Halfway to Anywhere - Cislunar and Deep Space Cubesat Missions From ISS

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Outline

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- Background & Motivation
- Advantages & Disadvantages
- Team Alpha CubeSat Example
- ISS as a launch platform
- Conclusion
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Introduction

Science fiction author Robert Heinlein once said, ”Once you're in low Earth orbit you're halfway to anywhere.”

This statement while playing a bit fast and loose with a strict accounting of kinetic energy requirements, is far from hyperbole.

This presentation examines both how to leverage the advantages and mitigate the disadvantages of using the International Space Station (ISS) as a beyond Earth orbit transportation node for multiple applications.

Background & Motivation - 1

Historically, most space missions have focused on single-use Earth-to-destination transportation

To develop a fully space-faring civilization, we need to evolve toward reusable, refueled, space vehicles that can provide transportation between multiple destinations - a different kind of space transportation architecture

This kind of transportation architecture is important for space development, space resource use, and space exploration.

Background & Motivation - 2

Elements of these kind of space architectures have been proposed or used in the past (Lunar orbit rendezvous and the LEM, ‘Earth orbit rendezvous’, Space Transportation System - Shuttle+Station+OTV, etc.).

Previously, the assembly and deployment of lunar and deep space vehicles was a major mission of the space station - but these missions were deferred as ISS was built

New opportunities with cubesats (including deployment from ISS) allow elements of these transportation architectures to be demonstrated e.g. propellant option demos, and isolate from developing infrastructure for test

Advantages & Disadvantages - 1

Spacecraft design:

- Assemble IVA or EVR in LEO
- Avoid aerodynamic loads
- Avoid launch loads
- Potential for large structures
- Potential for space manufacturing
- Design for vacuum
- Pure ‘space’ spacecraft

Different level of design optimization - optimize for in-space use

Advantages & Disadvantages - 2

ISS serves as a Propulsion Test Bed for many options:

- bi-propellants (non-toxic, non-hazardous)
- solar electric/ion thrusters
- power beaming
- resistojets (e.g., scavenged water, methane, etc.)
- mono-propellants (non-toxic, non-hazardous)
- solar sails

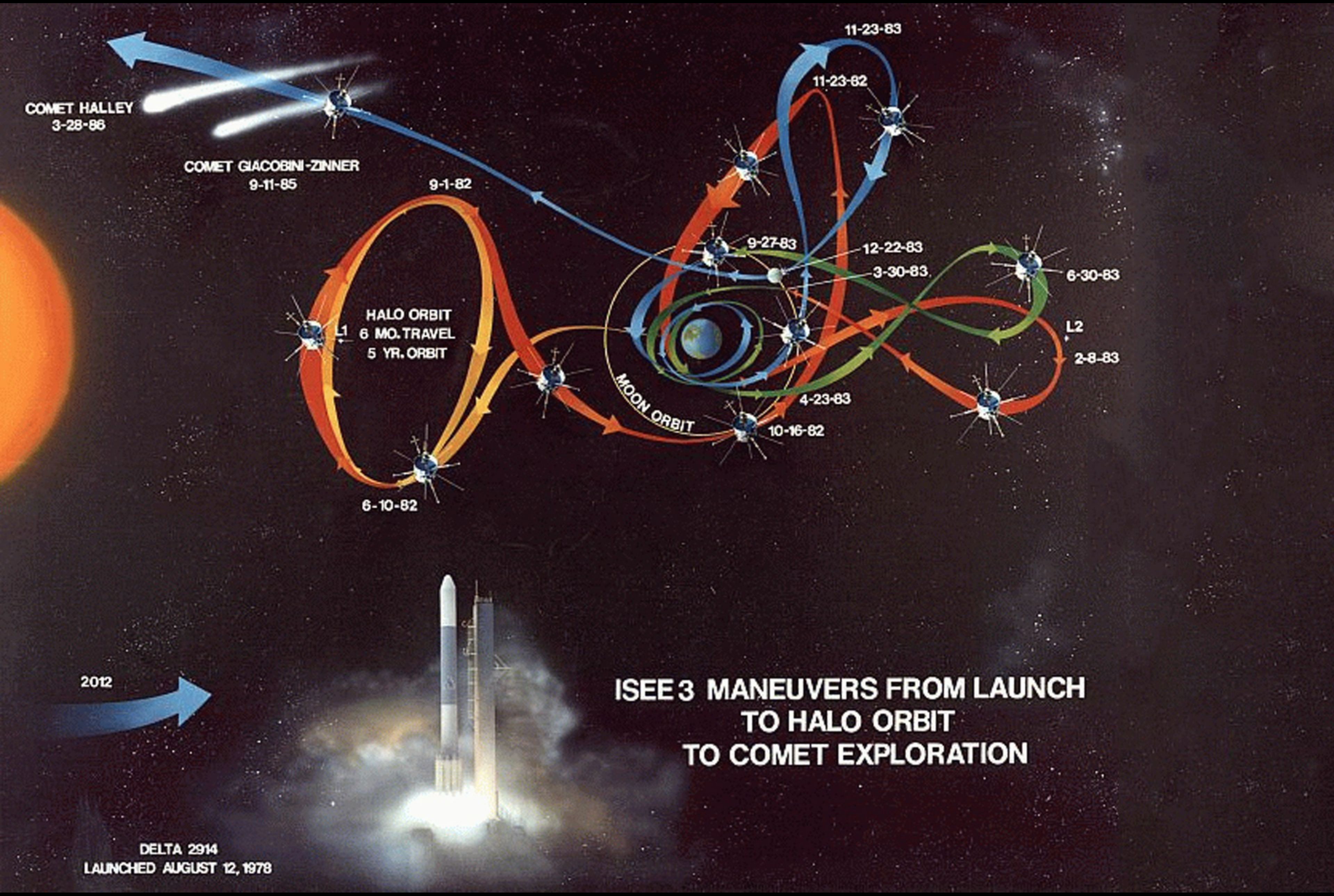
Provides for a wide range of low and high thrust options

Advantages & Disadvantages - 3

Trajectory and delta-v implications of starting from LEO:

- Classic “minimum” energy trajectories are not optimal
- Alternate minimum energy trajectories become tractable
- Longevity of spacecraft components becomes more critical
- Non-protected orbit transfers increases exposure time to
  - Orbital debris
  - Radiation belts
- The calculations required are more demanding and must be readily accomplished

There is an intersection between orbital dynamics and art . . .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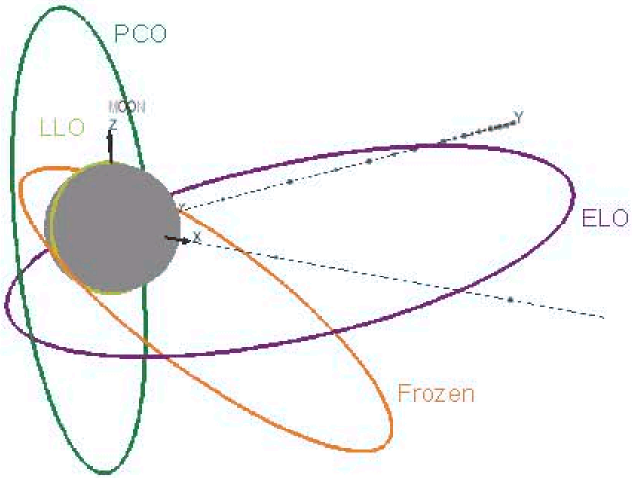
3-30-83
6-30-83
HALO ORBIT
6 MO. TRAVEL
5 YR. ORBIT
L1
L2
2-8-83
MOON ORBIT
4-23-83
10-16-82
6-10-82
2012
ISEE 3 MANEUVERS FROM LAUNCH
TO HALO ORBIT
TO COMET EXPLORATION
DELTA 2914
LAUNCHED AUGUST 12, 1978

LUNAR RESONANCE ORBITS

Smaller Cislunar (Lunar Two-body) Orbits

Orbit Type	Orbit Period	Amplitude Range	E-M Orientation
Low Lunar Orbit (LLO)	~2 hrs	100 km	Any inclination
Prograde Circular (PCO)	11 hrs	3,000 to 5,000 km	~ 75 ° inclination
Frozen Lunar Orbit	~13 hrs	880 to 8,800 km	40° inclination
Elliptical Lunar Orbit (ELO)	~14 hrs	100 to 10,000 km	Equatorial



Low Lunar Orbit (LLO): LLO is defined as a circular orbit of an altitude around 100 km. LLOs are favorable for surface access and polar orbit inclinations offer global landing site access.

An Elliptical Lunar Orbit (ELO), such as the 100 x 10,000 km shown, trades insertion costs with transfer cost to lunar surface.

