Lunar Sample Return

National Aeronautics and Space Administration

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MARSHALL SPACE FLIGHT CENTER

Agenda

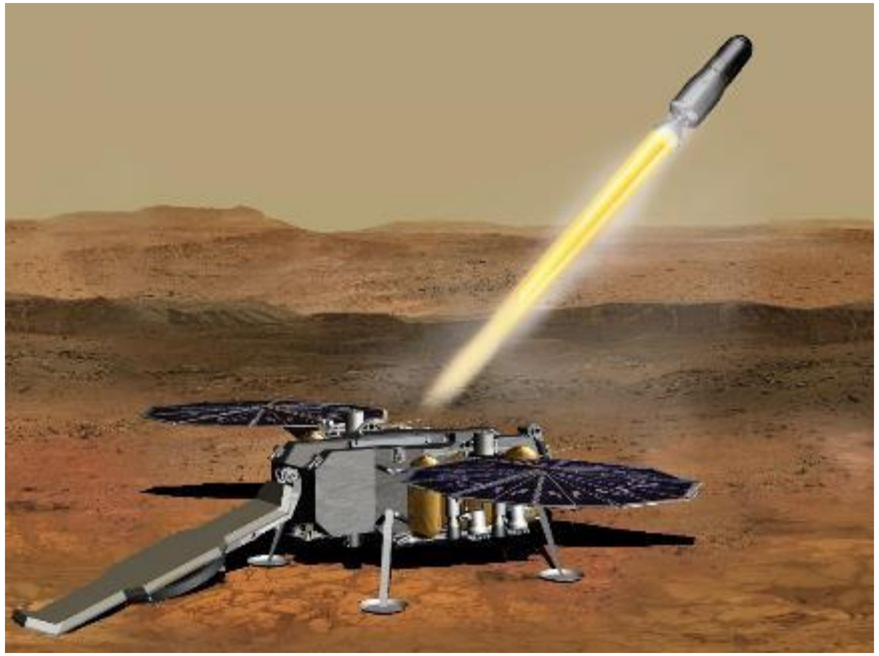
1. Mission Objective and Scope
2. Background and Heritage
3. Commercial Lunar Payload Service (CLPS)
4. South Pole Landing Sites
5. Concepts of Operation
6. System Details
   a) Propulsion System Candidate Evaluation
   b) Lunar Pole Thermal Environment
   c) Sample Handling
   d) Communication
   e) Spacecraft Mass Estimate
   f) Power Estimate and Battery Mass
7. Results and Selection
   a) Example Summary
8. Further work

Mission Objectives and Scope

- Return a sample of lunar water ice from a permanently shadowed crater at the south pole to either the crater rim or to lunar orbit
  - Select propulsion system for a hopper and or ascent vehicle
  - Determine total mission mass required as a CLPS payload
  - Determine CLPS providers that are able to deliver us to the lunar surface

- For this internship, the scope consisted of post landing operations on the lunar surface to the return of the sample.

Background and Heritage

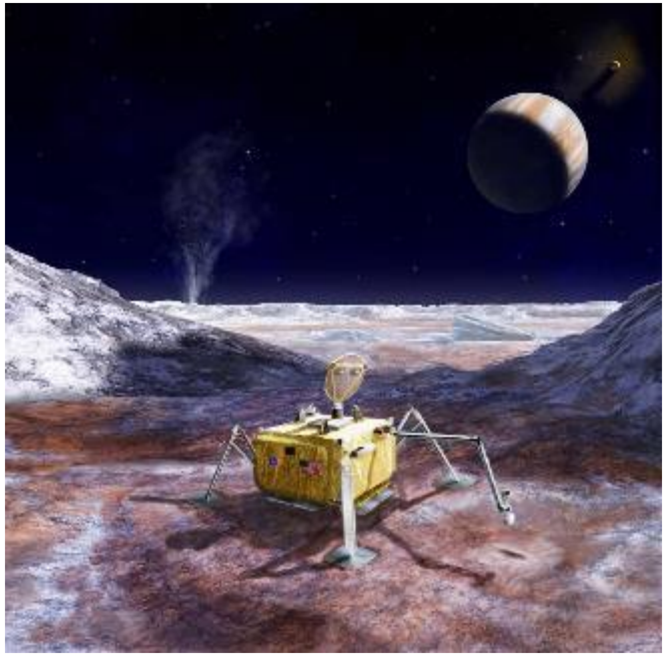


Mars Ascent Vehicle (2026)

- Concept
- Solid and Hybrid propulsion systems
- Mass Estimates
- Component thermal operating temps

VIPER Rover (2023)

- Science Instruments
  - Sample identification
  - Sample Verification
- Mass Estimates
- Power Estimates
- Rover traverse speed
- Lander Requirements
- Communication
- Sample Acquisition

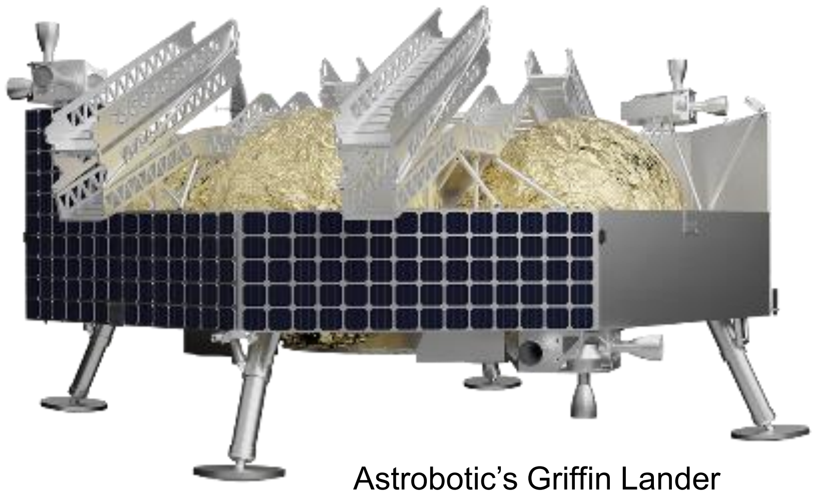


Europa Lander (2030s)

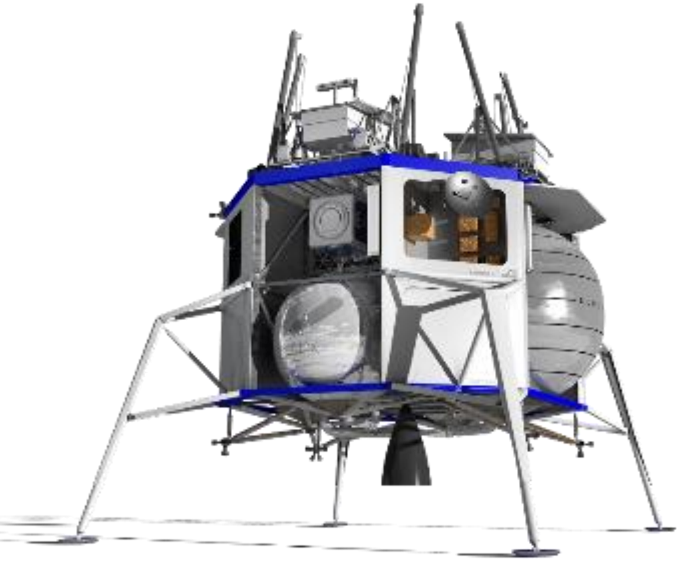
- Sample Acquisition
- Informed sampling timelines
- Scientific Instruments
- Power Estimates
- Mass Estimates

CLPS Providers

- Commercial Lunar Payload Service
- 14 Companies looked at:
  - **Astrobotic's Griffin Lander**
  - **Blue Origin's Blue Moon Lander**
  - Draper Artemis 7
  - Firefly's Genesis Lander
  - Masten's X-1
  - **Lockheed Martin's McCandless Lander**
  - SpaceX Starship



