PLANETARY CARTOGRAPHY: WHAT, HOW, AND WHY BEGIN WITH WHERE. R. L. Kirk[1], [1]Astrogeology Science Center, U.S. Geological Survey, Flagstaff, Arizona 86001 USA (rkirk@usgs.gov).

Introduction: In this abstract I offer a brief overview of planetary cartography, intended as an introduction to a session in which others will present their individual, institutional, and mission-derived perspectives on the subject. After suggesting a broad and inclusive definition of cartography, I list a few examples of its applications in planetary science, briefly summarize the state of the art, and outline the most significant challenges for future development.

What Is It?: The dictionary definition of cartography, "the science or art of making maps" [1] succeeds or fails on the breadth of one's definition of a "map". Printed maps and globes, the traditional examples, are still useful but have mostly been supplanted by digital and increasingly more dynamic products. The use of "cartography" as a blanket term in the NASA planetary exploration community is arguably a historical accident, related to the establishment of oversight and planning groups beginning with the Lunar Photography and Cartography Committee in 1974 and evolving into the Planetary Cartography and Geologic Mapping Working Group (PCGMWG) by 1994 [2]. Through the lunar/planetary cartography program overseen by these groups, NASA recognized its need for a wide range of spatial data products to support scientific research, generated by an evolving mix of technologies evolving from photographic processing, airbrush artistry, and analytical photogrammetry [3] toward an increasingly integrated set of solutions for processing, organizing and presenting spatial data in digital form. Perhaps unfortunately, the narrow term "cartography" remained in use as a cover for this evolving program over several decades. Yet, it would be equally naïve to define planetary cartography as "the activity of NASA's planetary cartography program." Not only does this leave out the crucial contributions of other national and international space agencies, it fails to recognize that a great deal of the work is done by missions (e.g., characterization, geometric and radiometric calibration of instruments by the teams of experts that developed them, implementation of data processing pipelines, and production of first if not always final drafts of key map products), as well as by investigators funded by other research and analysis programs.

Instead, I propose the working definition of what has been traditionally referred to as "planetary cartography" to be the totality of efforts needed to calibrate, localize, co-register, analyze, and present spatial data about planetary surfaces. This definition is consistent with historical usage in the terrestrial community [4] (though there has been a tendency to narrow this usage over time as discussed in a companion abstract [5]). It is also consistent with the decision of the recently constituted NASA Planetary Cartography Research Analysis Group (CRAG) [6] to adopt the more inclusive name of the Mapping And Planetary Spatial Infrastructure Team (MAPSIT) [7]. Although a narrower definition may need to be kept in mind when engaging with terrestrial experts [5], "planetary cartography" is likely to remain in use as shorthand for the full breadth of mapping and spatial infrastructure issues. The topic can usefully be divided into three areas:

Preparing the Framework. Before a new world can be studied, a reference coordinate system and frame must be defined in which observations can be located and compared. This requires determination of the size, shape, and rotation of the body (i.e., geodesy) as well as arbitrary (but agreed-upon) choices for zero longitude and zero elevation.

Locating the Data. Once a coordinate frame exists, observations can be located in it and then compared to other observations, theory, etc. The minimum requirements for doing this with remote sensing data are an understanding of how an instrument works (geometric calibration) and some estimate of the location and pointing of the instrument, plus software (known as a sensor model) that uses this information to identify the source of each observation on the target. Though *uncontrolled* products can be generated by taking position/pointing information at face value, the importance of *controlled* products cannot be overstated. These are generated by a process of statistically estimating position, pointing, and ground coordinates, which not only improves the consistency of results within and between data sets, but also provides reliable estimates of accuracy [8]. Having multiple observations, especially if they include multitemporal, multispectral, topographic, or even in situ information, in a single system vastly expands the range of qualitative and quantitative investigations that are possible.

Communicating Spatial Relations. Scientific conclusions that hinge on spatial relationships and analyses need to be communicated in spatial terms. The tools for such communication include "cartography" in its narrowest traditional sense (map projections, symbology, and design) but also geographical information systems, 3D and 4D visualization, and other computer graphics techniques. Here, too, agreed-upon standards for documenting data formats, map projections [9] as well as feature names are as important as processing capability if results are to be understood and used.

