Lunar Extraction for Extraterrestrial Prospecting

FROM SCIENCE FICTION TO SCIENCE

LEEP

EXPLORER 2017

Caltech
SPACE CHALLENGE
March 26-31, 2017

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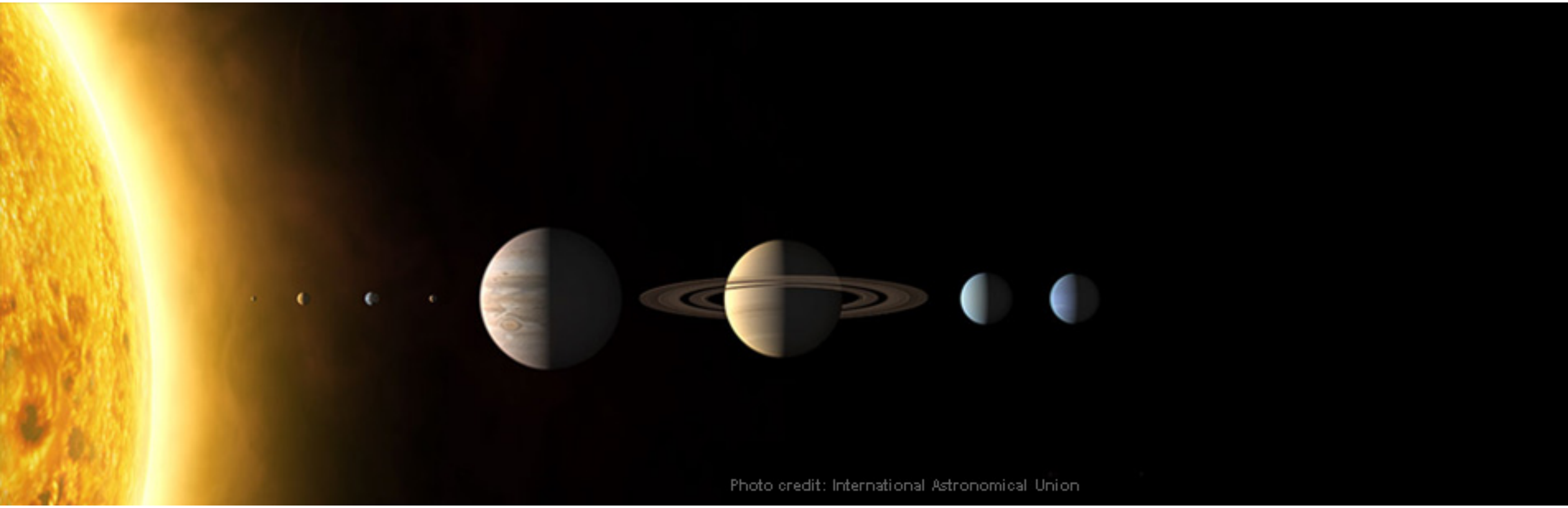
FROM THE MOON TO MARS IN ONE LIFETIME

LEEP is the Bridge Between Science Fiction and Science

- LEEP is the right platform to accomplish Proving Ground Technology Objectives:
  - *- Transportation: heavy launch capability, large cargo, deep space navigation and communication*
  - *- Working in Space: autonomous operation, in-situ resource utilization*
- Test autonomy without light time (if you want) and long-term potential recovery capability
- Fundamental platform for next stage of deep space exploration and a fuel-as-a-service industry

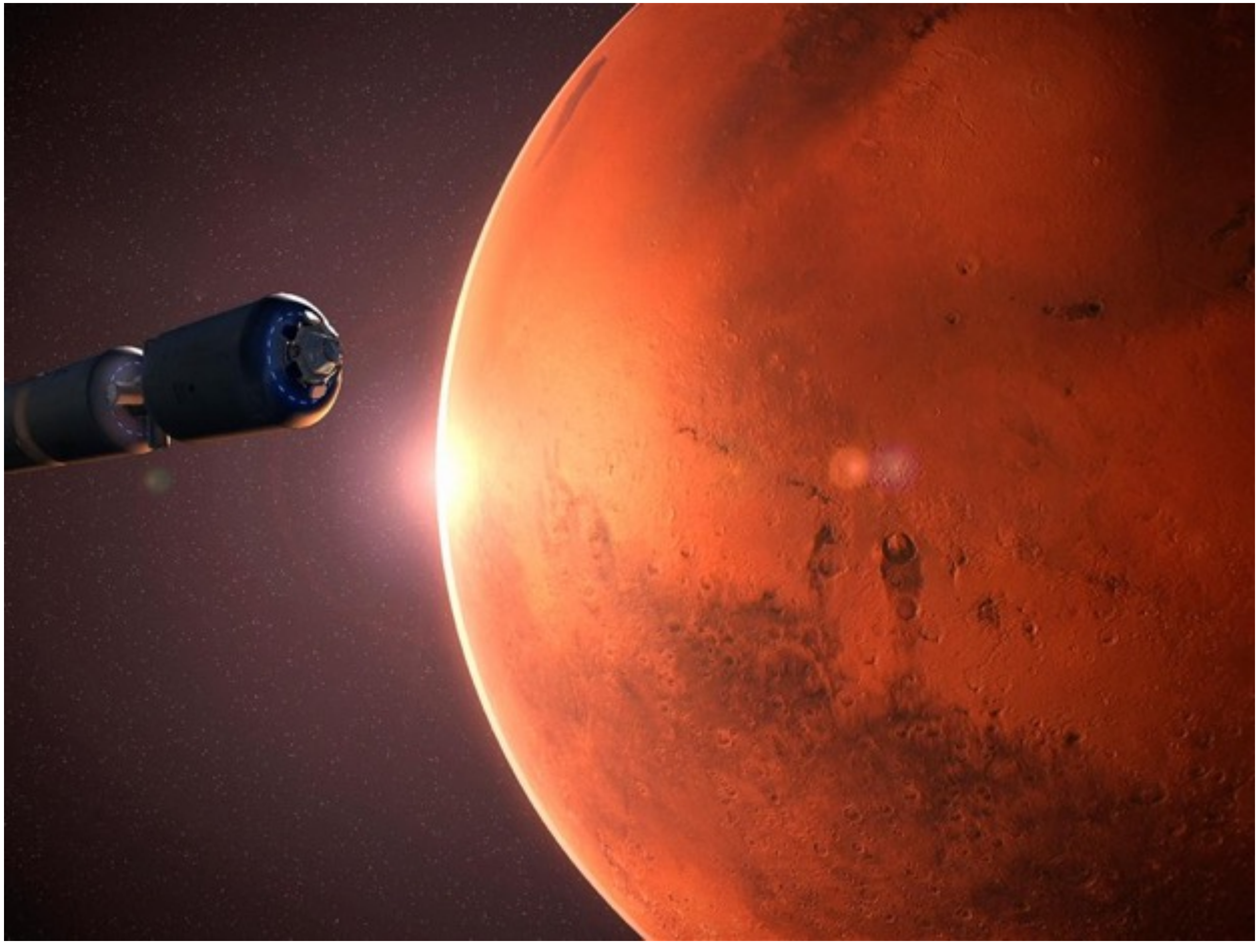
Benefits of LEEP

- Deep space exploration
- Open the universe to human kind
- Build partnerships



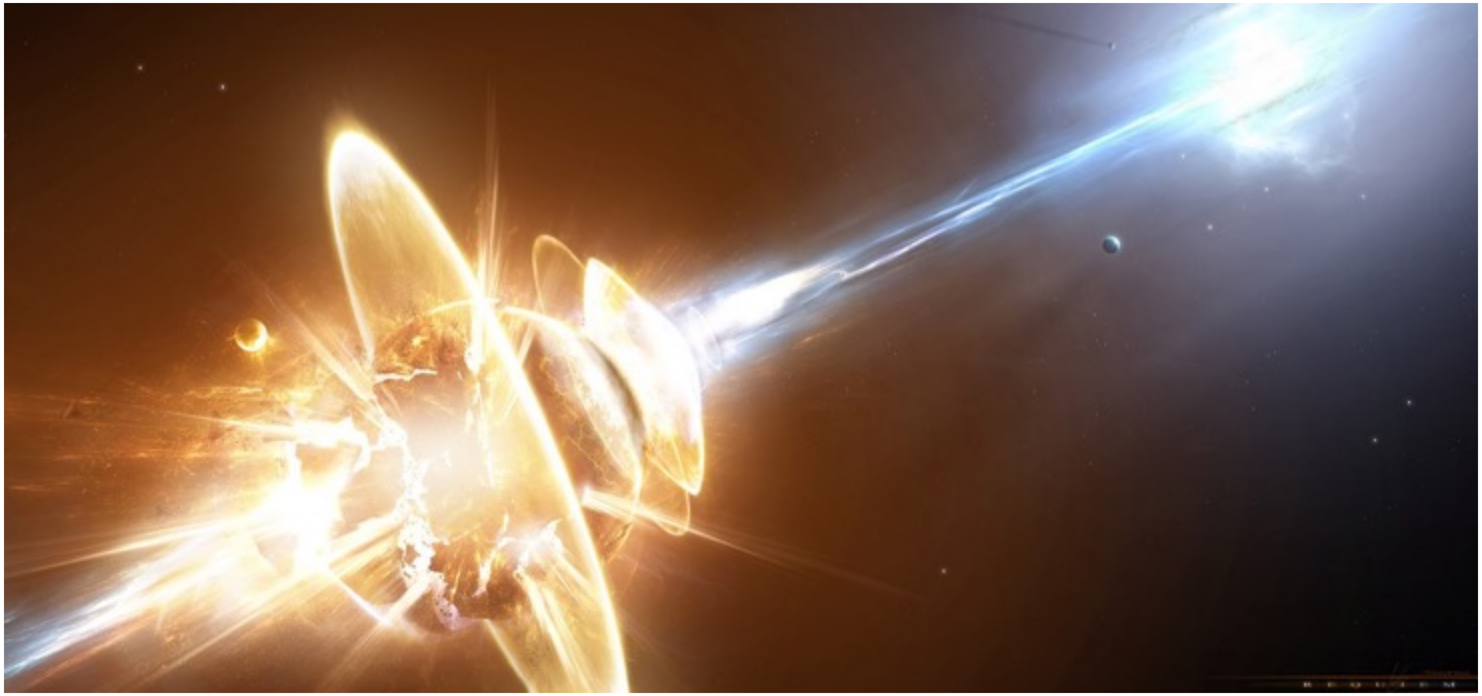
What is the mission?

In-space refueling of vehicle

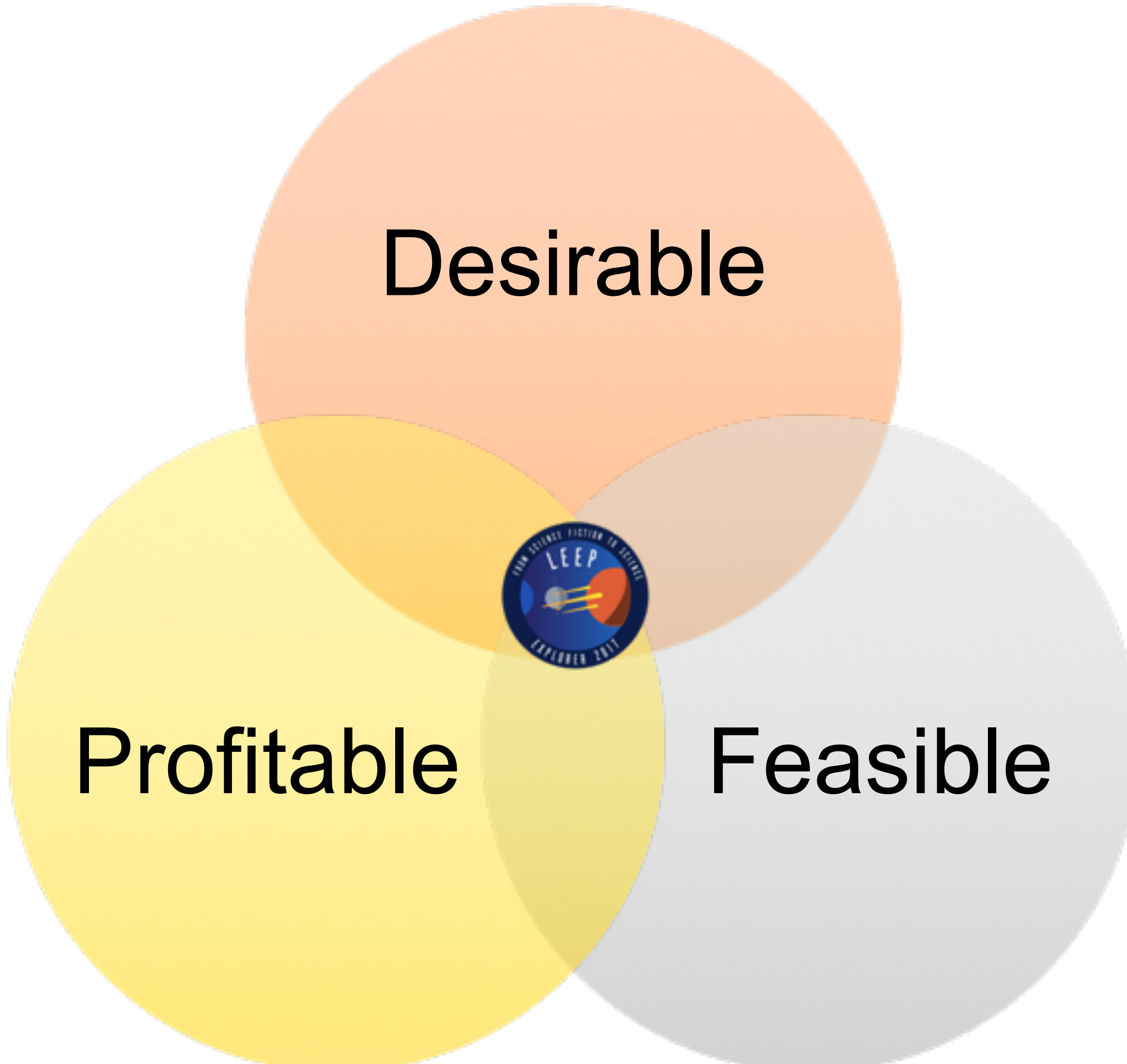


Risks

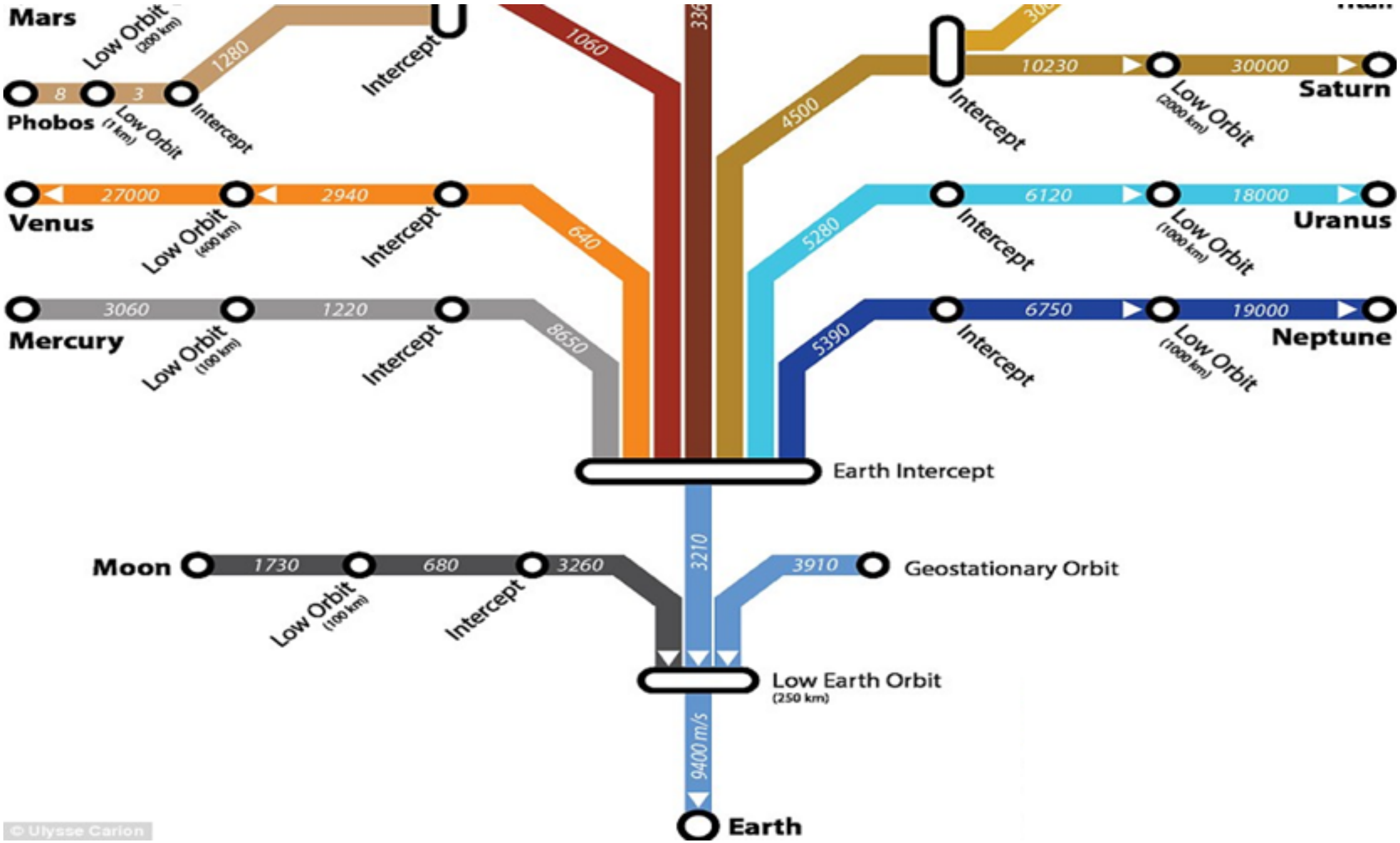
- Crash Rendezvous
- Single point of failure
- Failed Landing



