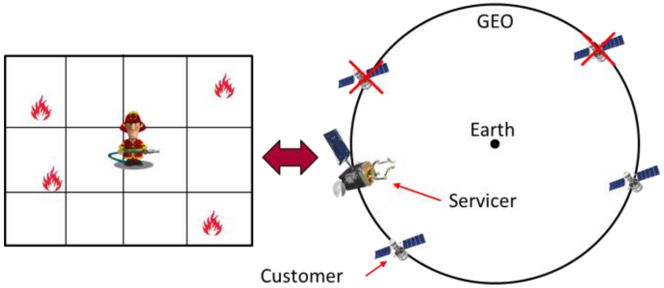
Credit: DARPA

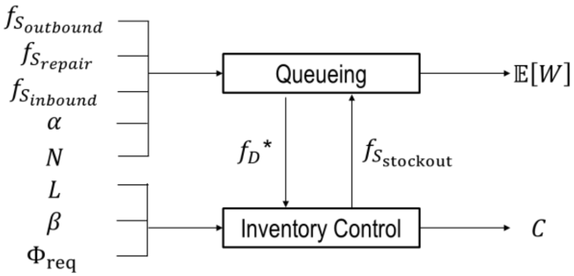
Motivation: Concepts of complex on-orbit servicing (OOS) infrastructures are emerging; traditional simulation-based analysis methods are computationally expensive.

$\Rightarrow$ Need an efficient **analytic/semi-analytic method to evaluate the performance of OOS infrastructures**.

Approach:

- Develop **a spatial (*orbital*) queueing model** for OOS evaluation, coupled with **a stochastic inventory model** for launches of parts/tools with launch vehicle constraints.
- Developed semi-analytic model can analyze the OOS performance without computational expensive simulations.
  - ➢ **Cutting down computational analysis time from hours/days to seconds,** enabling large-scale tradespace exploration.





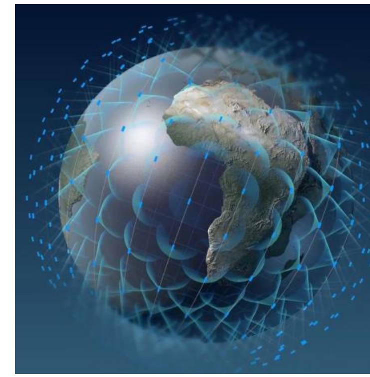
Sponsor: DARPA, US Space Force

* K. Ho, H. Wang, P. DeTrempe, T. Sarton du Jonchay, and K. Tomita, "Semi-Analytical Model for Design and Analysis of On-Orbit Servicing Architecture," *Journal of Spacecraft and Rockets*, Vol. 57, No. 6, pp. 1129-1138, 2020.

Space Logistics Research Example 3:
Spare Strategy for SmallSat Mega-Constellations

Motivation: Smallsat mega-constellations consist of unprecedentedly many satellites (100s to 1000s); traditional sparing strategies can result in too many spares and high costs.

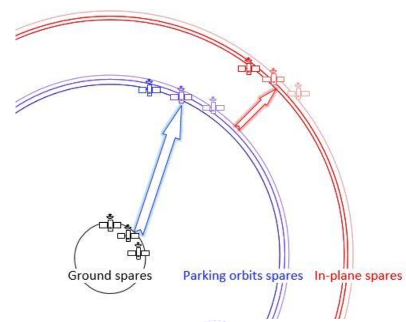
⇒ Need a strategy to **achieve the reliability requirements with fewer spares and lower costs.**

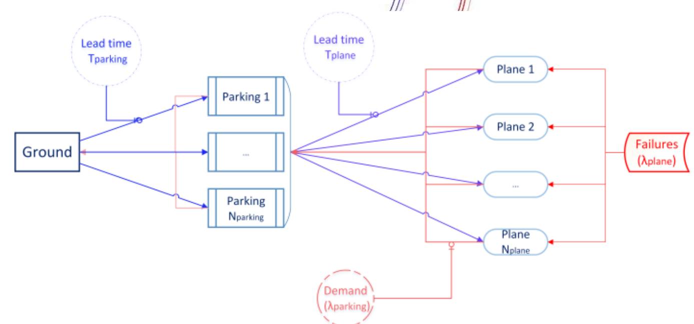


Credit: OneWeb

Approach:

- Develop an analytic **multi-echelon *orbital* inventory control model**, enabling the optimal choice of spare parking orbits and their sparing policies **leveraging natural orbital perturbations**.
- Developed model can be used to efficiently find the optimal spare strategies.
  - ➢ Enabling **up to 40% sparing cost savings** in the tested cases while achieving the reliability requirements.





Sponsor: Mitsubishi Electric Corporation

* P. Jakob, S. Shimizu, S. Yoshikawa, and K. Ho "Optimal Satellite Constellation Spare Strategy Using Multi-Echelon Inventory Control with Stochastic Demand and Lead Times." *Journal of Spacecraft and Rockets*, Vol. 56, No. 5, pp. 1449-1461, 2019.

Summary of Contributions and Impacts

- Pioneering the new research field of **space logistics**.
  - Incorporating **rigorous mathematical analytics** to (partially) automate large-scale space mission formulation, design, and planning process.
  - **Responding to the timely needs** given the growing complexity of space missions by governments (e.g., US Space Force, NASA, ESA, etc.) and private sectors (e.g., Northrop Grumman, ULA, Maxar, Airbus, etc.).
- Adding **a new dimension of multi-mission, multi-spacecraft campaign design** to the traditional astrodynamics field.

Space Logistics Modeling and Optimization Research will be <u>increasingly impactful</u> as future space systems become progressively more complex.

Acknowledgment

Space Systems Optimization Group (SSOG)
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Current PostDocs/Grad Students: Byeong-Un Jo, Tristan Sarton du Jonchay, Andrew Maxwell, Kento Tomita, Masafumi Isaji, Yuri Shimane, Nicholas Gollins, Malav Patel, Logan Feld, Polina Verkhovodova, Seungyeop Han, Julia Tepper, Lois Visonneau, Tomohiro Sasaki, Firas Sheikh
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… and many more undergraduate students

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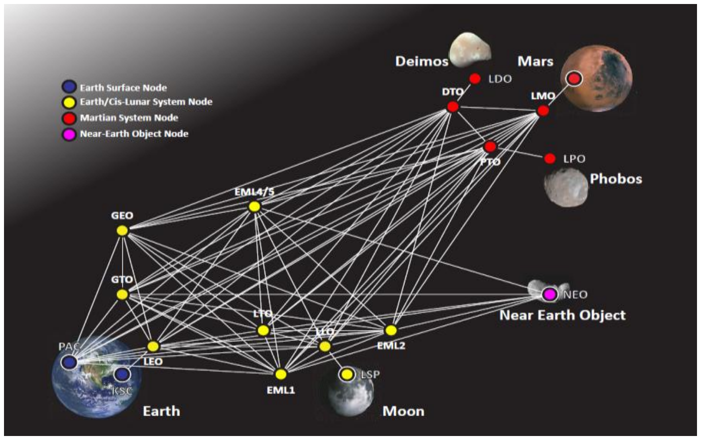
Backup

Space Logistics vs. Terrestrial Logistics

Space Exploration Map



VS.

World Airline Map

- **Conventional terrestrial logistics theories/methods cannot be applied to space logistics because…**
  - Computationally expensive and complex trajectory models (e.g., flow-dependent flight time for low-thrust trajectories; multiple time scales)
  - Launch and orbital mechanics constraints (e.g., time windows; capacity)
  - Deployment of infrastructures and their unique resource transformation mechanisms (e.g., in-situ resource utilization (ISRU))
  - Concurrent design of the vehicle/infrastructure and the network

$\Rightarrow$ **<u>New logistics theories/methods are necessary for space applications.</u>**