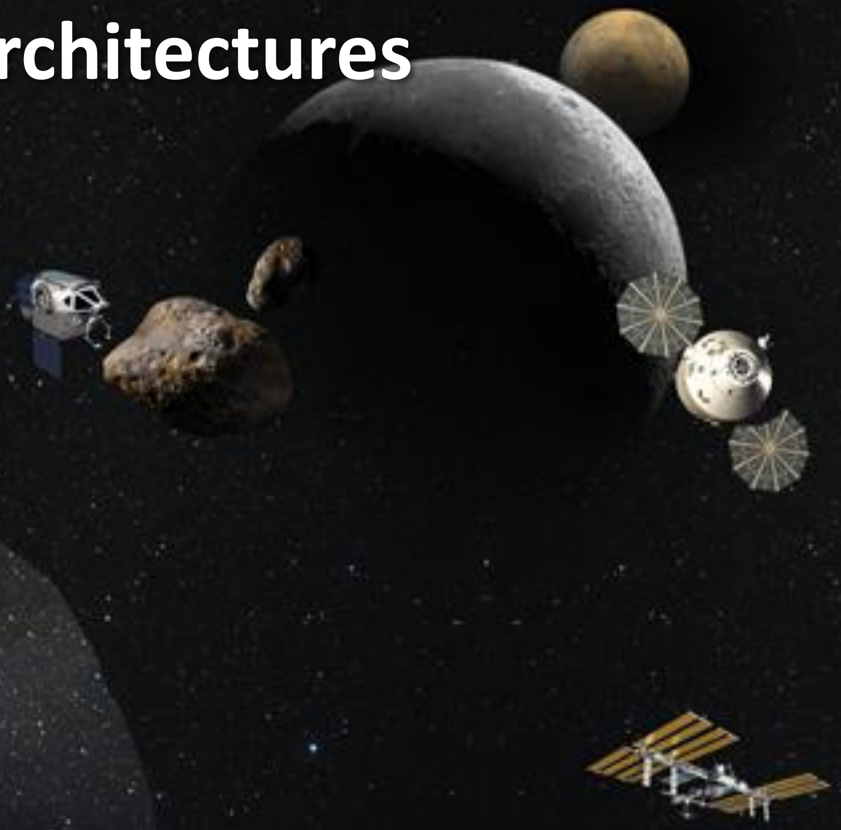
National Aeronautics and Space Administration

Human Lunar Exploration Architectures



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NASA – JSC

October, 2012

WELCOME ROCKET SCIENTISTS!

The Rocket Equation – It's Not Just a Good Idea, It's the LAW

$$\frac{dv}{dt} = \frac{T}{m} - g, \text{ rocket equation where}$$

$$m = m(t), \text{ mass of rocket and propellant a function of time}$$

$$\Longrightarrow dv = \frac{T}{m}dt - g \cdot dt$$

$$= \frac{-u\frac{dm}{dt}}{m}dt - g \cdot dt, \text{ where}$$

$$T = -u\frac{dm}{dt},$$

$$\text{since } \dot{m} = \frac{dm}{dt} \text{ is negative as the rocket}$$

$$\Longrightarrow dv = -u\frac{dm}{m} - g \cdot dt$$

$$\Longrightarrow \int_{v_o}^{v_{bo}} dv = \int_{m_o}^{m_{bo}} -u\frac{dm}{m} - \int_{t_o}^{t_{bo}} g \cdot dt, \text{ integrating from in}$$

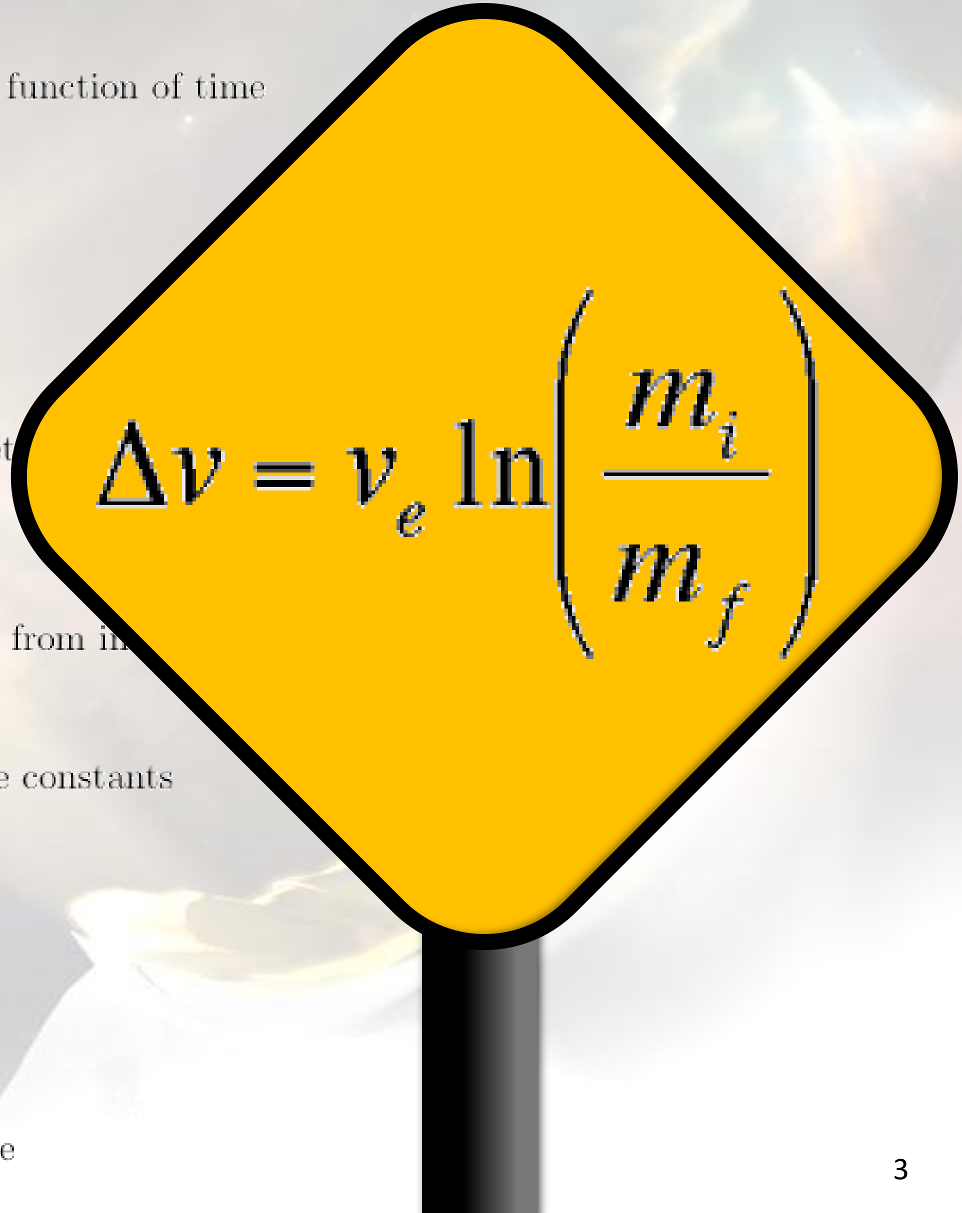
$$v\Big|_{v_o}^{v_{bo}} = -u\int_{m_o}^{m_{bo}} \frac{1}{m}dm - g\int_{t_o}^{t_{bo}} dt, \; u \text{ and } g \text{ are constants}$$

$$(v_{bo} - v_o) = -u \cdot \ln(m)\Big|_{m_o}^{m_{bo}} - g \cdot t\Big|_{t_o}^{t_{bo}}$$

$$= -u\left[\ln(m_{bo}) - \ln(m_o)\right] - g[t_{bo} - t_o]$$

$$= -u \cdot \ln\frac{m_{bo}}{m_o} - g[t_{bo} - 0]$$

$$\Longrightarrow \therefore \boxed{(v_{bo} - v_o) = u \cdot \ln\frac{m_o}{m_{bo}} - g \cdot t_{bo}}, \text{ using ln power rule}$$



