# ERWG Data Collection NASA's Inputs

ISECG Workshop

Montreal

March 25, 2010

# Agenda

| | |
|---|---|
| • Mars Design Reference Architecture 5.0 | Bret Drake/<br>Lee Graham |
| • Robotic Precursors targeting Near Earth Objects<br>for Human Exploration | Rob Landis |
| • Notional Human Exploration of Near Earth Objects | Bret Drake/<br>Lee Graham |
| • Low Earth Orbit Refueling to Augment Human Exploration | Andy Thomas/<br>Pat Troutman/<br>Chris Culbert |

# Human Exploration of Mars Design Reference Architecture 5.0
# (NASA Mars Architecture Study – 2007)

## Bret Drake/Lee Graham

# Mission Scenario Information, Mars DRA 5.0

| | | |
|---|---|---|
| **Mission Scenario** | **Primary** | **Secondary** |
| | M6 | M8, M9 |
| **Reference** | Human Exploration of Mars Design Reference Architecture (DRA) 5.0 (NASA Mars Architecture Study - 2007) http://www.nasa.gov/exploration/library/esmd_documents.html | |
| **Destination** | Mars Surface | |
| **Estimated Date** | No earlier than 2030 | |
| **Objectives/Goals** | See subsequent slides | |
| **Mission Operational Drivers** | See subsequent slides | |
| **Key Technology Needs** | See subsequent slides | |
| **Key Capability Needs** | See subsequent slides | |
| **Mission Profile** | See subsequent slides | |

# Mars DRA 5.0 Objectives/Goals, p 1 of 4

The following goals and objectives were extracted from the DRA 5.0 documentation. Many of these have been, or are currently being updated, and thus they should be used for reference purposes only to provide context for the 2007 study.

| Theme | Exploration Objective |
|---|---|
| **Goal I:** Life | Assess past and present habitability potential of Mars |
| | Characterize carbon cycling in its geochemical context (including its origin and distribution) |
| | Test for life (identify and determine the spatial distribution of biosignatures) |
| **Goal II:** Climate | Characterize the atmosphere and present climate and processes |
| | Characterize Mars' ancient climate and climate processes |
| | Atmospheric state and processes of critical importance for the save operation of spacecraft |
| **Goal III:** Geology | Determine the nature and evolution of the geologic processes that have created and modified the martian crust and surface |
| | Characterize the structure, composition, dynamics, and evolution of the martian interior |
| **Goal IV:** Preparation | Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk, and performance |
| | Conduct risk and / or cost reduction technology and infrastructure demonstrations in transit to, at, or on the surface of Mars |
| **Goal IV+:** Preparation for sustained human presence | Demonstration of Mars human habitability, exploration systems development, and long-duration space mission operations for missions beyond the first three. |
| **Goal V:** Ancillary | Understanding the fundamental processes that control Mars' space environment |
| | Understanding the influence of planetary magnetic fields |
| | Maximizing safety and productivity of human explorers |

# Mars DRA 5.0 Objectives/Goals, p 2 of 4

The following goals and objectives were extracted from the DRA 5.0 documentation. Many of these have been, or are currently being updated, and thus they should be used for reference purposes only to provide context for the 2007 study.

| Theme | Exploration Objective |
|---|---|
| **Geologic:** Determine the nature and evolution of the geologic processes that have created and modified the martian crust and surface | 1. Determine the present state, three-dimensional distribution, and cycling of water on Mars. |
| | 2. Evaluate fluvial, subaqueous, pyroclastic, subaerial, and other sedimentary processes and their evolution and distribution through time, up to and including the present. |
| | 3. Calibrate the cratering record and absolute ages for Mars. |
| | 4. Evaluate igneous processes and their evolution through time, including the present. |
| | 5. Characterize surface-atmosphere interactions on Mars, including polar, Aeolian, chemical, weathering, mass-wasting, and other processes. |
| | 6. Determine the large-scale vertical structure and chemical and mineralogical composition of the crust and its regional variations; this includes, for example, the structure and origin of hemispheric dichotomy. |
| | 7. Document the tectonic history of the martian crust, including present activity. |
| | 8. Evaluate the distribution and intensity of hydrothermal processes through time, up to and including the present. |
| | 9. Determine the processes of regolith formation and subsequent modification, including weathering and diagenetic processes. |
| | 10. Determine the nature of crustal magnetization and its origin. |
| | 11. Evaluate the effect of impacts on the evolution of the martian crust. |
| **Geophysics:** Planetary Scale | 1. Characterize the structure and dynamics of the interior. |
| | 2. Determine the origin and history of the magnetic field. |
| | 3. Determine the chemical and thermal evolution of the planet. |

# Mars DRA 5.0 Objectives/Goals, p 3 of 4

The following goals and objectives were extracted from the DRA 5.0 documentation. Many of these have been, or are currently being updated, and thus they should be used for reference purposes only to provide context for the 2007 study.

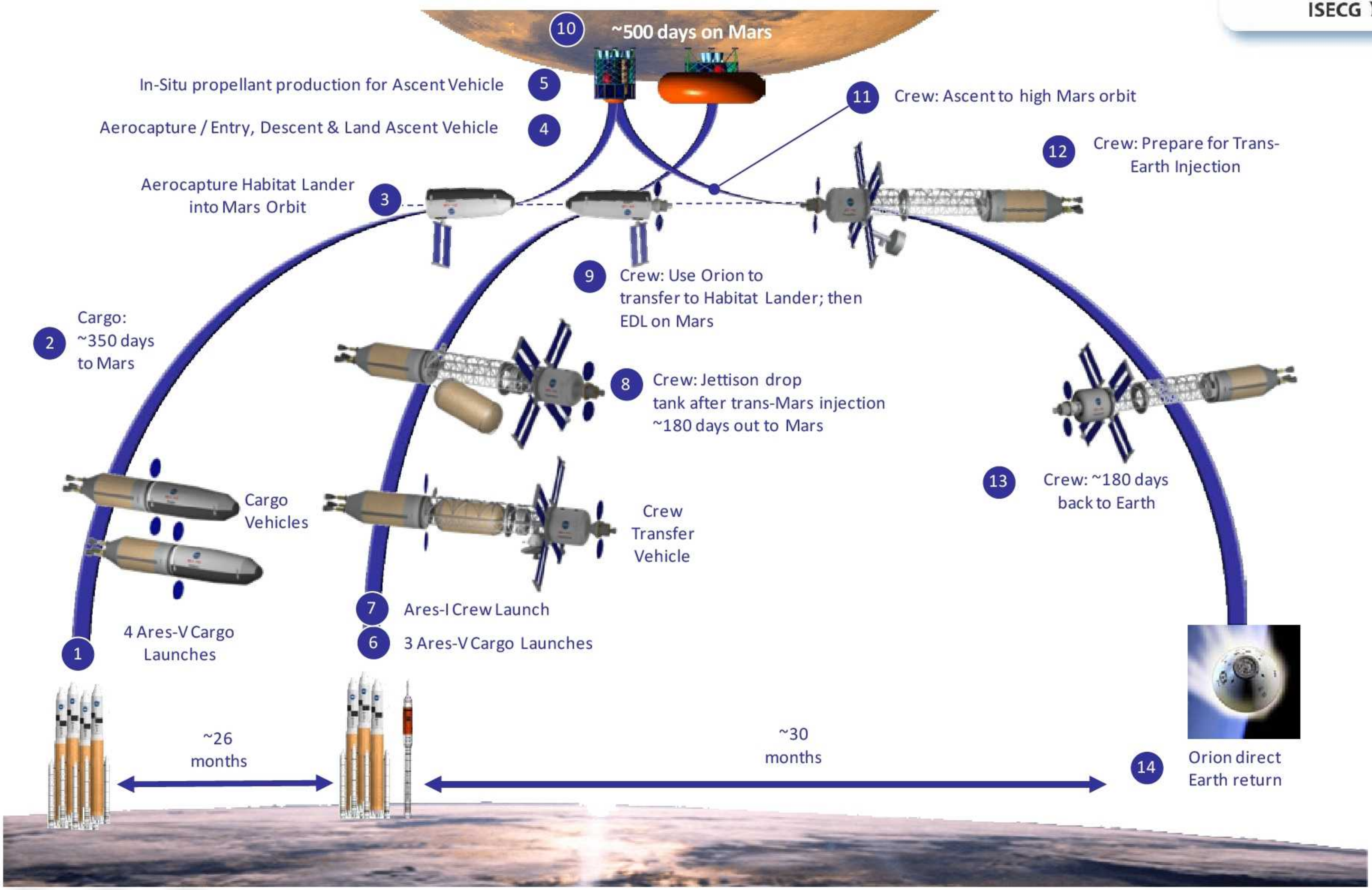
| Theme | Exploration Objective |
|---|---|
| **Geophysics:** Local Scale | 1. Evaluate fluvial, subaqueous, pyroclastic, subaerial, and other sedimentary processes and their evolution and distribution through time, up to and including the present. |
| | 2. Characterize the composition and dynamics of the polar layered deposits. |
| | 3. Evaluate igneous processes and their evolution through time. |
| | 4. Characterize surface-atmosphere interactions on Mars, including polar, aeolian, chemical, weathering, mass-wasting, and other processes. |
| | 5. Determine the large-scale vertical and horizontal structure and chemical and mineralogical composition of the crust. This includes, for example, the structure and origin of hemispheric dichotomy. |
| | 6. Determine the present state, three-dimensional distribution, and cycling of water on Mars. |
| | 7. Document the tectonic history of the martian crust, including present activity. |
| | 8. Evaluate the distribution and intensity of hydrothermal processes through time, up to and including the present. |
| | 9. Determine the processes of regolith formation and subsequent modification, including weathering and diagenetic processes. |
| | 10. Determine the nature of crustal magnetization and its origin. |
| | 11. Evaluate the effect of impacts on the evolution of the martian crust. |

# Mars DRA 5.0 Objectives/Goals, p 4 of 4

The following goals and objectives were extracted from the DRA 5.0 documentation. Many of these have been, or are currently being updated, and thus they should be used for reference purposes only to provide context for the 2007 study.

| Theme | Exploration Objective |
|---|---|
| **Atmosphere and Climate:** | Surface-atmosphere interactions: dynamics, heat and mass balance, non-equilibrium trace gases |
| | Search for sources of volatiles and trace gases |
| | Baseline chronology and characterization of the climate history of the north polar dome (deep core) |
| | Horizontal sampling of the North Polar Layered Deposits (NPLD) |
| | Long-term climatic evolution of the planet (billion-year temporal scale); implications of early climatic conditions in the emergence of early potential habitats and/or life, which includes inference in the atmosphere chemical state |
| | Sampling of Noachian to Amazonian deposits through soft drilling (~1 meter deep) along outcrops, or deep drilling to capture information in the sedimentary record |
| **Deep Drilling** | Deep core and baseline chronology and characterization of major climatic events in past 5 million years |
| | Polar cap mass and energy balance for current climate state and seasonal cap formation processes |
| | Shallow cores to investigate heterogeneity |
| | Emplacement of geophysical sensors |

# Mars DRA 5.0 Mission Profile



# Mars DRA 5.0 Innovation Requirements, p 1 of 3

| | Functional Capability | Elements | Innovation Requirement | | |
|---|---|---|---|---|---|
| | | | **Critical** | **Important** | **Desirable** |
| | **Crew Transportation** | • Heavy lift launch (x3)<br>• Crew launch (x1)<br>• In-space propulsion<br>• Earth return capsule<br>• Mars habitat lander<br>• Mars descent / ascent vehicle | • Nuclear Thermal Propulsion or advanced chemical<br>• Zero-boiloff cryo fluid management<br>• High-speed (12 km/s) Earth entry<br>• Automated rendezvous and docking (Low Earth Orbit)<br>• Entry, Descent and Landing of large payloads<br>• Methane lander propulsion<br>• ISRU Propellants | | |
| | **Cargo Transportation** | • Heavy lift launch (x4)<br>• In-space propulsion | • Nuclear Thermal Propulsion or advanced chemical/ aerocapture<br>• Zero-boiloff cryo fluid management<br>• Automated rendezvous and docking (Low Earth Orbit)<br>• Entry, Descent and Landing of large payloads<br>• Methane lander propulsion | | |
| | **In-space Habitation** | • In-space habitat to support 6 crew for 400 days (nominal) + 500 days (contingency) | • Radiation protection<br>• Closed-loop life support | | |

# Mars DRA 5.0 Innovation Requirements, p 2 of 3

| | Functional Capability | Elements | Innovation Requirement | | |
|---|---|---|---|---|---|
| | | | Critical | Important | Desirable |
| | On-surface Habitation | • Surface habitat to support 6 crew for 540 days | • Inflatable modules<br>• Radiation protection<br>• Closed-loop life support | | |
| | Extra Vehicular Activity | • Surface suit | • Dust mitigation | | |
| | In-space Power | • Solar arrays | | | |
| | On-surface Power | • Fission Power System | • Nuclear fission<br>• Robotic emplacement | | |
| | Surface Mobility | • Pressurized rovers for 100-500 km range | • Lightweight<br>• Low maintenance | | |
| | Servicing | | • Advanced maintenance and repair | | |
| | ISRU | • Locally produced propellants (oxygen) and crew consumables<br>• ISRU integrated with ascent vehicle | • Oxygen extraction from the atmosphere<br>• Generation of oxygen, water, and buffer gases | | |