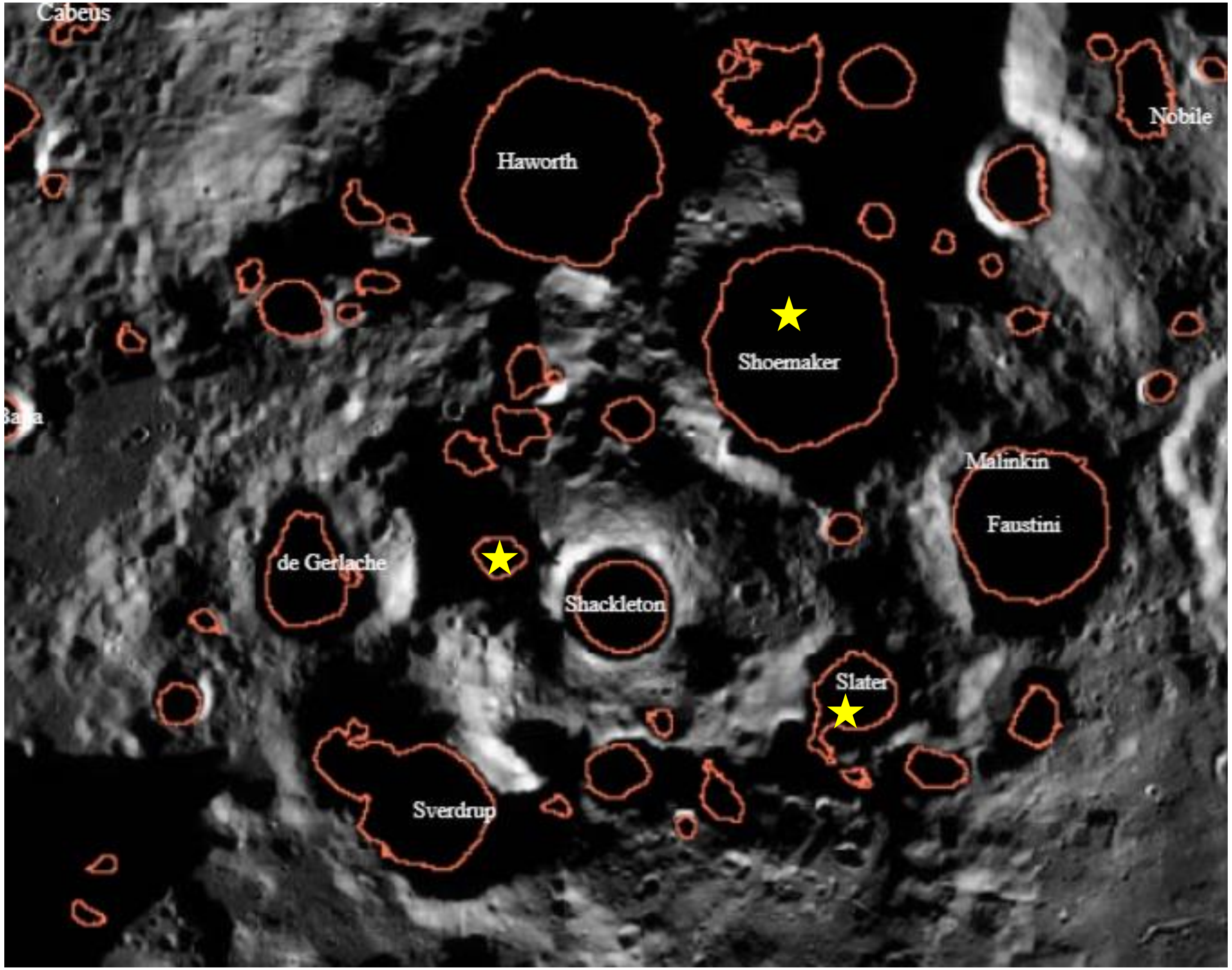
Astrobotic's Griffin Lander



Blue Origin's Blue Moon Lander

Lockheed Martin's McCandless Lander

South Pole Landing Sites



<u>Ranking</u>

#1 “Shoulder Crater”

#2 Slater Crater

#3 Shoemaker Crater

<u>Criteria</u>

Water Possibility

Sunlight Proximity

Elevation Change

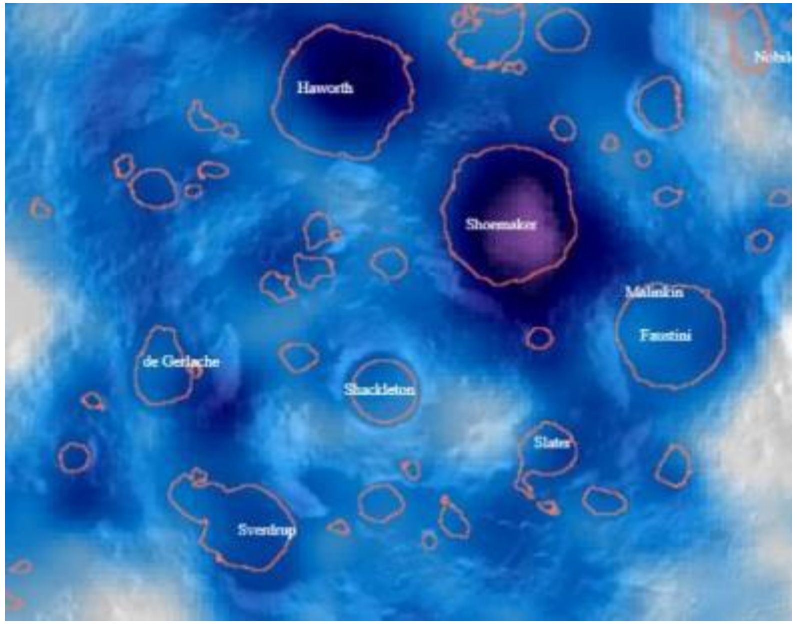
Shade Ranking

Crater	Depth	Diameter
Shoulder	500 m	13.1 km
Slater	1 km	26.5 km
Shoemaker	3 km	53.3 km

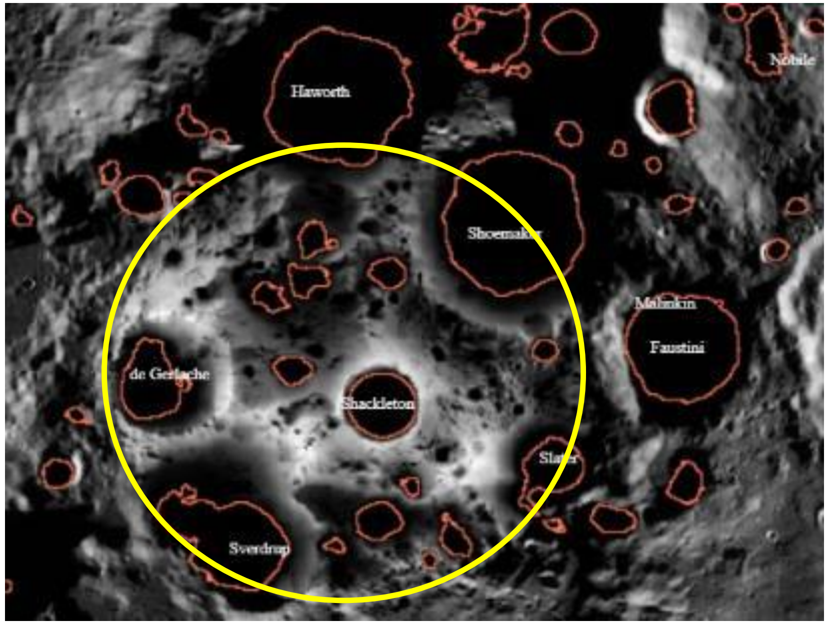
Image from Lunar Reconnaissance Orbiter Camera; Arizona State University

South Pole Landing Sites

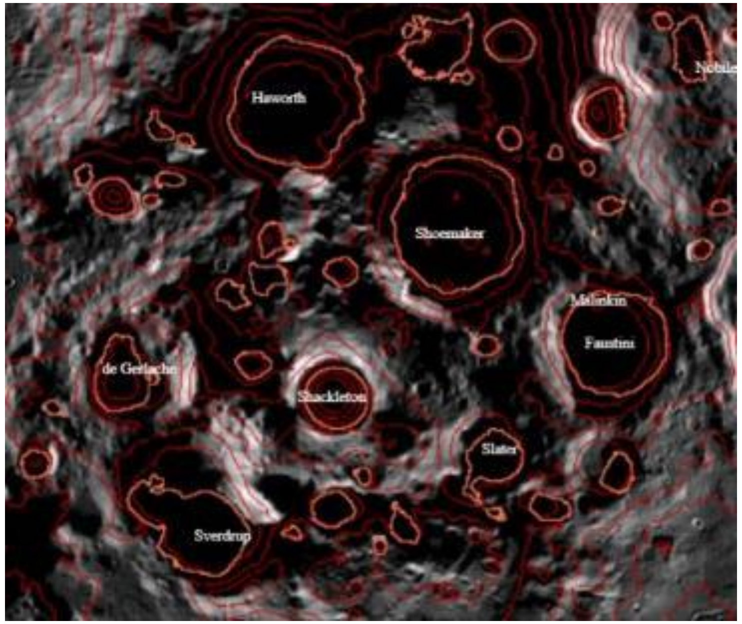
- Water-equivalent Hydrogen map shows the abundance of hydrogen indicating signs of water ice
- Proximity to permanently sunlit areas will influence the spacecraft model and will most likely be the location of the Artemis landing site
- Topographic map to show the elevation changes as that will have an affect on the spacecraft model
- Percentage of shaded areas in the craters were considered as there may be easier access to a permanently shaded area with proximity to non- permanent sunlight



