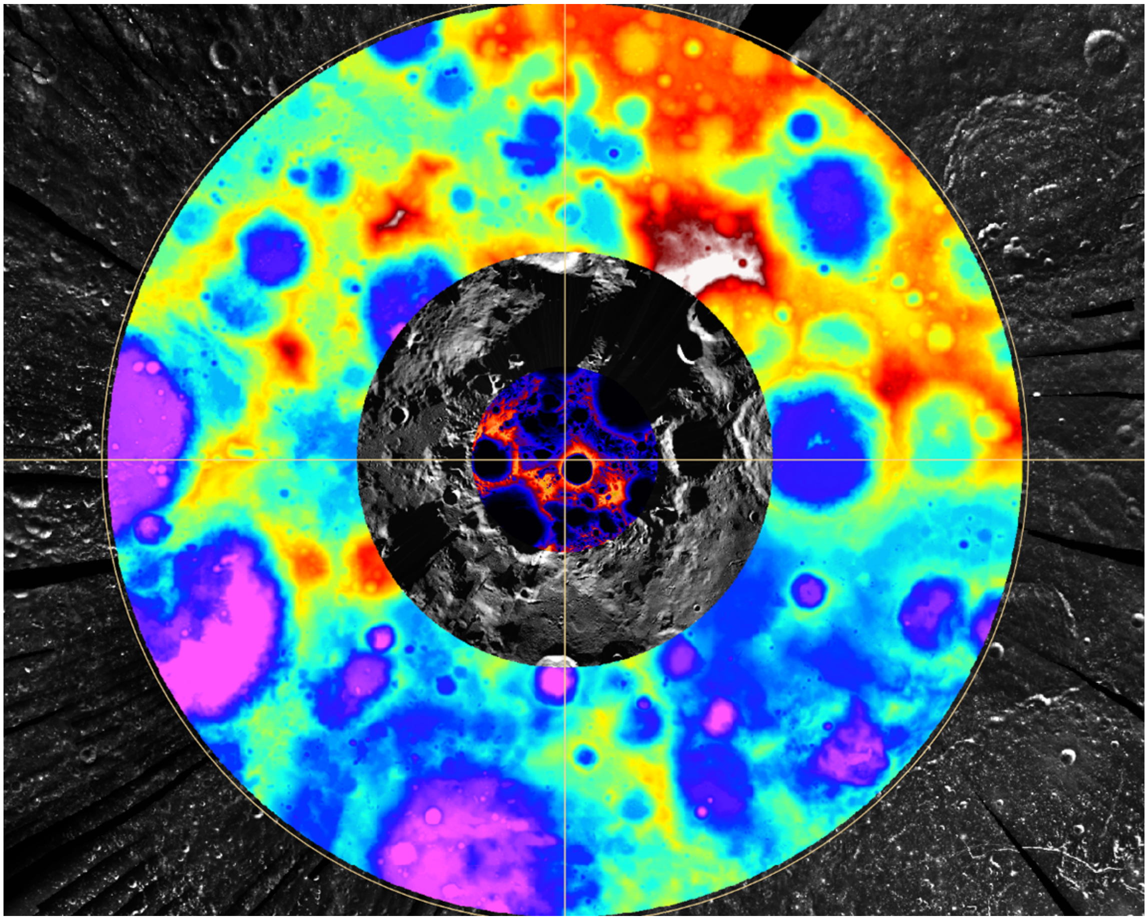
Final Report of the Lunar Critical Data Products Specific Action Team

A Joint Lunar Exploration Analysis Group (LEAG) - Mapping and Planetary Spatial Infrastructure Team (MAPSIT) Specific Action Team



(Data layers for the Moon’s south polar region from LRO Mini-RF, LOLA, LROC NAC, and LROC WAC illumination percent; rendered by Quickmap)

30 September 2021

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Summary

The success of human and robotic precursor missions to the lunar surface requires the use of lunar datasets from past and current orbital missions. The two analysis groups (AGs) with the relevant domain expertise for planetary cartography and lunar exploration, the Mapping and Planetary Spatial Infrastructure Team (MAPSIT) and the Lunar Exploration Analysis Group (LEAG), were requested and empowered to establish the Lunar Critical Data Products Specific Action Team (LCDP-SAT) by NASA's Science Mission Directorate (SMD) Planetary Science Division (PSD) and Human Exploration Mission Directorate (HEOMD[1]) to respond to several recommendations laid out in the Artemis III Science Definition Team (SDT) report (NASA, 2020a).

The SAT's approach was first to establish an understanding of currently available lunar spatial data (i.e., those that can be placed in a geographic context on a lunar map) and to identify potential critical gaps in those data or their discoverability, accessibility, and useability that could hinder planning for, or affect the safety of, upcoming human and precursor missions to the lunar south polar region. The Artemis III SDT report defined the south polar region as within six degrees of the pole, and this is the area currently planned as the home of the Artemis Base Camp (NASA, 2020a). NASA's Plan for Sustained Lunar Exploration and Development (NASA, 2020b[2]) provides a set of six proposed notional surface exploration zones for early Artemis landings that have a high degree of illumination identified in previously published work (Mazarico et al. 2011). Both site 001 and the site informally called Malapert massif (85.8° S, 356.4° E) were previously Project Constellation regions of interest (Gruener and Joosten, 2008), and, thus, they were a focus of data collection by the Lunar Reconnaissance Orbiter (LRO) during the early exploration mission phase. The sites outlined in the NASA Plan for Sustained Lunar Exploration and Development are also accessible by missions staged from the Gateway's planned orbit (Whitley et al., 2018).

The LCDP SAT's goals, as set forth in the terms of reference, stem primarily from the recent Artemis III SDT report (NASA, 2020a) recommendations, but are also influenced

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[1] The terms of reference laid out by HEOMD preceded its division into two directorates on September 21, 2021, as the Exploration Systems Development (ESDMD) and the Space Operations (SOMD) mission directorates.

[2] NASA's plan for sustained lunar exploration and development. Online version at https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf.

by the recent Planetary Data Ecosystem Independent Review Board report (2021[3]), the Lunar Surface Science Workshop (Session 6) on Foundational Data Products (2020[4]), recent community efforts and publications on the management of data over the long-term (e.g., Hare et al., 2021; Laura and Beyer, 2021; Laura et al., 2018), and experience stemming from past and currently active NASA lunar missions and the Commercial Lunar Payload Services (CLPS) program. The LCDP-SAT leverages expertise from the two most relevant AGs: LEAG and MAPSIT; membership was drawn from within the two AGs. Because of the urgency of the requested assessment, the LCDP-SAT activities were carried out virtually over a two-month period from August to September 2021. Additional input was requested from several invited speakers. The broader lunar and data communities were invited to comment on preliminary findings, which were presented at the annual meeting of the LEAG (held virtually 31 August through 2 September 2021). The final report was delivered to NASA on 30 September 2021. Documents from the LCDP-SAT can be found on the MAPSIT website[5]. The high-level goal of this report is to aid NASA in prioritizing resources for the development and planning of upcoming lunar missions, particularly to the south polar region, in an efficient way that will also facilitate future exploration and data preservation and useability.

Successful planning for, and data types identified for, the Moon's upcoming south polar exploration will likely have important linkages to landings elsewhere, and are, in many cases, useful in a broader context. For example, global improvements, methodology, tools, or new data sets created to support south polar landings can be useful for landings at any location across the lunar surface. In this report, we begin with an assessment of the south polar data products most relevant to the near-term landings there. In the later sections, we continue with a broader discussion to include non-polar data as well as the steps that can be useful in framing a lunar planetary spatial data infrastructure (PSDI, or lunar SDI).

Planetary Data Terminology

In crafting this report, we found it necessary to establish the definitions of certain types of data and their geodetic (or selenodetic) control, generally adopting the terminology

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[3] An online copy of the 2021 Planetary Data Ecosystem Independent Review Board report can be accessed here: https://science.nasa.gov/files/science-pink/s3fs-public/atoms/files/PDE%20IRB%20Final%20Report.pdf

[4] An archived copy of the 2020 Lunar Surface Science Workshop Session 6 report can be accessed here: https://lunarscience.arc.nasa.gov/lssw/downloads/Workshop-Report_LSSW-Virtual-Session-Six--Foundational-Data-Products.pdf

[5] https://www.lpi.usra.edu/mapsit/standup-committees

described in Laura and Beyer (2021) for **foundational data** and other spatial data products (**framework data**).

