An International Strategic Approach on In-Situ Resource Utilization (ISRU)

John Gruener, NASA Johnson Space Center

NASA Community Workshop on the Global Exploration Roadmap

NASA Ames Research Center

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ISRU: Global Exploration Roadmap

ISECG

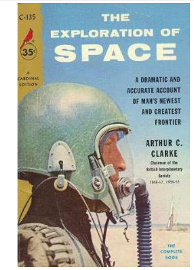
Major Themes:

- While In-Situ Resource Utilization (ISRU) has been proposed for decades as a way to limit the cost and complexity of long-term human presence beyond low earth orbit, **this concept of operation is still unproven in space**
  - ISRU components and systems tested on Earth (labs, environment chambers, analogues)
  - ISECG agencies see ISRU as an important component of long-term, sustainable exploration
- **Water is the most important space resource to pursue**
  - Present at the lunar poles, asteroids, and on the Mars surface
  - Greatest potential for reducing cost/risk and improving sustainability of exploration
- **The Moon is a good place to start** ISRU demonstrations
  - Proximity to Earth
  - Abundant and diverse resources, including water ice
  - Commercial opportunities
- **Initially build strategic knowledge around three ISRU functions**:
  - Robotic activity could be supported by crew at the Gateway/surface

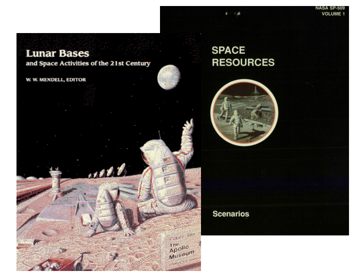
Resource Prospecting	Resource Acquisition Demonstrations	Resource Processing Demonstrations

The Use of Space Resources – A Short History

- **1951 – Arthur C. Clarke**
  - "The first lunar explorers will probably be mainly interested in the mineral resources of their new world, and upon these its future will very largely depend."

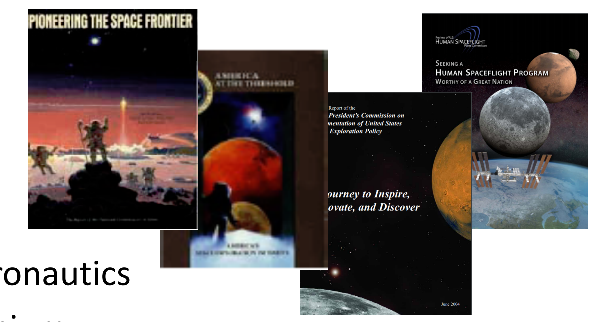


- **1985 – Lunar Bases and Space Activities of the 21st Century**
  - Followed up by second conference in 1988
  - NASA SP-509, Space Resources released in 1991



- **1986 thru 2009 – series of US Presidential appointed NASA advisory studies advocating utilizing local planetary resources**

- **1990 – Mars Direct by Robert Zubrin**
  - NASA DRMs 1 to 5 (1991-2009) include ISRU propellant for Mars ascent



- **ISRU Currently Discussed in Many Forums**
  - American Society Civil Engineers, America Institute of Aeronautics and Astronautics
  - Space Resource Roundtable, Planetary & Terrestrial Mining Science Symposium

- **Global Exploration Roadmap**
  - 2010 – Global Point of Departure includes oxygen from lunar regolith
  - 2011 – ISRU listed as a key supporting objective
  - 2013 - One page description of the use of local resources
  - 2018 - The beginning of international framework for ISRU and lunar polar volatiles

The Use of Space Resources – A Current Perspective

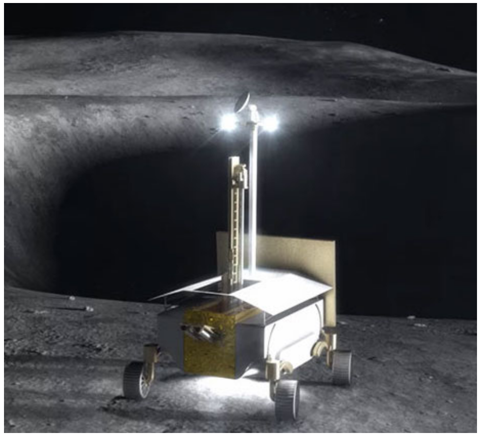
- **Characterizing and eventually using space resources is considered a important component for long-term, sustainable human exploration**

- **Despite over 65 years of discussion, there have been ZERO demonstrations of ISRU in space**

- **Until resource availability is assured and ISRU capabilities have been demonstrated, space agencies are hesitant to rely on space resources and ISRU for any mission critical function**