Water-Equivalent Hydrogen



Persistently Sunlit Areas



Topographic map

Yellow Circle shows where the map begins

Images from Lunar Reconnaissance Orbiter Camera; Arizona State University

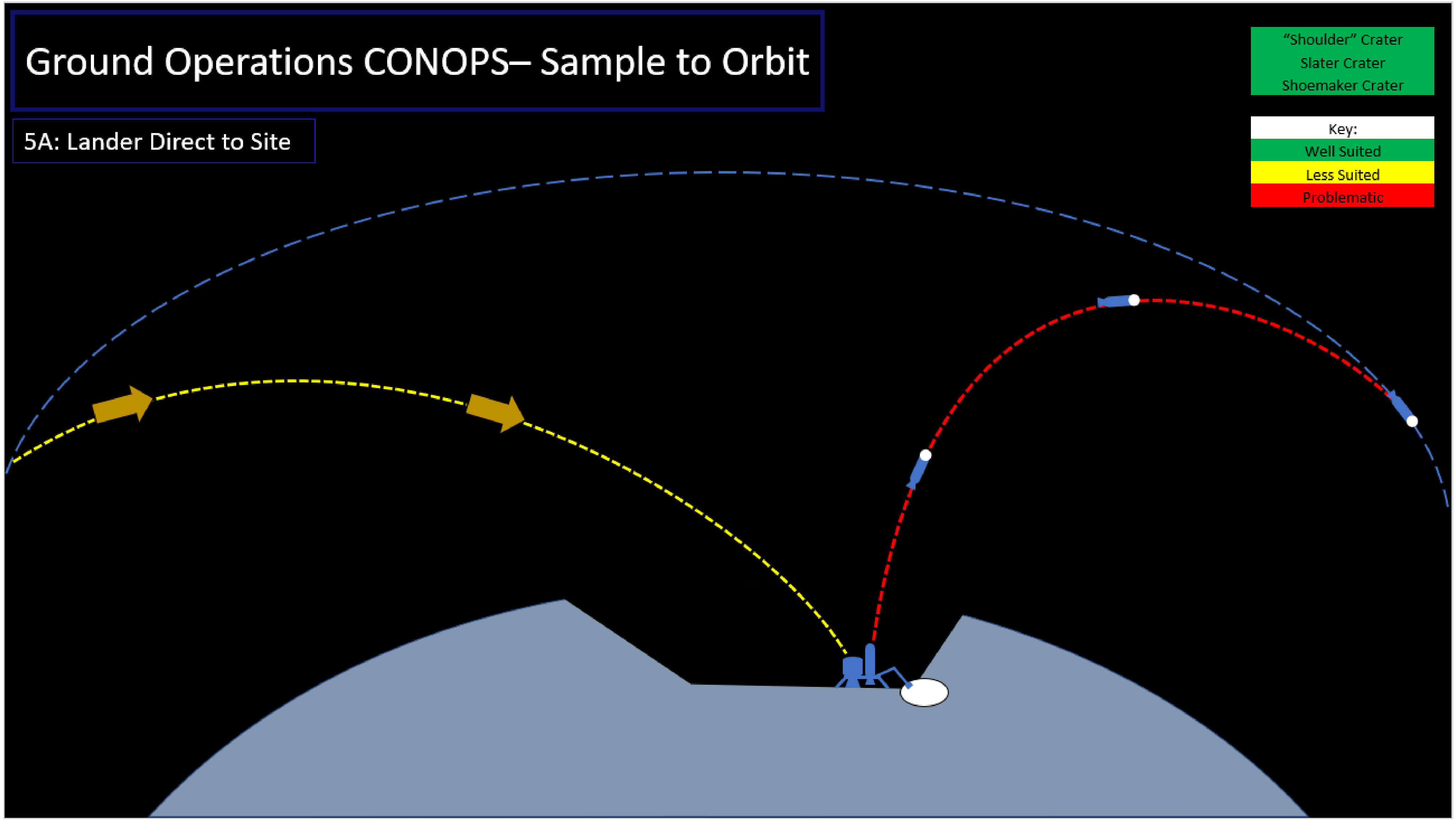
Concepts of Operation

- 11 total CONOPs
  - 2 landing areas (rim or in the crater)
  - 3 means of getting a sample (rover, hopper, lander)
  - 2 final destinations for the sample (to orbit, to crater rim)

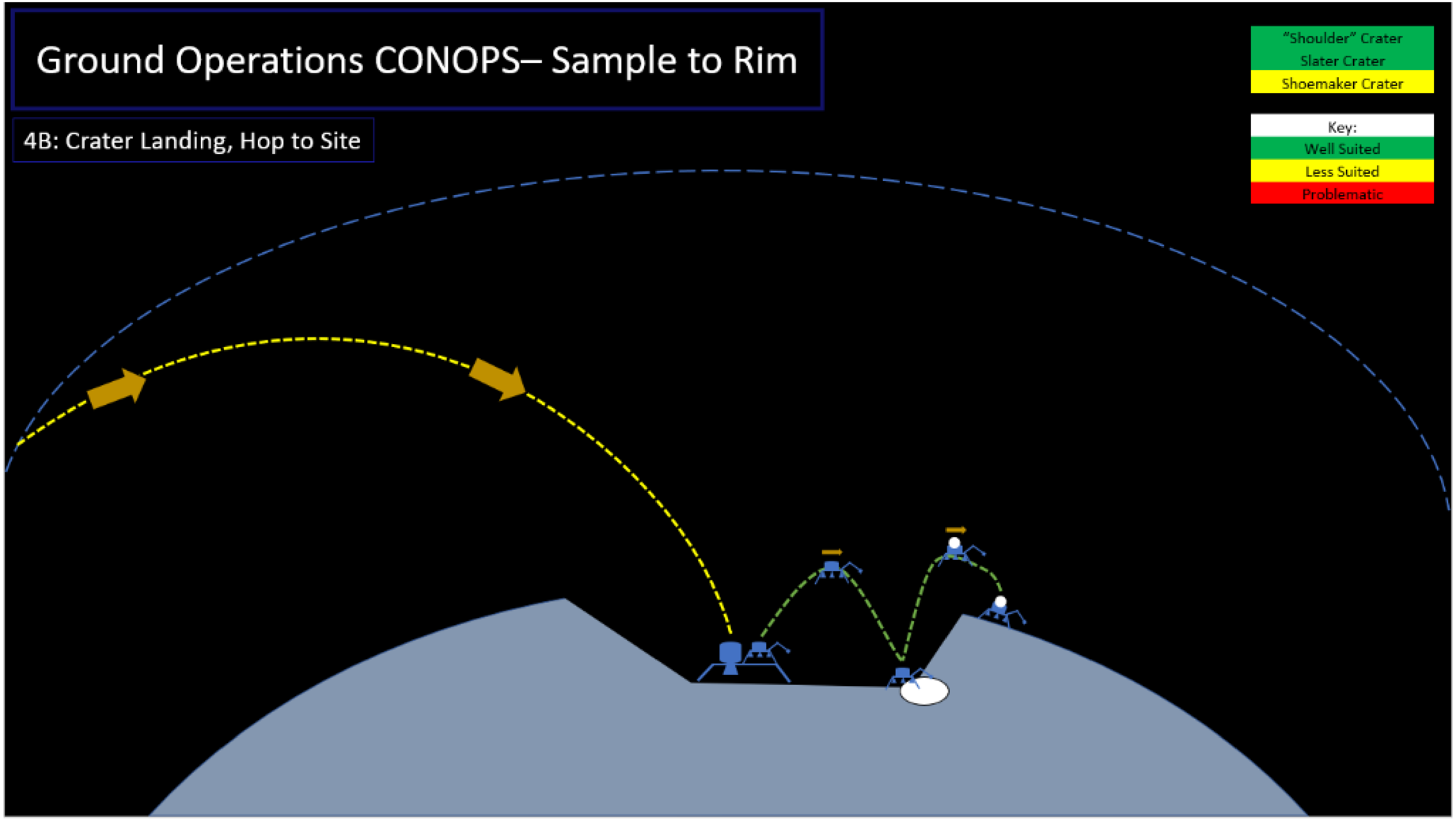
- Surface Operations Time dependent upon:
  - CONOP
  - Crater selected
  - Number of samples taken

Crater	Depth	Diameter
Shoulder	500 m	13.1 km
Slater	1 km	26.5 km
Shoemaker	3 km	53.3 km