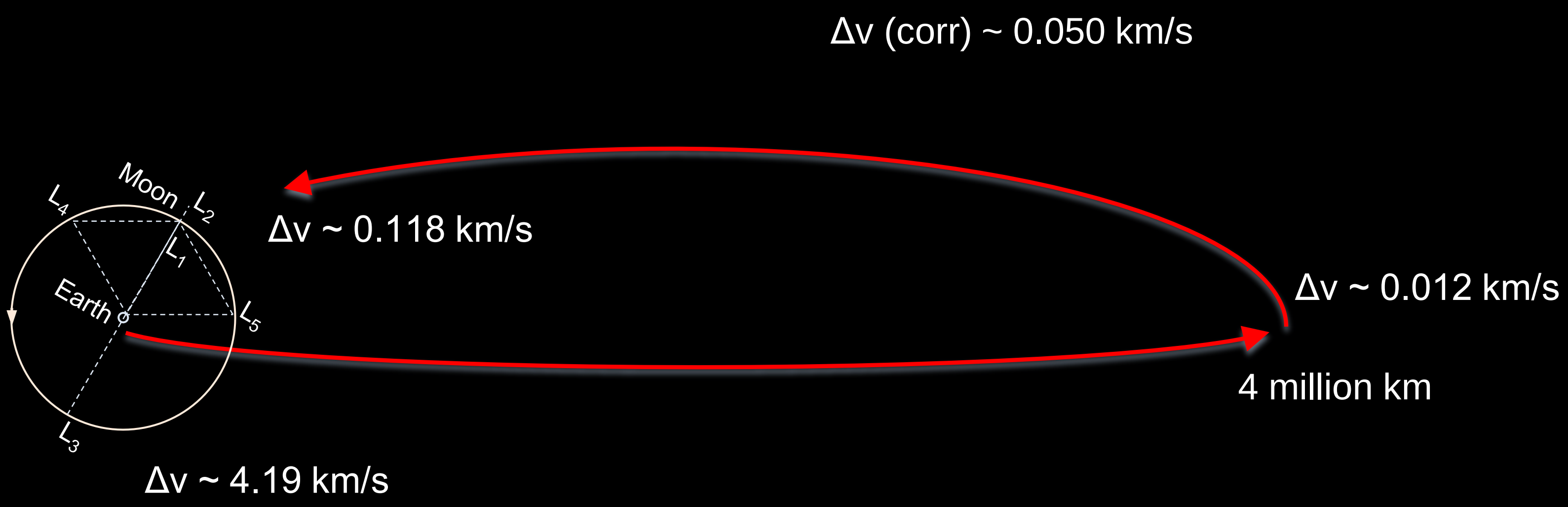
Prograde Circular Orbits (PCOs) are defined as circular orbits of various sizes that rotate in the prograde direction and are highly stable, requiring few to zero corrections to be maintained.

Frozen orbits are similar but need not be circular and have orbital parameters that oscillate around fixed values.

New Twists:

Frozen orbits include Lunar Resonance Orbits that work from at least four inclinations 27^o, 50^o, 76^o, and 86^o Spacecraft in these orbits can stay in lunar orbit indefinitely with little or no makeup propulsion.

Team Alpha CubeSat: Second Order Trajectory Solution



Total Δv ~ 4.37 km/s
(second order calculation)

ISS + Trajectory Insertion Bus Δv ~ 4.19 km/s Maximum
Alpha CubeSat Spacecraft Δv ~ .180 km/s Minimum

PROPULSION SUMMARY

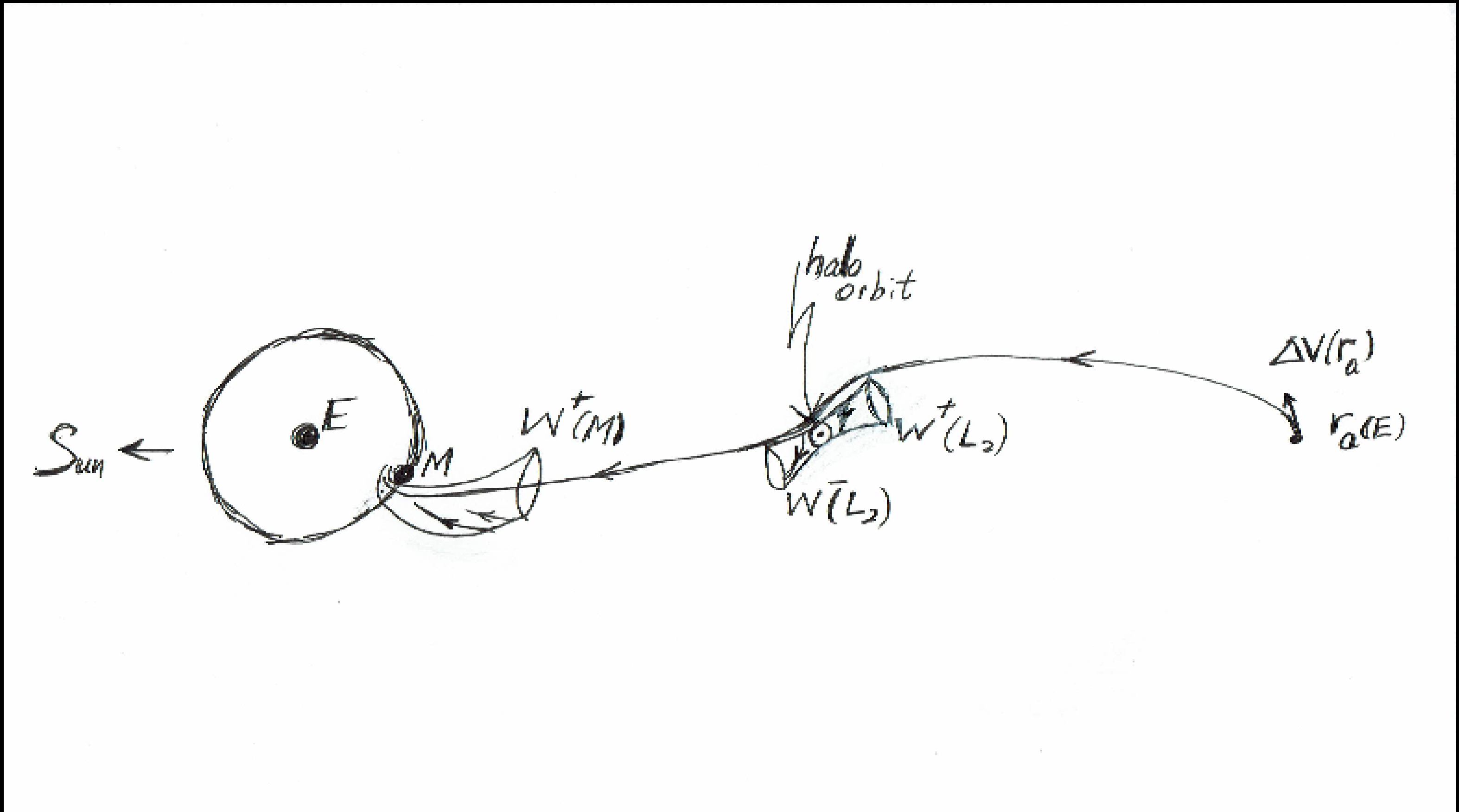
- Commercial Cargo Transport to ISS
- ISS → Trajectory insertion point via Launch Service Provider Trajectory Insertion Bus
  - Δv_E is 4.19 km/s (maximum)
- Alpha CubeSat Trajectory Makeup Propulsion to 4+ million km
  - $\Delta v_{\text{Deep Space Trajectory Insertion}}$ is ~0.0 km/s (minimum)
- Alpha CubeSat Deep Space (4+ million km) Maneuver
  - $\Delta v_{\text{Lunar Trajectory Insertion}}$ is ~0.012 km/s (minimum)
- Alpha CubeSat Trajectory Correction Budget
  - $\Delta v_{\text{Correction Budget}}$ is ~0.05 km/s (minimum)
- Alpha CubeSat stable lunar orbit injection
  - $\Delta v_{\text{Lunar Orbit Injection}}$ is ~0.118 km/s (minimum)

The required Alpha CubeSat Spacecraft
$\Delta v_{Mission}$ = .180 km/s

Lunar Orbit Manifold Trajectory

- Earth Escape to 4 million kilometers
  - Rp ~ 4.5E4 km, Δv ~ 4.19 km/s, e ~ 0.98, Ra ~ 4E6 km, time of flight ~ 166 days
- Enter Lunar Manifold, target lunar periapsis ~ 500 km
  - Δv ~ 0.012 km/s
  - Achieves plane change at the Moon, desired lunar inclination, other lunar arrival conditions
- Enter lunar elliptical orbit, 500 x 40000 km
  - Δv ~ 0.0 km/s
  - Ballistic capture into highly elliptical orbit with NO delta-v
  - Ballistic capture region is called a Weak Stability Boundary
  - (See references)
- Lunar Manifold trajectory passes near Earth-Sun L2 on a halo orbit
  - Approaches on W+(L2) stable manifold, departs on W-(L2) unstable manifold
- Lunar orbit apoapsis reduction, 500 x 40000 km to 500 x 10000 km
  - Δv ~ 0.118 km/s, total time of flight ~ 315 days

Lunar Orbit Manifold



Weak Stability Boundary and Lunar Manifold
References

1. Belbruno, E. , *Capture Dynamics and Chaotic Motions in Celestial Mechanics*, Princeton University Press, 2005.

2. Belbruno, E., A New Class of Low Energy Lunar Orbits and Mission Applications, *New Trends in Astrodynamics and Applications III*, Volume 886, American Institute of Physics, pp 3-19, 2007.