Develop for Success



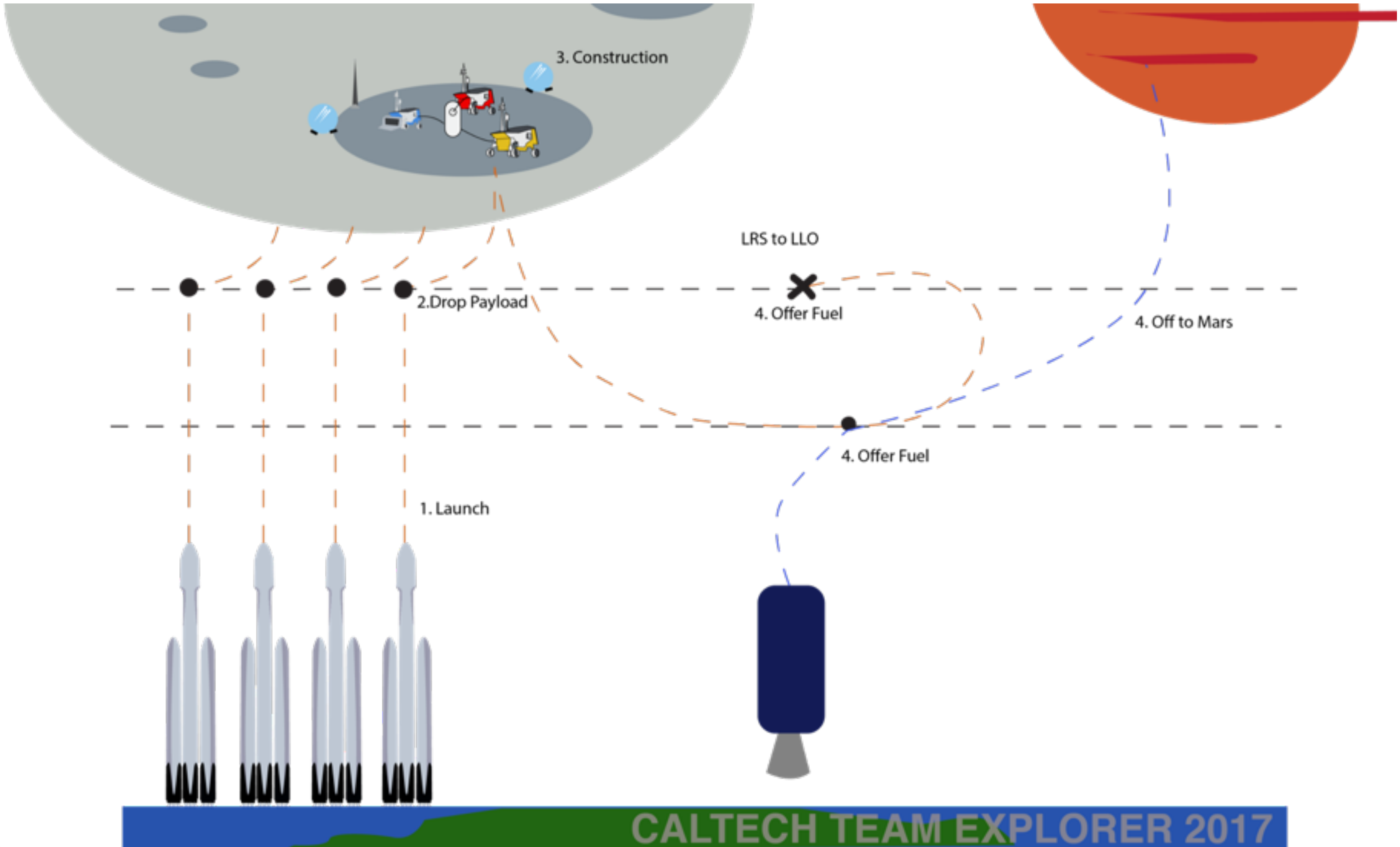
Construct for Success



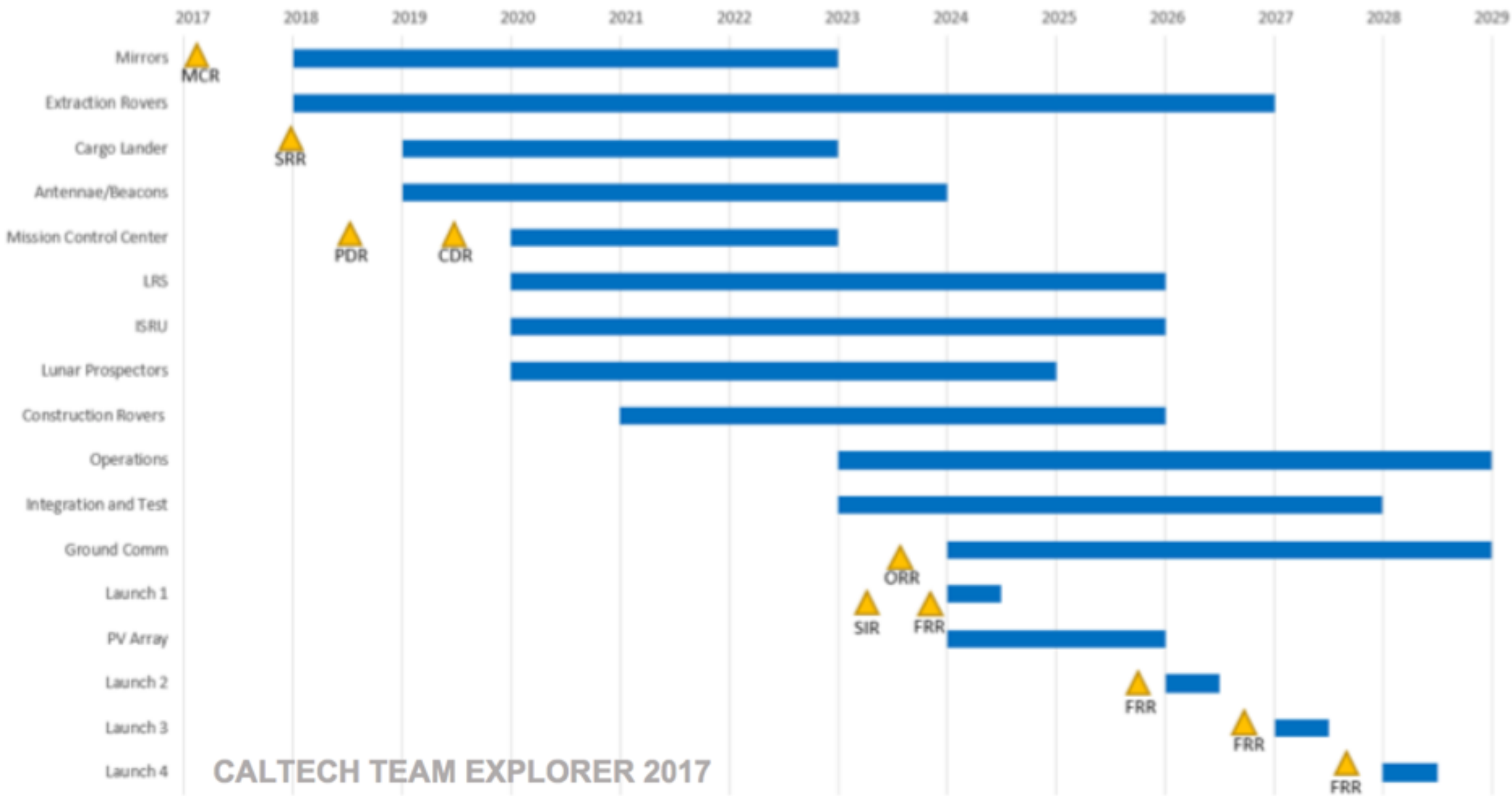
Options

- Rendezvous
- Location of transfer method:
  - Lunarport
  - Conversion
  - Storage
  - Power
- Resource Transfer to Orbit

Concept of Operations



Schedule



2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
Mirrors
MCR
Extraction Rovers
Cargo Lander
SRR
Antennae/Beacons
Mission Control Center
PDR
CDR
LRS
ISRU
Lunar Prospectors
Construction Rovers
Operations
Integration and Test
Ground Comm
ORR
Launch 1
SIR
FRR
PV Array
Launch 2
FRR
Launch 3
FRR
Launch 4
FRR
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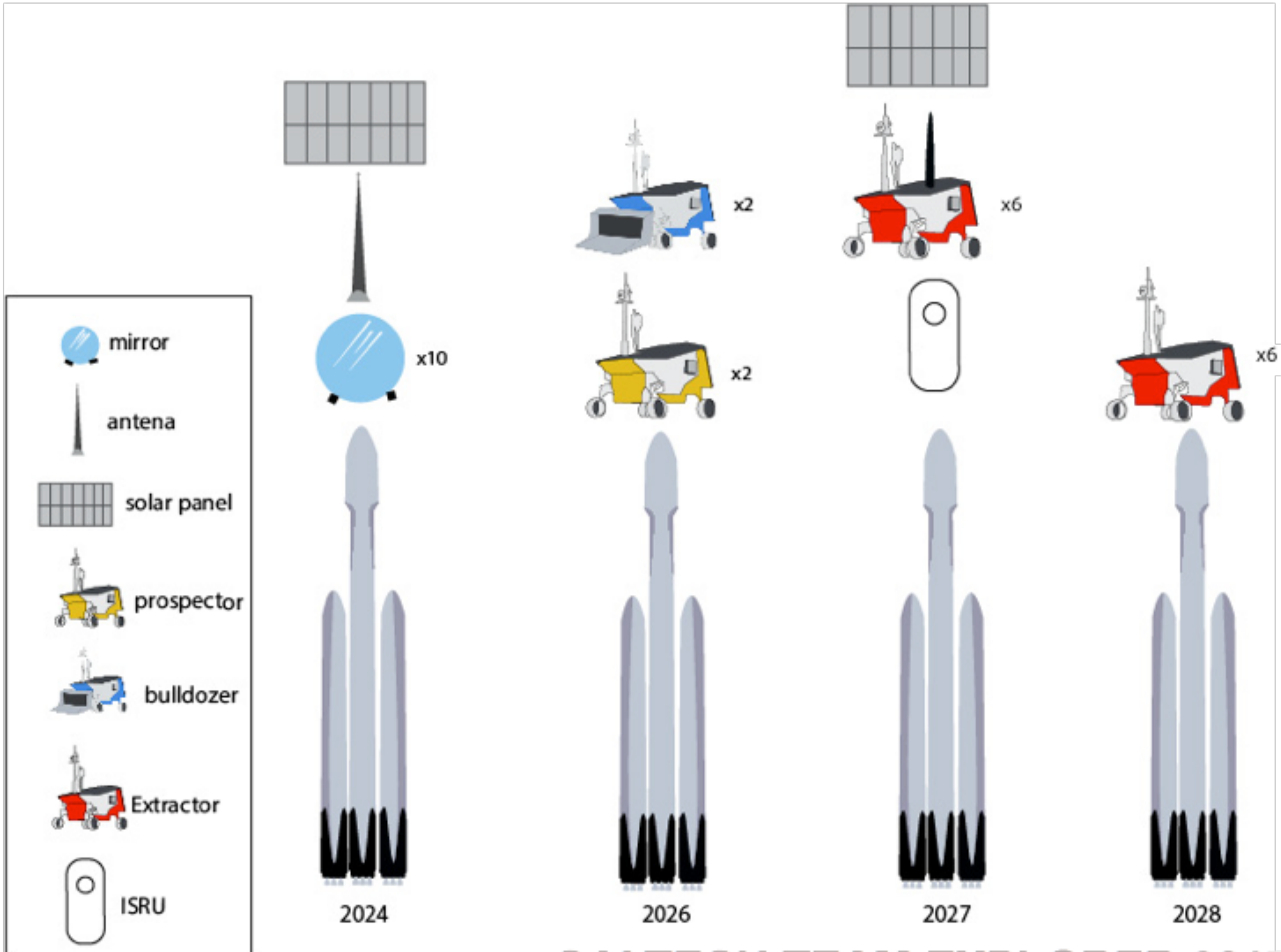
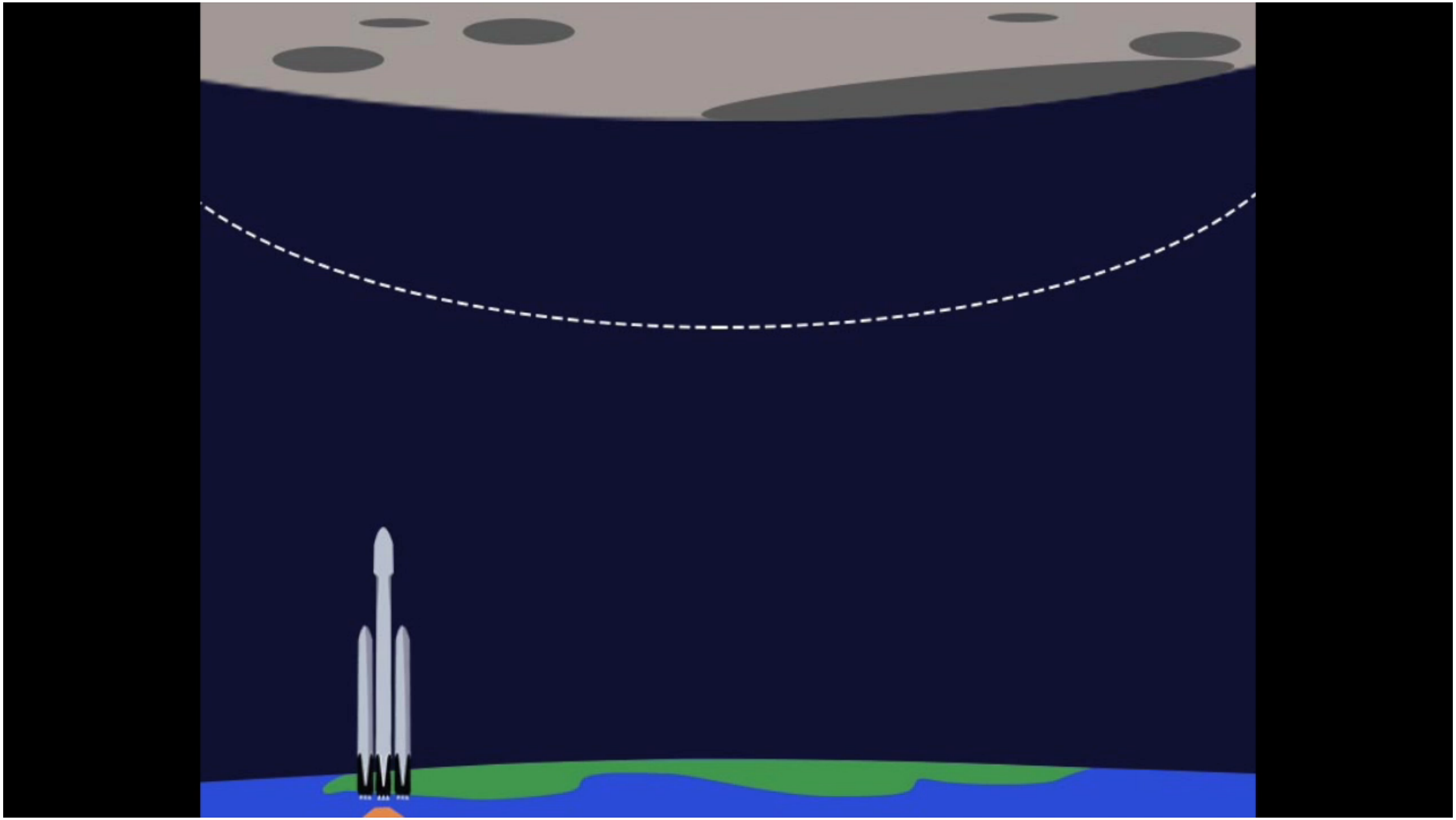
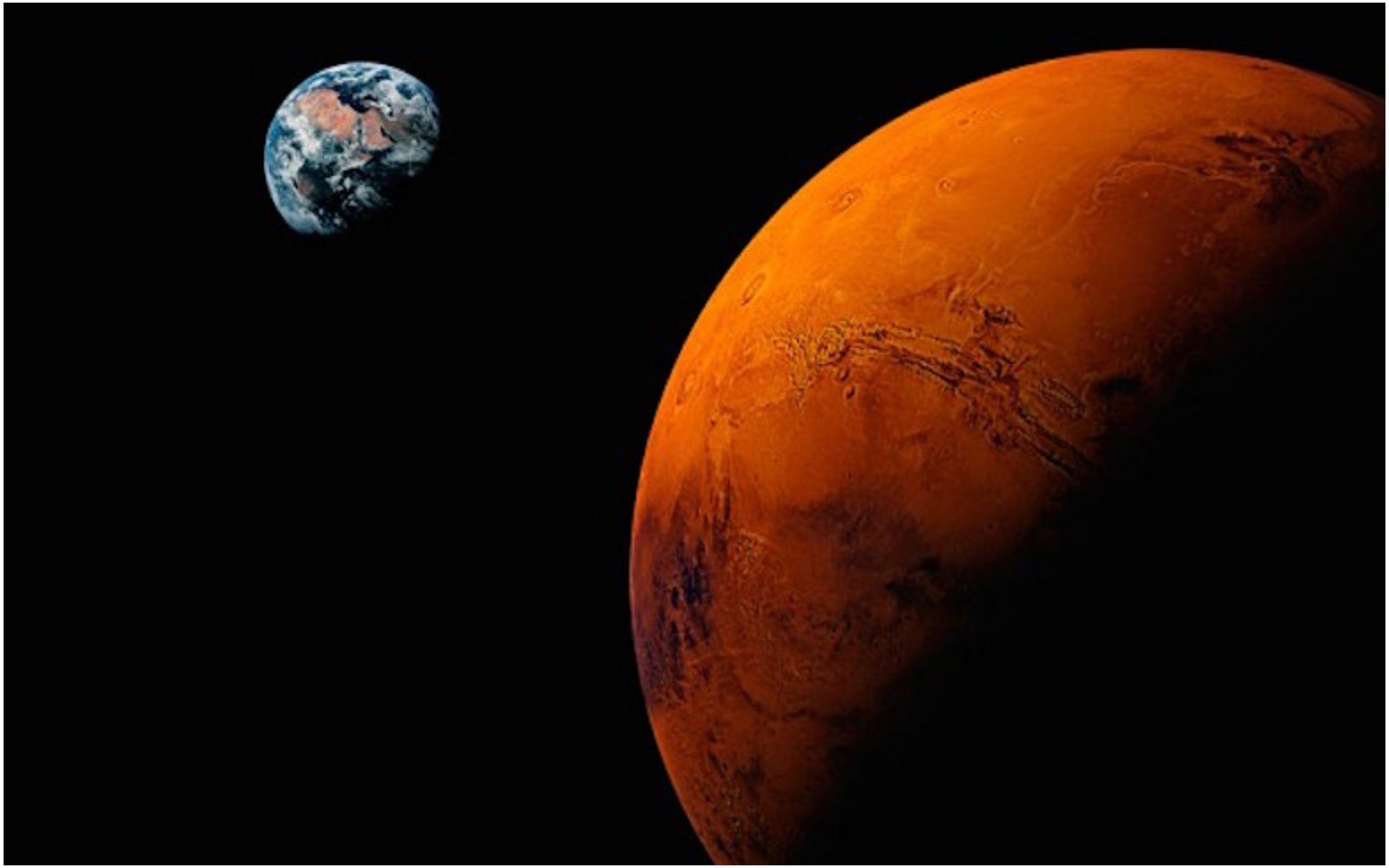
Launch Phase



