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RESOLVE for Lunar Polar Ice/Volatile Characterization Mission

G.B. Sanders (1), W.E. Larson (2), J.W. Quinn (2), A. Colaprete (3), M. Picard (4), D. Boucher (5)
(1) NASA Johnson Space Center, TX USA, (2) NASA Kennedy Space Center, FL USA, (3) NASA Ames Research Center, CA USA, 43) Canadian Space Agency, Quebec, Canada, (4) Sudbury, ON. Canada, gerald.b.sanders@nasa.gov/Fax (281) 483-2428

Abstract

Ever since data from the neutron spectrometer instrument on the Lunar Prospector mission indicated the possibility of significant concentrations of hydrogen at the lunar poles, speculation on the form and concentration of the hydrogen has been debated. The recent impact of the Lunar Crater Observation and Sensing Satellite (LCROSS) along with thermal, topographic, neutron spectrometry, and radar frequency data obtained from the Lunar Reconnaissance Orbiter (LRO) have provided more information suggesting significant amounts of water/ice and other volatiles may be available in the top 1 to 2 meters of regolith at the lunar poles. The next step in understanding what resources are available at the lunar poles is to perform a mission to obtain 'ground truth' data. To meet this need, the US National Aeronautics and Space Administration (NASA) along with the Canadian Space Agency (CSA) have been working on a prototype payload known as the Regolith & Environment Science and Oxygen & Lunar Volatile Extraction experiment, or RESOLVE.

1. Introduction

The presence of large concentrations of accessible hydrogen and/or water at the lunar poles could have profound implications on the design and affordability of initial and long-term human Lunar and solar system exploration architectures. In particular, the ability to make propellants, life support consumables, and fuel cell reagents can significantly reduce mission cost by reducing launch mass by eliminating the delivery of consumables from Earth and enabling transportation system reusability; lowering risk by reducing dependence on Earth; and enabling extended surface operations and science by providing an energy rich environment and affordable access to multiple surface targets. The purpose of the RESOLVE experiment is to address fundamental science and resource questions such as "What resources are available on the Moon, where are they, and in what form?" as well as critical engineering questions, such as "How will we mine these resources, what extraction process is the most practical and efficient, and what are the engineering challenges to be faced in this environment?" The environment in the permanently shadowed regions at the poles is especially challenging due to the extremely low temperature (<40 K) and the unknown physical properties and content of trapped gases in the regolith and ice (if present). Two generations of RESOLVE have been built and tested and the 2nd generation of RESOLVE was field tested twice in Hawaii on the slope of Mauna Kea. The RESOLVE experiment is now in the 3rd generation of design which is aimed at both a mission simulation field test in June of 2012 and lunar environment simulation (vacuum) testing in 2014.

2. RESOLVE Overview

The RESOLVE experiment is a payload that can be mounted on a lander or preferably a rover. It consists of the following subsystems: 1) sample site selection subsystem (neutron spectrometer and near infra-red spectrometer), 2) sample acquisition and transfer subsystem (1 meter core drill and core transfer device), 3) sample processing subsystem (reusable sample heating oven), and 4) volatile characterization and water capture subsystem (gas chromatograph/ mass spectrometer with water capture device). The RESOLVE experiment also includes its own structure, avionics, power conditioning and management, and thermal management subsystems, but requires power and communications from a lander or rover.

The mission of primary interest for lunar ice/volatile characterization will consist of a lunar rover and RESOLVE payload that is capable of mapping the horizontal distribution of hydrogen bearing volatiles, and be capable of taking subsurface ground samples at a depth of up to one meter for analysis. The one meter core will then be divided into 8 segments to be heated up to 900 C with released gases analyzed for water and other volatiles that may be present. After all volatiles have been released, hydrogen would then be added to the sample to remove oxygen via the hydrogen reduction reaction. The mission would last ~5 to 7 days and perform 3 to 5 sample collection and processing operations in an area of several square kilometers.

3. Previous RESOLVE Designs [1, 2]

The RESOLVE experiment project started in 2005 through a NASA Internal Call for Proposals. The 1st generation of RESOLVE was aimed at subsystem design feasibility. Subsystem hardware for all process steps were built and independently tested. For the 1st generation of RESOLVE, separate reactors were designed and built for evolving lunar volatiles and extracting oxygen from regolith via the hydrogen reduction method. For volatile characterization, a COTS Siemens gas chromatograph was modified to meet mission measurement requirements and both hydrogen and water adsorption capacitance beds were incorporated as redundant measurement methods. A core drill with sample capture device for the complete 1 meter sample length was designed and built by NORCAT under contract to NASA with support from CSA.

In 2007, the 2nd generation of RESOLVE was initiated with the aim at building a ‘flight-like’ experiment package. Packaging and mass reduction efforts for the major subsystems were started, but work on minimizing avionics, power, and ground support equipment to operate in Earth’s atmosphere were not. A new combined volatile extraction/ hydrogen reduction reactor was designed and built and both the sample collection drill and volatile characterization subsystems were modified from the 1st generation design. The 2nd generation RESOLVE was field tested for the first time in Nov. 2008 mounted on the ‘Scarab’ rover built by Carnegie Mellon University (CMU) under a NASA contract, and utilized a Neptec TriDAR camera for nighttime navigation and drill site selection, under a CSA contract.

After the success of the field test in 2008, a subsequent field test was planned and performed in 2010 at the same analog location on Hawaii aimed at examining terrain and remote mission operation aspects not evaluated in the first field test.

4. RESOLVE 3rd Generation

In June 2010, the design phase of the 3rd generation of RESOLVE was initiated. The aim of this generation is to design and build a complete RESOLVE experiment, including power and thermal management, avionics, and structure to flight mass and power requirements of <60 kg and <200 Watts average. Included in the next generation RESOLVE is the addition of a neutron spectrometer and near infra-red spectrometer for the new sample site selection subsystem. The 3rd generation design effort will be performed in two stages. Stage 1 is a design that can operate under field test conditions and evaluate all operations and procedures associated with a 5 to 7 day mission on the Moon operated from NASA and CSA centers with mission applicable communication capabilities. Stage 2 is to modify the design for full operation under lunar environment conditions including thermal and radiator capabilities.

At the time of submitting this abstract, the 3rd generation RESOLVE experiment has completed its Preliminary Design Review for Stage 1. Also planning between NASA, CSA, and the University of Hawaii Hilo have started for the 3rd International Hawaii analog field test planned for June 2012.

Acknowledgements

The authors would like to recognize the hard work and dedication of all the people at NASA, CSA, CMU, NORCAT, EVC, Neptec, and the University of Hawaii-Hilo involved in designing the 1st, 2nd, and 3rd generations of RESOLVE as well as those that planned and executed the two analog field tests in Hawaii.

References

[1] Sanders, G., Moore, L., McKay, D., et. al, “ Regolith & Environment Science, and Oxygen & Lunar Volatile Extraction (RESOLVE) for Robotic Lunar Polar Lander Mission”, International Lunar Conference 2005, Sept. 20, 2005, Toronto, Canada

[2] Captain, J., Quinn, J, Moss, T., and Weis, K., “RESOLVE’s Field Demonstration on Mauna Kea, Hawaii 2010”, AIAA Space 2010 Conference, Sept. 1, 2010, Anaheim, CA., USA

RESOLVE for Lunar Polar Ice/Volatile Characterization Mission

European Planetary Science Congress
Nantes, France

October 2011

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REGOLITH & ENVIRONMENT SCIENCE & OXYGEN & LUNAR VOLATILE EXTRACTION

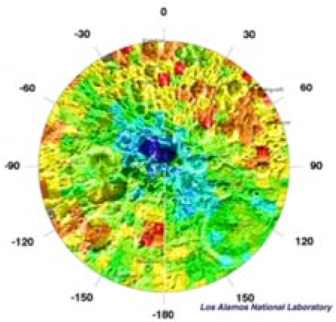
RESOLVE

What We Know About Volatiles On The Moon

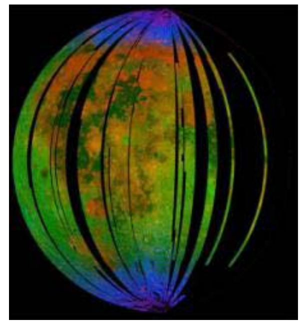
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Apollo Samples

