THE IMPORTANCE OF A PLANETARY CARTOGRAPHY PROGRAM: STATUS AND RECOMMENDATIONS FOR NASA 2013-2023

USGS ASTROGEOLOGY SCIENCE CENTER

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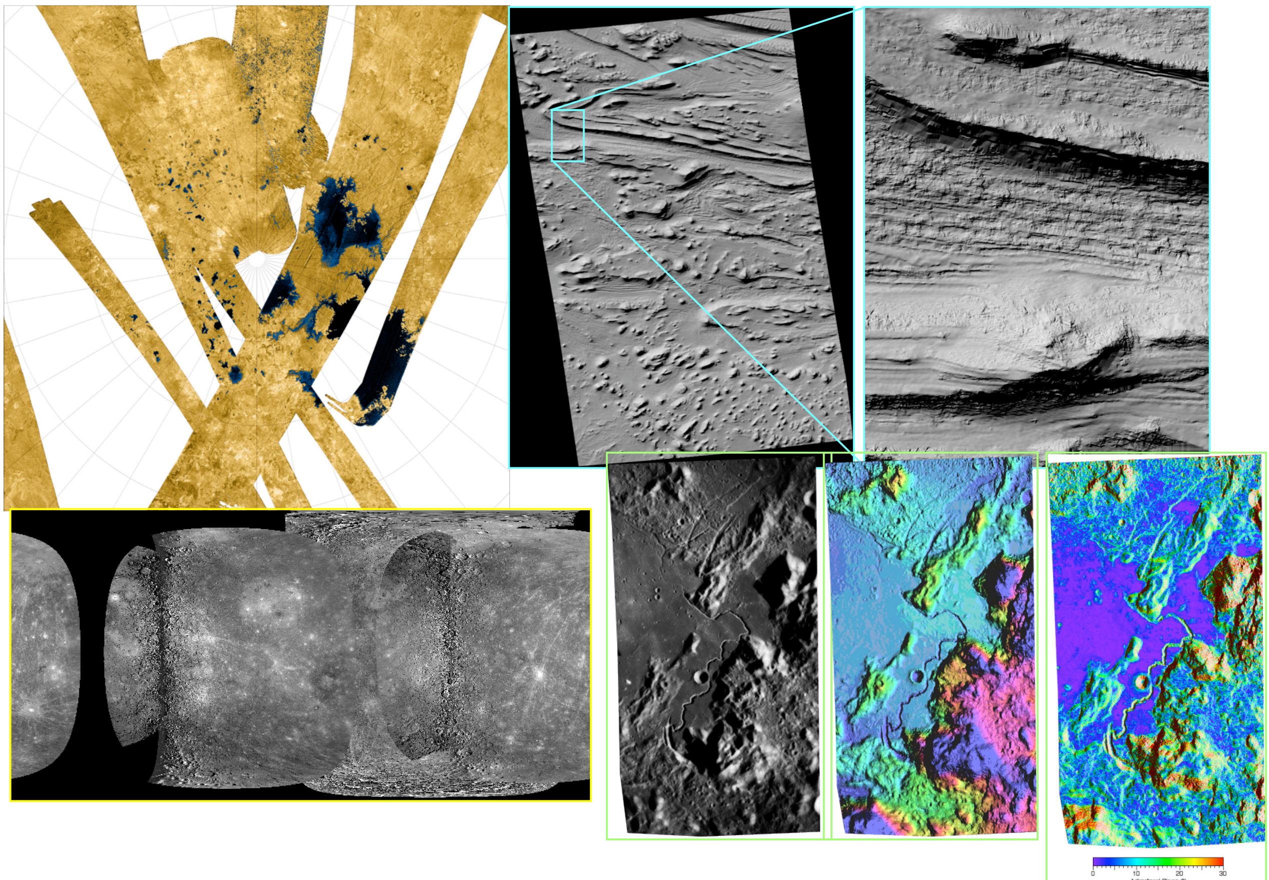

