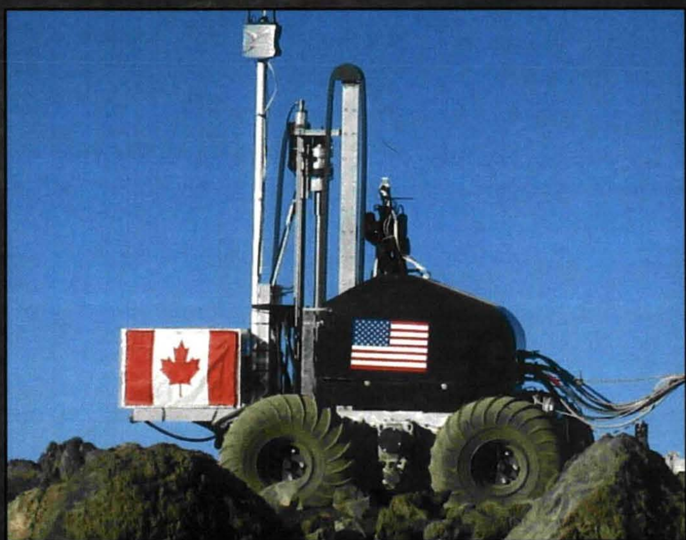
RESOLVE

Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



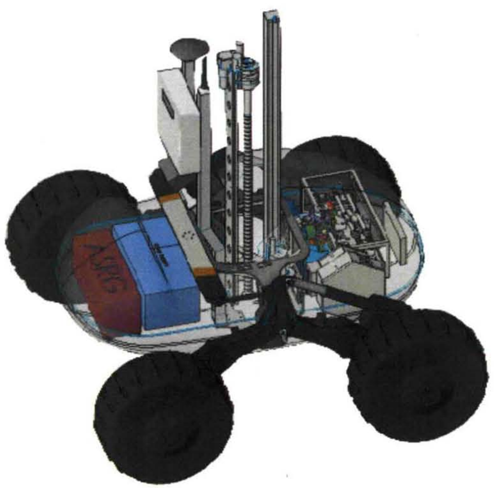
J. Quinn, R.S. Baird, A. Colaprete
W. Larson, G. Sanders, M. Picard

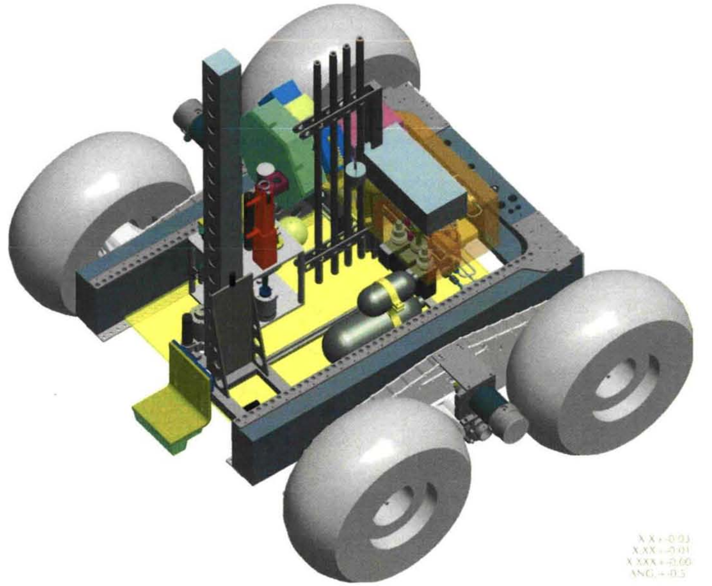
RESOLVE

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

- **RESOLVE is an internationally developed payload that is intended to prospect for resources on other planetary bodies.**

- **RESOLVE is a miniature drilling and chemistry plant packaged onto a medium-sized rover to collect and analyze soil for volatile components such as water or hydrogen that could be used in human exploration efforts.**





Why a Lunar Volatiles Prospecting Mission?
Background Rationale – Observed Volatiles at the LCROSS Site

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 LCORSS impact site regolith

Background Rationale – What Must Be Done

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?
  - 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.

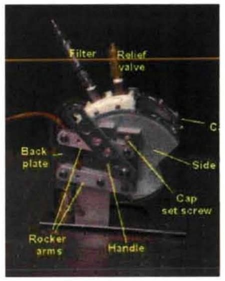
That prospector is

RESOLVE

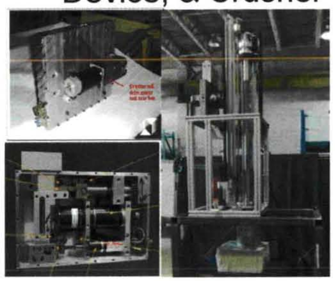
RESOLVE Development Background - Building on the Past

Engineering Breadboard Unit #1 (2007)

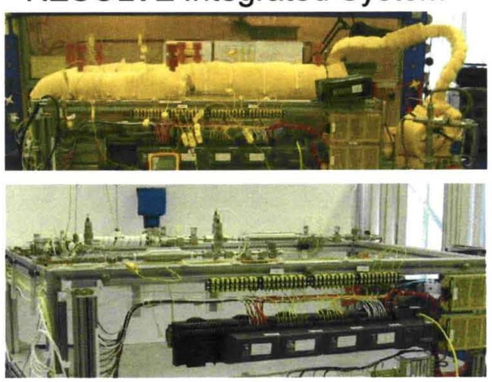

Volatile Reactor



Drill, Sample Metering Device, & Crusher

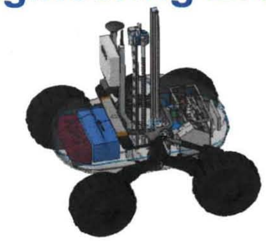


RESOLVE Integrated System



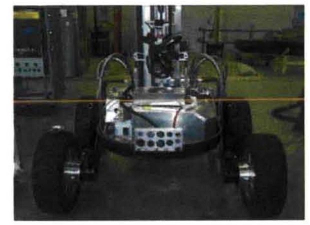
O_2 Production Demo

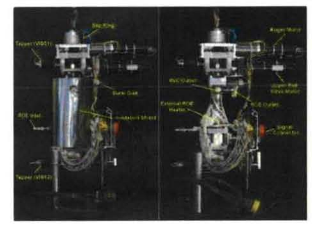
Engineering Breadboard Unit #2 (2008/2010)