How You Get There/What You Do There

Human Lunar Exploration is a function of two primary variables:

- The transportation architecture (“How You Get There”)

  and

- The Surface Mission Architecture (“What You Do There”)

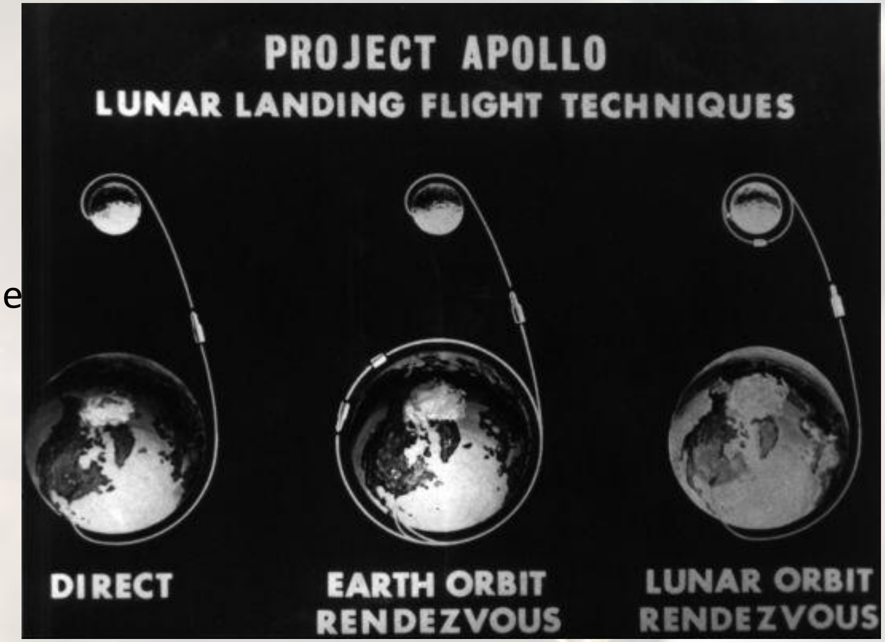
These two variables are utterly interrelated, but are often decided without regard to the other

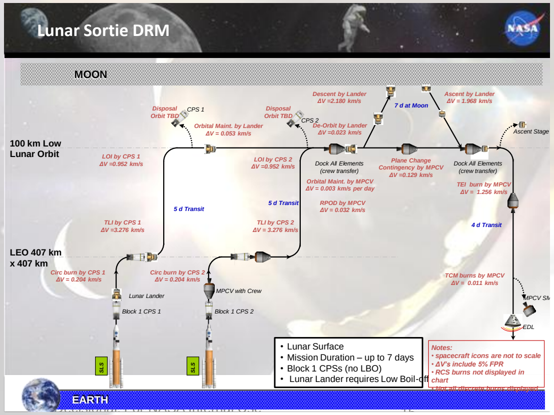
Further, “What you do there” is often a function of what you <u>can</u> <u>get</u> there!

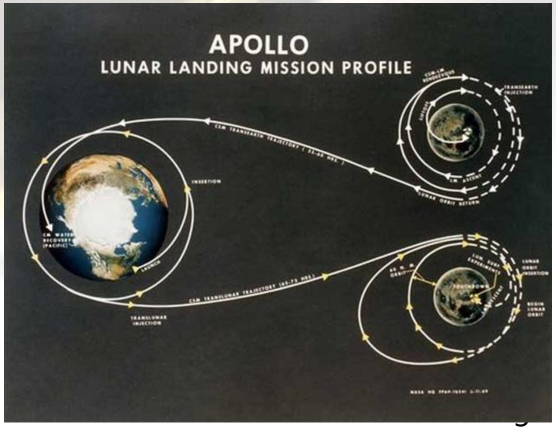
How You Get There:
Current Lunar Transportation Options

Lunar Transportation can be further defined by a series of architectural choices:

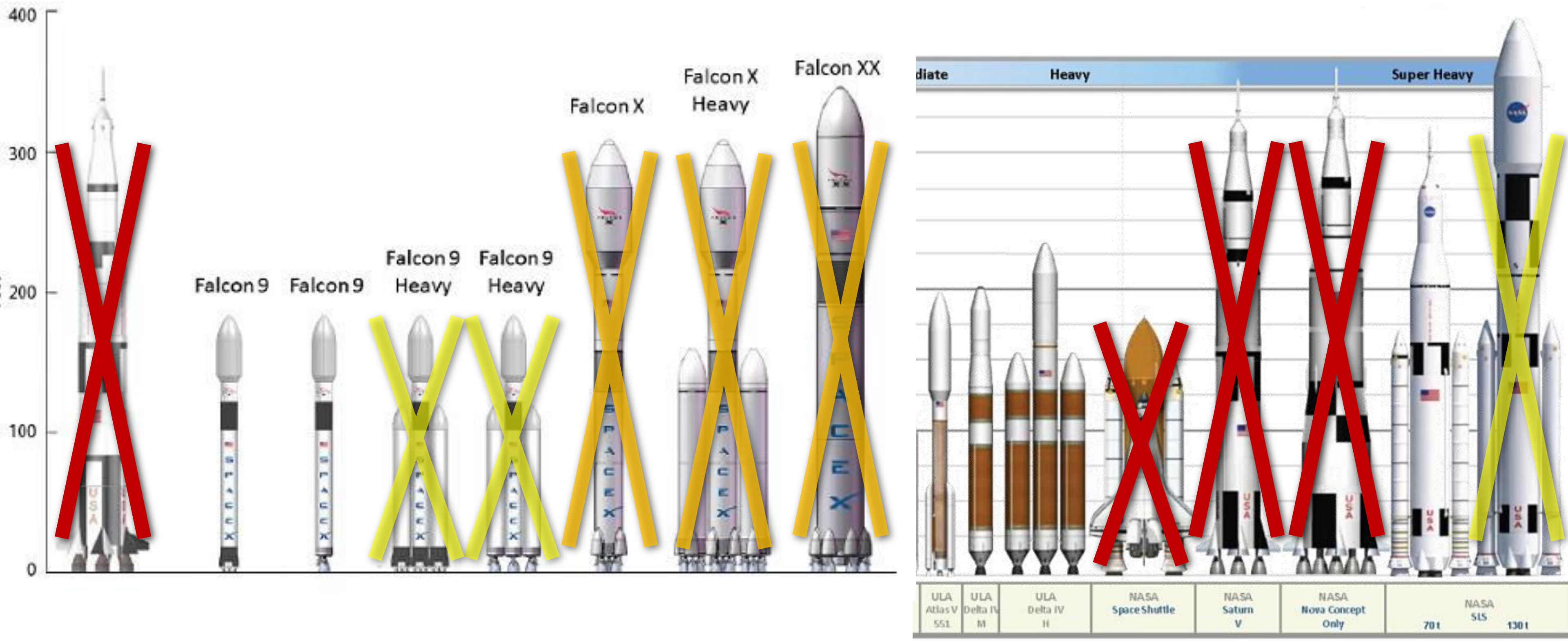
- Launch vehicle capability
  - Space Launch System (Block 1, 1A, II)
  - Falcon (9, 9 Heavy, X)
  - Delta IV (Medium, Medium+, Heavy)
  - International Launch Vehicles (HIIA, Ariane
- Staging locations
  - None (direct)
  - Low Earth orbit (LEO, includes ISS)
  - High Earth Orbit (HEO)
  - Libration Points (L1, L2)
  - High Lunar Orbit (HLO)
  - Low lunar orbit (LLO)







