RESOLVE: an International Mission to Search for Volatiles at the Lunar Poles

(Regolith & Environmental Science and Oxygen & Lunar Volatiles Extraction)

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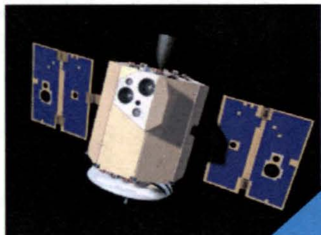
Our Evolving Understanding of the Moon and its Resources

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

1961: — 1970 — 1994 — 1998 — 2008 — 2009 — 2010

Watson, Murray and Brown theorize that cold traps at the moon's poles may contain water ice

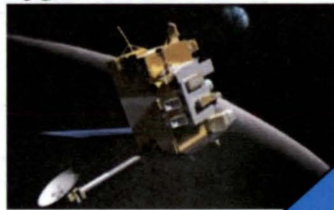


Clementine's Bi-Static Radar suggest Water Ice in permanently shadowed regions near the poles

Neutron Spectrometer aboard Lunar Prospector detects elevated levels of hydrogen that correlates with permanent shadow

Synthetic Aperture Radar on Chandrayaan 1 returns data that is consistent with water ice in the PSR's

LCROSS impacts Cabeus A and clearly detects significant quantities of water in the ejecta



Integrated data sets from instruments on LRO support the existence of large quantities of water ice in the PSRs and in partially sunlit regions

LCROSS & LRO Definitively Prove Existence of Volatiles at the Lunar Poles

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
H_2O(g)	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
NHCN					x			
NH					x			
NH_2					x			

Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

What's the Next Step?

- We now know with certainty that there are volatiles at one spot on the moon.
- Comparison's of orbital instrument data with the LCROSS plume seem to suggest that the water is not evenly distributed.
- Until we know the distribution and accessibility of the volatiles don't really know if we have a usable resource.
- A "Ground Truth" surface mission is the next logical step.
- RESOLVE is the payload that NASA and the CSA are designing to answer these questions

RESOLVE Mission Requirements

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Primary Mission:

✓ **Verify the existence of and characterize the constituents and distribution of water and other volatiles in lunar polar surface materials**

- **Map the surface distribution of hydrogen rich materials** (Neutron Spectrometer, Near-IR Spectrometer)
- Extract 1m core sample with minimal loss of volatiles from selected sites (Drill /Auger Subsystem)
  - to a depth of 1m
- **Heat multiple samples from each core to drive off volatiles for analysis** (OVEN Subsystem)
  - from 100°K to 473°K
  - from 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
- **Determine the constituents and quantities of the volatiles extracted** (LAVA Subsystem)
  - Hope to find and quantify H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2
  - Survive limited exposure to HF, HCl, and Hg

Secondary Mission:

✓ **Demonstrate the ISRU Hydrogen Reduction Process to extract oxygen from lunar regolith**

- **Heat sample to reaction temperature** (OVEN Subsystem)
  - from 473°K to 1173°K
- **Flow H_2 through regolith to extract oxygen in the form of water** (OVEN Subsystem)
- **Capture, quantify, and display the water generated** (LAVA Subsystem)

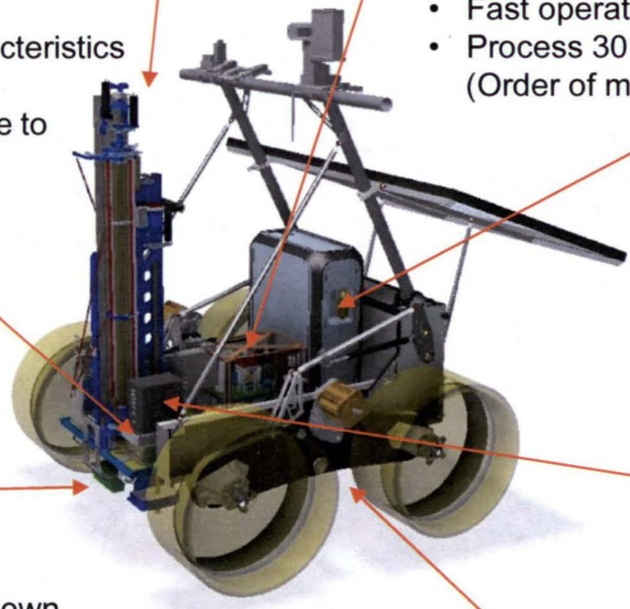
RESOLVE (Regolith & Environment Science and Oxygen and Lunar Volatile Extraction)

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Sample Acquisition –
Auger/Core Drill [CSA provided]
- Complete core down to 1 m; Auger to 0.5 m
- Minimal/no volatile loss
- Low mass/power (<25 kg)
- Wide variation in regolith/rock/ice characteristics for penetration and sample collection
- Wide temperature variation from surface to depth (300K to <100K)

Sample Evaluation –
Near Infrared Spectrometer (NIR)
- Low mass/low power for flight
- Mineral characterization and ice/water detection before volatile processing
- Controlled illumination source

Resource Localization –
Neutron Spectrometer (NS)
- Low mass/low power for flight
- Water-equivalent hydrogen $\geq$ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed



Volatile Content/Oxygen Extraction –
Oxygen & Volatile Extraction Node (OVEN)
- Temperature range of <100K to 900K
- 50 operations nominal
- Fast operations for short duration missions
- Process 30 to 60 gm of sample per operation (Order of magnitude greater than TEGA & SAM)

Volatile Content Evaluation –
Lunar Advanced Volatile Analysis (LAVA)
- Fast analysis, complete GC-MS analysis in under 2 minutes
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU

Operation Control –
Flight Avionics [CSA/NASA]
- Space-rated microprocessor

Surface Mobility/Operation [CSA mobility platform]
- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors
- NASA contributions likely for communications and thermal management

RESOLVE Instrument Suite Specifications
- Nom. Mission Life = 10+ Cores, 12+ days
- Mass = 60-70 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power; 200 W