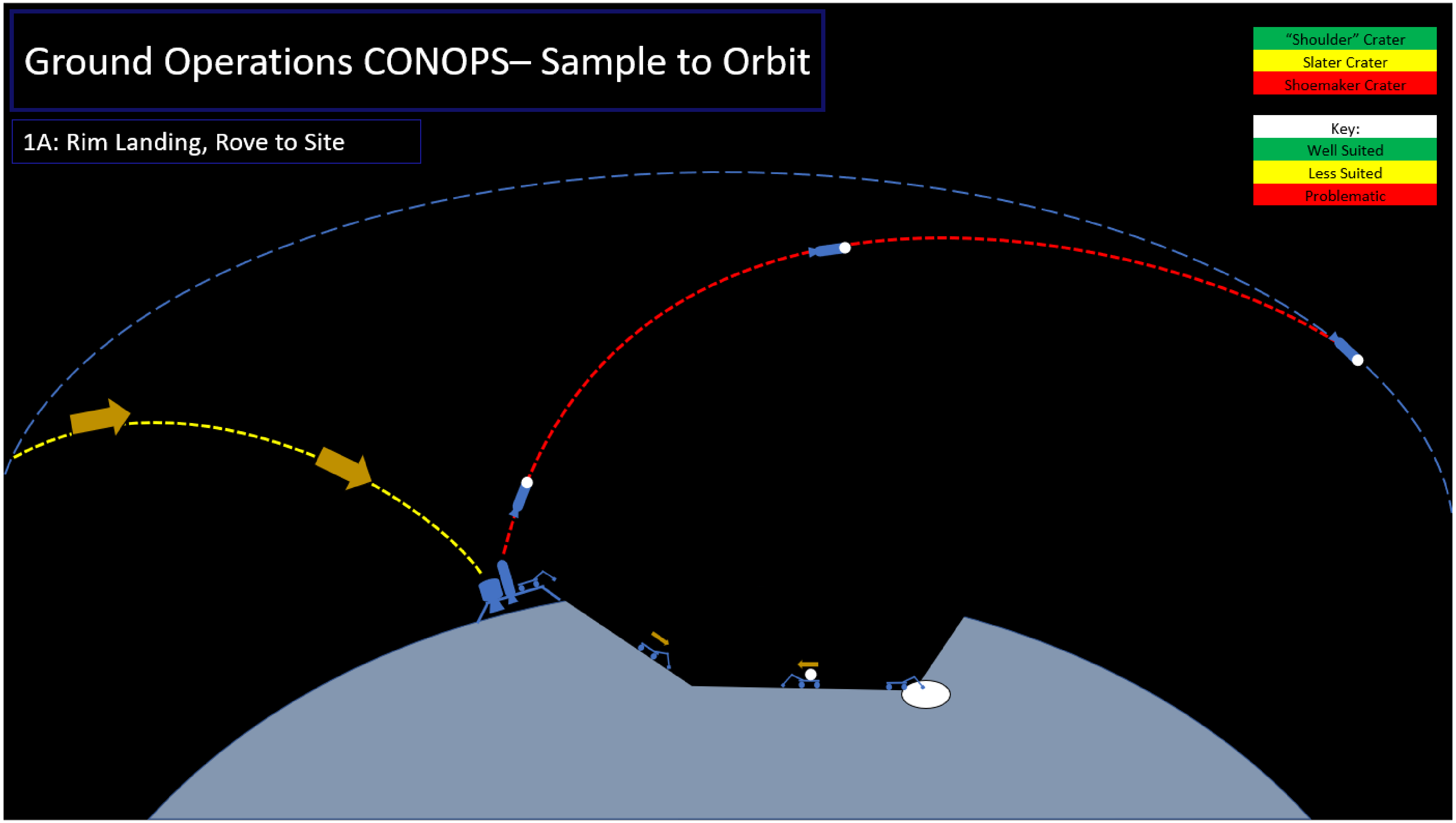
Concepts of Operation, to Orbit



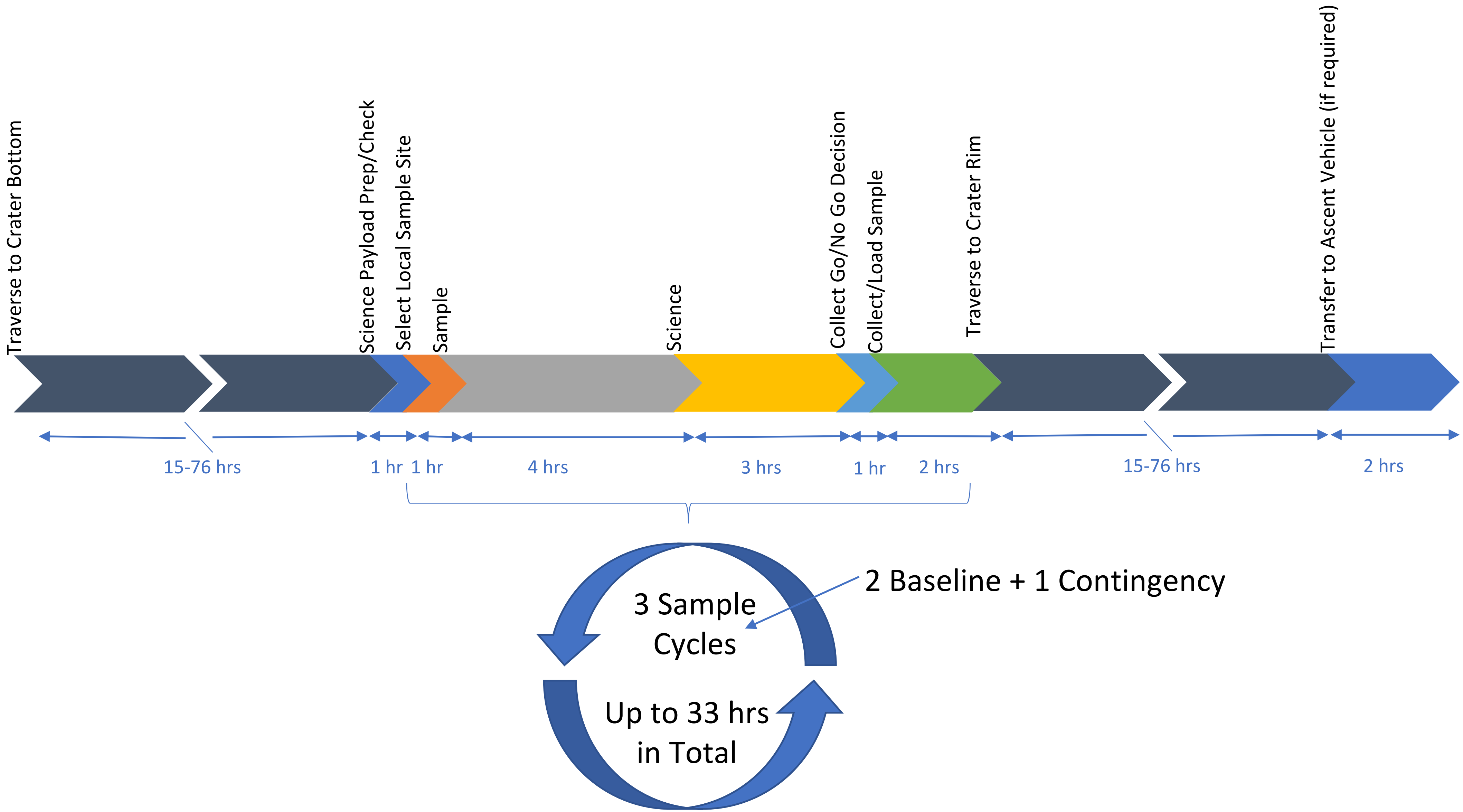
Concepts of Operation, to Rim



Concepts of Operation, to Orbit



Sample Vehicle Surface-Op Timeline, CONOP 1A



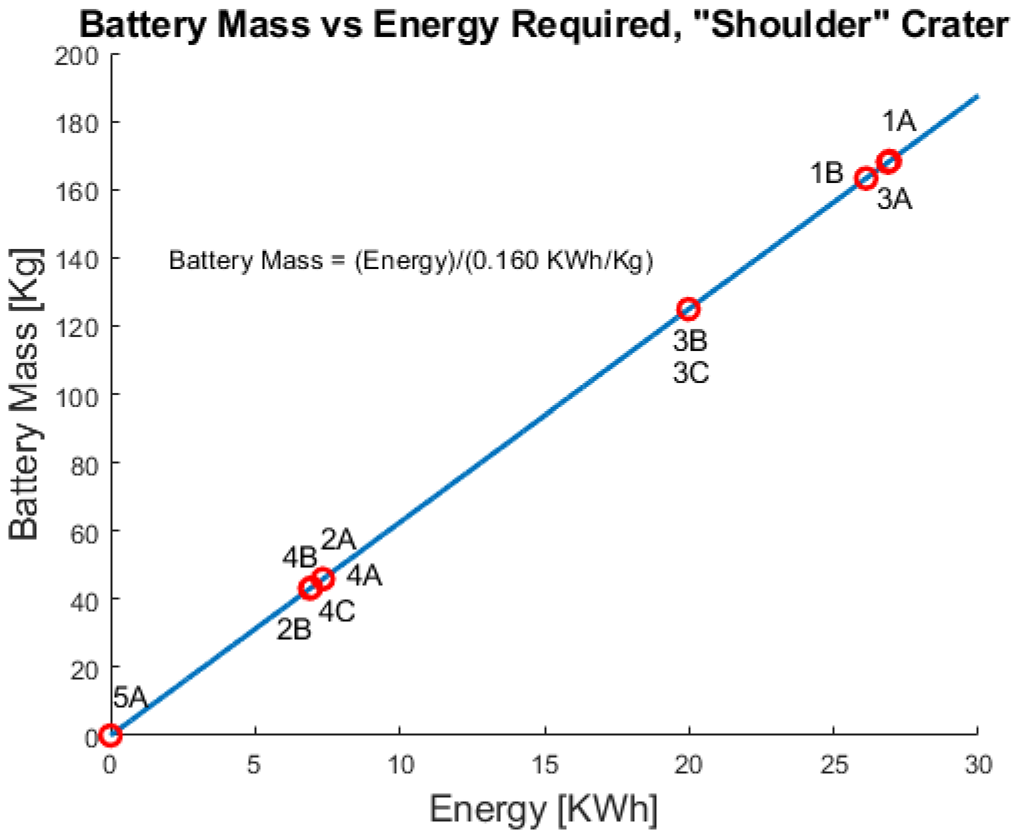
*Assumes No Comms LOS and Human in the Loop (Local Sample Select Decision and Collect Go/No Go Decision)

Traverse Vehicle Battery Mass, "Shoulder" Crater

- The battery carried on a rover or hopper depends on:
  - The time spent in darkness while disconnected from the lander
  - The power required by the rover or hopper subsystems

Conop	Independent Surface Time [Hrs]	Power [W]	Mission Energy [KWh]	Battery Mass Req'd [Kg]
5A*	36.00	0.00	0.00	0.00
2B	34.00	162.25	5.52	34.48
4B	34.00	163.21	5.55	34.68
4C	34.00	163.21	5.55	34.68
2A	36.00	163.21	5.88	36.72
4A	36.00	163.21	5.88	36.72
3B	49.07	325.71	15.98	99.89
3C	49.07	325.71	15.98	99.89
1B	64.15	325.70	20.89	130.58
3A	66.00	325.71	21.50	134.36
1A	66.15	325.70	21.54	134.66

*No Rover or Hopper is utilized in this CONOP. All battery mass may be carried on the lander.