Combined Sample Metering & Crusher Unit

Integration onto Scarab

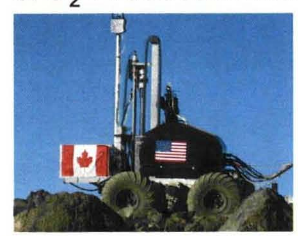





RESOLVE Integrated System #2

Combined Volatile Reactor & O_2 Production Demo

Field Tested twice at Analog site in Hawaii (2008 and 2010)

Large laboratory scale, proof of concept HW → Moderate scale, mobile COTS based HW

RESOLVE Generation 3 to be flight-like HW tested in both Earth and flight environments

RESOLVE Mission Options – Mission Fundamentals

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 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 -173 C to 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)
  - 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**

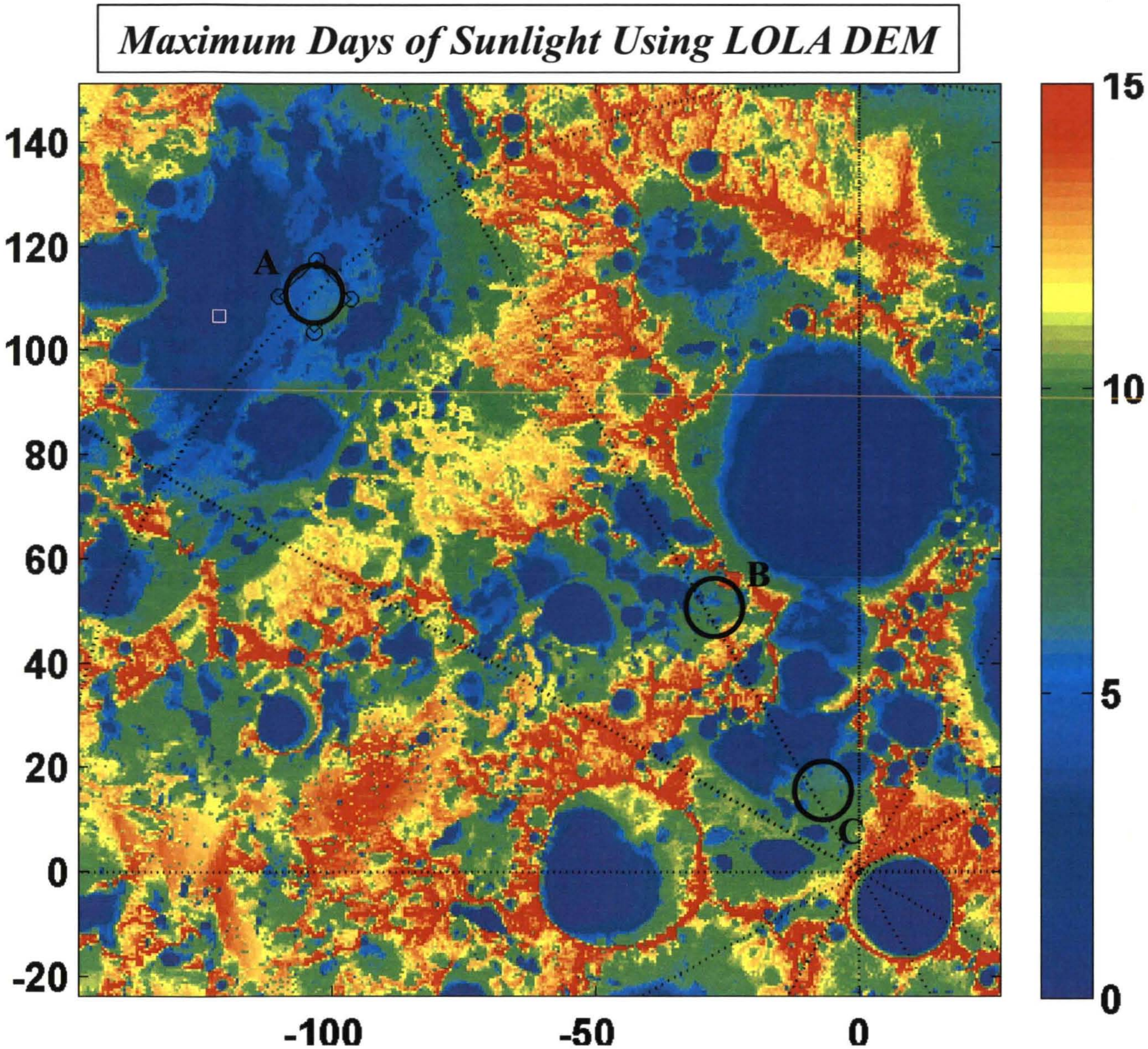
- **Heat sample to reaction temperature** (OVEN Subsystem)
  - from 150°C to 900°C
- **Flow H_2 through regolith to extract oxygen in the form of water** (OVEN Subsystem)
- **Capture, quantify, and display the water generated** (LAVA Subsystem)

RESOLVE Mission Options – Mission Architecture Qualitative Comparison of Scenarios

