Mapping Possible Locations for Lunar Ice Mining Using Topographic, Economic, and Elemental Data

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I. Introduction

In recent years, scientists have found evidence of lunar ice deposits, located mainly at the north and south poles. The objective of this research was to map the locations of these elemental deposits in a Geographic Information System (GIS) using hydrogen and oxygen abundance data from the Lunar Prospector (LP) and topography data from the Lunar Reconnaissance Orbiter (LRO). This research will help scientists and corporations to determine the most optimal places to mine lunar ice. In addition, an economic analysis of potential spacecraft will help to determine if mining lunar ice would be feasible. If economically feasible, lunar ice mining could potentially support both a scientific lunar base and future deep-space travel.

II. Background

The proposed theory for lunar water ice formation states that ice deposits formed in permanently shadowed craters at the lunar poles. Due to the 1.5° axis tilt of the Moon [3], the lunar poles face away from the sun, and cause craters at the poles to be permanently shadowed [2]. These permanently shadowed craters maintain temperatures low enough to sustain H_2O ice [3]. If mined, the ice can be converted into liquid hydrogen and oxygen, which can then be used to support deep space travel, or possibly a scientific lunar base [1, 4]. This research uses the ArcGIS mapping program. This program imports different data frames into layers that can be manipulated and used to create interactive maps with spatial reference data. The created map will be an easy-to-use, interactive source that will clearly locate the lunar ice deposits.

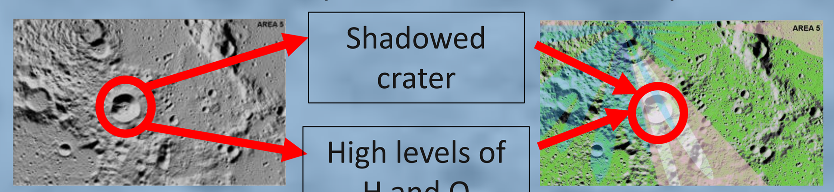

Figure 1: Shadowed impact crater at lunar north pole (left) and same shadowed impact crater with hydrogen, in blue (ppm), and oxygen, in white (higher)/pink (lower) (% by weight), abundance shown (right). Source: created map.

III. Problem

Determine ideal locations for a lunar mining site based on:

- Elemental abundance - to locate hydrogen- and oxygen-rich deposits
- Topography - ideal spacecraft landing sites based on slope
- Economic feasibility - cost/benefit analysis

IV. Methods

A map was created using the ArcMap ArcGIS program.

1. A basemap of the lunar surface containing topographic data was used, source Lunar Orbiter Laser Altimeter (LOLA) from the LRO.
2. A "hillshade" layer was calculated through the ArcGIS program using the LOLA topography layer, allowing for a clearer picture of the lunar surface and to correct bars/gaps in data.
3. The same topography layer was then used to calculate a slope layer through the program. Areas that had a ≦6° slope were highlighted and determined to be the ideal gradient for a spacecraft to land (based on NASA LM reports).
4. LP hydrogen and oxygen abundance data was imported and projected onto the basemap. Only the highest concentrations were highlighted in the layer, pink and white being highest oxygen, and blue and purple being highest hydrogen. This data was used to determine the possible locations of water ice deposits.
5. Further Assessment Criteria: American rockets that use liquid oxygen and liquid hydrogen fuel were researched, and costs per mission were compared. Payloads to Low Earth Orbit (LEO), Geostationary Transfer Orbit (GTO), and Trans-Lunar Injection (TLI) were also compared. Fuel capacity (kg) and fuel cost ($) were calculated using a fuel to spacecraft ratio and a fuel to oxidizer ratio, respectively.
6. Completed map and table are presented as an accessible source for scientists and/or others interested in the possibility of mining lunar ice.

ACKNOWLEDGEMENTS: We would like to thank Tabb Prissel and Jennifer Whitten for all of their guidance during this study!