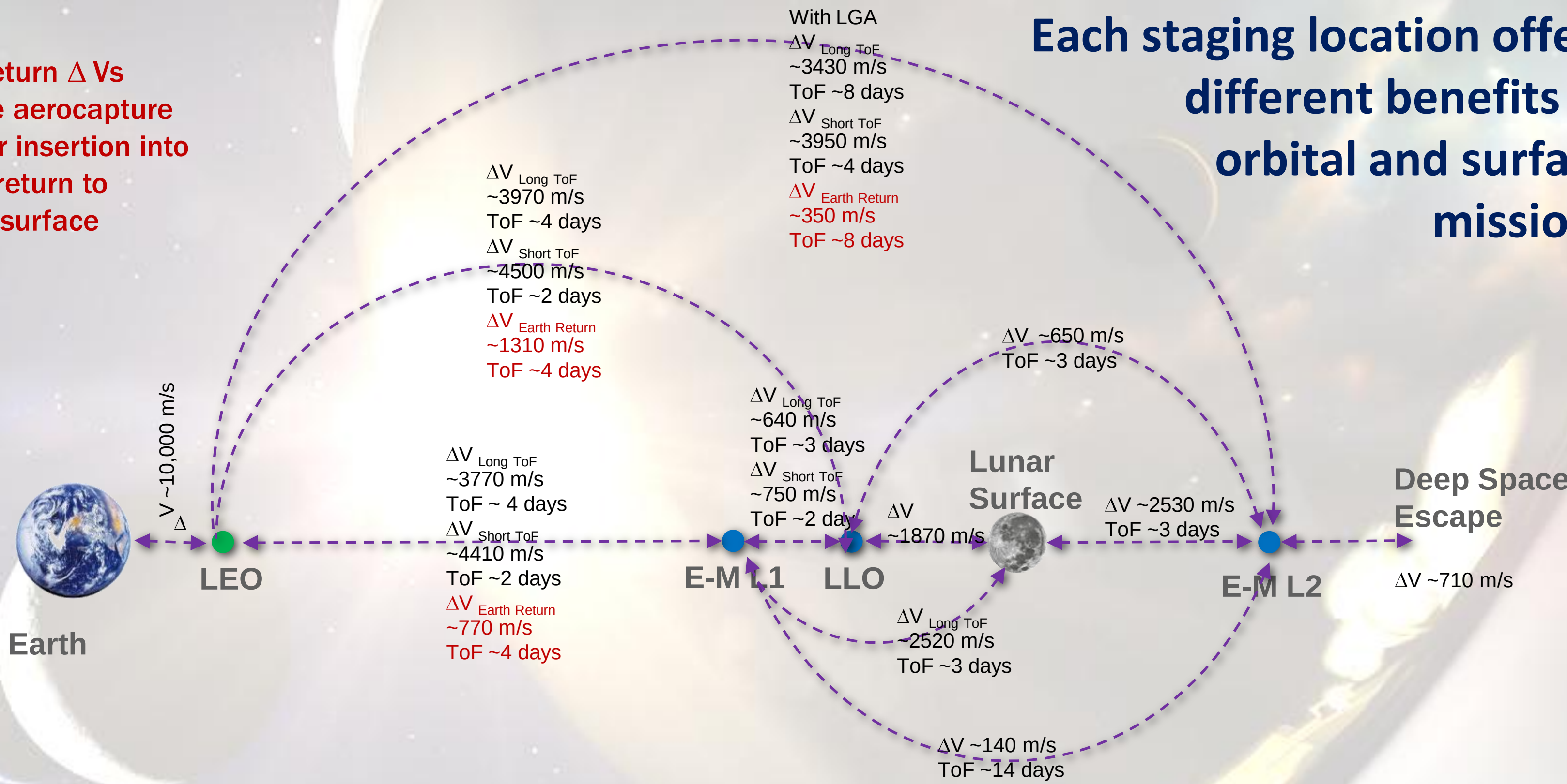
Current Launch Vehicle Options



Earth-Moon Delta-V/ToF Network

Earth return Δ Vs assume aerocapture used for insertion into LEO or return to Earth's surface

Each staging location offers different benefits to orbital and surface missions



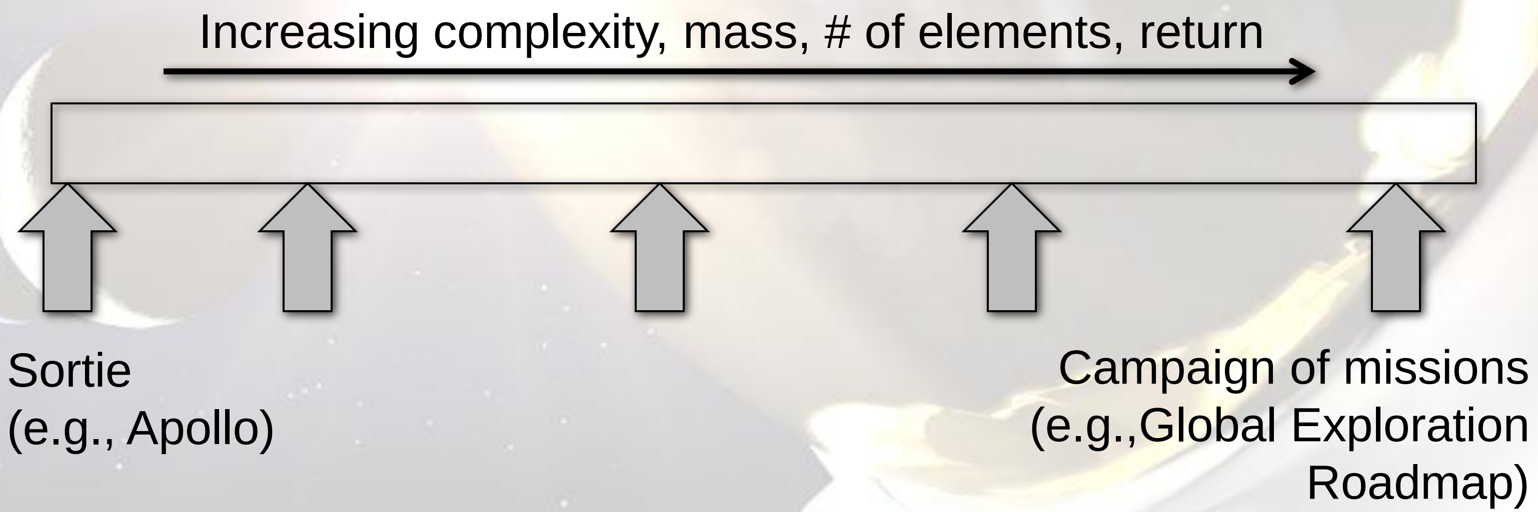
LTO	**Lunar Transfer Orbit**
LLO	**Low Lunar Orbit**
E-M L1	**Earth-Moon Libration Point L1**
E-M L2	**Earth-Moon Libration Point L2**
LEO	**Low Earth Orbit**