# Mars DRA 5.0 Innovation Requirements, p 3 of 3

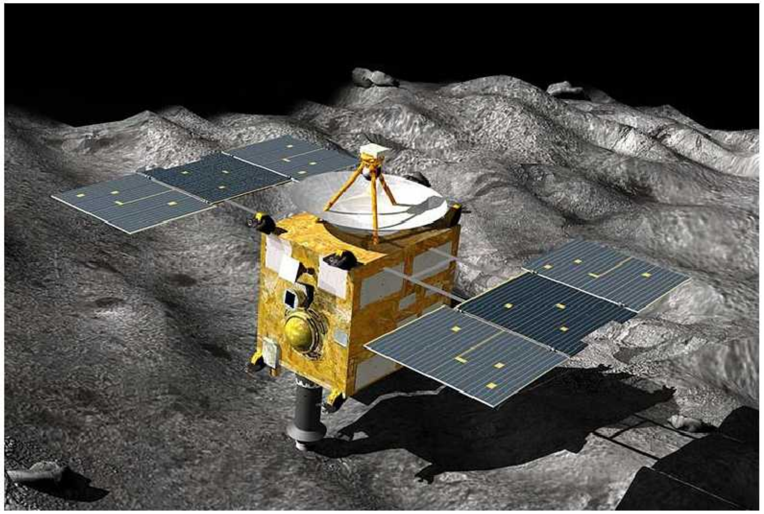
| | Functional Capability | Elements | Innovation Requirement | | |
|---|---|---|---|---|---|
| | | | **Critical** | **Important** | **Desirable** |
| | **Communication & Navigation** | | | | |
| | **Human Health & Performance** | | • Zero-gravity countermeasures for 180 day transits<br>• Partial-gravity countermeasures for 540 days<br>• Radiation protection<br>• Advanced medical care | | |

# Key Risks and Challenges for Humans to Mars

- Launch Campaign
  - 7+ Heavy Lift Launches within 26-month Mars injection opportunity (800 – 1,200 t total mass in Low Earth Orbit)
  - Large payload volume
- Entry Descent and Landing
  - The ability to land large (40 t) payloads on the surface of Mars. Current limit is ~ 2 t
- Human Support
  - Radiation protection (400 days deep space, 500 days on Mars)
  - Hypo-gravity (Mars surface) countermeasures
  - Reliable closed-loop life support (air and water)
- In-Situ Resource Utilization
  - Generation and use of oxygen produced from the atmosphere
- System Reliability, Maintenance, and Supportability
  - Lack of logistics and just-in-time supply necessitates highly reliable, maintainable systems
- Advanced In-space Propulsion
  - Nuclear Propulsion Thermal Propulsion
  - Advanced chemical with Aerocapture at Mars
  - Zero-boiloff cryogenic storage of hydrogen, oxygen, and methane
  - $LO_2/CH_4$ propulsion for descent and ascent
- Surface Nuclear Power
  - 40 kWe continuous power with demonstrated long-life reliability
- Mobility and Exploration
  - 100+ km roving range
  - Light-weight, dexterous, maintainable EVA
  - In-situ laboratory analysis capabilities

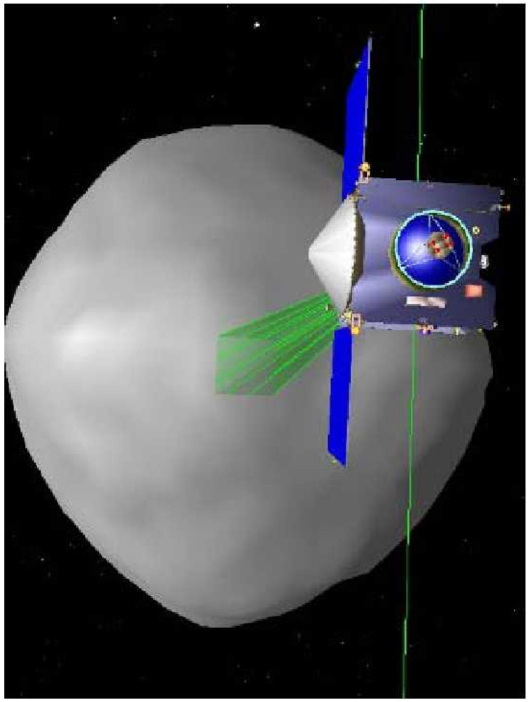
# Robotic Precursor Missions Targeting NEOs for Human Exploration

Rob Landis
(and the NASA NEO Team from JSC, GSFC, LaRC, ARC, HQ, JPL)



*Hayabusa*

*Philae* lander



*OSIRIS REx*

# Robotic Precursors to NEOs

| | Primary | Secondary |
|---|---|---|
| **Mission Scenario** | NEO reconnaissance | Science |
| **Reference** | See previous page | |
| **Destination** | Human accessible NEOs | |
| **Estimated Date** | No earlier than 2013 | |
| **Objectives/Goals** | Further characterization of NEO; obtain basic reconnaissance [see subsequent slides] | |
| **Mission Operational Drivers** | Assess surface for future activities to be conducted by human crew (improve mission ops efficiency for piloted mission) | |
| **Key Technology Needs** | Automated proximity ops and rendezvous flight techniques | |
| **Key Capability Needs** | Launch vehicle (EELV, Proton M + Briz M, H2-A, Ariane 5, Soyuz FG, Falcon 9) and necessary deep space delta v ($\Delta v$) | |
| **Mission Profile** | Launch from Earth → direct TNI burn to NEO. | |

# Robotic Precursors to NEOs: Objectives/Goals

| Theme | Exploration Objective |
|---|---|
| **Goal I:** Basic Reconnaissance | Additional characterization of NEO prior to human mission |
| | Obtain basic recon that may pose hazard to spacecraft & crew (i.e., binary bodies, non-benign surface morphologies, rapid rotators and non-primary axis rotators, gravitational field structure, shape model, mass/density estimates, general mineral composition, etc.) |
| | Assess the surface for future activities to be conducted by crew to maximize surface operations (i.e., proximity ops, surface ops, and macroscopic sample collection by crew). |
| **Goal II:** Piloted mission operations support | Aid in the navigation of the crewed vehicle stack to the NEO. |
| | Provide additional data coverage while crew is operating to/from and at the surface of the NEO (akin to the port and starboard cameras on the ISS truss during shuttle-ISS EVAs). |
| | Monitor NEO over time after crew departs; relay data from surface instruments left behind by the crew. |
| **Goal III:** Science | Determine nature, origin, evolution, and collisional processes of the target NEO. |
| | Characterize the structure, composition, dynamics, and evolution of the NEO's interior (some are rubble piles while others may be coherent monoliths or metallic or combinations there of). |
| **Goal IV:** Preparation | Obtain knowledge of a variety of NEOs sufficient to design and implement a human mission with acceptable cost, risk, and performance |
| | Reduce risk for other asteroid robotic missions (i.e., *OSIRIS REx*, *Hayabusa 2*, etc.) |
| **Goal V:** Ancillary | Applicability to other robotic (and eventual human) small body exploration (i.e., NEOs that also cross Mars' orbit, Main Belt asteroids and beyond). |
| | Understanding of the fundamental processes of planet-building in our Solar System |
| | Extensive (and proper) mapping of the meteorite record to parent NEO (and Main Belt) bodies |
| | Planetary defense |

# Robotic Precursors to NEOs: Ground-Based Observations

## Radar Study of Shape, Size, Motion & Mass of 1999 $KW_4$

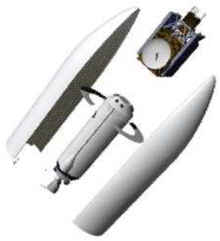
~2-km primary body losing material to a ½-km moonlet.
Rotation rate of primary body ~2.5 hours.

70-m Goldstone Antenna

305-m Arecibo Observatory

# Robotic Precursors to NEOs: Mission Profile

3 Cruise phase (1 to 24 months, depending on target NEO)



4 Operations and reconnoiter of NEO (1 – 3+ years)

- No new technology requirements
- Refinement of current capabilities
- NEO campaigns could begin as early as 2013
- Remarkable opportunities for int'l engagement
- The 'Big 6' currently include:

| | |
|---|---|
| - 1998 $HG_{49}$* | [143 m] |
| - 2001 $BB_{16}$ | [104 m] |
| - 2003 $SM_{84}$ | [100 m] |
| - 2000 $AE_{205}$ | [ 90 m] |
| - 2001 $QJ_{142}$ | [ 72 m] |
| - 2009 $OS_5$ | [ 70 m] |
| - 1999 $AO_{10}$ | [ 60 m] |

2 Shortly after launch - critical deployments; Direct to TNI

1 Launch from Earth

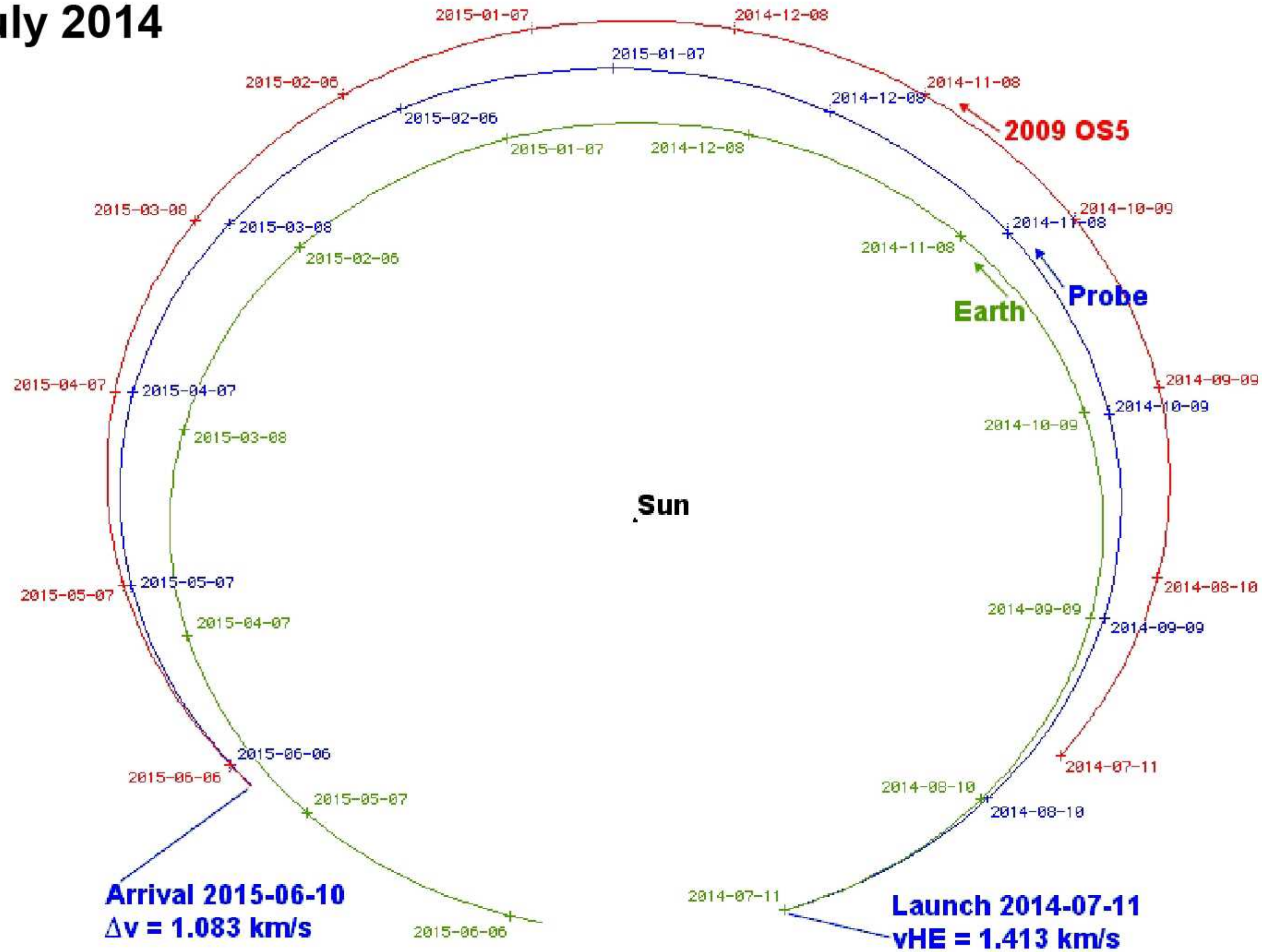
*(launch vehicles could be: Proton M + Briz M; Soyuz Fregat; EELV; H-2A; Ariane 5; Falcon 9)*

*Based on Ares V single launch, 1998 $HG_{49}$ is at the cusp of being accessible for human exploration. Depending on how the new heavy lift vehicle will develop, other targets that might fall into the realm of human exploration include 2001 $CC_{21}$ at 726 meters across; or, 2008 $EV_5$ at ~ 540 meters. None of these targets are well-characterized. Approximate sizes are based on albedo; could be larger [or smaller] by a factor of two.