--Recent planetary cartographic products from USGS (*clockwise from upper left*): Cassini RADAR mosaic of Titan showing dark methane lakes; HiRISE DEM of ridged plains on Mars; MESSENGER + Mariner 10 mosaic of Mercury; Views of Hadley Rille region, the Apollo 15 landing site, including topographic maps generated from photogrammetric processing of stereo images.--

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INTRODUCTION

U.S. and international spacecraft missions have acquired enormous numbers of images and volumes of other data about the planets and their satellites. Most of these data sets are spatial in nature and thus must be assembled, compared, and analyzed by the methods of cartography. For example, scientists commonly require maps showing the distribution and relative locations of features of interest to present the results of their investigations and to provide geographic context for their research. Moreover, temporal data documenting active changes and diverse thematic data (e.g., morphologic, topographic, and spectral/compositional) from different instruments can be exploited best by bringing the observations into a common set of cartographic coordinates. Seen in this light, cartography is an essential link between the collection of raw (and usually highly fragmented) data by missions of exploration on one hand and the exploitation of those data to answer scientific questions and plan future missions on the other. Too often, however, planetary cartography is perceived as a discipline seeking to acquire and process data for its own ends, and thus as a competitor with missions and researchers for limited funding, rather than as a valuable partner. As a result, missions are often designed and operated in ways that make the cartographic assembly of data products *needed for science* more difficult and costly, and efforts to assemble raw data into coherent maps for research are delayed, descoped, or simply left undone because of a lack of identified resources. Faced with this situation, but needing data in cartographic form in order to proceed with research, planetary scientists have often had to prepare their own maps. The result, in the best case, is a needless duplication of effort to develop and apply mapping tools. Worse, individual efforts result in a confusion of scales, reference systems, and standards. A lack of organization and standardization of cartographic data acquisition and product planning means that maps from one scientist cannot always readily be compared to those from another, and leads to even more duplication of effort as products have to be remade before they can be analyzed together.

Numerous working groups, most of which are represented by the authors of this white paper, already exist with responsibilities for providing technical (i.e., what is possible?) and programmatic (i.e., what is needed?) advice on how planetary data should be acquired and processed cartographically to meet the needs of NASA's solar system exploration program and those of its international partner agencies. However, missing from these efforts is a strong and unified vision of the role of cartography in planetary science, accompanied by a high-level commitment to make resources available to bridge the gap from raw data to scientific understanding through the systematic creation of critically needed map products.

Since 1994, the Planetary Cartography and Geologic Mapping Working Group (PCGMWG) has overseen cartographic research and data production. The PCGMWG comprises scientists and mission team members who are knowledgeable in planetary cartography and mapping, including geologic mapping. Members of this group represent the planetary science community in evaluating and recommending work to be done by the planetary cartography community, especially that of the U.S. Geological Survey Astrogeology Science Center in Flagstaff, AZ. This group has become increasingly involved with the long-term planning of planetary mapping efforts for NASA, including establishing planetary mapping standards. NASA and the communities of planetary scientists also are advised by ad hoc and permanent committees of experts in planetary science, cartography, geodesy, nomenclature, data standards and archive formats. These include cartographic working groups for Mars and the Moon, International Astronomical Union (IAU) and International Association of Geodesy (IAG) working groups, the Planetary Data System (PDS) Management Council, as well as numerous mission-specific working groups for data archive and cartographic planning.

Planetary cartographic products and software systems in Astrogeology and elsewhere are created as a result of ongoing team research and development activities in the fields of planetary science, digital data processing, calibration, analysis, photogrammetry, photoclinometry, geodesy, and geologic mapping. The proposed tasks are initiated in response to perceived research or programmatic needs by NASA-funded planetary scientists, or as a result of direct requests from the PGG Program Manager or members of the PCGMWG.