RESOLVE 3rd Generation Prototype
Near Flight Mass, Volume and Power

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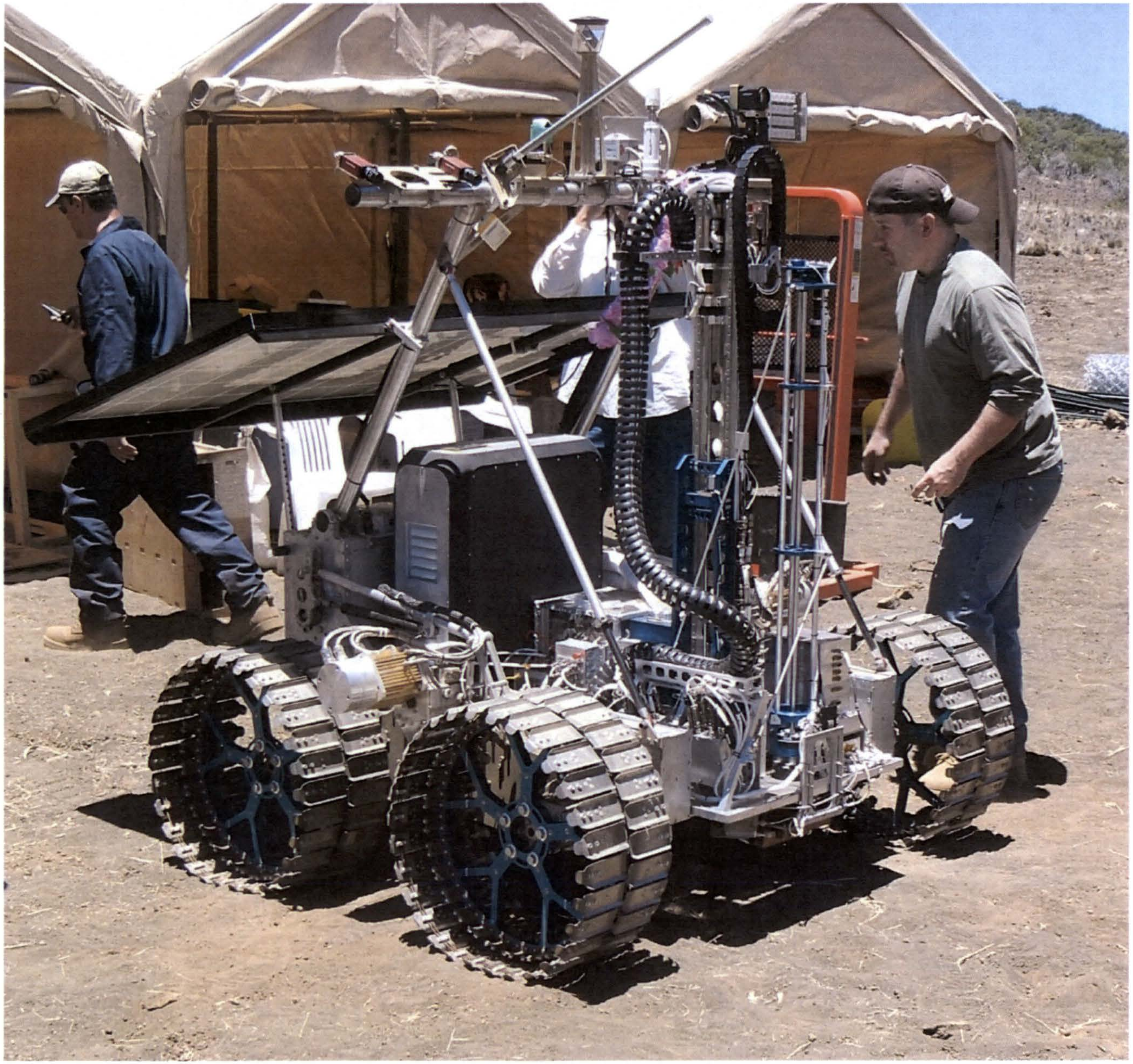


Planning the Mission: Where should we land?

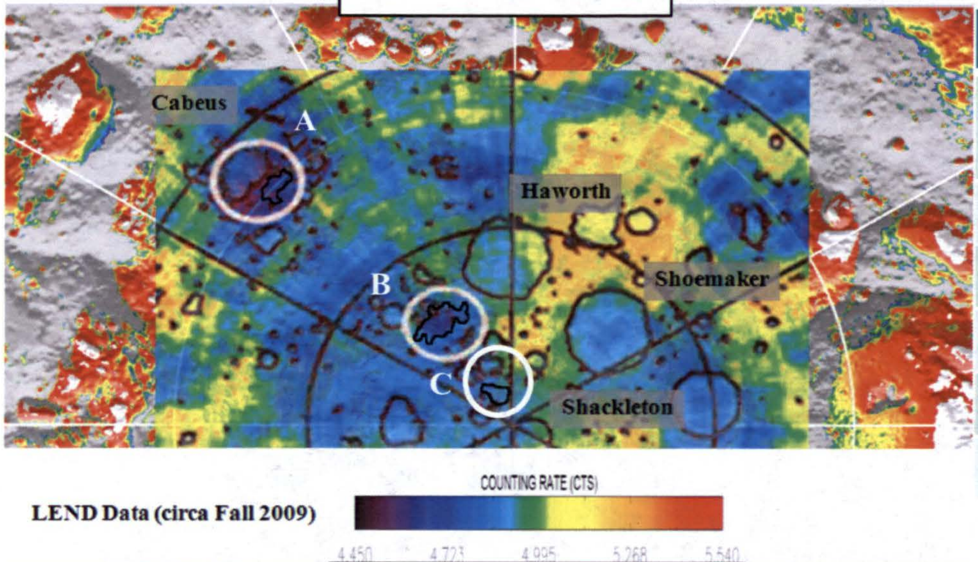
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

- Permanent Shadowed Craters?
  - LRO radar data suggests large, thick deposits of water ice in some of the Permanently Shadowed Craters
  - However, temperatures are extremely low (<40K), and a mission of any significant duration would probably require a nuclear energy source.
    - Mission would be prohibitively expensive for our current budget environment.
- Partially sunlit regions?
  - Lunar Exploration Neutron Detector (LEND) suggests that there are areas of neutron suppression (indicator of hydrogen) outside of the permanently shadowed regions.
  - David Paige and the DIVINER radiometer team published results indicating that there are many areas in the polar regions that have subsurface temperatures (<100K) that would support the existence of water ice.
  - Solar powered missions are more affordable and the operating environment for hardware is much less harsh.
  - Perhaps a location like this would make it easier to set up a future mining operation on the Moon if the resources were plentiful enough.

RESOLVE Mission Options – Potential South Pole Landing Sites

RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

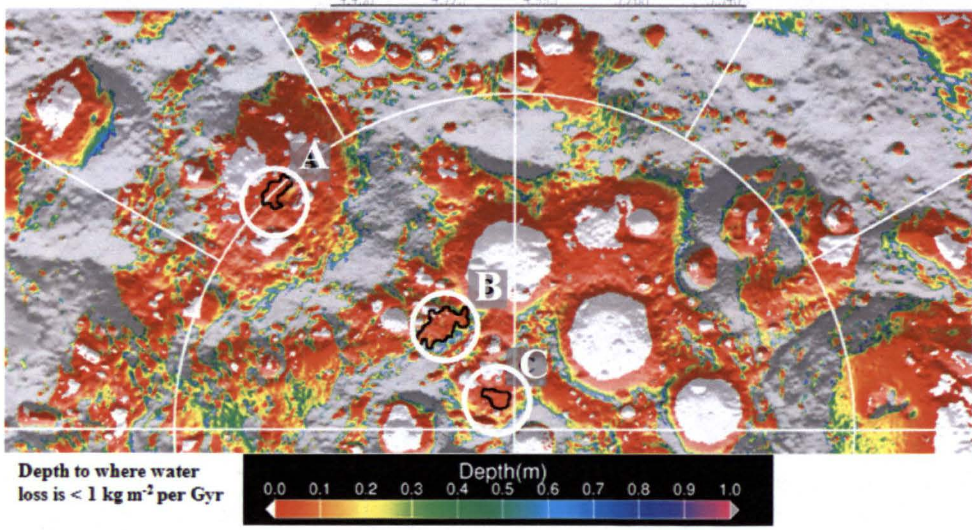
LEND Results



LEND Data (circa Fall 2009)