## An example mission profile to NEO 2009 $OS_5$ launch mid-July 2014

If hardware was available, a 170-day (round trip) piloted sprint mission could be mounted departing Earth in March 2020.

$\Delta v_{total}$ for the piloted mission taps out at 7.1 km/s. Earth return ($v_{EI}$) is 11.20 km/s; comparing favorably to *Apollo 10* at 11.07 km/s.




Courtesy Dan Adamo

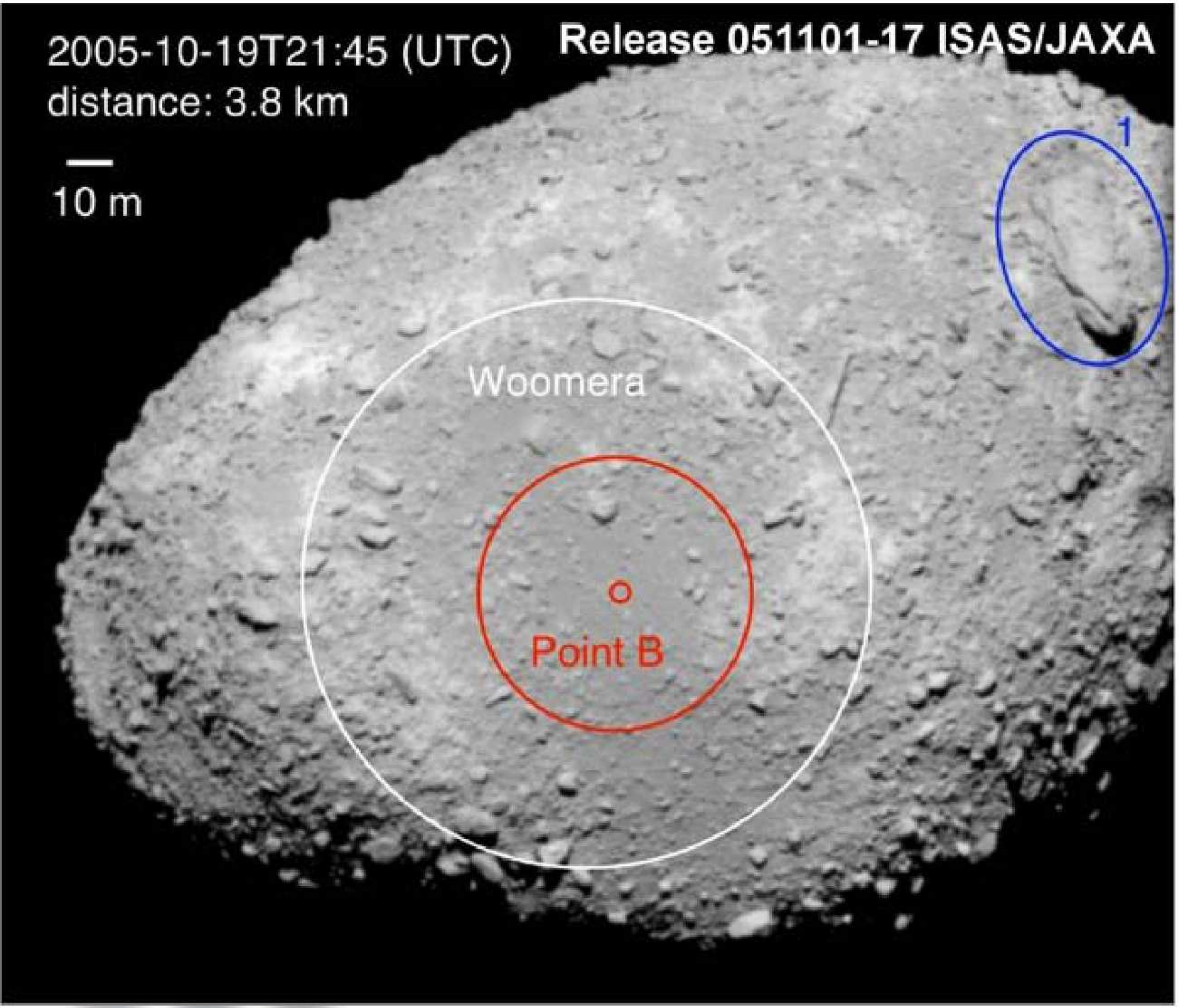
# Robotic Precursors to NEOs: Requirements

| | Functional Capability | Elements/Instruments | | | |
|---|---|---|---|---|---|
| | Deep Space $\Delta v$ | Upper stage storable prop | Fregat | Breeze M (Бриз М) | NRL Upper Stage |
| | Mapping | High-res optical camera system | Surface identification | Navigation | characterization |
| | | Hyperspectral camera | | | |
| | | LIDAR | Topography | Gravitational survey | Shape modeling |
| | NEO Composition | Visible & IR spectrometer | Surface mineralogy | | |
| | Small lander package | APXS, Mössbauer, microscopic imager, solar wind collector, dust detector, radiometer | | | |
| | Radiation | $\gamma$-ray spectrometer (GRS) | Measure gamma radiation as a function of photon energy (feed forward to human missions to NEOs) | | |
| | Communication & Navigation | X-, S-, and Ku-band | Op navs; $\Delta$DOR nav | Data comm | Piloted mission support |

**Note**: '1st Stage Innovative Technology' is not required for the first robotic precursors to reach and explore NEOs. The first step to explore NEOs could be accomplished via conventional means, buying us time to develop cryo-coolers; new technology propulsion units (i.e., refinements to SEP; VASIMR); human tissue equivalent radiation counter; optical comm (first demonstration will be on LADEE); etc. Another key element for success of a precursor series of missions will be a common spacecraft bus.