- **Space Agencies are planning and initiating missions that begin to better understand space resources and demonstrate key ISRU technologies and capabilities**
  - Initial focus is on:
    - Lunar polar volatiles (i.e., Luna 27, Resource Prospector, Chandrayaan-2, SELENE-R)
    - Water on Mars (i.e., Mars 2020, ExoMars 2020) and asteroids
    - Mars atmosphere processing (i.e., Mars 2020)

Luna 27



Resource Prospector

International Lunar Robotic Exploration Mission Timeline

Agency	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
CNSA		Chang'E-4 (Farside, +rover) Chang'E-5 (Nearside, Sample Return)		Polar and non-polar landing and sample return mission concepts under study									
CSA ASC											Participation w/HERACLES		
esa							Participation w/Luna 27 Lunar Pathfinder		ISRU Demo		Participation w/HERACLES		
ISRO		Chandrayaan 2 Chandrayaan 2 (Nearside, +rover)											
JAXA		EQUULEUS (EML2) OMOTENASHI (impactor)		SLIM		SELENE-R (+rover)					Participation w/HERACLES		
KARI				KPLO									
NASA		Lunar Flashlight Lunar Ice Cube LunaH-Map Skyfire (flyby)				Resource Prospector (+rover)							
ROSCOSMOS				Luna 25 Glob (nearside)		Luna 26 Ressurs-1	Luna 27 Ressurs-1 South Pole			Luna 28 Grunt Sample Return (After 2025)			

= Orbiting Missions

= Polar Landed Missions, (> 85˚ lat)

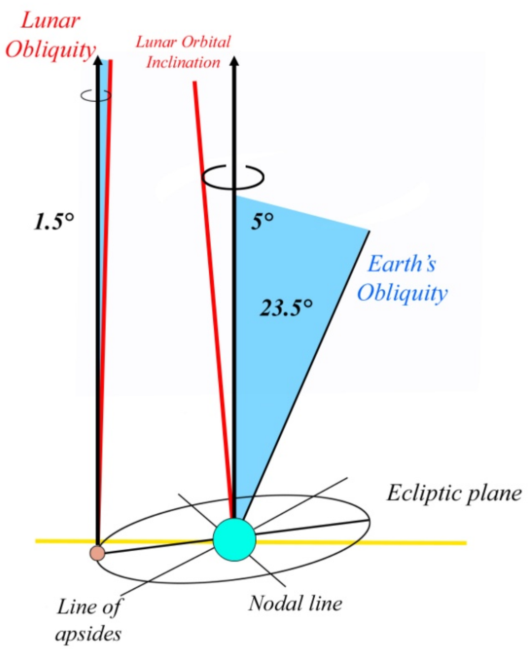
= Non-polar Landed Missions, (≤ 85˚ lat)

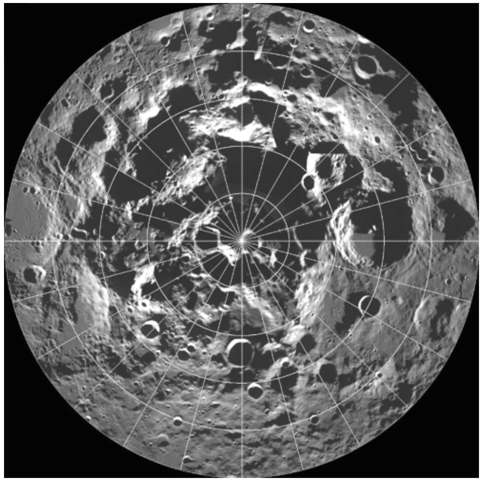
= Landing Region TBD

As of November 2017

Lunar Polar Environment

- **Low lunar obliquity (1° 32’)**
  - Geometry stable for the last ~2 billion years
  - Grazing sunlight and extended shadows at the poles
  - Terminator always nearby
- **Areas of quasi-permanent light**
  - Local topographic highs stand above the local horizon
  - Low, constant surface temperatures (~220 K ± 10 K)
  - High solar flux on vertical surfaces
  - Serve as locations for solar power generation
- **Areas of permanent darkness**
  - Local depressions with only scattered light or starlight
  - No direct solar illumination
  - Very low temperatures (~30-50 K)
  - Serve as ‘cold traps’ for volatiles, including water ice
- **View from Earth**
  - Sunlit areas – approx. two weeks of visibility followed by two weeks obscured
  - Shadowed areas – permanently obscured