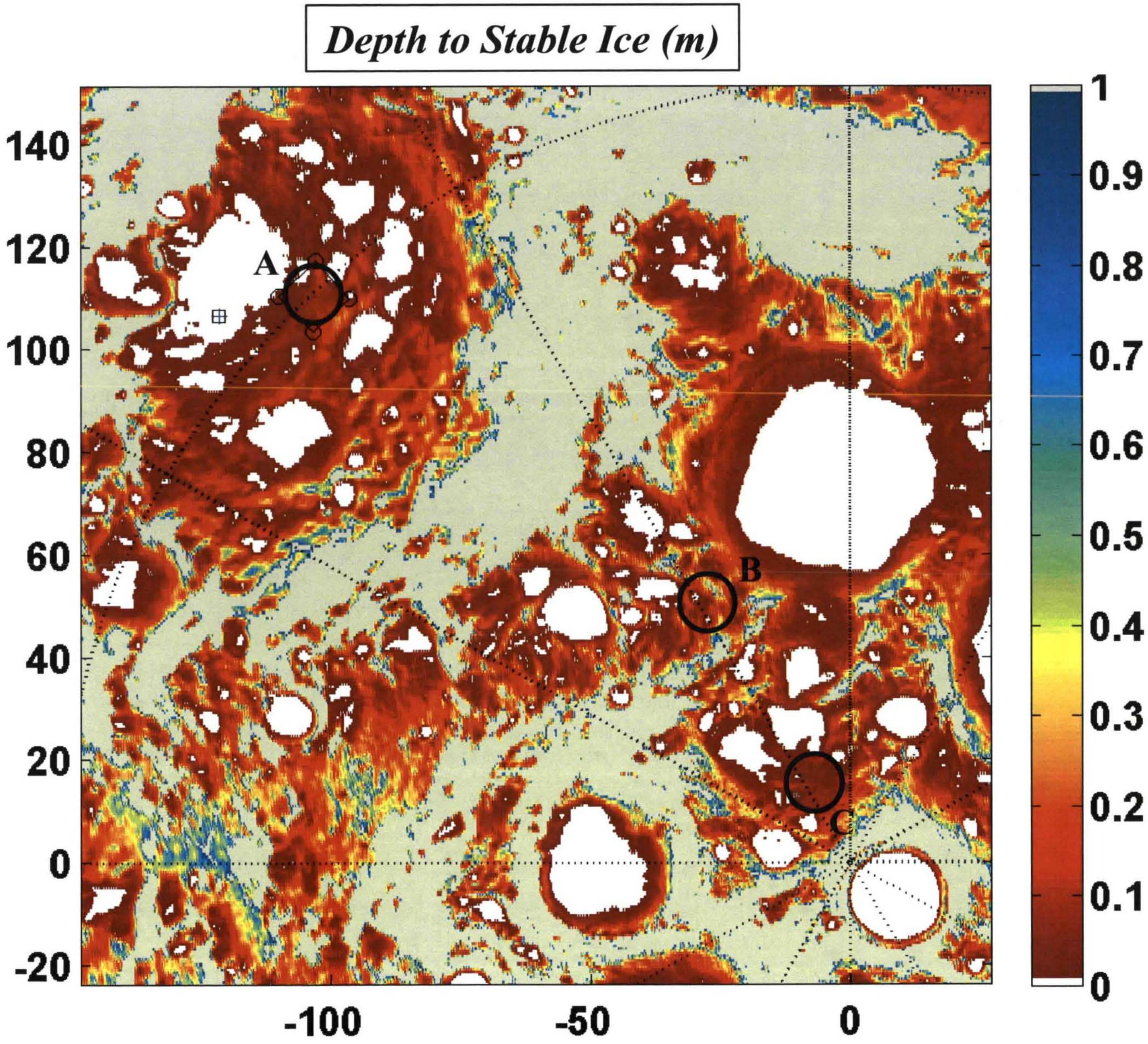
		MISSION SCENARIO:						
		Land & Die	Hopper	Crawl & Die	Sun-Loving Rover	Sun & Shadow Rover	X-Prize Lander & Rover	Radioisotope Rover
FIGURE OF MERIT	LOCATION	PSR	PSR, Regional	PSR	Sunlit	Sunlit w/ brief shadow	Sunlit	PSR, Regional
	SCIENCE RETURN	PSR, 1 Bore, No Horiz. Surveys	Regional Exploration	PSR	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 Options – Potential South Pole Landing Sites