# Necessity of Robotic Precursors to NEOs

## *Touch Down Site Candidate B: Little Woomera*



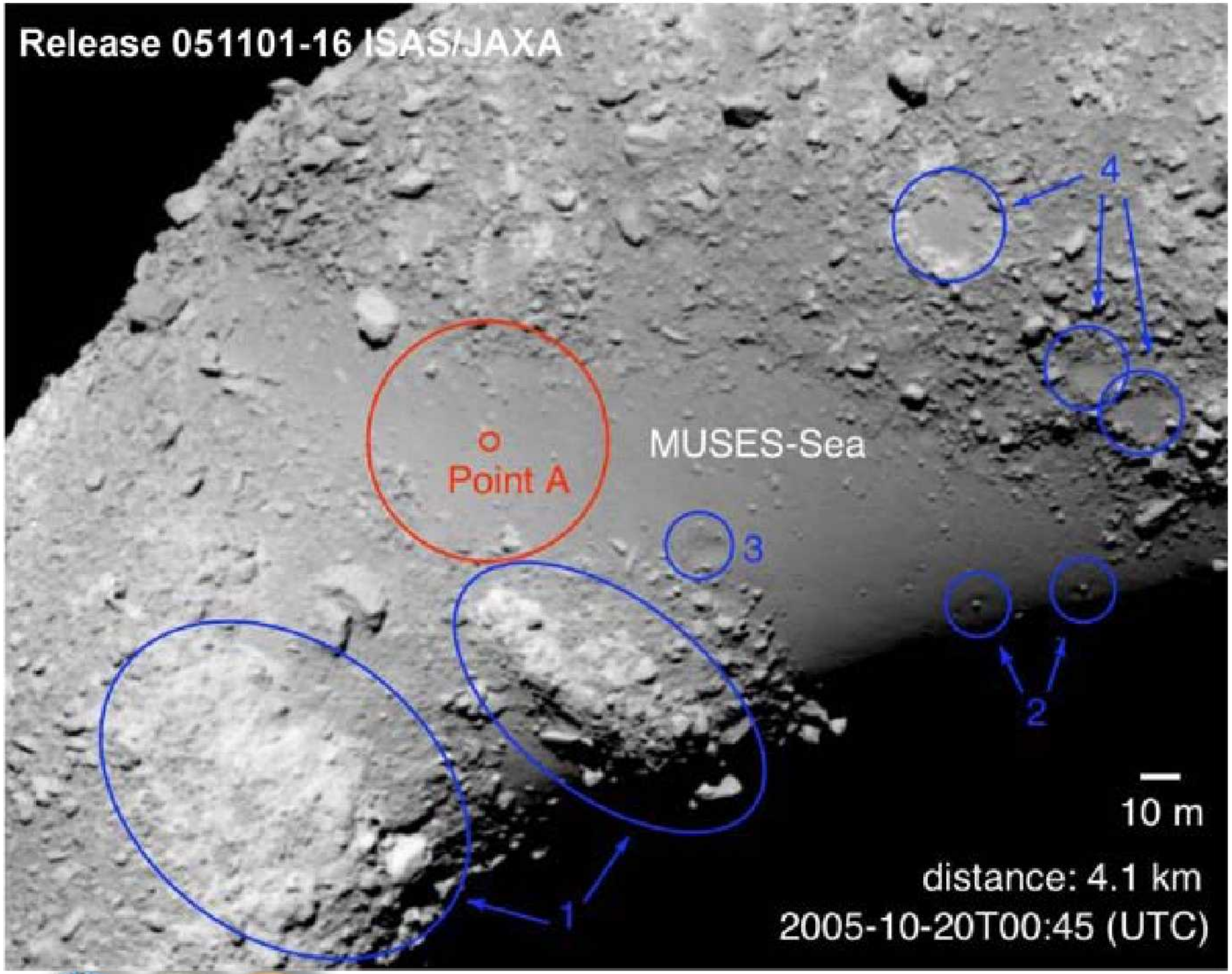

**Little Woomera was selected as a possible landing site.**

**Subsequent high resolution images showed that this area still held too many meter-sized boulders.**

**Courtesy JAXA**

# Necessity of Robotic Precursors to NEOs

## *Touch Down Site Candidate A: Muses Sea (smooth terrain)*

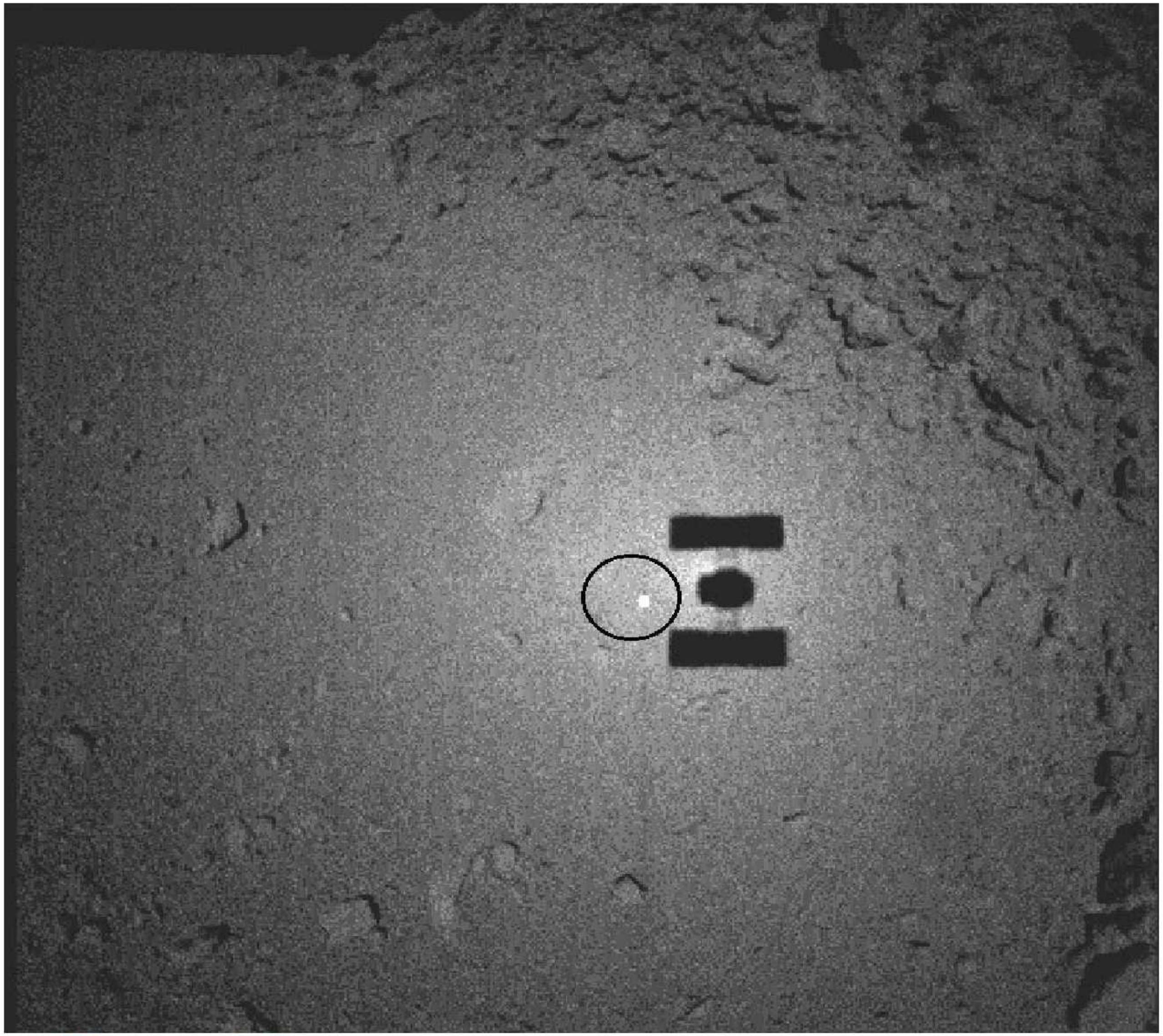



**Largest smooth terrain located between the "Head" and "Body" of the Otter-like [shape of Itokawa]**

**~60 m across at its widest point.**

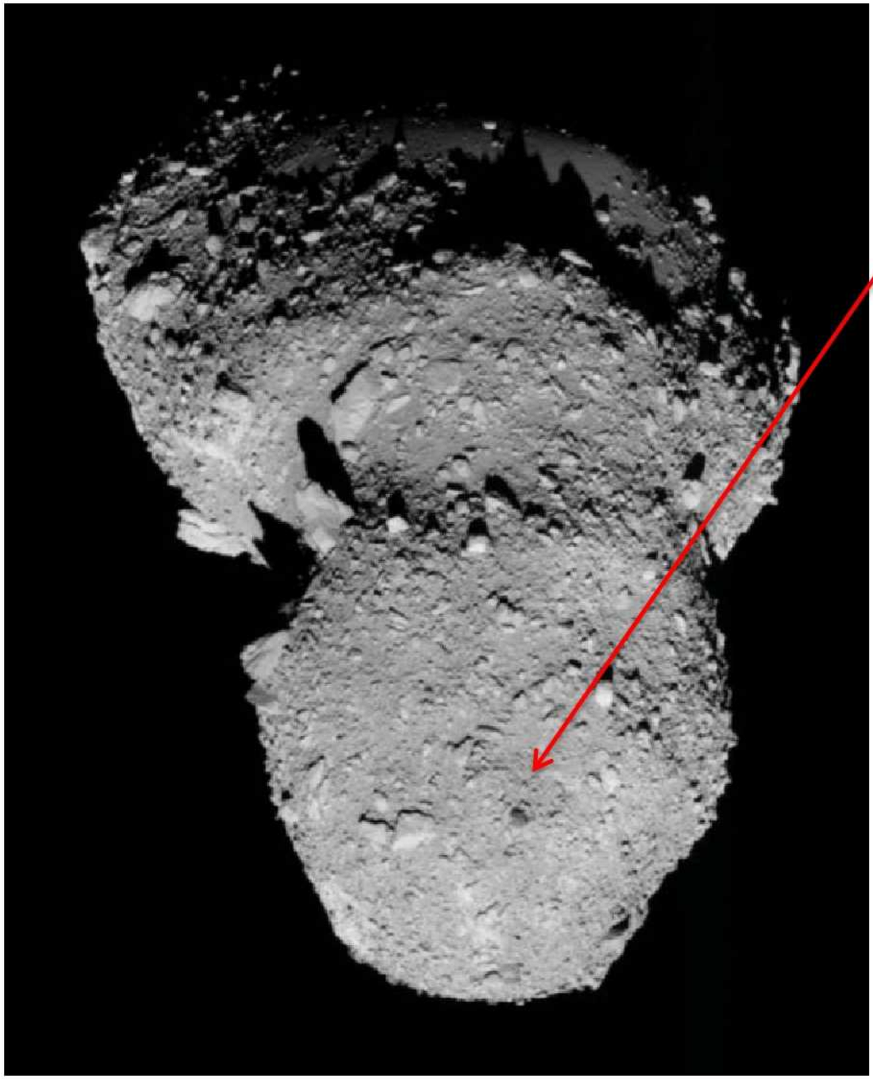
**Courtesy JAXA**

# Necessity of Robotic Precursors to NEOs



*Touch Down Site Approach*

# Necessity of Robotic Precursors to NEOs



***Black Boulders on Itokawa!***

**Note the large boulders, steep up- and down-sloping terrain, lighting conditions, etc.**

**Several large black boulders have been imaged on the surface of Itokawa.**

**Largest of these is located on the "Head" of Itokawa.**

**Possible material from another object.**

**Courtesy JAXA**

# Notional Human Exploration of Near-Earth Objects

Bret Drake/Lee Graham

# Mission Scenario Information, Human Exploration of NEOs

| Mission Scenario | Primary | Secondary |
|---|---|---|
| | M2 | M8 |
| **Reference** | See reference list, plus various unpublished NASA internal studies | |
| **Destination** | Near Earth Objects | |
| **Estimated Date** | To be determined | |
| **Objectives/Goals** | See subsequent slides | |
| **Mission Operational Drivers** | See subsequent slides | |
| **Key Technology Needs** | See subsequent slides | |
| **Key Capability Needs** | See subsequent slides | |
| **Mission Profile** | See subsequent slides | |

# Human Exploration of NEOs References


Abell, Paul A. *et al*.. “Scientific Exploration of Near-Earth Objects via the Orion Crew Exploration Vehicle.” *Meteoritics and Planetary Science* **44**:1825-1836 (2009).

Adamo, Daniel R., Jon D. Giorgini, Paul A. Abell, Rob R. Landis, “A Survey of Asteroid Destinations Accessible for Human Exploration.” *Journal of Spacecraft and Rockets* (2010: in peer review).

Davis, Donald R. *et al.,* “The Role of Near-Earth Asteroids in the Space Exploration Initiative,” SAIC-90/1464, Study No. 1-120-232-S28 (1990).

Griffin, Michael, Owen K. Garriott, *et al., Extending Human Presence into the Solar System: An Independent Study for the Planetary Society on the Proposed U.S. Space Exploration Policy.* The Planetary Society, Pasadena, (2004).

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Jones, Thomas D. *et al.,* “Human Exploration of Near-Earth Asteroids,” in *Earth Hazards Due to Comets and Asteroids*, University of Arizona Press, Tucson, Arizona (1994). 683-708.

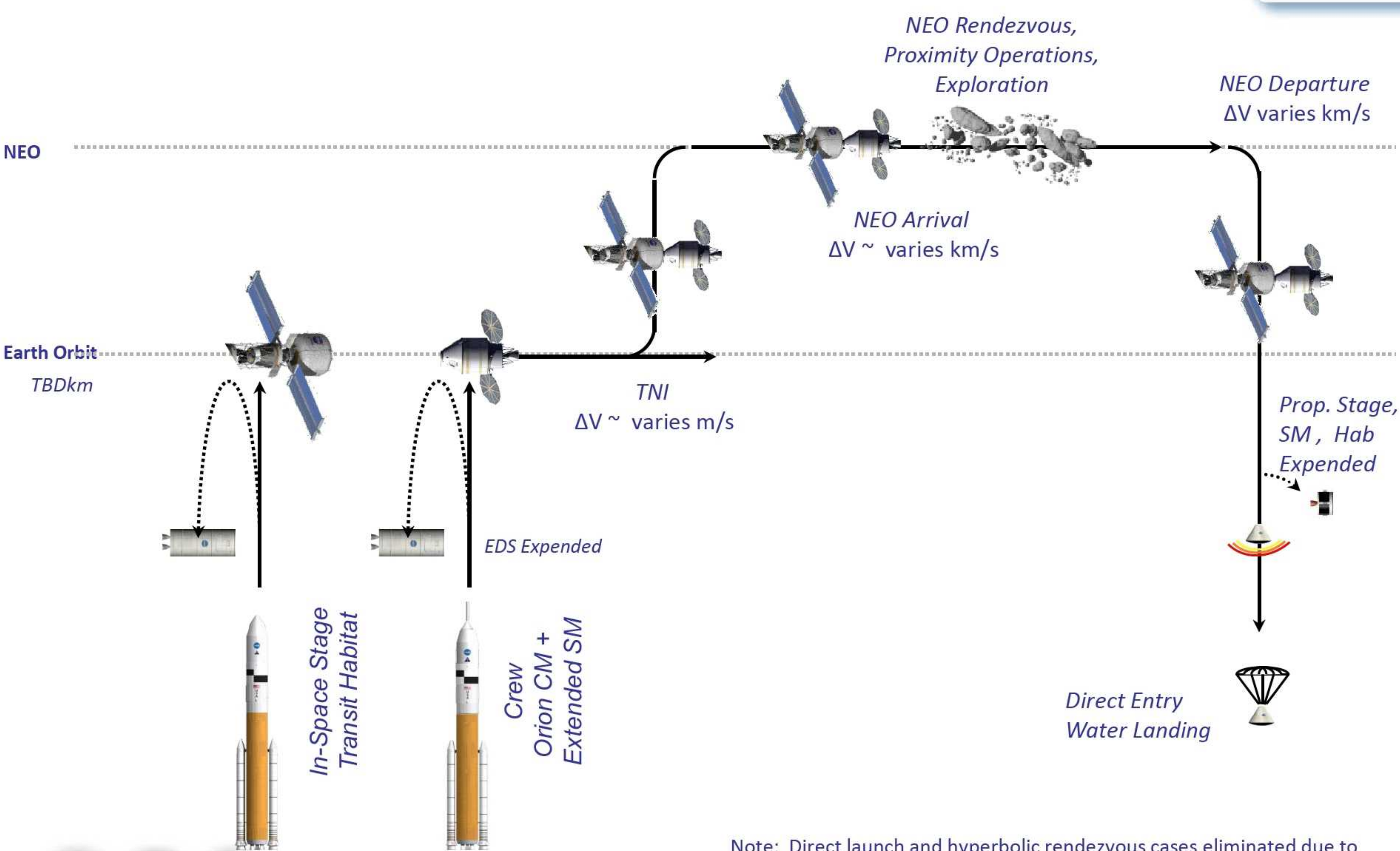
Landis, Rob R., *et al*., “Piloted Operations at a Near-Earth Object (NEO).” *Acta Astronautica* **65**:1689-1697 (2009).

Nash, Douglas B. *et al*., *Science Exploration Opportunities for Manned Missions to the Moon, Mars, Phobos, and an Asteroid* NASA Office of Exploration, Doc No. Z-1.3-001 (1989).

# Human Exploration of NEOs Objectives/ Goals

| Theme | Exploration Objective |
|---|---|
| Human Exploration | Expand human exploration of space beyond Earth orbit |
| Risk Reduction | Gain operational knowledge and system performance for longer durations beyond low-Earth orbit (90 – 360 days away from Earth) |
| Mars Demonstration | Mars in-space flight demonstration. Puts humans demonstrably on the way to Mars while producing exciting new science |
| Geologic Context | Supports NEO characterization for planetary defense |
| | Sample return from solar system bodies radically different from Moon/Mars. Samples from known geologic context. |
| | Study the internal structure of asteroids |
| | Knowledge of NEO internal strength refines physics models |
| Participation | Unprecedented deep space voyages with dramatic perspective of Earth-Moon system |
| | Point to continued exploration progress using Constellation investment |
| | Cultivate and maintain public support by taking on dramatic new, relevant challenges |
| | Provide opportunities for international and commercial participation |

# Example NEO Mission Sequence




Note: Direct launch and hyperbolic rendezvous cases eliminated due to performance limitations and risk