3. Belbruno, E.; Gidea, M.; Topputo, F., Weak Stability Boundary and Manifolds, *SIAM J. Appl. Dyn. Sys.*, Vol. 9, No. 2, pp 1061-1089, 2010.

Team Alpha CubeSat: Approximate Δv in Cis-Lunar Space

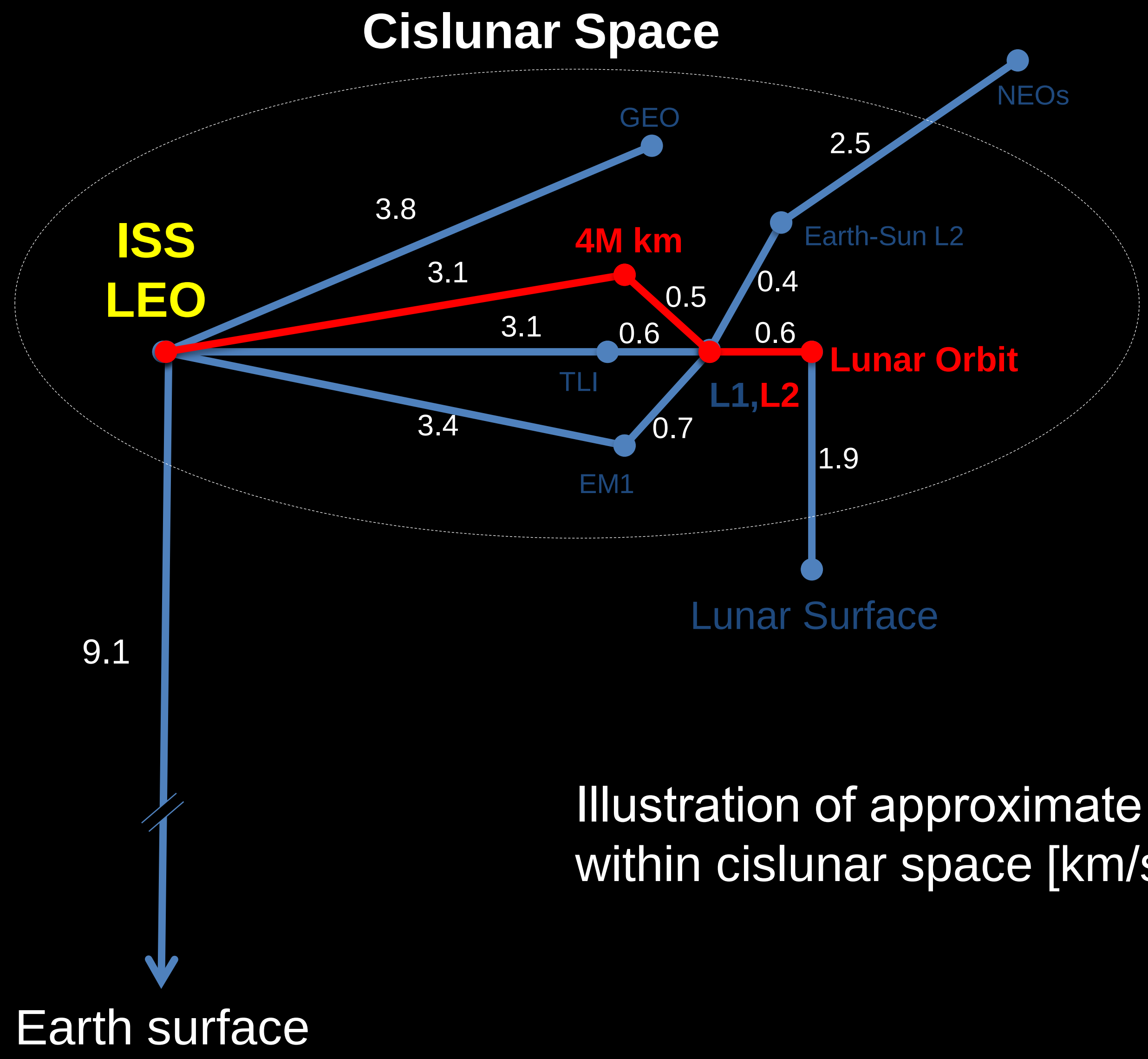
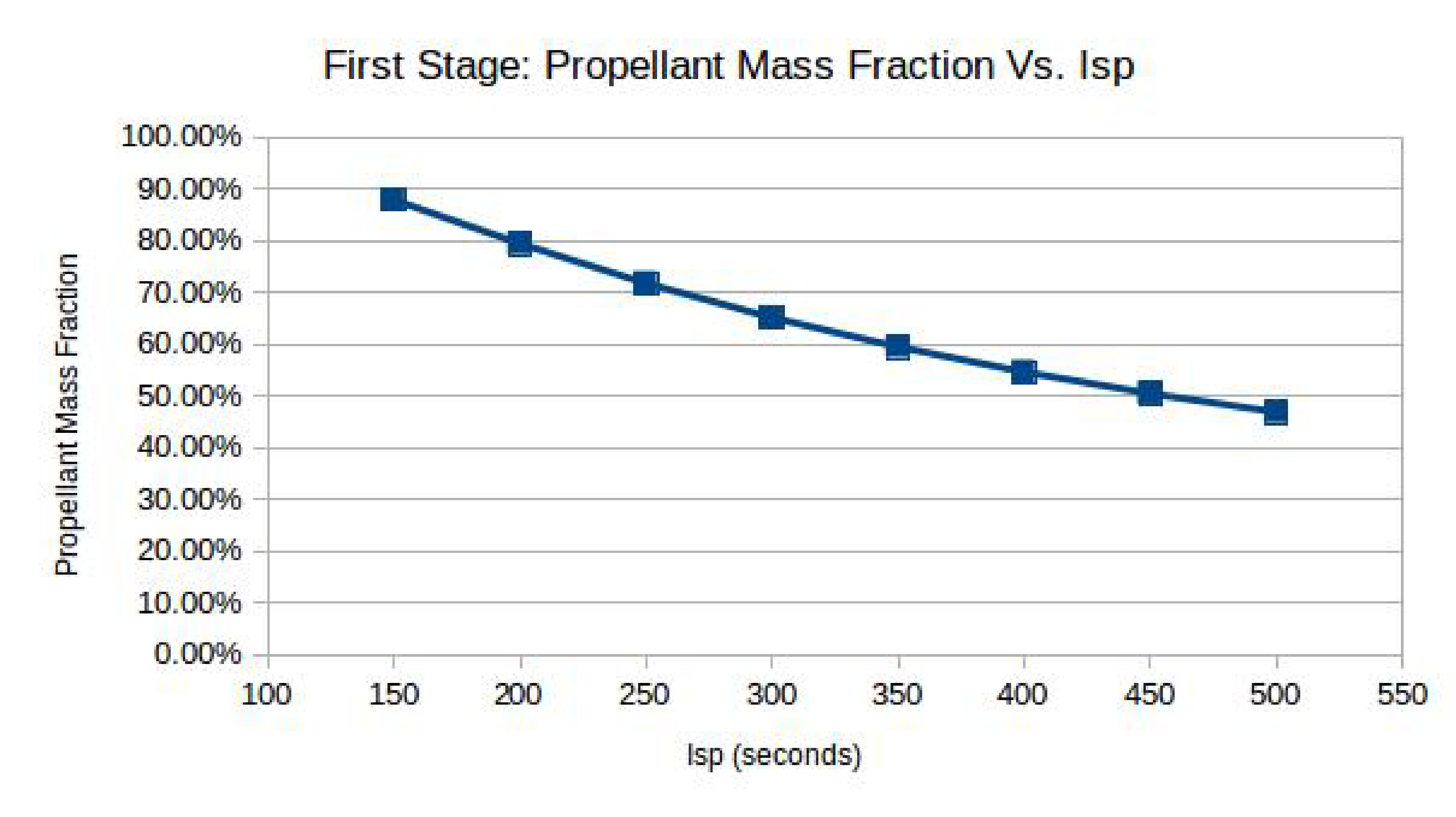
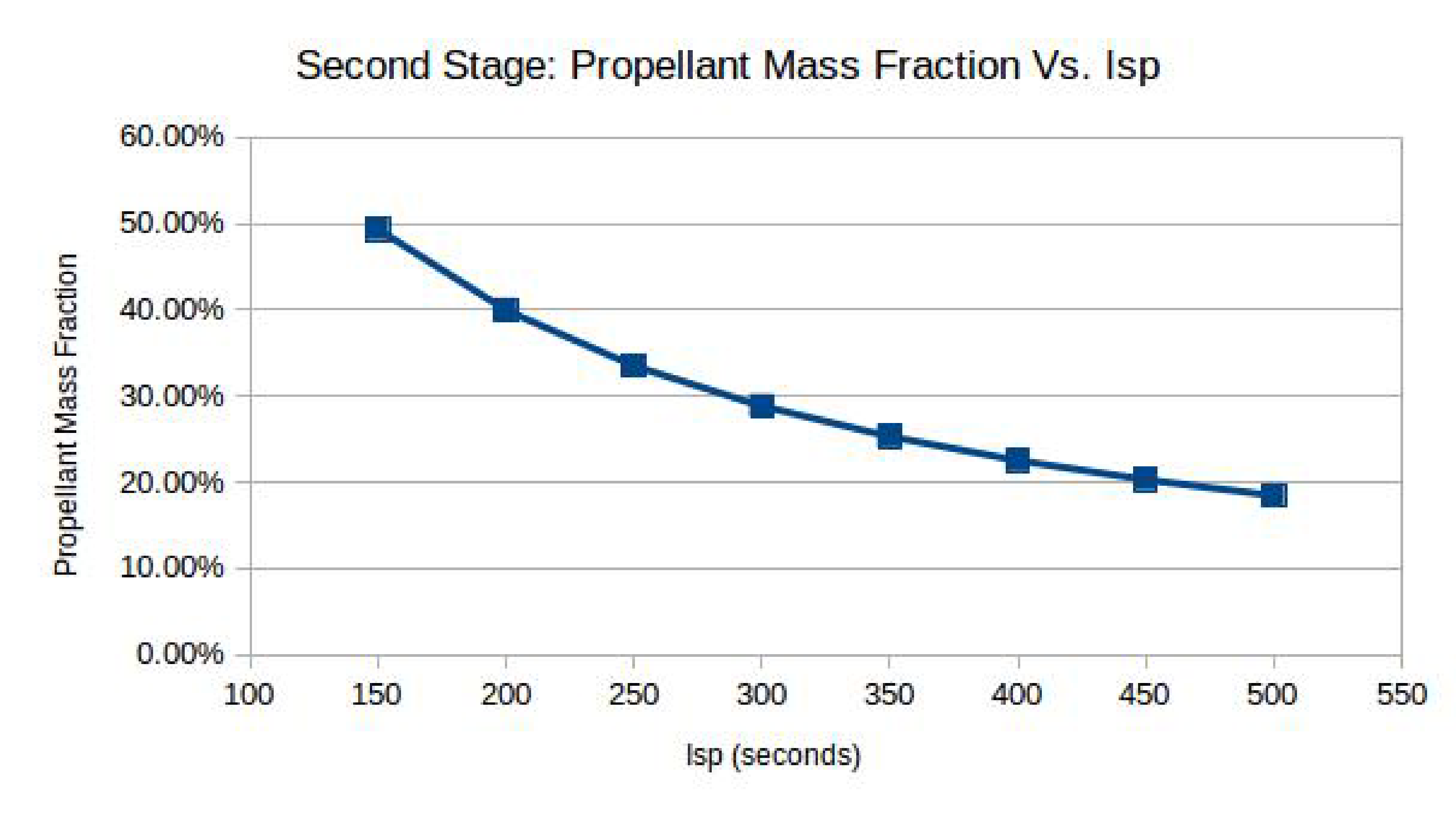