Lunar Prospector Lunar Recon Orbiter (LRO)- LEND

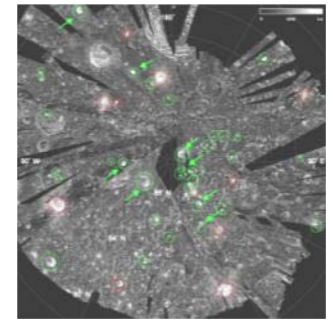


Moon Mineralogical Mapper (M³)



Lunar Crater Observation & Sensing Sat. (LCROSS)

Clementine Chandrayaan LRO Mini SAR/RF



	Solar Wind	Core Derived Water	Water/Hydroxyl	Polar Volatiles	Polar Ice
Instrument	Apollo samples Neutron Spectrometer	Apollo samples	M3	LCROSS	Mini SAR/RF
Concentration	Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)	0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass	0.1 to 1% water	3 to 10% Water equivalent Solar wind & cometary Volatiles (CO, H_2, NH_3, organics)	Ice layers
Location	Regolith everywhere	Regolith; Apatite	Upper latitudes	Poles	Poles; Permanent shadowed craters
Environment	Sunlit	Sunlit	Low sun angle	Low or no sunlight; Temperatures sustained at <106 K	<100 K, no sunlight
Depth	Top several meters; Gardened	Top 10's of meters	Top mm's of regolith	Below 10 to 20 cm of desiccated layer	Top 2 meters

Why a Lunar Volatiles Prospecting Mission?

Observed Volatiles at the LCROSS Site

					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 LCORSS impact site regolith

*Chart courtesy of Tony Colaprete

Background Rationale – What Must Be Done

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

Given: **There are potentially substantial hydrogen rich resources on the Moon…**

Then: **We must gain the necessary knowledge to guide future mission architectures to allow effective utilization of in-situ resources to their fullest extent and optimum benefit.**

- **Understand the resources**
  - What resources are there (minerals, volatiles, water/ice)?
  - How abundant is each resource?
  - What are the areal and vertical distributions and hetero/homogeneity?
  - How much energy is required to locate, acquire and evolve/separate the resources?
- **Understand environment impact on extraction and processing hardware**
  - What is the local temperature, illumination, radiation environment?
  - What are the physical/mineralogical properties of the local regolith?
  - Are there extant volatiles that are detrimental to processing hardware or humans?
  - What is the impact of significant mechanical activities on the environment?
- **Design and utilize hardware to the maximum extent practical that has applicability to follow-on ISRU missions**
  - Can we effectively separate and capture volatiles of interest?
  - Can we execute repeated processing cycles (reusable chamber seals, tolerance to thermal cycles)?

Send a prospector to the surface of the moon to obtain this knowledge first hand.

That prospector is

RESOLVE

What is RESOLVE?

Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

RESOLVE is an internationally developed payload (NASA and CSA) that that can perform two important missions for Science and Human Exploration of the Moon

Prospecting Mission: (Polar site)

✓ **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 core sample from selected sites** (Drill Subsystem)
  - To a depth of 1m with minimal loss of volatiles
- **Heat multiple samples from each core to drive off volatiles for analysis** (OVEN Subsystem)
  - From <100K to 423 K (150 C)
  - From 0 up to 100 psia (reliably seal in aggressively abrasive lunar environment)
- **Determine the constituents and quantities of the volatiles extracted** (LAVA Subsystem)
  - Quantify important volatiles: 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

ISRU Processing Demonstration Mission: (Equatorial and/or Polar Site)

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

- **Heat sample to reaction temperature** (OVEN Subsystem)
  - From 150 C to 900 C
- **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 Mission Requirements and Objectives

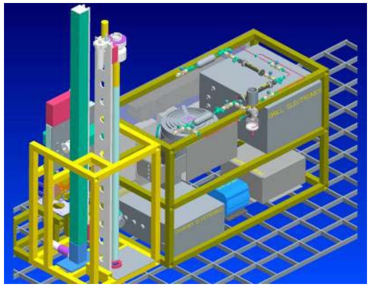
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

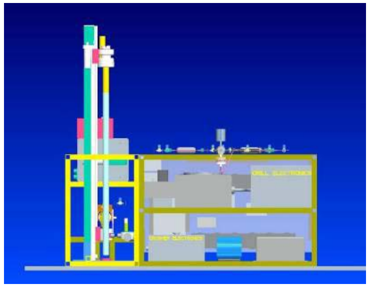
- Operate for the duration of the destination site's illumination
  (est. 4-7 Earth days)
- Landing site shall have direct line of sight communications with Earth
  (eliminates cost of relay-sat)
- Rover shall explore, map/prospect potential water sites, and collect samples at multiple locations within a square km of the Lander at a depth up to ~1 meter
- Examine/measure composition, state and distribution of polar volatiles
- Measure geotechnical forces associated with acquiring samples
  (engineering data for future missions)
- Mass and power approximately 60 kg and 200W average power

	#	Objective	Focus
Resource Characterization	1	**Determine form and conc. of H_2/H_2O in shadowed regions**	*Science - Resource Focused*
	2	Determine other volatiles available (CO, NH_3, CH_4, HCN, ?)	
	3	Determine grain size distribution and morphology of regolith	
	4	Determine quantity of which volatile(s) are evolved by crushing	
	5	Determine chemical/mineralogical properties	
	6	Determine difference between sunlit and shadowed regions	
	7	Determine spatial distribution of resources	
In-Situ Resource Utilization Demo	8	Determine bulk excavation related physical properties of regolith	*Engineering - Processing Focused*
	9	Demonstrate capture and separation of water	
	10	Demonstrate scalable oxygen production technique	
	11	Engage & Excite Public/Education Outreach	

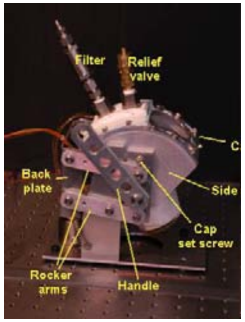
RESOLVE Development Background

Engineering Breadboard Unit #1 (2008)



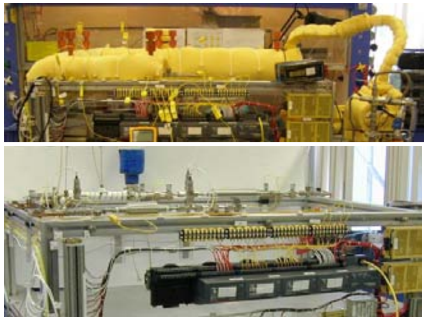


Volatile Reactor



Drill, Sample Metering Device, & Crusher

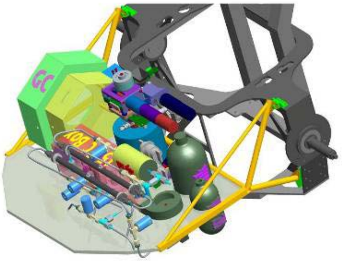
RESOLVE Integrated System



O_2 Production Demo

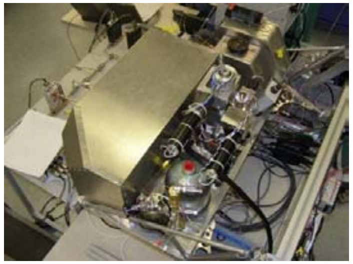
Demonstrate Subsystem Performance

Engineering Breadboard Unit #2 (2010)