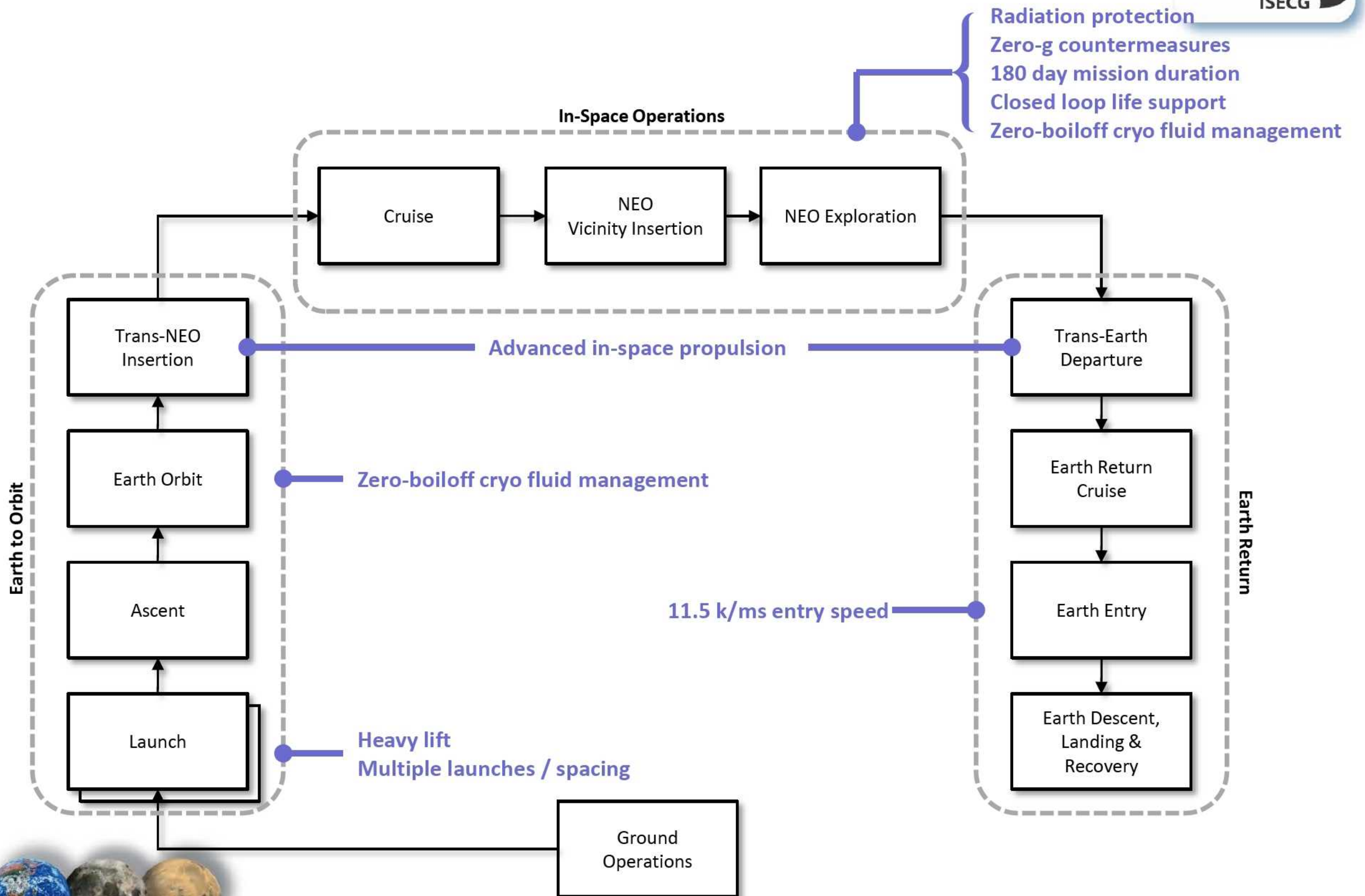
# Human NEO Missions Innovation Requirements, p 1 of 2

| | Functional Capability | Elements | Innovation Requirement | | |
|---|---|---|---|---|---|
| | | | Critical | Important | Desirable |
| | **Crew Transportation** | • Heavy lift launch<br>• Crew launch (x1)<br>• In-space propulsion<br>• Earth return capsule<br>• In-space habitation | • Advanced in-space propulsion<br>• Zero-boiloff cryo fluid management<br>• High-speed (11.5 km/s) Earth entry | | |
| | **Cargo Transportation** | | | | |
| | **In-space Habitation** | • In-space habitat to support 6 crew for 180-360 days | • Radiation protection<br>• Closed-loop life support | | |

# Human NEO Missions Innovation Requirements, p 2 of 2

| | Functional Capability | Elements | Innovation Requirement | | |
|---|---|---|---|---|---|
| | | | Critical | Important | Desirable |
| | **On-surface Habitation** | | | | |
| | **Extra Vehicular Activity** | • Zero-g EVA<br>• NEO vicinity proximity operations | | | |
| | **In-space Power** | • Solar arrays | | | |
| | **On-surface Power** | | | | |
| | **Surface Mobility** | | | | |
| | **Servicing** | | | | |
| | **ISRU** | | | | |
| | **Communication & Navigation** | | • High bandwidth deep space communication | | |
| | **Human Health & Performance** | | • Zero-gravity countermeasures for 180 - 360 day transits<br>• Radiation protection<br>• Advanced medical care | | |

# Human Exploration of NEOs Key Challenges and Risks

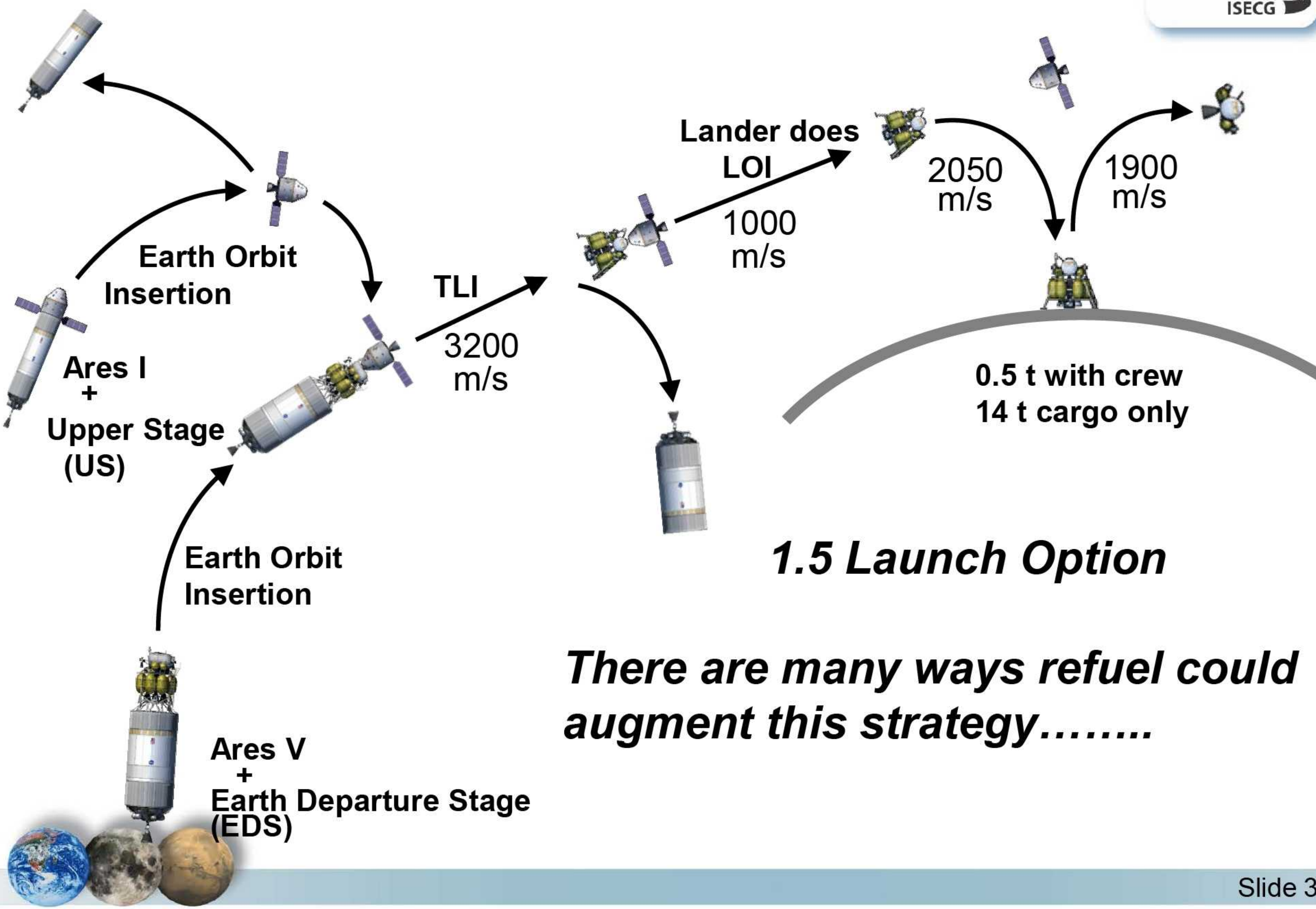


# LEO Refueling to Augment Lunar Exploration

**Andy Thomas/Pat Troutman/**
**Chris Culbert**

Refueling Ares V Class Missions in LEO
Refueling Delta/Atlas V Class Missions in LEO

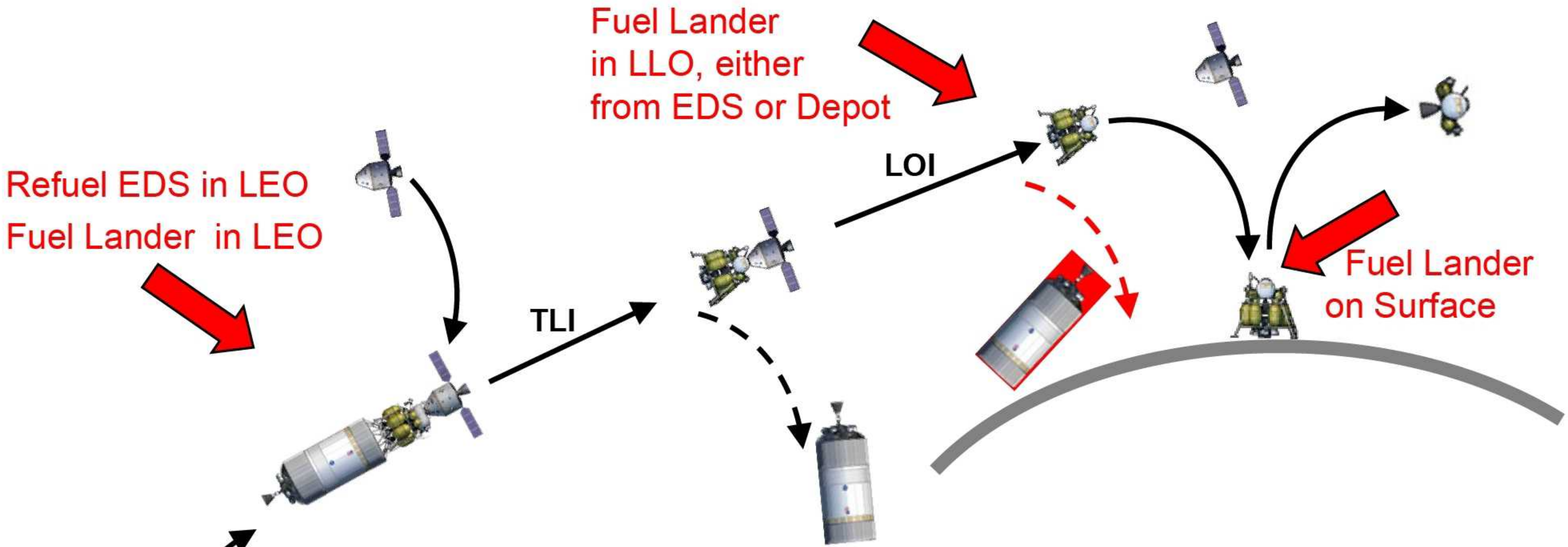
# Ares V/Ares I Lunar Mission Strategy




***1.5 Launch Option***

***There are many ways refuel could augment this strategy……..***

# Present Crew Mission Strategy – Ares V Class, and Opportunities for Refueling





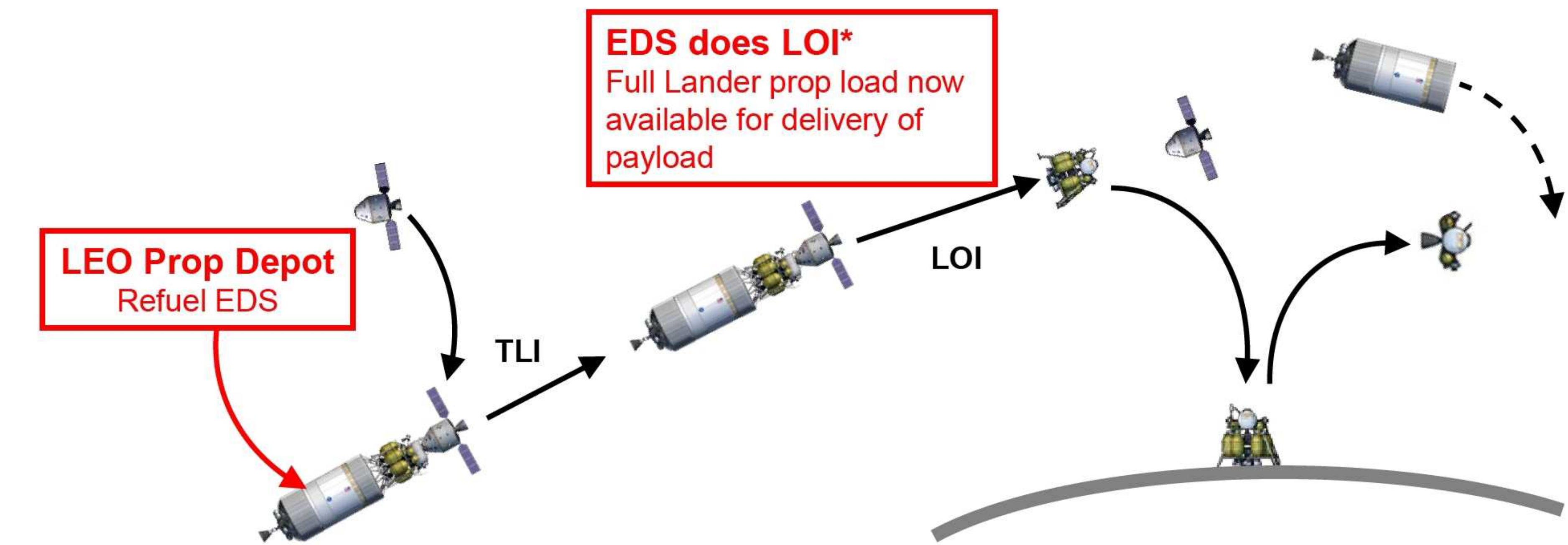
Refueling EDS in LEO allows LOI capability on EDS giving larger delivered payload, or greater surface access,