South pole

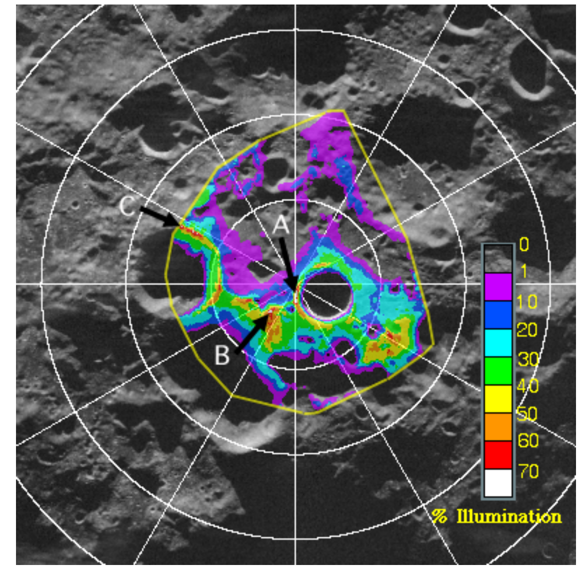
Lunar Polar Lighting Studies

Historical Perspective

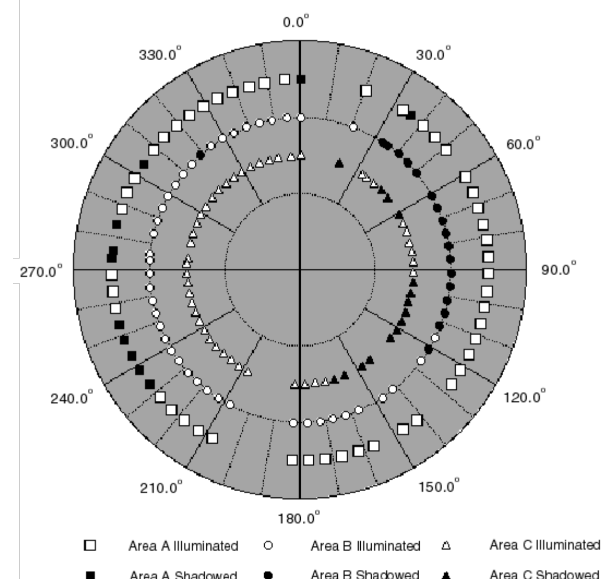
- In 1837, German astronomers Beer and Madler originated the idea of some lunar polar mountain peaks receiving "eternal sunshine", later supported by French astronomer Flammarion in 1879
- The idea of permanently shadowed craters was discussed by Urey in The Planets, Their Origin and Development (1952)
- The possibility of ice existing on the floors of polar shadowed craters suggested by Watson et al., *J. Geophys. Res.* **66**, 3033 (1961)

Spacecraft Observations

- Imagery from Clementine was first used to understand the lunar polar lighting conditions - Bussey et al., *Geophy. Res. Let.* **26**, 1187 (1999)
- Similar studies have been conducted using imagery from SMART-1, SELENE-1, and LRO
- Lunar Orbiter Laser Altimeter (LOLA) and Lunar Reconnaissance Orbiter Camera (LROC) on the LRO spacecraft allowed new modeled analyses of lighting conditions – i.e., Mazarico et al., *Icarus* **211**, 1066 (2011)
- The are no peaks of 'eternal light', however there are numerous locations that are illuminated >75 % of the time at the surface, some are illuminated >85% of the time
- Solar arrays reaching 10 m above the surface would receive even greater illumination, up to 93% of the time
- Multiple locations working together can provide 100% illumination, but these are generally separated by 10s of km