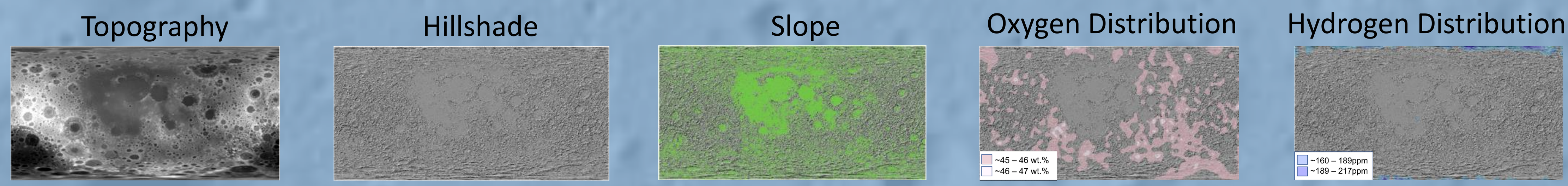

Figure 2: Global map of the moon with individual data layers shown. Low slope (middle) and highest concentrations of oxygen and hydrogen (right) were highlighted in the layers. Scales of oxygen abundance (pink/white, % by weight) and hydrogen abundance (blue/purple, ppm) also shown. Source: created map.

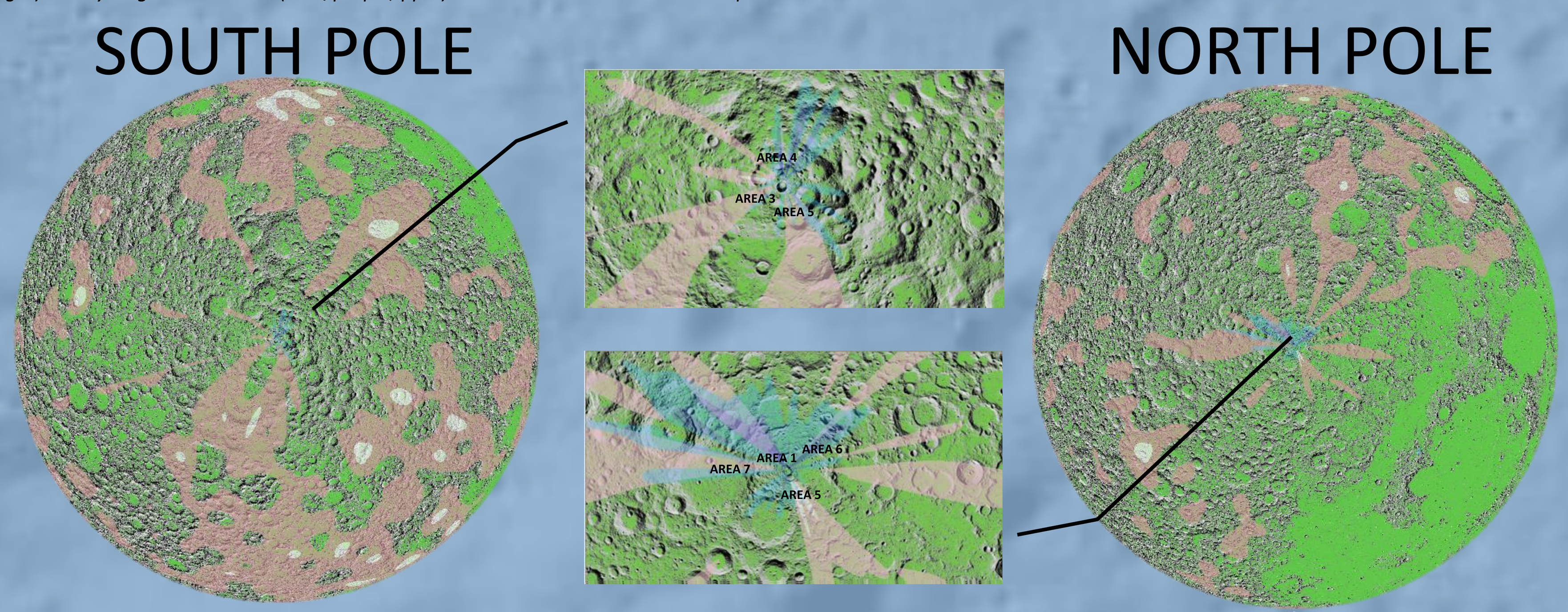

Figure 3: Full map of lunar north and south poles with highlighted areas labelled. All layers shown. Source: created map.