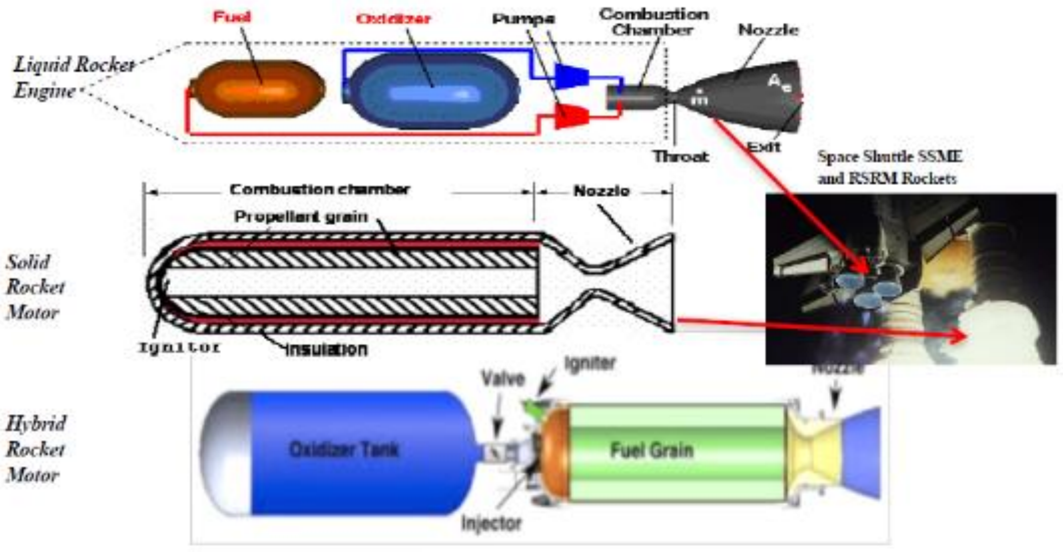


Propulsion Systems

- Solid
  - Various candidates selected depending on CONOP
    - Aerojet
    - Star motors
    - previous MAV solid trades
  - Propellant Mass 6.1-106 kg
  - Inert Mass 3.3 – 27.6 kg
- Liquid
  - Engine: Aerojet R-42
  - Propellant Mass: 5.9 kg – 16.4 kg
    - Fuel (MMH): 1.9 kg – 5.5 kg
    - Oxidizer (N_2O_4): 4.0 kg – 11.9 kg
  - Inert Mass: 6.6 – 13.3 kg
- Hybrid
  - Based on MAV hybrid performance projections
  - With an Inert Mass Estimate of 5 Kg
    - Propellant (Paraffin) Mass: 3.28 kg
    - Oxidizer (MON25 or MON30) Mass: 15.5 kg

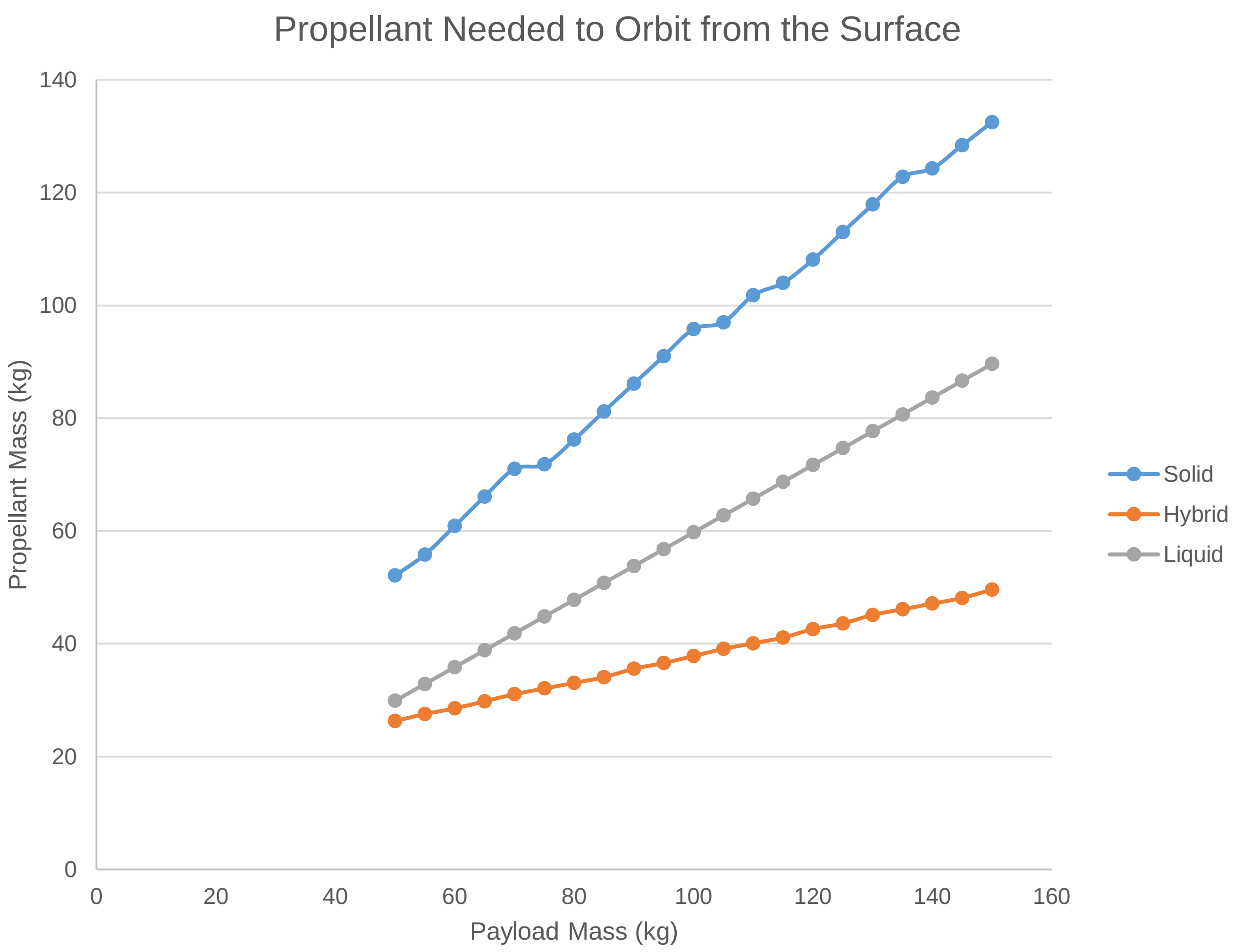
<u>Developed Lunar Ascent Trajectory Model</u>

- CONOPS to rim
  - Rim height achieved and diameter landing- Can it get out of the crater?
  - Impact and Horizontal Velocity – can it survive landing?
- CONOPS to Orbit
  - Orbital velocity achieved
  - Orbital altitude reached



Sutton and Biblarz: Chapter 15, Appendix 4 …

Prop Mass to Orbit



For a 100 km orbit

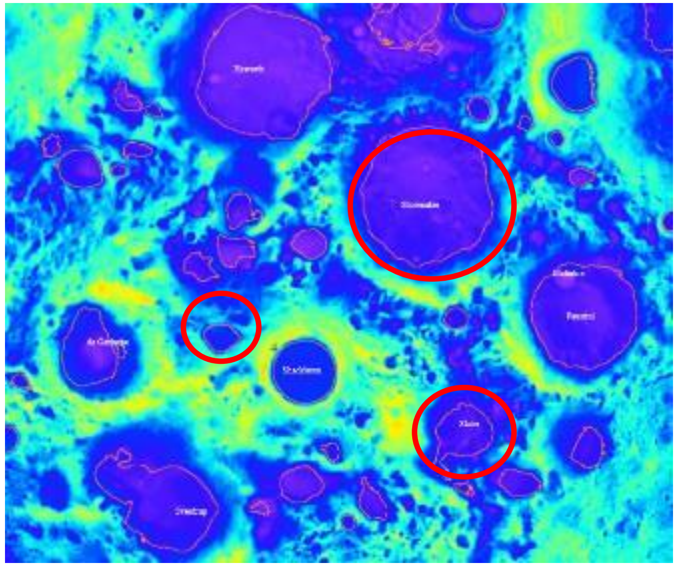
- Solid
  - Engine: NGIS Star 15G
- Hybrid
  - Engine: MAV hybrid engine
- Liquid
  - Engine: R-42