Illustration of approximate Δv within cislunar space [km/s]

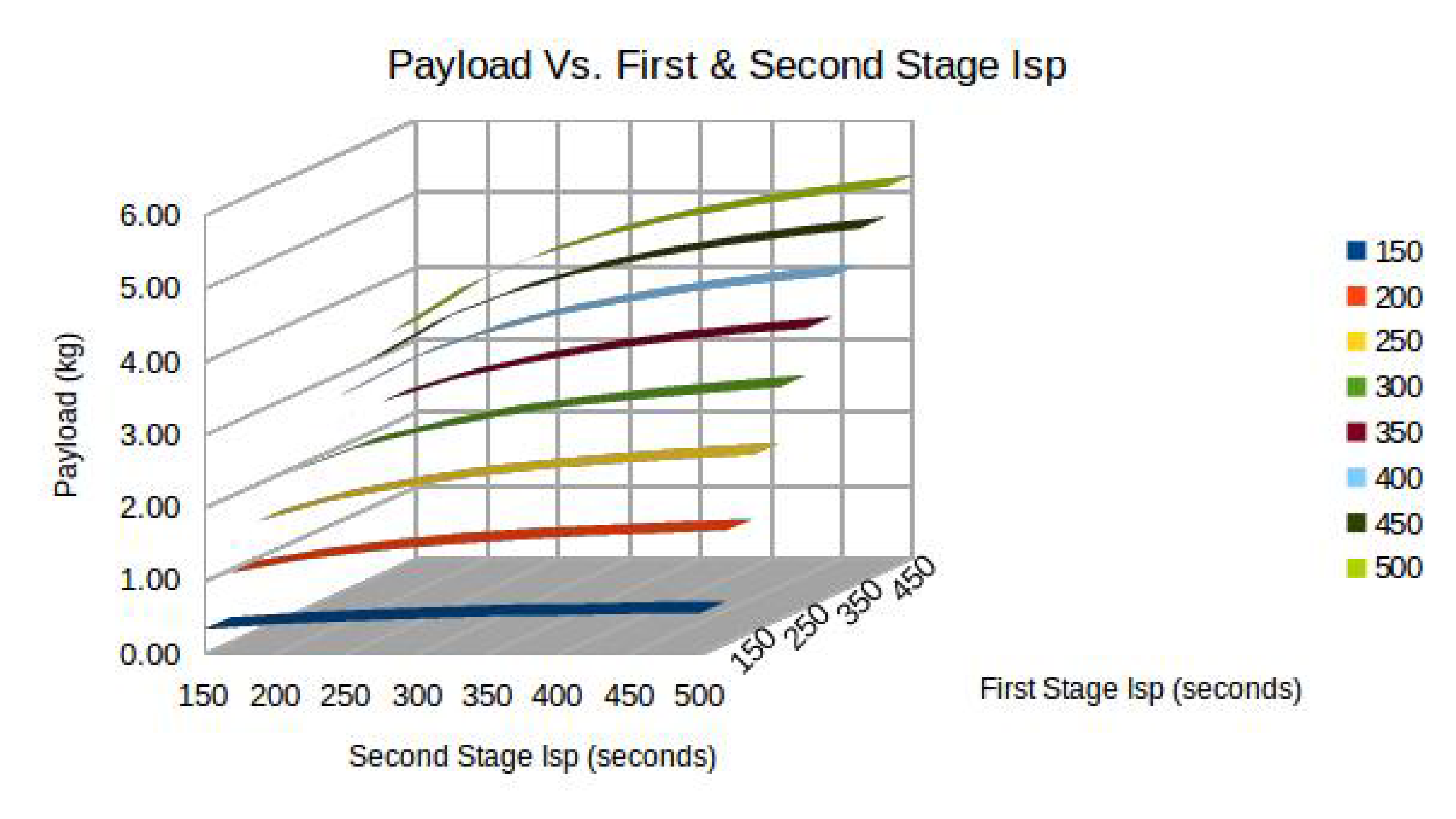
Propulsion Backup - 1



Propulsion Backup - 2

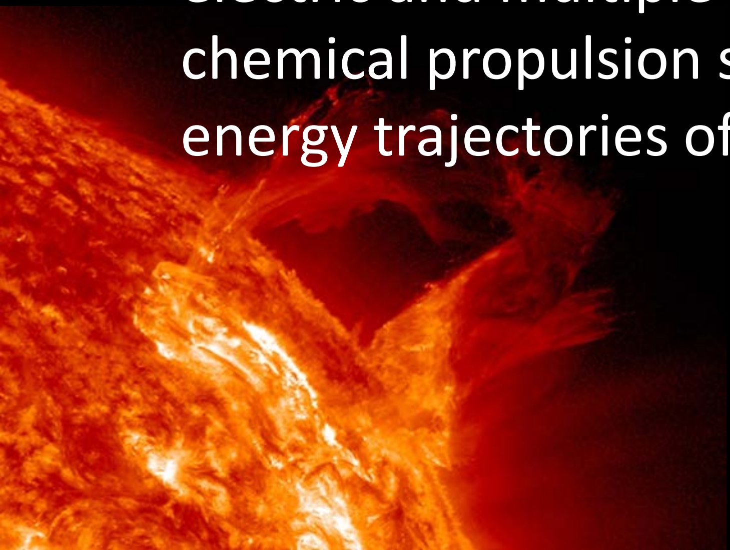


Propulsion Backup - 3



Team Alpha CubeSat: Propulsion Considerations

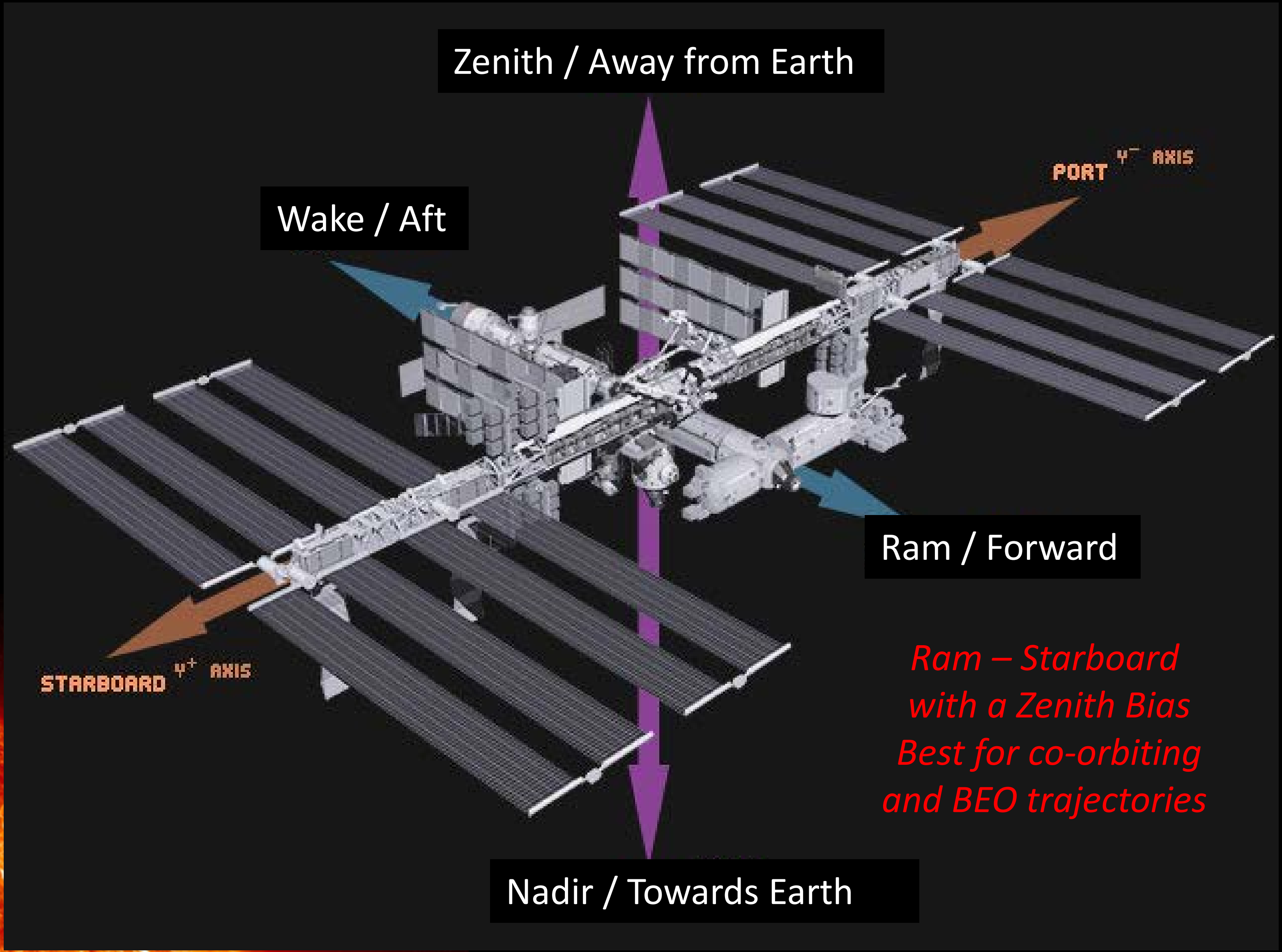
- Current propulsion analysis shows that the second order trajectory is tractable.
- The use of Weak Stability Boundaries and ballistic escape and capture trajectories take advantage of Sun-Earth and potentially Earth-Moon Libration Points to achieve trajectories and orbits of interest, radically reduces the delta V requirements.
- Using a combination of long-term low-thrust, high-I_sp electric and multiple impulse high-thrust, low-I_sp chemical propulsion systems and the alternate minimum energy trajectories offers new mission opportunities.