A foundational data product is one that has broad relevance to a large degree of other spatial data sets and ideally has rigorous spatial error assessment and description available. Put simply, it is a data set that has been rigorously transformed from direct observations into a geospatial product that maintains accurate spatial relationships, preferably with well-quantified uncertainty. Some products currently being used as foundational data have general (e.g., global, or approximate) as opposed to detailed uncertainty information. Foundational data products may be global or cover smaller regions. A foundational data product is tied to a specific reference coordinate system and frame and may also be used to define a coordinate frame.

Although the terms **coordinate system** and **coordinate frame** are often used interchangeably, they have specific meanings. A reference coordinate system is an overall concept, including the physical environment, theory, and conventions forming an idealized model to allow the location of features on a body. A reference coordinate frame is a specific realization of a system; for example, a solution that defines the coordinates of points (usually in spherical coordinates of latitude and longitude or Cartesian *x*-, *y*-, and *z*- coordinates) on a body based on observational data (Kovalevsky and Mueller, 1981).

For the Moon, as explained in more detail below, the mean Earth/polar axis (ME) coordinate system is the current lunar reference coordinate system and the JPL DE 421 lunar orientation ephemeris rotated to the ME system is the currently recommended reference coordinate frame. The ME system inherently defines the direction of north and the equator, and the system usually includes a separate definition for longitude direction. The IAU Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE), for historical reasons, continues to recognize both -180° west to +180° east longitude for the Moon, as well as 0° to 360° east longitude (Archinal et al., 2018), with the latter being used by the LRO mission based on recommendations of the (now dormant) Lunar Reconnaissance Orbiter Data Working Group (LDWG) and NASA Lunar Geodesy and Cartography Working Group (LDWG and LGCWG, 2008). For the vertical frame in the ME system, a spherical reference surface with radius 1737.4 km is recommended; this surface provides a reference for measuring elevation and for providing a scale for map projection.

Once a foundational dataset is tied to the defining reference frame, it may serve as a proxy for that frame. For example, the Lunar Orbiter Laser Altimeter (LOLA) global Digital Elevation Model (DEM) (Smith et al., 2017) has been created using the JPL DE421 ME frame and provides a topographic surface that other data can in turn be referenced to.

The height of this surface is given in separate products from both the center of the Moon and the reference sphere.

Framework data can be transformed, to improve positional accuracy, by controlling (e.g., via a least-squares photogrammetric, radargrammetric, or altimetric solution) to a foundational data product that either is, or has been tied to, a reference frame. The absolute positional uncertainty of a **controlled data product** is tied to the absolute uncertainty associated with the data set referenced as control. A **control network** is a collection of tie points that identify common features between data sets or images that can be used to control different data sets to each other. **Semi-controlled** data are generally products of warping or "rubber-sheet" georeferencing to another data product, which reduces positional errors but is not rigorous. **Uncontrolled** data have not been transformed to minimize positional errors (as an example, uncontrolled image mosaics can have seams, duplicated landforms, and other imprecisions). An **orthographically rectified image (orthoimage)** or image mosaic (orthoimage mosaic) is one that has been controlled using both horizontal and vertical data (*x-, y-,* and *z-* coordinates) and projected into an orthographic map projection for two-dimensional representation. The control for orthoimages that provides the best positional accuracy will be performed to a reference frame using the best available DEM to correct for errors associated with elevation differences, and the absolute spatial accuracy of the controlled product can be well-described.

Artemis III SDT Report Recommendations

The following recommendations, directly from the Artemis III SDT report (NASA, 2020a), guide the goals of the LCDP SAT, and are included here for reference:

Recommendation 8.2-1: Any needed updates to the standard lunar geodetic coordinate reference frame (e.g., currently used by the Lunar Reconnaissance Orbiter (LRO)) should be identified in 2021, and foundational products should be mapped onto it and/or developed to use it directly. Establishing a standardized coordinate reference frame can significantly improve data reliability and reduce the risk of errors.

Recommendation 8.3-1b: To support the level of accuracy and precision needed for landing and surface operations, new cartographic products, including mosaics and topographic models, for the south pole should be developed using the highest quality data available (e.g., LRO NAC and WAC frames; SELENE/Kaguya Terrain Camera (TC), SELENE/Kaguya Multiband Imager (MI), and Chandrayaan-1 Moon Mineralogy Mapper (M^3)) and using the standard (possibly updated) lunar geodetic coordinate reference frame.

Recommendation 8.3-1c: New derivation of higher-order data products from existing missions should also be supported where needed for Artemis III. For example, it is vital that more detailed geologic mapping of candidate landing sites be accomplished at a scale similar to what was done in preparation for Apollo.

Recommendation 6.5-1b: LEAG and CAPTEM serve an important community role synthesizing community input across diverse stakeholders in the engineering, science, and commercial communities, and should be leveraged as the program continues to promote external community engagement to the fullest practical extent.

LCDP-SAT Terms of Reference

The LCDP-SAT was established by the NASA HEOMD and SMD PSD to engage the LEAG and MAPSIT communities to begin the process of responding to the Artemis III SDT recommendations listed above. The LCDP-SAT was tasked to present non-binding findings to NASA in the form of a final report. Draft findings were due 3 September 2021 and were presented at the Annual LEAG Meeting for open comment. A final report was due 30 September 2021. The LCDP-SAT executed the following functions on a best-effort basis, considering the timeframe in which the upcoming Artemis and commercial activities will occur:

1a. Based on the outcomes of the Artemis III SDT report, summarize the current lunar coordinate reference schema and practices known to be employed by active NASA lunar flight missions.

1b. Assess whether any updates to the standard lunar geodetic coordinate reference frame (e.g., currently used by LRO mission teams) are required or highly desirable to enable near-future a) safe landings on the lunar surface, b) successful surface operations by humans and spacecraft for science, exploration, or economic development, or c) to maximize the science obtained from current and upcoming lunar datasets.

2. The SAT will assess and prioritize what new mission-derived cartographic products, including mosaics and topographic models, for the south pole region (prioritizing proposed Artemis III landing sites) could be developed to facilitate science or exploration using the highest quality data available (e.g., LRO Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) and Wide Angle Camera (WAC) images, SELENE/Kaguya TC and MI, and Chandrayaan-1 M^3). It is understood that some number of these might need to be created to support early human landed missions and surface operations, robotic precursor missions, as well as early commercial activity on the lunar surface.

3. The team will assess and prioritize which higher-order data products, such as geologic maps or resource availability maps, need to be created to support early human landed missions and surface operations and any robotic precursor missions as well as early commercial activity on the lunar surface near the south pole.

4. Assess, in a general sense, what new mission-enabling data or products (including maps) may be required from existing or future orbital and surface assets within the south pole region and beyond.

5. Assess the general availability and accessibility of lunar data as well as tools to evaluate and analyze data for the science community, the Artemis program, and the general public.

6. While the focus of this activity will be on identifying specific critical data products per the recommendations of the Artemis III SDT, the team is also requested to issue non-binding findings detailing preliminary steps to catalog/register for the discoverability of existing data products; the development of standards and best practices on how to characterize, report, and represent uncertainty and distortion within data; and the longer term considerations of establishing a lunar PSDI (including benefits, maintenance, and evolution).

Membership

Chairs

- Angela Stickle (Johns Hopkins Applied Physics Laboratory)
- Julie Stopar (Lunar and Planetary Institute/USRA)

Regular Members

- Brent Archinal (USGS Astrogeology Science Center)
- Maria Banks (NASA Goddard Space Flight Center)
- Ross Beyer (SETI & NASA Ames)
- Lisa Gaddis (Lunar and Planetary Institute/USRA)
- Trent Hare (USGS Astrogeology Science Center)
- Jose Hurtado (University of Texas at El Paso)
- Samuel Lawrence (NASA Johnson Space Center)
- Myriam Lemelin (Université de Sherbrooke)
- Pete Mouginis-Mark (University of Hawaii)
- Noah Petro (NASA Goddard Space Flight Center)
- Emerson Speyerer (Arizona State University)
- Jean-Pierre Williams (UCLA)
- Kelsey Young (NASA Goddard Space Flight Center)

Ex-officio Members

- Sarah Noble (NASA HQ)
- Jacob Bleacher (NASA HQ)
- Rebecca McCauley-Rench (NASA HQ)
- Amy Fagan (LEAG chair, Western Carolina University)
- Brad Thomson (MAPSIT chair, University of Tennessee)

Outcomes

1. Lunar Coordinate Systems and Frames

Summarize the current lunar coordinate reference schema and practices known to be employed by active NASA lunar flight missions. Determine if any updates to the standard lunar geodetic coordinate reference frame is required or highly desirable to enable near-future landings, surface operations, and maximize science.