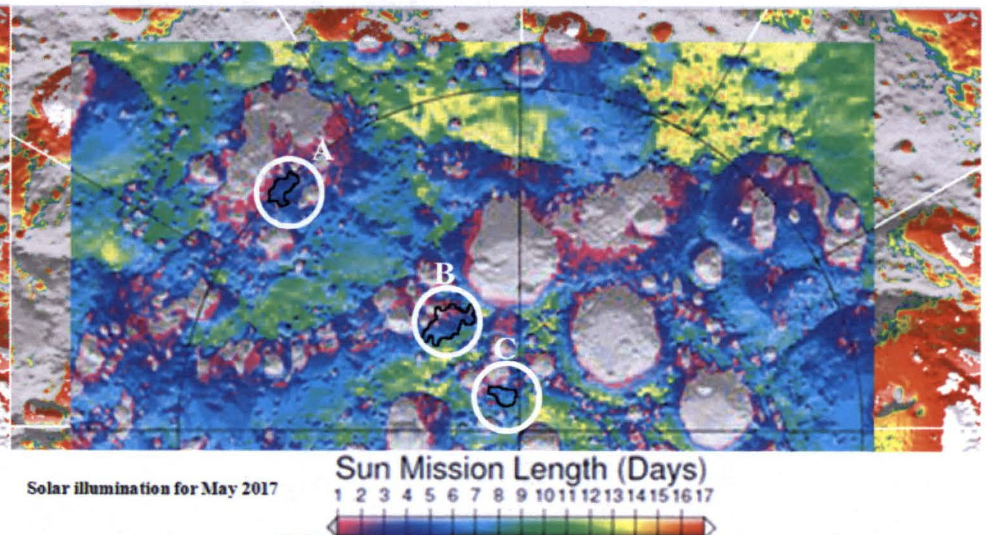
Site Analysis

Site:	A	B	C
Shallow "Frost Line"	<0.1 m	<0.2 m	<0.1 m
Slopes	<10°	<15°	<10°
Neutron Depletion	4.5 cps	4.7 cps	4.9 cps
Temporary Sun*	4 days	2-4 days	5-7 d
Comm Line of Sight*	8 days	17 days	17 days
* may not coincide			



Depth to where water loss is < 1 kg m^{-2} per Gyr

Predicted Volatile Stability



Solar illumination for May 2017

Solar Power Potential

RESOLVE Mission Options – Potential South Pole Landing Sites

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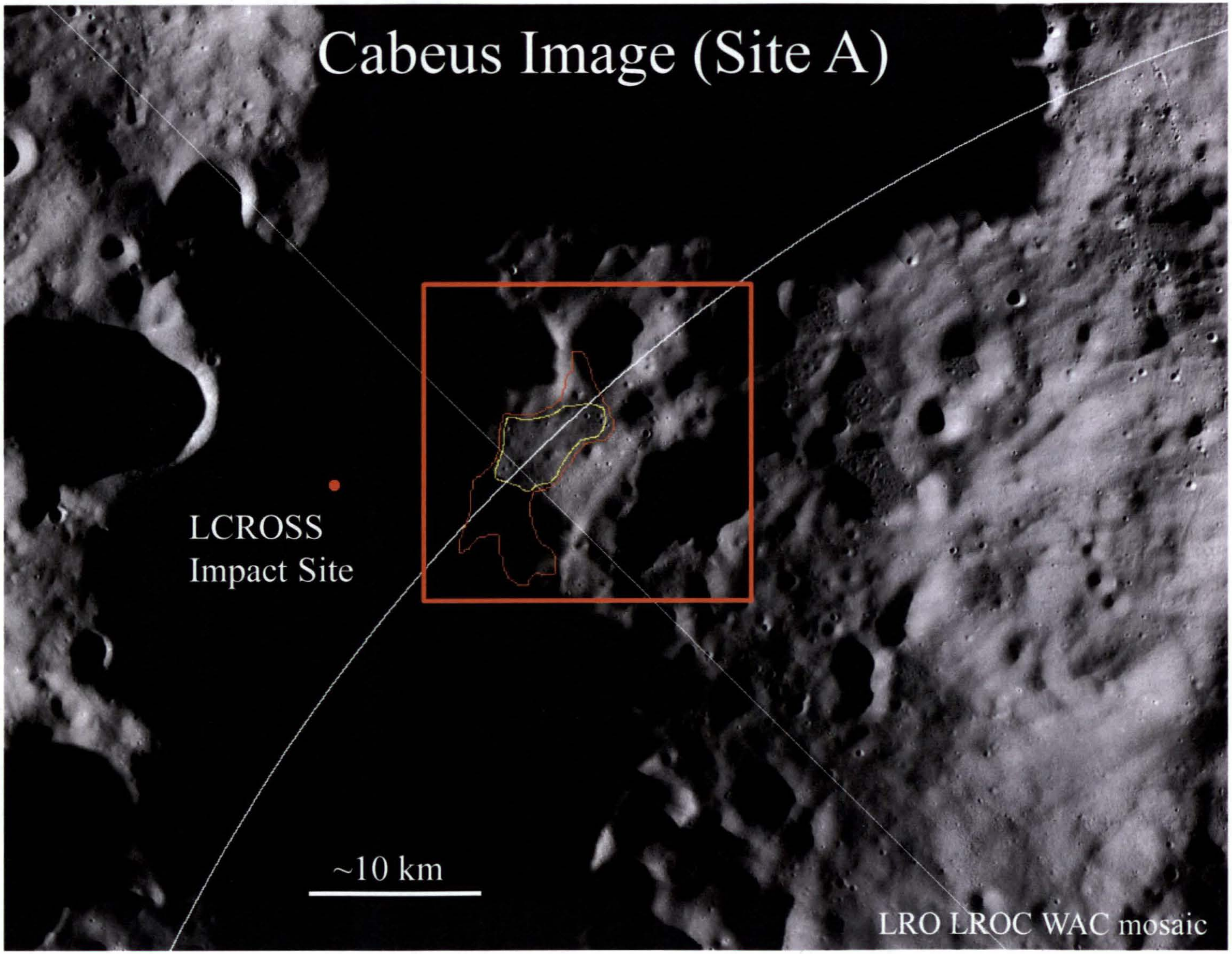

Sun and Shadow Ops

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SUN (2.5 days)

