Blurring the Boundary: Integrating Systems of Systems at the Edge of Earth and Space

INCOSE IS 2023 - Systems Engineering Fundamentals

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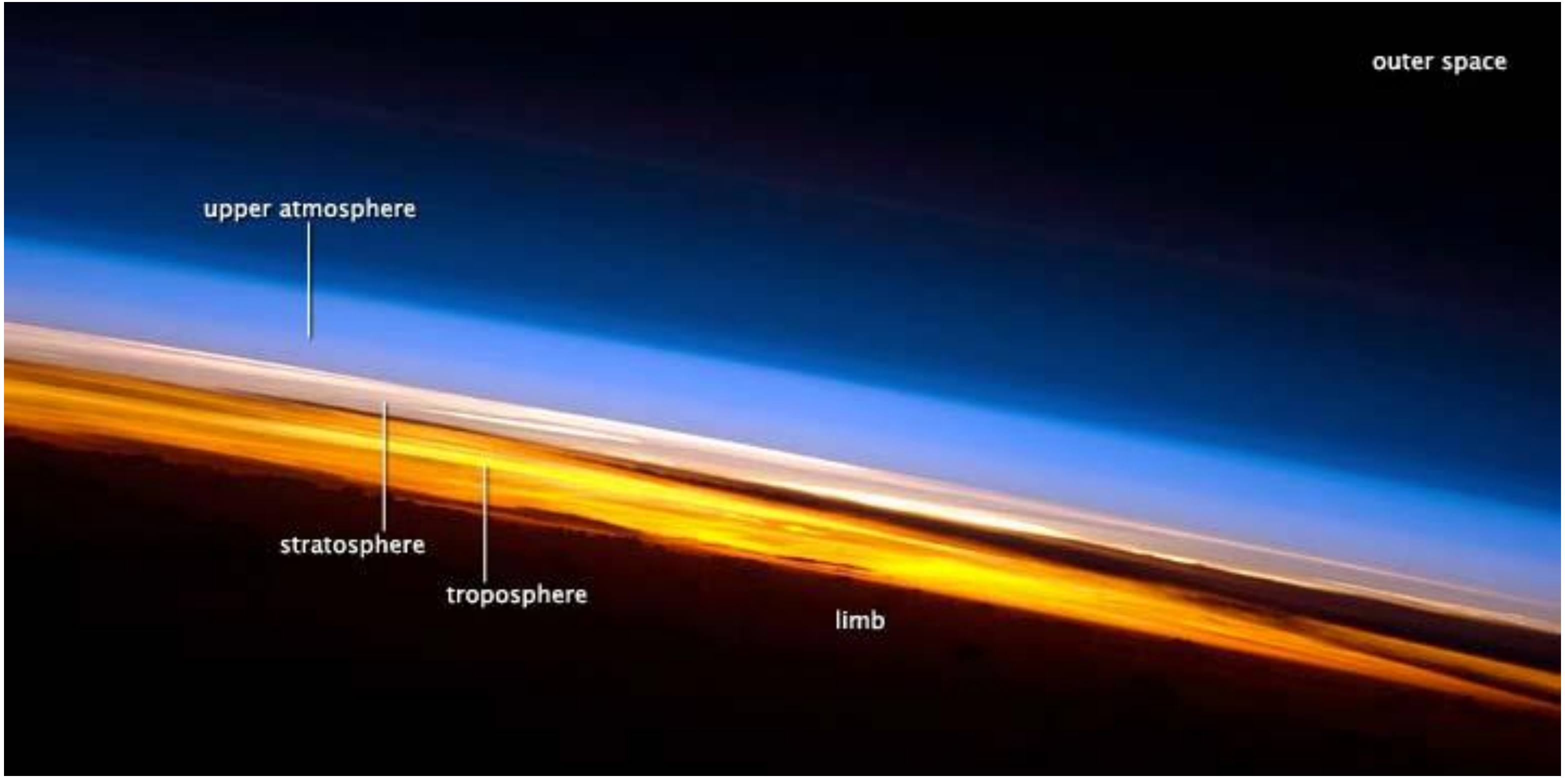
Engineering Systems Laboratory (ESL)

Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

Earth's atmosphere as viewed from space



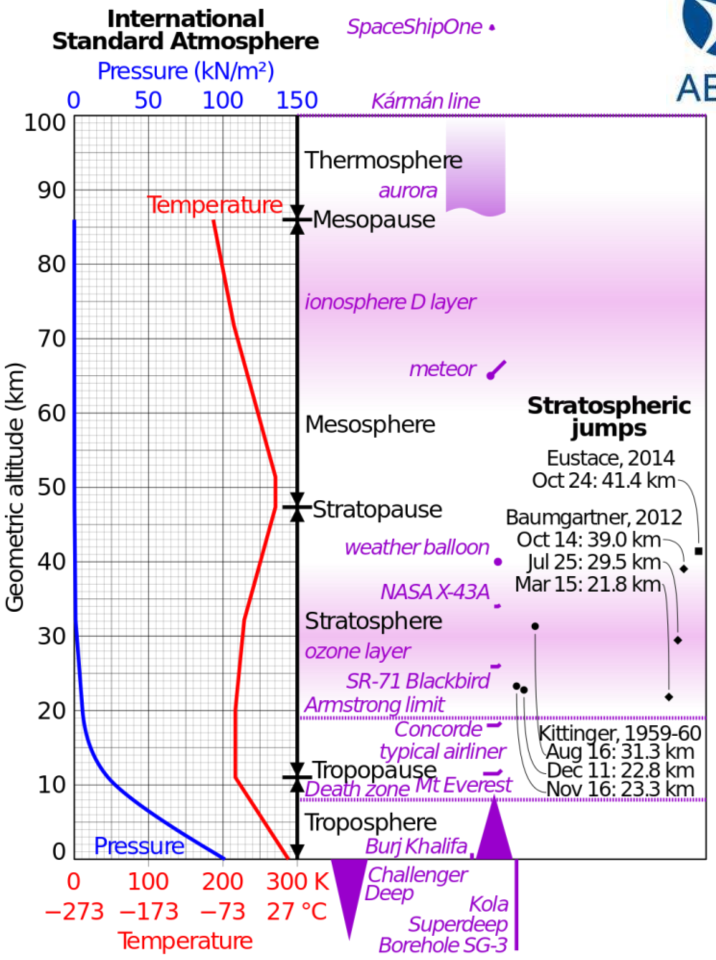
Source: https://www.space.com/8596-earth-colorful-atmospheric-layers-photographed-space.html

Earth’s Lower Atmosphere

Below <100 km (the [Kármán Line]) we have the lower atmosphere. It is broken into the following layers, and transition points:

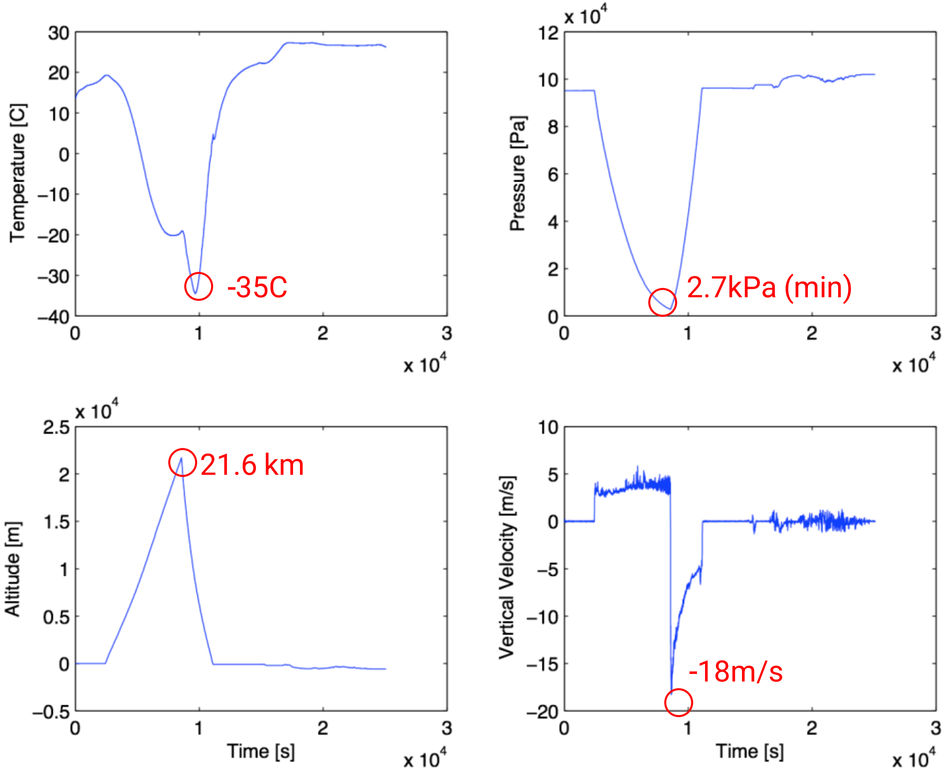
- **Troposphere**
  - Tropopause is between 9 km (polar) - 17 km (equator) and has a reversed thermal gradient
- **Stratosphere**
  - Stratopause is at 50-55 km altitude and has a maximum temperature of about -15C
  - The air density here is about 1/1000 of MSL
- **Mesosphere**
  - Mesopause is the point of coldest temperature in the atmosphere (<100 C) with two minima at 85 km and 100km

https://en.wikipedia.org/wiki/International_Standard_Atmosphere



Atmospheric measurements confirm models

High Altitude Weather Balloon (burst altitude 21.6 km)