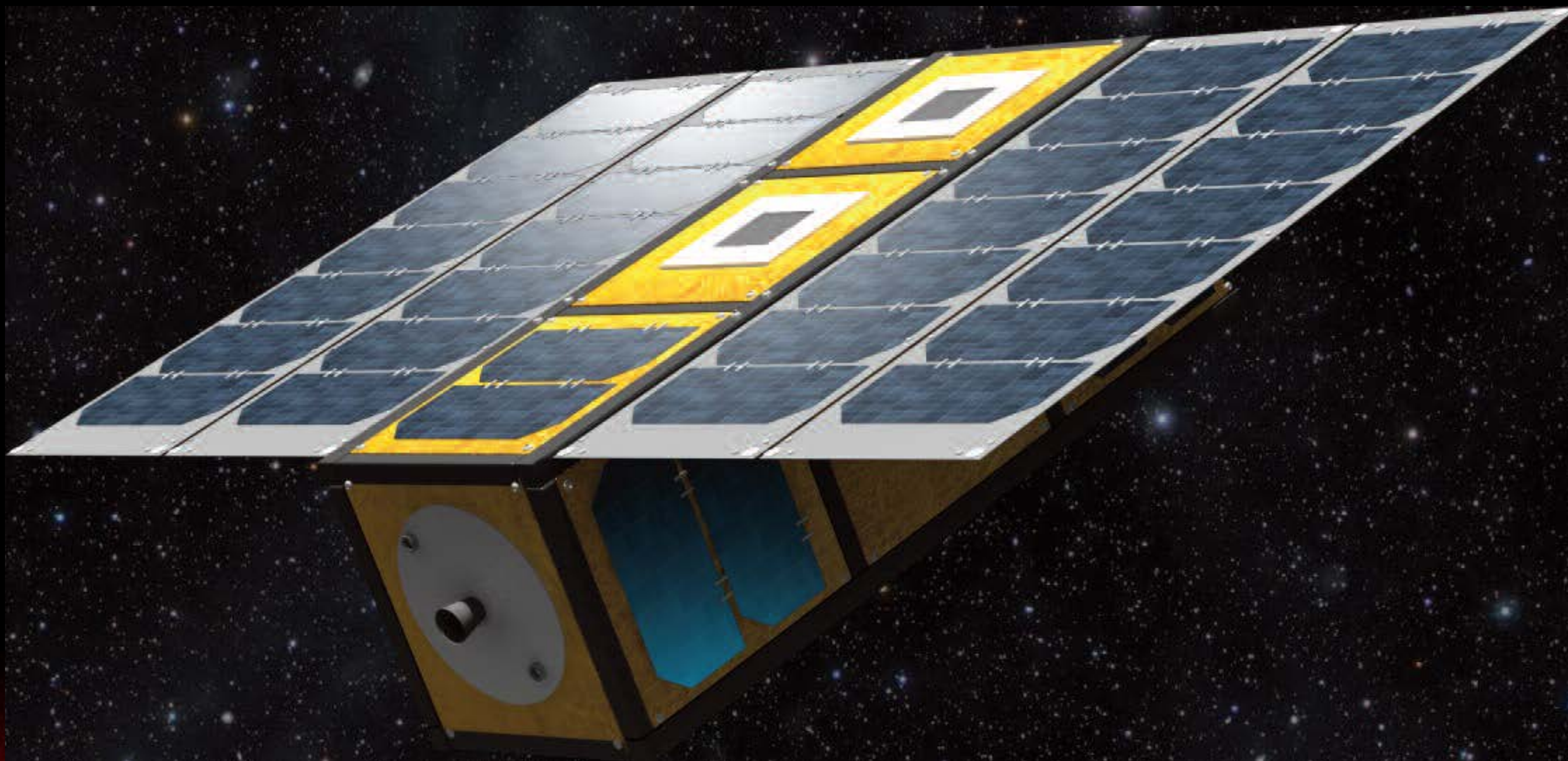
ISS as a Launch Platform - 1

- Commercial Cargo Pressurized “Softpack” launch & stow
  - IVA unpack & final assembly
  - CYCLOPS JEM Airlock IVA → EVR Transition
  - EVR handoff to Mobile Servicing Centre (MSC)
- Commercial Cargo Unpressurized Cargo launch & stow
  - EVR unpack & final assembly
  - EVR handoff to Mobile Servicing Centre (MSC)
- Support services
  - EVR MSC relocate & position for deployment
  - MSC SPDM Deployment RAM + Starboard + Zenith Bias
  - Final proximity checkout services (e.g., imaging, communications, navigation & power)
  - Optimized access to alternative minimum energy trajectories
  - Single & Multi-use Trajectory Insertion Buses
  - Opportunities for Low Cost Earth Applications, Space Operations, and Space Exploration Missions