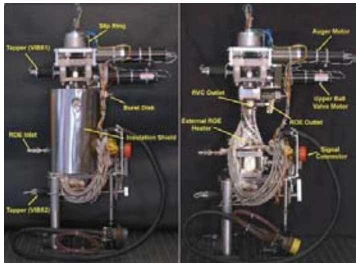


Combined Sample Metering & Crusher Unit

Integration onto Scarab



RESOLVE Integrated System #2



Combined Volatile Reactor & O_2 Production Demo

Demonstrate Integration & Operations

RESOLVE 3rd Generation
(Precursor to Flight)

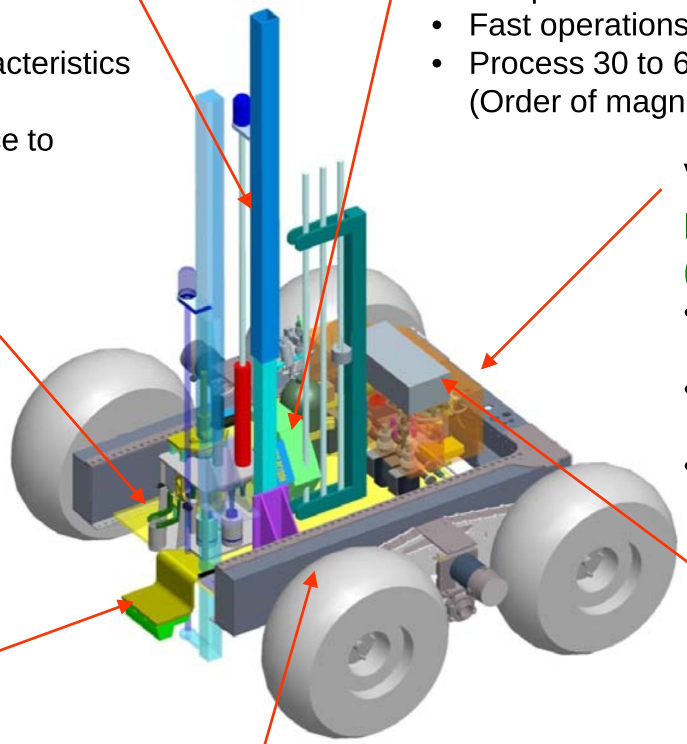
Two-Phase Development
- Develop miniaturized unit for field test in June 2012
- Develop lunar vacuum compatible unit for testing in 2014

Subsurface Sample Collection –
Core Drill [CSA]
- Complete core down to 1 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)

Volatile Content 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

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



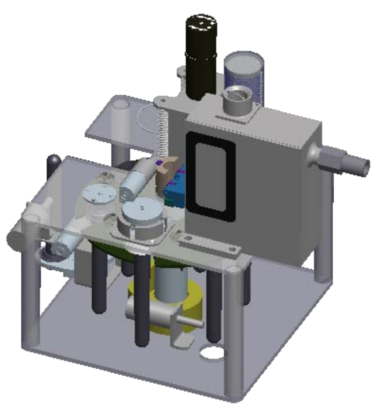
Operation Control –
Flight Avionics [CSA/NASA]
- Space-rated microprocessor

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

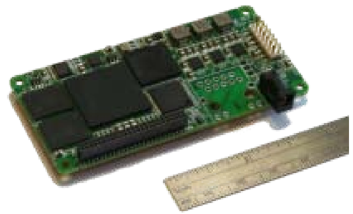
Surface Mobility/Operation [NASA/CSA]
- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors

RESOLVE 3rd Generation Hardware & System

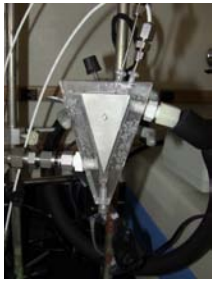
1 m Core Drill & Sample Metering [CSA]



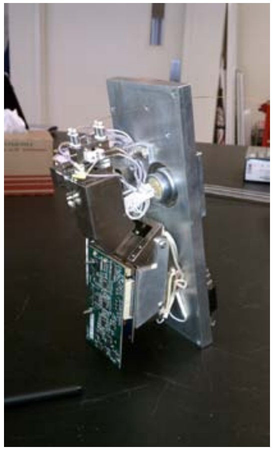
Oxygen & Extraction Node (OVEN)