Staging location will affect :

- Flight time to/from the surface
- Surface access
- Mass that can be landed
- "Split" of maneuvers among propulsive stages

"What You Do There" – Lunar Surface Mission Options

- **Like transportation, the lunar surface mission is further defined by a series of mission content and operational choices**
- **The combination of these choices will determine the overall scope of the mission**



Lunar Surface Mission Variables

Increasing complexity, mass, # of elements, return →

Sortie — Campaign

Science Content	Sortie geology	Multidisciplinary science
Surface Area Explored	Local (EVA walking distance)	1000's of km
Landing site diversity/access	Polar/equitorial	Global access
Surface Mission Duration	Lunar daytime	Multiple months
EVA hours	2 crew minimum EVA	Full crew maximize EVA hours
Amount of self reliance	None	Autonomy + full ISRU
SKG's addressed	Few	Most
Human Research addressed	Few	Most
Technology infusion	TRL now	Maximize new technology
Contribution to Mars preparation	Minimal	Fully Mars focused
International participation	None	Fully integrated
Commercial participation	None	Fully integrated

Lunar Surface Mission Study History

- 1985 Lunar Bases book (Mendell)
- 1988 Eagle Engineering LBSS Study
- 1989 90-day study
  - 4 options
- 1990 LMEPO Architectures
  - 4 options
- 1991 Synthesis Group
- 1992 First Lunar Outpost
- 1993 LUNOX
- 1999 Decadal Planning Team (DPT)
- 2001 NEXT
- 2003 Space Architect Studies
- 2004 Concept Exploration and Refinement (CE&R) Studies
- 2004 LaRC/JSC Transportation Studies
- 2005 ESAS
- 2006 LAT 1
- 2007 LAT2
- 2008 Cx/LSS Surface Architecture Reference (SARD)
- 200x LSS Scenarios
- CxAT-Lunar
- 2010 GPOD
- 2011 HAT

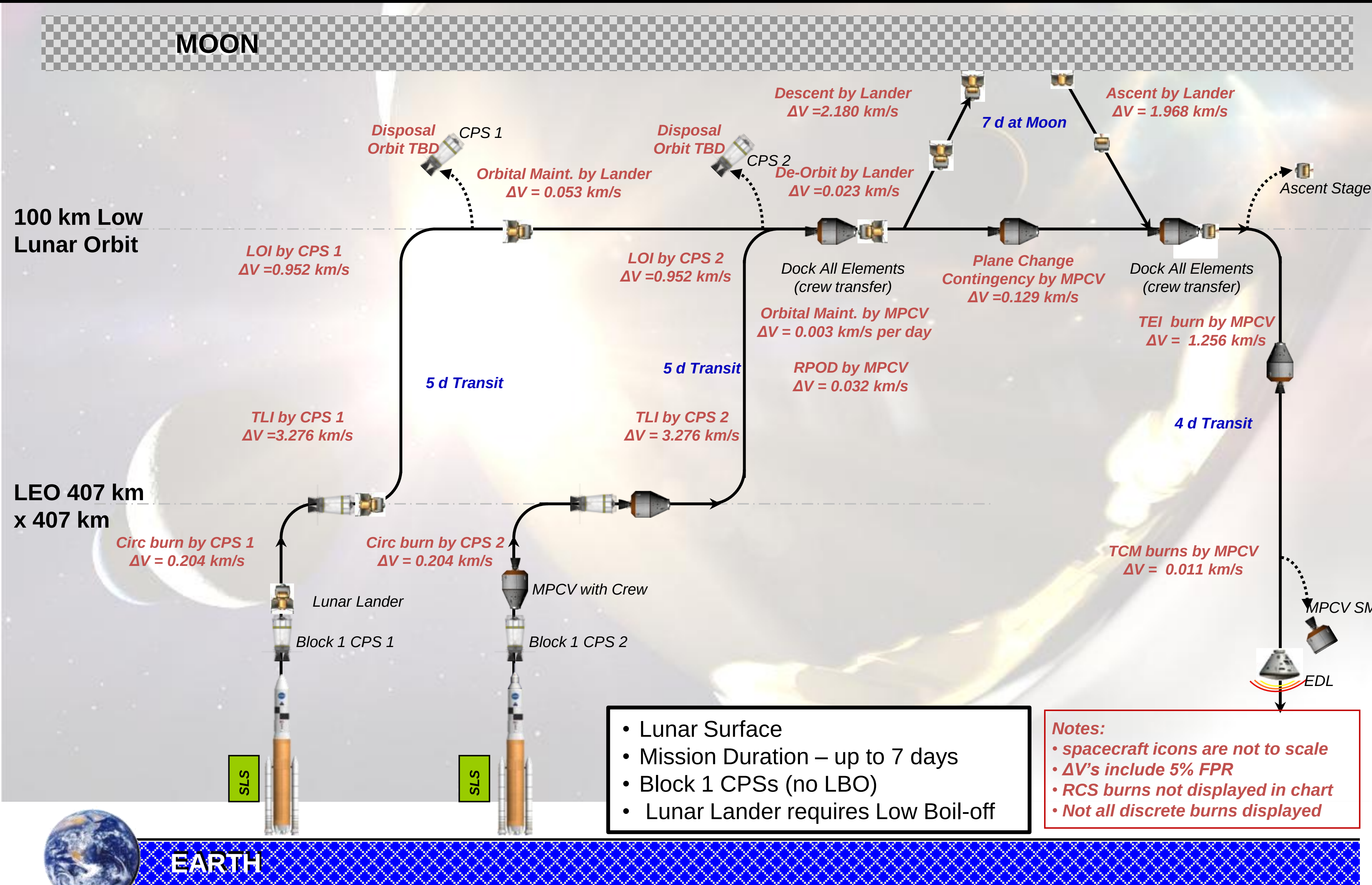
Option 1 – Mini-habitat elements with Crew Lander (LAT-1)
Option 2 – Mini-habitat elements with Crew/Cargo Lander
Option 3 – Single Delivery, Monolithic Habitat
Option 4 – Mobile Lander Habitat System
Option 5 – Early Delivery of Pressurized Rover
Option 6 – Nuclear Surface Fission Power