ISS as a Launch Platform - 2

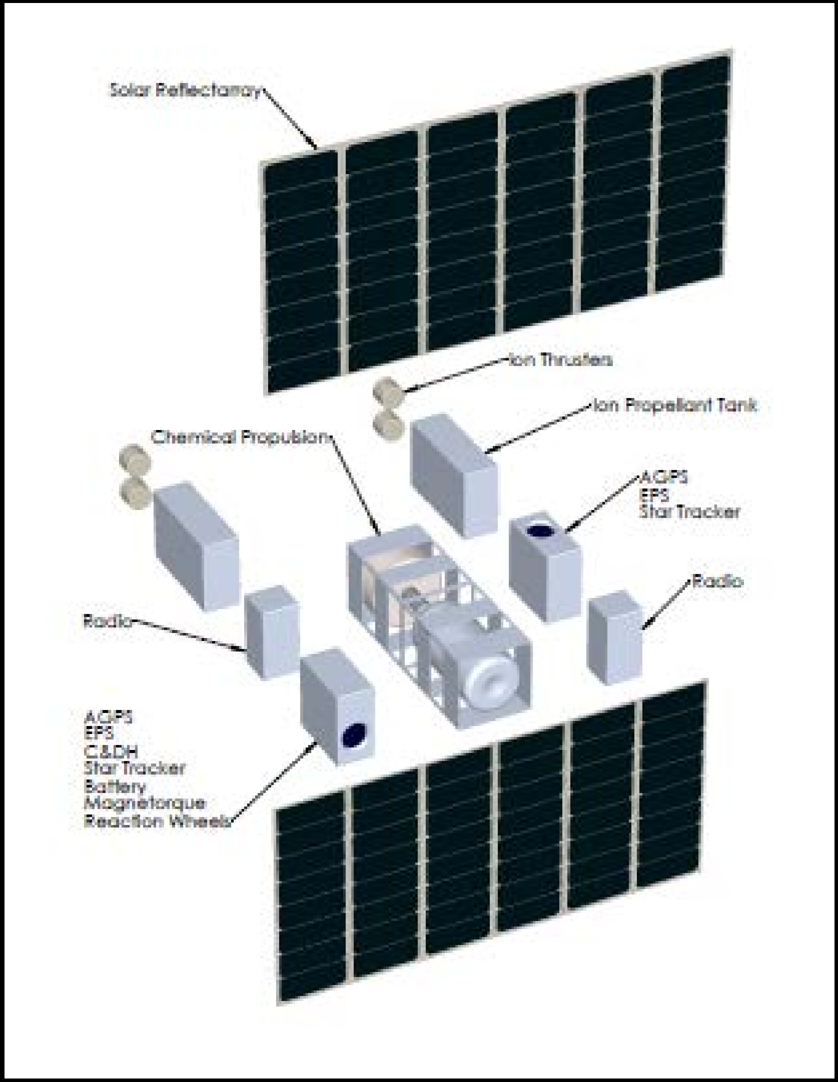


XISP-Inc/DSI 3U SSPB Flight Test Article Concept*



* Shown with DSI COMET-1 Water Thruster Integrated. Flight articles used will incorporate Reflectarray Rectennas (combination solar/receive & transmit antennas).

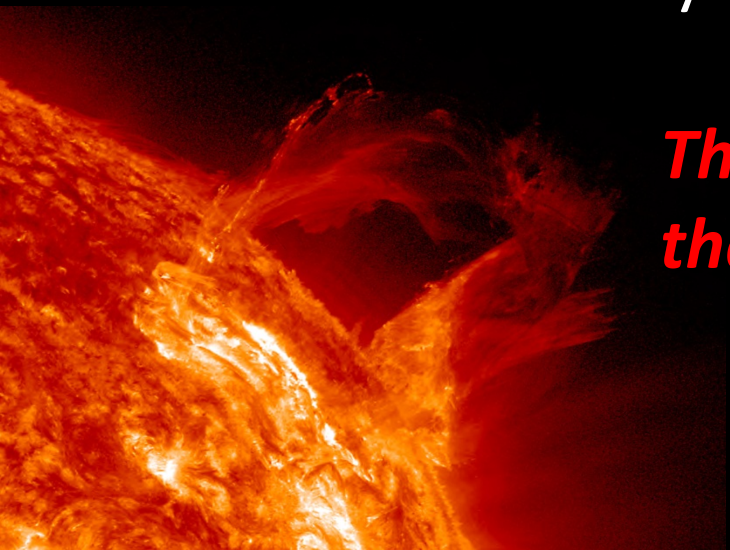
Alpha CubeSat Derived Flight Test Articles*



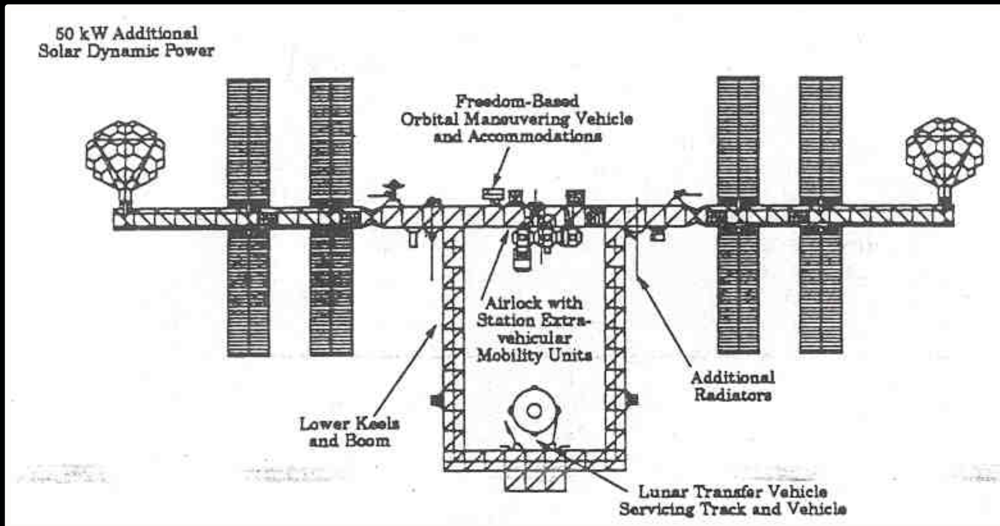
* Alternate 6U flight test article concept derived from NASA CubeQuest Challenge Team Alpha CubeSat design

Conclusion

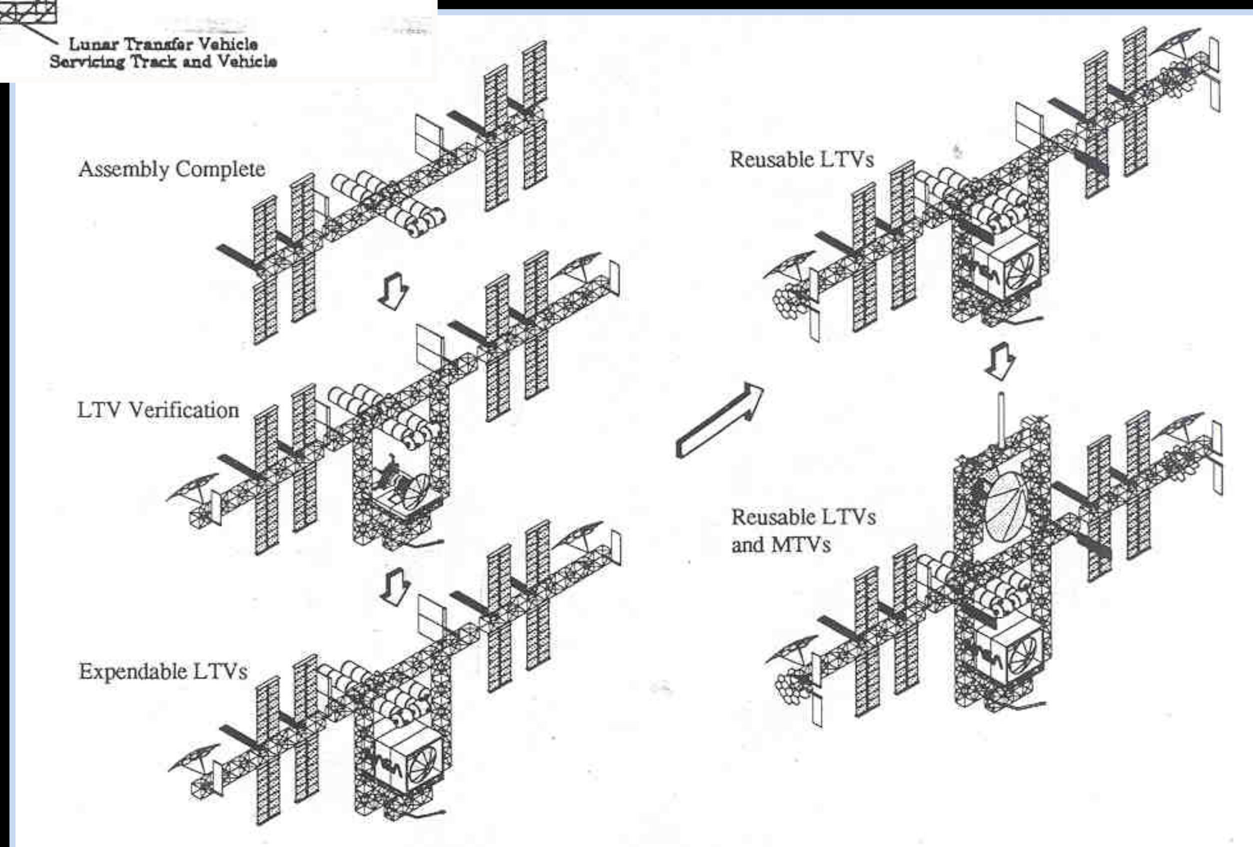
- Multiple solutions exist for ISS launch in theory, in practice we need to test & optimize alternatives
- We need to learn how to scale to larger systems
- We need to create opportunities for collaboration
- We need to find ways to do more with less resources
- On-orbit final assembly and checkout needs to be move from theory to practice



