THE NEED FOR LUNAR AND PLANETARY CARTOGRAPHY PLANNING.
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Introduction: Cartography is the science and art of placing information in a community-recognized spatial framework. Cartography involves geodetic control, geographic standards, geospatial registration, and data processing. Cartography is essential for comparing or combining data taken at different times or by different instruments. As such, cartography is the foundation for lunar and planetary science and exploration, especially when addressing important questions by looking for subtle variations (e.g., spectral, photometric, and temporal) between different observations.

A lack of planning in planetary cartography has had and will have serious consequences for the operation of and scientific return from planetary missions. Here we highlight the current, unprecedented lack of formal cartographic planning for the U.S. space program and recommend a community-driven solution.

Background: While the USGS has been heavily involved in planetary cartography for over 50 years, this work has always been part of a broad community effort. During the late 1960s and 1970s multiple organizations helped plan and carry out this work, including NASA JSC, the National Geodetic Survey, the Defense Mapping Agency, RAND, and various universities. The table below lists the various groups chartered to coordinate these efforts, effectively disseminate information to the broader community, and/or advise NASA leadership on cartographic matters [1].

Start Date	Name
1974	Lunar Photography and Cartography Committee
1977	Lunar and Planetary Photography and Cartography Committee
1979	Planetary Cartography Working Group
1994	Planetary Cartography & Geologic Mapping Working Group (PCGMWG)

The last of these, the PCGMWG, includes the chair of the NASA Geologic Mapping Subcommittee (GEMS). Other groups have been active in making recommendations on cartographic standards (e.g., IAU WGCCRE, 1976-present; MGCWG, mid-'90's-present; LGCWG, 2007~2009) but not in general cartography planning [2-4].

From 1994-2012, the PCGMWG made cartography recommendations to NASA, including submitting a white paper on the importance of planetary cartography [5] to the NRC Decadal Survey. The PCGMWG ceased making cartography recommendations in 2012. The group continues its other responsibilities.

The Need for Lunar Cartography Planning: In the absence of an official plan, many important questions related to cartographic and mapping support to missions and research are unanswered. *Below are examples of practical issues for lunar researchers:*

• LRO LOLA data are archived in the Planetary Data System (PDS) in two different coordinate systems – how can users convert these cartographic data for their use? Should they need to?

• Kaguya, Chandrayaan-1 (C-1), and Chang'E data have been released in different reference frames than LRO data. Who is going to register them to one coordinate frame so they can be used together at known accuracy levels?

• Clementine and Lunar Orbiter datasets currently have displacements of up to several km relative to LRO data. Clementine multispectral data are still unique in some bandpasses and so are still needed for applications such as resource determination and optical maturity measurements. Who will register them to LRO to enable coanalysis with the more recent datasets at acceptable cartographic accuracy levels?

• How will the multitude of lunar topography datasets be merged and who will do it? Current sources are LRO LOLA, LROC WAC stereo, and LROC NAC stereo; Kaguya LALT and TC stereo; C-1 TMC stereo; and Apollo Metric and Panoramic stereo. A merged global set is essential for the best projection of all types of data, in order to compare such data at accuracy levels that approach their resolution.

• What is the absolute positional accuracy of the LROC WAC data? Do these data need to be controlled to the LOLA reference frame?

• Will the usability of all the LROC NAC stereo pairs be checked to see if they can be used to generate DTMs in the future?

• Who is going to perform high-resolution lunar topographic mapping once LRO funding runs out?

• Is a new mission needed in order to characterize lunar topography and landing sites with sufficient accuracy and coverage for future exploration mission operations (landing, resource location and extraction, surface activities, etc.) and science (registration of datasets)?

• What requirements should be placed on future lunar missions to gather the most valuable data and to ensure that their data can be integrated at high precision? For example, should there be uniform requirements for instrument calibration and cartographic processing?

More general issues:

• Who is responsible for establishing lunar cartographic standards and how can compliance be assured?

• What new techniques need to be developed or perfected to support cartographic data processing and the analysis of existing and future data? How will such techniques be tested to quantify their accuracy?