Source: de Weck et al. , MIT Aero Astro Unified Engineering, 2013

Example “System of Systems”: US Coast Guard

U.S. Coast Guard secures national territorial waters and creates situational awareness

Complementary assets on see and in the air collaborate on missions and day-to-day operations

Example: Deepwater Systems Program ($24 Billion - defunct since FY 2012)

Source:

https://en.wikipedia.org/wiki/Integrated_Deepwater_System_Program

System of Systems (SoS)

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Maier, Mark W. "Architecting principles for systems-of-systems." Systems Engineering: The Journal of the International Council on Systems Engineering 1, no. 4 (1998): 267-284. Cited > 2,500 times

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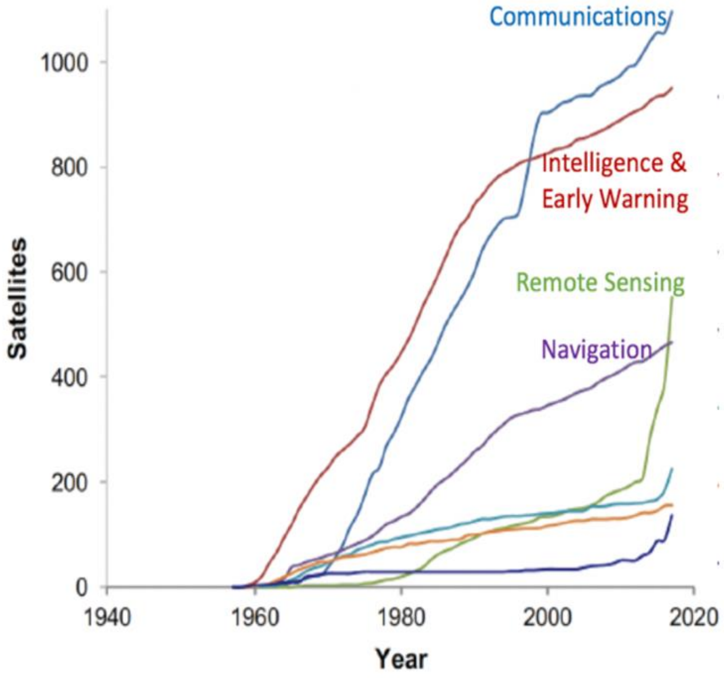
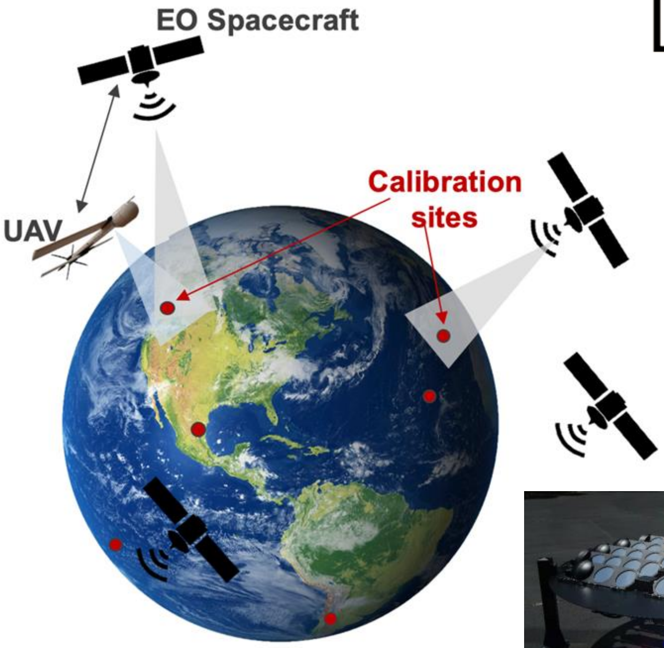
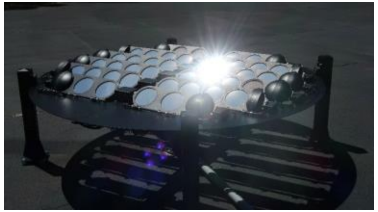
4. How can SoS create a **dynamic supply chain to** extend humanity's presence beyond Earth's surface?

Increasing platforms deployed for Earth Observation





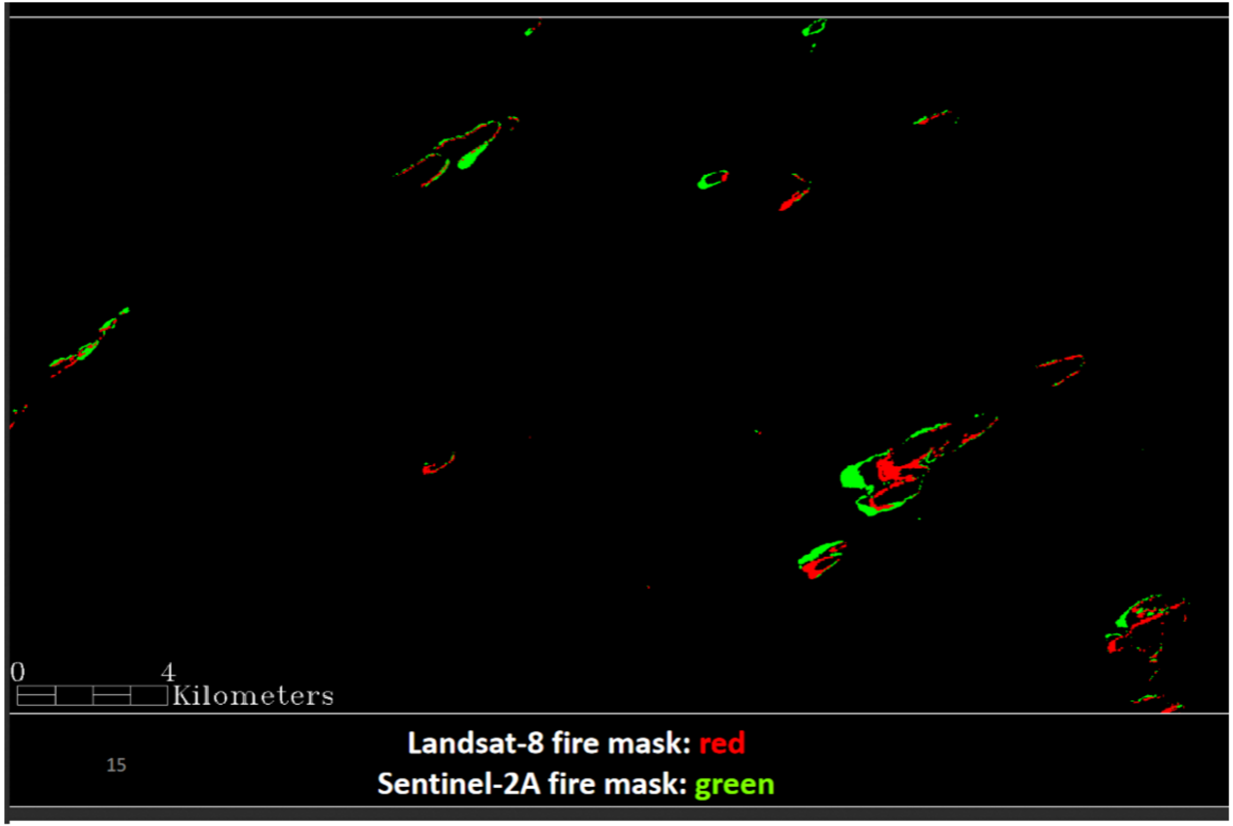
Labsphere

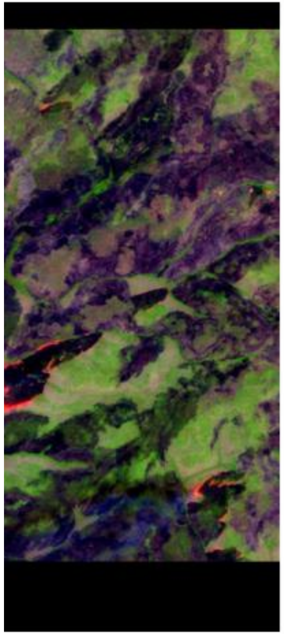


Flare Calibration Station

Foreman, Veronica Lynn. "Emergence of second-generation low earth orbit satellite constellations: a prospective technical, economic, and policy analysis." TPP Thesis., Massachusetts Institute of Technology, 2018. * Best Thesis Award