Several other research or operational programs in the U.S. and abroad also provide support and/or guidance to NASA and plans for planetary cartography. Programs at the Jet Propulsion Laboratory such as the Multi-Mission Image Processing Laboratory (MIPL), the Solar System Visualization Project (SSV), and the Navigation and Ancillary Information Facility (NAIF) provide expertise in cartography and planetary data processing. Members of the Management Council of the PDS assist NASA and data providers with long-range planning for data acquisition, format standards, archiving, storage, distribution, and retrieval. An active cartography research program is conducted at the German Aerospace Center (DLR) Institute for Planetary Research in Berlin, and among colleagues at research institutes in the 17 member states of the European Space Agency (ESA). Scientists from other nations consult with NASA experts on planetary data acquisition instruments, plans, data analysis and archiving.

The NASA Planetary Cartography Program has a direct and immediate role to play in the development and implementation of the NASA Vision for Space Exploration (especially beyond low-earth orbit) and of the Strategic Plan 2006. Cartographic standards such as uniformity of coordinate systems, accurate horizontal and vertical positioning, mapping methods, and scales and schema should be vital components of plans for imaging and mapping the surface of the Moon, Mars, and other planetary solid surfaces in order to assist in characterizing and analyzing features, and to prepare for surface exploration by robots and humans. Multiple missions are underway or planned by the U.S. and other nations to collect unprecedented volumes of data from lunar orbit, and coregistered cartographic products generated from these data will be essential for planning and operating these and subsequent missions to the Moon. Similarly, plans for exploring and mapping Mars, asteroids, and the satellites of Jupiter will require application of rigorous cartographic standards, knowledge of current digital map databases and coordinate systems, and a clear understanding of how these databases might be expanded to accommodate new data.

Insufficient preparation has made the generation of these types of data products historically difficult. The best and most current example to illustrate this problem comes from the challenge of creating a global digital elevation model (DEM) for the Moon from existing and upcoming data sets. Data from the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) would comprise the dominant data set from which to construct a global DEM. However, LOLA's spatial resolution is only few km at the equator and insufficient to create a uniform, global DEM unless supplemented by small DEMs generated from overlapping stereo Narrow Angle Camera (NAC) images acquired by LRO, as well as DEMs from international missions (e.g., Chinese, Japanese, Indian missions, and perhaps upcoming missions from Germany, Italy and Russia). Indeed, there are no current U.S. plans to create a uniform global topography model, partly because such a product is deemed unnecessary for future NASA lunar planning, but also because LRO alone is not collecting the necessary data. International missions may collect the necessary data, but it is unclear whether those teams have the capabilities to create such a model. Other supplemental programs such as the Lunar Mapping and Modeling

Program have insufficient funding to fully accomplish this goal. Thus, the problem is larger than one program can accomplish alone. Despite this, the Constellation/Altair planning group (*ALHAT; Autonomous Landing and Hazard Avoidance Technology*) assumes DEMs will be made available when needed for future landings. Although the above example concentrates on lunar data products, similar examples can be drawn from martian data sets or cartographic products derived for the moons of the outer planets or asteroids.

In this white paper, we briefly describe seven key areas where greater attention should be paid in the next decade for data returned from all planetary missions. Although individual missions or instrument teams may well meet their minimum "mission success" criteria without considering these recommendations, the planetary community at large will suffer from duplication of efforts and greater chances for errors, thereby diminishing the cost return and scientific potential provided by the unprecedented quality and volume of planetary data to be returned in the coming decade.

CONCERNS AND RECOMMENDATIONS

1. Data Volumes

Figure 1 demonstrates the increasing volume of returned data expected for current and upcoming lunar spacecraft missions compared to data generated by current and historic martian missions. One year of images from the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) will represent approximately 1600 times the size of the entire Clementine ultraviolet-visible image dataset. It is important to realize that the numbers displayed in Figure 1 account for data only through the 2011-2012 timeframe. Data generated by LRO extended missions may exceed 1 Petabyte (1000 Tbytes), particularly if all reduced data products are accounted for. Additional data sets of likely use for lunar studies include recently digitized Apollo metric and panoramic images, LRO Lunar Orbiter Laser Altimeter (LOLA), Kaguya's Laser Altimeter (LALT) and Terrain Camera (TC), and Chandrayaan-1's Lunar Laser Ranging Instrument (LLRI) and Terrain Mapping Camera (TMC).