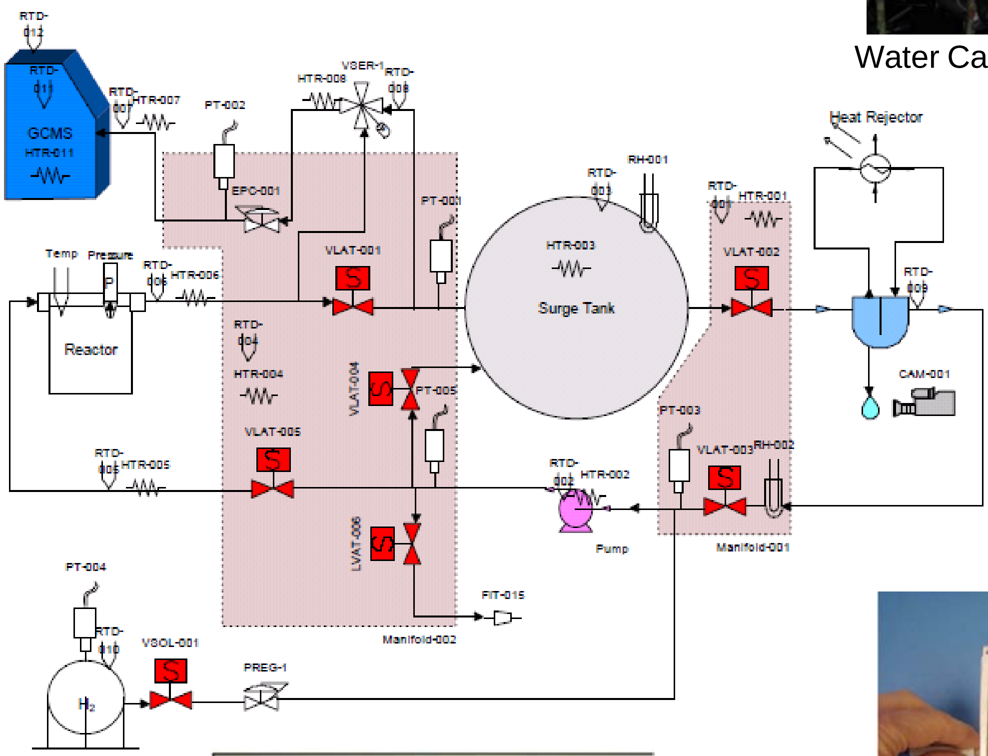
Avionics

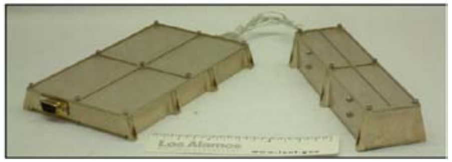


Water Capture

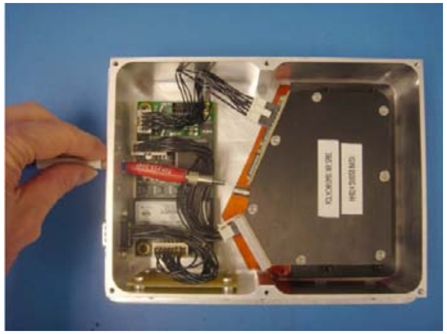


Gas Chromatograph - Mass Spectrometer





Neutron Spectrometer



Near Infrared Spectrometer

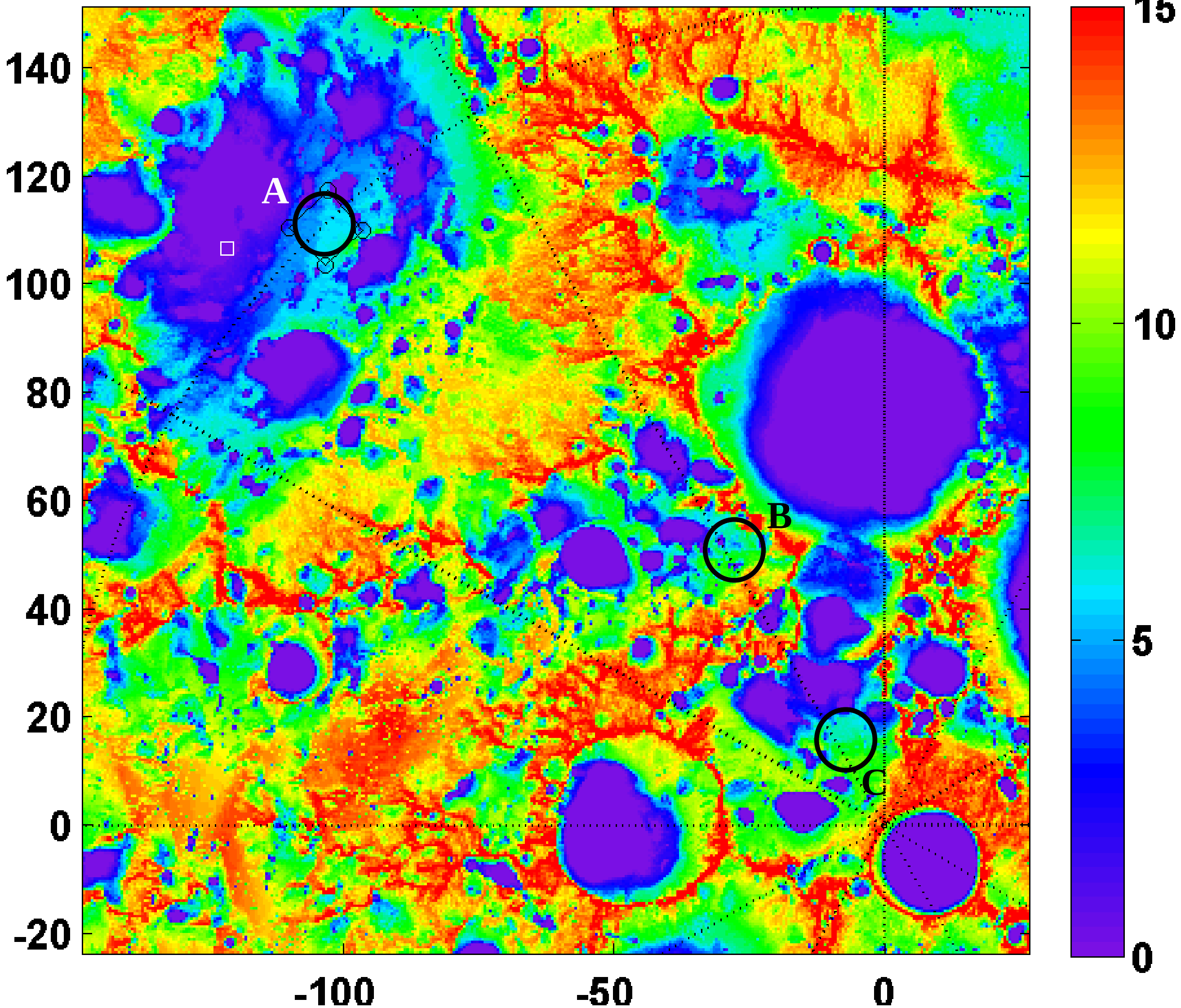
Key Mission Drivers

Key Mission Design Drivers		Option	Description/Attributes
Science	Location (Resource of interest)	Sunlit	Solar wind volatiles & M3 hydroxyls Pro: Most simple mission, long-duration possible Con: Lowest science value
		Short Duration Sunlit	Ice/volatiles below desicated layer in thermally stable zone Pro: Can design to operate in sunlight with chance for good science Con: Short duration mission (<7 days)
		Shadowed Near Sunlit	Ice/volatiles near surface and depth (LCROSS crater) Pro: Good science and ISRU resource value Con: must design for extreme low temperature conditions
		Permanently Shadowed	Ice/volatiles and potentially thick ice (Spudis craters) Pro: Great science value Con: Extreme low temperatures and nuclear required for longer missions
	Sample Acquisition (Science value)	Downhole Device	Pro: Simple and quick verification of ice/water Con: Limited sample size and number of volatiles that can be characterized
		Auger (Honeybee) w/ Volatile Chamber	Pro: Simple, lower mass, and material broken up for easy transport Con: Volatiles and ice may be lost (test required)
		Sample Core Drill (CSA) w/ Volatile Chamber	Pro: Volalites/ice contained; most pristine sample; International Partner Con: Most complex and massive
Mission Approach - Power - Communication - Payload - Mobility	Lander Only	Lander Mounted	Pro: Lowest mass and simplist integration/mission operations Con: Sample only below lander (contaminated); limited control on selecting location
		Hopper Mounted	Pro: Similar to Lander but more locations can be examined Con: Limited number of samples (2 to 3); limited control on selecting location
	Lander/Rover	*Power, Comm, & Payload on Lander/ Sample Collection on Rover*	Pro: Rover allows selection of sample locations; lowest mass rover option Con: Rover must return to lander limiting distance; sample transfer more difficult
		Power & Comm on Lander/ Sample Collection & Payload on Rover	Pro: Rover allows selection of sample locations; Simpler sample transfer Con: Rover must return to lander limiting distance
	Rover Only	*Solar or Battery Powered Rover*	Pro: Rover has wide lattitude to find best samples; simple mission ops concept Con: Mission duration based on getting back to sun for recharging
		Nuclear Powered Rover	Pro: Rover has greatest lattitude to find best samples Con: Most complex and massive mission concept

Bold Blue denotes current mission driver option selected
Red Italic denotes backup option under consideration

RESOLVE Mission Options
Potential South Pole Landing Sites (1)