- **Checkout**
  - *6.17 hrs*

- **1st Navigation 0.6 km**
  - *3.88 hrs, 0.6 km total*
- **Drill 1st Hole 4.33 hrs**
  - *Two 0.5m Augers (1-2)*
  - *One 1.0m Core (1)*
- **Process Segments (1-8)**
  - *8 segments, 26.84 hrs*

- **2nd Navigation 0.6 km**
  - *3.88 hrs, 1.2 km total*
- **Drill 2nd Hole 4.33 hours**
  - *Two 0.5m Augers (3-4)*
  - *One 1.0m Core (2)*
- **Process Segments (9-10)**
  - *2 segments, 9.59 hrs*

SHADOW (2 days)

- **Hibernate**
  - *48 hrs*
- *Consider using this "down time" to downlink detailed RESOLVE data (pics, detailed plant data, etc.)*

MISSION SUMMARY

- Mission Length 9.5 days
  - 2.5 days Sun
  - 2.0 days Shadow
  - 5.0 days Sun
  - 8.2 days of Scheduled Activities
  - 1.3 days of Reserve Time
- Samples Processed
  - 25 processed at 150 deg C
  - 3 processed at 900 deg C
- Navigation
  - 5 navigation periods
  - Distance traveled is 3.0 km
- Drilling
  - Ten 0.5 m Augers
  - Five 1.0 m Cores

SUN (5 days)

- **Battery Recharge**
  - *6.8 hrs*

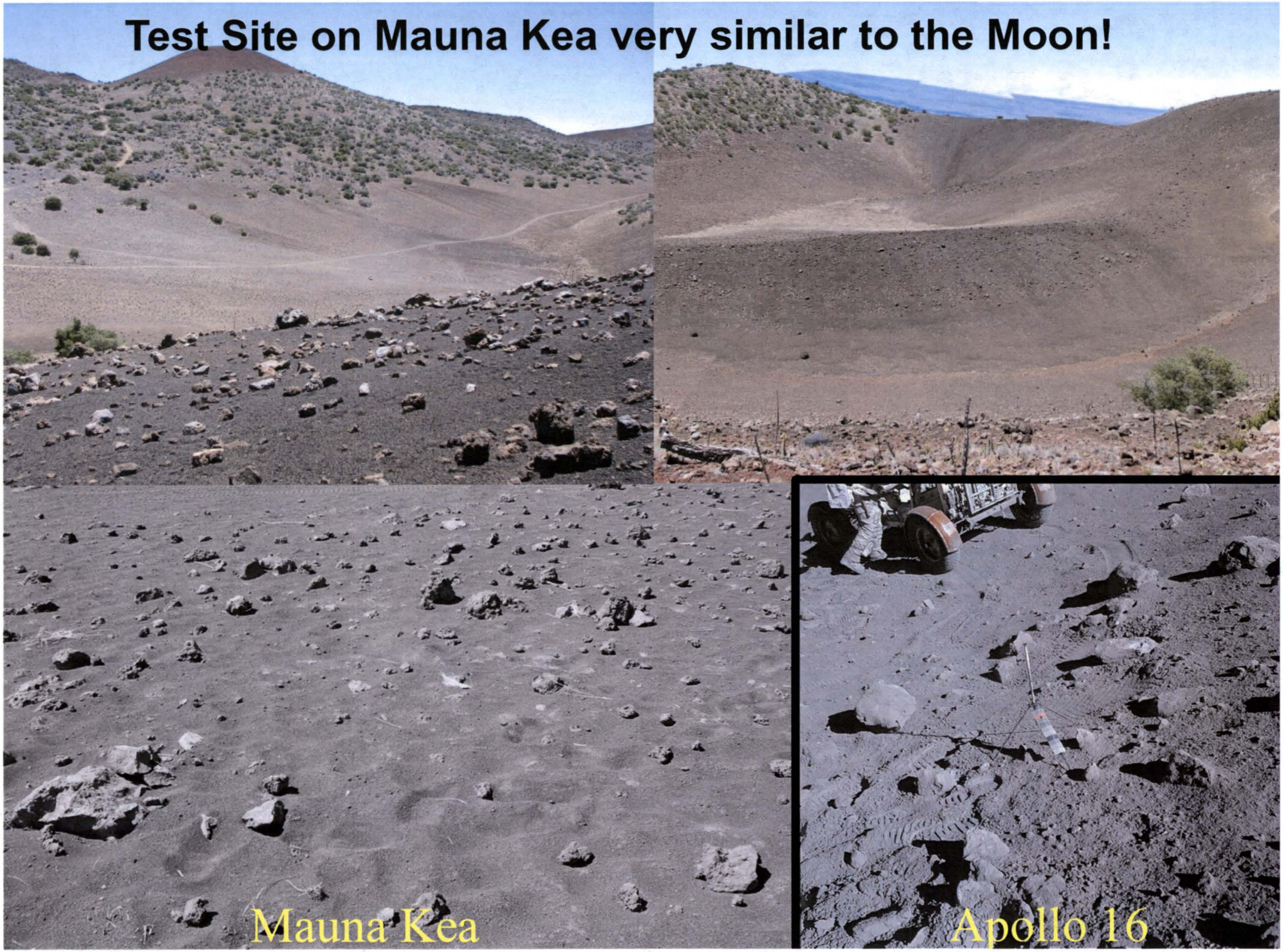
- **3rd Navigate 0.6 km**
  - *3.88 hrs, 1.8 km total*
- **Drill 3rd Hole 4.33 hrs**
  - *Two 0.5m Augers (5-6)*
  - *One 1.0m Core (3)*
- **Process Segments (11-15)**
  - *5 segments, 19.85 hrs*
  - *1st H2 Reduction*