AREA 1 (88.6°N, 143.1°E)

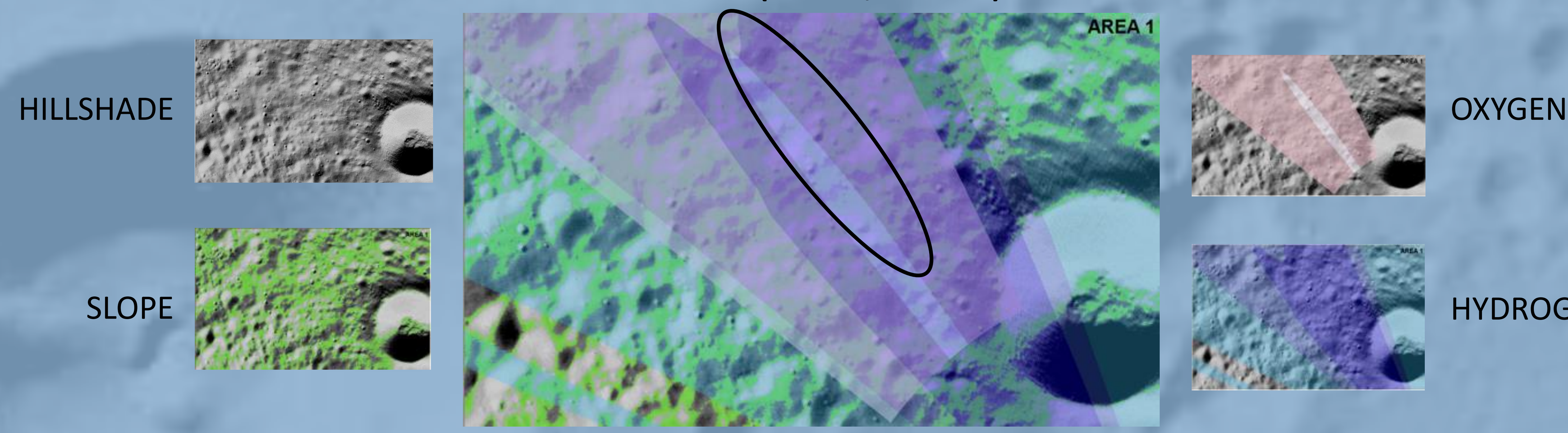

Figure 4: AREA 1. Location: North Pole, area: 647 sq. km, concentration O: 46-47% ,concentration H: 189- 217ppm. Source: created map.

AREA 2 (88.6°S, 65.1°E)

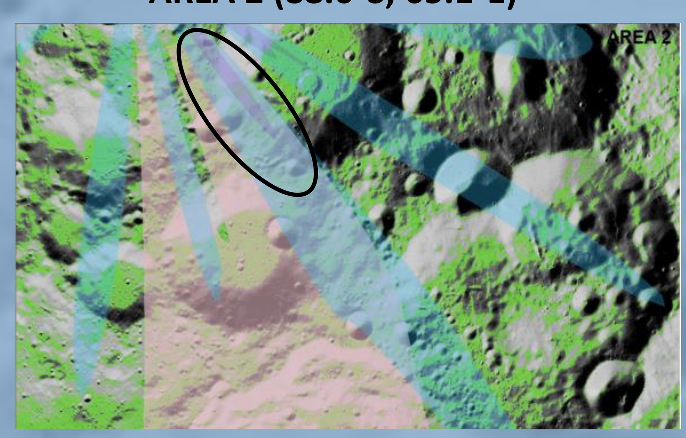

Figure 5: AREA 2. Location: South Pole, area: 1,562 sq. km, concentration O: 45-46%, concentration H: 189-217ppm. Source: created map.