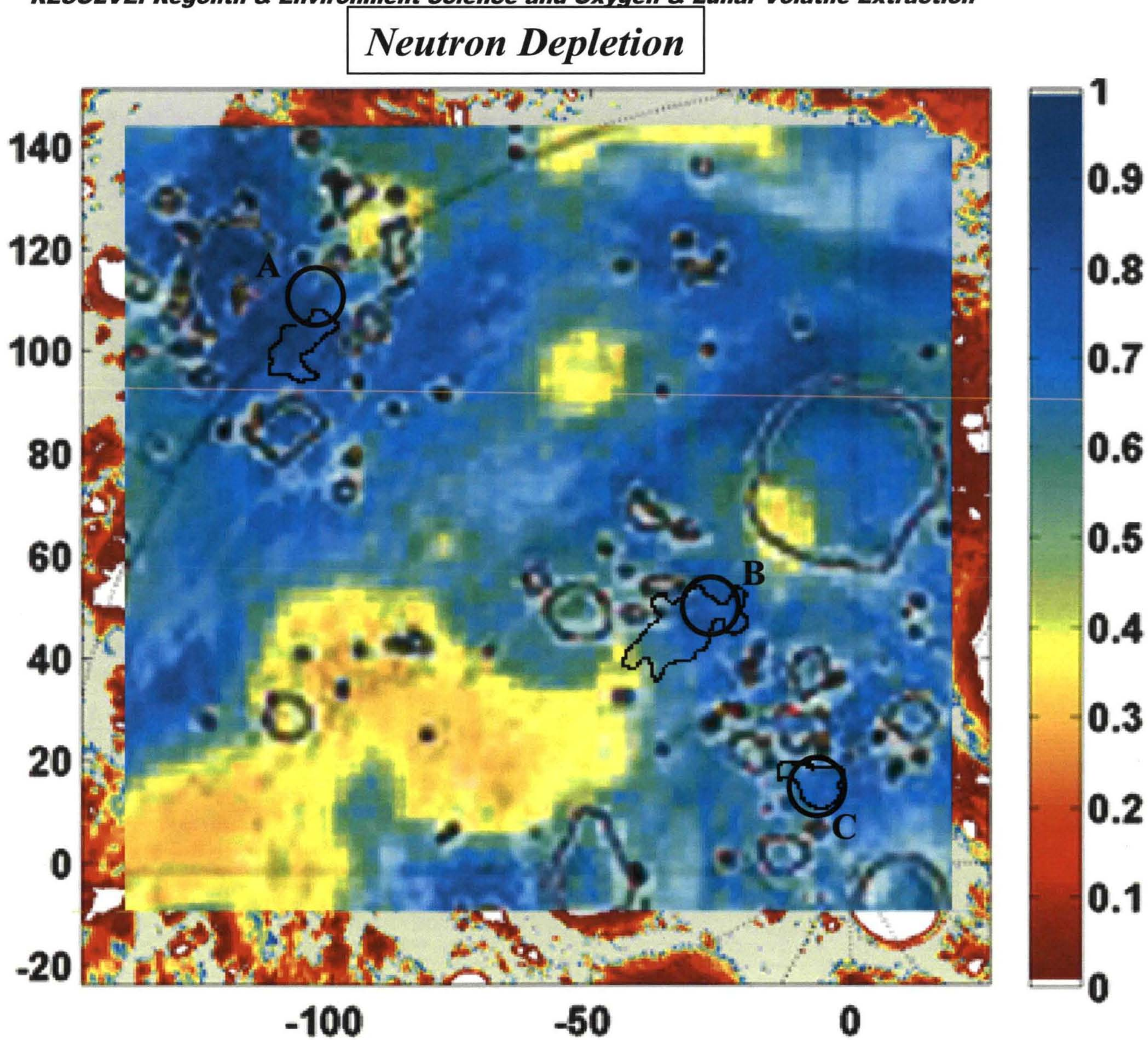


RESOLVE Mission Options – Potential South Pole Landing Sites



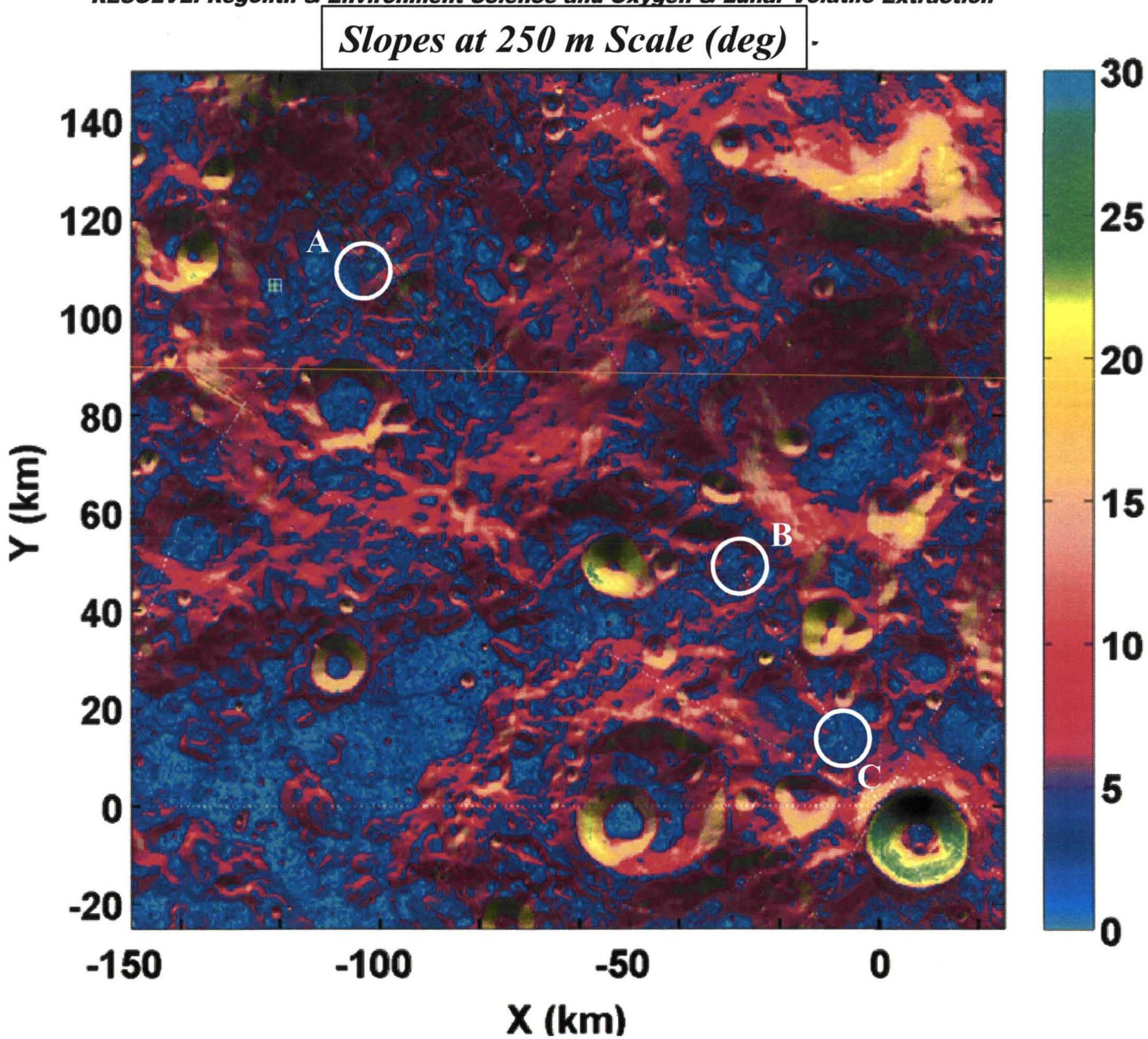
RESOLVE Mission Options – Potential South Pole Landing Sites