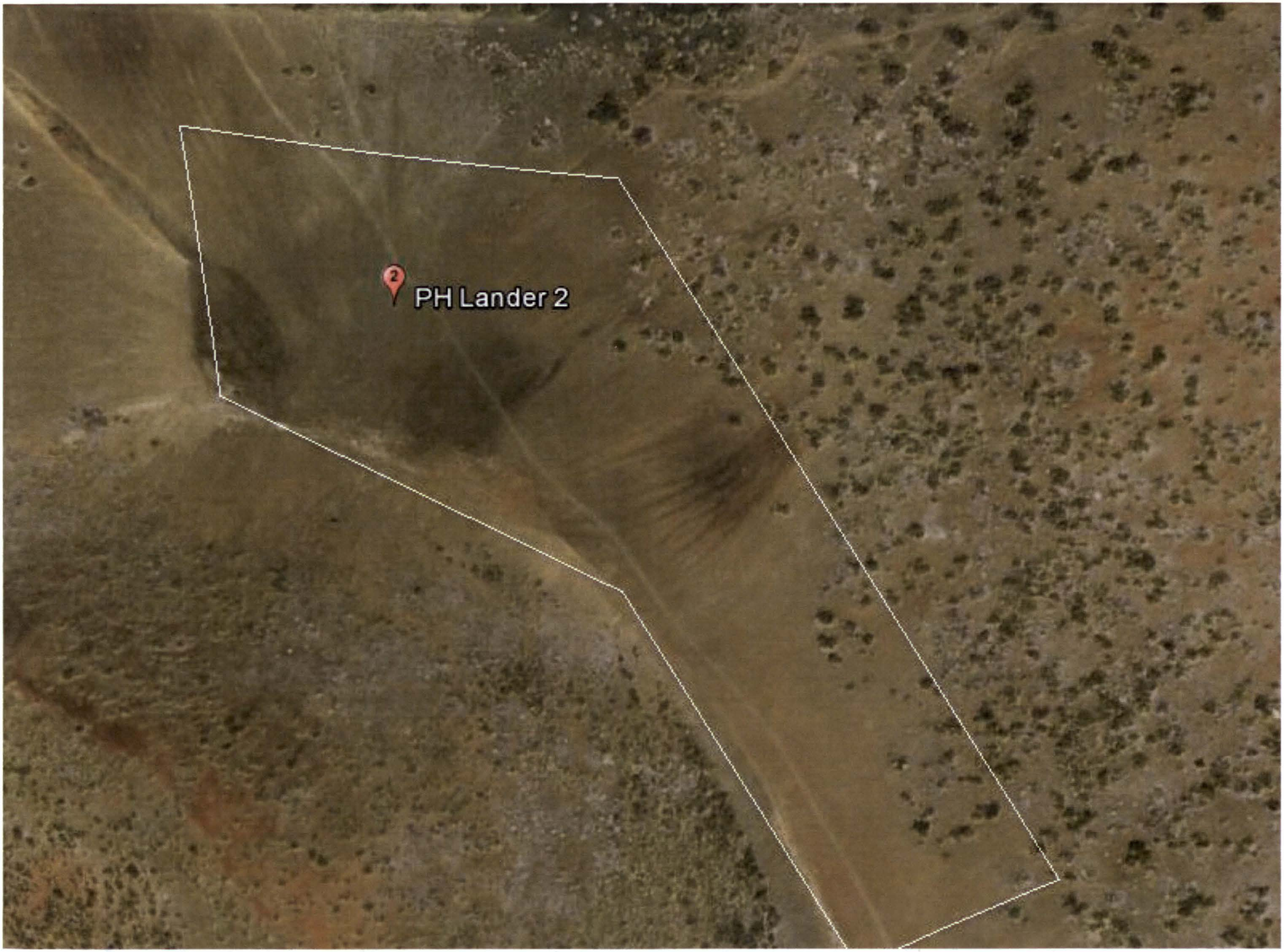
- **4th Navigate 0.2 km**
  - *2.29 hrs, 2.0 km total*
- **Drill 4th Hole 4.33 hrs**
  - *Two 0.5 m Augers (7-8)*
  - *One 1.0m Core (4)*
- **Process Segments (16-20)**
  - *5 segments, 19.85 hrs*
  - *2nd H2 Reduction*

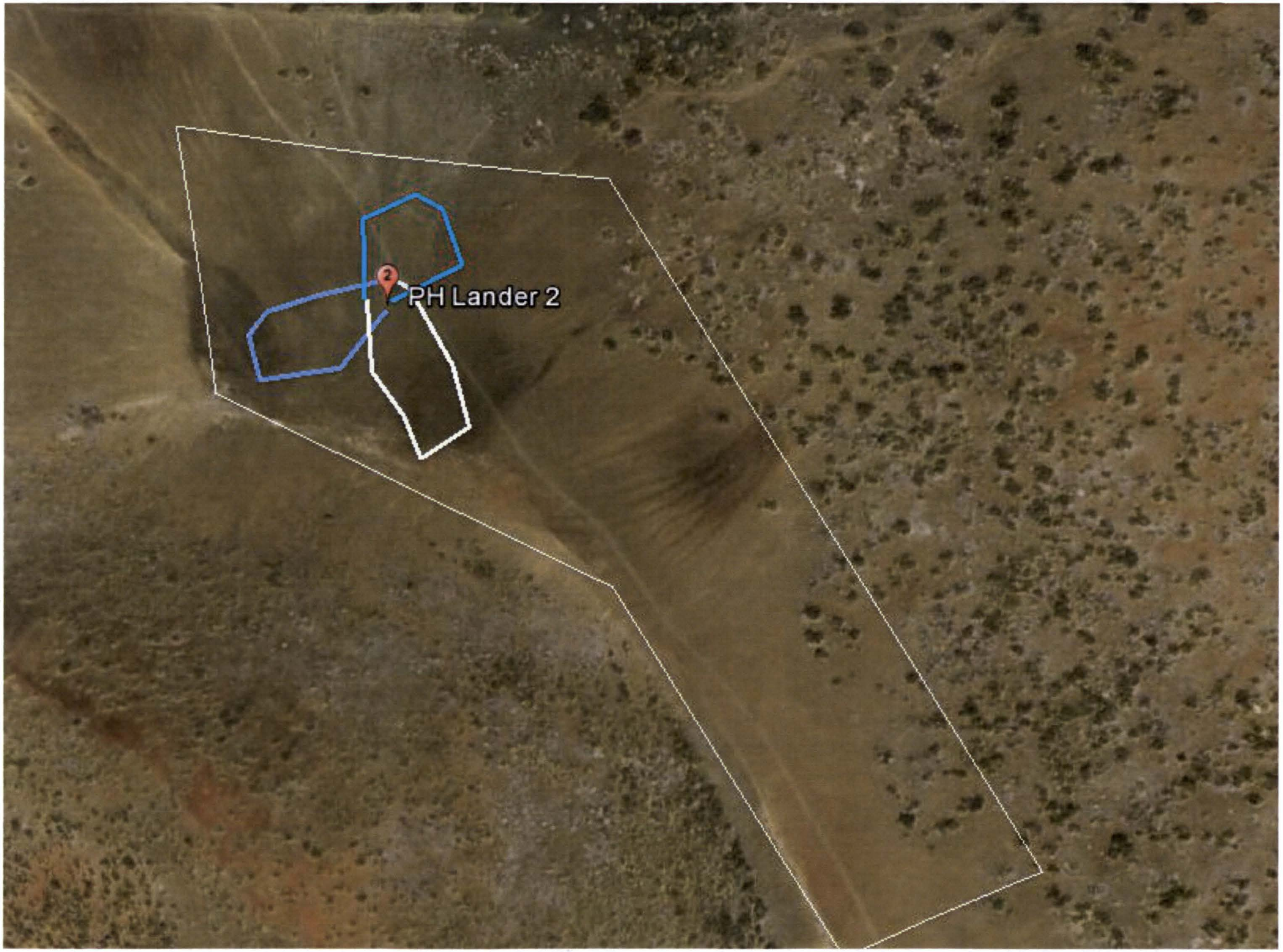
- **5th Navigate 1.0 km**
  - *5.47 hrs, 3.0 km total*
- **Drill 5th Hole 4.33 hrs**
  - *Two 0.5m Augers (9-10)*
  - *One 1.0m Core (5)*
- **Process Segments (21-25)**
  - *5 segments, 18.41 hrs*
  - *3rd H2 Reduction*