AREA 3 (88.8°S, 158.1°W)

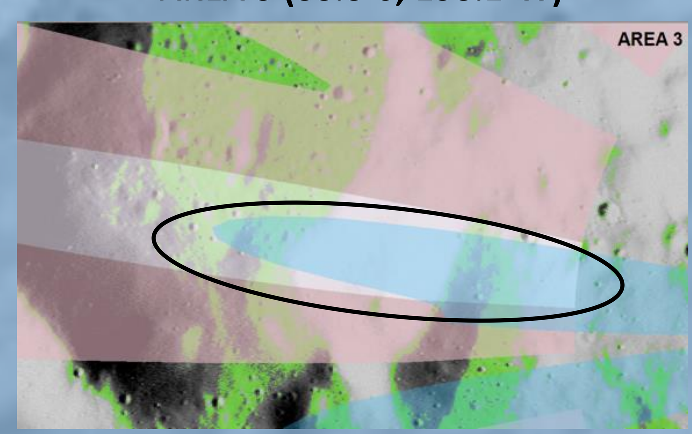

Figure 6: AREA 3. Location: South Pole, area: 1,250 sq. km, concentration O: 46-47%, concentration H: 160-189ppm. Source: created map.

AREA 4 (88.9°S, 84.1°W)

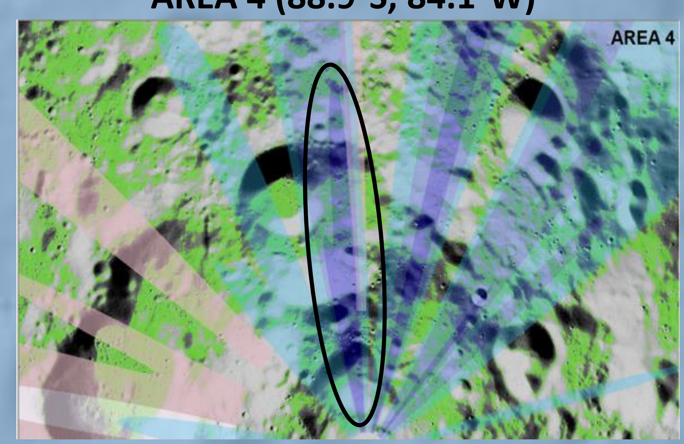

Figure 7: AREA 4. Location: South Pole, area: 3,418 sq. km, concentration O: 46-47%, concentration H: 160-189ppm. Source: created map.

AREA 5 (88.4°N, 48.5°W)

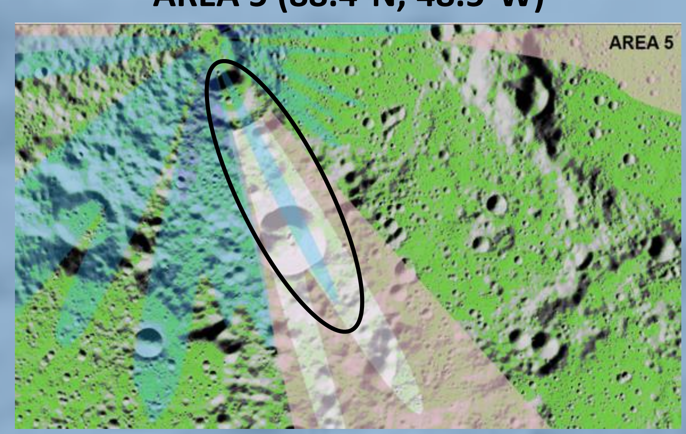

Figure 8: AREA 5. Location: North Pole, area: 3,975 sq. km, concentration O: 46-47%, concentration H: 160-189ppm. Source: created map.