The mean Earth/polar axis (ME) system (sometimes called the mean Earth/mean rotation (MER) system) has been used for centuries as the coordinate reference system for making cartographic products of the Moon (Davies and Colvin, 2000). The 2008 JPL DE 421 ephemeris (Folkner et al., 2008, 2009; Williams et al., 2008), as rotated into the ME system, currently serves as the fundamental horizontal reference frame for the Moon, following LDWG and LGCWG (2008) recommendations, and later IAU WGCCRE (Archinal et al., 2011, 2018). A spherical radius of 1737.4 km has served to define a vertical reference frame since being specified by the IAU WGCCRE in 1989 (Davies et al., 1989). Thus, most – if not all – modern lunar data are based in the ME system and these horizontal and vertical frames.

Not yet addressed by any past or current standards group are recommendations for a lunar geoid. A future lunar standards or lunar spatial data infrastructure group may choose to make recommendations regarding a lunar gravity field that could be used to define a geoid and allow for calculations of equipotential height differences for the Moon. The most recent lunar gravity field model is the GRGM1200B (Goossens et al., 2020), which was produced using data primarily from the Gravity Recovery and Interior Laboratory (GRAIL) mission (Zuber et al., 2013).

Findings:

[1] Currently the Lunar Reconnaissance Orbiter (LRO) mission and International Astronomical Union (IAU) standards use the lunar ME system, a 1737.4 km lunar radius, and the 2008 JPL DE 421 ephemeris rotated to the ME system as the lunar coordinate frame.

[2] Because it would be beneficial to utilize an updated reference frame based on the latest ephemeris, NASA's upcoming missions and data providers should consider adopting the 2021 DE 440 ephemeris rotated to the ME system going forward. A lunar mean Earth/polar axis (ME) coordinate reference system with the **2021 JPL DE 440** ephemeris in that system represents the best available option for upcoming mission planning and data analysis activities.

[3] The new 2021 JPL DE 440 ephemeris in the ME system shows differences that are generally less than 1 meter compared with the 2008 coordinate reference frame. Because of the small difference, there is no urgent need to recompute existing data products.

[4] To avoid any possible confusion, by standard practice, provenance information including the reference system and frame must be provided with data products.

[5] Laser ranging (both at new sites and established sites) and new Very Long Baseline Interferometry (VLBI) observations of active radio transmitters on the lunar surface would support the continued improvement of the fundamental lunar reference frame and data tied to it, serve as navigational benchmarks, and aid in fundamental scientific investigations.

Rationale:

There is a newly available 2021 JPL DE 440 ephemeris and parameters to rotate it into the ME system (Park et al., 2021). Information provided by Ryan Park and Boris Semenov (JPL) indicates that the differences in position in the lunar ME frame using the 2008 JPL DE 421 ephemeris compared to the 2021 JPL DE 440 ephemeris are less than a meter and typically half a meter or less (personal communication to B. Archinal, 2021). This small difference facilitates a practical changeover between use of these ephemerides, allowing older data based on the 2008 JPL DE 421 ephemeris to remain useful without an update, but also allowing new work going forward to be based on the new, more accurate ephemeris.

Thus, in response to *Recommendation 8.2-1* of the Artemis III SDT report, the updated horizontal lunar frame that should be adopted in mission planning and data analysis activities going forward is one based on the 2021 JPL DE 440 ephemeris and rotated to the ME system. However, due to the small difference with respect to the lunar ME frame realization based on the 2008 JPL DE 421 ephemeris, there is no urgent need to recompute existing data already in the current frame. Typically, positional accuracies for the finest scale data products are refined through either photogrammetric or altimetric adjustments. For example, LROC mosaics and DEMs, and gridded LOLA DEMs and associated data products, achieve excellent results using photogrammetric (LROC) or altimetric (LOLA) adjustment processes, and the differences between the *a priori* ephemerides will not have a significant impact on the resultant data product.

The main benefit of adopting the new horizontal frame primarily would be a slight (pixel scale) improvement in *a priori* positioning of higher resolution datasets, such as LROC NAC and the Chandrayaan-2 Orbiter High-Resolution Camera (OHRC) images, as well as slight improvement in the *a priori* positions of LOLA laser shots. Although the current primary limitation on *a priori* positioning of such products is spacecraft pointing and, to a lesser extent, spacecraft positioning information, the improvement in the knowledge of the lunar frame (orientation) should be systematically beneficial when considering measurements and positioning at the sub-meter level. It will also prepare for the possible, if not likely, future adoption of the new horizontal frame by others outside of NASA, including independent investigators, other U.S. government agencies such as the National Geospatial-Intelligence Agency, international instrument teams and missions, and the IAU WGCCRE.

One possible disadvantage in adopting the new horizontal reference frame is that there may be confusion when comparing between datasets, particularly those of high resolution, prepared with different references. Thus, by standard practice, it is critical that provenance information including the reference system and frames be provided with data products. It is crucial that data product developers provide adequate provenance information to permit the successful use of geospatial data and to allow data users to be aware of the aspects and potential uncertainties associated with a product before it is used. Provenance information should include the methods of geodetic control, reference system and frames, and method of topographic rectification. While the overall differences between data referenced to the old and new frames will be less than one meter, uncontrolled (unadjusted) mosaic products with a higher resolution than this may show differences.

The Artemis III SDT report (NASA, 2020a) recognizes the importance of lunar laser ranging (LLR; Mueller et al., 2019) for investigations of the Moon's interior structure and the existence of an inner core (SDT Goals 1a, 1b) and for tests of general relativity (SDT Goal 5a). LLR and VLBI (e.g., S/X-band) (Slade et al., 1977) observations of appropriate radio transmitters on landers or rovers are also needed to support the continued improvement of the fundamental lunar reference frame and to monitor changes in the Moon's orientation, as well as the SDT recommended tasks of solving for parameters regarding the interior structure of the Moon and general relativity. Such observations can be used to tie high-resolution image and lidar data to the lunar reference frame, by locating the retroreflectors or radio beacons in the data (Archinal et al., 2010). Such surface targets could be used as benchmarks for orbital or surface optical or radio navigation services. For LLR, retroreflectors can be constructed at relatively low cost compared to other science instruments, can be observed passively, and observations can be continued in the far future, with the Apollo 11 retroreflector array still being usable more than five decades after its deployment.

The LLR and VLBI observations serve as orthogonally independent data sets (providing range and angular information respectively), and the VLBI observations can additionally provide a direct connection between the lunar reference frame and the (quasar radio source based) International Celestial Reference Frame 3 (ICRF3; Charlot et al., 2020). Therefore, it is important to continue the collection of LRR data from terrestrial stations, and to deploy new retroreflectors on the lunar surface and collect data from them as well, both from the Earth or orbiting spacecraft. It will also be necessary to continue to support operation of terrestrial stations and the processing of LLR and VLBI data. Our findings here agree with the Artemis III SDT report *Recommendation 6.2.4-1b* about the use of LLR for geodetic monitoring of the Artemis III site, and the use of interferometry to "complement the laser ranging technique" (SDT Section 6.2.1).

2. Critical New Foundational Data Products for the South Pole

Assess and prioritize any new mission-derived cartographic products, including mosaics and topographic models, that could be developed for the south pole region using the best currently available data.

There are several types of possible **foundational data products**, including coordinate reference frames, elevation data or topography, and orthographically rectified images (or orthoimages), any of which have a rigorous spatial error assessment (Archinal et al., 2018; Laura and Beyer, 2021). Foundational data products form the basis for mission planning, reconnaissance, and *in situ* mapping, landing, and surface operations. Other geospatial data (i.e., **framework data products**) and image mosaics are controlled by registering their data to a foundational topographic data product, which in turn is referenced against a foundational reference frame. Here we focus on the most essential inputs used in mission planning for the lunar south polar region, specifically elevation or topographic data and reference image mosaics derived from best-available data (e.g., those with the densest elevation points, least uncertainty, or highest spatial resolution). (The many other existing and possible framework data products and derived higher-order products are discussed later in task 3).

Findings:

[6] It is crucial that foundational (and other) data products are paired with adequate metadata and description, including provenance and an assessment of potential sources of uncertainty and error, to permit their successful use and to allow users to be aware of these aspects. Provenance information should include the methods of geodetic control, reference system and frames, method

of topographic rectification, and methods of radiometric and cartographic processing (including any resampling or interpolation).