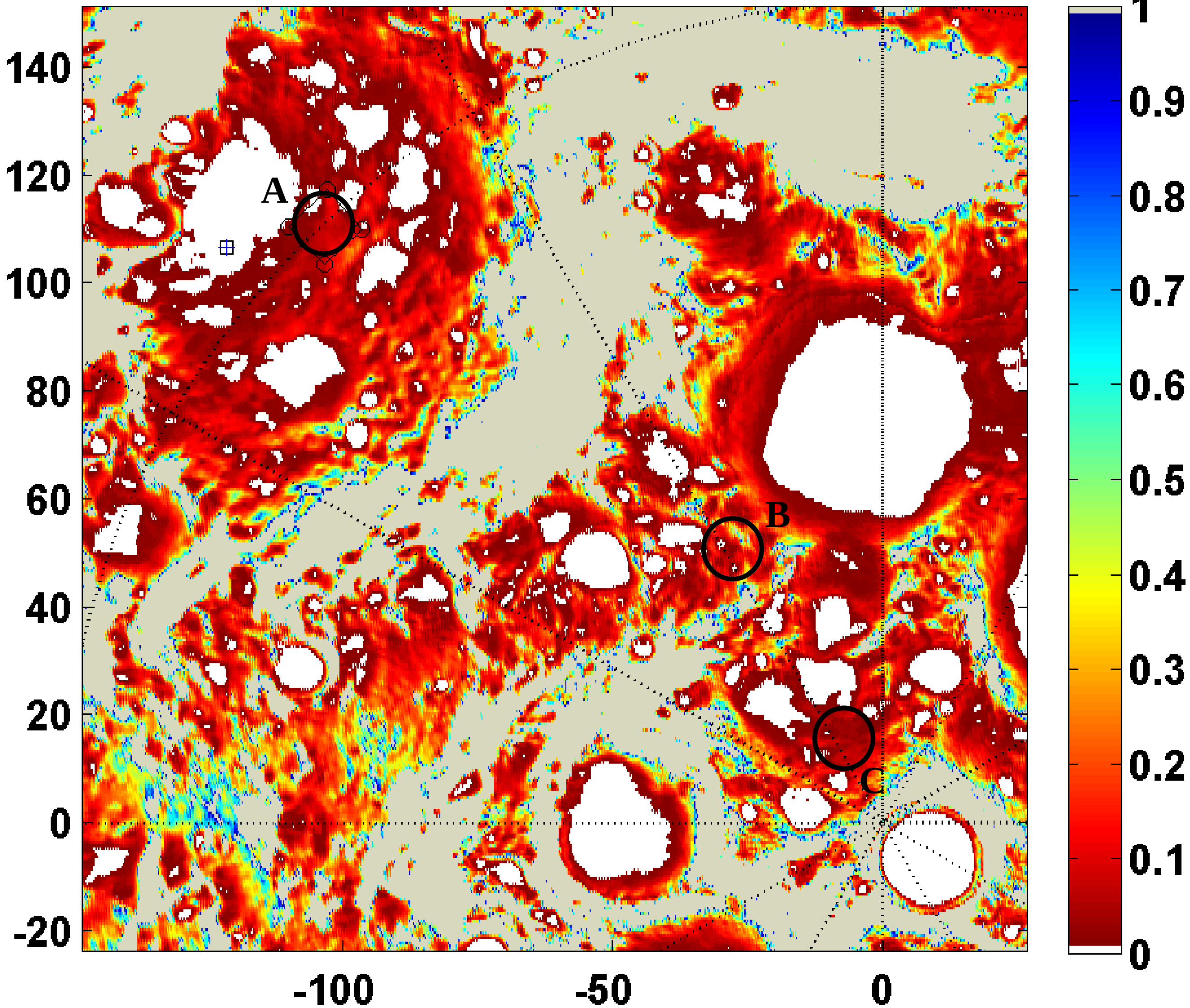
Maximum Days of Sunlight Using LOLA DEM



RESOLVE Mission Options

Potential South Pole Landing Sites (2)

Depth to Stable Ice (m)

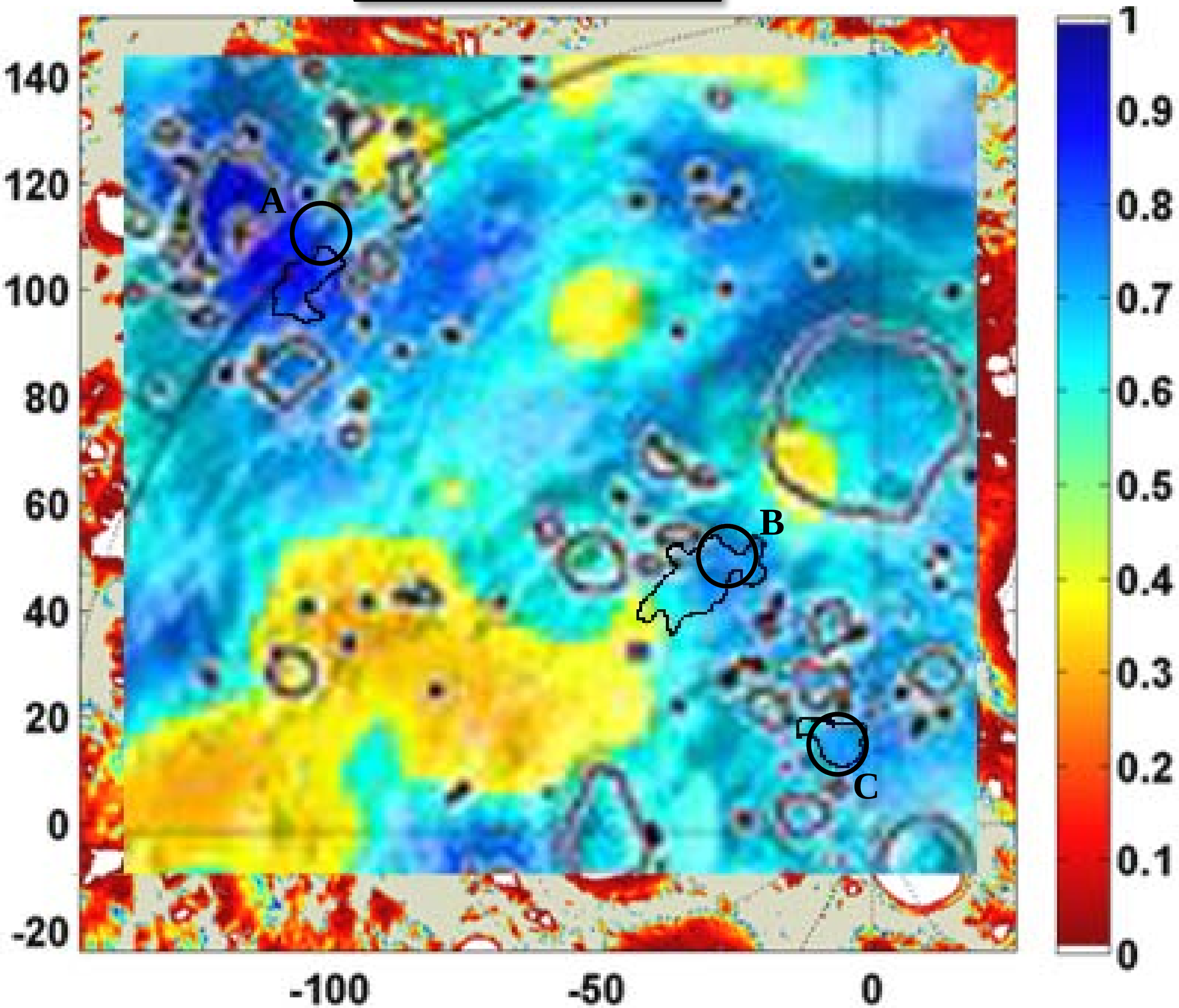


RESOLVE Mission Options

Potential South Pole Landing Sites (3)

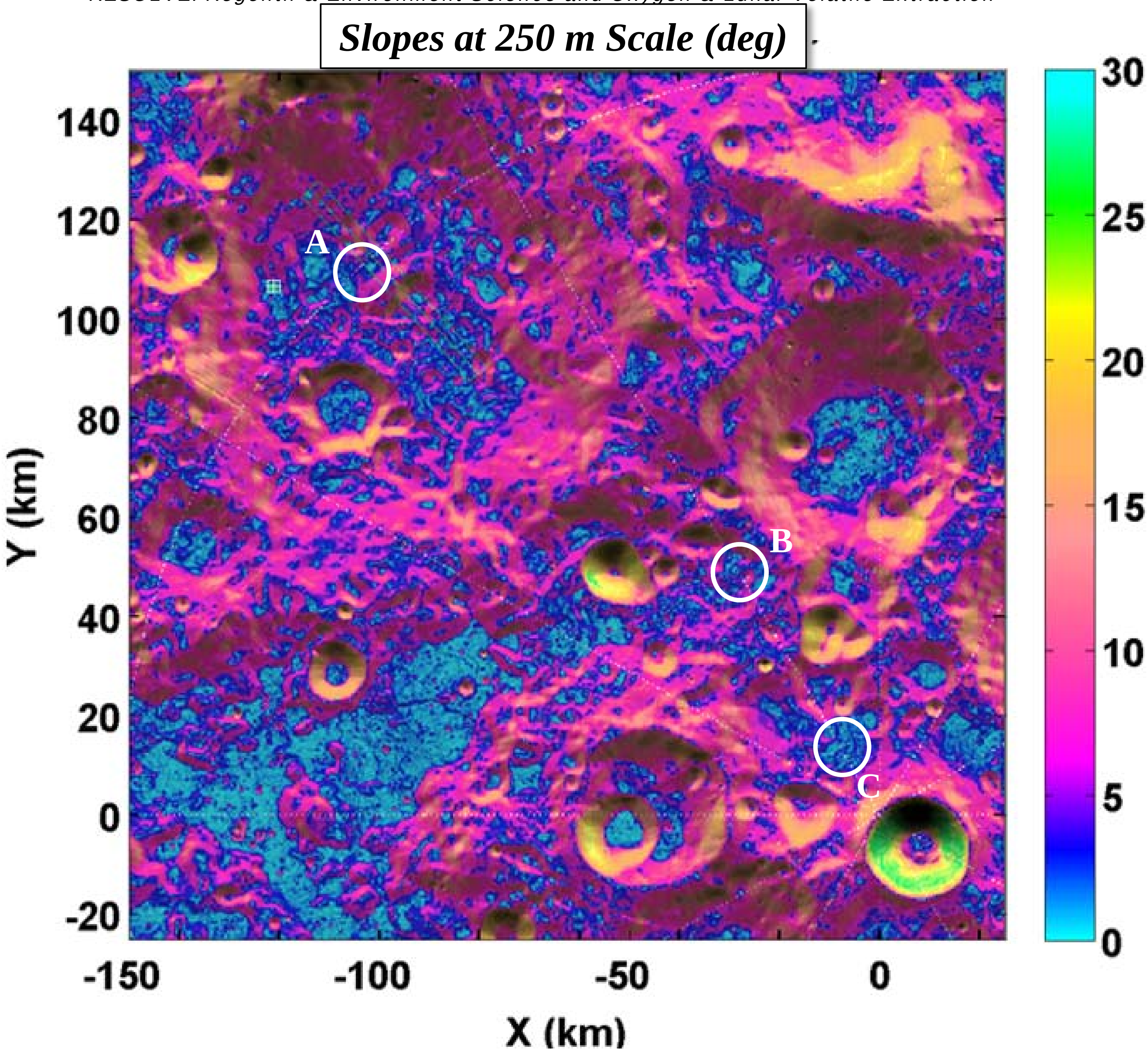
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