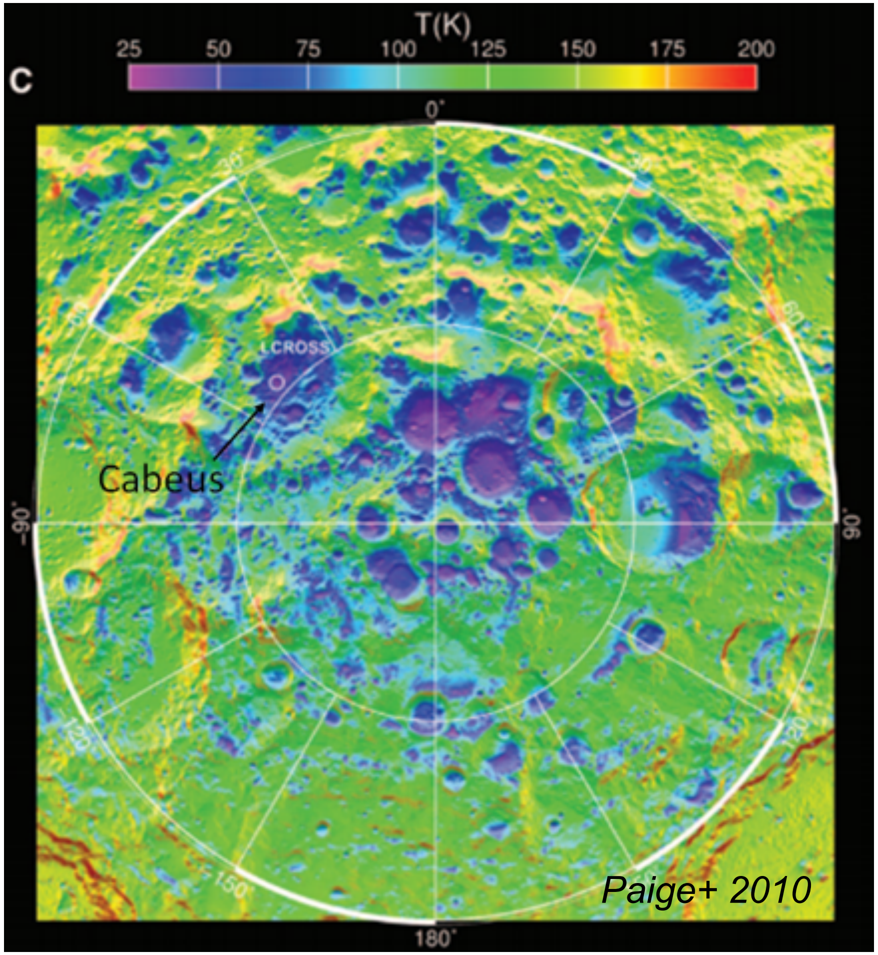
Launch Phase

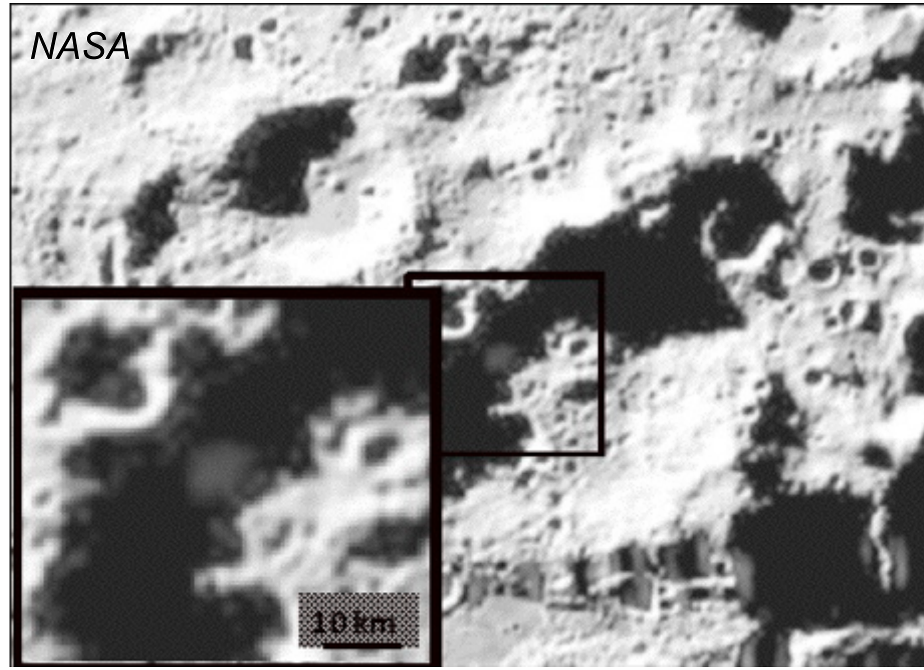


Missions to Mars by 2031



Site Selection: Cabeus Crater





Cabeus: the ***only*** Lunar location with verified H_2O in minable quantities

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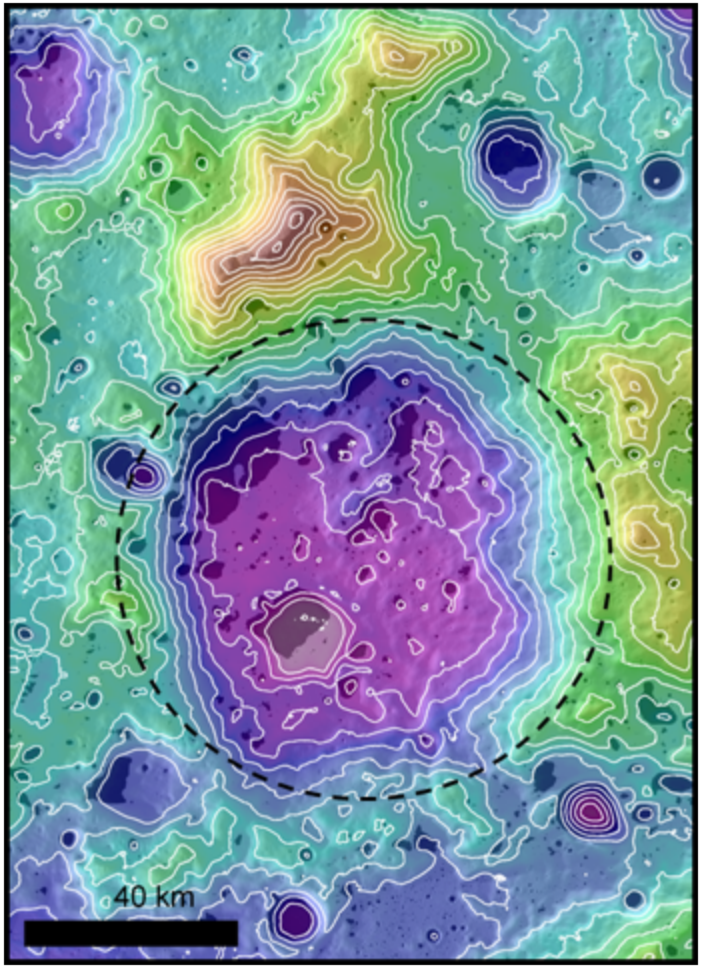
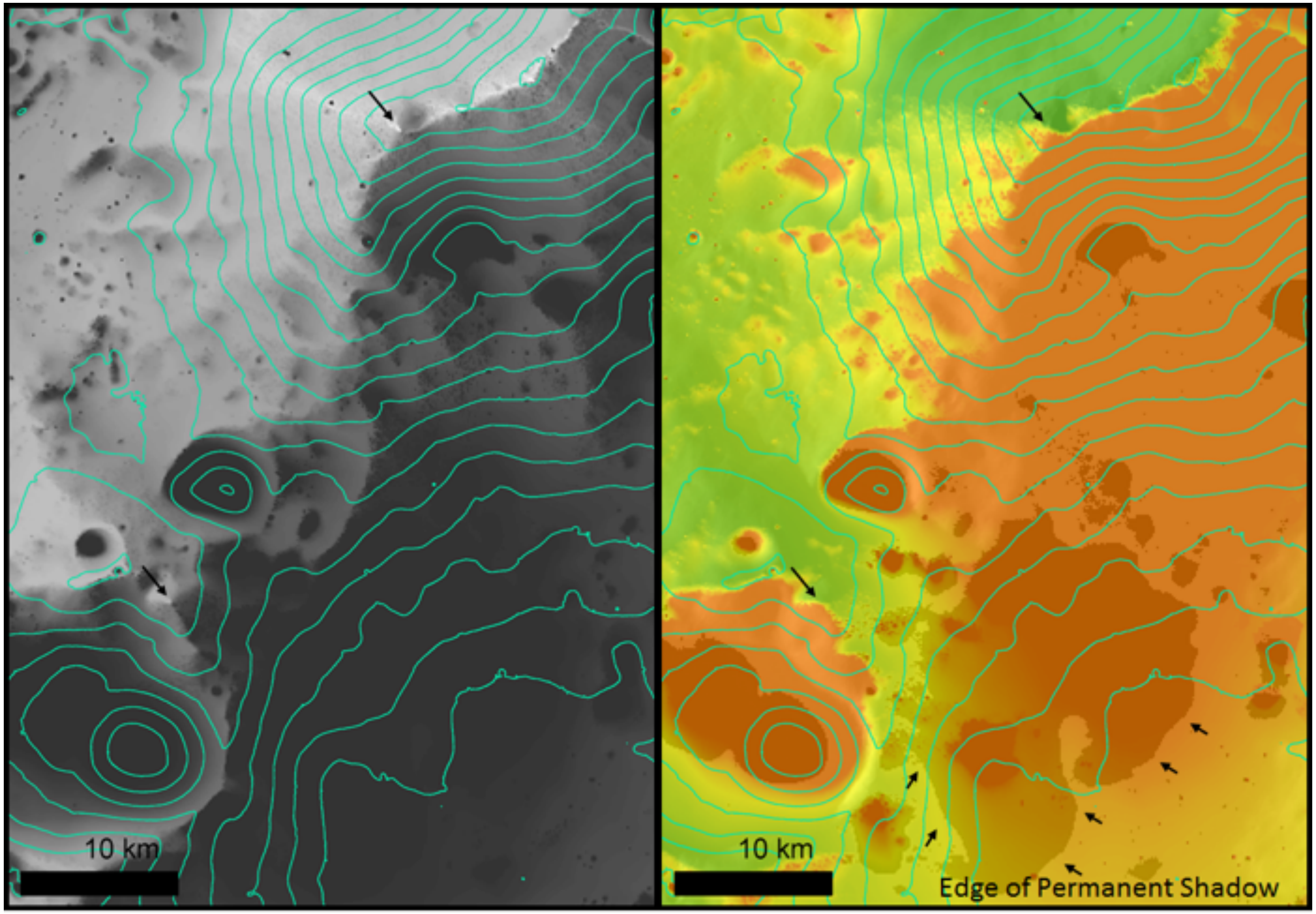
Site Selection: Where in Cabeus Crater?



- Water
- Power
- Communications
- Flat

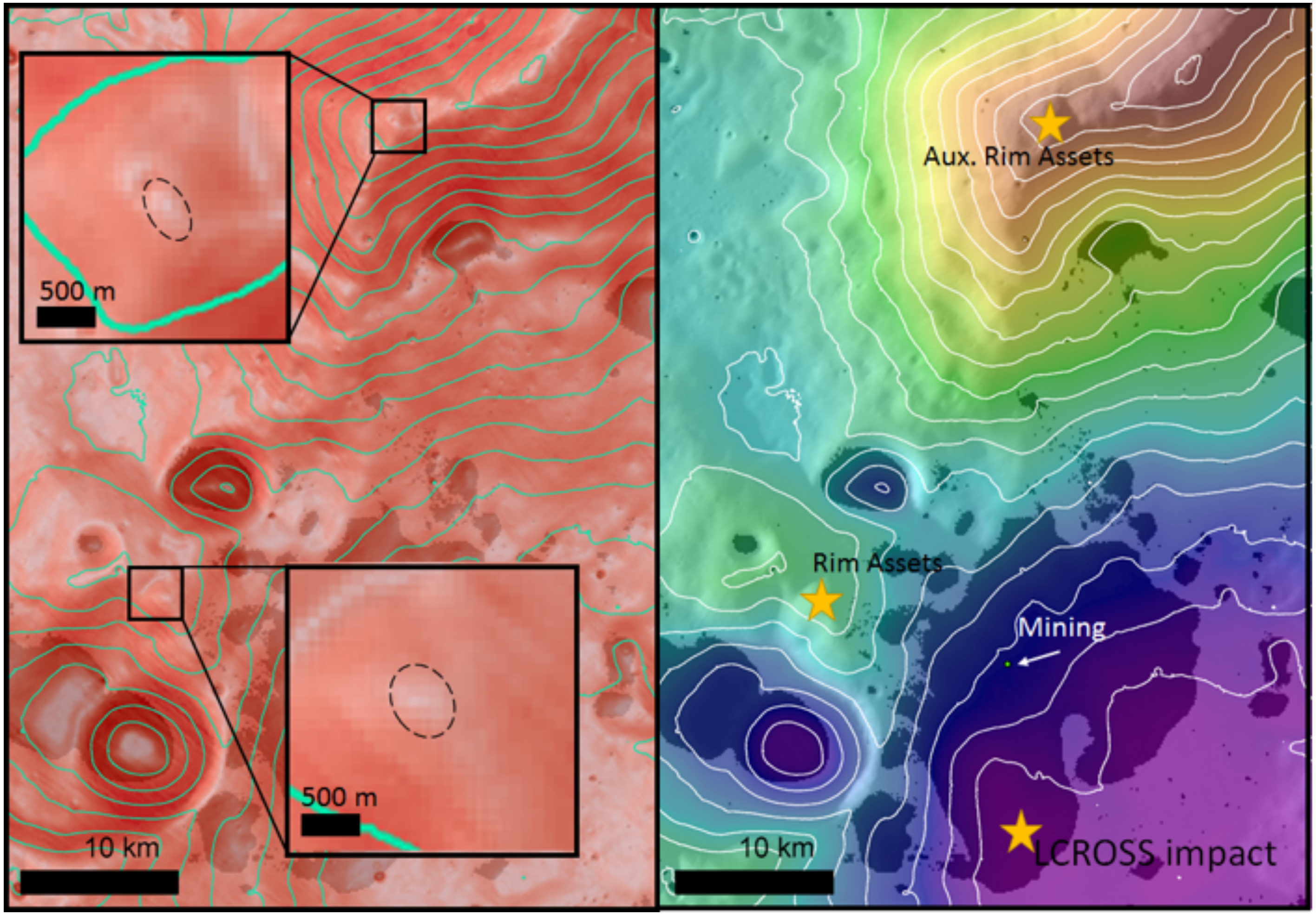
Cabeus crater, 500 m contours
Elevation: -4 -> +4 km

Site Selection: Rim Station



Left: Sunlight, Right: Earth Line-of-sight, 500 m contour

Site Selection: Entire Asset Deployment



Left: Slopes, Right: Elevation (-4 -> +4 km), 500 m contour

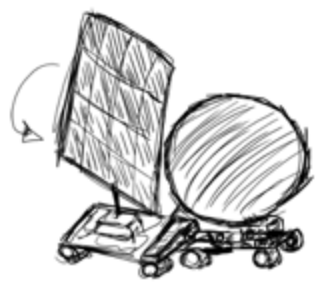
Phase I: Power Station Deployment (2024)

Lunar Landing System (LLS)

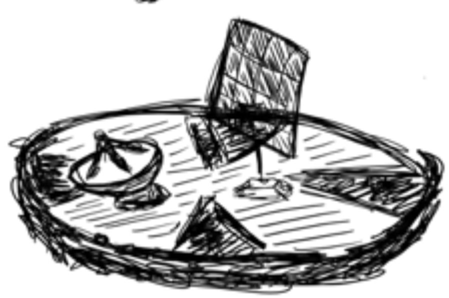
Nickname: The Pizza Delivery Truck
Rovers delivered: max 6
Diameter: 4 m
Deliverable mass: 4 mT
Launch mass: 9 mT
Additional uses:

- Carries constructor modules instead of unplaced rovers
- Can deliver and house ISRU unit

Each concentrator is deployed into location by a wheeled rover hauling a tractor with deployable solar array.