[7] The generation of additional high-spatial resolution topographic products (e.g., 1-m Shape-from-Shading (SfS, also known as photoclinometry), 2- to 5-m LROC NAC DEMs, and 5-m LOLA DEMs) at high-priority locations where they do not already exist would be highly beneficial to ongoing planning efforts and science analyses.

[8] Of higher near-term priority are release of image mosaics with the best available resolution, for example the 2048 pixels/degree Mini-RF south pole mosaics (awaiting release to NASA's Planetary Data System or PDS) and development of new, controlled LROC NAC mosaics (1 m/pixel or best-available resolution).

[9] New, consistently controlled, high- to moderate-spatial resolution reference image mosaics and topography (e.g., international datasets like SELENE/Kaguya TC, Chang'E 2 CCD Camera, and Chandrayaan-2 Terrain Mapping Camera-2 or TMC-2) might also be beneficial but are of lower priority for landing site evaluations.

[10] Upcoming missions should agree on best practices for control and mosaicking, and standardize data formats to facilitate data interoperability.

[11] If resources are available, it would be beneficial to produce longer-term efforts to produce globally controlled foundational products, from both new and older data sets, using the most recent or agreed-upon reference frame, which would reduce processing time, provide additional references for controlled data products, and improve analyses overall for upcoming studies and facilitate planning for future landed missions. It is understood these products would likely not be available for near-term landings.

Rationale:

Foundational elevation data and reference image mosaics are necessary to select landing sites, characterize them in detail, and plan surface activities. As foundational data products, they might be controlled to either a global reference or to a local or regional reference for specific purposes. To support the accuracy and precision needed for upcoming landings, and in keeping with the Artemis III SDT *Recommendation 8.3-1b*, new mosaics and topographic foundational data products should be developed for the lunar south pole and other high-priority locations using the standard (i.e., slightly updated) lunar reference frame and, whenever possible, controlled to an agreed-upon foundational topographic data product.

Controlling image mosaics reduces seams and dislocations between images. One of the more widely used global image mosaics is the LROC WAC morphologic product (Wagner et al., 2015); several other WAC mosaics are also available in the NASA PDS for the globe as well as the south pole. The WAC mosaics are often used as a reference, or positional control, for other LRO products. Due to careful calibration and the use of refined LRO spacecraft position and orientation data, they are likely accurately located to better than the pixel (100-m) level but have not been fully controlled to a foundational topographic product.

There are several existing global foundational topographic products to use as control for data; the global LRO LOLA DEM (Smith et al., 2017) and the global SLDEM2015 (Barker et al., 2016) are the more recent, and both are sampled to 512 pixels per degree (~60 m/pixel at the equator). Examples of existing high-resolution topographic products are detailed below; however, additional products of these types are still needed for many possible high-priority areas in both the near-future and longer-term. Meter-scale products are particularly important as they would improve knowledge of topography at scales needed for extravehicular activities (EVAs) and traverses. If rigorously produced, high-resolution topographic products can also serve as foundational data products, and precise control for other data sets, as well as for landings and site evaluations.

The LOLA (Smith et al., 2010; Smith et al., 2017) is a laser ranging system that provides precise lunar topographic measurements. Individual tracks of LOLA observations provide 25-m spacing with a five-shot laser pattern projected onto the lunar surface. Gridded products are interpolated between these tracks. These are available as LOLA gridded data records (GDRs) via the PDS and are foundational topographic data (i.e., DEMs) for the Moon’s poles. Besides global products, there are products with 20-m grid spacing for both poles within 10° of the poles, 10-m grid spacing within 5° of the poles, and 5-m grid spacing within 2.5° of the poles. There are several local and regional south pole LOLA DEMs with improved accuracy and pixel scales of 5 m/pixel (Barker et al., 2021). The Barker et al. (2021) method improves upon the original 5-m LOLA products by including fewer outliers and better error characteristics. While representing some of the best available topographic data, users should be aware of the pixel interpolation.

LROC NAC images with appropriate stereo viewing geometry can be used to create terrain models with pixel scales down to 2- or 5-m, depending on the characteristics of the individual images (Henriksen et al., 2017). LRO’s orbit has changed over the lifetime of the mission, and the orbit is drifting slowly from the poles, making collection of new high-resolution stereo image data more difficult over the polar regions. Additional options might be investigated to make further use of older images with stereogrammetry as well as for acquiring new stereo images. For example, new NAC images might potentially be used to produce DEMs with 15-m, or coarser, scales.

Photoclinometry or SfS terrain models can be created from a much broader set of images than strict pairwise stereogrammetry (see Alexandrov and Beyer, 2018, for a review). This technique works well at the poles where there is a limited range of incidence angles if there is a very wide range of illumination azimuths resulting in a sizable amount of the surface being illuminated from several directions. Given a large enough collection of LROC NAC images with input scales of 1 m/pixel, terrain can be derived at 1 m/pixel. Such models benefit significantly from a high-resolution DEM as part of the inputs because the absolute RMS error is identical to the input DEM upon which it is registered. However, relative errors are generally less than ten centimeters. The images used must be controlled to each other and it is useful to have any available lower resolution DEM (such as from LROC NAC stereo images or a LOLA gridded product) for calibration purposes.

There are a variety of additional useful foundational data products and reference image mosaics that could be generated from medium- to high-spatial resolution data sets, as resources permit, to facilitate analyses of upcoming landing sites. Recent listings of currently available (as of publication) foundational and framework data products for the Moon along with some information on their reported resolution, source, and uncertainty are provided in Laura and Beyer (2021) and the 2020 Lunar Surface Science Workshop on Foundational Data Products[6]. Highly-beneficial new products in the near-term include consistently controlled, high-spatial resolution image mosaics from the LRO Mini-RF instrument and the LROC NAC. International mission image mosaics of potential interest include SELENE/Kaguya TC (Haruyama et al., 2008), Chang’E 2; (Wu et al., 2020), and Chandrayaan-2 Terrain Mapping Camera-2 (TMC-2) and Dual-frequency Synthetic Aperture Radar (DFSAR) (Chowdhury et al., 2020a; Bhiravarasu et al., 2021). These image mosaics, if consistently controlled, would provide additional views of the surface. Several radar image mosaics of the lunar poles have been created using Mini-RF data that can “see” into permanently shadowed regions (PSRs), with scales up to 2048 pixels per degree and include east-looking and west-looking products (Kirk et al., 2013). These mosaics are controlled to the LROC WAC mosaic and are awaiting delivery to NASA’s PDS. They are presently available to view in the Quickmap tool online, but these should be delivered to the PDS as soon as possible.

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[6] An archived copy of the 2020 Lunar Surface Science Workshop Session 6 report can be accessed here: https://lunarscience.arc.nasa.gov/lssw/downloads/Workshop-Report_LSSW-Virtual-Session-Six--Foundational-Data-Products.pdf

Additional terrain models of potential interest include SELENE/Kaguya TC DEMs (~10 m/pixel stereo; Haruyama et al., 2008), Chang'E 2 DEM (~7 m/pixel stereo; Zuo et al., 2014), and the currently operating Chandrayaan-2 TMC-2 DEM (~5 m/pixel stereo and 15-m post spacing of the DEM; Chowdhury et al., 2020a). These data still need to be fully assessed for suitability and availability from their originating organizations before prioritizing NASA investments in new products from international missions.

To be used by the broadest possible audience, any new data products should be controlled using a common foundational product and reference frame whenever practical. With the high number of upcoming missions and stakeholders, data providers should standardize on best practices (e.g., controlling to LOLA 5-m DEMs) to facilitate data interoperability. It is understood that some data types, by necessity, use a different coordinate reference system. Controlled data is recognized as the best practice for geospatial products (and is the default for most terrestrial products), and is recommended for Solar System bodies (e.g., NASA Advisory Council, 2007[7], 2008). Adequate control is considered the cornerstone of modern “analysis ready data" and should continue to be the standard by which data are produced to support scientists, engineers, and explorers. New data products should be generated using methods consistent with the generation of foundational data products, including adequate metadata and description, and be made widely accessible to data users with detailed information on uncertainty and provenance.