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

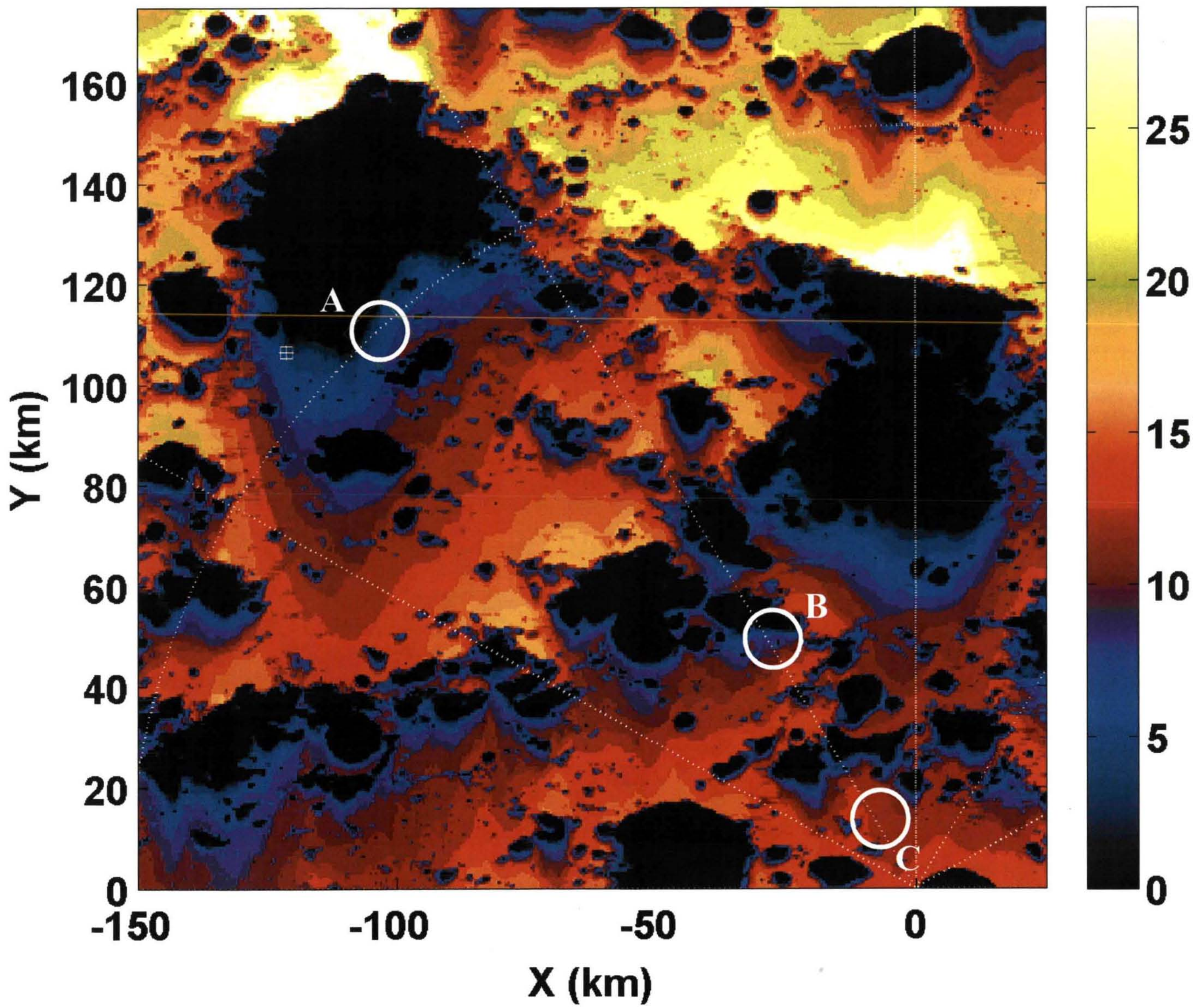


RESOLVE Mission Options – Potential South Pole Landing Sites

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



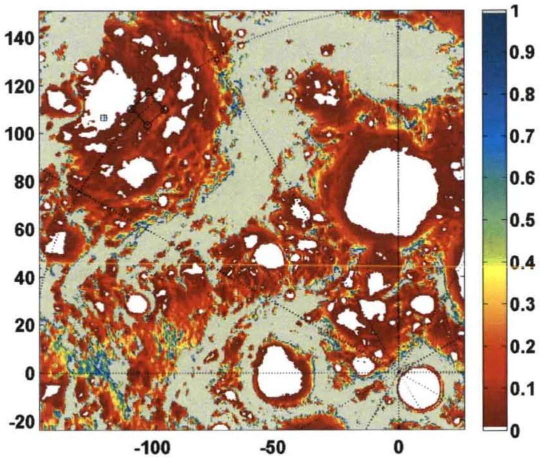
Net DTE Visibility Over Month (days): 2015-6-4



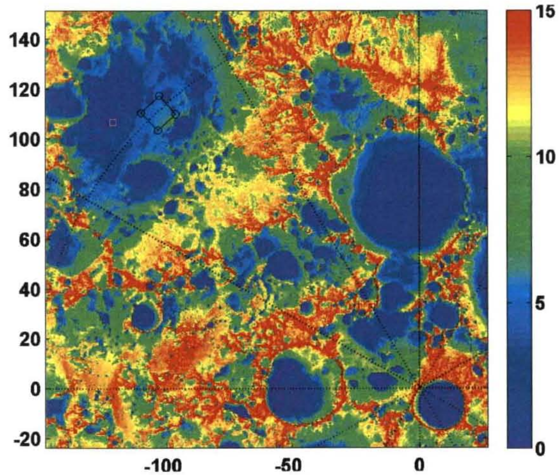
RESOLVE Mission Options – Potential South Pole Landing Sites

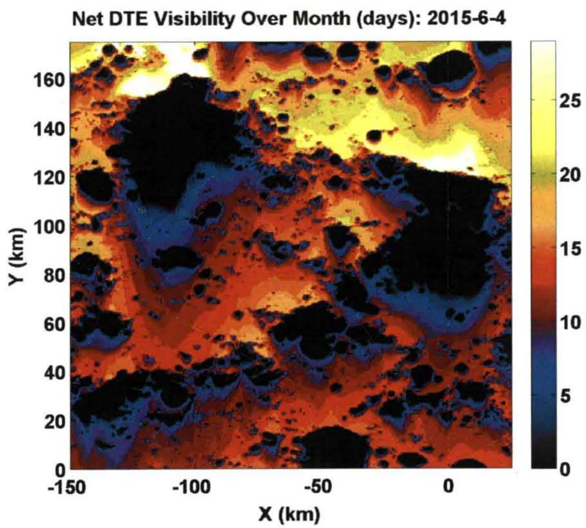
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction

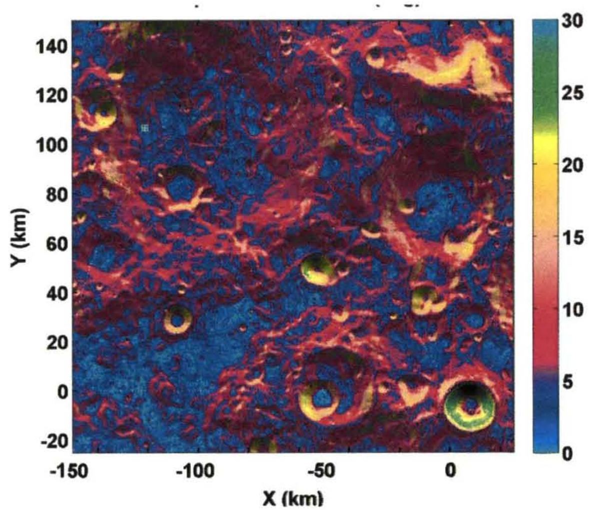
Combined Site Analysis



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			

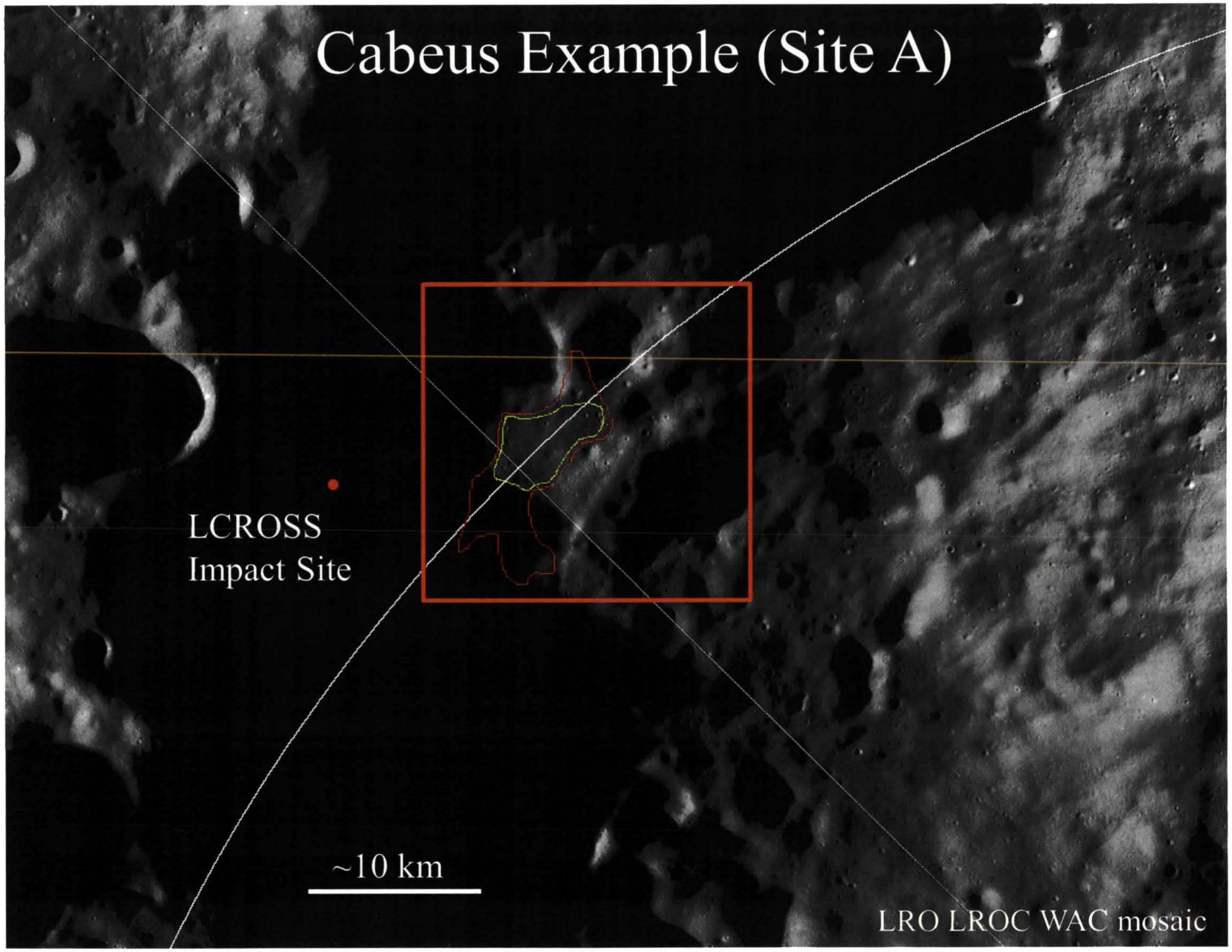






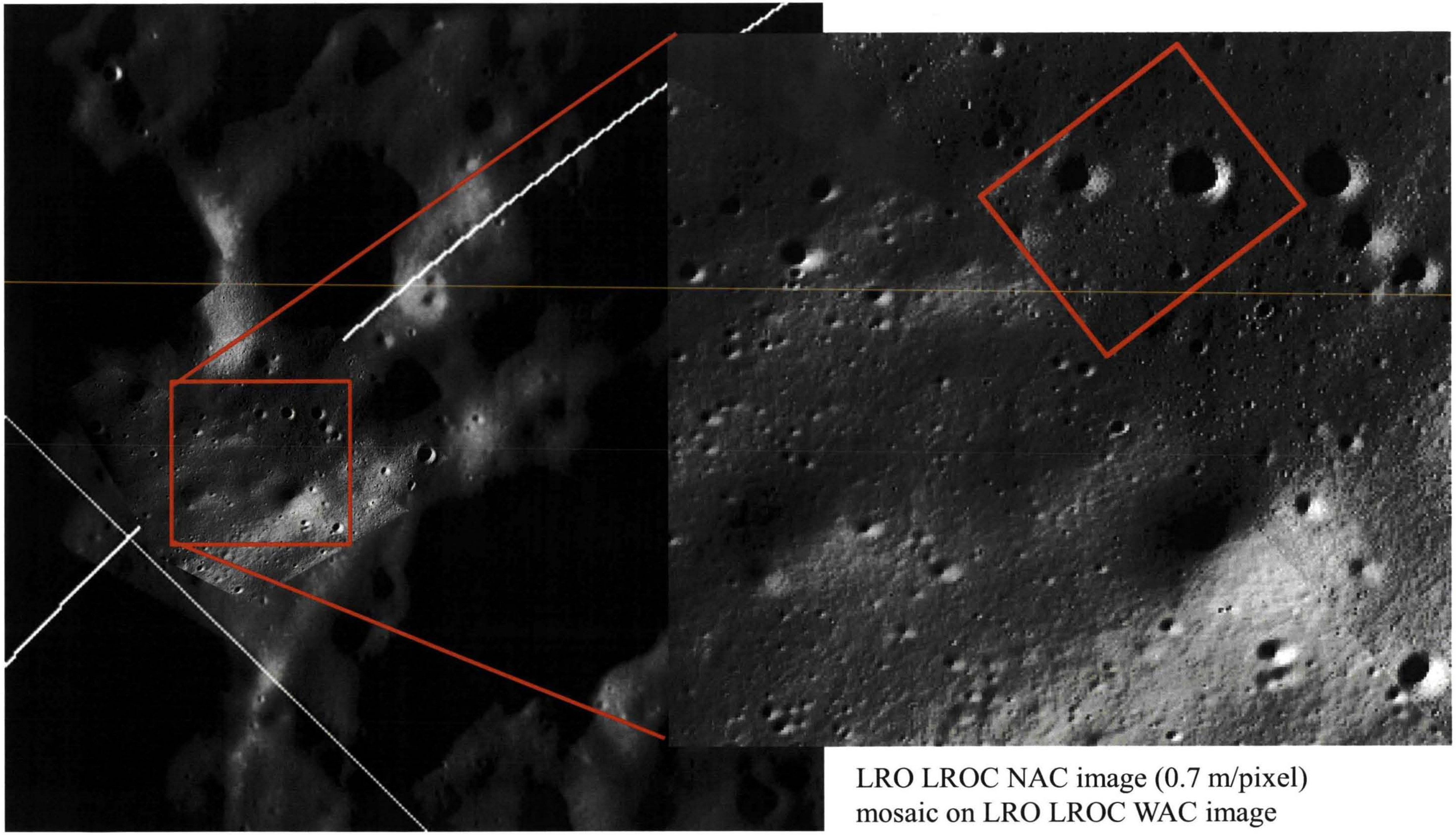
RESOLVE Mission Options – Potential South Pole Landing Sites