• How will resources for research and analysis of data be prioritized to address these issues? How will the reorganization of NASA-funded research, with cartographic processing concentrated in the PDART program [6], affect prioritization?

The most salient of these issues are discussed below in greater detail.

Need for geodetic control. Controlling datasets with photo- or radar-grammetric, or altimetric solutions is the only way to register data in a common frame at known levels of accuracy to meet data fusion needs. Such knowledge is critically important for science (e.g., analysis of body orientation variations, photometric correction for spectral/mineral studies, geologic mapping, change detection, and multi-instrument comparisons) and mission operations (e.g., landing site selection, targeting images from orbit, and landed surface operations), making control one of the most fundamental cartographic activities. Though some analyses can tolerate uncontrolled data, we underscore the fact that spatial accuracy can only be quantified through the control process. Recognizing the importance of controlled datasets for science and exploration purposes, in 2007 *the NASA Advisory Council recommended that* ***all lunar datasets*** *be geodetically controlled* [7].

Cartographic Standards. Controlling each data set to a different cartographic standard only minimally improves the scientific value of the data. In a spacecraft operational environment, confusion regarding coordinate systems could have catastrophic consequences. The effect is comparable to that of not standardizing measurement units. While the development of standards may seem an arcane subject, the pragmatic goal is universal acceptance of a single standard – even when there is no one clear choice based on technical considerations.

As such, a current and recurring concern is to find the most effective inducements to obtain the widest acceptance of planetary cartographic standards, especially by active missions. NASA has the opportunity to lead by example; however such leadership cannot occur without a plan developed by key stakeholders.

Prioritizing tool development. The need for improved techniques is driven both by the increasing volume of data and the increasing complexity of instruments. Examples of new capabilities that are needed include (1) faster, more robust, automatic feature matching between disparate data types, enabling new types of data fusion; (2) ability to simultaneously adjust data from different platforms (e.g., flyby, orbital, descent, lander, and rover) and data types (e.g., images, spectra, radar, and altimetry); (3) new tools to combine different methods for generating topographic information, especially combining LIDAR and image-based and new techniques, including those based on photoclinometry.

Multi-mission data analysis. Individual instrument teams usually understand and address their mapping needs, but without broader guidance, multi-mission cartography can be neglected. Such concerns are relevant to exploration and mapping of the entire Solar System. For the Moon, petabytes of data have been collected by multiple nations, missions, and instruments, posing both challenges and opportunities for co-analysis [8]. The coordination of national efforts both to develop tools for data processing and to process lunar datasets, in particular to process such datasets jointly in order to ensure their consistency, would be of tremendous benefit to all spacefaring nations.

Recommendation: In principle, re-instituting a program of cartography planning should be straightforward – a new working group should be chartered to resume this essential work. This issue cuts across all disciplines of planetary science. So ***we recommend that the present planetary Advisory Groups (including LEAG) issue a "finding" that a new cartographic planning group should be chartered, to consider lunar and general planetary mapping needs.***

References: [1] PCWG, 1993, "Planetary Cartography 1993-2003." [2] Archinal, B. et al., 2011, *Cel. Mech. Dyn. Ast.* 109, 101. [3] Duxbury, T. et al., 2002, http://astrogeology.usgs.gov/search/details/Research/ISPRS/Duxbury/pdf. [4] Archinal, B. et al., 2009, *LPS XL*, #2095. [5] Johnson, J. et al., 2010, http://www.lpi.usra.edu/decadal/sbag/topical_wp/JeffreyRJohnson.pdf. [6] NASA, 2014, Research Opportunities in Space and Earth Sciences - 2014, C.7, Planetary Data Archiving, Restoration, and Tools. [7] NAC, 2007, Tracking Number: S-07-C-1, http://bit.ly/x0HnnM. [8] Archinal, A. et al., 2012, *LPS XLIII*, #2394; Kirk, R. et al., 2012, "Lunar Cartography…", *ISPRS Comm. IV*.