Neutron Depletion



RESOLVE Mission Options
Potential South Pole Landing Sites (4)

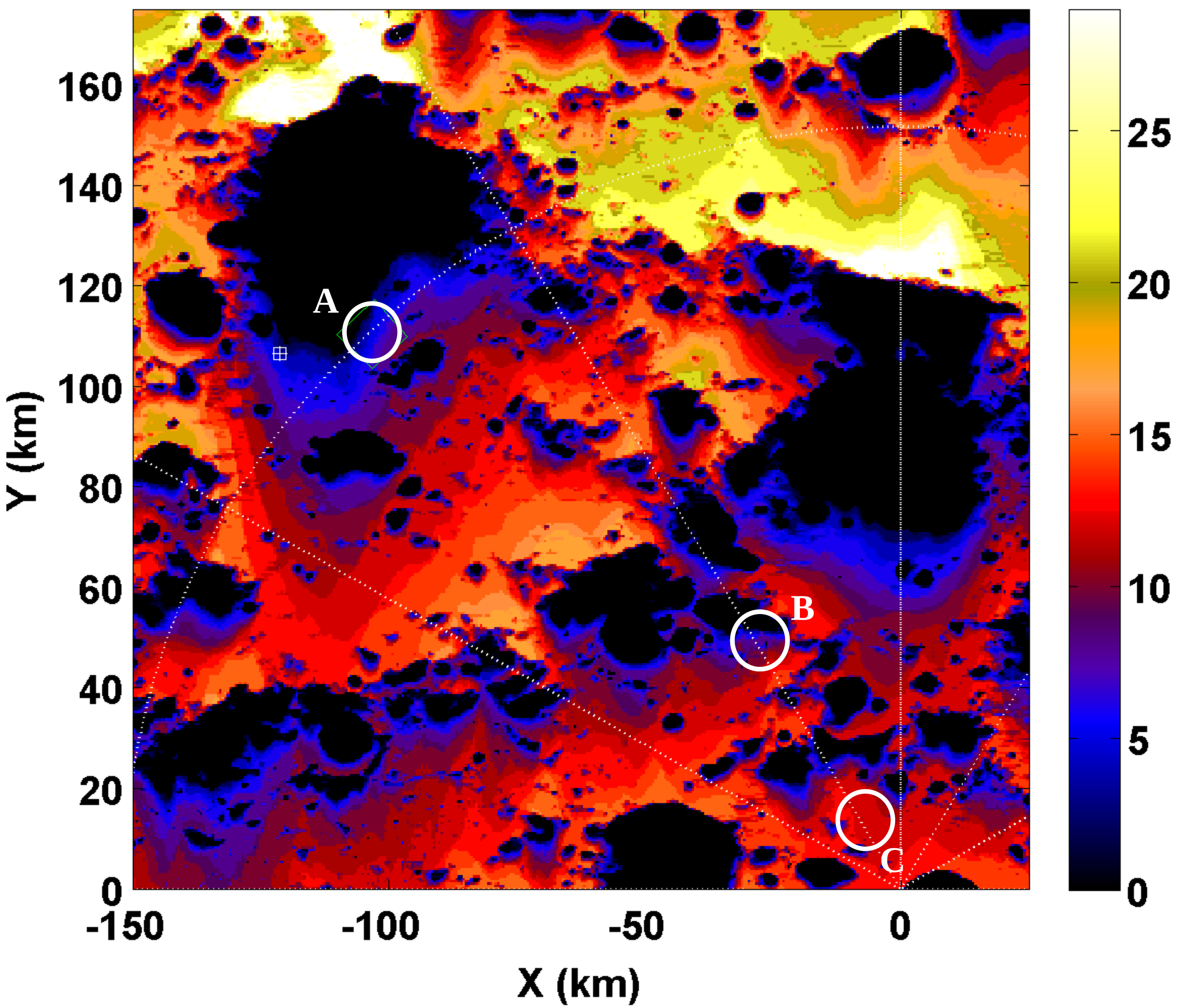
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



RESOLVE Mission Options
Potential South Pole Landing Sites (5)

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

Net DTE Visibility Over Month (days): 2015-6-4

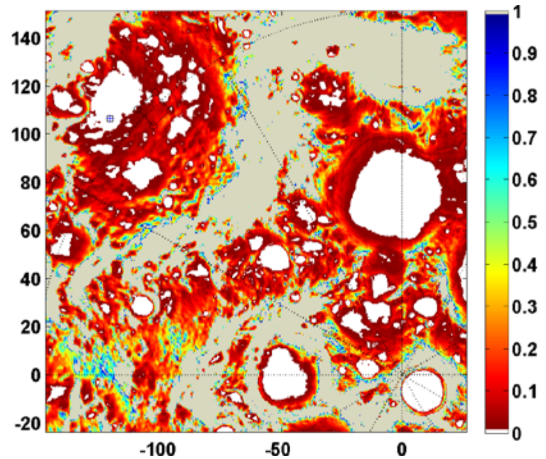


RESOLVE Mission Options

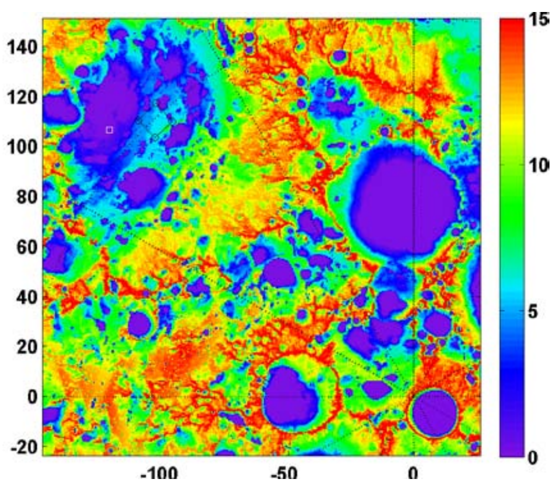
Potential South Pole Landing Sites (Summary)