Fueling Lander in LEO reduces launch loads, allows lighter structure, possibly more payload

Fueling Lander in LLO allows larger payload, Lander reuse or greater surface access

Refueling Lander on the surface allows larger payload, Lander reuse or hopper flights

# Example 1: EDS Refuel in LEO, and Use Extra EDS Capacity for LOI Burn – Crew Mission





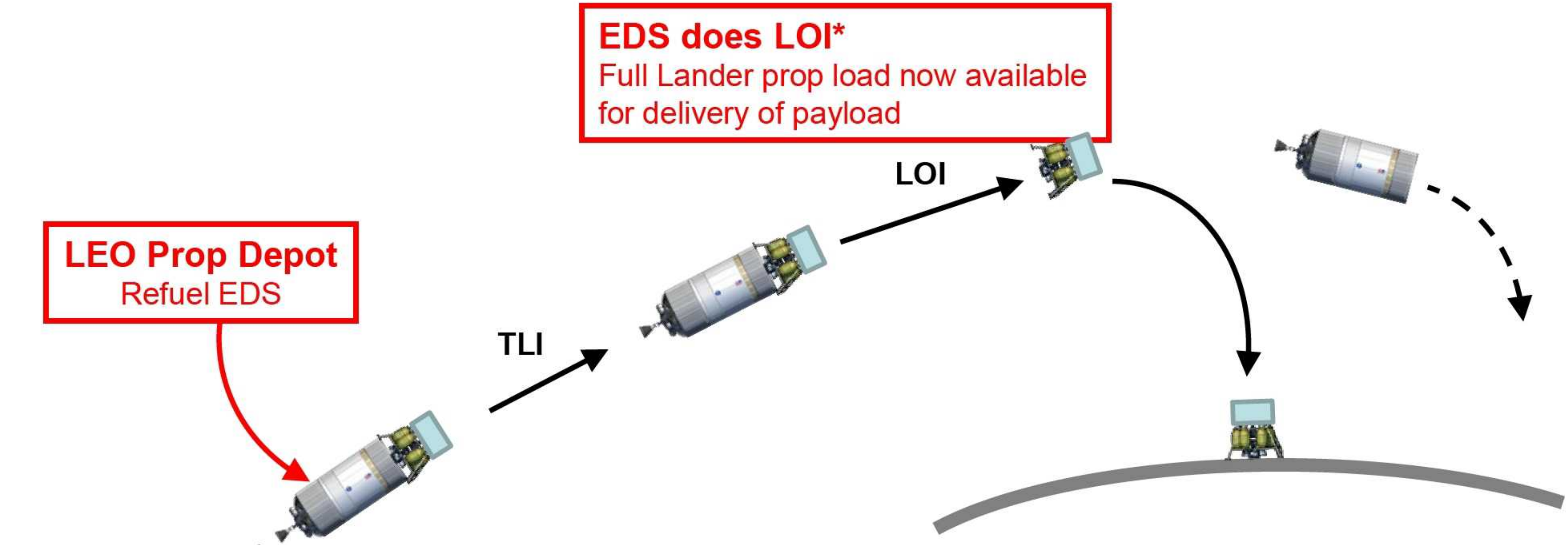
- Significant LEO propellant depot required
  - Need ~ 40 tons just to enable mission (set by EDS size and need to push Lander and EDS through LOI)
  - Thereafter 3 extra tons of prop in LEO will give 1 ton of additional payload
  - 10 extra tons on the surface requires ~70 tons of prop in LEO
- In reality Lander size, structure and launch loads will reduce this

- It may be lower risk and cost to deliver 10t of assets directly to the surface rather than 70 t of prop to LEO (fewer launches)



* A dedicated LOI stage would probably be preferable

# Example 2: EDS Refuel in LEO, and Use Extra EDS Capacity for LOI Burn – Cargo Mission





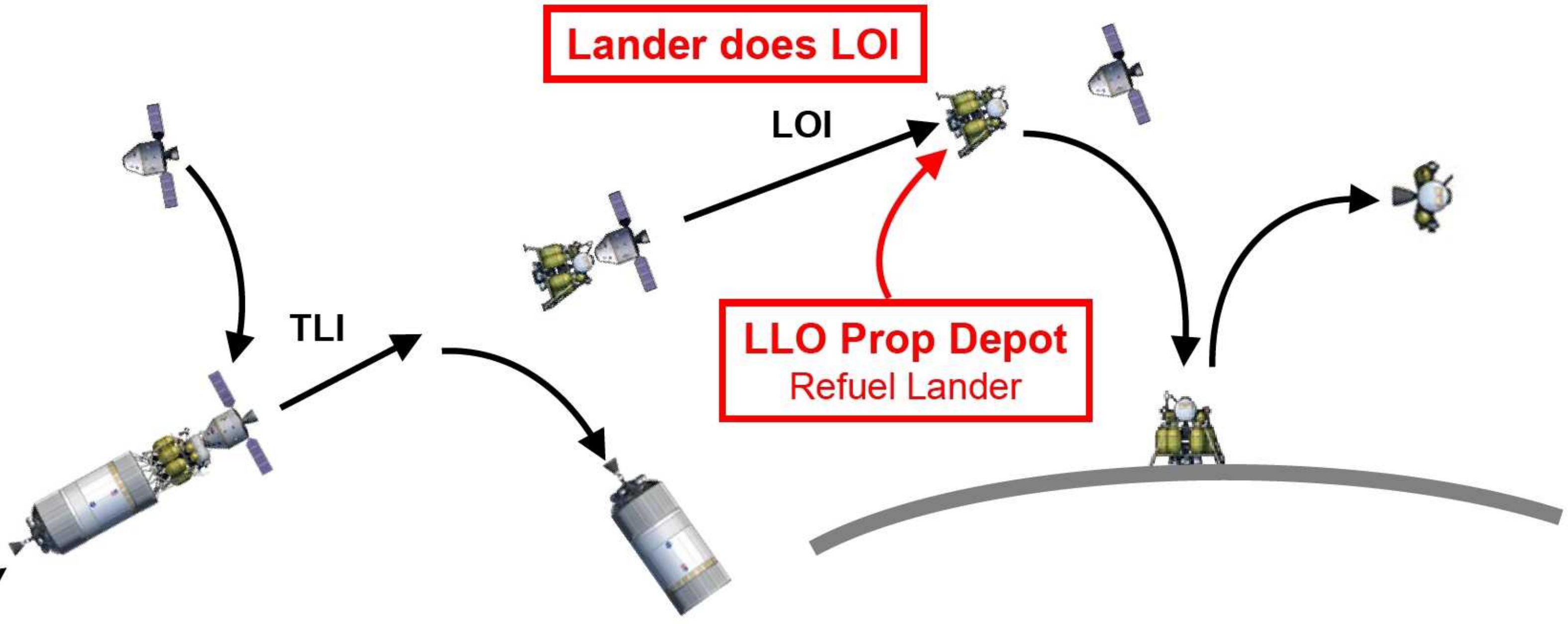
- Basic architecture delivers about 14 tons without refueling
- Thereafter 4.5 extra tons of prop in LEO will give 1 ton of additional payload.
- Lander tank size limits this to a maximum of about 30 tons that can be landed (with 70 t of prop transferred - in theory)
- In reality Lander structure, launch and landing loads will reduce this

- It may be lower risk and cost to deliver additional payload directly to the surface rather than 70 t of prop to LEO (fewer launches)



* A dedicated LOI stage would probably be preferable

# Example 3: Launch Lander with LOI Load Only, Add Additional Fuel Post-LOI for Descent



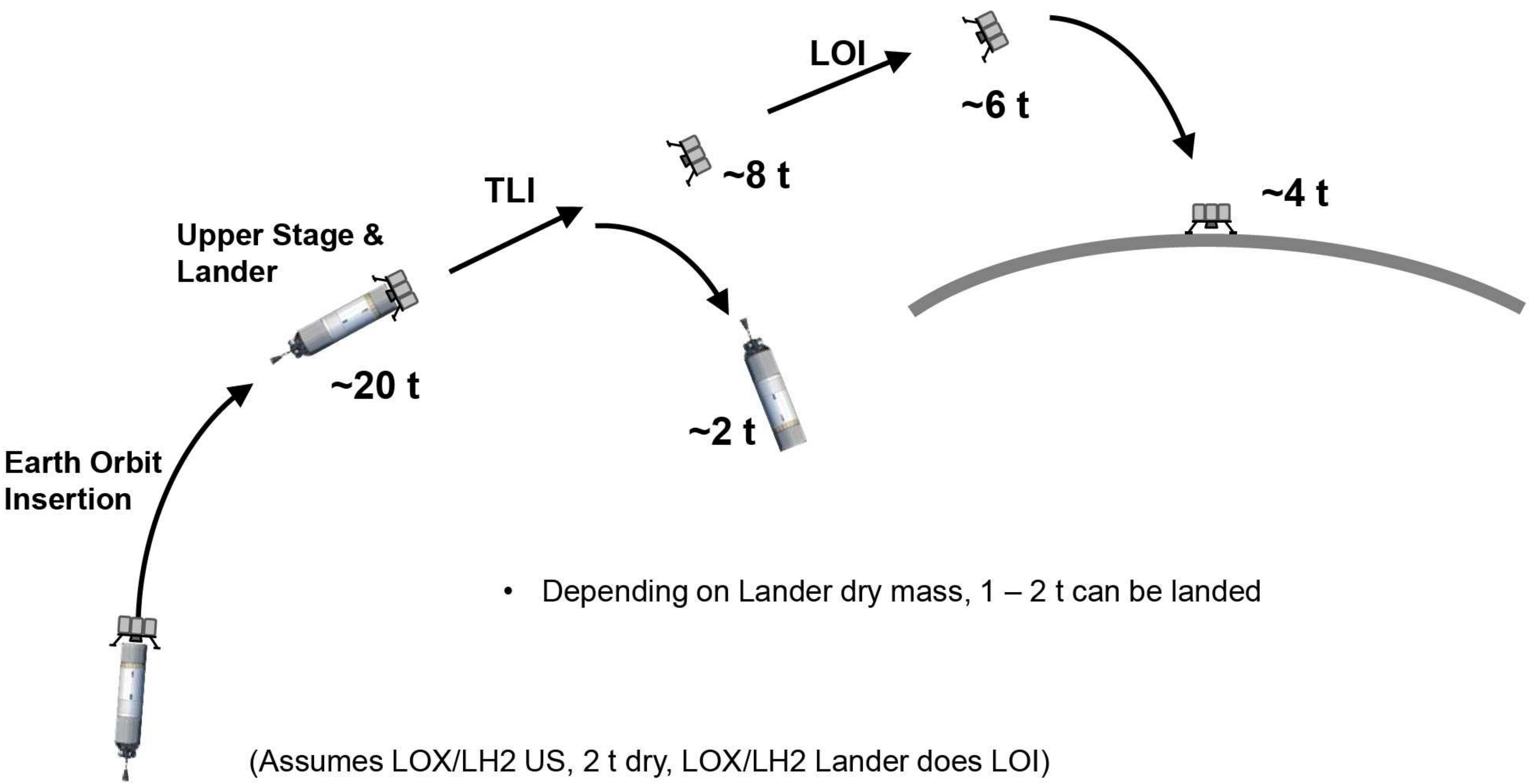


- Lander launches with increased payload, but only prop for LOI, and is then refueled in LLO
- Can get an additional 6 tons of payload for about 15 tons of propellant provided in LLO (set by EDS launch capacity)
- Direct surface delivery of 6t payload may be easier than 15 t of prop to LLO