This is a new way of doing business, that we need to learn to leverage . . .



Plans for Space Station Freedom to evolve to become an exploration transportation node (1992)

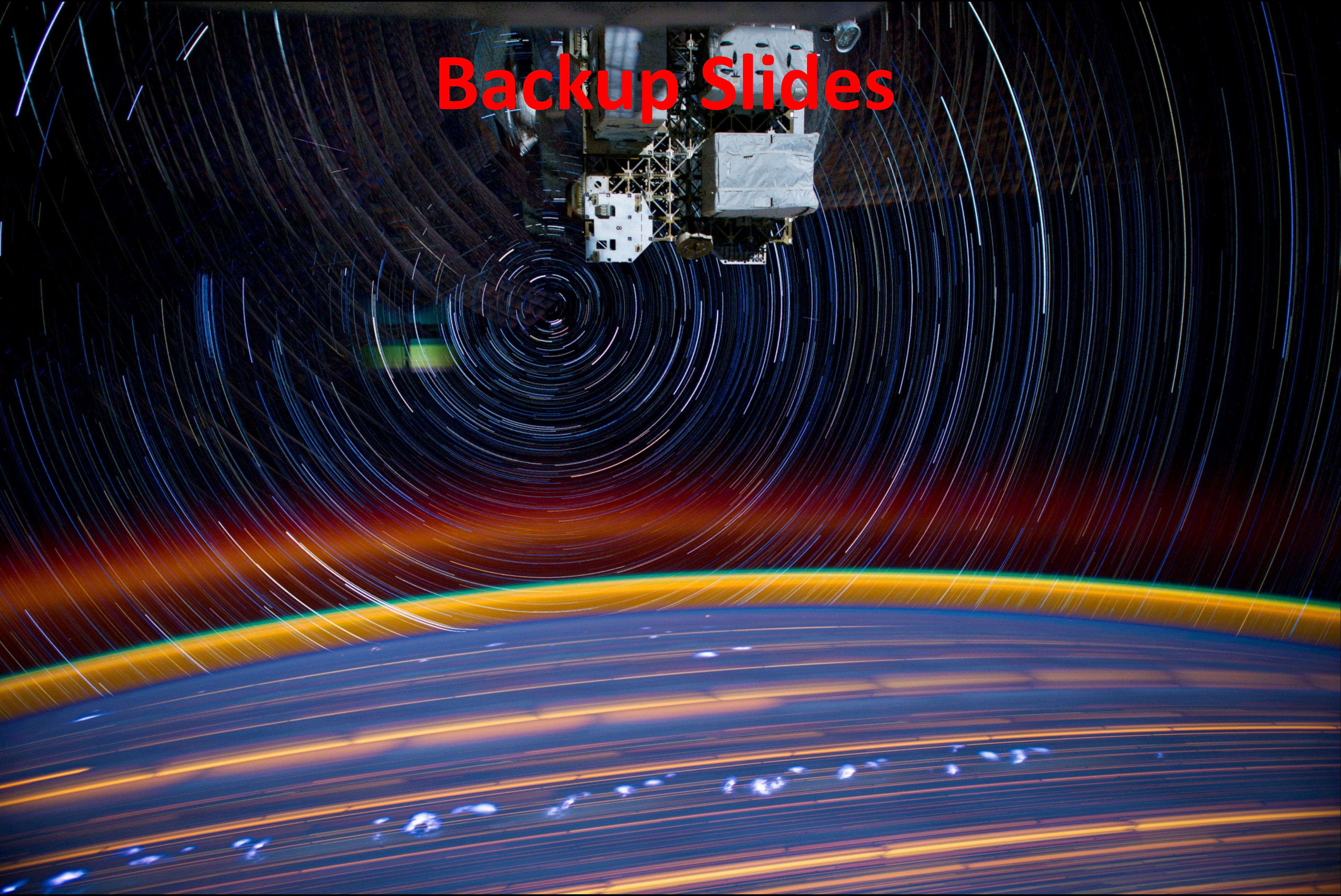


Next Steps

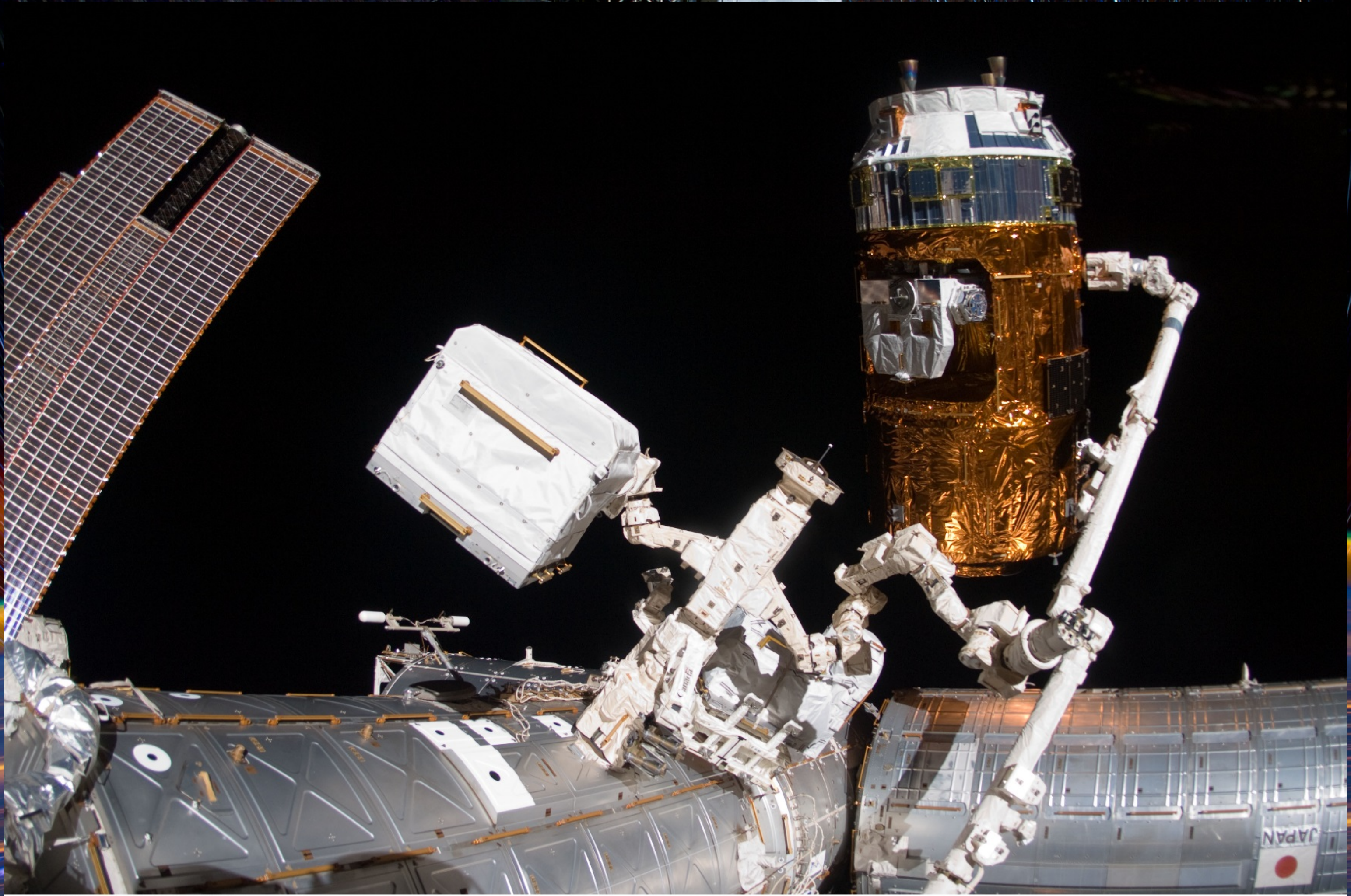
- Design and implement a propulsion testbed environment for ISS
  - Testbed will provide the common infrastructure required
- Safety protocols required for each mission stage must be defined
  - Experiments need a known path to flight
- Each experiment will start with the defined operations and safety protocols augmented as needed based on any mission unique aspects added
- The possibilities for final assembly and checkout support need to be actualized by meeting real mission requirements