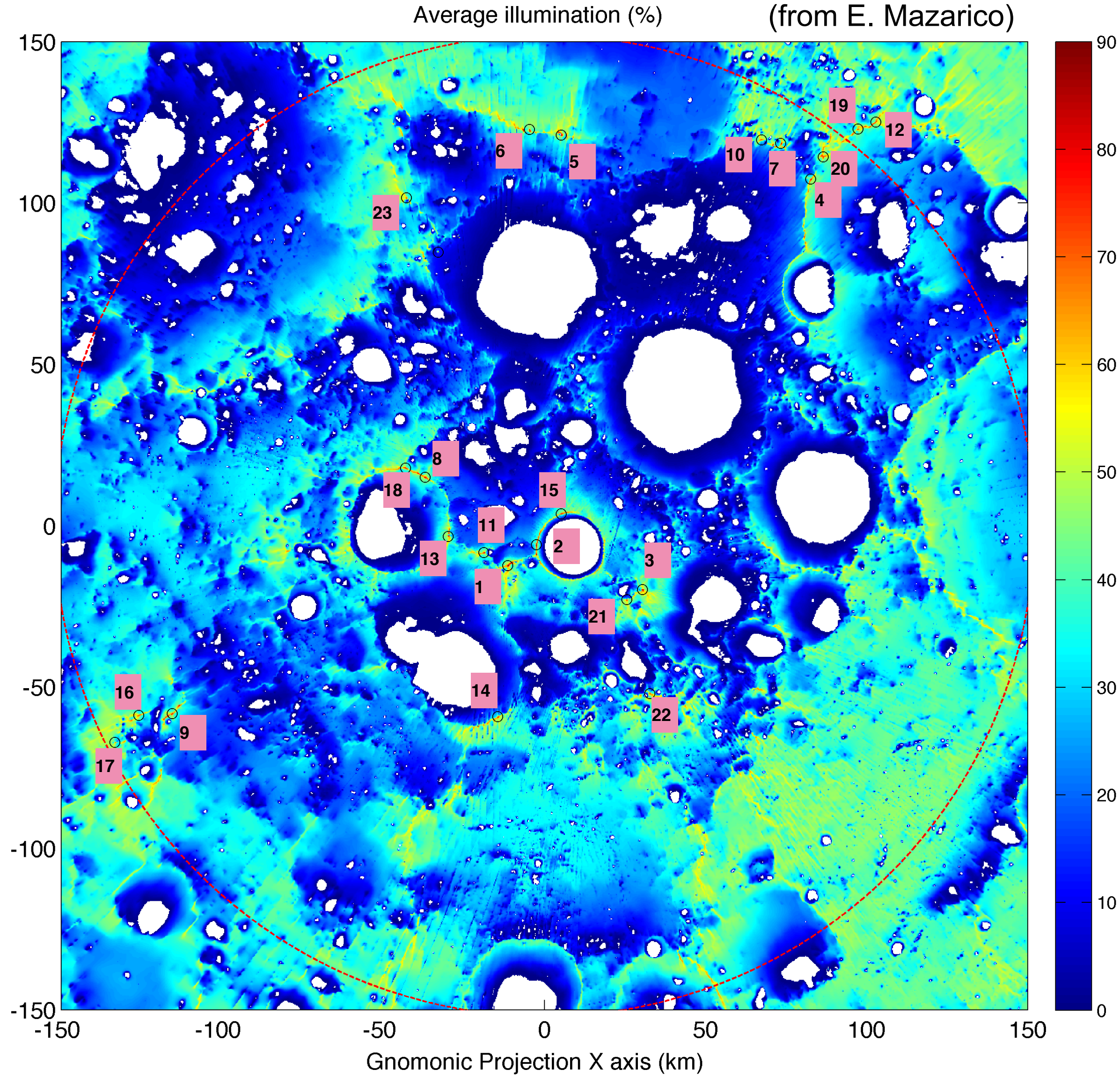


Illumination Conditions at Areas A, B & C



LRO/LOLA Results
Average Illumination: Lunar South Pole Region

site	average illumination	longitude	latitude	altitude
1	87.94	222.69	-89.45	1.958
1	84.54	223.25	-89.45	1.955
1	83.86	222.08	-89.45	1.956
2	86.65	203.20	-89.79	1.733
2	85.54	202.38	-89.78	1.732
2	82.63	204.08	-89.80	1.728
3	85.57	123.11	-88.80	1.643
4	82.29	37.59	-85.54	6.111
5	82.28	2.44	-86.01	5.130
6	82.21	357.82	-85.96	4.991
7	82.03	31.76	-85.42	6.442
8	80.23	292.02	-88.68	1.800
9	80.07	243.27	-85.74	2.841
9	78.29	243.85	-85.83	2.675
10	78.41	29.37	-85.48	6.174
11	78.05	246.27	-89.32	1.682
12	77.57	39.41	-84.67	7.001
13	77.38	263.81	-89.01	1.546
14	77.15	193.79	-87.99	1.276
15	76.99	54.21	-89.79	1.433
16	76.79	245.01	-85.43	3.226
17	76.58	243.29	-85.09	3.751
18	76.51	292.54	-88.46	1.574
19	75.89	38.35	-84.84	6.880
20	74.65	37.11	-85.28	6.738
21	73.11	131.88	-88.87	1.435
21	71.62	132.18	-88.86	1.433
22	72.49	147.77	-87.98	0.936
23	72.29	337.15	-86.37	2.790
23	72.15	324.44	-83.68	5.532