# Summary – Refueling Ares V/Ares I Class Missions

- Refueling transportation elements in flight can augment architecture
  - Larger payload mass to the surface
  - Much smaller 'bone yard' because of improved delivery
  - Greater surface access
  - Expanded mission options e.g. longer surface stays
- Assessment of impacts on architecture needed (cost, PLOC, PLOM)
- But substantial amounts of LEO propellant are needed (70 ton range to get around 10 tons of additional payload, ~7:1 ratio)
- Cost effectiveness of resupplying a large depot versus sending assets directly to the lunar surface needs assessment
- Refueling not easy to retrofit into an existing approach – better to optimize the architecture around refueling by designing it in from the start, even if not initially used
- An additional benefit is that refueling may allow the Lander to be reused and flown repeatedly to and from the surface (Lunar Taxi - see later slides)

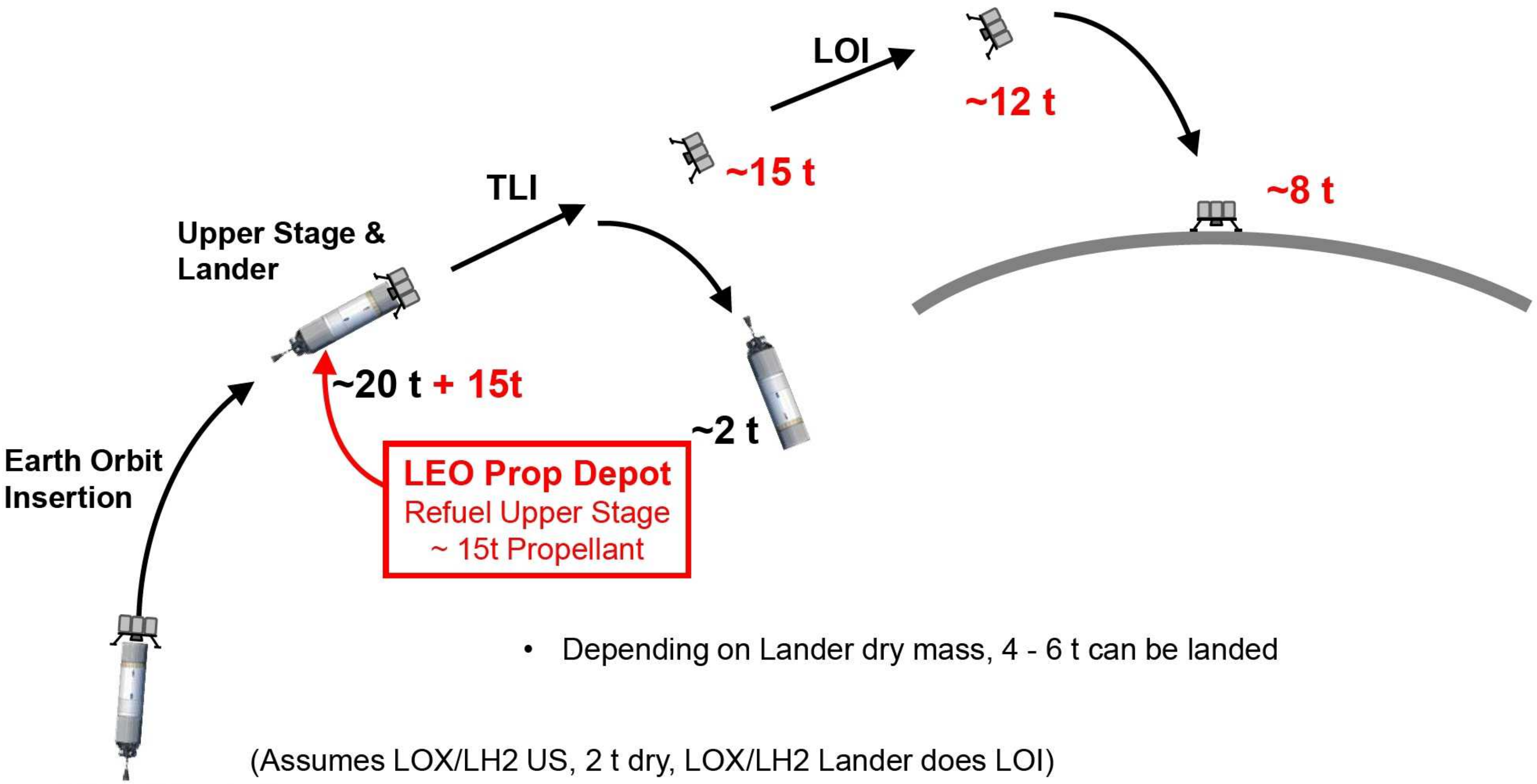
# Current Atlas or Delta Class Mission Capability




- Depending on Lander dry mass, 1 – 2 t can be landed

(Assumes LOX/LH2 US, 2 t dry, LOX/LH2 Lander does LOI)

# Current Atlas or Delta Class Mission Capability With LEO Refueling




- Depending on Lander dry mass, 4 - 6 t can be landed

(Assumes LOX/LH2 US, 2 t dry, LOX/LH2 Lander does LOI)

# Summary – Refueling Atlas or Delta Heavy Class Missions

- Refueling in LEO can significantly improve payload delivered to lunar surface for this class of launch vehicle
  - Major surface elements can potentially be delivered (e.g. ISRU, LER)
  - Surface access can also be improved
  - Could provide propellant for reflight of the Lander (Lunar Taxi)

- Provides better leveraging of refueling - less propellant transfer gets significant payloads to the lunar surface than required for Ares V class missions (3:1 versus 7:1 ratio)

- If any exploration strategy is to exploit this, it is better to implement it up front

# Candidate Depot Locations – Pros and Cons

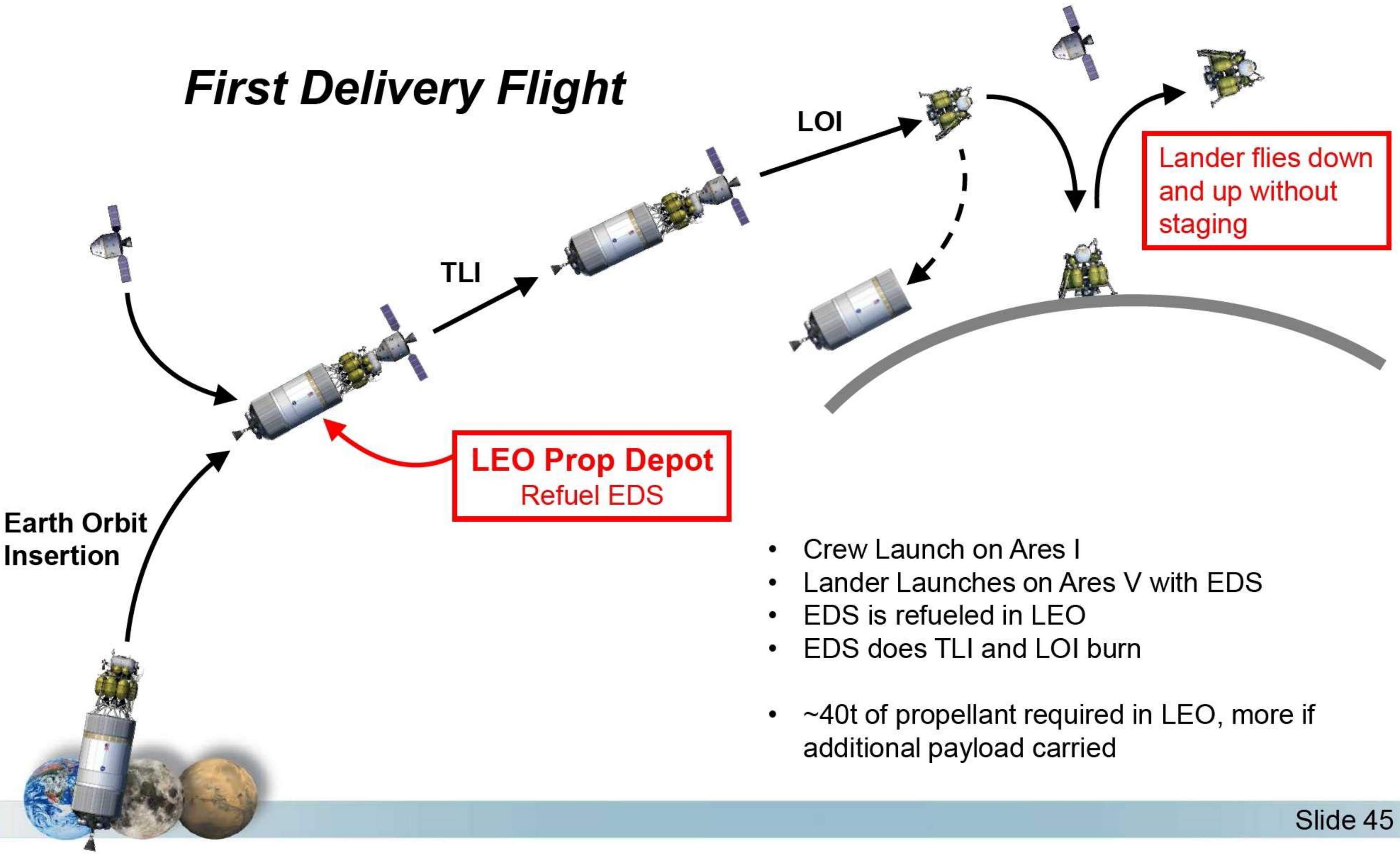
- LEO
  - Easy access, serviceable site
  - Poor thermal environment
  - Discontinuous illumination
- L1
  - More difficult to reach, but allows greater surface access
  - Imposes additional delta-V on transportation elements
  - Good thermal environment for cryo storage
  - Continuous illumination
- LLO
  - Difficult to reach
  - Places constraints on TLI opportunities and restricts surface sites
  - Poor thermal environment
  - Discontinuous illumination
- Surface
  - Poor thermal environment
  - Discontinuous illumination
  - Best suited for ISRU at an Outpost site

# Propellant Resupply and Depot Technologies

**Technology advancements are needed in the following areas to realize a working, sustainable, in-space propellant resupply infrastructure:**

1. Thermal Control
    - Passive storage
    - Active storage (refrigeration)
    - MMOD protection
    - Sub-cooling
2. Liquid Acquisition
3. Mass Gauging
4. 0-g Liquid Transfer
5. Transfer Couplings
6. Pressure Control
7. Tank Pressurization
8. Leak Detection
9. Integrated Depot Design
10. Autonomous Rendezvous and docking

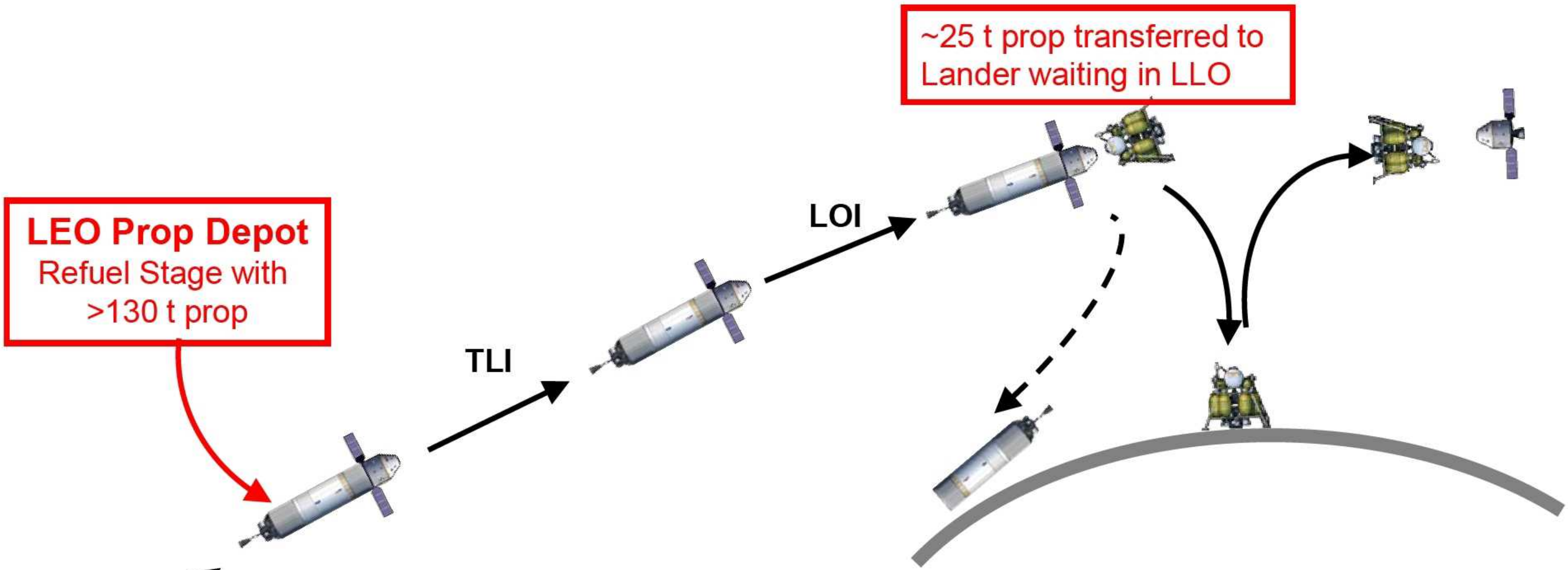
# Example 4: LEO Refuel to Allow Lander Re-flight