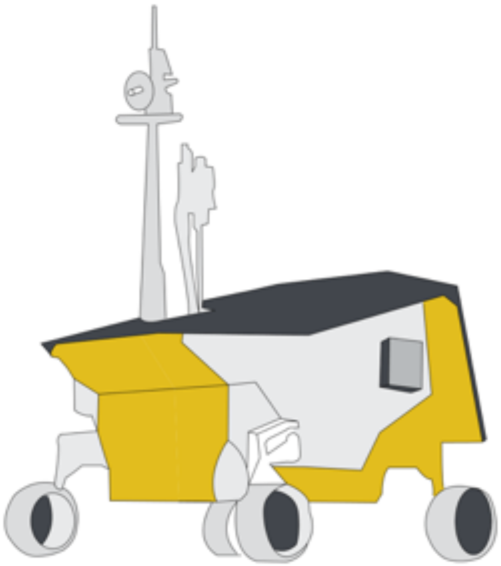


The used delivery vehicle deploys telecom system.



Five solar concentrators are located at each rim station

Phase II - Ice Location (2026)



Prospector:

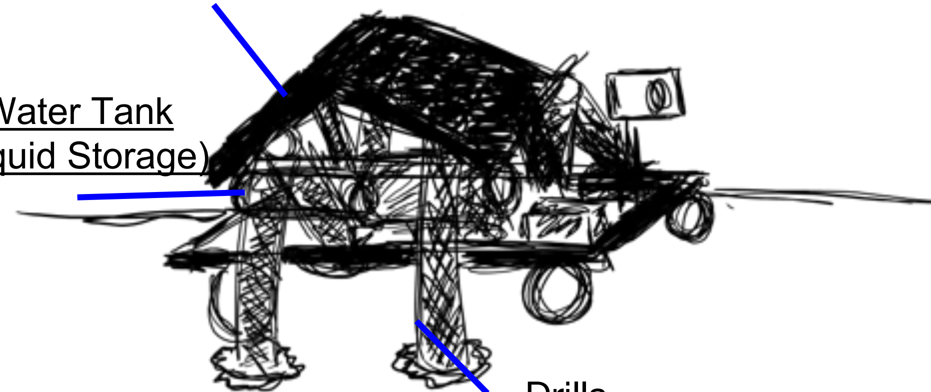
- Existing vehicle used for simplicity
  - *- Based on Lunar Polar Volatiles Extractor (LPVE) mission.*
- Identifies volatile deposits around landing site
  - *- Likely heterogeneous ice distribution*

Constructor:

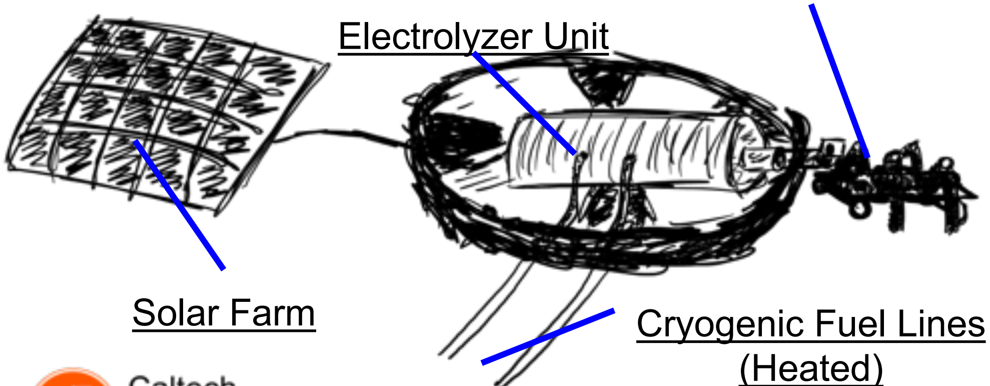
- Tractor carries trailer modules
  - *- Bulldozer Unit*
    - - Clears loose regolith
  - *- Robotic Arm*
    - - Attaches cryo hoses ar power cabling.

Phase III - Extraction (2027 & 2028)

Extractors
(+) Total Number: 12 (6+6)
(+) PVEx Drills: 4 per rover
(+) H_2O Rate: 12 kg/day/rover
(+) Power: 1 kW solar



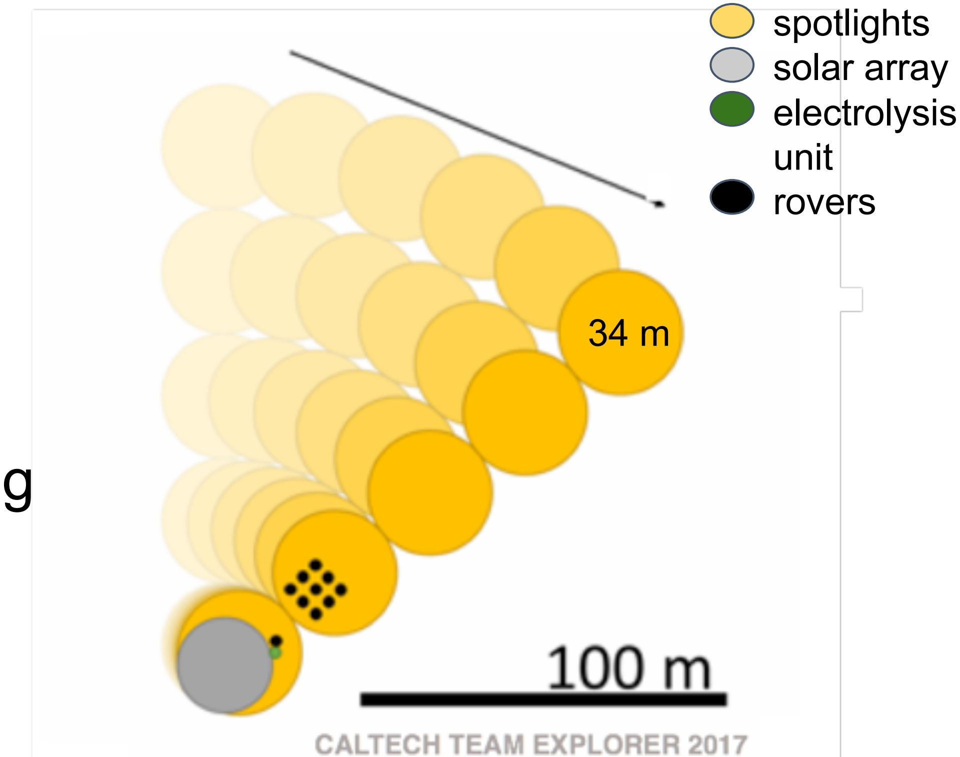
ISRU System:



ISRU Unit
(+) Splits H_2O at 70 kW beamed from Cabeus rim.
(+) Pressurized vapor-fed PEM Electrolyzer.
(+) LOX/LH_2 stored in LRS vehicles (landed Centaurs).

Operations

- Phased autonomous operations
- Proximity fail-safe mode
- Low energy operations during blackout
- Access to 600x fuel needed
- Future human friendly



Regolith → Water → LOH + LH2

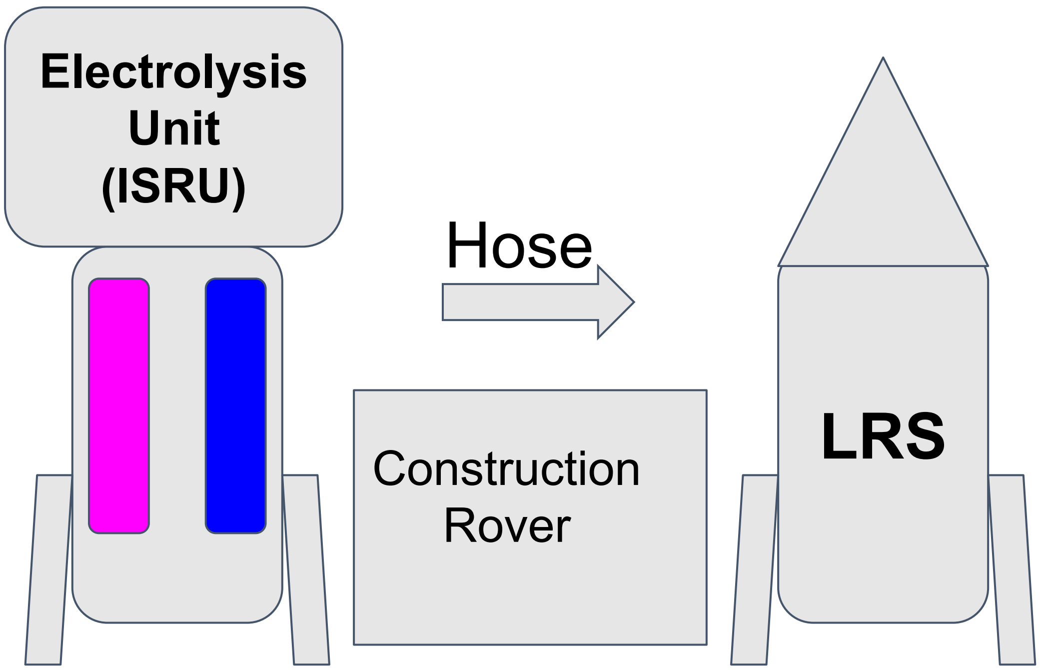
Extractors (Rovers with Honeybee core drills)

PEM Electrolyzer

Powered using solar using concentrated mirrors

Operations: Transfer

- As rovers collect ice, it is brought back to the ISRU
- Electrolysis
- Transferred to Landing Resupply Shuttle (LRS)



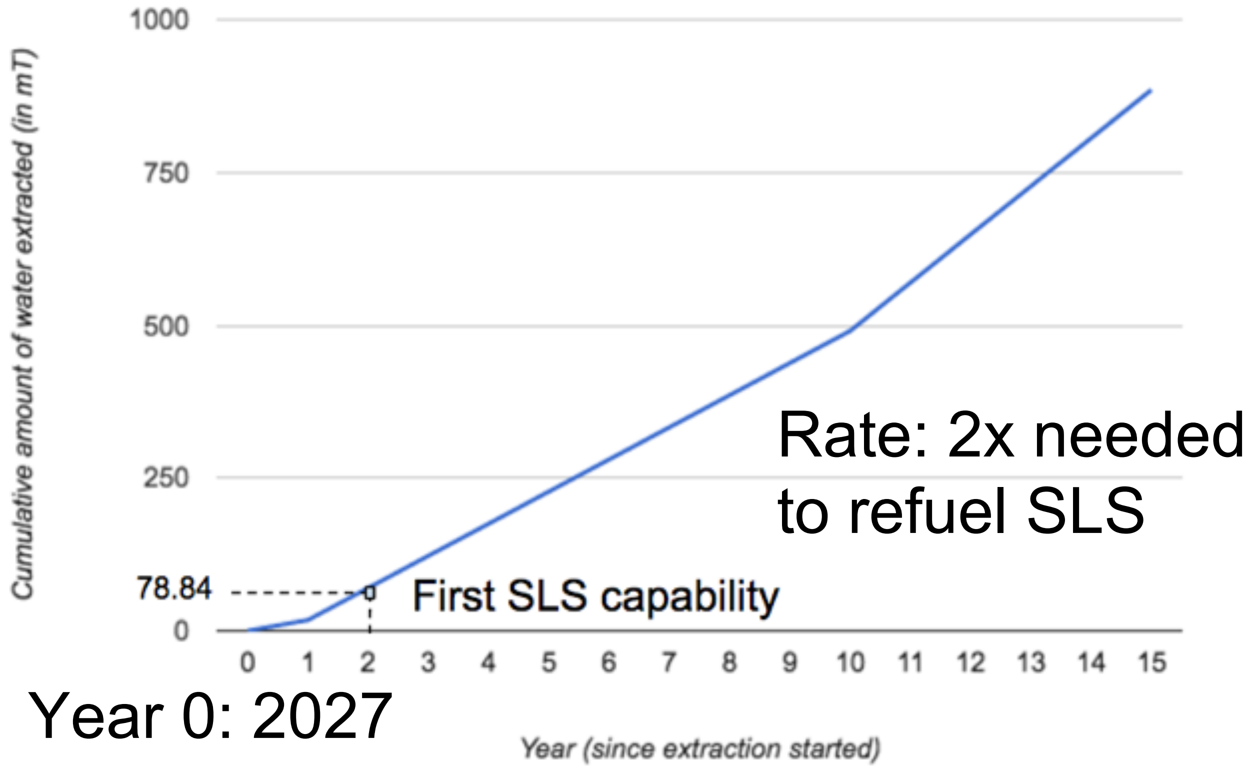
Architecture Pros

- SOLAR: Scalable, movable, does not sublimate ice
- Many redundant systems
- Existing or near-existing technology (High TRL)
- Modular
- Easy maintenance

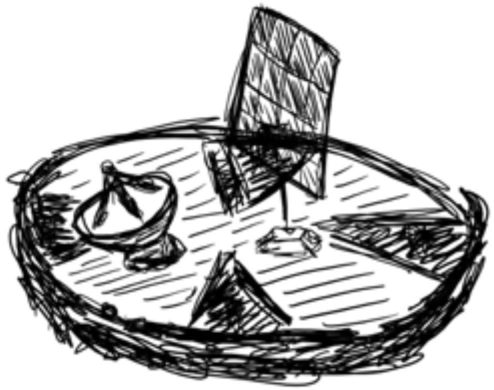
- Lasers have double loss from photon -> electric conversion
- Nuclear is also expensive (entire $15G to fuel mining ops)
- Microwave couples to regolith and sublimates ice

Production | Operation Estimates

- **50 mT** of H_2O processed every year with **12 rovers**
- Lifetime: Estimated 15 years due to radiation on PVs



Communications



Groun Station Link

Xband Uplink Budget		
LINK PERFORMANCE ESTIMATION, VIOLET		output
Constants		intput
Temperature	270	
k (Boltzmann's Const. In J/K)	1.38E-23	
c (Speed of Light in Mm/s)	3.00E+08	
AOS=Acquisition of Signal		
	Option 1	
R (Data rate)	2,000,000	
Bandwidth(MHz)	30	
Modulation Scheme	GMSK	
Pwr (Tx Power in W)	4000.00	
Pwr (Tx Power in dBm)	66.02059991	
Ll (Line Loss in dB)	1	
Antenna variation factor (in dB)	0	
Gt (Tx Total Antenna Gain in dB)	16.23	
EIRP	81.25059991	
Raos (Dist to SAT @ AOS in km)	384400	
f (Desired Tx Frequency in GHz)	8	
FSPL (Space Loss @ AOS in dB)	222.31	
ISAB (Ionospheric Absorption Loss in dB)	1	
Latmo (H20 & O2 Atmo-/Ionospheric Losses i	0.5	
Gr (Rx Antenna Gain in dB)	45.9	
Power Received dBm	-93.65686741	
Figure of Merit(G/T)(dB/K)	25	
Noise Power (dBm)	-99.51635895	
C/N	4.36	

- Rovers/ground support locally communicates with repeater station on rim, with 95% line of sight to Earth
- Rim repeater deployed with the rover platform
- Rotating photovoltaic panel for power supply
- Phased Autonomy:
  - *- systems start off with high levels of telepresence*
  - *- phases to more autonomy as tasks become more general*
- Specs:
  - *- X-band communication*
  - *- 4kW TX*
  - *- Spaceflight Industries ground station for constant cheap communication*

Lunar Resupply Shuttle (LRS)

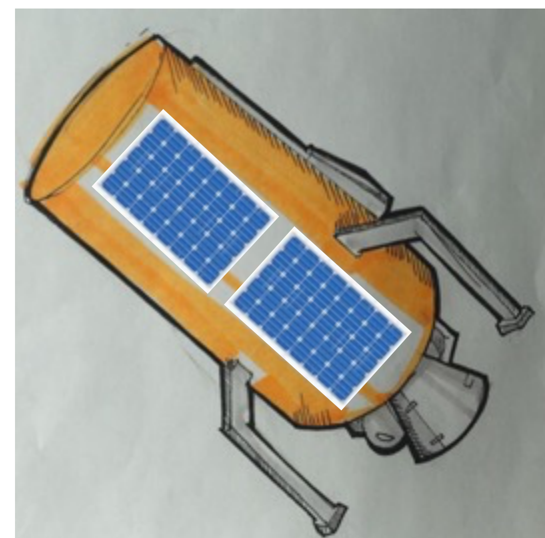
Centaur Single Engine

Requirements:

- Must use LH_2/LOX as propellant
- Must be massive enough to transport reasonable amount of fuel
- Must have self-sustaining power systems
- Must be modified to be reusable/landable
    - *- More sensors, update avionics system*
    - *- Landing legs*
    - *- Attitude control thrusters*
    - *- Internal pressurant supply*

Considerations:

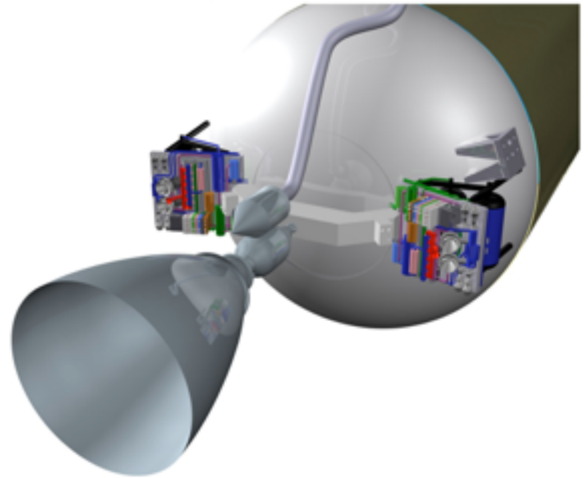
- EUS
- Centaur
- ACES



Cryogenic Propellant Storage

Existing technology
ULA's Integrated Vehicle Fuel system + 60-layer multi-layer Insulation (MLI)