Globally controlled products have long-term benefits including reducing processing time for landing site and surface operations analyses and facilitating comparisons between datasets. Longer-term efforts to produce globally controlled foundational products, from both new and older data sets, updated to the most recent or agreed-upon reference frame would generally make data more analysis-ready and would reduce future processing time, provide additional references for controlled data products, and improve analyses overall for upcoming studies. However, because of the large effort involved in making and updating global data sets, these data would likely not yet be available for upcoming landings in the immediate near-term.

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[7] Recommendation S-07-C-13 of the NASA Advisory Council to NASA Administrator Griffin, p. 14, see http://bit.ly/x0HnnM for Internet Archive copy (formerly available at http://www.hq.nasa.gov/office/oer/nac/reccommendations/Recommend-5-07.pdf)

3. Critical New Derived Data Products for Near-future Missions to the South Pole

Assess and prioritize which higher-order data products need to be created to support early human landed missions and surface operations, robotic precursor missions, and commercial activity on the lunar surface near the south pole.

Framework data products – such as multi-spectral and hyperspectral image mosaics, measurements of surface properties, and higher-order derived data including geologic, model-based, or thematic maps – are controlled by registering their data to a foundational topographic data product, which is itself referenced against a foundational reference frame. Maps and mosaics based on measurements and models help to characterize the lunar surface and environment and are necessary for ensuring selection of safe landing sites that meet the scientific and engineering goals of each mission, including those of Artemis. These maps are also crucial for planning surface operations, including traverses and EVAs away from the landing sites. Higher-order data products necessary for science and mission planning for the south polar region include, but are not limited to: geologic and geomorphologic maps; surface mineralogy; soil maturity; regolith grain size (and other geotechnical properties); temperature at and near the surface; terrain roughness, slope, and aspect; hazard maps, including the distribution of impact craters and boulders; maps of potential science targets, such as boulder locations and outcrops; time-dependent models of illumination conditions, including permanent shadows, transient shadows, and illuminated areas; communication lines-of-sight (both to points on the lunar surface as well as between the Moon and Earth); radiation hazards for surface operations; and resource maps.

Findings:

[12] New controlled LROC NAC image mosaics with early-morning illumination angles matching the time and date of targeted landing would be highly beneficial in evaluating sites for planning near-future landings.

[13] New controlled multi- and hyperspectral image mosaics are essential for mapping surface color and composition. Such mosaics, with the best illumination, photometric correction, and spatial coverage, should be developed as soon as possible to support geologic mapping and site selection.

[14] Radiometrically calibrated and controlled multi- and hyperspectral image mosaics can be used to derive quantitative mineral maps; new maps of this type would be highly advantageous in geologic mapping and site selection and should be developed as soon as possible.

[15] Newly derived geologic (and other) maps at a variety of scales are needed (e.g., 1:10,000 scale for surface operations to 1:250,000 scale for regional context). Near-term efforts should focus on high-priority locations.

[16] Terrain hazard (e.g., slope, surface roughness), line-of-sight (i.e., viewshed), and time-dependent illumination maps at appropriate scales (e.g., best-available supported by the data) are high-priority derived products essential in mission planning, and they should be made available as soon as possible.

[17] South polar data products could be initially controlled to coarser data and known surface reference points to support early Artemis missions and other surface activities, but establishment of a local control network applied to all necessary data layers would facilitate interoperability and provide more precision for specific sites.

Rationale:

Higher-order data products are tied to controlled foundational data and are derived from source data, such as measurements of elemental abundance, temperature or reflectance at multiple wavelengths, observations of solar illumination, and output from space weather models. Higher-order data products derived from these source data will play an essential role in planning and executing south polar missions. Planning the science activities to be carried out on the lunar surface will be based on these higher-order data products, and, in turn, the science returned by those activities will be used to update those same products. For example, geologic maps based on remotely sensed data prior to early Artemis landings will be a likely outcome of site assessments and will form the critical basis for traverse plans and planning of science tasks. The observations, samples, and measurements made during Artemis surface activities will feed back into updating the geologic maps, to the benefit of future crewed or robotic missions to the same area. Similarly, resource maps will drive the selection of landing sites for missions focused on resource discovery, characterization, and utilization, and the findings of those missions will be used to iteratively update the resource maps. In these cases, and others, the utility of the ground-truth information gained during a mission – and the efficiency and effectiveness of gathering that information in the first place – will be maximized by having a high-quality preliminary map made prior to the mission. We reiterate *Recommendation 8.3-1c* from the Artemis III SDT report that key higher-order data products should be generated to support upcoming landings, particularly the most near-term mission-relevant higher-order data products, geologic maps, terrain hazard maps, thermal and illumination models and maps, and Earth-visibility and communications maps.

New controlled high-resolution image mosaics with illumination angles matching the time and date of a targeted landing are useful for planning crewed and uncrewed landings, including upcoming landings for CLPS deliveries. Once a specific location is identified for a landing site, the subsolar latitude and longitude associated with the targeted date and time of landing can be used to identify LROC NAC images with best matching illumination conditions. CLPS deliveries, for example, will typically land early in the lunar morning to maximize the amount of illuminated operations time on the surface, and, thus, low-Sun angles at a specific solar azimuth are desirable. Controlled mosaics derived from these data are valuable to provide actual illumination to inform and provide comparisons for illumination simulations. Such products support precise landing site selection in identifying specific locations where instruments and solar panels will not be in shadow. These mosaics will also assist with terrain relative navigation and autonomous hazard avoidance systems.

Because of low Sun angles at the south pole, images and color data may suffer from inadequate lighting and limited coverage. However, where the lunar surface is illuminated adequately, controlled mosaics created from existing multispectral and hyperspectral data (e.g., LRO WAC at 100 m/pixel and derived mosaics at 400 m/pixel [Robinson et al. 2010; Sato et al. 2018], SELENE/Kaguya MI at 20-60 m/pixel [Ohtake et al., 2008], and SELENE/Kaguya Spectral Profiler (SP) at 500 m/pixel [Haruyama et al., 2008], Chandrayaan-1 M^3 at 140-280 m/pixel [Pieters et al., 2009], and Chandrayaan-2 Imaging Infra-red Spectrometer at 80 m/pixel [Chowdhury et al., 2020b]) are essential for mapping of color and composition. Controlled mosaics for the lunar south polar region have not been developed from these data, so they should be created as soon as possible. Some such as a WAC south pole color mosaic and derived TiO_2 maps might yet require additional observations including special forward-pitch obliques to extend the available phase angle range (e.g., Sato et al. 2018). Global M^3 data products are available, but not mosaics. The available M^3 data have residual errors in radiometry, photometry, and lunar surface registration. The data would likely need to be tied to a local control network for comparison to other data. These data would supplement elemental abundance maps from NASA's Lunar Prospector (e.g., Prettyman et al., 2006) and derived products such as rock abundance from NASA's Diviner radiometer (e.g., Bandfield et al., 2011). At the south pole, some existing products would also benefit from updated control to facilitate interoperability with other data.

Since 1961, planetary geoscience maps have been used in nearly every facet of planetary exploration, from landing site characterization for human (e.g., Grolier, 1970) and robotic (e.g., Anderson and Bell, 2010) missions to scientific interpretations. Modern planetary geoscience maps are either standardized or non-standardized. The former includes maps published by the United States Geological Survey (USGS) that require adherence to the

USGS cartographic standards, conventions, and principles. Non-standardized maps are those published by other organizations that are not required to, but might, adhere to the same cartographic standards, conventions, and principles. Whenever possible, it is best practice for maps to follow established cartographic standards and symbologies. Maps should use controlled foundational data as input. Initially, coarser control and referencing might be adequate, but over time and for detailed purposes, a local control network may be needed as well to tie all the data together more precisely.

Map production requires significant time investments, so early establishment of agreed-upon top-priority areas, science and exploration goals for those areas, the necessary scale(s), and map types will help organize and focus community efforts. For example, if the south polar region is defined as poleward of 84°S, this could potentially require dozens of new maps at both the regional and higher-resolution scales to be produced.

Geologic and geomorphologic maps are useful for identifying interesting targets of study, including for human exploration missions. This mapping can progress using the data we now have in hand, with the understanding that such maps would be iteratively improved with time, as ground-truth and “field perspective” knowledge are obtained. Geologic and other maps should be produced at useful scales from 1:10,000 scale (and larger) for surface operations to 1:250,000 scale for regional context. The nested scales of maps (broader scales for context and close-up scales for local activities) should be similar to the Apollo-era landing site maps, where medium-scale maps (1:250,000) set context for targeted high-resolution (1:10,000 to 1:25,000-scale) maps. Some recent community efforts include a 1:10,000 scale geomorphologic map of the de Gerlache-Shackleton ridge (Bernhardt and Robinson, 2021) and geologic maps of the south polar region at 1:500,000 scale (Pöhler et al, 2021).