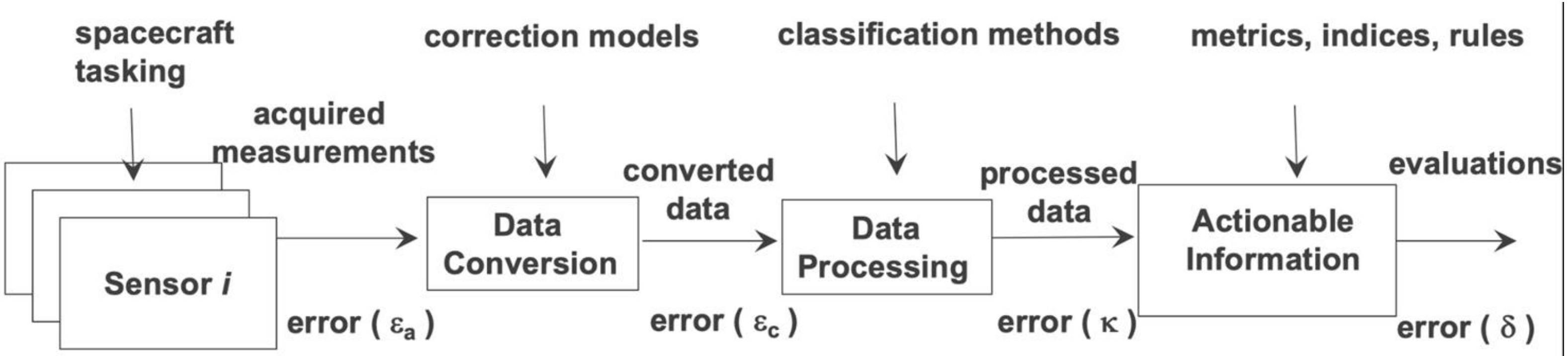
Same scene observed by different satellites … different results





Credit: Wilfrid Schroeder – NOAA/NESDIS

Modeling the Value of Calibration in Remote Sensing



Acquisition **Conversion**

Effective Data Acquired (EDA)
(Data quantity adjusted by quality)

Modeling & Classification

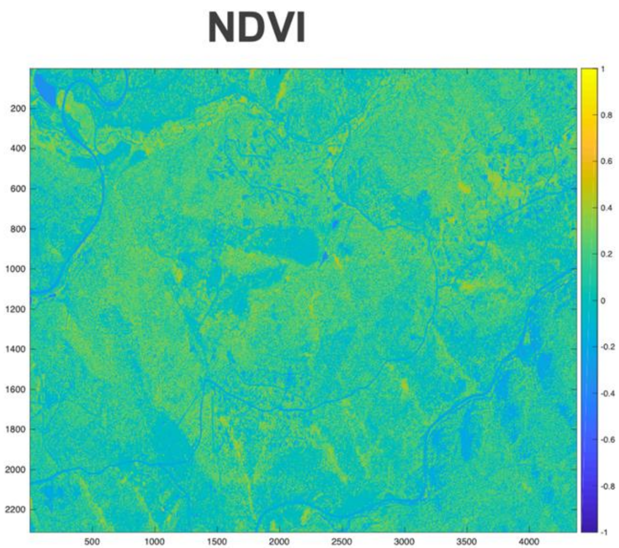
Error propagation, non-linear impacts due to thresholds

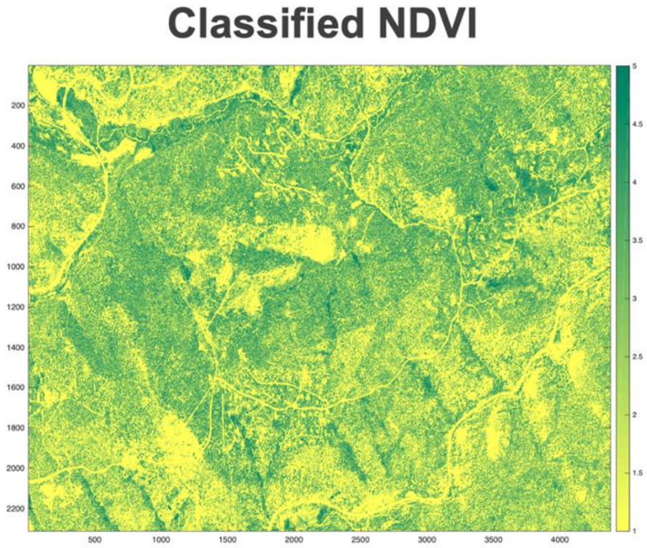
Evaluation & Decisions

Value of information (difference in economic outcomes)

Return on Investment for use of calibration services for Data Providers

Example Case: NDVI analysis





Cold Springs, Colorado
NAIP imagery data, 2015

1m ground pixel resolution

Leica Geosystem's
ADS100/SH100 digital sensors

class 1: NDVI < 0	No Vegetation
class 2: 0 ≤ NDIV < 0.1	Bare Area
class 3: 0.1 ≤ NDVI < 0.25	Low Vegetation
class 4: 0.25 ≤ NDVI < 0.4	Moderate Vegetation
class 5: NDVI ≥ 0.4	High Vegetation

$$NDVI = \frac{\rho_{NIR} - \rho_R}{\rho_{NIR} + \rho_R} = \frac{SR - 1}{SR + 1} \qquad SR = \frac{\rho_{NIR}}{\rho_R}$$

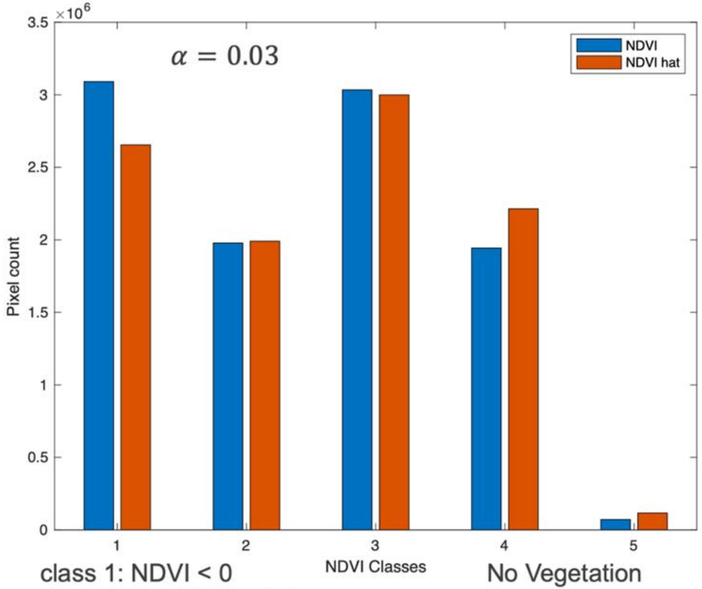
Siddiqi, A., Baber, S., de Weck, O. L., and Durell, C., "Error and Uncertainty in Earth Observation Data Value Chains", IEEE IGARSS 2020

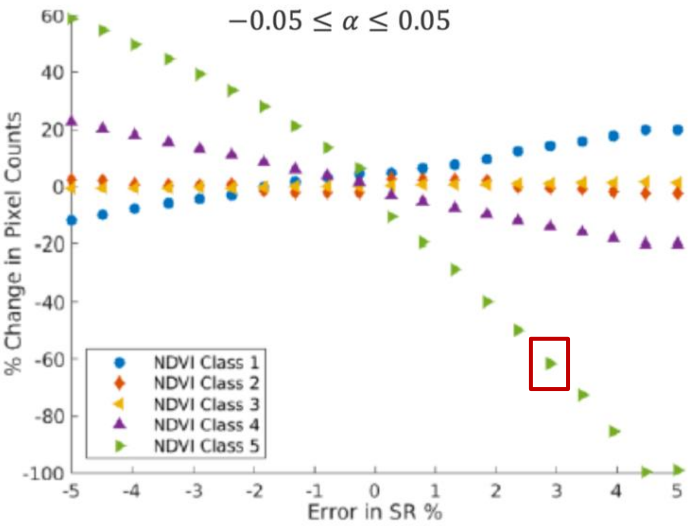
NDVI classification: Discrete thresholds create large errors

Assume the spectral ratio, $\widehat{SR}$, is simply:

$$\widehat{SR} = SR(1+\alpha)$$

*parameter α aggregates all the error parameters





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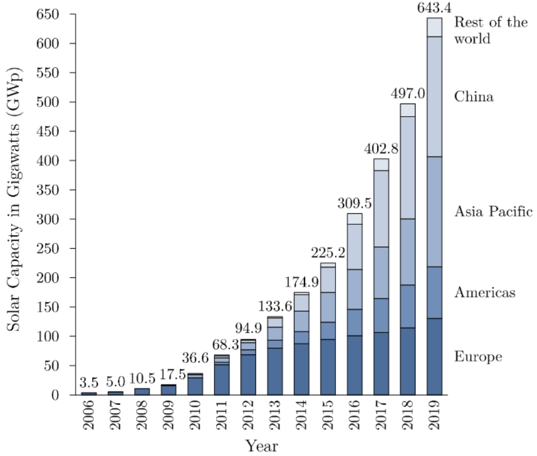
A 3% error in SR leads to a -60% change in class 5 pixel count in this case