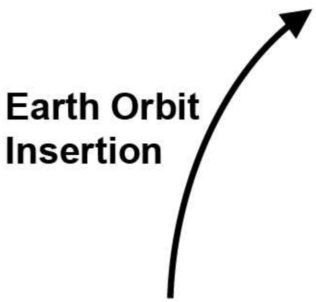



- Crew Launch on Ares I
- Lander Launches on Ares V with EDS
- EDS is refueled in LEO
- EDS does TLI and LOI burn

- ~40t of propellant required in LEO, more if additional payload carried

# LEO Refuel, Lander Re-flight - Subsequent Flights




- Crew can launch on Ares I, Ares V not needed
- Upper Stage (US) is refueled in LEO and does TLI and LOI
- Stack docks with Lander in LLO, crew transfer over fuel from Upper Stage to refill Lander tanks
- Lander flies down and up mission, Upper Stage discarded

- But equivalent capacity of Ares V needed for propellant load to LEO (multiple heavies)

# Re-flight Enabled Through Refueling - Advantages

- Do not discard high-dollar items (Descent and Ascent Stage) every time
- Much smaller bone yard, old Landers parked on surface for spares and storage, rather than crashed in (swap Landers on the surface, not in LLO).
- Pre-ascent vehicle failure can be mitigated with backup ascent capability
- Abort capability on both ascent and descent.
- Allows (and significantly benefits from) smaller Crew and Cargo Landers, facilitating unloading, pressurized mating to LER, etc.

# Lander Reflight – Technologies Needed

- Propulsion System
  - Need reliable cryogenic propellant transfer
  - Need multi start engine with long operating time
  - Engine health monitoring and reuse qualification criteria
  - Thermal management of engine for extended periods on the surface and in LLO will be an issue (valve lifetimes, seal integrity, wetted lines)
  - He resupply may also be needed to support tank pressures for engine start and He actuated valves
  - Contamination of engine due to dust impingement during landing and launch
  - Control of cryogenic boil-off control will be important for long surface stays
- Power Subsystem
  - May need to also transfer reactants for fuel cells
  - System must be sized to maintain vehicle thermal health for extended periods
- Spacecraft Thermal Management
  - Will need extended and untended LLO thermal management capability, e.g. transfer additional water if sublimator used
- Structures and Mechanisms
  - Significant landing gear design impacts to allow multiple landings

# Re-flight Enabled Through Refueling - Key Risks and Challenges

- Needs additional transportation element (In-Space Tanker Vehicle) of significant capability (possibly providing up to 100's of tons of prop)

- Need additional Flight Operations (rendezvous, docking, fuel transfer)

- In addition to fuel transfer capability on vehicles, probably also need transfer of pressurants and other consumables

- Firing an engine, then maintaining it for months at a time, followed by certifying for restart, and doing this repeatedly is a challenge

- LOM and LOC need assessment:
  - No lifeboat for serious CEV system failure in transit (Apollo 13)
  - Cumulative risks may be the driver

- A reusable vehicle is very different from a one-time use vehicle

# Refueling Options Backup

# Mission Operations Concepts
# Altair-Class, Single-Use Lander

| Mission Ops Concept | Element Refueled in LEO | LOI Stage | Lunar Refueling | | Notes |
|---|---|---|---|---|---|
| | | | Element Refueled in LLO | Element Refueled on Lunar Surface | |
| 1. Cargo Lander Launches Empty and Tanks in LEO | Cargo Lander | Cargo Lander | N/A | N/A | Launching the Cargo Lander unfueled minimizes launch loads and may enable a lower mass primary structure. |
| 2. Global Sortie with LEO Top-Off of the EDS | EDS | EDS | N/A | N/A | This concept enables global access without the need for post-LOI extended loiter. |
| 3. Dual Mission Operations: Outpost-Based Sortie | EDS | EDS | N/A | N/A | The original concept of dual, sequential missions utilizing a common crew and a single Ares I/Orion (developed during LAT 2) is enhanced with EDS top-off in LEO. |
| 4. Dual Mission Operations: Dual Sortie Missions | EDS | EDS | N/A | N/A | The original concept of dual, sequential missions utilizing a common crew and a single Ares I/Orion (developed during LAT 2) is enhanced with EDS top-off in LEO. |

# Mission Operations Concepts
# Altair-Class Refuelable, Reusable Lander, p 1 of 3

| Mission Ops Concept | Element Refueled in LEO | LOI Stage | Lunar Refueling | | Notes |
|---|---|---|---|---|---|
| | | | Element Refueled in LLO | Element Refueled on Lunar Surface | |
| 1. Crew Delivers New Reusable Lander to LLO | EDS | EDS | N/A. Reusable Lander is delivered to LLO fully fueled. | N/A | This is the initialization mission for Concept 2. The Reusable Lander with crew descends and ascends without staging. The Lander AM is used as an abort stage only. |
| 2a. Crewed Mission; EDS Serves as Tanker for Reusable Lander in LLO | EDS | EDS | Pre-delivered Reusable Lander is fueled in LLO by the EDS. | N/A | Concept 1 is the initialization mission for this ops concept. This concept is a “single launch solution” (not including flights to deliver propellant to LEO) if the Orion launches on the Ares V. The Reusable Lander with crew descends and ascends without staging. The Lander AM is used as an abort stage only. |
| 2b. Crewed Mission; EDS Serves as Tanker for Reusable Lander in LLO. The Reusable Lander is also Fueled on the Lunar Surface | EDS | EDS | Pre-delivered Reusable Lander is fueled in LLO by the EDS. | Reusable Lander DM is fueled on the lunar surface. | Full EDS capability is underutilized. Alternatives are to launch crew on Ares V with EDS or on Ares I with the Upper Stage serving as the TLI stage. |
| 2c. Crewed Mission; Ares I Upper Stage Serves as Tanker for the Reusable Lander in LLO | Ares I Upper Stage | Ares I Upper Stage | Pre-delivered Reusable Lander is fueled in LLO by the Ares I Upper Stage. | N/A | Concept 1 is the initialization mission for this ops concept. This concept is a “single launch solution” (not including flights to deliver propellant to LEO) since no Ares V/EDS is required. |

# Mission Operations Concepts
# Altair-Class Refuelable, Reusable Lander, p 2 of 3

| Mission Ops Concept | Element Refueled in LEO | LOI Stage | Lunar Refueling: Element Refueled in LLO | Lunar Refueling: Element Refueled on Lunar Surface | Notes |
|---|---|---|---|---|---|
| 3. Reusable Cargo Lander Delivers Crew and Cargo | EDS | EDS | N/A. Reusable Cargo Lander is delivered to LLO fully fueled. | N/A | This is the initialization mission delivering a Reusable Cargo Lander to the lunar surface for Concept 4. The fully fueled Ascent Module is mounted on an SSU/PUP and is removed by an ATHLETE providing Ascent Module mobility on the lunar surface and allowing the Reusable Cargo Lander to return to LLO. |
| 4a. Reusable Cargo Lander Delivers Cargo to the Lunar Surface | EDS with Cargo Pallet | EDS | Pre-delivered Reusable Cargo Lander is fueled in LLO by the EDS. | N/A | Concept 3 is the initialization mission for this ops concept. In this concept, the EDS-mounted Cargo Pallet is transitioned to the Reusable Cargo Lander in LLO prior to descent to the lunar surface. After cargo is delivered to the lunar surface, the Reusable Cargo Lander returns to LLO for refueling and reuse. |
| 4b. Reusable Cargo Lander delivers cargo to the lunar surface | EDS with Cargo Pallet | EDS | N/A. | Pre-delivered Reusable Cargo Lander is fueled on the lunar surface prior to return to LLO for cargo transfer. | This is a variation on Concept 4a with refueling occurring on the lunar surface. |

# Mission Operations Concepts
# Altair-Class Refuelable, Reusable Lander, p 3 of 3

| Mission Ops Concept | Element Refueled in LEO | LOI Stage | Lunar Refueling | | Notes |
|---|---|---|---|---|---|
| | | | Element Refueled in LLO | Element Refueled on Lunar Surface | |
| 5. Crewed Mission Delivers Reusable, Refuelable Ascent Module to LLO after Surface Stay | EDS | EDS | N/A. The Reusable, Refuelable Ascent Module is fueled during follow-on crewed missions. | N/A | This is the initialization mission for Concept 6. In this concept, only the Ascent Module is reused and refueled in LLO. |
| 6. Crewed Mission with Reusable, Refuelable Ascent Module | EDS | EDS | Pre-delivered Ascent Module is fueled in LLO by the EDS. | N/A | The EDS delivers the CEV, single use Lander Descent Module, and propellant to LLO. The CEV, Descent Module, and Reuseable, Refuelable Ascent Module mate in LLO prior to descent to the lunar surface. |
| 7. Dual Mission Operations: Outpost-Based Sortie | EDS | EDS | Pre-delivered Reusable Lander is fueled in LLO by the EDS. | N/A | This dual mission concept utilizes a common crew, a single Ares I/Orion, and a pre-delivered Reusable Lander to maximize performance, cost, and risk benefits across both missions. |
| 8. EDS performs TLI and LOI with No Refueling | N/A | N/A | N/A | N/A | This is a special case concept with no pre-defined lander. The purpose of this operations concept is to determine the maximum landed mass possible for both crew and cargo landers if LOI is offloaded to the EDS. This is a "no lander LOI" mission concept. |

# Mission Operations Concepts
# Optimized Refuelable, Reusable Lunar Taxi, p 1 of 2

| Mission Ops Concept | Element Refueled in LEO | LOI Stage | Lunar Refueling | | Notes |
|---|---|---|---|---|---|
| | | | Element Refueled in LLO | Element Refueled on Lunar Surface | |
| 1a. Crewed Delivery of New Lunar Taxi to LLO | N/A | Modified CEV SM (20 klb-class LOX/CH4 engine) | N/A. Lunar Taxi is delivered to LLO fully fueled. | N/A | This is the initialization ops concept for Concept 2. The propellant tanker is used to fuel the CEV SM prior to TEI. The Lunar Taxi loiters in LLO until the next crewed mission. |
| 1b. Uncrewed Delivery of New Lunar Taxi to LLO | N/A | Lunar Taxi | Lunar Taxi is fueled in LLO on subsequent crewed mission. | N/A | This is the initialization ops concept for the crewed mission ops concepts. Lunar Taxi loiters in LLO until the next crewed mission. |
| 1c. Large Cargo Lander Delivery of Lunar Taxi to LLO | N/A | Large Cargo Lander | Lunar Taxi is fueled in LLO on subsequent crewed mission. | N/A | Large Cargo Lander delivers unfueled or partially fueled Lunar Taxi to LLO and cargo to the lunar surface. |
| 2. Crewed Mission with Propellant Tanker | N/A | Modified CEV SM (20 klb-class LOX/CH4 engine) | Pre-delivered Reusable Lunar Taxi loitering in LLO is fueled by propellant tanker | N/A | Concept 1 is the initialization mission for this concept. Propellant tanker is used to fuel LOX/CH4 Lunar Taxi loitering in LLO and the CEV SM prior to TEI. |

# Mission Operations Concepts
# Optimized Refuelable, Reusable Lunar Taxi, p 2 of 2

| Mission Ops Concept | Element Refueled in LEO | LOI Stage | Lunar Refueling | | Notes |
|---|---|---|---|---|---|
| | | | Element Refueled in LLO | Element Refueled on Lunar Surface | |
| 3a. Large Cargo Lander Mission to Support Lunar Taxi-Based Campaign | N/A | Large Cargo Lander | N/A | N/A | The Large Cargo Lander is assumed to be a single-use vehicle. |
| 3b. Lunar Taxi-Derived Cargo Lander Mission to Support Lunar Taxi-Based Campaign | N/A | Lunar Taxi-Derived Cargo Lander | N/A | N/A | The Lunar Taxi-Derived Cargo Lander is assumed to be a single-use vehicle. |
| 4. Large Cargo Lander Delivery of Lunar Taxi to the Lunar Surface | N/A | Large Cargo Lander | Lunar Taxi is fueled in LLO on the subsequent crewed mission. | N/A | Lunar Taxi is delivered to the lunar surface with ascent propellant load only. |