Maps of surface mineralogy derived from controlled and radiometrically calibrated inputs with topographic corrections are a high priority for the south pole. Radiometric corrections used to generate reflectance mosaics generally assume a flat sphere; however, at the poles, this leads to anomalous values, especially on steep slopes such as crater walls. Therefore, topography needs to be accounted for to produce the most accurate and useful maps. Mineral maps derived from calibrated and corrected SELENE/Kaguya MI and SP, as well as M^3 from Chandrayaan-1 (e.g., Lemelin et al., 2019; Blalock et al., 2020; Moriarty et al., 2021), are especially needed for geologic mapping. These products also support more detailed scientific analysis such as identification of possible water-rich sites (e.g., Li et al., 2020) and exposed lunar mantle material that would inform science objectives or support *in-situ* exploration (e.g., Moriarty et al., 2021). SELENE/Kaguya MI and SP mineral maps at 60-1000 m/pixel scale

(Lemelin et al., 2017, 2021; Blalock et al., 2020) are currently in production but should be released to the PDS as soon as possible.

Terrain hazard maps highlighting slopes, roughness, and boulder and crater distribution will be essential for landing site selection, supporting surface mobility, assessing trafficability, and planning safe and efficient traverses to high-priority targets. In planning a traverse, these maps might also be helpful in finding potential targets for in-field investigation, such as boulders and outcrops.

Temperature maps are currently provided by the Diviner Lunar Radiometer Experiment (Diviner) in polar stereographic projection at 240 m/pixel scale at the pole for different local times and seasons (Williams et al., 2019). To characterize the thermal environment at the resolution necessary for mission planning, these data sets will need to be augmented with coupled illumination and thermal models to provide greater spatial resolution and temporal (diurnal and seasonal) resolution. The ability to model and characterize the lunar surface and environment and visualize temporal changes will be needed. Temperature and volatile resource mapping will require modeling to augment existing thermal data sets to provide the temporal coverage and spatial resolution necessary to support missions. Such modeling requires substantial computational resources as capturing direct illumination, indirect illumination, and thermal emission from both near-field and far-field topography is necessary. Nested scales in models can make this tractable by providing higher resolution near-field thermal conditions within a broader regional-scale model.

Illumination maps are currently generated from topography, primarily LOLA (e.g., Mazarico et al., 2011; McGovern et al., 2013; Glaser et al., 2014; Smith et al., 2017; Scharringhousen and Witte, 2020). Near the south pole, solar illumination is perpetually at high incidence angles (i.e., low on the lunar horizon). Therefore, topography plays the dominant role in illumination conditions and surface temperatures, which can vary in complex ways with local time and season. General illumination maps (e.g., PSR maps and average illumination models based on Mazarico et al. 2011 are in the PDS) are a good first-order basis for understanding the distribution of highly illuminated or shadowed regions; however, customized illumination maps (and thermal models) that vary with time will be needed for a given mission profile. Alternatively, interactive tools for temperature and illumination might be desired. These are essential for: determining surface temperatures; predicting the availability of solar power; ensuring astronaut safety and survival during periods of darkness (including traverses in low light and complete darkness); assessing local hazards; and identifying cold traps and areas of surface and near-surface volatile stability.

Earth- and ground-station visibility maps are also currently generated using topographic products as a base. Line-of-sight between a point on the lunar surface is calculated to the Earth, or to a specific ground station location, to evaluate Earth visibility and line-of-sight communication possibility. Surface communication relies either on a relay satellite, or direct line-of-sight to a ground station or other surface asset (e.g., rover, lander, communication relay tower, base asset), which makes these products highly beneficial for future mission planning. General Earth-visibility (the percentage of timestep where any part of the Earth was visible to a pixel) and sky-visibility maps are available from the PDS that give the percentage of time a portion of the Earth was visible to a given pixel, based on the 60-, 120-, and 240-m LOLA products (Mazarico et al., 2011) and are useful first-order products. To support surface communications planning for upcoming lunar landed missions near the south pole, however, either *in situ* (e.g., aimed at or tied to a specific nearby location on the lunar surface) or to/from Earth line-of-sight maps tailored for each mission, will also be required, including at highest possible scale.

4. New Mission-Enabling Data and Products for Further Lunar Exploration

Identify any new mission-enabling data or products that are required from existing or future assets at the south pole or beyond.

The focus of this report so far has been on south polar data; however, some data products are also relevant to areas outside of the south polar region. For the most part, the types of data that exist for the south pole are also available for other locations on the Moon. There are also a variety of global data products that serve as foundational data or framework data that could be made from existing data. We have already discussed those data products in the text above. Here, we focus on assessing critical data that have not yet been collected or measured, and possible future types of data that would be highly beneficial to NASA's goals of establishing a persistent lunar base of operations or future landings outside of the south polar region. As mentioned in Section 1 (above), Apollo, Lunokhod, and future retroreflectors could be used to improve the global reference frame, as could radio transmitters used as VLBI targets.

Findings:

[18] LRO and other spacecraft have, and are, providing an abundance of critical data for planning a return to the surface (e.g., topography, images, radar, resources, geologic information). Continuing to give high priority to opportunities using existing assets that fill in critical data gaps for future landings will maximize the use of those assets.

[19] There is an essential need for continuing surface and environmental observation capabilities via remote sensing to follow LRO, including the ability for positioning of surface assets and surface station monitoring.

[20] Earth-based radar observations at high resolution, with broad near side coverage, and using a variety of wavelengths (e.g., X-, S-, L-, P-band) continue to be beneficial as a complement to observations made by LRO's Mini-RF.

[21] Upcoming missions and instruments such as PRIME-1, Lunar Trailblazer, VIPER, and Korea Pathfinder Lunar Orbiter (KPLO) ShadowCam will provide new data for later missions, complementing or improving on currently available data, particularly for the polar regions. Standardizing data formats and best practices early would be beneficial for enabling interoperability of data.

[22] "Field-scale" (better than 1-m scale) images, terrain maps, topography, resource maps, line-of-sight communication maps, and illumination products, particularly for the Artemis human landings and base camp, and will be especially important for real-time surface operations (e.g., power and navigation). These products are not possible with NASA's existing orbital data sets; future missions could be specifically designed to support these data products.

Rationale:

LRO and other spacecraft have been, and are, providing an abundance of critical data for planning a return to the surface (topography, images, radar, resources, geologic information); these data are useful for a multitude of possible landing sites in the south polar region and globally. In the near-term, as additional high-priority landing sites are identified for human and robotic missions, there are likely still opportunities to fill in critical data gaps with existing assets. For example, the LRO orbit will be over illuminated terrain 6° from the pole on nearly every orbit through 2025. In addition to observations of non-polar sites, LROC and other LRO instruments can acquire oblique and limb views of anywhere up to and including the south pole from almost every orbit; summer lighting is more favorable.

As highlighted by a finding of the LEAG (LEAG, 2020[8], Finding 2.8), there is an essential need for continuing observation capabilities and remote sensing that follow LRO, including the ability for positioning of surface assets and surface station monitoring. A similar recommendation was made in the Lunar Surface Science Workshop (Session 6)

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[8] https://www.hou.usra.edu/meetings/leag2020/LEAG2020AnnualMeetingFindings_FINAL.pdf

on Foundational Data Products (2020[9]). Future important observations include high-resolution (stereo and photometric) mapping for high-priority landing sites, and temporal mapping of anthropogenic changes (including construction at human landing sites and craters formed by spacecraft impacts) and natural changes (e.g., monitoring of the impact rate, boulder movements, and fault changes). At the poles, near nadir coverage is only possible for a few years at a time due to the natural nutation of the Moon during the 18.6-year cycle. Therefore, for regular coverage directly over the poles, a new spacecraft or significant orbit maintenance might be needed every few years.