- Reduces boil-off by 50-70%
- Uses boil-off for:
  - *- Pressurant*
  - *- Attitude control*
  - *- Ullage acceleration*
- Simplifies plumbing
- Reduces all fluids to LH2 and LOX
- Provides some spacecraft power

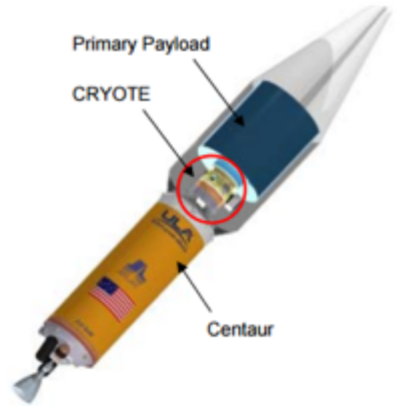


Centaur Converted to IVF
Approximate Liftoff Mass Benefit: 0.5t

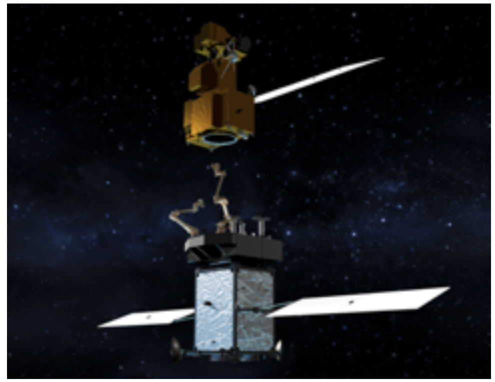
Centaur tanks with MLI loose ~0.1% per day

Total boil-off: >3% per month

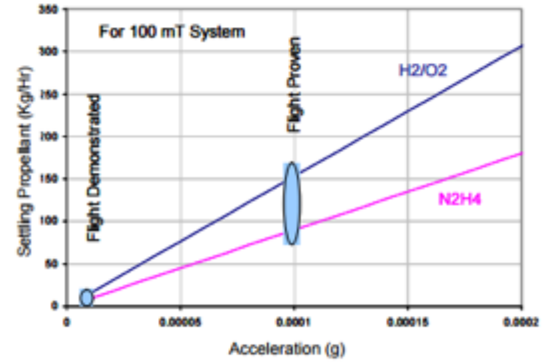
Cryogenic Propellant Transfer in Space



Cryogenic Orbital Test



NASA Restore-L Robotic Refueling mission

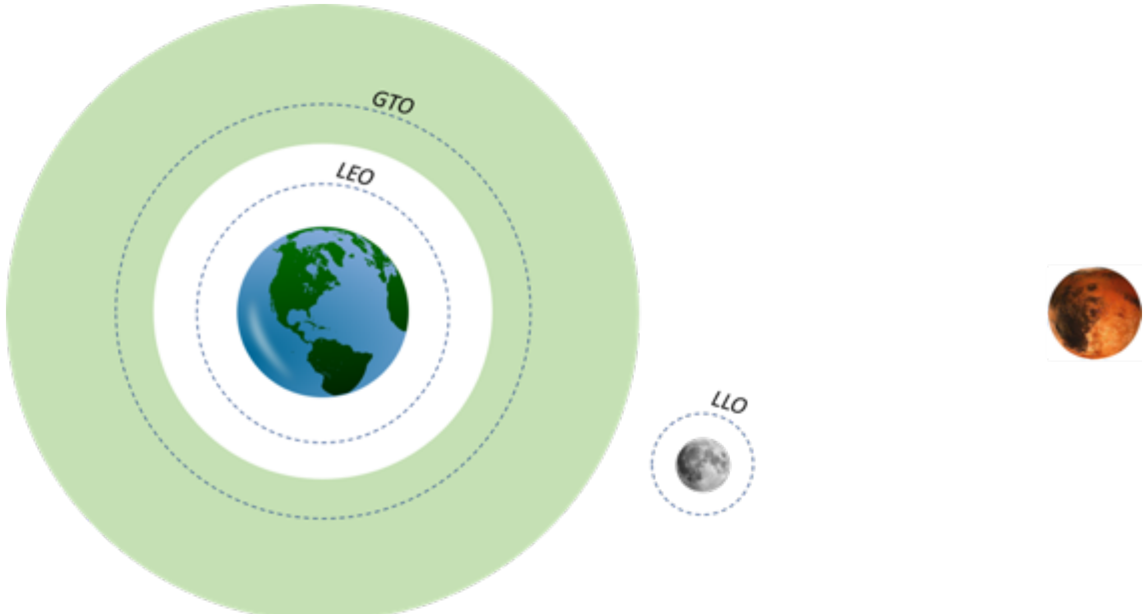


Flight proven fuel transfer rates

- Transfer rates of 150 kg/hour flight proven
- Low centrifugal acceleration (0.001 g from 5 rpm rotation)
- Approximately 2 days to transfer 6 mT of propellant from Centaur
- TRL of cryogenic transfer technology fully mature this decade

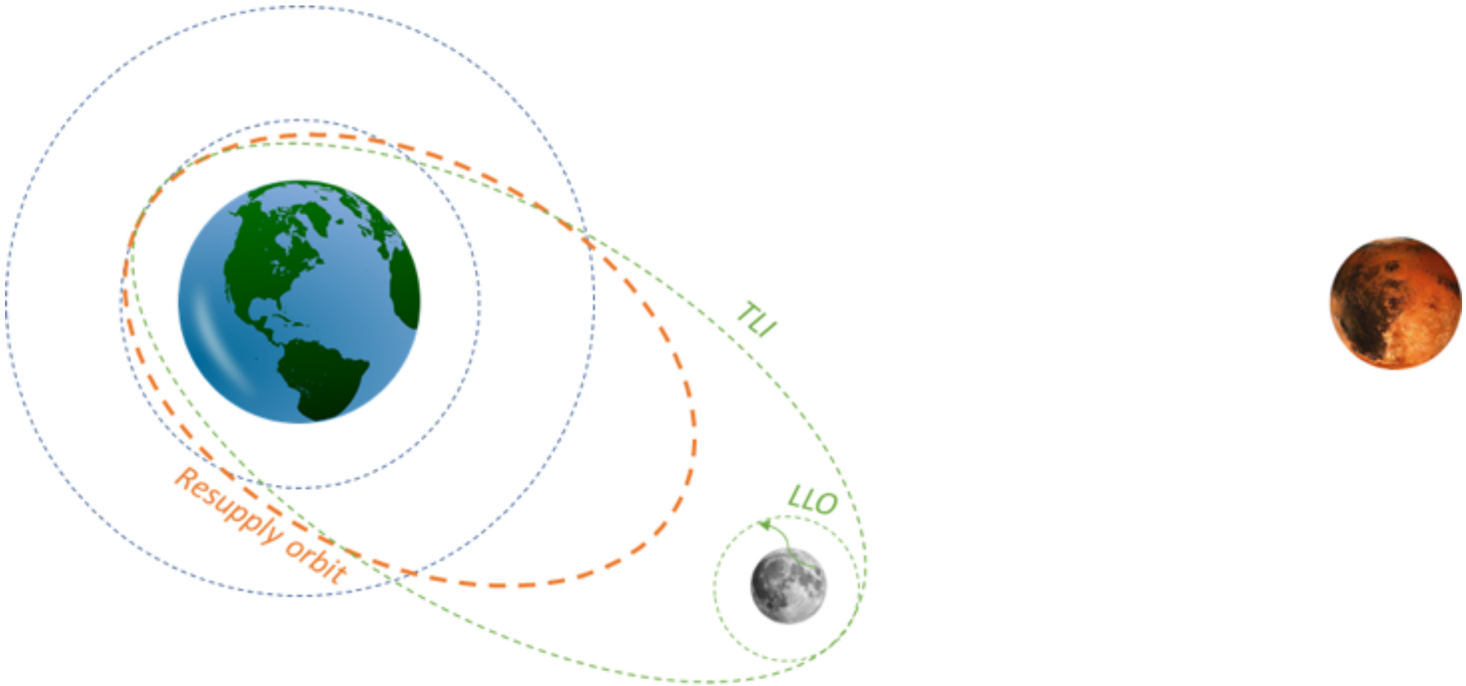
Cryo Transfer Technology	Current TRL		TRL Post-CRYOTE Lite		TRL Post-CRYOTE Pup, Free Flier	
	0-g	Stld	0-g	Stld	0-g	10^{-4} g
Transfer System Operation	4	5	4	9	9	9
Pressure Control	4	9	6	9	9	9
Low Acceleration Settling	N/A	9	N/A	9	N/A	9
Tank fill operation	4	5	4	9	9	9
Thermodynamic Vent System	5	5	7	7	9	9
Multi-layer insulation (MLI)	9	9	9	9	9	9
Integrated MLI (MMOD)	6(2)	6(2)	9(7)	9(7)	9	9
Vapor Cooling (H_2 para-ortho)	9(4)	9(4)	9	9	9	9
Passive Broad Area Cooling (active)	9(4)	9(4)	9(4)	9(4)	9	9
Active cooling (20k)	4	4	4	4	9	9
Ullage and Liquid Stratification	3	9	9	9	9	9
Propellant acquisition	2	9	9	9	9	9
Mass Gauging	3	9	9	9	9	9
Propellant Expulsion Efficiency	3	9	9	9	9	9
System Chilldown	4	5	4	9	9	9
Subcooling P>1atm (P<1atm)	9(5)	9(5)	9(5)	9(5)	9(5)	9(5)
Fluid Coupling	3	3	3	3	9	9

Fuel Resupply Orbit Tradeoffs



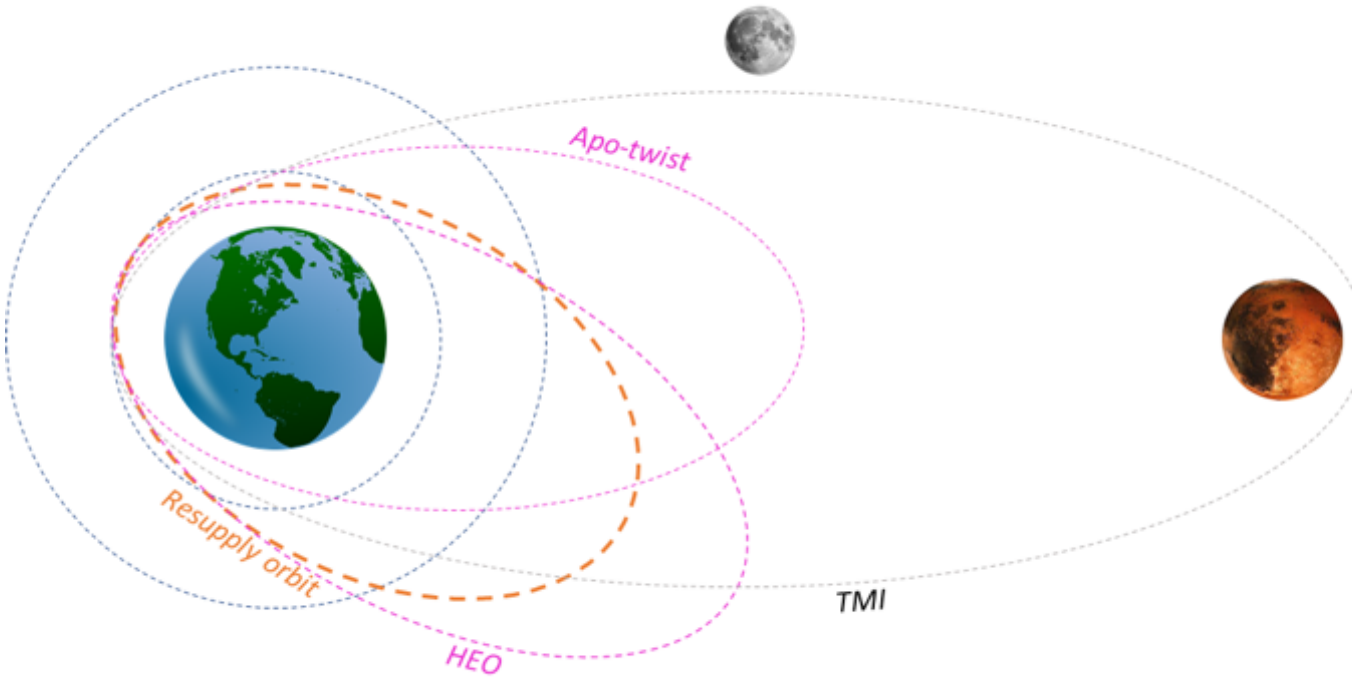
- LEO:
  - Large EUS payloads can be injected to Mars
  - Too costly for the LRS (~11 km/s round-trip)
- LLO:
  - EUS Payload mass to Mars limited to ~38 mT
  - Additional ΔV required to lower perigee
  - Docking difficulties: No GPS at LLO. Autonomy issues.
- L1, L2:
  - Restricted three-body problem (further analysis require)
  - Docking challenges

LRS Baseline Trajectory



- Injection into polar LLO (~1.6 km/s)
- Trans Earth Injection (~0.8 km/s)
- Elliptical Resupply Orbit Injection (**Apogee altitude is our optimization variable**) and rendezvous (Time of flight: 60 to 100 hours)
- Docking (~20 m/s): Autonomous/non-autonomous docking using GPS, IMU, AVGS (Advanced Video Guidance System)
- Trans Lunar Injection
- Landing (~1.6 km/s)

EUS Baseline Trajectory



SLS injects EUS into the Resupply Elliptical Orbit (**Apogee altitude is our optimization variable**)

- Rendezvous and docking
- HEO injection: apo-twist cost reduction
- Apo-Twist required for the 2033 launch (~45^{o} change in argument of periapse, ~1.5 km/s)
- Docking (~20 m/s): Autonomous/non-autonomous docking using GPS, IMU, AVGS (Advanced Video Guidance System)
- Trans Mars Injection