Siddiqi, A., Baber, S., de Weck, O. L., and Durell, C., "Error and Uncertainty in Earth Observation Data Value Chains", IEEE IGARSS 2020

Deep Telemetry Project

Extracting insights from satellite imagery using ML and advanced feature extraction algorithms

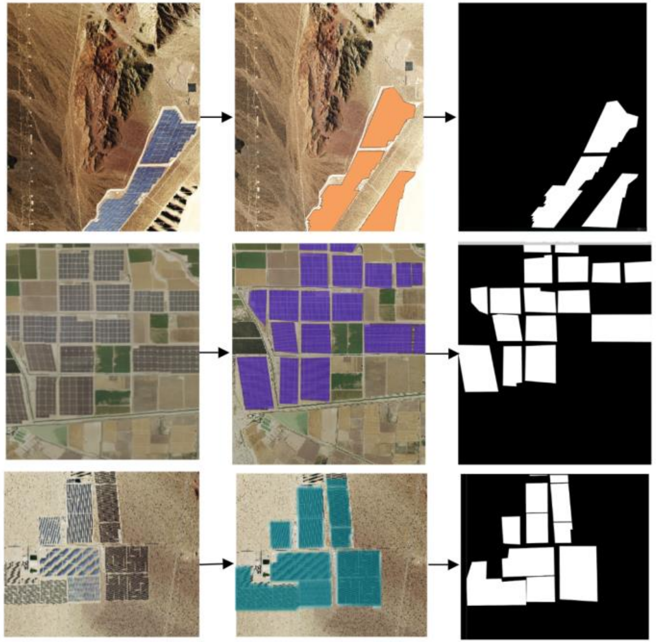


Solar Farm	Pixels Detected	Area Detected	Total Area Reported	Photovoltaic Panel Type	Panel Area	# Panels Counted	# Panels Reported	Annual Capacity Calculated (GWh)	Annual Capacity Reported (GWh)
Mount Signal	34.27	12.34	15.9	FS Series 3&4	4.93	6.85	6.8	1165.1	1197
Agua Caliente	21.65	7.79	9.7	FS Series 4	3.12	4.33	4.8	736.0	740
Desert Sunlight	38.53	13.87	16	FS Series 4	5.55	7.71	8.0	1309.9	1287
Solar Star	25.33	9.12	13	Sunpower	3.65	1.45	1.7	861.2	831
Springbok	18.33	5.52	5.7	FS Series 4	2.21	3.07	3.0	623.2	717

remote sensing
MDPI
Article

Detection and Mapping of Solar Farms using Satellite Imagery

Elaf AlMahmoud [1,2,†], Rashmi Ravishankar [1,*,†], Olivier L de Weck [3], Abdulelah Habib [3]



Original imagery   Shapefile/mask   Pixel wise annotation

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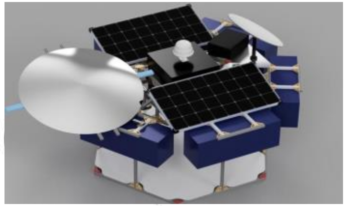
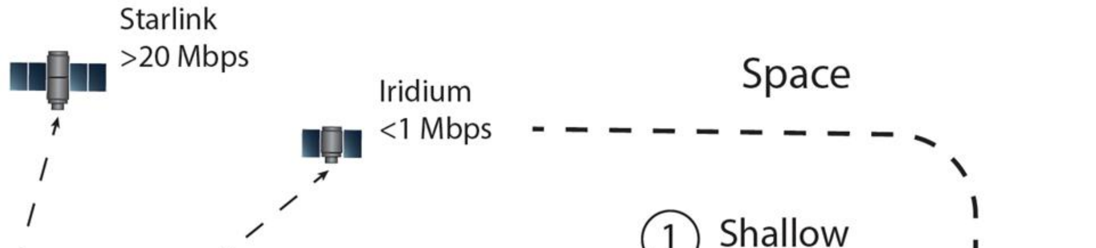
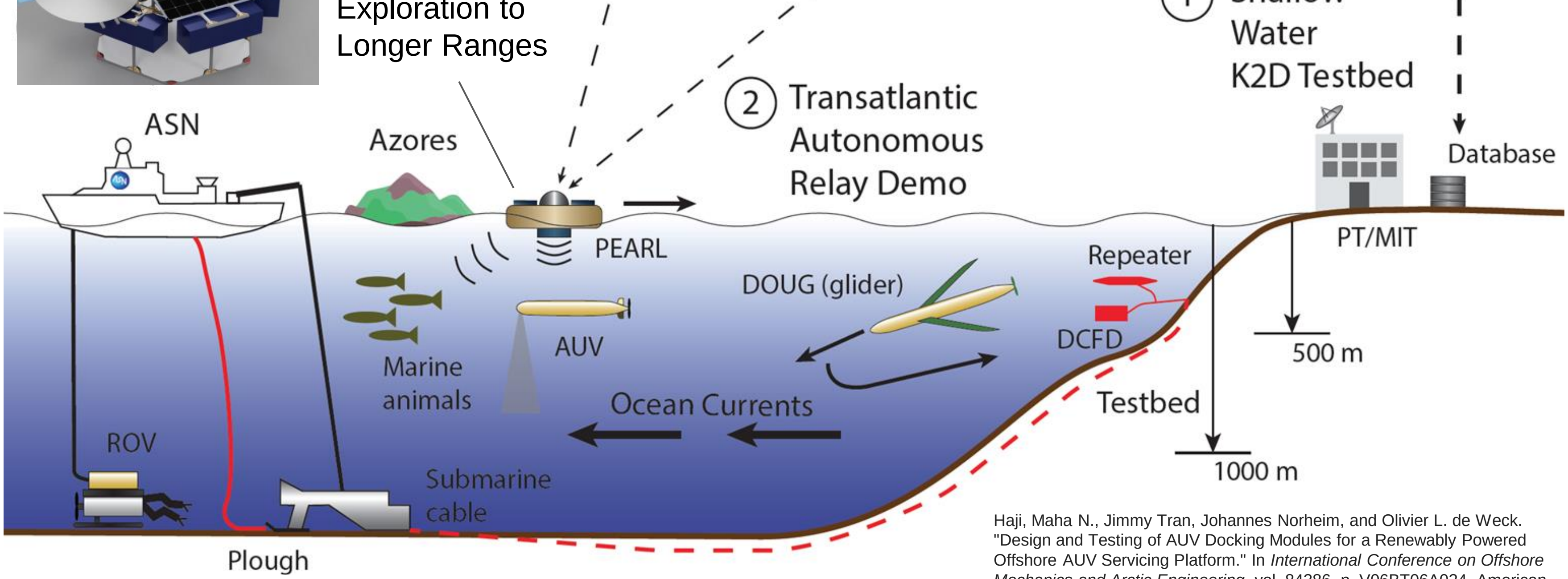
Example of a System of Systems at the Oceans-to-Space boundary

MIT Portugal



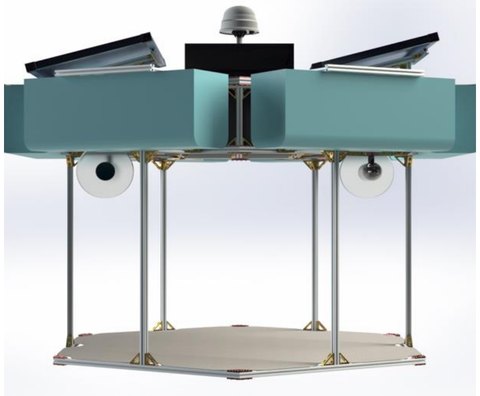
Platform for Extending AUV Exploration to Longer Ranges

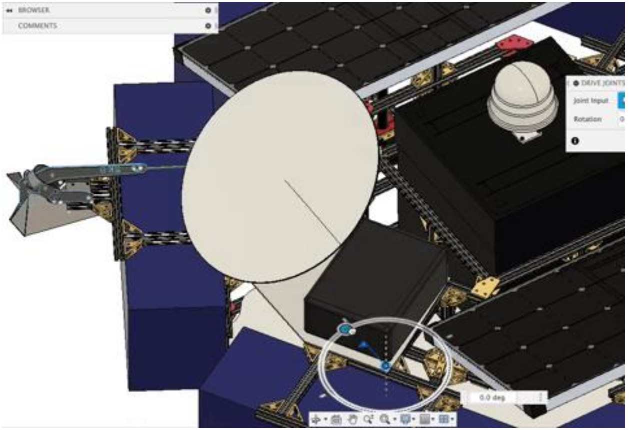
Haji, Maha N., Jimmy Tran, Johannes Norheim, and Olivier L. de Weck. "Design and Testing of AUV Docking Modules for a Renewably Powered Offshore AUV Servicing Platform." In *International Conference on Offshore Mechanics and Arctic Engineering*, vol. 84386, p. V06BT06A024. American Society of Mechanical Engineers, 2020.