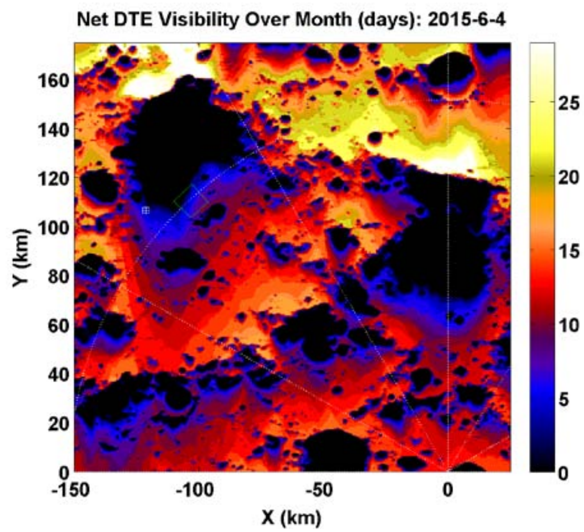
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

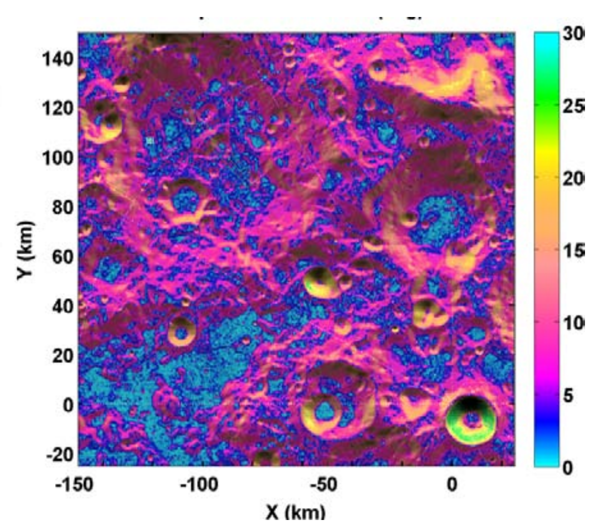
Combined Site Analysis



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			

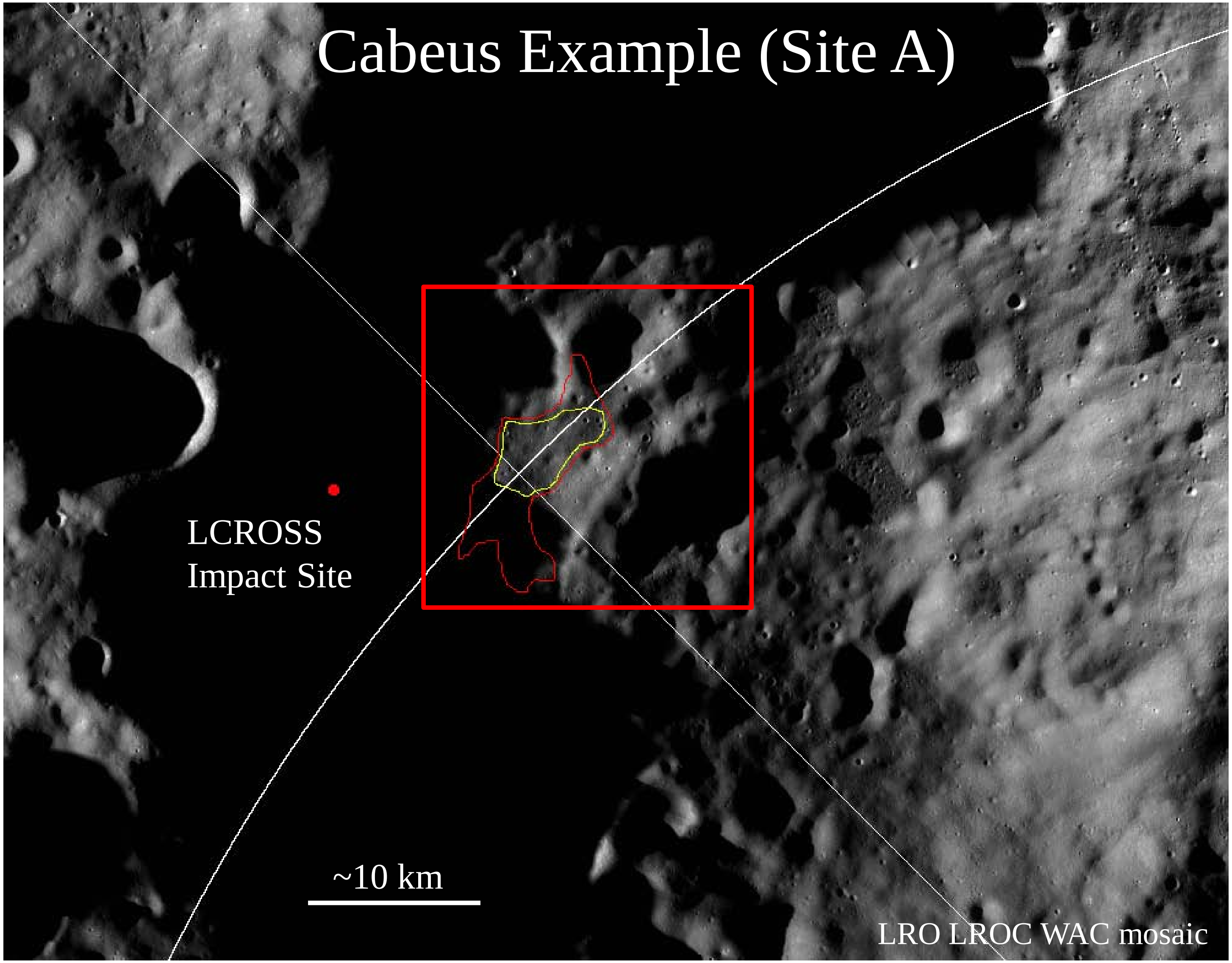






RESOLVE Mission Option – Site A

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



RESOLVE Mission Options

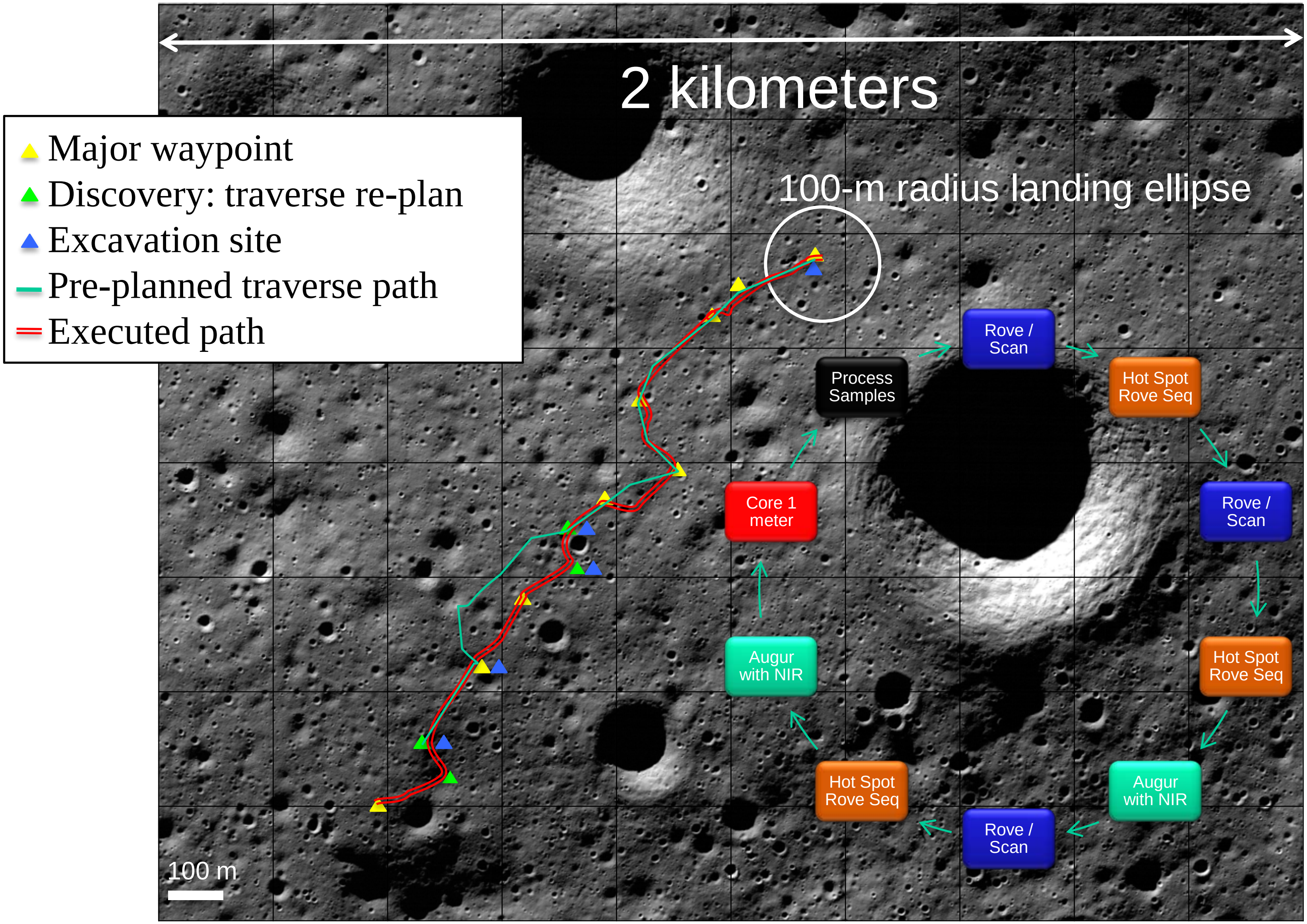
Mission Architecture Qualitative Comparison of Scenarios