Lunar Polar Thermal Environment

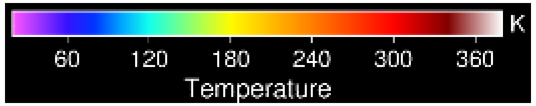
- Highly challenging environment
    - Impacts propellant, avionics, mechanics and batteries
    - Requires heating to meet minimum operation/storage temperatures

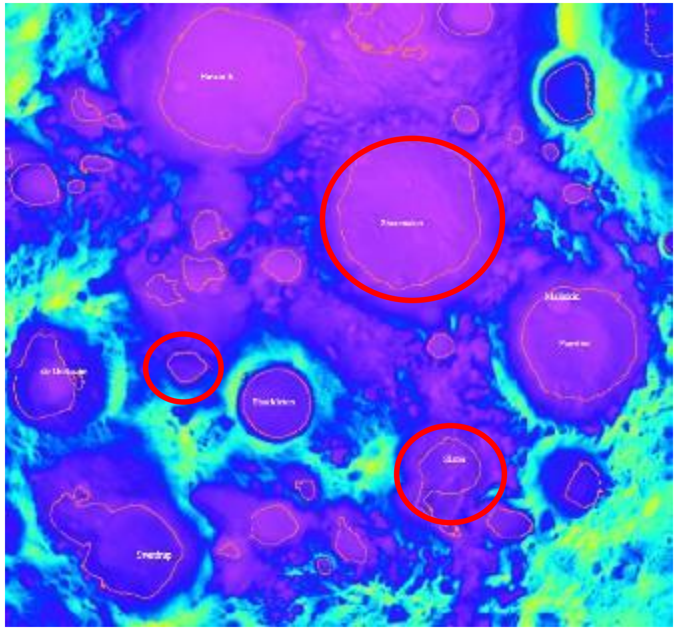
- Persistently Illuminated Region (PIR) Average Surface Temperature at Pole ~ 230 K
- Permanently Shaded Region (PSR) Average Surface Temp in Crater ~ 40 K

- Environmental Drivers at PIR vs PSR–
    - Radiation
        - Solar - lunar albedo and solar incident
        - Blackbody exchange from sky and lunar surface
    - Conduction to lunar surface



Worst Case Hot

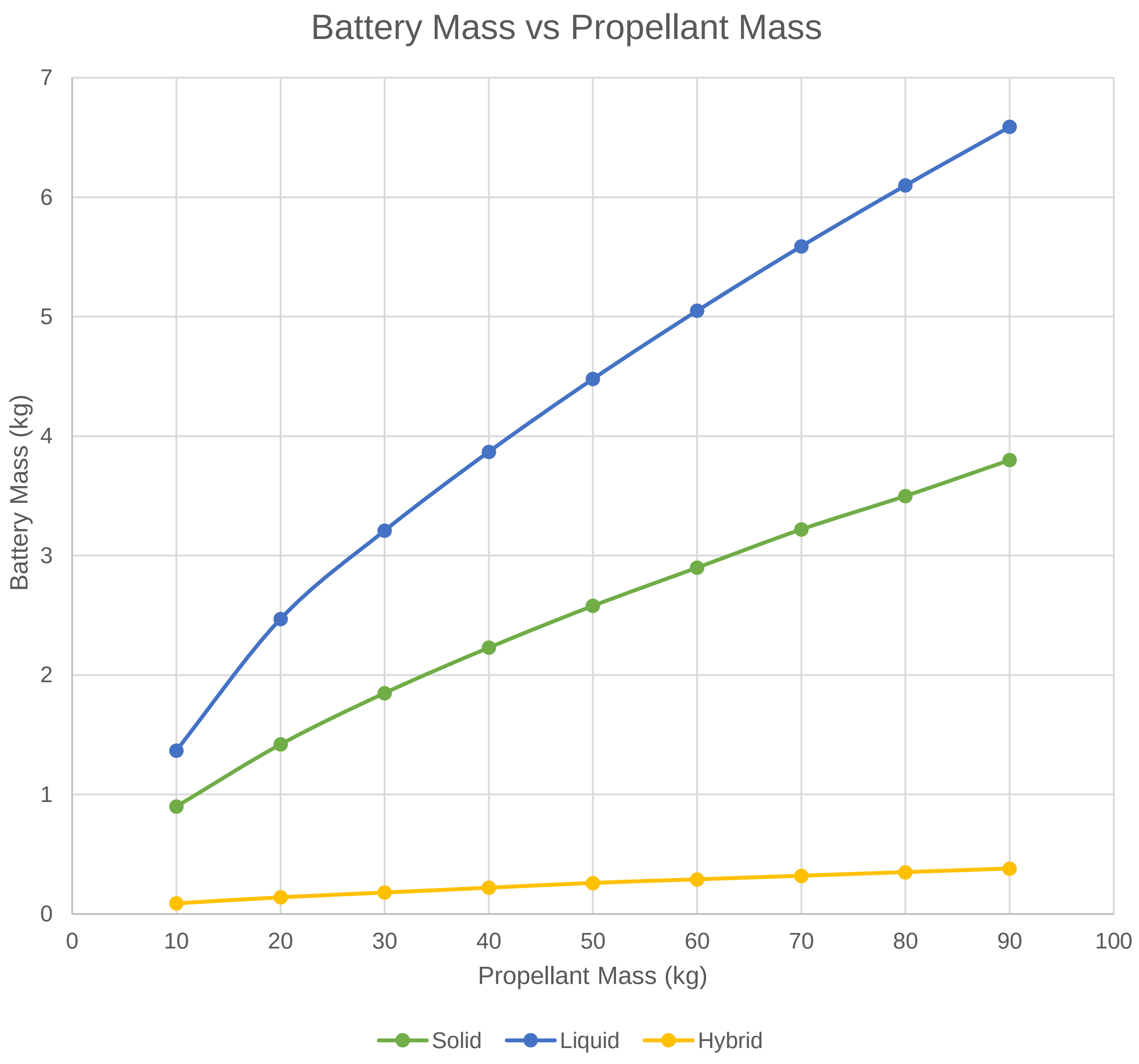




Worst Case Cold

Images from Lunar Reconnaissance Orbiter Camera; Arizona State University

Battery Mass and Propellant



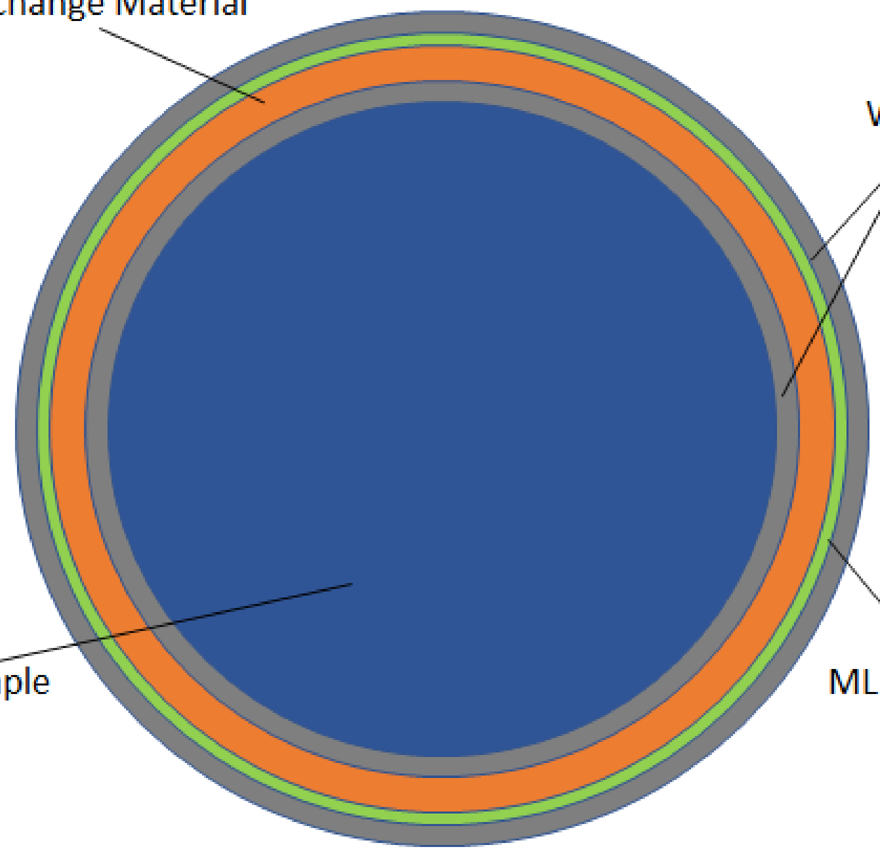
How much battery mass is needed to keep propellant warm?