PEARL: Complexity throughout the lifecycle

Conceive

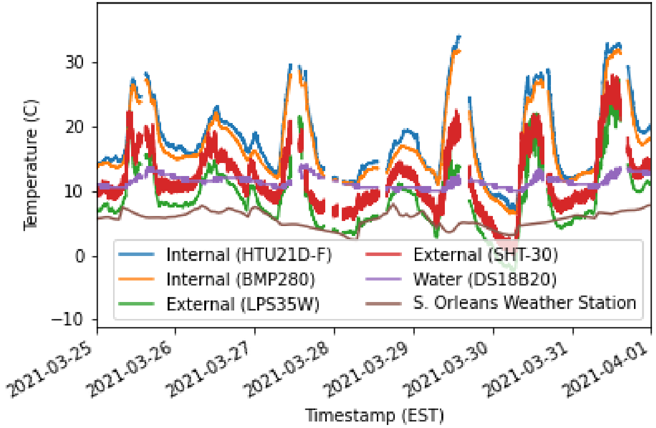


Design



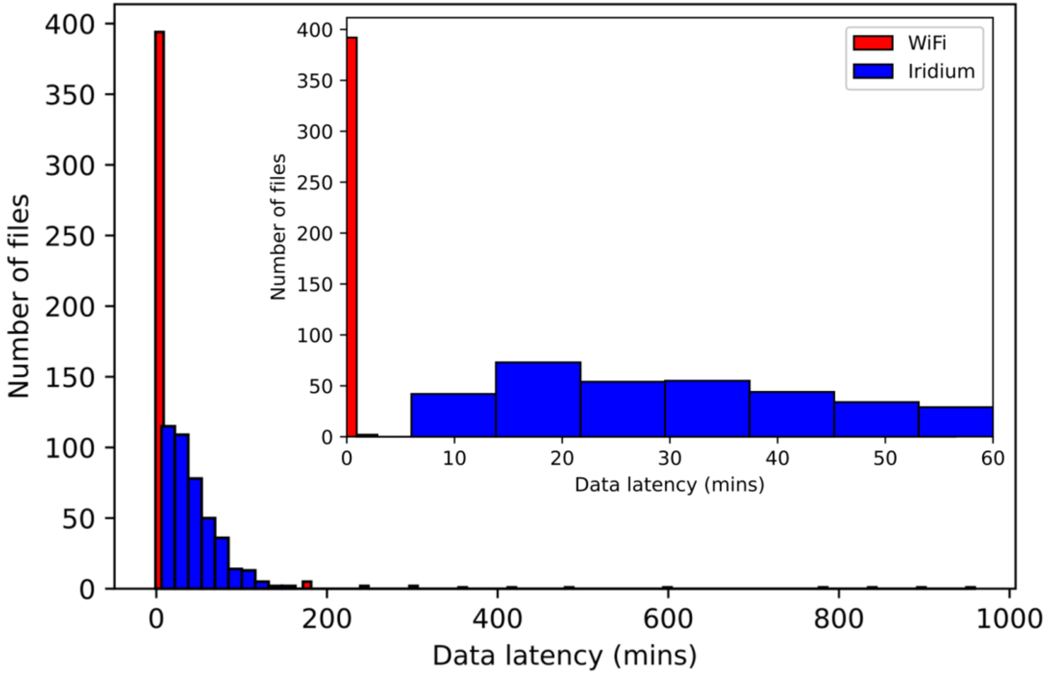
Implement

Operate



PEARL Data Transmission Latency

- Mean latency for:
  - WiFi transfers: 19.59 minutes
    - Vast majority < 1 minutes
  - **Iridium transfers: 42.48 minutes**
- How much is due to:
  - file formatting and saving on RPi,
  - transfer from RPi to Iridium terminal
  - file compression and encoding on Iridium terminal,
  - waiting for a successful handshake for an uplink with an Iridium satellite,
  - data transfer to Iridium uplink,
  - handoff to another satellite via ISL and ground station.
  - decoding at ground station and transfer to FTP server.



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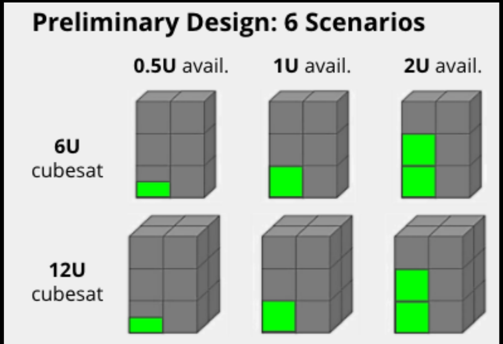
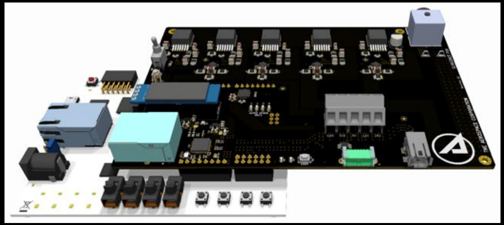
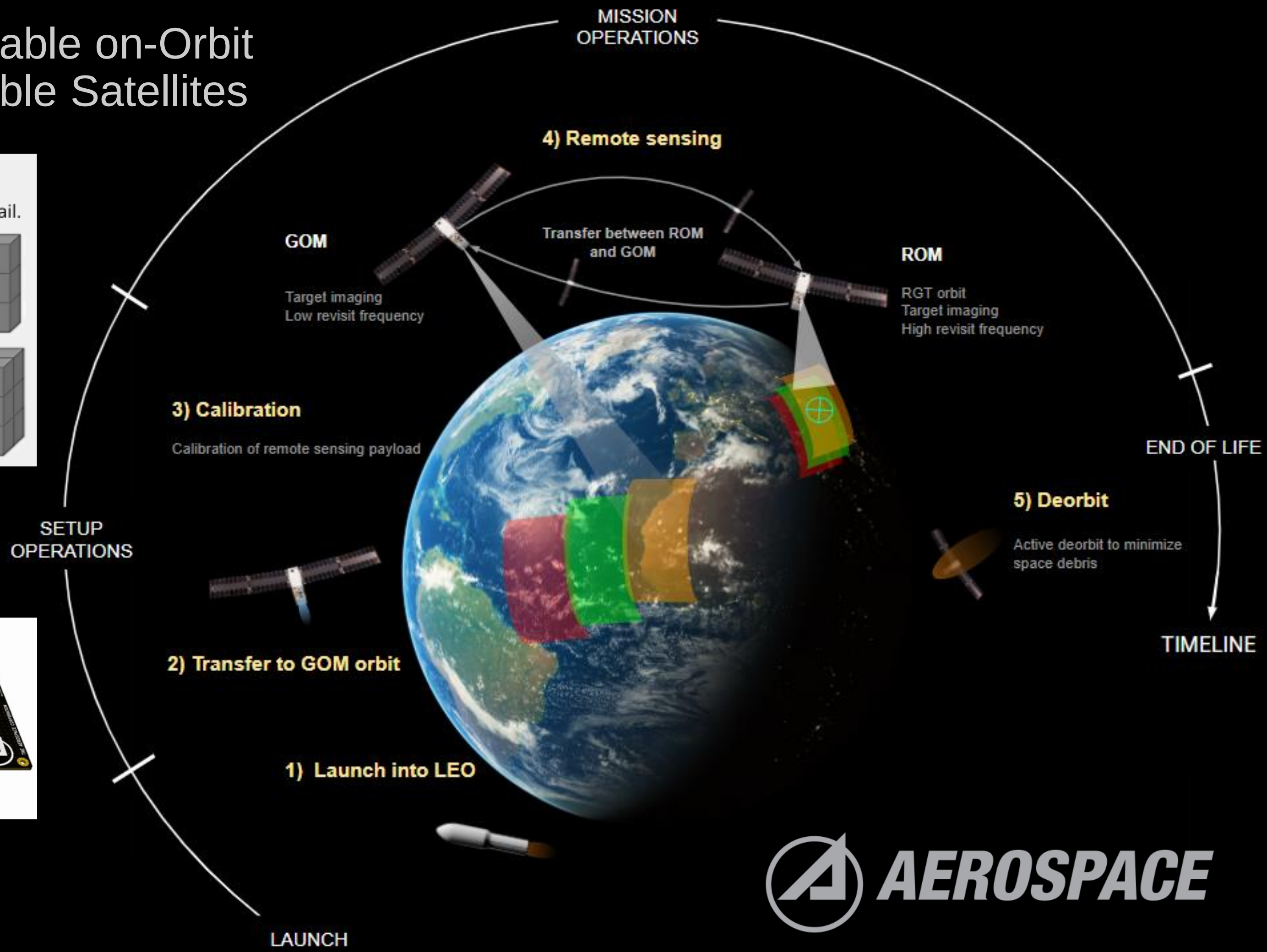
ROAMS: Reconfigurable on-Orbit Adaptive Maneuverable Satellites