Earth-based radar observations at high-resolution, with broad coverage, and using a variety of wavelengths remain highly relevant as a complement to Mini-RF. The Mini-RF radar collected monostatic X-band data of ~15-20% of the lunar surface and S-band data of ~67%, including 99% coverage of the polar regions at ~15 m/pixel (e.g., Cahill et al. 2014). Since 2012, the Mini-RF radar has collected in a bistatic architecture in concert with the Arecibo radar (at S-band) and the Goldstone DSS-13 antenna (at X-band). For bistatic observations, Mini-RF is limited in its coverage to the nearside along LRO orbit tracks. Earth-based radar can cover large regions of the near-side of the Moon at wavelengths different than those collected by current orbital radars (e.g., X- and S-band, Mini-RF; S- and L-band DFSAR, Chandrayaan-2). Different radar wavelengths are sensitive to different sized scatterers (e.g., boulders with a size near the radar wavelength) and have different penetration and sensing depths. Continuing Earth-based radar observations of the lunar nearside and poles thus allow mapping of surface roughness and scattering characteristics at a variety of length-scales, and filling in gaps in Mini-RF coverage, which can aid in creating terrain roughness, geologic unit, and hazard maps (among other things).

Upcoming missions and instruments including PRIME-1 (launch planned for 2022), KPLO ShadowCam (launch planned for 2022), VIPER (launch planned for 2023), and Lunar Trailblazer (launch planned for 2024 or 2025), will provide new data for later missions, and will be particularly relevant to south polar landings. Multi- and hyperspectral image data at a variety of wavelengths (including data that will be acquired by the upcoming Lunar Trailblazer) would also be highly beneficial in supplementing existing M^3 data and other datasets for making surface geologic and resource maps. International missions will provide beneficial and complementary data; however, an analysis of their interoperability with other lunar data will need to be undertaken prior to broad usage. Establishing

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[9] An archived copy of the 2020 Lunar Surface Science Workshop Session 6 report can be accessed here: https://lunarscience.arc.nasa.gov/lssw/downloads/Workshop-Report_LSSW-Virtual-Session-Six--Foundational-Data-Products.pdf

standard formats and data practices early would be beneficial for upcoming missions and interoperability of their data.

For surface operations, and human missions with a particular focus on long-term surface activities, “field-scale” (i.e., better than 1-m scale) images, topography, communications, resource and other maps, as well as illumination products, will be highly beneficial in future mission and traverse planning. Field-scale data and products will be critical for: (a) surface mission planning (e.g., identifying high priority targets for crew imaging, sampling, and payload deployment; locating and planning surface infrastructure; and planning safe and efficient traverses); (b) real-time surface operations (e.g., assisting science and operations teams in aiding the crew in traverse execution through providing situational awareness for science and navigation, in all illumination conditions); and (c) post-mission analysis and localization (i.e., placing all collected images, samples, and payload data in geologic context). New topographic data at the field-scale could be used in conjunction with currently available lower resolution regional products to enable simulations of detailed surface illumination and line-of-sight or direct-to-Earth communication availability.

The Chandrayaan-2 orbiter has a high-resolution imaging system onboard that is acquiring and deriving orthoimages and DEMs at ~0.3 m/pixel scales (Amitabh et al., 2021). These scales are ideal for identifying impact crater hazards and boulders; however, it would be beneficial to perform an assessment of these data before assuming their usability for Artemis or other surface mission planning. Future NASA missions could be designed to support field-scale observations and data products as part of NASA’s ongoing exploration goals, including a sustained lunar presence and base camp activities.

5. Lunar Data and Tools

Assess the general availability and accessibility of lunar data and tools for the science community, the Artemis program, and the general public.

We focused on several themes related to lunar data and tools:

Data Availability: The wide variety of existing lunar data generally have sufficient availability and accessibility for use. The usability of the data varies, but, in general, source data and derived products are available and accessible through sites such as the NASA PDS. For example, more than 1.3 petabytes of data products from the NASA Lunar Reconnaissance Orbiter Camera (LROC) are available online.

Data Discovery and Visualization Tools: Several publicly available lunar data discovery, analysis, and visualization tools currently exist within the planetary and mission communities (e.g., Arizona State University's Java Mission-planning and Analysis for Remote Sensing (JMars), Arizona State University and LROC's Lunaserv, NASA's MoonTrek, and Applied Coherent Technology's QuickMap), and many of these are widely used by scientists, students, and members of the general public. These tools facilitate access to a majority of the available lunar data products, enable data identification, and provide some ability to derive measurements, perform analysis and view results.

Data Processing and Analysis Tools: Various open-source and commercial tools used for processing and analyzing planetary data are available; these support gathering data, map-projection, layering, and 2- and 3-D analysis of a variety of raw and derived lunar data products resulting from recent lunar missions.

Findings:

[24] To facilitate data interoperability between tools and suitability for specific uses, it is vital that data be in standard formats, with appropriate metadata and description, including provenance. This is true for data in the PDS as well as products derived by scientists, engineers, and mission planners intended for broad use.

[25] Many available lunar data tools are purpose-made and require specialized training and knowledge; mission planning, in particular, tends to need specialized tools and interfaces. While it is understood that unique data processing and visualization capabilities are usually needed by missions (e.g., for mission planning and real-time operations support), developers of new tools should consider basing these on existing, open-source software when feasible and effective.

[26] Investments are needed to improve and continue to develop algorithms and existing data processing tools to make them more efficient, user-friendly, or more planetary-capable. This is particularly true regarding tools to control large lunar datasets. Additional tools might be available and leveraged from the data science and technology communities, including those within NASA, the USGS, universities, commercial, or non-traditional sources.

Rationale:

Upcoming missions will benefit immensely from the availability and accessibility of data products for much of the lunar surface and subsurface, along with the derived products, measurements, and models needed to support safe landing and surface operations.

These lunar data are supported by widely used tools for planetary data processing, discovery, visualization, and analysis.

Several tools enabling discovery of lunar data are available (e.g., Arizona State University's JMars, Arizona State University and LROC's Lunaserv, NASA's Treks, and Applied Coherent Technology's QuickMap); these tools also have some data visualization and analysis capabilities. It is understood that these tools are already facilitating mission planning for upcoming missions, and that typically each mission requires a customized version of a tool. However, there may be examples where existing tools cannot readily be adapted for a specific use, and in these cases new tools might need to be developed. Mission-specific tools and capabilities are less general, and sometimes less available. Many available lunar data tools are purpose-made and can require specialized training and knowledge, so it is also important that tool providers continue to provide documentation and tutorials for specific use cases. Some specialized tools will always be necessary, but to the extent possible and practical, these tools should be built upon existing tools (or with existing standards where no tool exists) and using open-source software.

Considerable support for planetary geospatial data exists in tools like the Geospatial Data Abstraction Library (GDAL), Esri ArcGIS, and QGIS. These tools have enabled the development, distribution, and analysis of many cartographic products. Some of the available data processing tools – for example specialized cartographic tools such as the public domain USGS Astrogeology's Integrated Software for Imagers and Spectrometers (ISIS) or the Ames Stereo Pipeline (ASP) – require specialized knowledge and a deep understanding of the data acquisition characteristics and quality of lower-level input data. Depending on the dataset, the use of advanced tools also requires adequate local data storage and processing power for each user. This limits the usability of these advanced tools to expert users with sophisticated processing capabilities. Investment in cloud storage and processing for lunar data, along with improvements in the documentation, usability, and efficiency of such software would support a larger number of users.

Other investments to improve existing data tools should focus on making them more efficient, user-friendly, or more planetary-capable. For example, many large image datasets are not yet controlled because of the large processing effort required using existing software and algorithms. Additionally, some existing data mosaics would benefit from updated control (photogrammetric and radargrammetric) to register all data to the agreed-upon lunar reference frame, at known levels of precision and accuracy, to achieve this best-possible joint registration, and use of foundational and framework datasets. Geometric sensor models (e.g., the Community Sensor Model [Laura et al. 2020]) also need to be developed for many instruments so that data can be processed at all.

Improvements to software for deriving DEMs from stereo images (e.g., improved matching algorithms and outlier detection methods) also are needed to handle the massive amounts of higher-resolution observations being obtained by missions such as LRO and SELENE/Kaguya. Such improvements to software and algorithms that increase their efficiency and throughput would benefit processing of data sets throughout the Solar System.

Because there are many tools available for lunar data, it is critically important that data are provided in standard formats, provide descriptions and metadata (e.g., through white papers, publications, and/or PDS labels and headers) that includes provenance and an error or uncertainty assessment to ensure interoperability with the widest range of available tools, make data useful to the broadest possible user-base (now and in the future), and to allow users to evaluate data products for suitability for a specific use. Standardization of data and supporting information aids with discoverability and usability and are in keeping with findings from the Lunar Surface Science Workshop on Foundational Data Products report, which states that surface characterizations would be advanced by continuing to “calibrate and improve foundational data products and provide error analysis to improve use and interpretation”[10].