- 72 hours in PIR
- 160 W-h /kg

- Solid: TP-H-3340
- Liquid: MMH + N2O4
- Hybrid: Paraffin + MON-25

Sample Handling

- Passive thermal control using Neon as a phase change material
- 24.55 K – 27.1 K temperature range
- Capable of keeping a sample cool for 30 days
- ~ 10 kg chamber
  - With 50% mass growth allowance (MGA)
- 1 kg sample



Communication

- Why we need communication
- Human in loop communication to evaluate potential samples
- Line of Slight (LoS)
  - Critical to our communications. Due to being at the South Pole we won't always have LoS, so when LoS is available we will be using a S-band antenna and transmitter to communicate back to Earth.
  - When the hopper/ ascent vehicle is in the crater it won't have LoS to Earth therefore we plan to use a relay to the lander at the crater rim

Antenna/ Transmitter	Mass	Operating Frequency	Transmit Power	Bandwidth
S-Band (Antenna)	64 g	2025-2110 MHz	4 Watts	7 dBi
S-Band (Transmitter)		2200-2290 MHz	2 Watts	60 dBc

Data source: Enduroset Website

Spacecraft Mass Estimate (Not including prop)

- Rover/Hopper ~ 244 kg
  - 25% MGA
  - Avionics/Comms, Payload, Thermal, and Structures
- Ascent Vehicle ~ 80 kg
  - 25% MGA
  - Avionics/Comms, Payload, Thermal, TVC, and Structures
  - Does not include propulsion systems
    - Propellant, engine mass, prop heater batteries

Lunar Rover/Hopper Mass Breakdown	Predicted Mass [kg]	Percent Mass %
Avionics/Comms	76.06	31.22
Payload	45.91	18.84
Thermal	6.69	2.74
Structures	115.00	47.20
Total	243.66	100.00

Ascent Vehicle Mass Breakdown	Predicted Mass [kg]	Percent Mass %
Avionics/Comms	23.96	29.92
Payload	10.10	12.61
Thermal	7.81	9.75
TVC	8.21	10.25
Structures	30.00	37.46
Total	80.09	100.00

Power Estimate and Battery Mass

Best Case

ConOps	Power Needed (W)	Battery Mass (kg)	Power Blue Moon can provide (W)	Mass of Batteries with Blue Moon (kg)	Power McCandless can provide (W)	Mass of Batteries with McCandless (kg)
1A	159.9	82.6	4200	11.6	400	11.6
2A	184.4	51.9	4200	20.3	400	20.3
1B	72.9	36.6	4200	11.1	400	11.1
3A*	144.4	74.5	4200	11.5	400	74.5
2B	122.2	32.5	4200	19.2	400	19.2

Worst Case

ConOps	Power Needed (W)	Battery Mass (kg)	Power Blue Moon can provide (W)	Mass of Batteries with Blue Moon (kg)	Power McCandless can provide (W)	Mass of Batteries with McCandless (kg)
1A	465.9	404.9	4200	168.30	400	168.3
2A	303.4	85.3	4200	45.9	400	45.9
1B	375.6	320.5	4200	163.2	400	163.23
3A*	493.4	254.4	4200	167.9	400	254.4
2B	212.3	56.4	4200	43.1	400	43.1

ConOps	Mission Timeline (hr)
1A	66.1
2A	36
1B	64.1
3A	66
2B	34

- Blue Moon and McCandless are able to provide their own source of power using either hydrogen cells or solar panels
  - That additional CLPS power will only be applied to our payload that remains on the lander (Ascent Vehicle). The hopper or rover that will have to survive on their own batteries or through a wireless power transmission
- Battery/Rechargeability Options
  - Lithium Ion Batteries
  - Hydrogen Cells
- Wireless Power Transmission (Future work)
  - Microwave
  - Laser

ConOps	Blue Moon Spacecraft + Battery Mass (kg)
1A	358.6
2A	356.2
1B	276.5
3A	361.9
2B	271.47

ConOps	Blue Moon Spacecraft + Battery Mass (kg)
1A	515.3
2A	381.8
1B	428.6
3A	518.5
2B	295.4

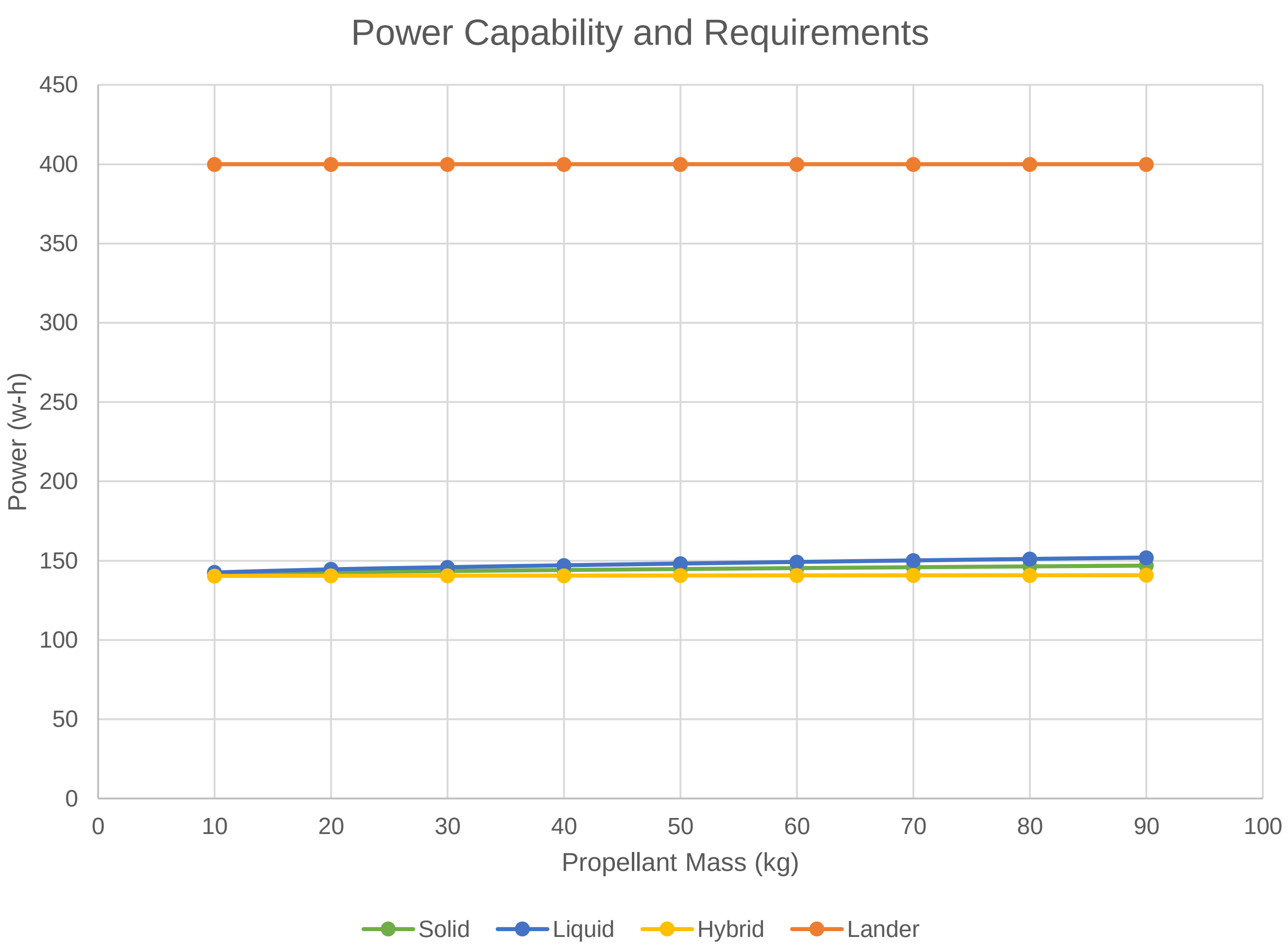
ConOps	McCandless Spacecraft + Battery Mass (kg)
1A	358.6
2A	356.2
1B	276.5
3A	424.9
2B	271.5

ConOps	McCandless Spacecraft + Battery Mass (kg)
1A	515.3
2A	381.8
1B	428.6
3A	604.9
2B	295.4

Best Case (Green) = essential systems running for entire duration of mission
Worst Case (Orange) = all systems running for entire duration of mission

Mass calculations do not include propellant system
Calculations are based off our top ranked "Shoulder" Crater