AEROSPACE

Global Observation Mode (GOM)

Demo

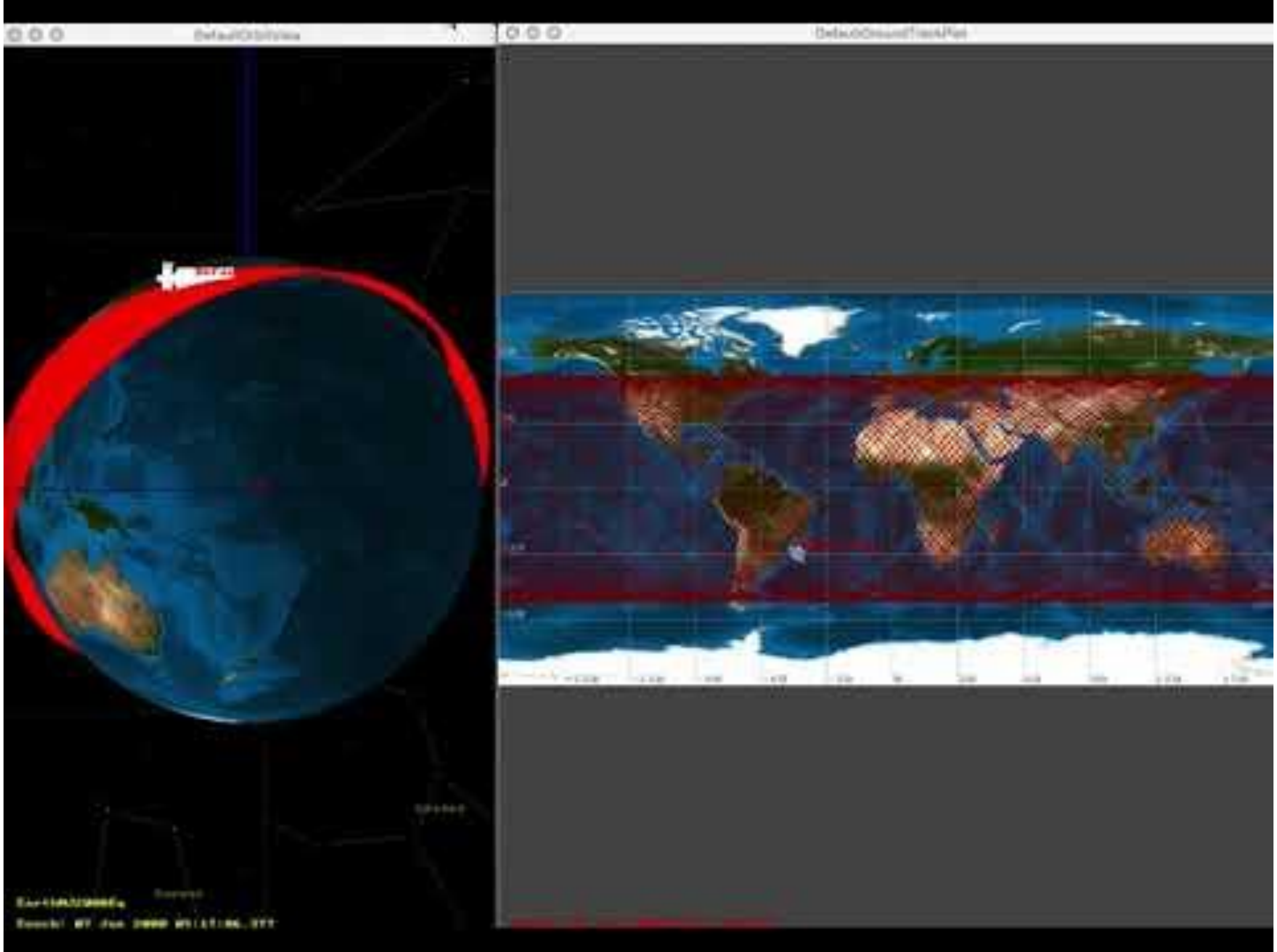
Single spacecraft

a=6828 km (h=450 km)

i = 51.6 deg (ISS orbit)

e=0 (circular)

Orbit drifts and covers all lat/lon within range in about 16 days



Repeating Ground Track (RGT) Orbits

- Trade global coverage for higher frequency localized coverage

$$\dot{\lambda} = -\underbrace{\left[\frac{3}{2}\frac{\sqrt{\mu}J_2R^2}{(1-e^2)^2 a^{\frac{7}{2}}}\right]\cos i}_{d\Omega/dt} - \omega$$

$$\sigma = \frac{k\,P_\Omega\,\dot{\lambda}}{2\pi}$$

Nodal period

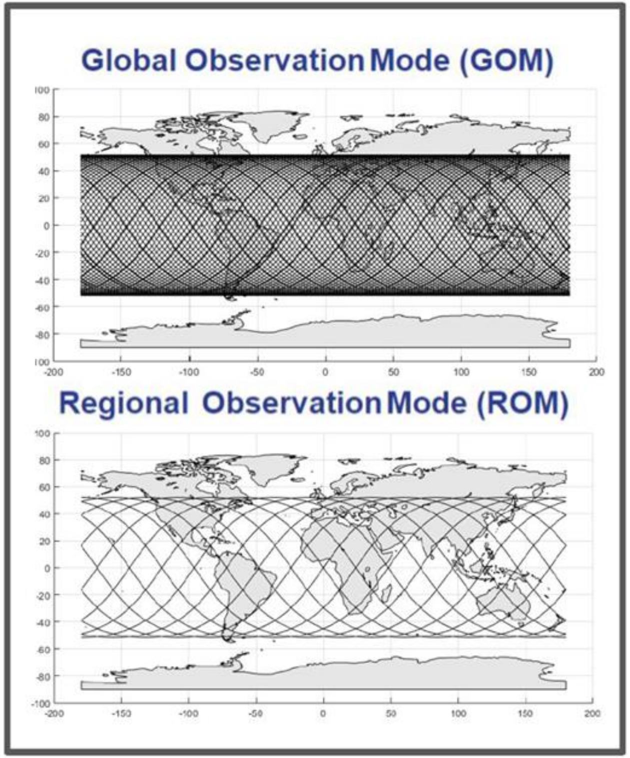
dΩ/dt

Earth's rotation rate

Should be an integer for RGTs

Design Parameters

- Once ROM is selected, ground track geometry is fixed!



Ground tracks for proposed trajectories over one week
(ROM is an RGT orbit)

Paek, Sung Wook, Sangtae Kim, and Olivier de Weck. "Optimization of reconfigurable satellite constellations using simulated annealing and genetic algorithm." *Sensors* 19, no. 4 (2019): 765.

Regional Observation Mode (ROM)