LSS Scenarios Families

Scenario	Description
4	Rebuild of LCCR scenarios increasing crew flights to at least 2 per year
5	Nuclear power based scenarios – Use a fission reactor as the primary power source
6	Power beaming scenarios – Consider ways to beam power from orbit or surface to systems
7	Recyclable lander – Scenarios that make massive reuse of lander components to build up the Outpost and surface infrastructure
8	Extreme mobility – Scenarios that deploy Small Pressurized Rovers early and use them as primary habitation
9	Side-mount or underslung Lander – Scenarios that support a lander configured to make unloading much easier than 6m deck
10	Refuelable lander – Scenarios that support a lander designed for multiple flights to and from LLO
11	Mars Centric – Scenarios that optimize Mars exploration needs early
12	Pre-Global Point-of-Departure Architecture
13	Cargo Capability Limited Architecture Study

LUNAR SURFACE- SORTIE

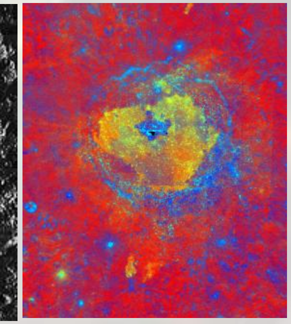
Lunar Sortie DRM

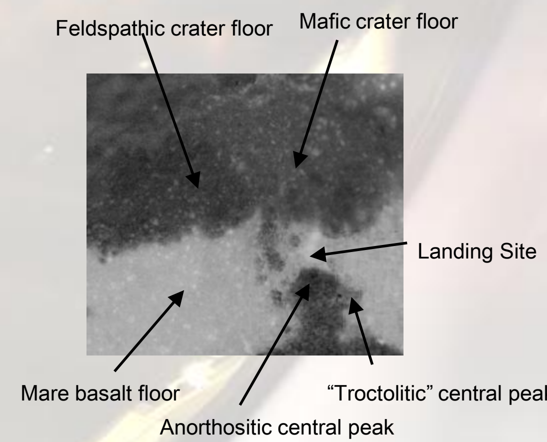


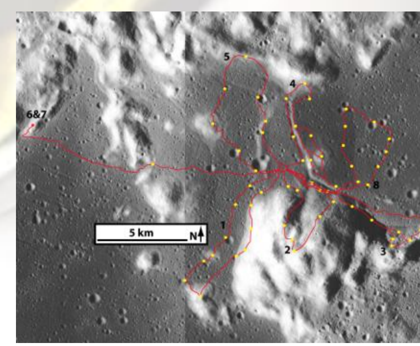
Tsiolkovsky Sortie Overview

(Helper, Shearer, Spudis, Bleacher, 2006)

- **Landing site near the central peak of Tsiolkovsky Crater**
- **4 Crew performs EVA each landed day (28 EVA days total)**
- **Crew lives out of lander's hab module**
- **2 unpressurized rovers**
- **<u>Geology emphasis – sampling of 4 different geological units within roving distance of landing site</u>**
- **1 long EVA of ~32 km round-trip (EVA "6/7")**
- **All other EVAs < 20 km round trip**
- **LRV traverse geological sampling**
  - Stop every kilometer and sample regolith
  - Selected rake samples
- **Ground penetrating radar**
  - Map subsurface structure and determine mare thickness
- **Deploy network of instrument station sites**
  - Geophones
  - Seismic sources
  - Surface magnetometers



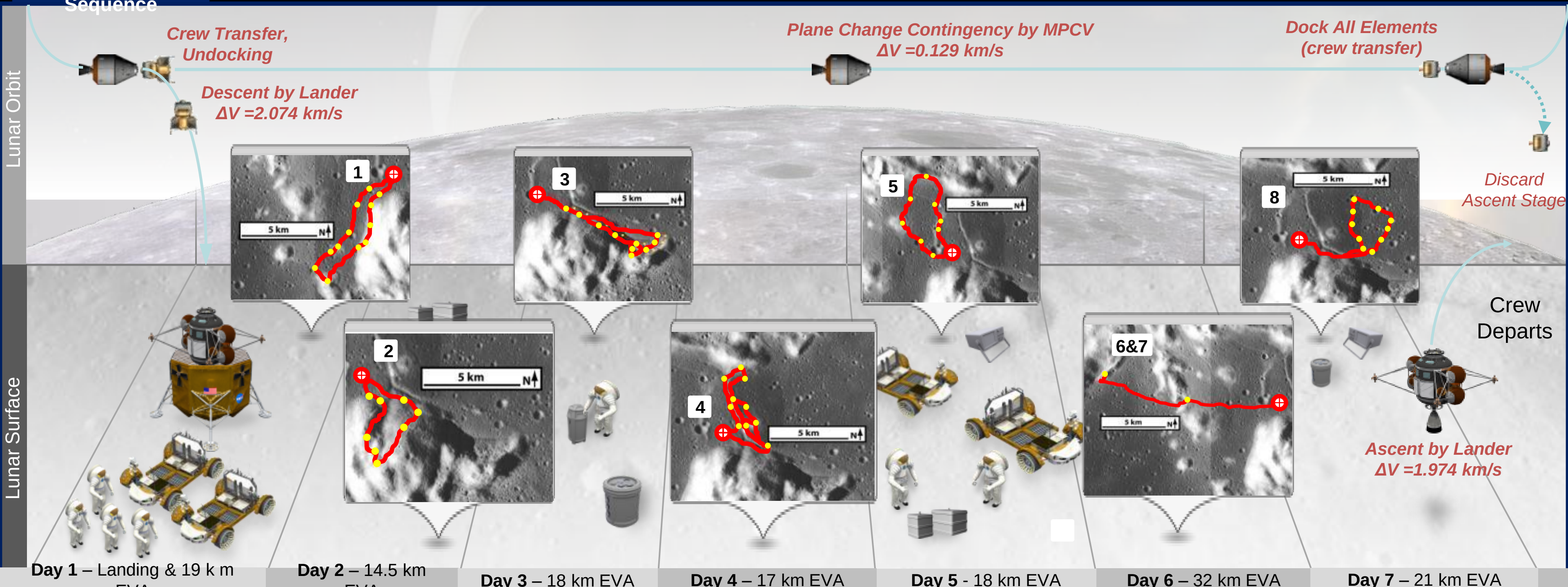




Tsiolkovsky Sortie Overview

"Street View" Chart

Mission Sequence



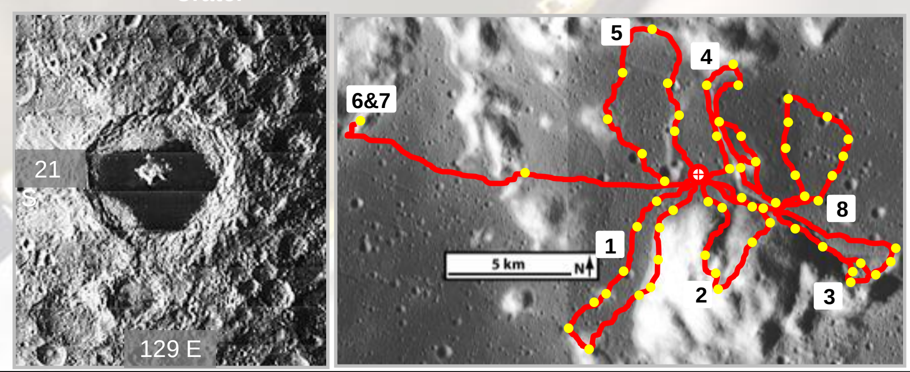
Mission Summary

- Four crew spend one week exploring the Tsiolkovsky Crater in daily EVAs.
- Geology focus with significant sample return
- Unpressurized rovers, maximum 32 km traverse
- Ground penetrating radar to map subsurface structure and determine mare thickness
- Geologic instrument deployment