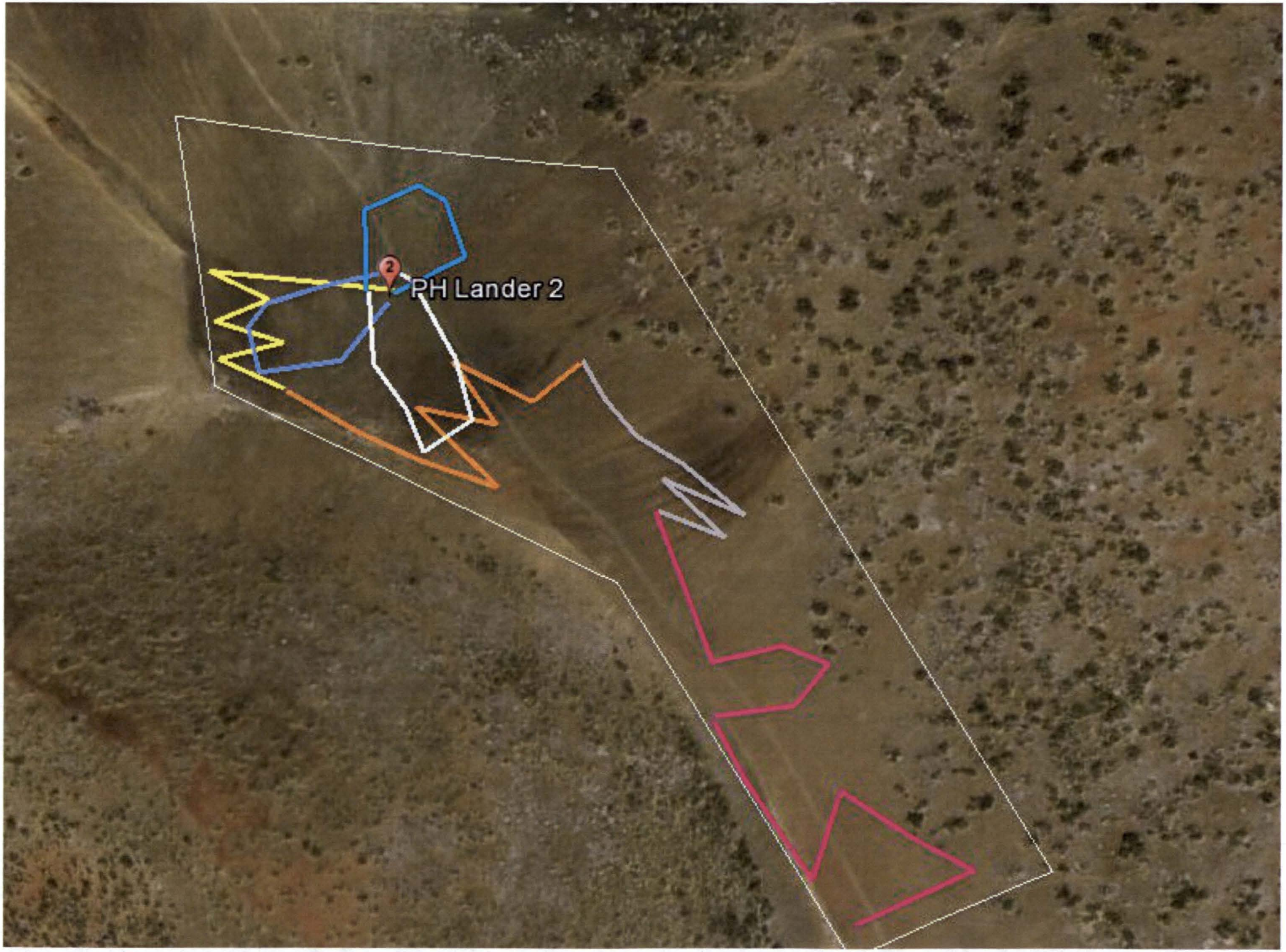
Resource Prospector Mission Simulation

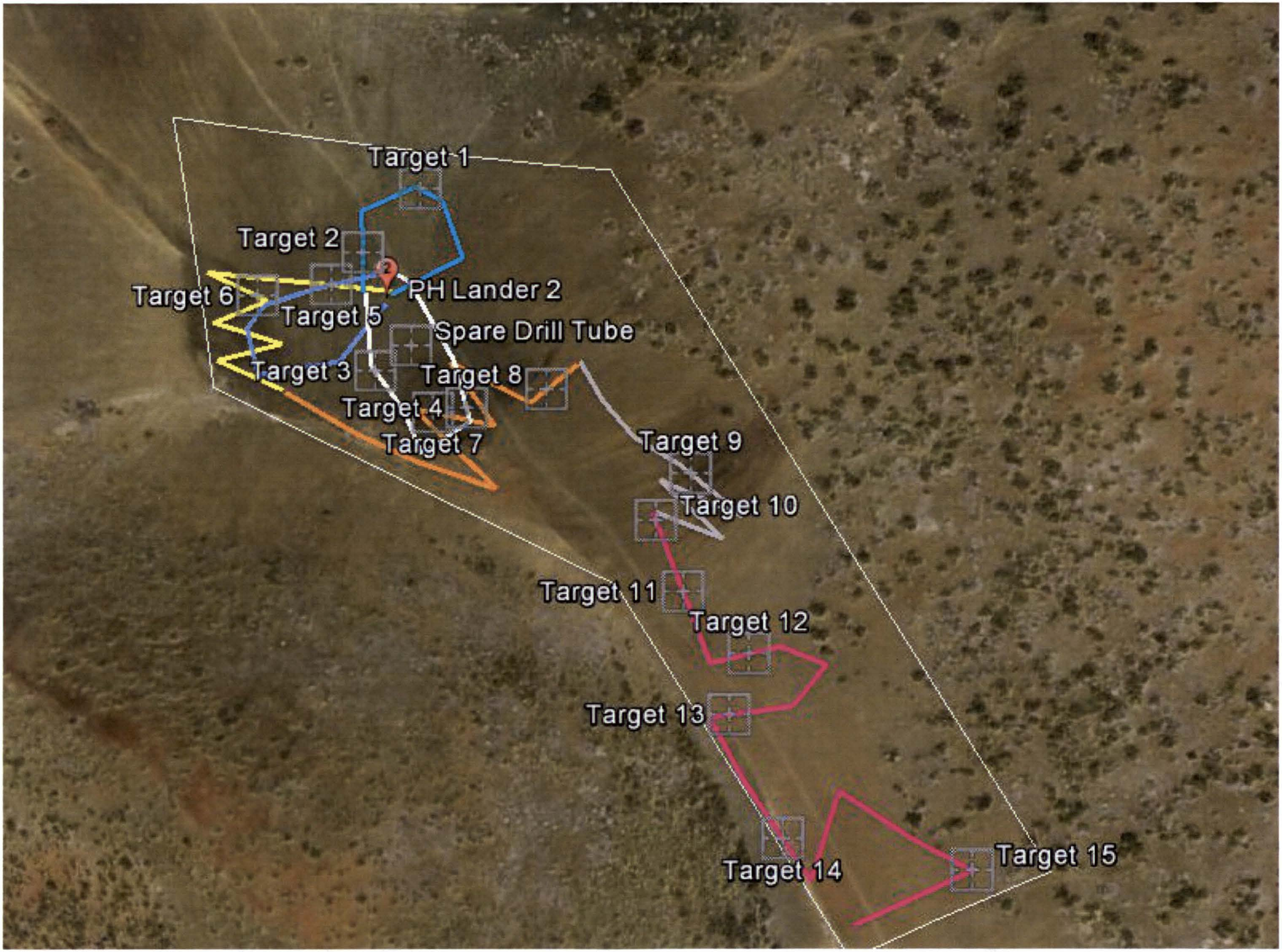
- This mission has the most challenging surface mobility timeline ever considered
- To insure that the mission objectives can be met a mission simulation using the Field Prototype was executed
- Goal was to test the hardware in a harsh environment, and test our ability to meet mission objectives in a restricted timeline.
- Full Mission Control with Shift Operations planned.
- Test was conducted on the slopes of the volcano Mauna Kea (background image)
  - Some accommodations had to be made due to natural water table, solar power availability, safety, etc.