As stated previously, data provenance should include spatial resolution, accuracy and precision, reference frame, coordinate system, and information on methods of radiometric and cartographic processing (including any resampling or interpolation) to be documented along with the data. Whenever supported, provenance should be provided in the PDS labels for the source products, as well as in the derived products. Data products such as models and associated derived products, are typically not supported by the PDS. In those cases, products need to be made available in simple, interoperable formats with adequate provenance and documentation in public data repositories. For example, use of digital map formats for geological maps that can be viewed and manipulated in GIS software are beneficial.

6. Realize a Lunar Spatial Data Infrastructure (SDI)

Define the preliminary steps to realize a “Planetary Spatial Data Infrastructure” (PSDI) for the Moon.

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[10] An archived copy of the 2020 Lunar Surface Science Workshop Session 6 report can be accessed here: https://lunarscience.arc.nasa.gov/lssw/downloads/Workshop-Report_LSSW-Virtual-Session-Six--Foundational-Data-Products.pdf

In general, a PSDI comprises several themes: data, standards, policies, and the user community (e.g., Hare et al., 2021). A PSDI for the Moon, or lunar SDI, would incorporate the topics addressed in the LCDP SAT tasks above (e.g., coordinate systems and frames, current and future data needs, and tools) through a framework (or infrastructure) that makes data and tools discoverable, accessible, usable, and enduring. A lunar SDI would encompass a set of "best-practices" and data standards that facilitate interoperability. The activities of this SAT, our findings, and the broader goals for lunar data are highly relevant to NASA's interests in developing an integrated planetary data ecosystem (e.g., Planetary Data Ecosystem Independent Review Board, 2021[11]).

Findings:

[27] Establishing a lunar SDI Working Group (WG) should be a high priority and would be highly beneficial in the upcoming era of exploration. The WG membership should include mission planners, engineers, scientists, and data providers. The WG should coordinate and communicate with NASA missions and other internal activities, the user community, international partners (e.g., missions, working groups, organizations like the IAU), the AGs, and the public.

[28] Development of a lunar SDI that includes infrastructure and a WG would benefit from a strategic investment of resources, support, and funding.

[29] As part of a lunar SDI, a common lunar data catalog or registry would be highly beneficial for the identification of existing "analysis ready data," facilitating development of new products, and promoting the use of consistent standards.

[30] In the near-term, a WG could support the Artemis missions by focusing on infrastructural and best-practices data goals to support landing site selection and *in-situ* operations, as well as define needs for future data and products, flight and sample materials, and tools.

[31] A WG would be highly appropriate to guide and perform the initial steps needed to realize a lunar Spatial Data Infrastructure (SDI).

Rationale:

A PSDI for the lunar community would incorporate and carry forward many aspects of the findings from this report. A PSDI provides common policies and a framework for the standardization of data formats and supporting metadata. The user community is an inherent part of a PSDI, and a PSDI helps to ensure that data remains accessible and usable for a wide variety of needs. A lunar SDI WG could be responsible for ongoing

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[11] An online copy of the 2021 Planetary Data Ecosystem Independent Review Board report can be accessed here: https://science.nasa.gov/files/science-pink/s3fs-public/atoms/files/PDE%20IRB%20Final%20Report.pdf

communications within the user community, providing guidance in developing the framework for data goals, as well as defining the needs for future data and tools and identifying and promoting a set of best practices for a broad community of mission planners, engineers, scientists, data providers, and the public (e.g., educators and media). Thus, establishing a lunar SDI WG comprising a diverse group of experts is a high priority. The WG should coordinate and communicate with NASA missions and internal activities, the user community, international partners and missions, other working groups, the AGs, and international organizations like the IAU to facilitate awareness, interoperability, and compatibility.

Development and consistent use of a lunar SDI's framework would support coordination, accessibility, interoperability, and completion of tasks, transcending individual missions or tasks. A lunar SDI would benefit from a strategic investment of resources and funding that likewise can enable persons or a WG to evaluate and communicate ongoing data needs as a wealth of new lunar data is acquired that transcends a particular mission. High-level support, beginning as soon as possible, of the initial steps toward a lunar SDI would help foster a knowledgeable community that could then provide guidance to all users of lunar data and aid them in processing data and publishing their results in standardized formats and with appropriate metadata.

For the Artemis sites (and beyond), a lunar SDI and WG could facilitate the coordinated development of specialized tools and shared methods, as well as initiate and maintain a publicly available common lunar catalog or data registry that supports the identification of existing "analysis ready data" and promotes the use of standards such that accuracy, precision, fit-for-use, and level of control (e.g., controlled, semi-controlled, and uncontrolled) are clearly and consistently defined (e.g., Laura and Beyer, 2021; Lunar Surface Science Workshop (Session 6) on Foundational Data Products, 2020[12]). One possible additional function of a lunar SDI WG could be to facilitate updates to lunar nomenclature by coordinating with the IAU Task Group for Lunar Nomenclature.

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[12] An archived copy of the 2020 Lunar Surface Science Workshop Session 6 report can be accessed here: https://lunarscience.arc.nasa.gov/lssw/downloads/Workshop-Report_LSSW-Virtual-Session-Six--Foundational-Data-Products.pdf

List of Acronyms

AG: Analysis Group
ASP: Ames Stereo Pipeline
CAPTEM: Curation and Analysis Planning Team for Extraterrestrial Materials (a NASA AG, now the Extraterrestrial Materials Analysis Group, ExMAG)
CCD: Charge Coupled Device Stereo Camera (on board Chang'E 2, China)
CLPS: Commercial Lunar Payload Services
DEM: Digital Elevation Model
DFSAR: Dual-frequency Synthetic Aperture Radar (on board Chandrayaan-2, India)
ESDMD: Exploration Systems Development Mission Directorate (NASA)
EVA: Extravehicular Activities
GDAL: Geospatial Data Abstraction Library
GDR: Gridded Data Records
GIS: Geographic Information System
GRAIL: Gravity Recovery and Interior Laboratory
HEOMD: Human Exploration Operations Mission Directorate
IAU: International Astronomical Union
ICRF: International Celestial Reference Frame
ISIS: Integrated Software for Imagers and Spectrometers
KPLO: Korea Pathfinder Lunar Orbiter (South Korea)
LEAG: Lunar Exploration Analysis Group
LCDP: Lunar Critical Data Products
LDWG: LRO Data Working Group
LGCWG: Lunar Geodesy and Cartography Working Group
LLR: Lunar Laser Ranging
LOLA: Lunar Orbiter Laser Altimeter
LRO: Lunar Reconnaissance Orbiter (NASA)
LROC: Lunar Reconnaissance Orbiter Camera
M^3: Moon Mineralogy Mapper (on board Chandrayaan-1, India)
MAPSIT: Mapping and Planetary Spatial Infrastructure Team
ME: Mean Earth/Polar Axis
MER: Mean-Earth/ Mean-Rotation system
MI: Multiband Imager (on board SELENE/Kaguya, Japan)
Mini-RF: Miniature Radio Frequency (on board LRO)
NAC: Narrow Angle Camera (part of LROC on board LRO)
OHRC: Orbiter High-Resolution Camera (on board Chandrayaan-2, India)
PDS: Planetary Data System
PRIME-1: Polar Resources Ice Mining Experiment-1 (NASA, Intuitive Machines CLPS)
PSD: Planetary Science Division (within SMD)

PSDI: Planetary Spatial Data Infrastructure
PSR: Permanently Shadowed Region
RMS: Root-mean-square
SAT: Specific Action Team
SLDEM: SELENE-LOLA Digital Elevation Model
SDI: Spatial Data Infrastructure
SDT: Science Definition Team
SELENE: SElenological and Engineering Explorer (Japan)
SfS: Shape-from-Shading
SMD: Science Mission Directorate
SOMD: Space Operations Mission Directorate (NASA)
SP: Spectral Profiler (on board SELENE/Kaguya, Japan)
TC: Terrain Camera (on board SELENE/Kaguya, Japan)
TMC-2: Terrain Mapping Camera (on board Chandrayaan-2, India)
USGS: United Stated Geological Survey
VIPER: Volatiles Investigating Polar Exploration Rover (NASA)
VLBI: Very Long Baseline Interferometry
WAC: Wide Angle Camera (part of LROC on board LRO)
WG: Working Group
WGCCRE: Working Group on Cartographic Coordinates and Rotational Elements

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