*NOTE: 87.94% at surface level, at 10 m above surface it increases to ~95%

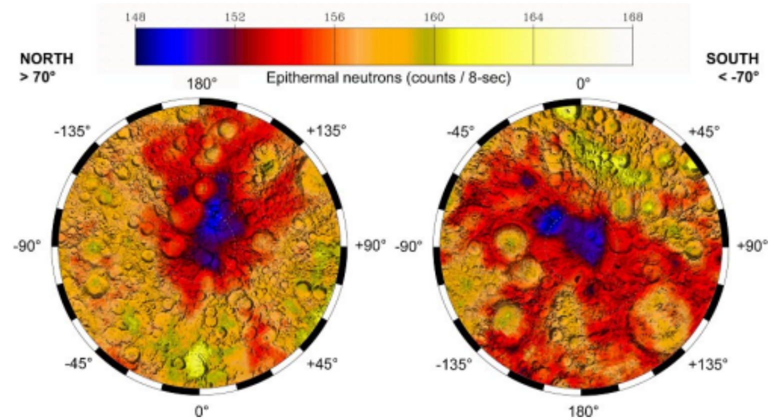
Lunar Polar Water Ice

Radar Experiments

- Clementine bi-static radar experiment; Chrandrayaan-1 Mini-SAR instrument; LRO Mini-RF instrument
- Spudis et al., *Sol. Sys. Res.* **32**, 17 (1998); Spudis et al., *J. Geophys. Res. Planets* **118**, 1 (2013)
- Circular polarization ratio (CPR) and coherent backscatter opposition effect (CBOE) from polar locations on the Moon suggest the presence of water ice

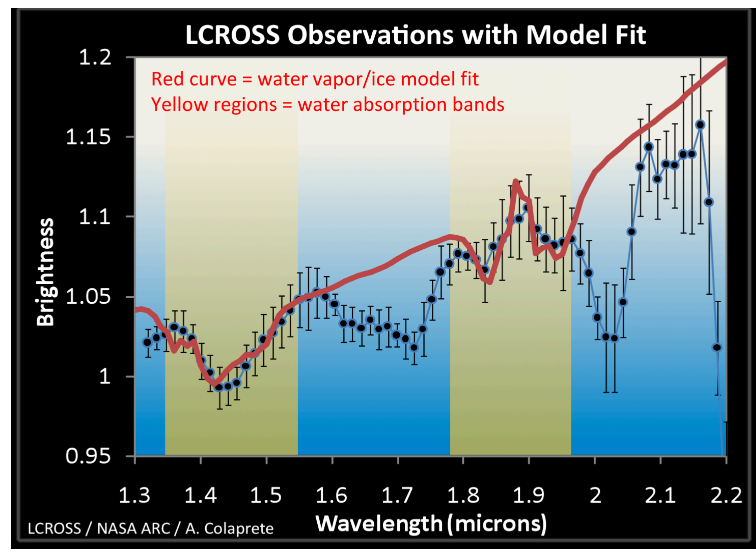
Neutron Spectroscopy

- Neutron spectrometers flown on both Lunar Prospector and Lunar Reconnaissance Orbiter (LRO)
- Feldman et al., *Science* **281**, 1496 (1998); Mitrofanov et al., *Science* **330**, 483 (2010)
- Detected "excess" hydrogen (~2-3x global average) associated with large polar regions, particularly permanently shadowed regions
- Enhanced hydrogen over poles consistent with ~1-2% water ice or increased amount of retained solar wind
- State, or nature, of hydrogen not determined



Lunar Crater Observation and Sensing Satellite (LCROSS)

- Impacted permanently shadowed floor of Cabeus crater near south pole
- Provided direct evidence of water vapor in ejecta plume
- Colaprete et al., *Science* **330**, 463 (2010)
- Average concentration of water ice in the regolith is estimated to be 5.6 ± 2.9% by mass
- Results suggest there is spatial heterogeneity of water ice at scales <10km



LCROSS Polar Volatile Abundances

Table 1. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV. Values shown are the average value across the averaging period, and errors are 1 SD.

	Water mass (kg)			
Time (s)	Gas	Ice	Dust mass (kg)	Total water %
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Table 2. Abundances derived from spectral fits shown in Fig. 3. The uncertainty in each derived abundance is shown in parenthesis [e.g., for H_2O: 5.1(1.4)E19 = $5.1 \pm 1.4 \times 10^{19}$ cm^{-2}] and was derived from the residual error in the fit and the uncertainty in the radiance at the appropriate band center.

Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$*
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

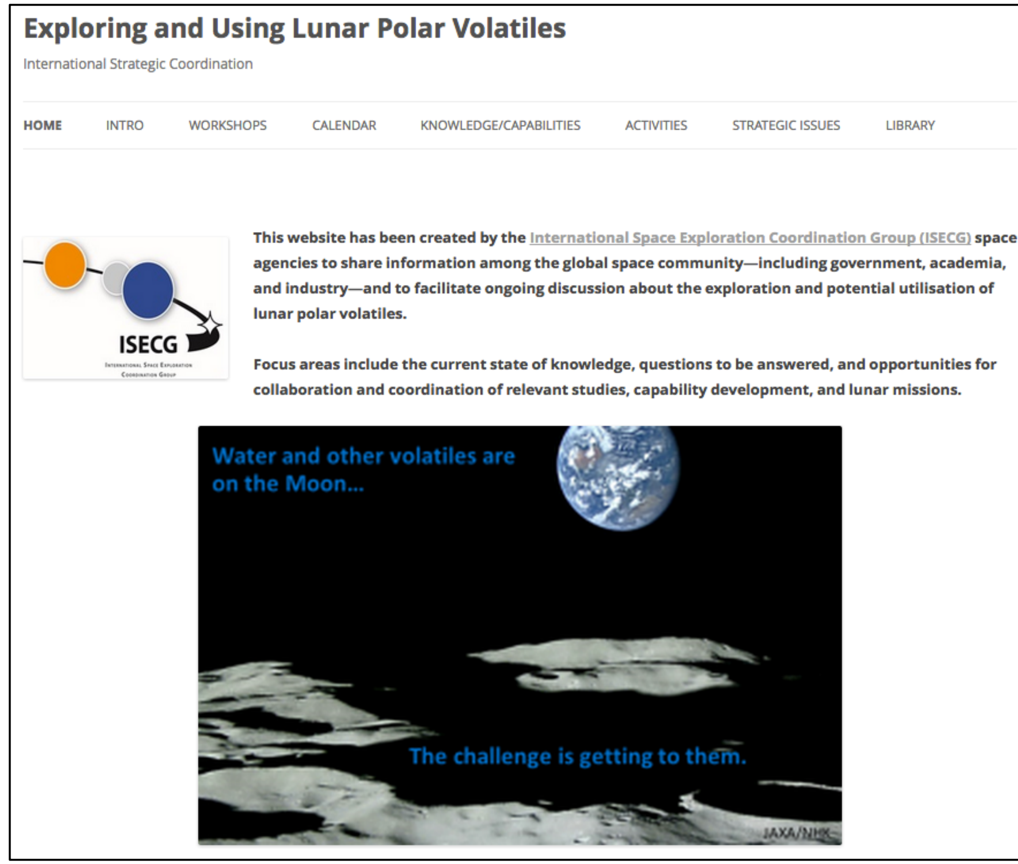
*Abundance as described in text for fit in Fig. 3C.

NOTE: from Colaprete et al. 2010, Detection of Water in the LCROSS Ejecta Plume, SCIENCE, Vol. 330, 22 Oct. 2010