Test Site on Mauna Kea very similar to the Moon!
Mauna Kea
Apollo 16

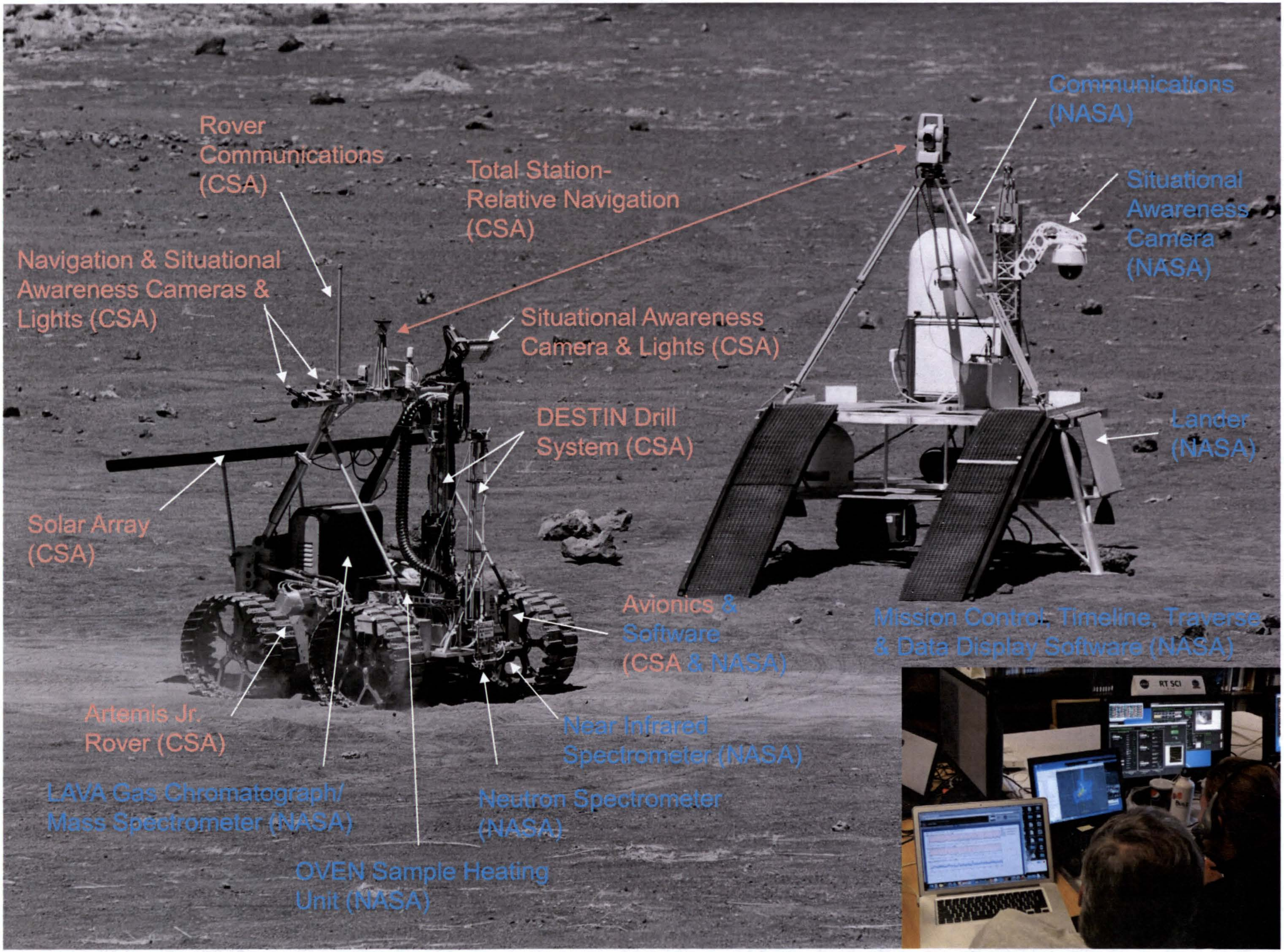

PH Lander 2


PH Lander 2


PH Lander 2


Target 1
Target 2
PH Lander 2
Target 6
Target 5
Spare Drill Tube
Target 3
Target 8
Target 4
Target 7
Target 9
Target 10
Target 11
Target 12
Target 13
Target 14
Target 15

Test Site Preparation



Rover Communications (CSA)
Total Station-Relative Navigation (CSA)
Communications (NASA)
Situational Awareness Camera (NASA)
Navigation & Situational Awareness Cameras & Lights (CSA)
Situational Awareness Camera & Lights (CSA)
DESTIN Drill System (CSA)
Lander (NASA)
Solar Array (CSA)
Avionics & Software (CSA & NASA)
Mission Control: Timeline, Traverse & Data Display Software (NASA)
Artemis Jr. Rover (CSA)
Near Infrared Spectrometer (NASA)
LAVA Gas Chromatograph/ Mass Spectrometer (NASA)
Neutron Spectrometer (NASA)
OVEN Sample Heating Unit (NASA)
RT SCI