What Is It Good For?: Very nearly everything one might want to do in in the study of solid bodies in the solar system. The application of spatial data processing and spatial data representation to the remote sensing observations that loom large in the field is relatively obvious, but the interpretations of in situ observations and returned samples also depend critically on their spatial context so that it is essential to record their location and relate this to data sets that cover wider areas. Even if one focuses relentlessly on the scientific questions of the processes that operate on a given planetary body and their history, the relevant evidence is largely laid out spatially and requires spatial documentation and correlation to be unraveled [10]. A pair of examples serves to illustrate how cartography contributes to both mission operations and scientific research—and how each of these applications typically involves the other.

Landing Site Selection. The Apollo program, which delivered 12 humans to the Moon in the 1960s-70s and returned them safely to Earth with geologic samples and remote sensing data, was preceded by five successful Lunar Surveyor landings and followed by four landers and four rovers that successfully reached the surface of Mars. Mapping programs to locate safe yet scientifically valuable landing sites were essential to these successes. (Other probes have achieved important scientific goals without being targeted to a specific landing point or being required to operate on the surface). This process will be equally critical to surface or proximate operations by humans and robotic spacecraft in the future regardless whether the target is Mars, the Moon, other satellites, or a small body [11, 12, 13].

The Mars Science Laboratory (MSL *Curiosity* [14]) provides a recent and well-documented case study that is discussed at length in a companion abstract [12] Selection of its landing site began in 2005 with discussions of the scientific merits of candidates on the basis of geologic mapping and integration of remote sensing data by community members. Sample observations of high resolution morphology from HiRISE [15] and spectral images from CRISM [16] were obtained and analyzed over the next few years, leading to the identification of four final candidates by 2009. Complete HiRISE image coverage and substantial coverage with stereo-derived digital topographic models (DTMs) were amassed for these sites. Substantial advances in the automated mapping of rock abundances [17] were made and factors such as thermal environment (from THEMIS infrared imaging [18]) and weather (contingent on topographic models) were considered. Topographic and thermal information obtained by orbital remote sensing continue to be key ingredients in planning the operation of the rover.

Recurring Slope Lineae on Mars. RSLs are among the most dynamic features on Mars discovered by HiRISE. They take the form of elongated, dark streaks on slopes that appear, slowly fade, and often recur from year to year [19]. Though the first examples were likely discovered fortuitously, documentation of their behavior has required repeated imaging, achieved by using targeting software equipped with a large number of co-registered remote sensing data sets [20]. Precise rectification of repeat image based on HiRISE stereo DTMs was required to quantify the changes of individual streaks. Mapping of the global distribution of RSLs showed that they were associated with warm slopes at low and mid latitudes and active primarily in the warmest part of the year, leading to the conjecture that they are formed by release of liquid water or brine. Recently, examination of CRISM spectral data precisely registered to HiRSE images shows that hydrated salts (most likely perchlorates) are present in the lineae [21], supporting the hypothesis that brine flows are responsible. Thus, although the first example of slope lineae was revealed in a single HiRISE image, map-based targeting and cartographic processing of multi-temporal and multi-instrument data sets was required to determine where, how, and why they form.

Where Do We Stand?: Planetary cartography in the 2010s depends almost entirely on digital data processing, a tool of formidable power. The topographic data sets for each of MSL's final candidate sites contained a million times the information available for Mars Pathfinder in 1997, and were comparable to the entire global topographic model of Mars [22]. Controlled image mosaics of the lunar poles containing tens of thousands of images totaling 13 Terabytes of data are being constructed [23]. Deliveries of raw mission data are approaching the Petabyte level. Unfortunately, the software tools needed to deal with these data are poorly integrated. A few software systems dedicated to planetary research (VICAR, ISIS, ASP) are each capable of processing many (not all) current and legacy planetary data sets. Commercial (ESRI ArcGIS, BAE SOCET SET/GXP) and open source (GDAL, QGIS, GRASS) software designed for mapping the Earth are critical for some applications, and the adoption of planet-agnostic data standards is a major help in this respect [24]. Practical data processing in many of these systems requires the use of multiple modules plus help from more general purpose software (databases, graphics, scripting languages). Finally, a large fraction of cartographic processing is carried out with ad hoc applications developed in environments ranging from C to IDL and MATLAB to Python.

Whither?: The cartographic needs of the planetary exploration program depend in detail on political and programmatic decisions that are hard to predict, but several technical and organizational challenges are relatively easy to identify.

Technical Challenges.