Demo

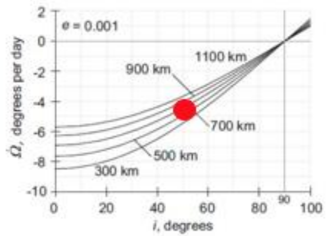
Single spacecraft

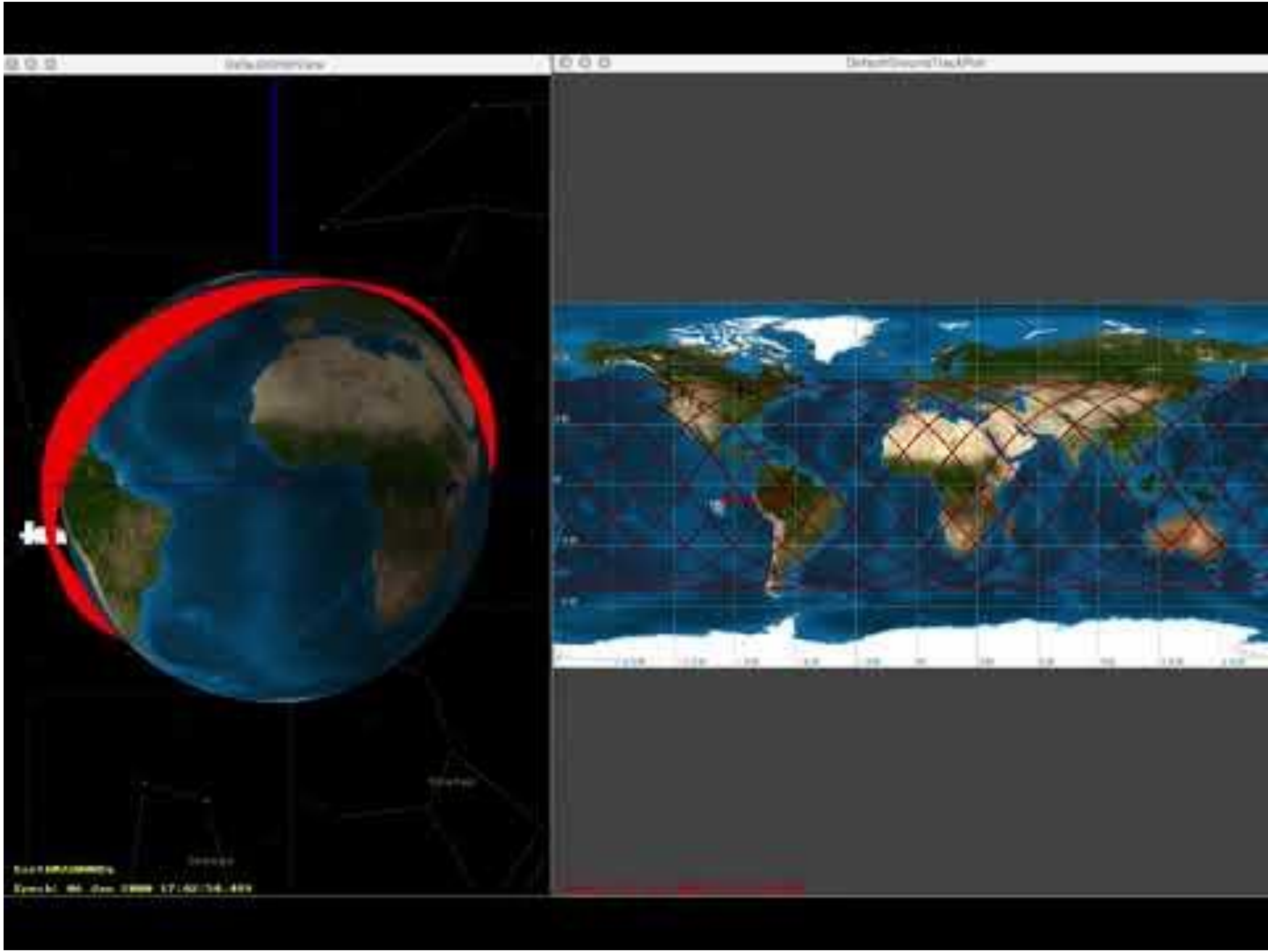
a=6828 km (h=497 km)

i = 51.6 deg (ISS orbit)

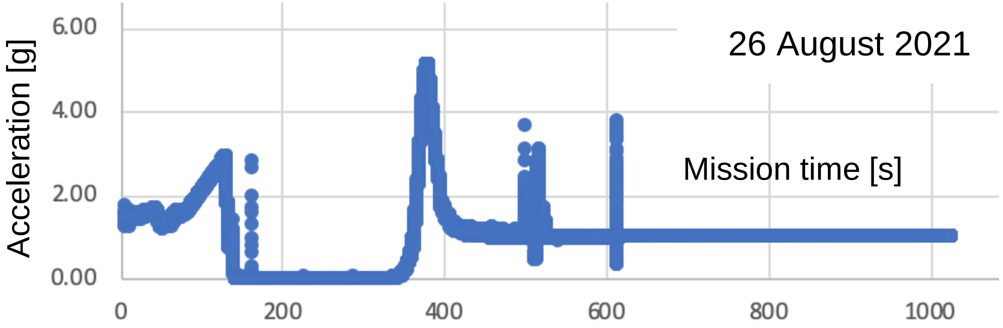
e=0 (circular)

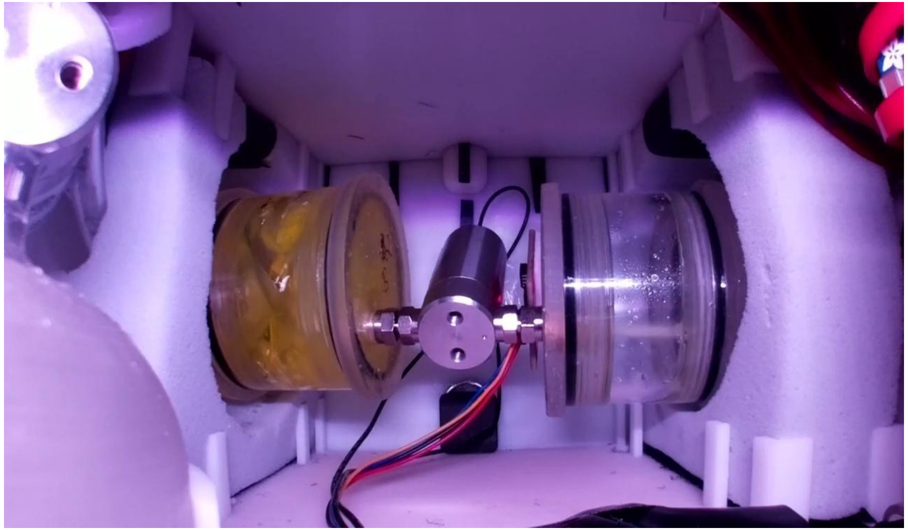
Orbit is locked in a RGT





Fuel Transfer Research in Microgravity
Blue Origin New Shepard NS-17





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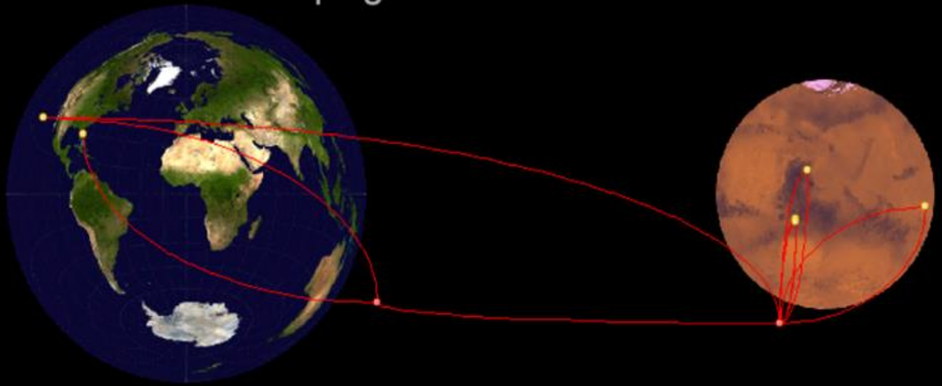
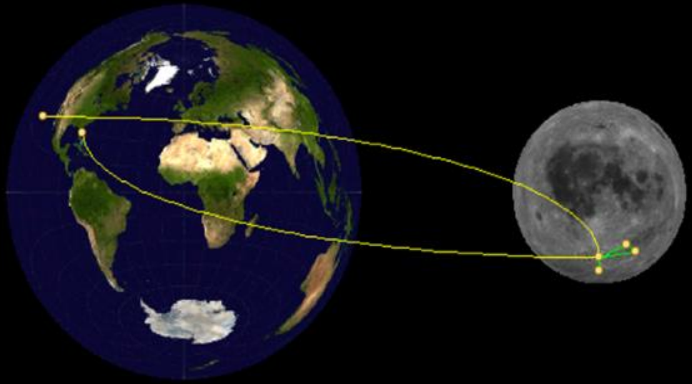
ISS Resupply

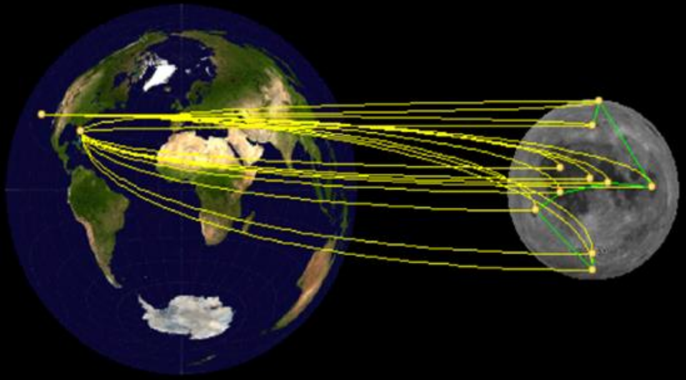
Mars Campaign with Robotic Pre-cursors



Lunar Outpost (South Pole)



Lunar Global Exploration (Nomadic)