AREA 6 (88.3°N, 52.6°E)

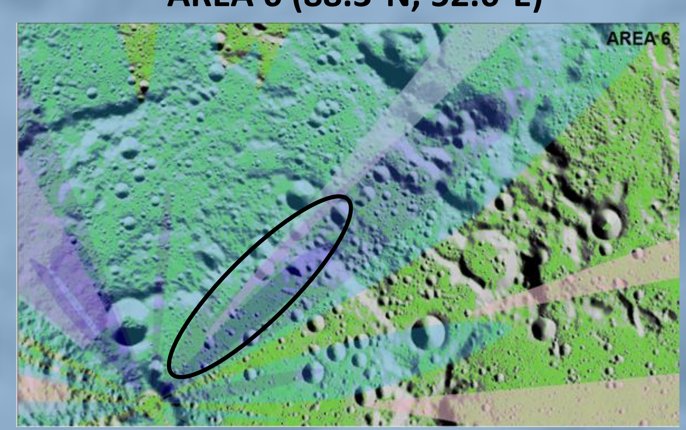

Figure 9: AREA 6. Location: North Pole, area: 2,769 sq. km, concentration O: 45- 46%, concentration H: 160-189ppm. Source: created map.

AREA 7 (84.2°N, 179.6°W)

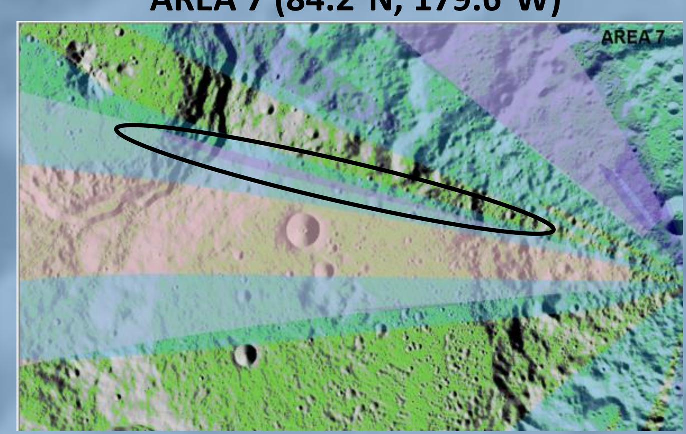

Figure 10: AREA 7.Location: North Pole, area: 4,218 sq. km, concentration O: 45-46.%, concentration H: 189-217ppm. Source: created map.

Table 1. Economic Feasibility. Potential Initial Payload from Apollo 15: 46,782 kg. LOX (liquid oxygen) and LH2 (liquid hydrogen)

	Atlas V	Saturn V	Delta IV	Delta IV Heavy	Delta II	Falcon 9	Falcon Heavy	SLS
Fuel Used	LOX/LH2	LOX/LH2	LOX/LH2	LOX/LH2	LOX/RP-1	LOX/RP-1	LOX/RP-1	LOX/LH2
Payload to LEO(kg)	9.8-18.8 x 10^3	118.0-140.0 x 10^3	9.4-28.8 x 10^3	26.0 x 10^3	2.7-6.1 x 10^3	22.8 x 10^3	54.4 x 10^3	70.0-130.0 x 10^3
Payload to GTO(kg)	4.8-8.9 x 10^3	N/A	4.4-14.2 x 10^3	14.0 x 10^3	0.9-2.2 x 10^3	8.3 x 10^3	22.0 x 10^3	N/A
Payload to TLI(kg)	N/A	48.6 x 10^3	8.9 x 10^3	10.0 x 10^3	N/A	17.2 x 10^3	16.0 x 10^3	39.0-45.0 x 10^3
Mass fully fueled(kg)	.33 x 10^6	3.0 x 10^6	.23 x 10^6	.73 x 10^6	.23 x 10^6	1.4 x 10^6	1.4 x 10^6	1.0 x 10^6
Fuel Capacity(kg)	.28 x 10^6	2.7 x 10^6	.20 x 10^6	.66 x 10^6	.21 x 10^6	1.2 x 10^6	1.3 x 10^6	0.9 x 10^6
Cost of mission($)	109.0 x 10^6	1160.0 x 10^6	164.0 x10^6	435.0 x 10^6	51.0 x 10^6	61.2 x 10^6	100.0 x 10^6	500.0 x 10^6
Status	Active	Retired	Active	Active	Active	Active	In development	in development
Cost of Fuel($)	.21 x 10^6	2.0 x 10^6	.15 x 10^6	.49 x 10^6	.19 x 10^6	1.2 x 10^6	1.2 x 10^6	.66 x 10^6