Mission Elements

- 2x Rechargeable unpressurized rovers
- Geological Sampling tools
- Ground penetrating radar
- Network of instrument station sites
  - Geophones
  - Seismic sources
  - Surface magnetometers

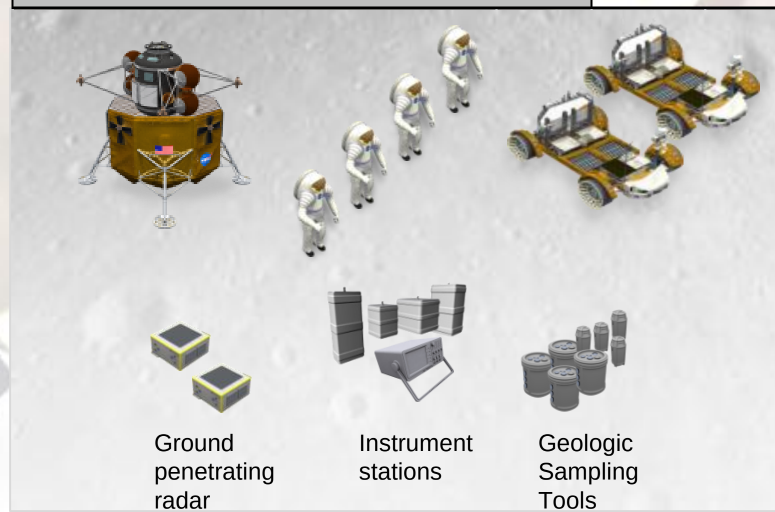
Mission Site: Tsiolkovsky Crater



Tsiolkovsky Sortie Overview
Destination Elements

- **Unpressurized rovers (2)**
- **Ground penetrating radar**
  - Map subsurface structure and determine mare thickness
- **Instrument stations**
  - Geophones
  - Seismic sources
  - Surface magnetometers
- **Geological sampling tools**
  - Core drills
  - Sample rakes
  - Bulk sample tool
  - Sample bags
  - Cameras

Element	SAIF ID	Mass (t)	FSE (t)
Unpressurized Rovers (2)		400.00	
Ground Penetrating Radar (2)		40.00	
Instrument Stations (4):			
Geophones		44.80	
Seismic sources		incl. above	
Surface magnetometers		34.40	
Geologic Sampling Tools:			5.90
Core drills (2)		33.80	
Sample rakes (2)		3.00	
Bulk sample tools (4)		16.80	
Sample bags		8.00	
Cameras (4)		25.00	
Sample Return Container (6)		24.00	
Total		635.70	
Capability		500.00	
Difference		-135.70	



GER-DERIVED LUNAR DESTINATION DRM

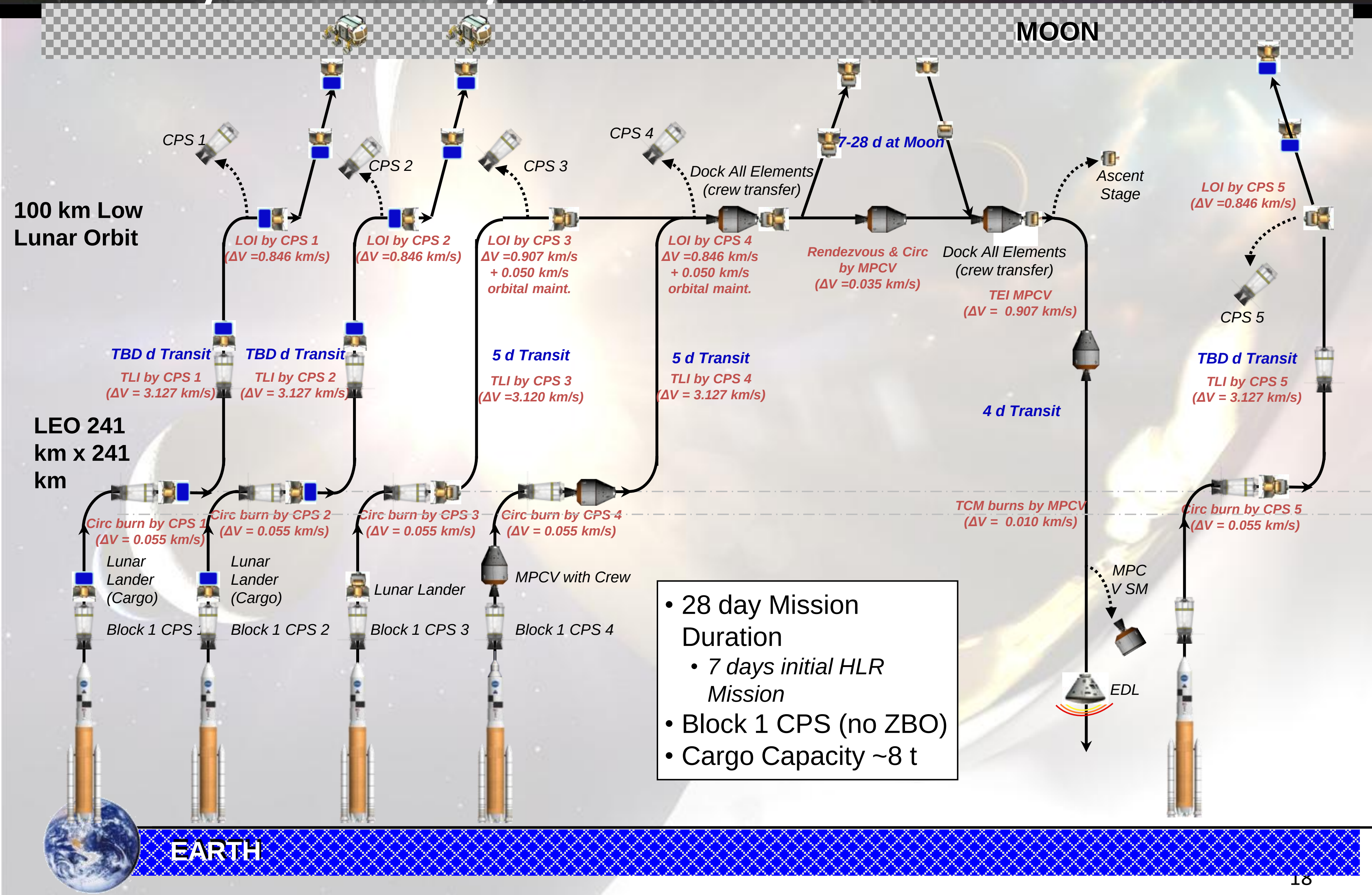
GER-Derived Lunar Destination DRM

This lunar destination DRM is derived from the GER Lunar mission:

- Multiple (5) extended stay (up to 28 day) missions, beginning with robotic precursors and initial cargo landers
- Lunar surface emphasis is to test the capabilities and learn self-sufficiency in preparation for human Mars missions
- 4 crew
- Polar site
- Small cargo landers (1 mt)
- Larger cargo landers (8 mt)
- Automated predeployment
- Rover chassis
- Resources
- Pressurized Rover: Mobile Habitation
- Long-distance mobility (100’s km)
- Technologies:
  - Mobility
  - Dust control
  - Habitation
  - Autonomous landing and hazard avoidance
  - Advanced surface power (if available)

GER – Lunar Surface Mission

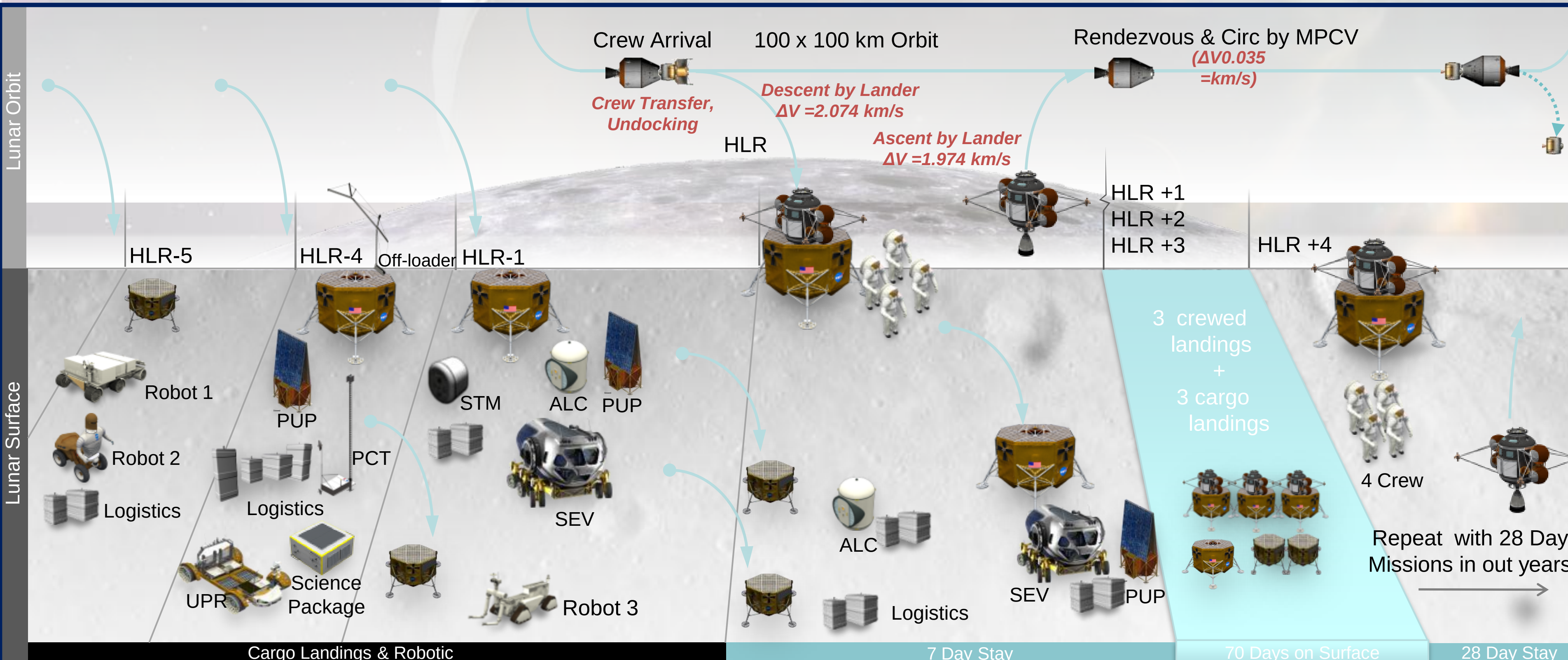
7-28 day Extended Stay Mission with HLLV



- 28 day Mission Duration
  - *7 days initial HLR Mission*
- Block 1 CPS (no ZBO)
- Cargo Capacity ~8 t

GER Extended Stay & Surface Mobility Emphasis

4 large cargo landers, 6 small cargo landers, 5 crewed missions



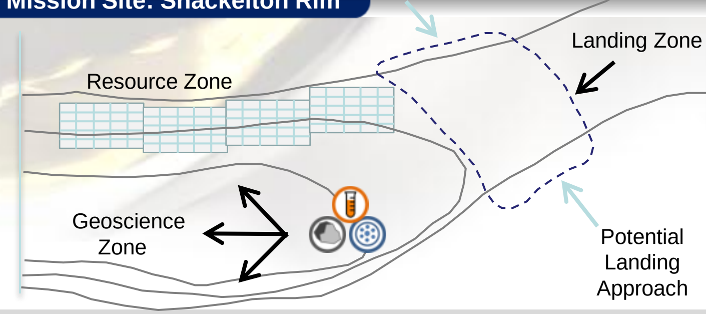
Mission Summary

Five years prior to Human Lunar Return, cargo missions begin to deliver robotics and science equipment. The crew arrives with two large cargo landers and two small logistics landers, and spends 7 days on the surface. Over the next five years, a total of five crewed missions with surface stays of up to 28 days are completed.

Select Elements

Element	QTY	Element	QTY
Centaur 2	1	ALC	7
Rapier	1	STM	1
PUP	3	SEV	2
PCT	1	Selene	1

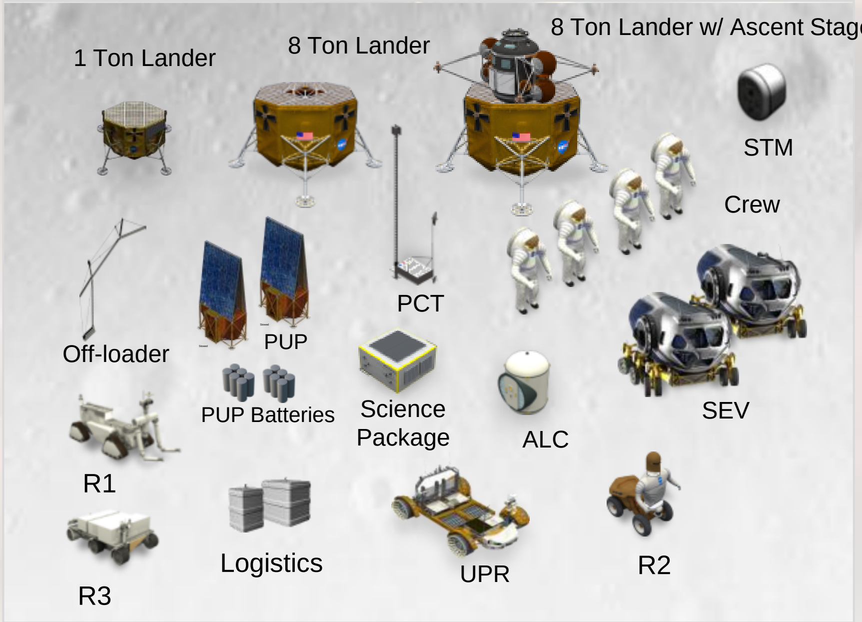
Mission Site: Shackelton Rim



GER Destination Elements

- **The GER DRM accumulates surface elements prior to the crew's arrival via a combination of small (~1 mt) and large (~8 mt) cargo landers**