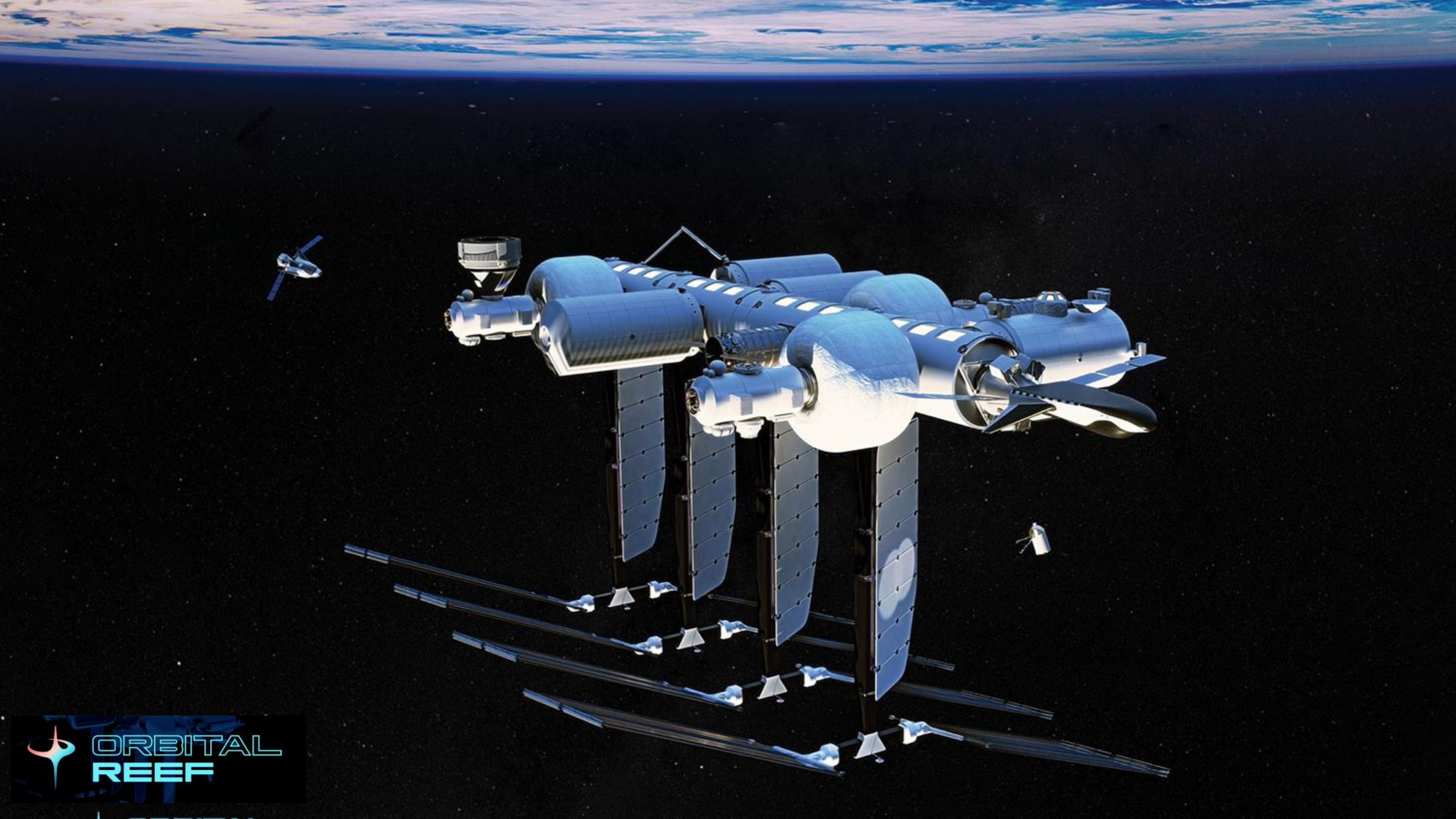


SpaceNet 2.5: Quantifying future exploration campaigns

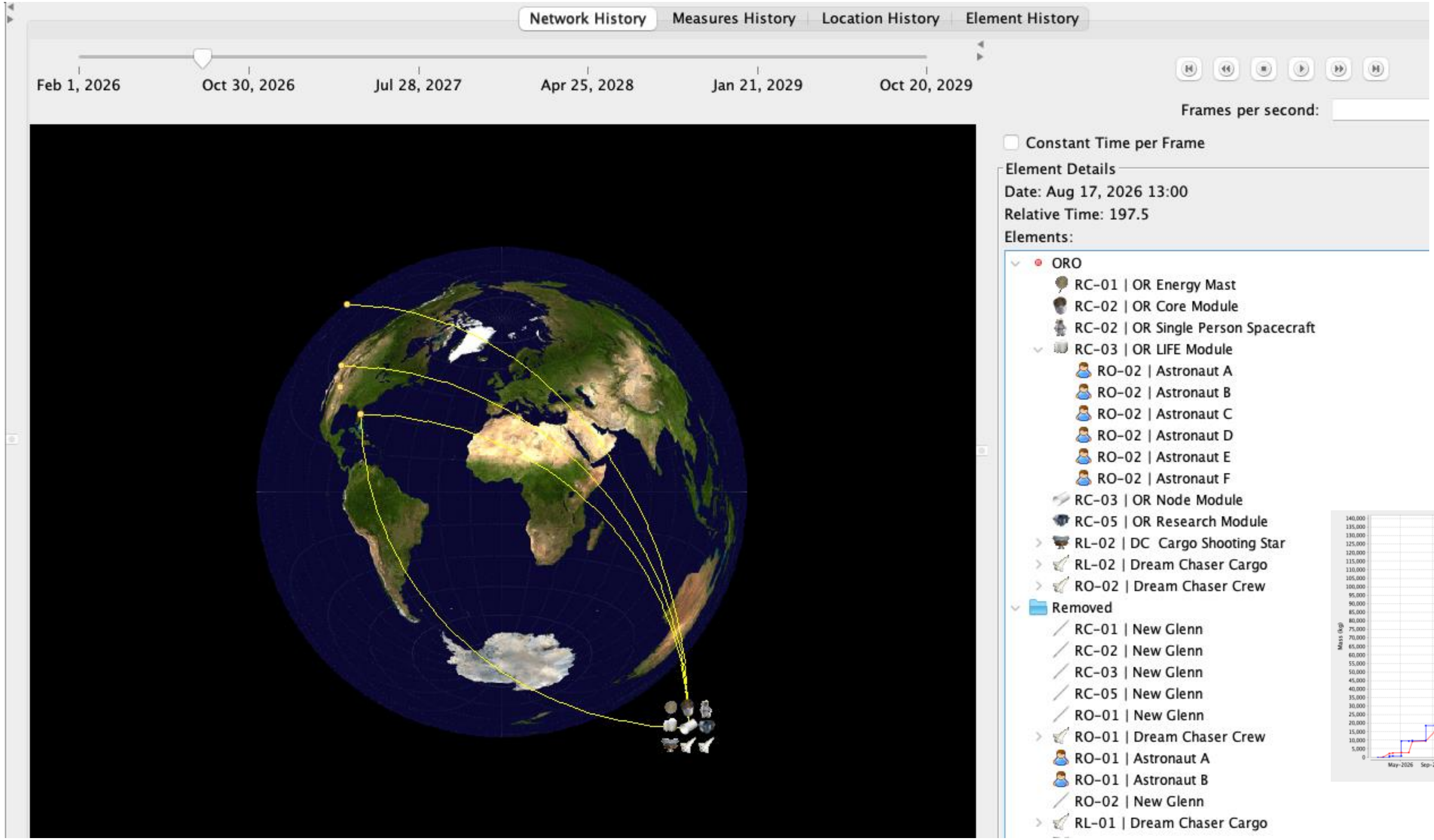
	ISS Resupply	Lunar Outpost	NEO Sortie	Mars Exploration Campaign
Nodes	9	5	4	10
Edges	13	6	3	23
Missions	78	17	1	21
Events	271	156	6	337
Elements Types	14	30	11	32
Elements	90	140	12	234
Duration (days)	1,920	2,628	148	6,911

- **Exploration campaigns involve 100's of events and vehicles over 1000's of days**
- **Bringing everything from Earth is not sustainable**
- **We need to start thinking of it as a supply chain network in space**

Grogan P.T., Yue H., de Weck O., "Space Logistics Modeling and Simulation Analysis using SpaceNet: Four Application Cases", AIAA-2011-7346, AIAA Space 2011 Conference & Exposition, Long Beach, California, September 27-29, 2011


ORBITAL
REEF

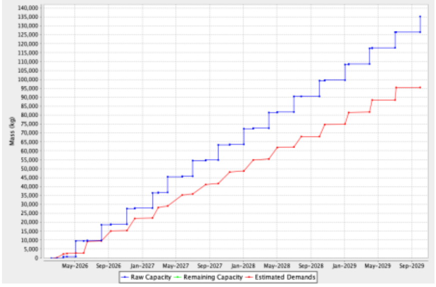
Integrated Space Logistics for Orbital Reef



Orbital Reef station buildup simulation

Resupply scenario v0.51 with SpaceNet

Determining customer cargo capacity 2026-2029



Takeaway messages

http://systems.mit.edu

System of Systems at the Earth-Space Boundary:

- Are *rapidly increasing* in many application areas (Remote Sensing, Telecommunications, ISR) etc..
- Critical issue is cross-platform *calibration* and data fusion for disparate sensors
- SoS behave *stochastically* due to random processes, e.g. communications delays
- *Reconfigurability* in SoS is valuable to increase revisit frequency, improve view angles for targets of interest, and ensure redundancy
- SoS are an enabler of interplanetary supply chains to *extend human presence* beyond Earth

Engineering Systems Laboratory

Questions?

Comments?