ISECG Lunar Polar Volatiles Website

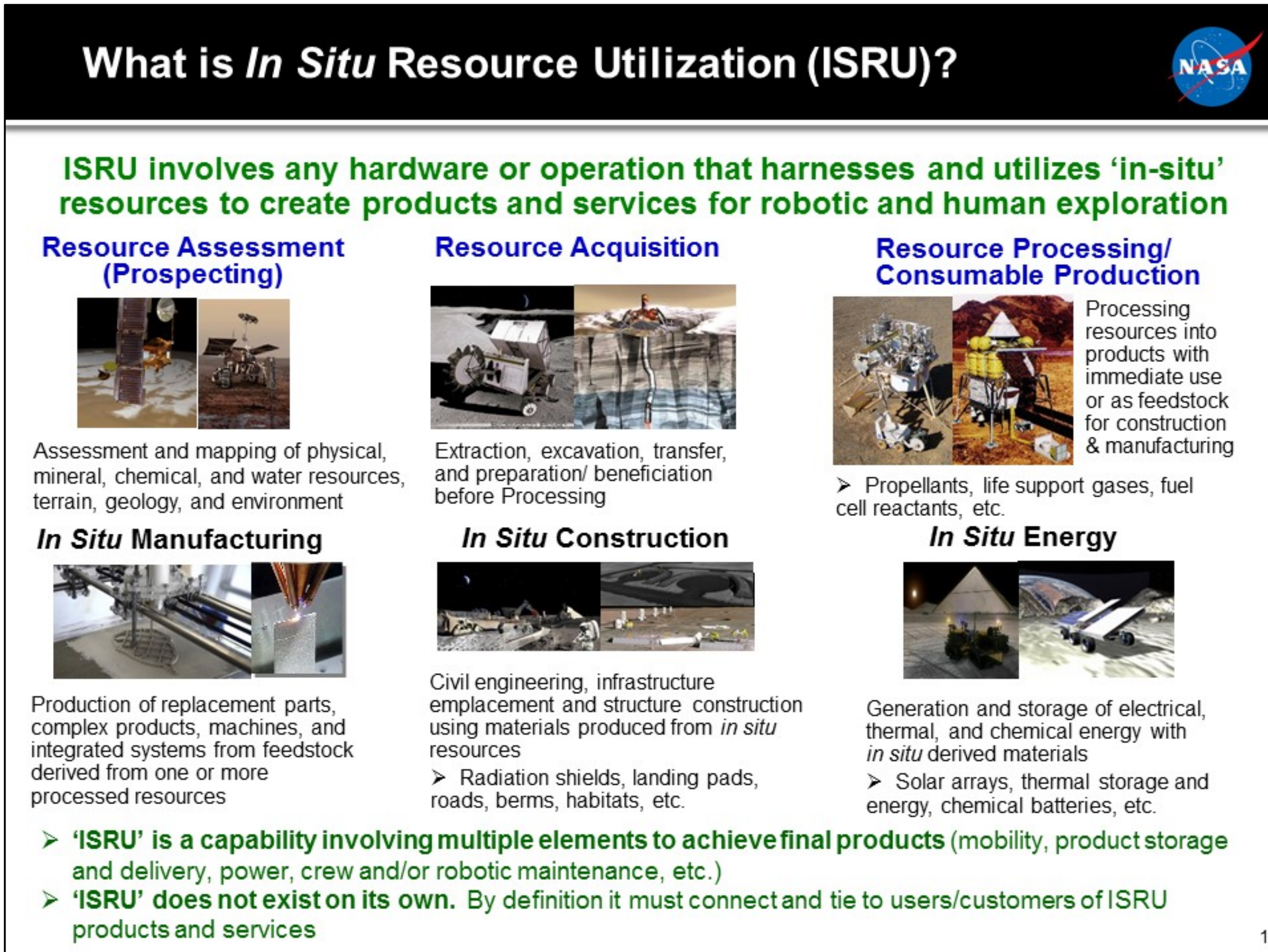
- **http://lunarvolatiles.nasa.gov**

- **Information Repository**
  - The case for polar volatiles
  - Strategic issues
  - Knowledge/capability gaps
  - Agency activities
  - Calendar
- **Virtual Workshops**
  - Hosted by NASA SSERVI
  - Archived audio/video
  - Archived presentations (.pdf)
  - Findings
- **Library**
  - Scientific data
  - Engineering tests
  - Architecture/mission concepts
  - Links to journals/meetings