On-Site & Remote Operations Centers

5 Centers; 4 different time zones

On-Site Control Center

ExDoc at CSA HQ

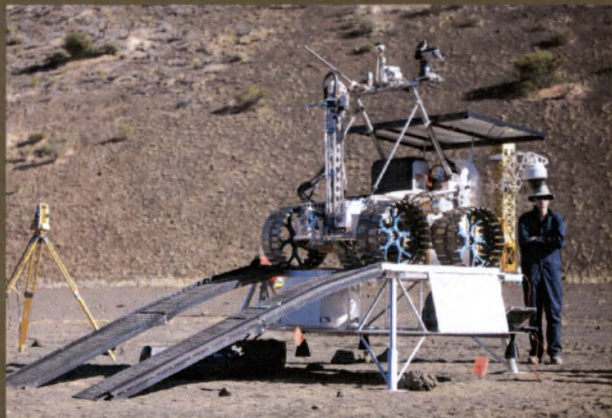
Johnson Space Center

Kennedy Space Center

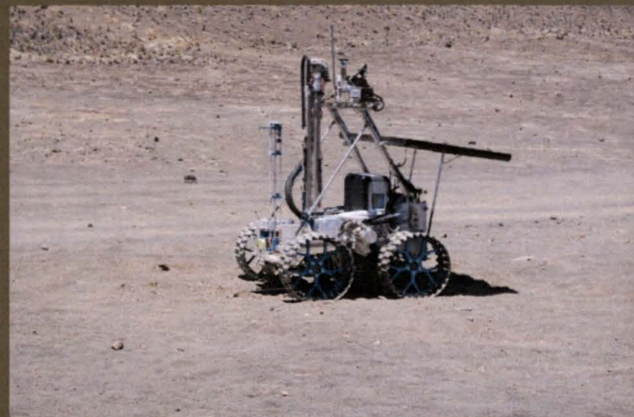
Science Backroom at ARC

Lunar Polar Resource Mission Simulation

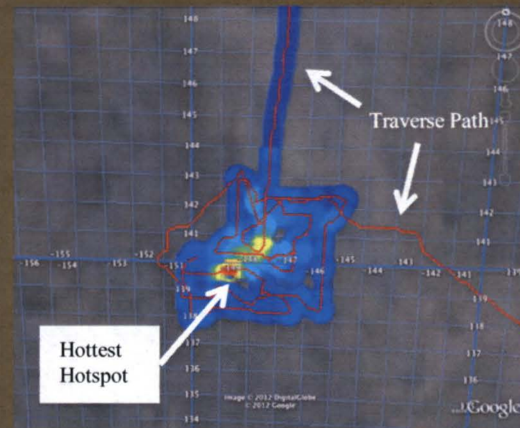
'Flight' like hardware and operations



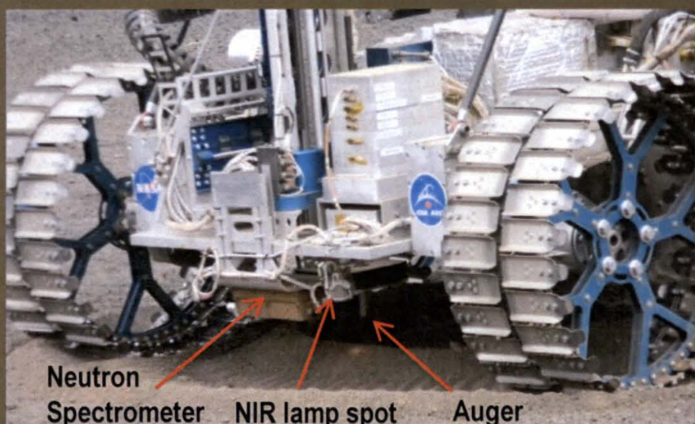
Rover Egress from Lander



Rover Searching Exploration Site



Data from Neutron Spectrometer and Rover Navigation displayed on xGDS showing 'hot spot' found by RESOLVE



Auger and Examine Cutting Pile for Ice with Near Infrared Spectrometer

Drilling, Sample Collection, Sample Transfer, & Processing to Measure Water and Other Volatiles

RESOLVE Mission Objectives/Results

CAT 1 Objectives (Mandatory)

- ✓ Travel at least 100m on the lunar surface to map the horizontal distribution of volatiles (FD1)

CAT 2 Objectives (Highly Desirable)

- ✓ Perform at least 1 coring operation. Process all regolith in the drill stem acquired during the coring operation. (FD2)
- ✓ Perform at least 1 water droplet demo during volatile analysis. (FD2)

CAT 3 Objectives (Desirable)

- ✓ Map the horizontal distribution of volatiles over a point to point distance of 500m (FD4) (lunar objective is 1km.)
- ✓ Perform coring operations and process regolith at a minimum of 3 locations. (FD4)
- ✓ Volatile analysis will be performed on at least 4 segments from each core to achieve a vertical resolution of 25cm or better.
- ✓ Perform a minimum of 3 Augering operations (FD4). (Note that the Lunar objective is 6)
- ✓ Perform at least 2 total water droplet demos. Perform 1 in conjunction with hydrogen reduction and perform 1 during low temperature volatile analysis.

CAT 4 Objectives (Goals)

- ✓ Perform 2 coring operations be separated by at least 500 m straight line distance. (FD4) (lunar objective is 1km.)

2. Travel 3 km total regardless of direction
3. Travel directly to local areas of interest associated with possible retention of hydrogen
4. Process regolith from 5 cores

- ✓ Perform hardware activities that can be used to further develop lunar exploration technologies

Mission Simulation Conclusions

- As expected, the mission timeline is extremely challenging
- Problems, which are always going to occur, delay ability to achieve objectives
  - Essential to develop contingency plans for as many problems that can be envisioned
  - Lost a lot of time during simulation troubleshooting when we should have just been executing alternate plans
- In spite of the hardware and operational problems experienced we achieved most of the mission objectives
  - Vaporizing, transferring and sampling the water vapor took longer than expected (need to increase transfer tank size)
  - OVEN design may be sensitive to slope rover is on
- Bottom line.... Mission appears to be achievable. Development will continue

2013 Design & Test Activities

- In FY13 the major subsystems have been designing and fabricating engineering test prototype
  - Risk reduction activity will test prototypes in flight conditions
  - Some integration of subsystems that are tightly coupled is likely to occur (e.g. OVEN and LAVA)
- More detailed assessment of potential landing sites will occur
  - We'd like to find an area of partial sunshine close to an area of permanent shadow
  - North Pole sites will be analyzed in more detail
- Critical Trade Studies will be conducted
  - Thermal management, Communications architecture, Power management, etc.

The Path to Flight

- Some important decisions remain open
  - Canada has two open design study contracts on the flight rover and sample acquisition system (decision late 2013)
  - NASA must decide on a Lander (decision this summer)
    - Internal design based on Morpheus and/or Mighty Eagle?
    - Commercial Partner?
    - International partner?
- Mission Concept Review scheduled for mid-September
- Flight Program Office anticipates Authority to Proceed (ATP) in 2014
- Assuming we receive ATP
  - Mission design activities would take place in 2014-16
  - Integration and final test in 2017
  - Launch/Landing April/May of 2018
    - Date dependent on final landing site selection


Questions?
REGOLITH & ENVIRONMENT SCIENCE & OXYGEN & LUNAR VOLATILE EXTRACTION
RESOLVE