Propellant and Power Required

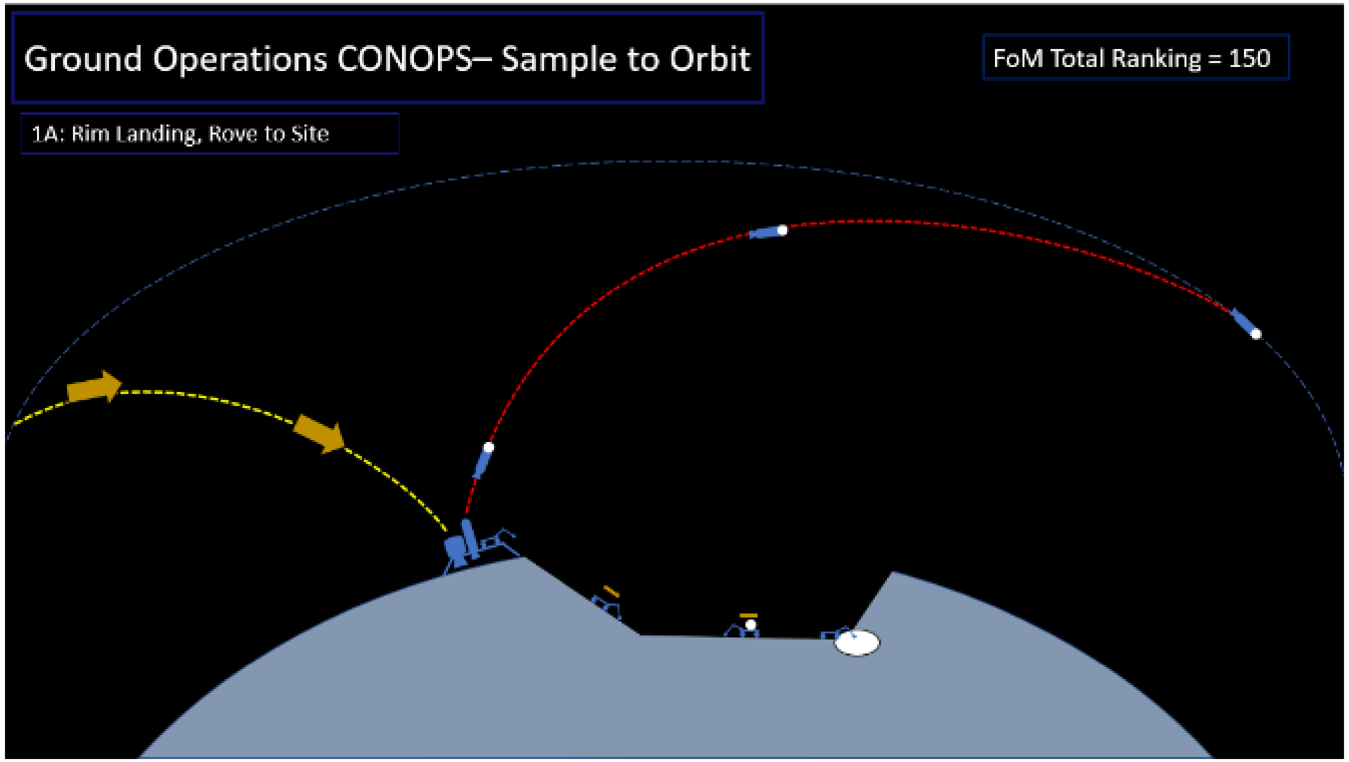


- 72 hours in PIR

- Solid: TP-H-3340
- Liquid: MMH + N2O4
- Hybrid: Paraffin + MON-25
- Lander: McCandless

Selection and Results

- Identified 12 Figures of Merit (FoM) and scored all CONOPS and locations using these

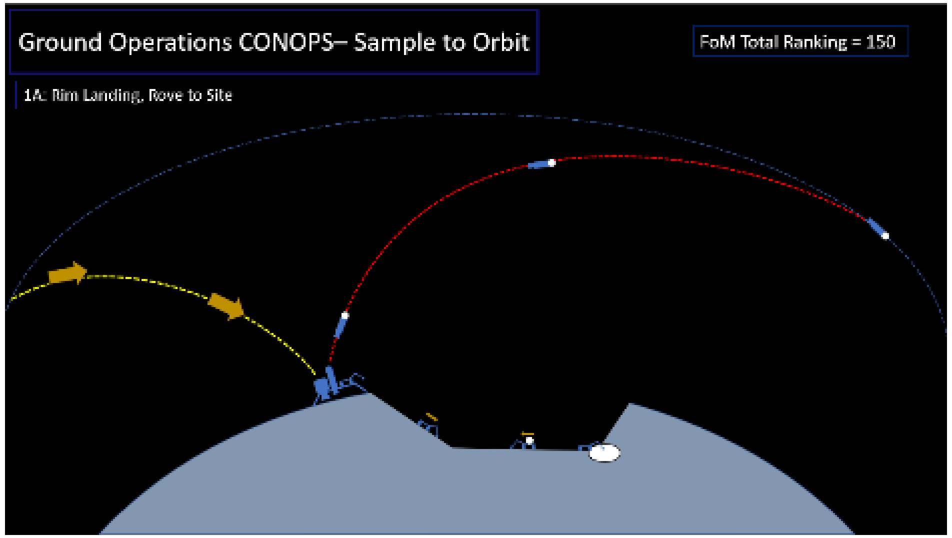


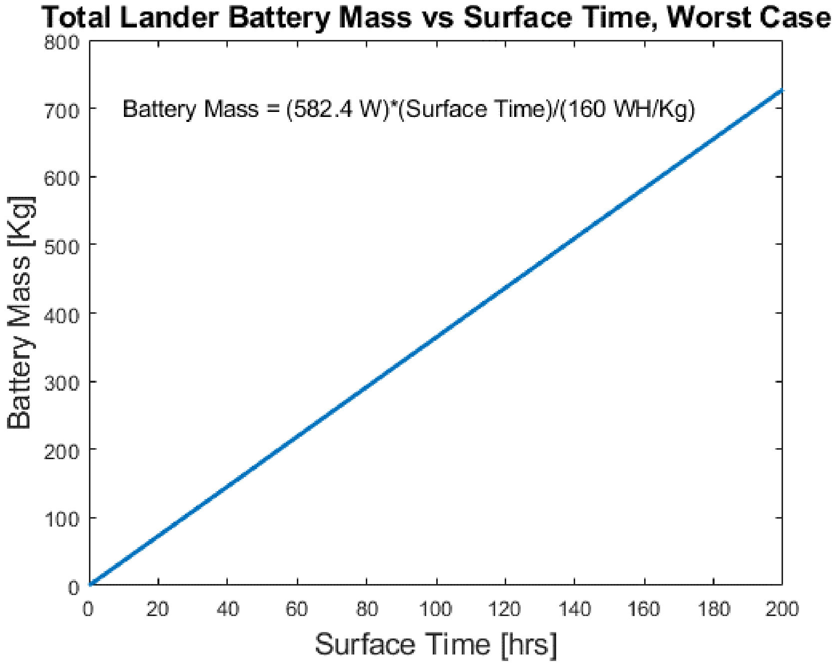
FoM	FoM Weight	Ground CONOPS 1A: Rim Landing, Rove to Site	CONOPS 1A Ranking	CONOPS 1A Weighted Ranking
Description		Lander lands at crater rim, rover roves inside crater, collects sample, and comes back. Then launches sample to orbit		
Rover/Hopper TRL	2	6 (better)	2	4
Mothership landing site precision required for mssion success	10	No	2	20
Rover/Hopper Distance Travelled required (Shoulder, Shoemaker, Slater) Includes both distance to sample and distance to destination on Lunar surface.	5	Shoulder: Neutral Shoemaker: Poor Slater: Poor	1	5
Sample Site Integrity preserved	10	Good: Roving to the sample site	2	20
Sample Site observation time prior to commit (roving vs. hovering)	7	Good: Roving to the sample site	2	14
Opportunity for Multiple Sample Sites	2	Good: Roving to the sample site	2	4
Human in the Loop Communication	10	Good: landing on crater rim (lander as a relay)	2	20
Complexity (Movements)	7	Poor: 4 movements	0	0
Requires charged batteries at landing?/Power Generation (Keep ascent vehicle powered/warm without batteries)	8	Good: Landing on crater rim	2	16
Mission Benefit (Earth Return vs Crater Rim)	20	Good: Going to Earth Orbit	2	40
Ease of precise sample transfer	7	Rover: Must transfer sample from rover to ascent vehicle	1	7
Total Mass (kg) (No Prop, no engine)	12	386.4	0	0
Total Ranking	**100**			**150**

Example Summary

- Best Mission – CONOP 1A to Shoulder Crater
  - Power = 582.38W
  - Mission Time = 66.1 hours
  - Mass = 515 kg
    - Rover
    - Ascent Vehicle
    - Batteries
  - Engine = 94.63 kg (Solid)
  - Total = 609.63 kg

- CLPS Providers
  - Griffin Lander -- 475 kg
  - McCandless Lander -- 1000 kg
  - Blue Moon -- 3500-6500 kg





Further Work

- Select prop system
- Sample return to Earth (including reentry capsule)
- Power Systems
  - Wireless power transmission
  - Hydrogen Cells
  - Day to day power calculations
- Further investigation on communication
- Improve thermal estimates
  - Experiment with different reflections
- Sizing of ascent vehicle and rover
- Interface with CLPS provider

Thank you

- Our mentors at Marshall Space Flight Center
  - Pat Lampton
  - Britt Oglesby
  - George Story
- Dr. Stephen Whitmore and Dr. Matt Harris
  - Utah State University
- Dr. Daniel Harris
  - Auburn University
- Marshall Space Flight Center

Questions?

Thank you!