ISRU: Overall Scope

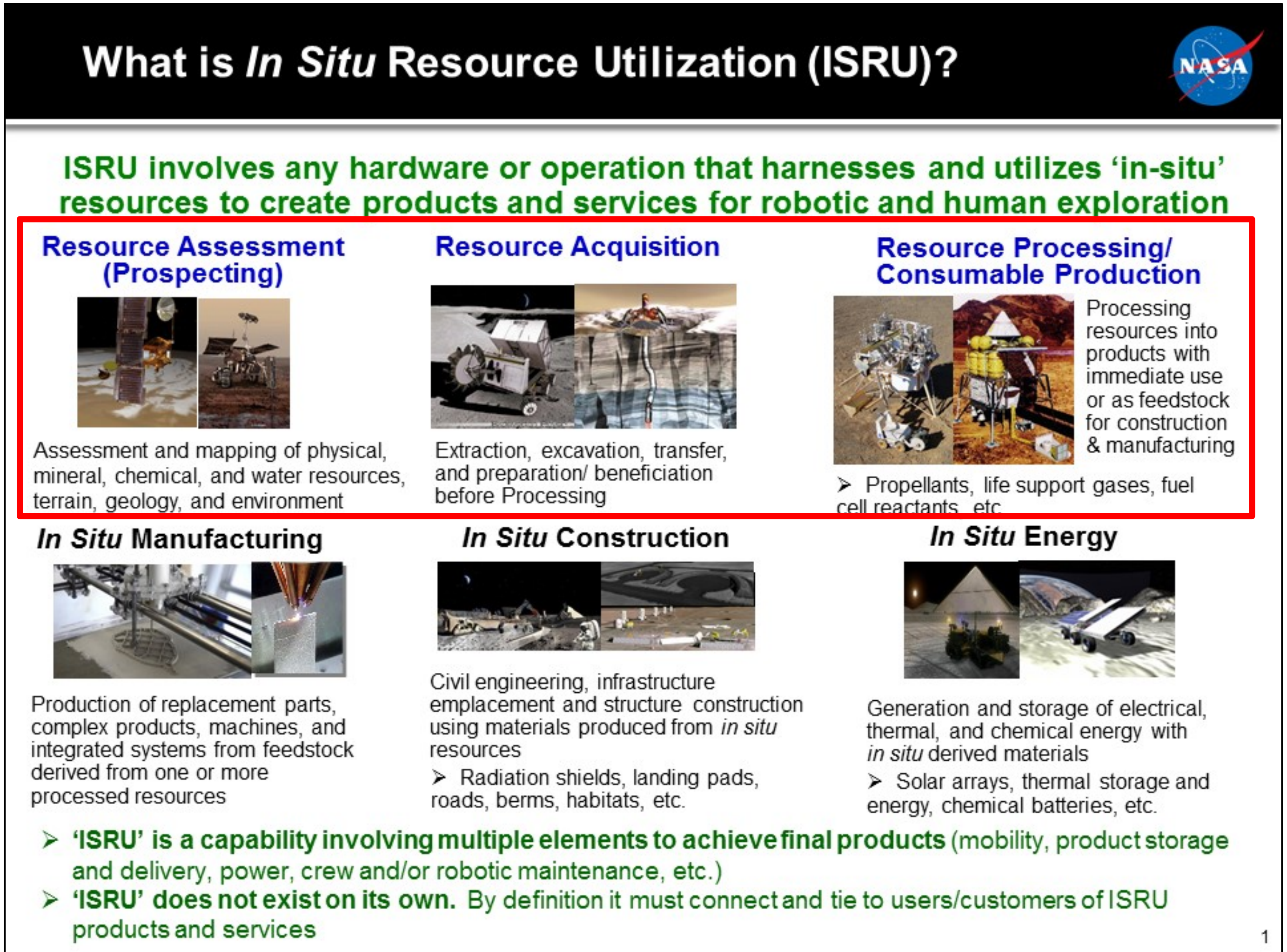
- **ISRU overall scope includes broad array of functions:**



International Near-term Focus for Space Resources and ISRU

- **ISRU overall scope includes broad array of functions:**

GER ISRU approach to initially focus on these three functions →



Understanding the ISRU Potential: The Initial Steps

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Resource Prospecting

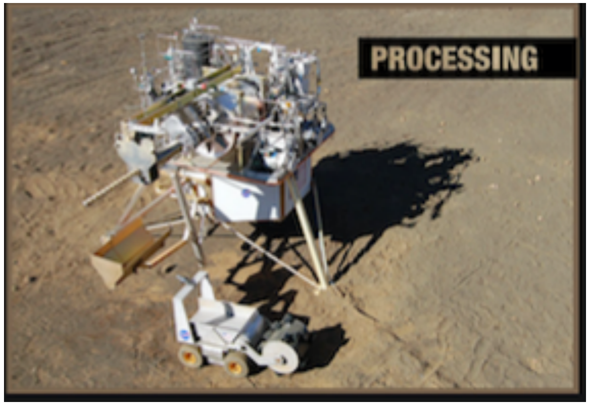
- Objectives
  - Ground truth that resources are present and accessible
  - Establishing the grade and tonnage of the resource 'ore'
- ISECG agencies focusing initial efforts on;
  - lunar polar volatiles
  - Subsurface water ice on Mars (ExoMars 2020 WISDOM)
  - Hydrated minerals/water ice on near-Earth asteroids

Resource Acquisition Demonstrations

- Physically acquiring identified resources
  - Subsurface drills (Luna 27, Resource Prospector)
- Demonstrating critical technologies for larger scale operations
  - Mars atmosphere (MOXIE – Mars 2020)

Resource Processing Demonstrations

- Objective: Turning raw materials into useful products
- Water production from ice-bearing regolith and hydrated minerals
- Oxygen production from regolith
- Oxygen and fuel production from Mars atmosphere



ISRU: Commercial Opportunities

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- **The production of material goods and energy from natural resources, is routinely done on Earth by commercial enterprises and entrepreneurs.**

- **An important role of space agencies is to develop new ISRU technologies to drive down the risks associated with using space resources**

- **If the use of space resources is proven to be not only possible, but economically advantageous, it is envisioned that commercial companies will play a larger role in executing ISRU capabilities and needs.**

- **Potential commercial opportunities**
  - Lunar delivery of ISRU payloads and demonstrations
  - Utility services (i.e., electricity, communications)
  - Production of rocket propellants and life support consumables
  - Technology spin-in and spin-off to terrestrial industry and applications for mining and renewable energy