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



RESOLVE Mission Options – Potential South Pole Landing Sites

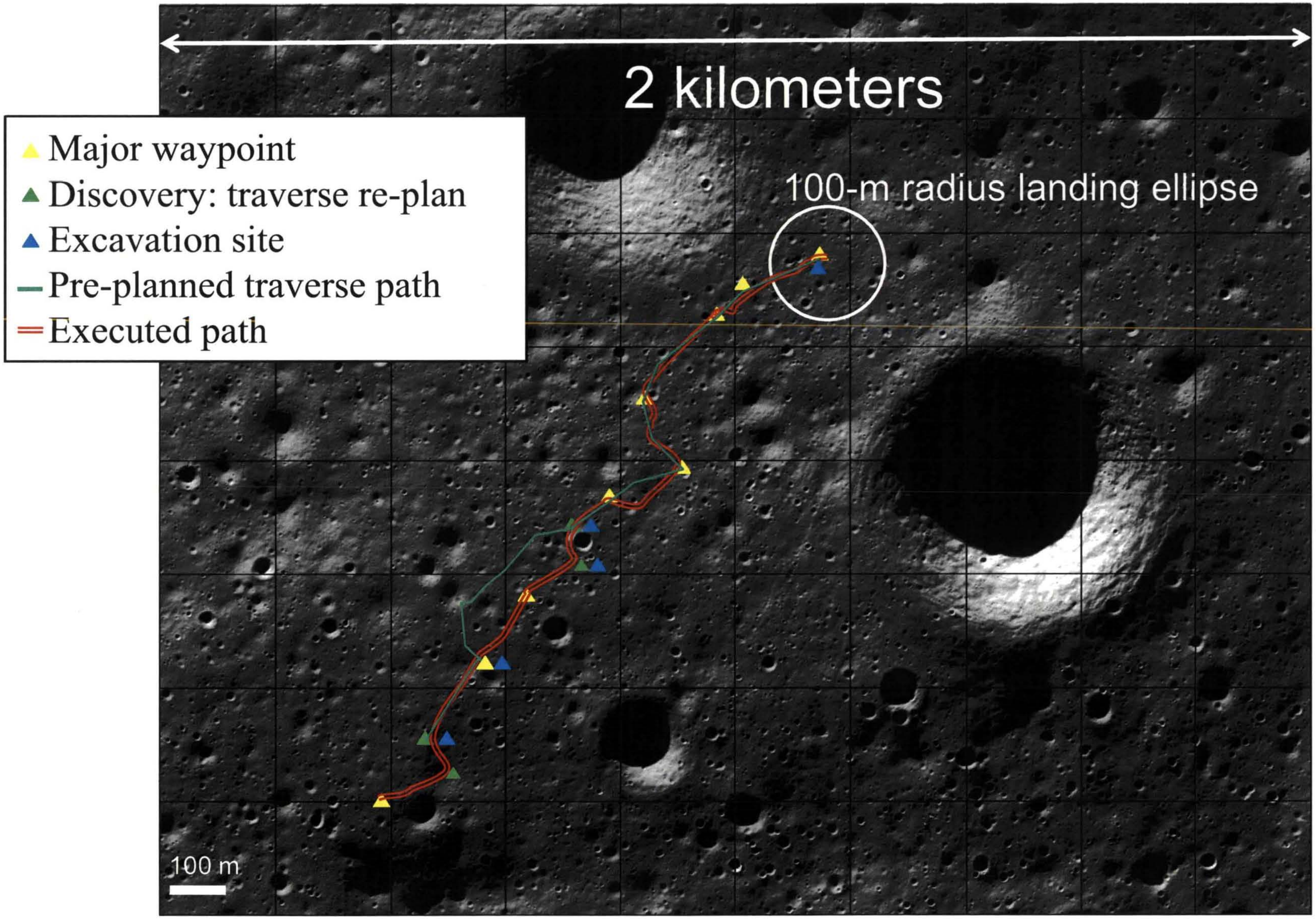
RESOLVE: Regolith & Environment Science and Oxygen & Lunar Volatile Extraction