"Once you're in low Earth orbit halfway to anywhere."
– Robert Heinlein

Backup Slides



Dextre & Space Station Remote Manipulator System (SSRMS)



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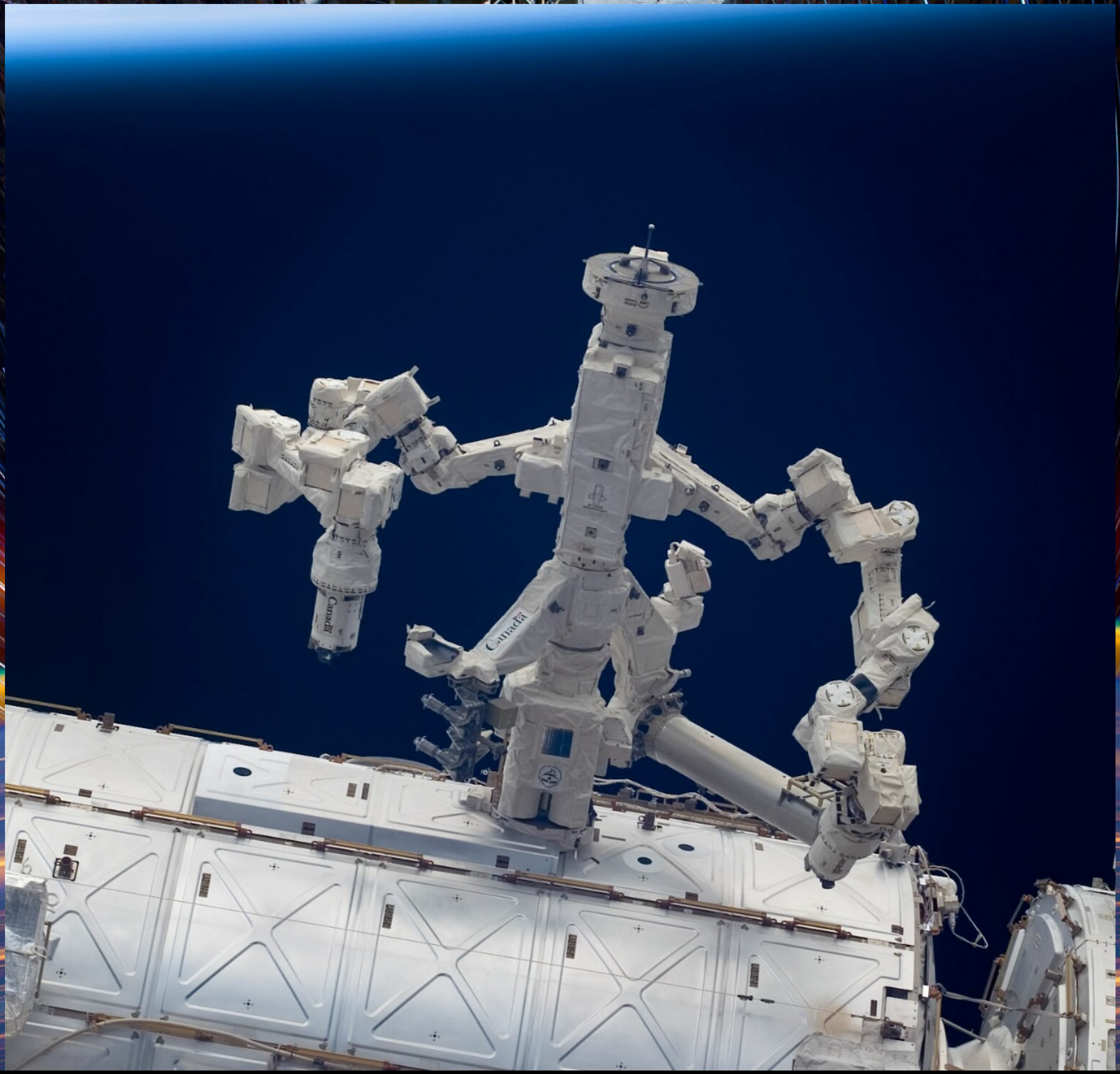
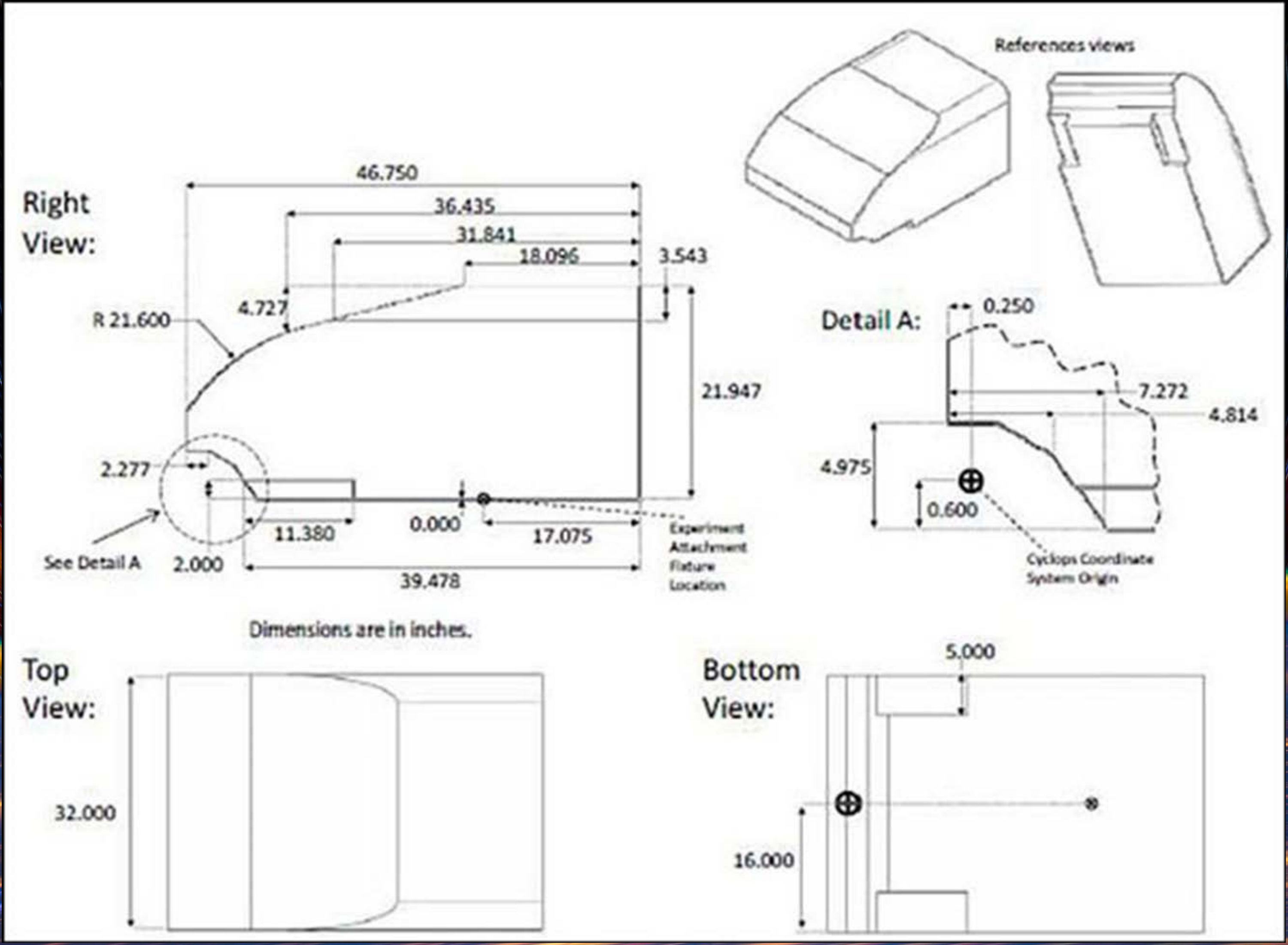
Dextre – Special Purpose Dexterous Manipulator



CYCLOPS JEM Airlock IVA-EVR Transition



Common Trajectories by the Numbers