1. Automation. More is almost always good. Reducing the need for expert interaction in data processing reduces costs and enables larger projects—provided it can be done without sacrificing accuracy and precision.
2. Integration. This is needed at every level, from more streamlined workflows for challenging tasks such as geodetic control within a given software package [25], more fluid communication of data between dedicated planetary software and other useful applications [24], and potential approaches to modeling and documenting sensor behavior with a generic standard [26].
3. Novel targets. Many small bodies are irregular in shape, so the projections and processing approaches of classical cartography do not apply. Planetary surfaces are irregular and littered with irregular small bodies (rocks). Modeling techniques adapted from computer graphics can be applied to these targets [27] and may be helpful even for large, spheroidal bodies but they need to be integrated deeply into processing software. A companion abstract discusses these needs at greater length [13].
4. "Novel" instruments. Laser altimetry, pushframe imaging, and radar sounding have been in use for more than a decade, but techniques to coanalyze the first along with images, work efficiently with the second, and to map three-dimensions with the third are far from mature. The future will bring even more exotic instruments such as ranging in imaging form [28] requiring even more advanced processing techniques to be developed.

Organizational Challenges. The recent restructuring of NASA research programs has eliminated the Planetary Geology and Geophysics Program that provided major support for spatial data processing for decades along with the PCGMWG, which provided programmatic oversight for much of this time [2]. Fortunately, NASA officials have expressed their understanding of the need for spatial infrastructure and mapping and their support for its continued presence in the planetary program. The future shape of cartographic work may be hazy at present but this is clearly a time of opportunity to better serve the community. Some of the salient challenges can readily be identified:

1. Inreach. Experts in mapping and spatial infrastructure owe their peers in the planetary research community a clear explanation of the broad definition of "cartography" and the many ways in which it contributes to their research.
2. Funding. Significant funding increases may be unlikely, but the recent trend in which declining budgets are dedicated to maintaining theoretical capabilities while increasingly abandoning actual data processing need to be reversed. Missions also need to have a clear mandate *and budget* to carry out tasks such as instrument calibration that only they have the knowledge to accomplish.
3. Prioritization. Given finite budgets, the priorities for technique development and spatial data processing must be continuously evaluated based on input from the full community.
4. International Cooperation. Planetary science is an increasingly international activity, and data sets not only should be shared, they need to be processed and analyzed jointly to maximize scientific return.

The session to which this abstract is submitted is one of the first steps of the CRAG/MAPSIT to address these pressing issues, which are discussed at length in a companion abstract [7].

References: [1] http://www.merriam-webster.com/dictionary/cartography, retrieved 1/4/16. [2] PCWG, 1993, "Planetary Cartography1993-2003. [3] Batson, 1990, *Cartography* in Planetary Mapping, Cambridge Univ. Press, 60. [4] Goodrick, 1982, *Cartography, 12*, 146. [5] Laura, 2016, this conference. [6] Lawrence, 2015, LPI Contrib.1846, 7068. [7] Lawrence et al., 2016, this conference. [8] Archinal et al., 2016, this conference. [9] Hare et al., 2016a, this conference. [10] Williams et al., this conference. [11] Grant et al., this conference. [12] Bussey et al., this conference. [13] A'Hearn et al, this conference. [14] Golombek et al., 2012, *SSR, 170*, 641. [15] McEwen et al., 2010, *Icarus, 205*, 2; —, 2016, this conference [16] Murchie et al., 2007, *JGR, 112*, E05S03. [17] Huertas and Cheng, 2011, *LPS, 42,* 1272. [18] Fergason, et al., 2012, *SSR, 170*, 239. [19] McEwen et al., 2011, *Science*, *333*, 740; —, 2014, *Nat. Geosci., 7*, 53. [20] Christensen et al., 2009, *AGU FM*, IN22A-06. [21] Ojha et al., 2015, *Nat. Geosci., 8*, 829.. [22] Kirk et al., 2011, EPSC-DPS2011-1465. [23] Archinal et al., 2015, LPI Contrib. 1863, 2040. [24] Hare et al., 2016b, this conference. [25] Edmundson et al., 2015, *LPS, 46*, 1454. [26] Community Sensor Model Working Group, 2010, Community Sensor Model Technical Requirements Document, v. 3.0, NGA.STND.0017_3, http://www.gwg.nga.mil/documents/csmwg/documents/CSM_TRD_Version_3.0__15_November_2010.pdf, retrieved 1/4/16. [27] Kahn et al., 2011, *LPS, 42*, 1618. [28] DellaGiustina et al., this conference.