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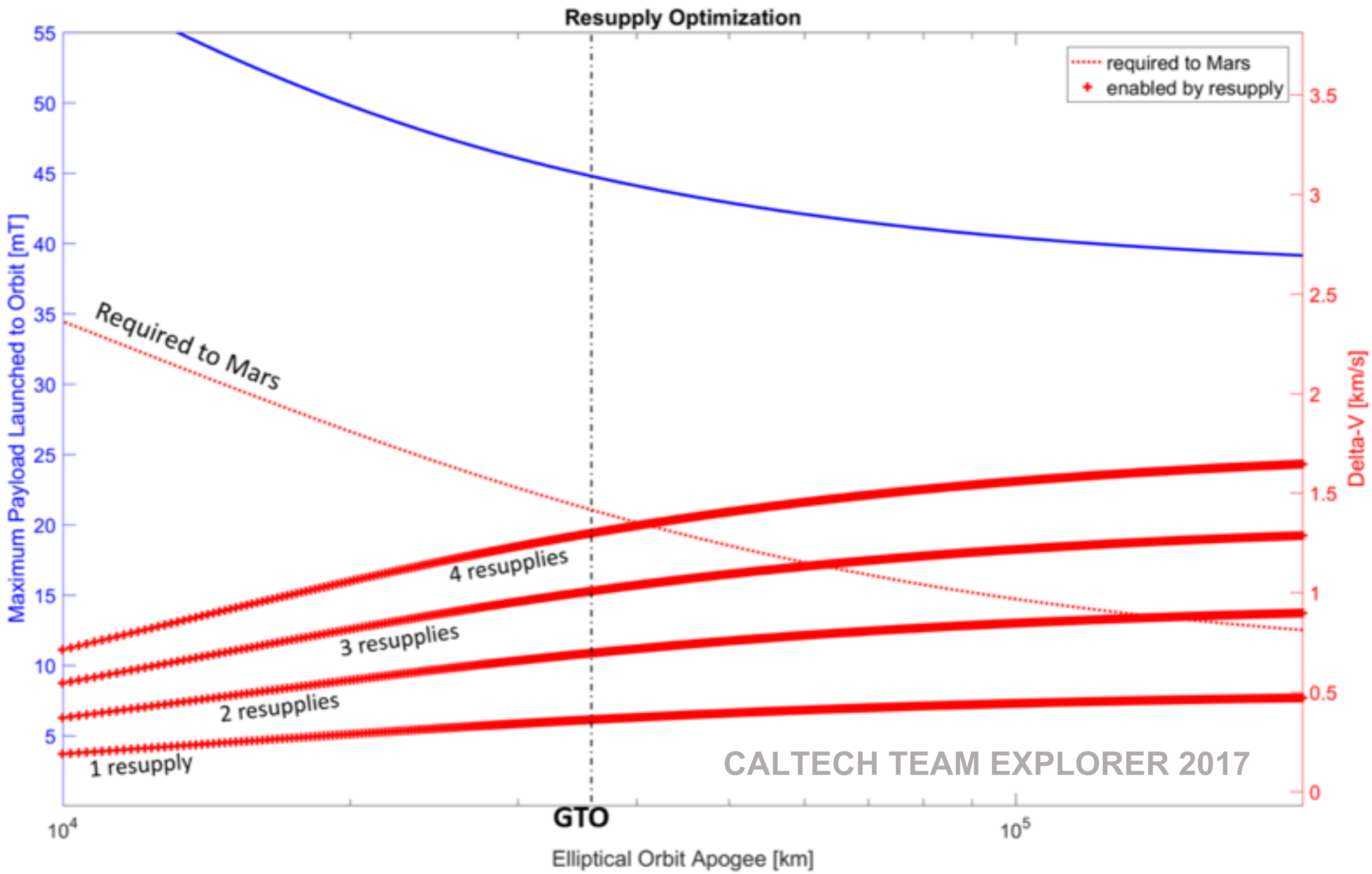
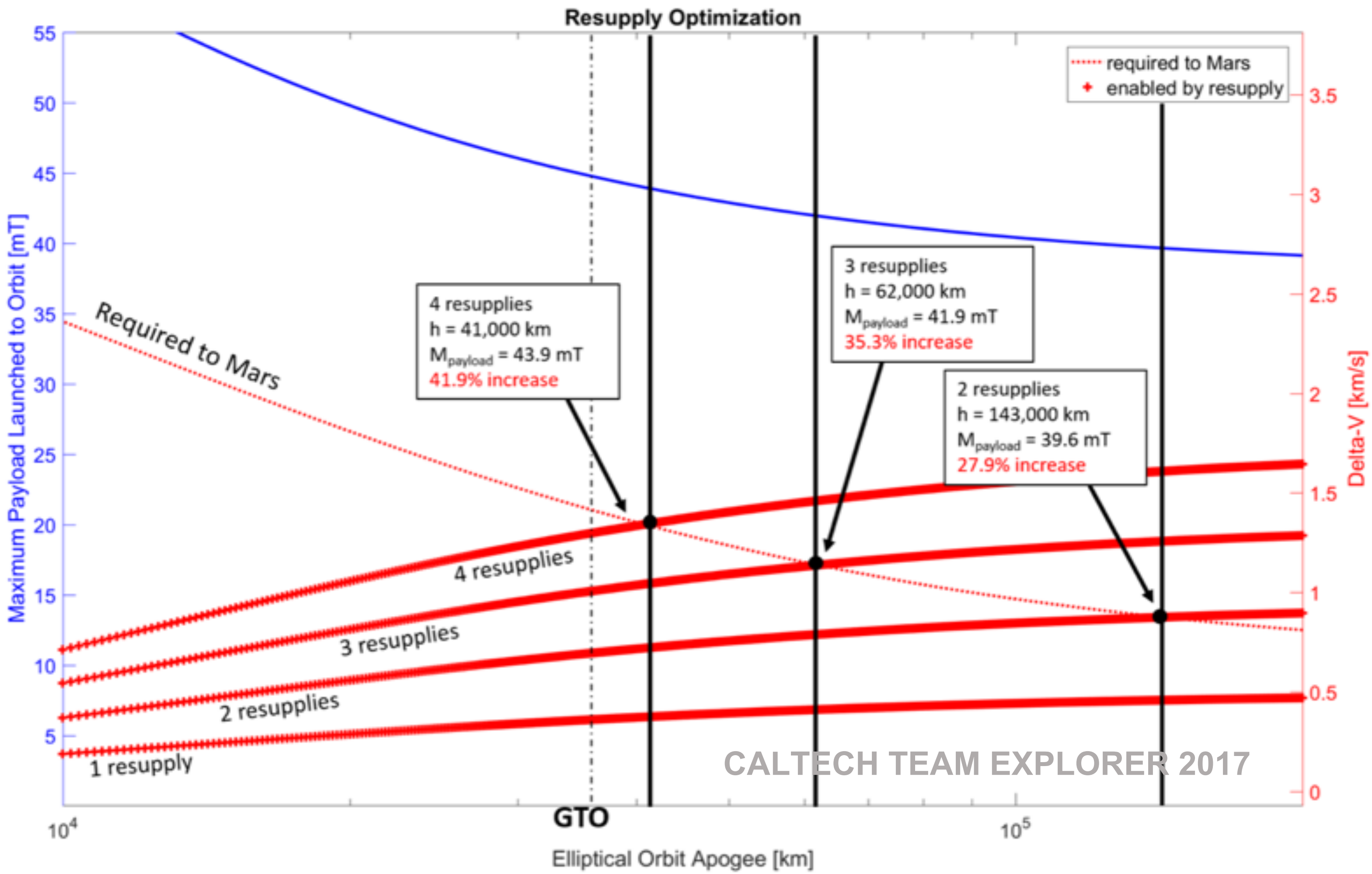
Propellant Resupply Optimization



Propellant Resupply Optimization



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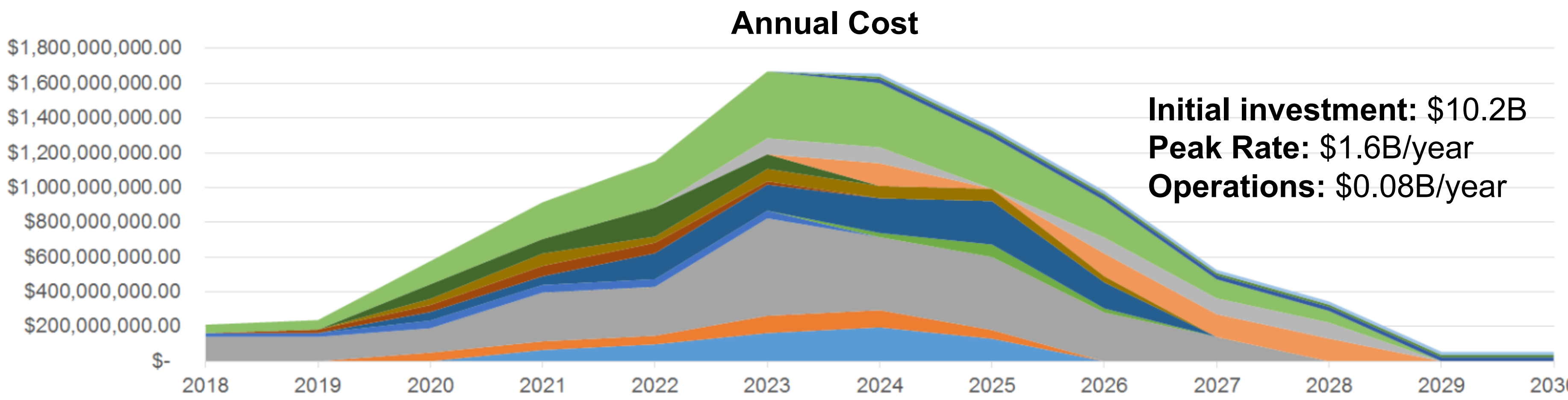
Missions to the Outer Solar System

- Not yet fully characterized or optimized
- Initial calculations suggest excellent performance

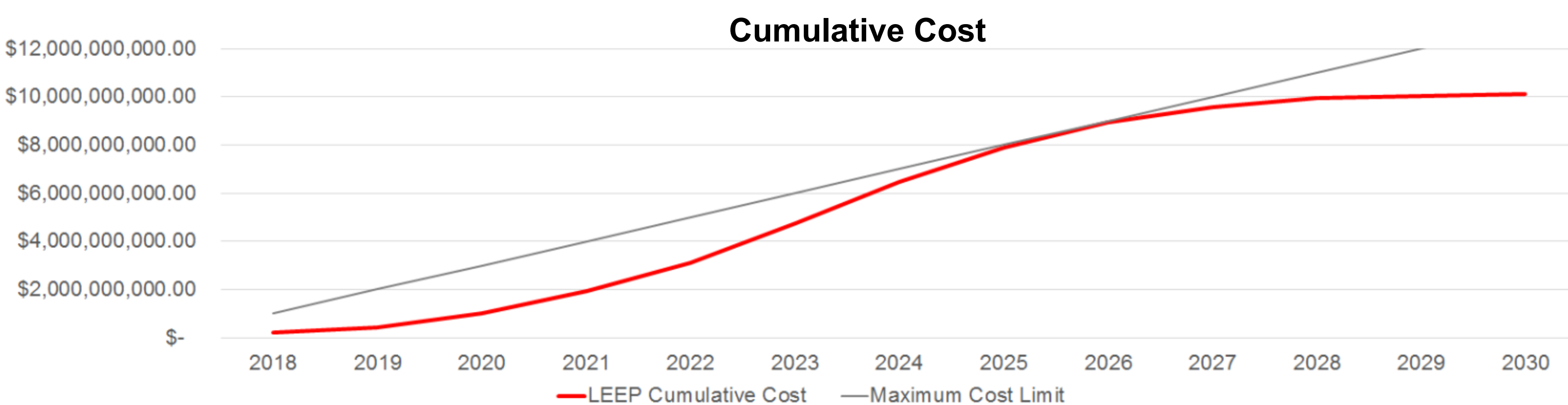
- +250% direct to Saturn
- +700% direct to Pluto
  - Assuming launch on an Atlas V 551 and refuel in GTO

- Bigger missions, bigger science, better value

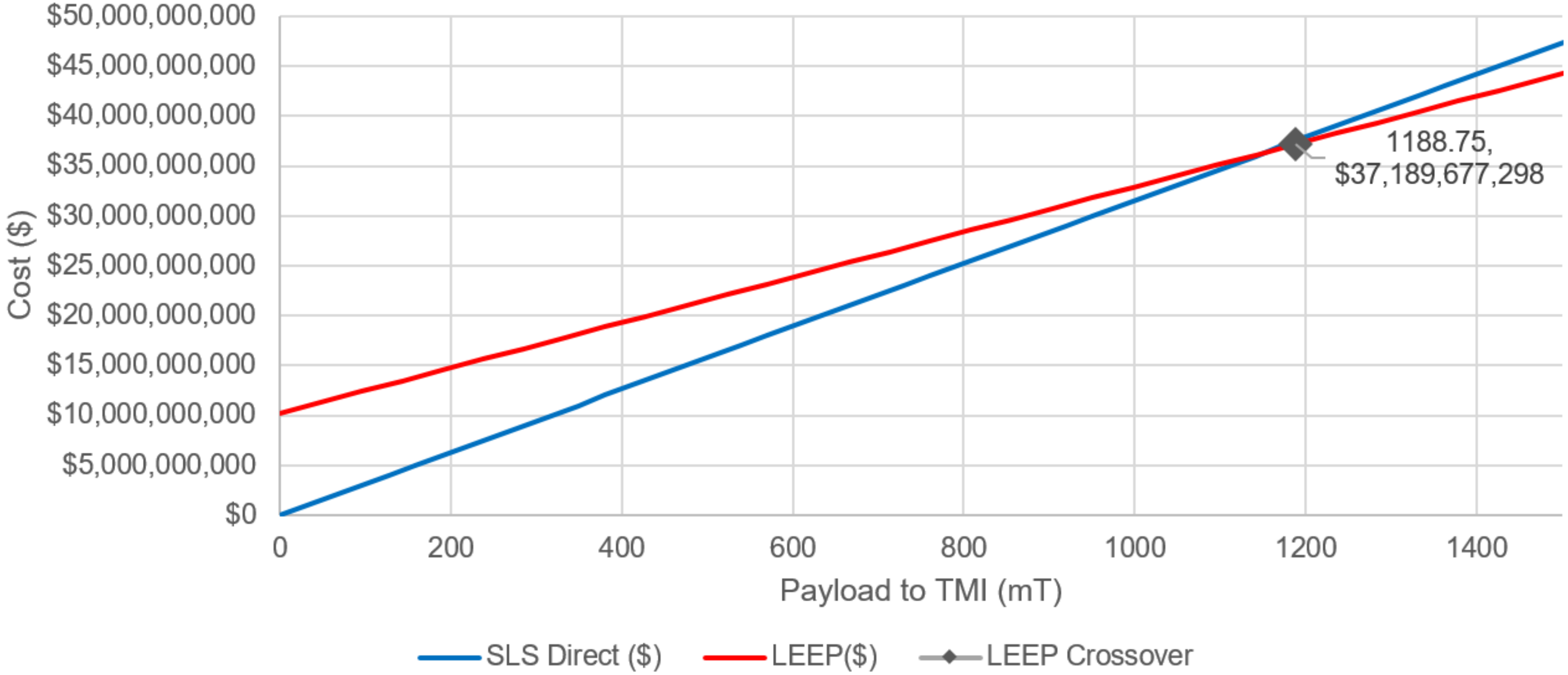
Estimated Cost To Full Operation



Initial investment: $10.2B
Peak Rate: $1.6B/year
Operations: $0.08B/year



TMI Payload Cost



Project Risk

- Knowledge Management
- Stakeholder and Funding Stability
- Scope Creep

Regulatory and Political Risk

U.S. Domestic

- Economic incentives
- Environmental impacts
- Space policy alignment
- Funding stability

International

- Export Control Compliance
- Compliance with International Law: Outer Space Treaty and Moon Treaty

Public Outreach Strategy

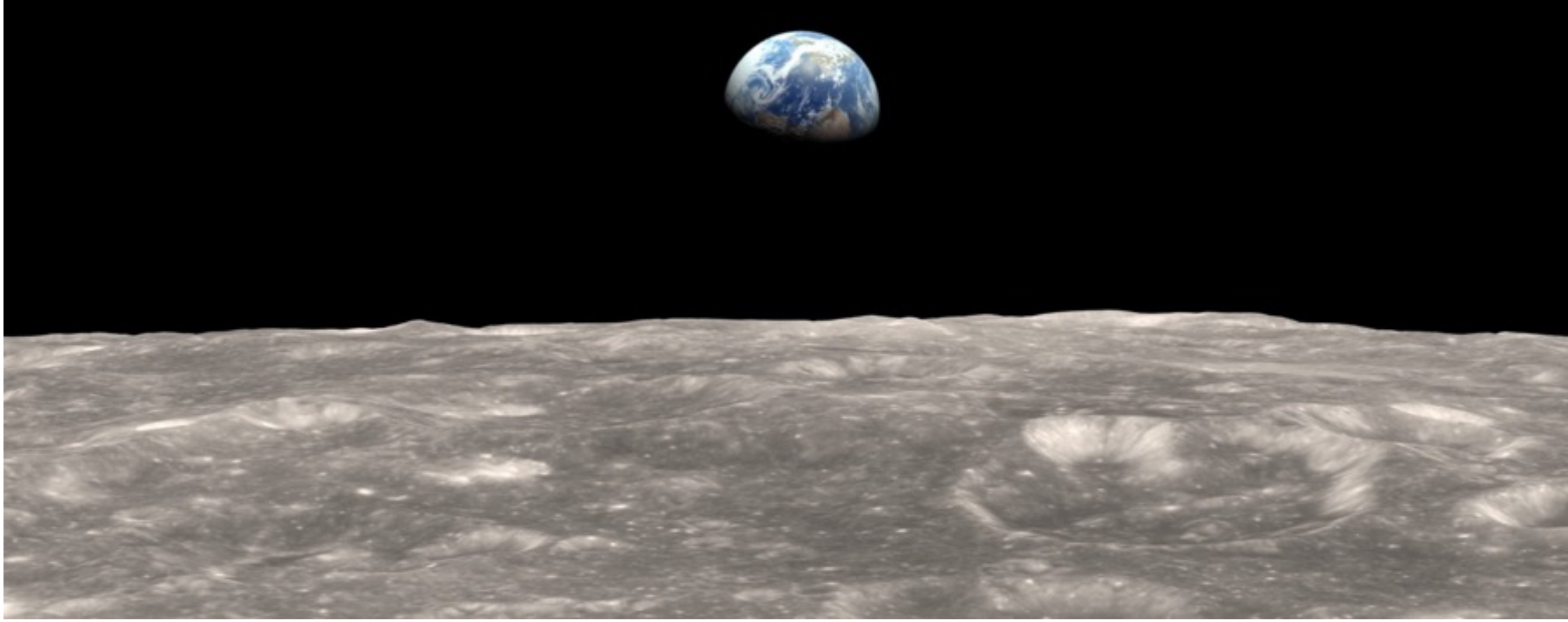
- Audience: broad appeal, broad audience
- Impacts:
  - *- 1) Drive momentum towards SLS's upcoming launches*
  - *- 2) Normalize the idea of extended human establishments off earth*
  - *- Inspire students indirectly and directly with internships*
- Schedule:
  - *- Students through internships through design phases and operations*
  - *- Launch, landing, and "firsts."*
- Media Mix:
  - *- Traditional media*
  - *- New media channels*
  - *- Tangible experience for members of the public to interface directly with the mission.*

Public Outreach Ideas

- Virtual reality & games
- Student project partnership with a university team: continuing from the example of missions like the REXIS sub-mission on OSIRIS-REx mission and IRIS on the proposed Moonrise mission
- Time capsules: this mission will create a lot of holes! Members of the public could even drive a rover to place their time capsule in the hole.

Public Outreach Ideas

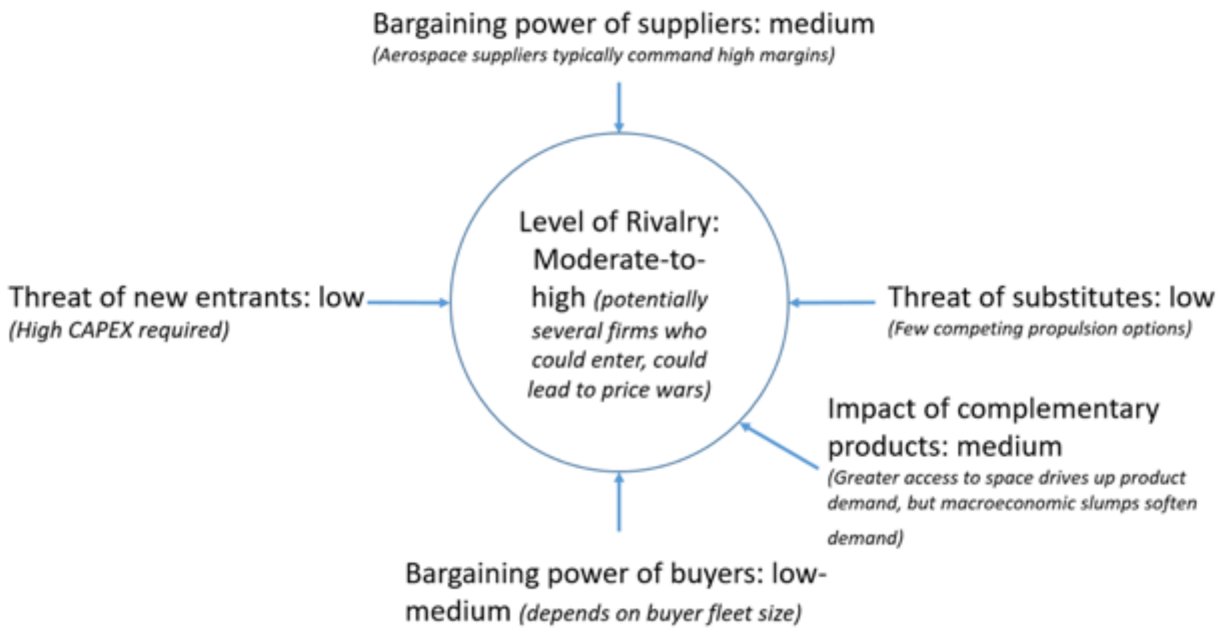
Lunar streaming webcam: short-duration live stream or a semi-frequently updated “earthrise” image could fundamentally change the public’s relationship with their own planet by allowing anyone to view earth at a distance at any nearly time.