V. Results

- In the completed map, the created layers were overlaid and compared. It was observed that the lunar poles had the highest abundance of hydrogen and oxygen.
- After further analysis of the North and South Poles, seven areas with the highest concentrations of hydrogen and oxygen were highlighted to be the best locations for lunar ice mining. All areas had a slope ≦6°.
- Area 1 was determined to be the most optimal area to mine, as it had the highest concentration of both oxygen and hydrogen, and an ideal slope.
- Areas 2-7, found on the North and South Poles, were less optimal as they had lower concentrations of hydrogen and oxygen. For example, Area 6 had the second highest concentration of both hydrogen and oxygen, rather than containing the highest of at least one, making it the least feasible to mine of the selected areas.
- Based on our criteria, economic feasibility was calculated to determine if a mining mission would be cost/fuel efficient. An initial payload from Apollo 15 was used to model, as Apollo 15 was a human-based, scientific mission that best fit our criteria. After careful analysis of the table, the Space Launch System was decided to be the most feasible option, as it could carry a similarly-sized payload with the lowest cost/fuel used per mission, and could sustain human life.

VI. Implications

- Launching spacecraft from the Moon would only require 1/6 of the energy as launching from Earth due to the Moon's thinner atmosphere and weaker gravity. The prospect of lunar mining could lead **to reduced fuel costs and energy used,** because lunar ice would be used as a fuel source, meaning that the fuel source would not have to be transported from Earth.
- Lunar mining could also sustain scientific missions. The **South Pole-Aitken Basin** is an area of interest for scientists and could give insight as to how the Moon formed. Lunar ice mining could potentially **sustain a lunar base** near the South Pole-Aitken Basin, drawing from the nearby South Pole water ice deposits to **use as coolant or to create breathable oxygen** to sustain human life.

VII. Conclusion

The purpose of this study was to **determine possible locations for a lunar ice mining mission** based on topographic, economic, and elemental data. Seven areas between the north and south poles were highlighted to be feasible for mining, as they contained **high H- and O-concentrations** and a **low slope.** Economically, the **Space Launch System** was determined to be the best rocket to use for a lunar mining mission. Plotting these areas through ArcGIS enables scientists to have a **clearer understanding of the exact locations of lunar ice deposits** through coordinate data and layer comparisons. As more technological advancements take place, it will become easier to verify these results and obtain more data outlining the locations of these deposits.

Selected References: [1] Durda, D. D. (2007). South pole aitken base (D. A. Kring, Ed.). Retrieved from Center for Lunar Science and Exploration database. [2] Lucey, P. G. (2009). The poles of the moon. *Elements*, *5*, 41-46. [3] Speyerer, E. J. and Robinson, M. S. (2012). Persistently illuminated regions at lunar poles: Ideal sites for future exploration. *Icarus, 222*(2013) 122-136. [4] Steigerwald, B. (Dec. 20, 2016). NASA's LRO discovers lunar hydrogen more abundant on moon's pole-facing slopes. URL: *https://www.nasa.gov/content/goddard/lro-lunar-hydrogen*

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