Element	QTY	Notes
Crew	4	International Astronaut Crew
PUP (Portable Utility Pallet)	3	• 100 kW-hr battery storage each • 2 kW solar array each • Transported by SEVs
PCT (Portable Communications Terminal)	1	Provides high bandwidth communications Transported by PUP It is assumed that at lease 1 LRS is on orbit
Robotic Precursor 1 (R1)	1	Small International Science Rover
Robotic Precursor 3 (R3)	1	Small International Science Rover
UPR (Unpressurized Rover)	1	Provides Excursion Capability before second SEV arrives
Off-loader (LSMS or Cradle)	1	Can tele-robotically offload cargo landers or be used off the back of an SEV.
Science Package	1	Pre-deployed in second mission
Logistics	9	Multiple logistics payloads required for 28 day capability
STM (Suitport Transfer Module)	1	Allows transfer of material through a Suit-port
SEV (Space Exploration Vehicle)	2	200 kW-hr battery storage each Average speed toward destination = 5 km/hr

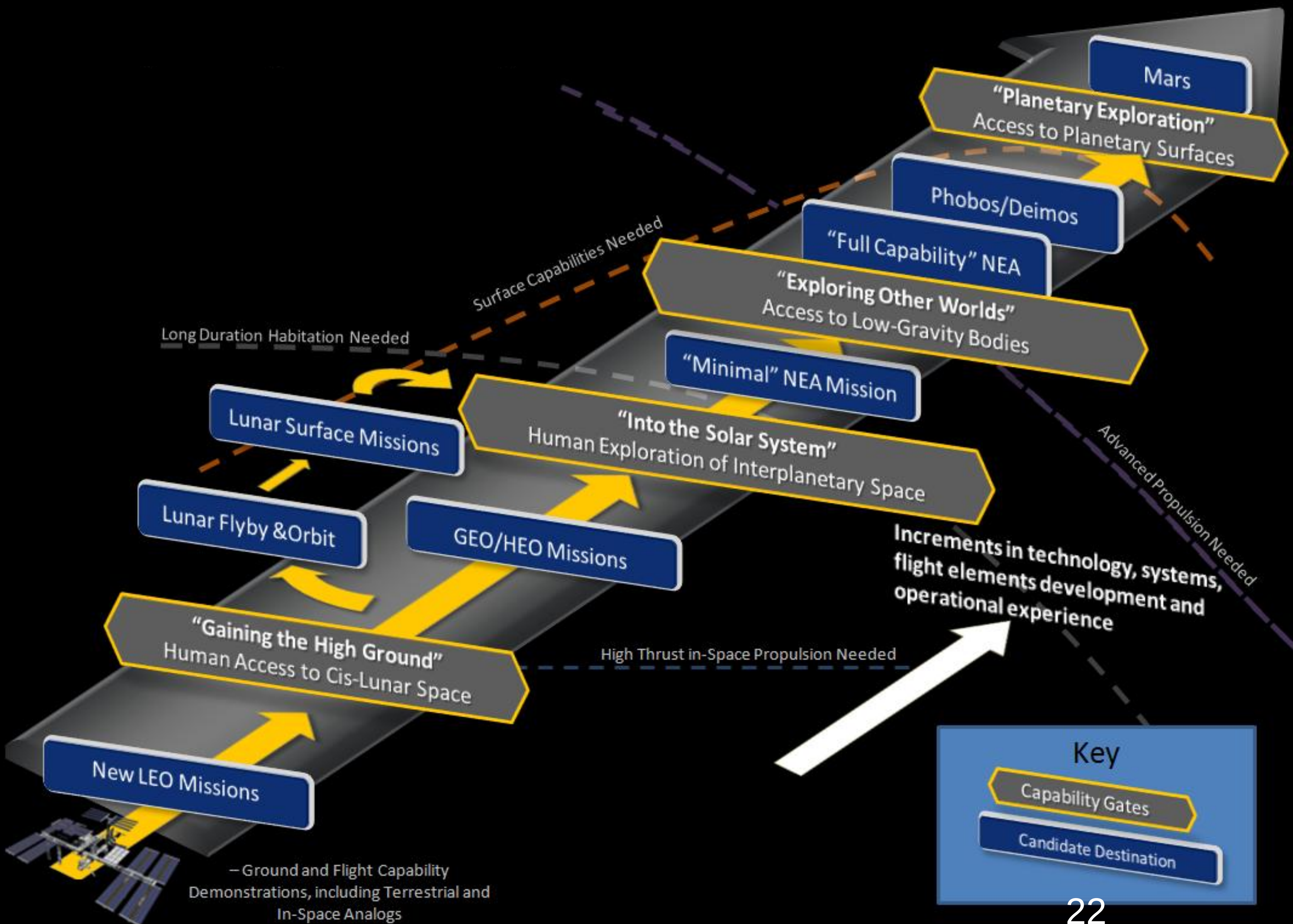


Element	QT(Y	Notes
Robotic Precursor 2 (R2)	1	Small NASA Robotic Assistant & Science Rover
ALC (Airlock Logistics Carrier)	7	Pressurized Logistics

Mission-Driven vs. Capability Driven

- In a perfect world, all space missions would be "Mission Driven" – the desired science (or other end goals) would dictate the size and scope of the mission.
  - Apollo example: "land a man on the moon and return him safely to the Earth" drove technology development and the design of all the mission elements.
  - Space Shuttle: reusability and large payload carrying requirements
- Most ALL current space missions are "Capability Driven" – the capabilities of existing launch vehicles and spacecraft technology limit what missions CAN be done, and missions are proposed within these capabilities
- Incremental capability increases (due mainly to new or incremental technology insertion) provides some relief to capability limitations
  - Mars Science Laboratory: 6 wheel rocker-bogey rover, Viking entry system, RTG power system (demonstrated capabilities); "sky crane" landing system, aeromaneuvering precision guidance (increased capabilities)

"Flexible Path" Exploration Architecture



Concluding Observations

- **Human lunar missions are shaped by 2 distinct, but related variables:**
  - Transportation architecture
  - Surface mission architecture
- **A wide range of lunar surface mission content is possible from most any cis-lunar staging location**
- **The physics of spaceflight has not changed since Apollo**
- **Technology has changed only incrementally since Apollo**
- **Therefore, the options available for the conduct of space missions have changed only incrementally since Apollo**
- **What HAS changed is NASA's shift to a capability-driven "Flexible Path Architecture"**
  - Near-term human exploration capabilities include the Space Launch System (SLS) , the Orion crew vehicle, commercial LEO capabilities, and the international partnership begun with the ISS

Thank you and congratulations, Rocket Scientists!

$$\Delta v = v_e \ln\left(\frac{m_i}{m_f}\right)$$