A leap for mankind: **LEEP as a platform for the future**

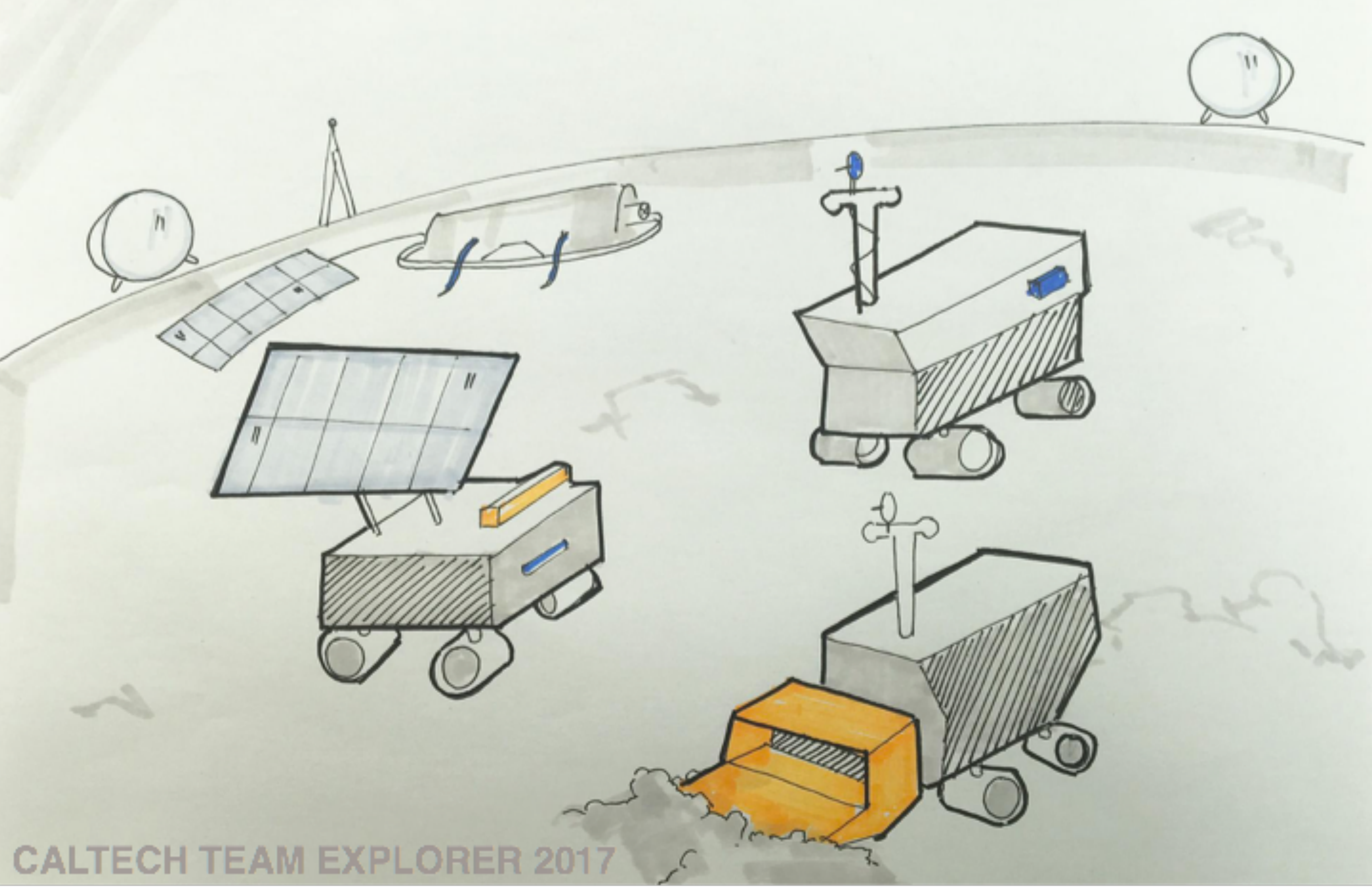
Fuel As A Service: The Next Space Industry

Key Businesses	
• Fuel transfer for Martian or Jovian system human missions • Fuel transfer for DS robotic missions • Rescue	• Satellite removal tug • Waypoint destination for interplanetary tourists • Transfer tug for lunar operations



Areas for Public-Private Cooperation

- Subsystem design and operation (rover, extraction technology, power systems)
- Autonomous operations
- long-duration mission planning
- extreme condition engineering (Permanently shadowed regions)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Blue Origin

Boeing

Lockheed Martin

Schlumberger

Honeybee Robotics
Spacecraft Mechanisms Corporation

GALCIT

JPL

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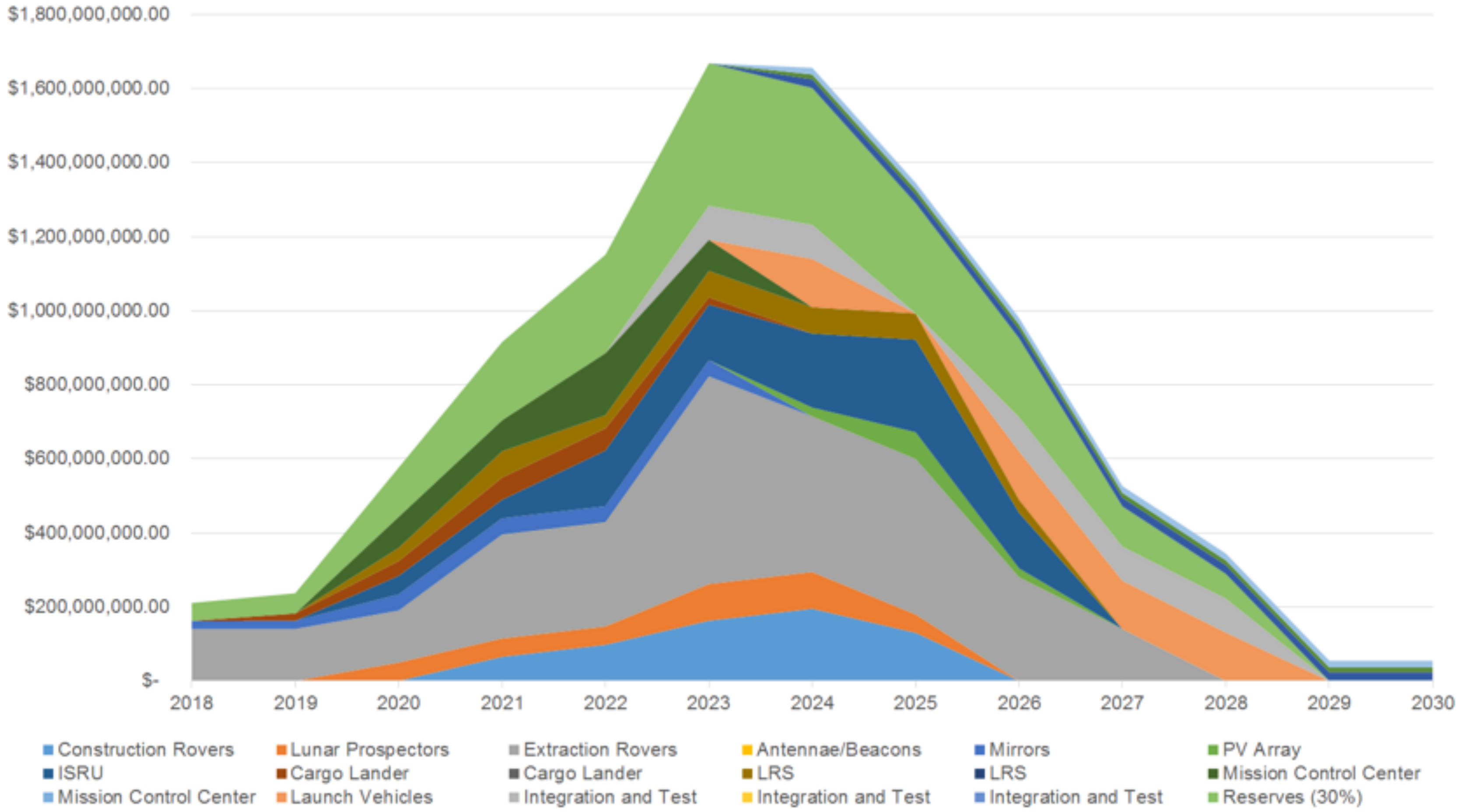
Backup

Cost



$1,800,000,000.00
$1,600,000,000.00
$1,400,000,000.00
$1,200,000,000.00
$1,000,000,000.00
$800,000,000.00
$600,000,000.00
$400,000,000.00
$200,000,000.00
$-
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Construction Rovers
Lunar Prospectors
Extraction Rovers
Antennae/Beacons
Mirrors
PV Array
ISRU
Cargo Lander
Cargo Lander
LRS
LRS
Mission Control Center
Mission Control Center
Launch Vehicles
Integration and Test
Integration and Test
Integration and Test
Reserves (30%)

Cost

NON-RECURRING COST				
Mission Hardware		**Item**	**Cost**	
	Ground Seg			
		Construction Rovers	$	649,770,250
		Lunar Prospectors	$	397,052,475
		Extraction Rovers	$	2,801,001,935
		Antennae/Beacons	$	2,400,000
		Mirrors	$	220,000,000
		PV Array	$	120,000,000
		ISRU	$	1,000,000,000
		Cargo Lander	$	200,000,000
	Space Seg			
		LRS	$	355,000,000
	Earth Seg			
		Mission Control Center	$	420,000,000
Launch costs				
		Launch Vehicles	$	522,400,000
Integration and Test	0	Integration and Test	$	459,617,973
Program Management				
	Prog Level	Mgmt, SE, MA		$714,724,263
		Reserves (30%)	$	2,358,590,069
Total Non-Recuring Cost			**$**	**10,220,556,965**

Cost

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Mission Hardware		**Item**	**Cost**	
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		PV Array	$	120,000,000
		ISRU	$	1,000,000,000
		Cargo Lander	$	200,000,000
	Space Seg			
		LRS	$	355,000,000
	Earth Seg			
		Mission Control Center	$	420,000,000
Launch costs				
		Launch Vehicles	$	522,400,000
Integration and Test	0	Integration and Test	$	459,617,973
Program Management				
	Prog Level	Mgmt, SE, MA		$714,724,263
		Reserves (30%)	$	2,358,590,069
Total Non-Recuring Cost			**$**	**10,220,556,965**

RECURRING COST				
Operations costs	Earth Seg			
		Ground Comm	$	660,000
		Operations	$	41,704,813
	Space	Resupply Launch	$	23,400,000
		Resupply Rover	$	13,000,000
		Resupply LRS	$	18,460,000
Total Recurring Cost			**$**	**78,764,813**

Risk Management

Risk analysis based on the **NASA Risk Management Handbook**

3 levels of risk: System, Ground segment and Space segment.

System Level:

- Budget
- Service Availability - Single Point of Failure

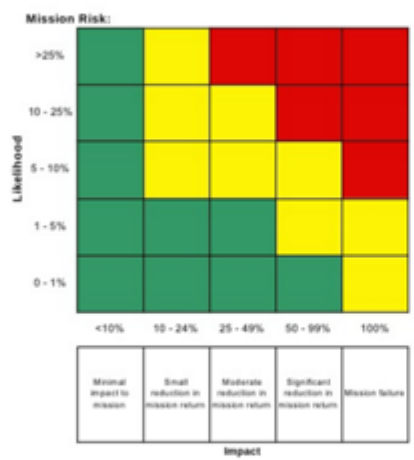
Ground Segment Level:

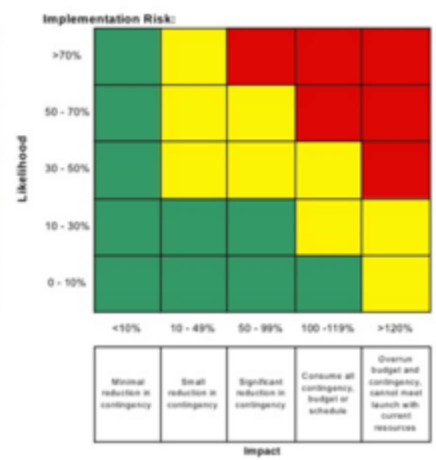
- Lack of water
- LRS crash into main base
- Mirror technology
- Excavation, prospection or construction rover loss

Space Segment Level:

- Crash during rendezvous
- Landing
- Leaking
- Zero boil-off

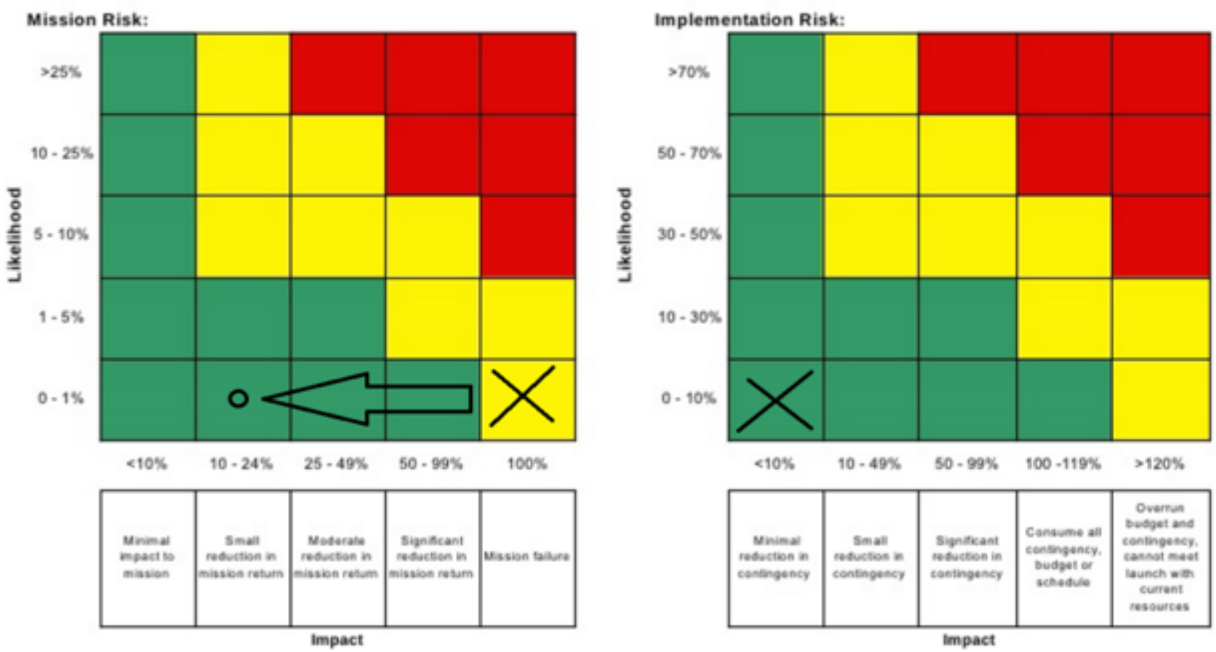
=> Translation of impact and likelihood ratings into Red-Yellow-Green for **NASA 5x5 risk matrix**





Technical Risk

Risk: Crash during rendezvous and proximity operations.

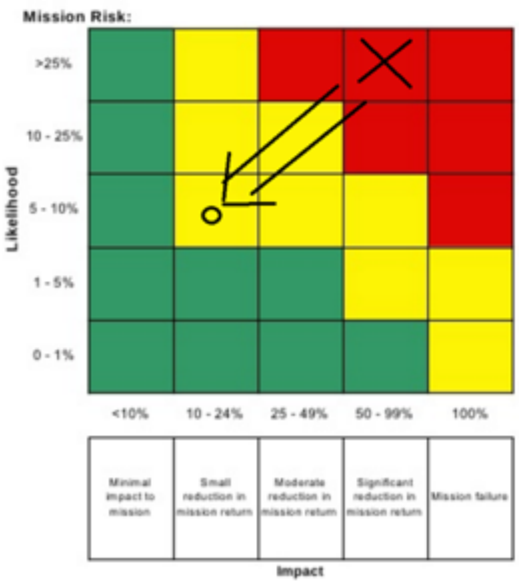


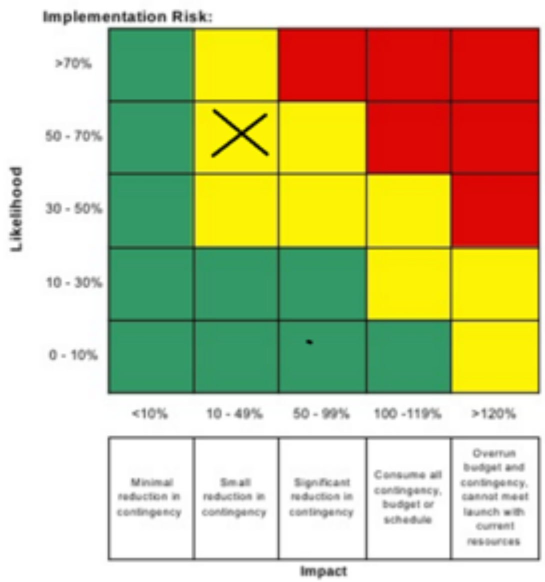
Mitigations: Software safe-modes, use of high-experience systems, and teleoperations.