		MISSION SCENARIO:						
		Land & Die	**Hopper**	**Crawl & Die**	**Sun-Loving Rover**	**Sun & Shadow Rover**	**X-Prize Lander & Rover**	**Radioisotope Rover**
FIGURE OF MERIT	**LOCATION**	PSR	PSR, Regional	PSR	Sunlit	Sunlit w/ brief shadow	Sunlit	PSR, Regional
	SCIENCE RETURN	PSR, 1 Bore, No Horiz. Surveys	Regional Exploration	PSR	Sunlit	Sunlit w/ brief shadow	Shallow Drill	Regional Exploration, Extended Mission
	COST	1 DDT&E	1 DDT&E, Large ELV	2 DDT&E	2 DDT&E	2 DDT&E	2 DDT&E, Industry Cost-Sharing	2 DDT&E, Nuclear, Extended Ops
	RISK	Low Tech, Low Prog, Hi Sci	Med Tech	Med Tech (cold)	Low Tech, Low Prog, Med Sci	Low All	Can they deliver at low cost?	Hi Prog., Hi Cost
Comments:		Cheapest groundtruth.	Intriguing.	Cuts to the chase.	Limited Science, Limited Risk.	Good Balance, Blend.	Gamble.	Great return but most expensive.

"Sun & Shadow" Rover Selected as Point-of-Departure for next Analysis Phase

RESOLVE Mission Notional Traverse

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



RESOLVE Status

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

Field Development Unit (FDU)

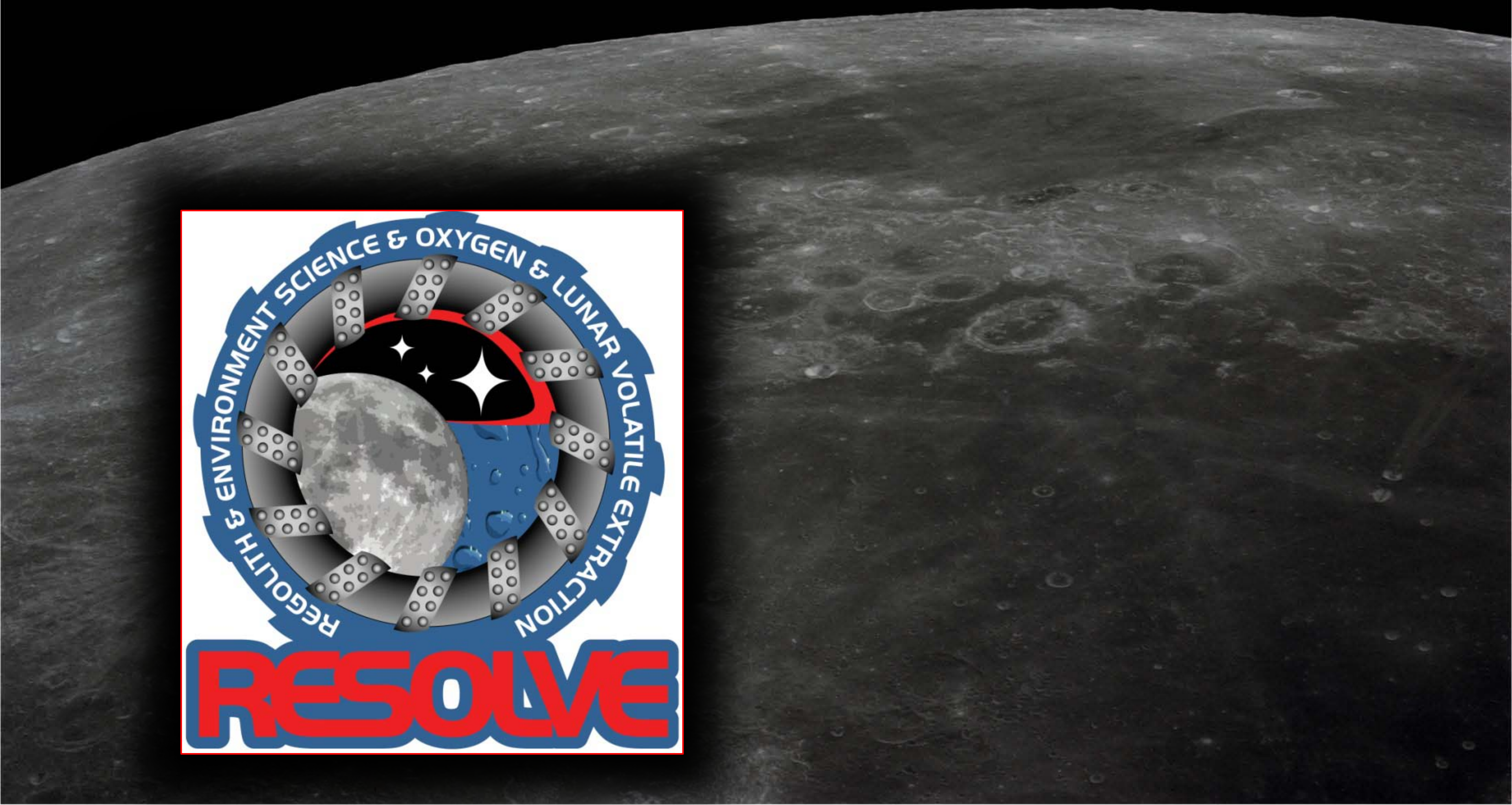
▪ System Requirements Review	1/28/11	***Completed***
▪ Preliminary Design Review	5/25/11	***Completed***
▪ Critical Design Review	7/26/11	***Completed***
▪ Subsystem delivery for integration	2/6/12	
▪ Integration and checkout complete	3/23/12	
▪ Integrated testing on rover complete	4/20/12	
▪ Field test	6/12	

Vacuum Development Unit (VDU)

▪ System Requirements Review	7/27/12
▪ Preliminary Design Review	11/30/12
▪ Critical Design Review	7/26/13
▪ Integration and checkout complete	3/28/14
▪ Vacuum chamber testing under lunar conditions	7/30/14

Partnership opportunities for VDU still possible

QUESTIONS?


REGOLITH & ENVIRONMENT SCIENCE & OXYGEN & LUNAR VOLATILE EXTRACTION
RESOLVE