LRO LROC NAC image (0.7 m/pixel) mosaic on LRO LROC WAC image

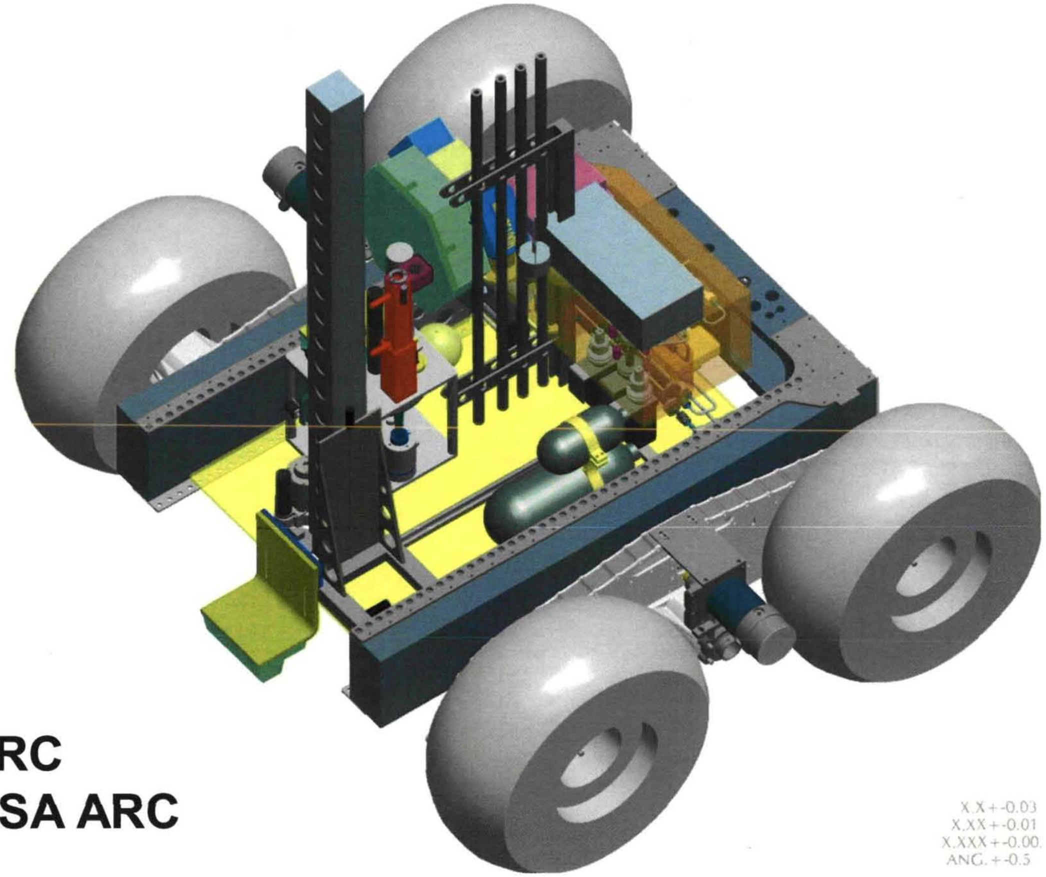
RESOLVE Mission Options – Notional Traverse

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



RESOLVE's Planned Instrument Suite International and Across NASA Centers

- Avionics - NASA KSC and CSA
- Software - NASA KSC and CSA
- Mission Ops - NASA JSC
- Structures - NASA GRC
- Thermal - NASA JSC
- Power - NASA GRC



- Neutron Spectrometer - NASA ARC
- Near Infrared Spectrometer - NASA ARC
- Drill (1 meter depth) - CSA
- Gas Chromatograph/Mass Spectrometer - NASA KSC
- OVEN for volatile heating/hydrogen reduction operations - NASA JSC
- Water droplet capture and visual transmission to Earth - NASA KSC

RESOLVE Instrumentation

- The **Neutron Spectrometer Subsystem** will be used to verify the presence of hydrogen rich materials and then map the distribution of these materials to assist in sample site selection and better understand the morphology of the resource.

- The **Near Infrared (NIR) Spectrometer Subsystem** will be used to provide an additional means of surveying the surface and immediate excavation site for water and other volatiles. Provides surface and regolith mineral context. The Near Infrared (NIR) Spectrometer instrument will be used to scan the immediate vicinity of the drill site before and during drill/auger operations to look for near real-time changes in the properties of the materials exposed during the drilling process.

- The **Drill Subsystem** includes the hardware to physically excavate/extract regolith from the lunar surface to a depth of 1 m and perform any type of preparation necessary (grinding, crushing, sieving, etc.) before delivering the sample to one or more reactor chambers for further processing by the Reactor Subsystem. This subsystem will be provided by the Canadian Space Agency (CSA) through a partnering agreement and integrated into the RESOLVE. The excavation device will be instrumented to measure forces/displacements etc. to determine critical bulk properties of the regolith.

- The **O**xygen and **V**olatile **E**xtraction **N**ode **(OVEN)** Subsystem will accept samples from the Drill Subsystem and will evolve the volatiles contained in the sample by heating the regolith in a sealed chamber and will also extract oxygen from the remaining regolith sample. Each sample will be sealed in the OVEN chamber and heated up to 150°C to evolve volatiles (H_20, CO, etc.). At most 1 (one) sample from each core will continue to be heated up to ~900°C and be subjected to hydrogen reduction processing

- The **Lunar Advanced Volatile Analysis (LAVA) Subsystem** will accept the effluent gas/vapor from the OVEN Subsystem and analyze that effluent gas using gas chromatograph and/or mass spectrometer sensor technologies. LAVA Subsystem will design, develop, test, and provide all of the fluid system hardware necessary to support OVEN Subsystem and LAVA Subsystem instrumentation operations. The system will measure constituents below atomic number 70 (including H_2, He, CO, CO_2, CH_4, H_2O, N_2, NH_3, H_2S, SO_2, etc.).

QUESTIONS?