Others: Low water content, mirror technology, excavation rover rate.

System Level Risk (1/9)

Risk: Budget

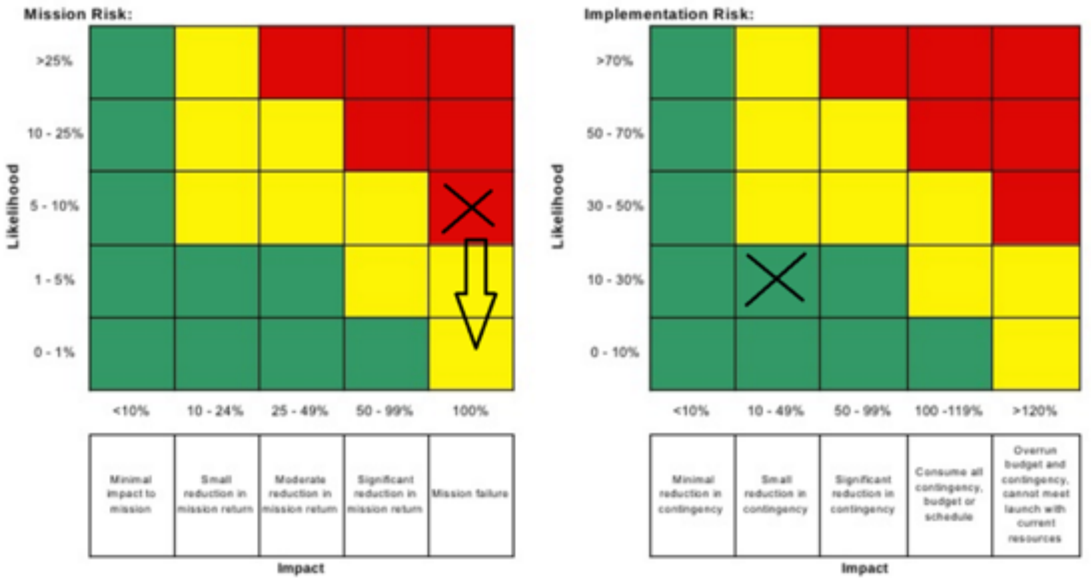




Mitigations: Use margins, use off-the-shelf products

System Level Risk (2/9)

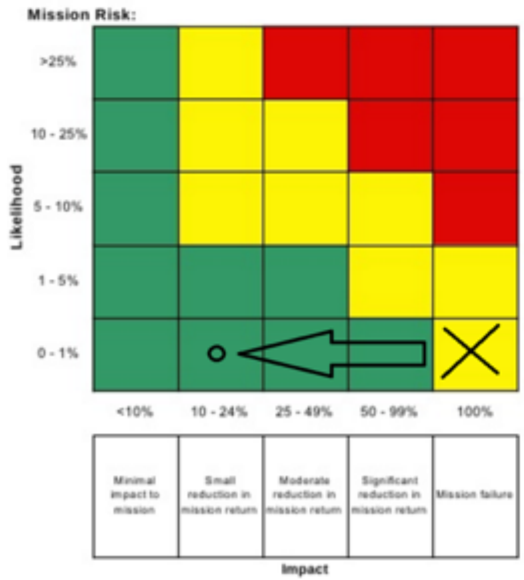
Risk: Service Availability - Single Point of Failure

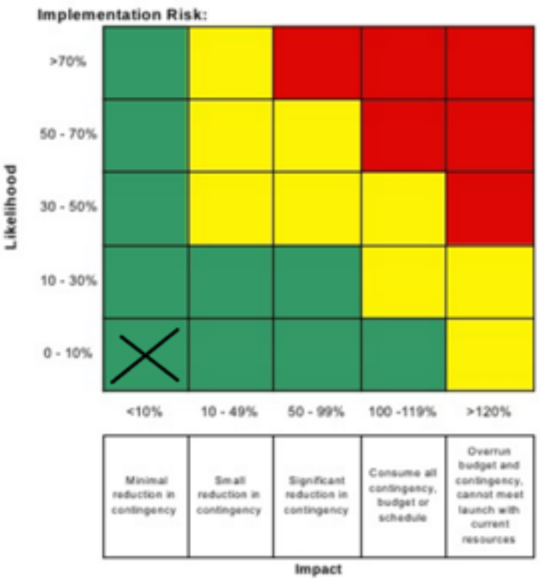


Mitigations: installing a reservoir station

Technical Risk (3/9)

Risk: Landing

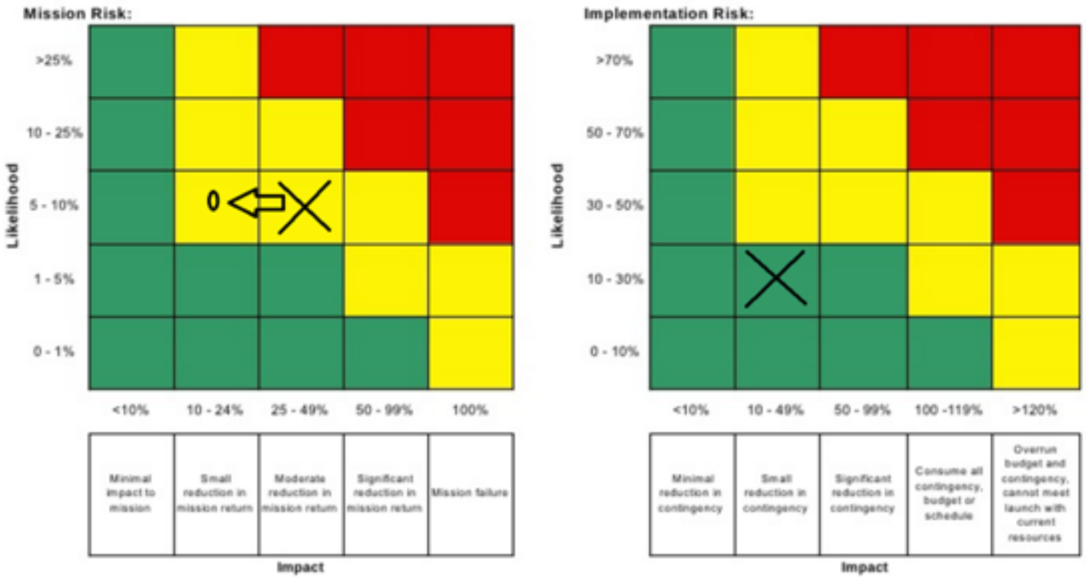




Mitigations: algorithm and sensor improvements, smoother pads, LRS backups

Technical Risk (4/9)

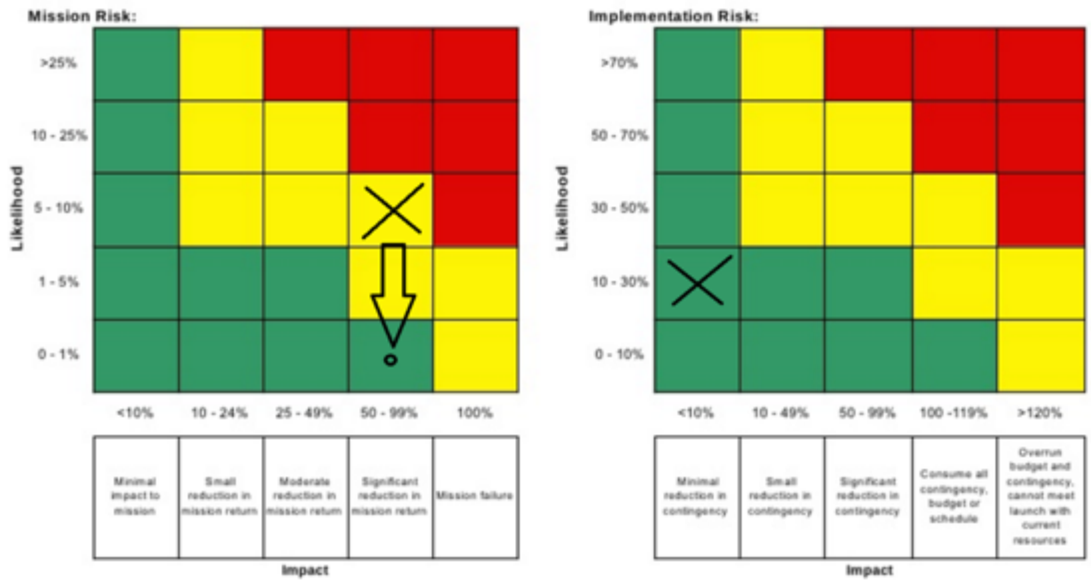
Risk: fluid leaking



Mitigations: leaking detection sensor, security checkpoints

Technical Risk (5/9)

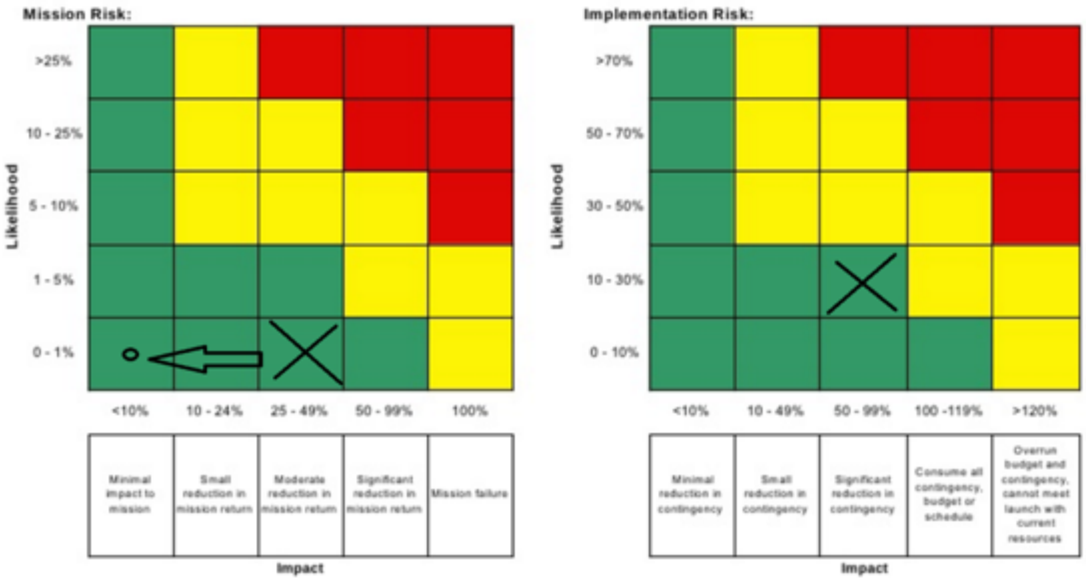
Risk: Zero boil-off



Mitigations: implement 60-layer MLI on the hydrogen tank and implement ULA's IVF system for integrating vehicle fluids and limiting boil-off.

Other Technical Risk (6/9)

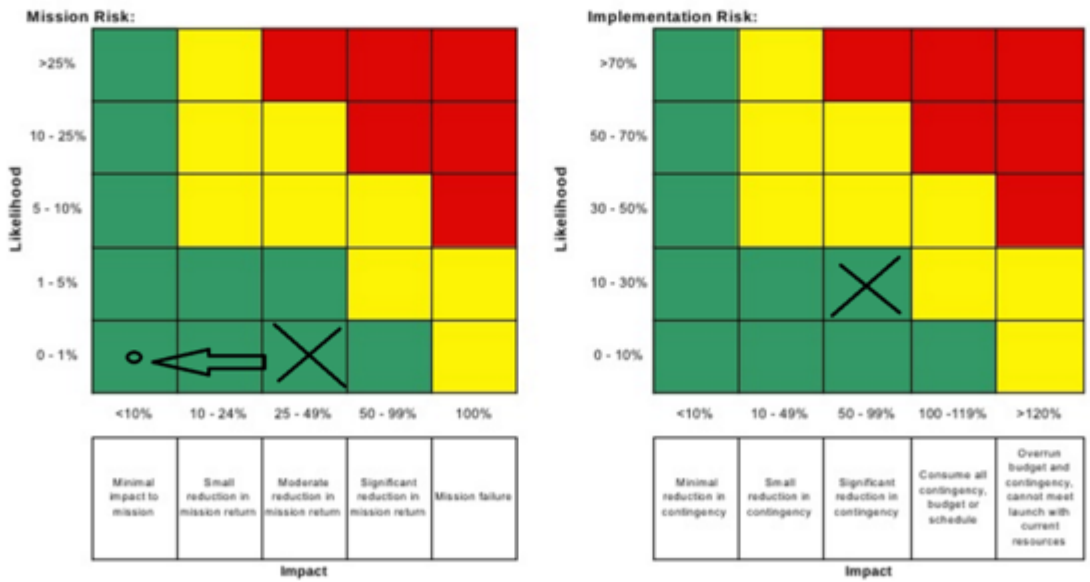
Risk: lack of water



Mitigations: using prospecting rover, deploy to another crater

Other Technical Risk (7/9)

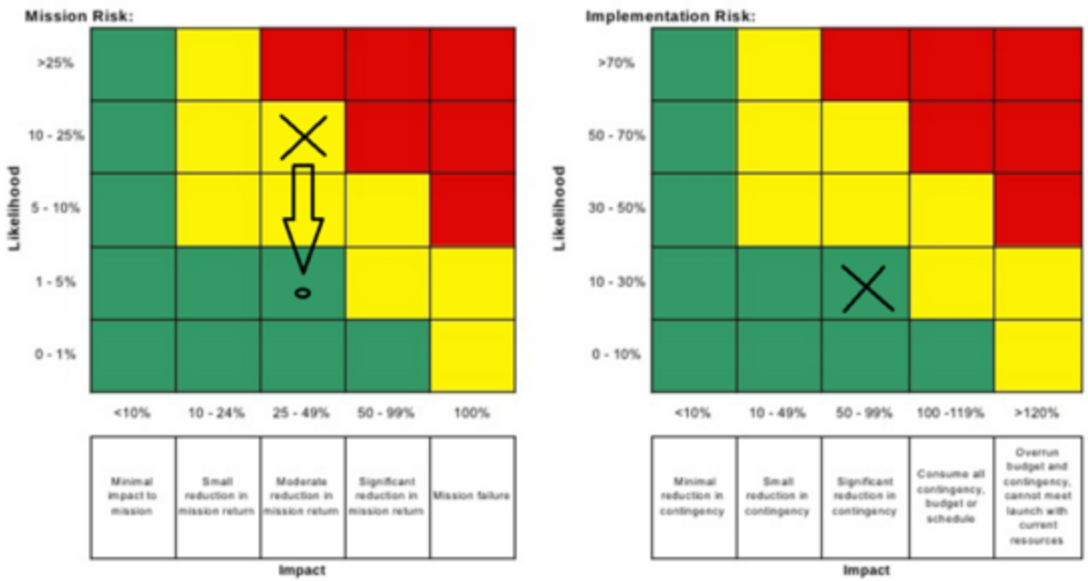
Risk: LRS crash into main base



Mitigations: reasonable distance between launching pad and ISRU, fixing the damages with the rovers, launch maintenance from Earth

Other Technical Risk (8/9)

Risk: Mirror (Technology Readiness Level)



Mitigations: deploy smaller mirrors on the rim.

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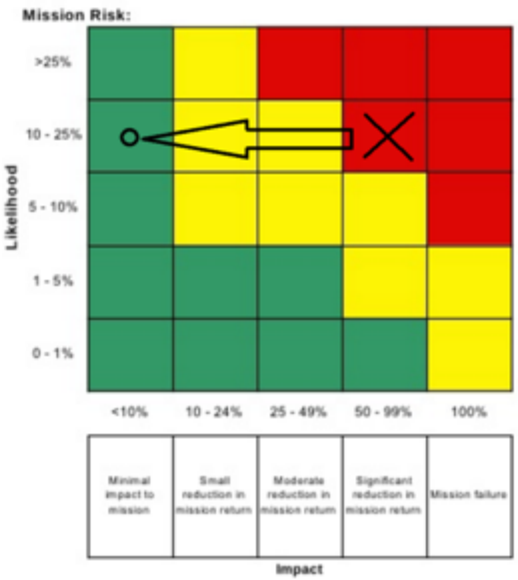
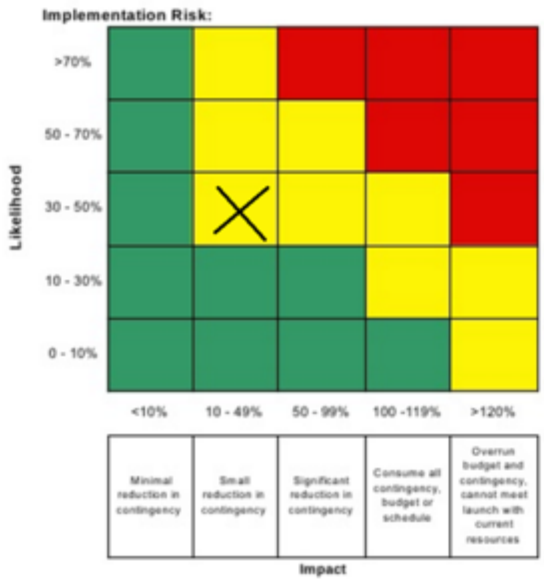
Other Technical Risk (9/9)

Risk: Excavation, prospection or construction rover loss





Mitigations: having rover spares, having in-built maintenance capability, launch maintenance material from Earth