Our recommendations are to plan for sufficient algorithm, software, and technique development to support processing of large datasets *in advance* of missions. Given data volumes of this magnitude, waiting until the data have been collected before beginning such technology development delays the anticipated science results from the missions, which ultimately negatively impacts the ability of exploration programs from progressing efficiently.

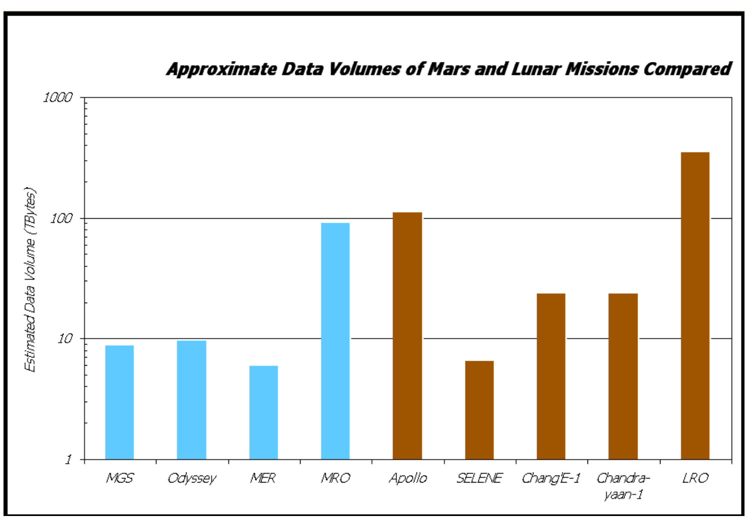

Figure 1. Historic and estimated data volumes (anticipated through 2011-2012) for lunar (*orange*) and martian (*blue*) missions. Log scale is from 1 to 1000 Terabytes. Not shown are totals from Mariner-9 (0.005 Tb), Viking lander and orbiter (0.059 Tb), Mars Pathfinder (0.002 Tb) and Phoenix (0.019 Tb) missions.

2. Data Complexity

Considering the escalating complexity of data sets acquired by modern instruments, it is becoming increasingly critical to plan data collection strategies well prior to missions. The array of current instruments includes line scanner, pushframe, and pixel scanning cameras, as well as altimeters and synthetic aperture radar instruments of various designs. The ability to successfully and precisely handle the complicated data sets collected by these instruments requires significant foresight into planning instrument design as well as operating the instruments during the missions. Figure 2 provides a useful example of the complexity associated with modern raw data sets, taken from the Mars Color Imager (MARCI) pushframe camera, in which 16-pixel framelets of image data are acquired in five sequential wavelengths and the pattern is then repeated along the flight track, resulting in the banded appearance of the raw image. For this camera, the narrow and barely overlapping "slices" of multispectral coverage were selected over the simultaneous coverage that could have been obtained with a set of framing cameras or a pushbroom with multiple detector lines.

The Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) provides a useful example of how new camera designs can result in inefficient data reduction. Collection of MOC images began in 1996, but it was not until 2003 that the complexity of the instrument and the data it acquired while on a jittering spacecraft were sufficiently understood by groups such as the USGS Astrogeology team to allow generation of DEMs from overlapping images acquired during multiple orbits. The capability to geometrically control and mosaic images from generic line scanner cameras was not fully generalized until 2007. Future challenges will have to be faced in order to develop techniques to geometrically "tie" images from altimeter data sets to images, or to combine altimeter data sets from different missions. Such steps are necessary to create uniform global lunar or martian DEMs. This capability is critical for landing site mapping and surface operations (e.g., MER, Phoenix, MSL, Altair), as well as for detailed science analyses (e.g., DEMs created from HiRISE and MOC images).

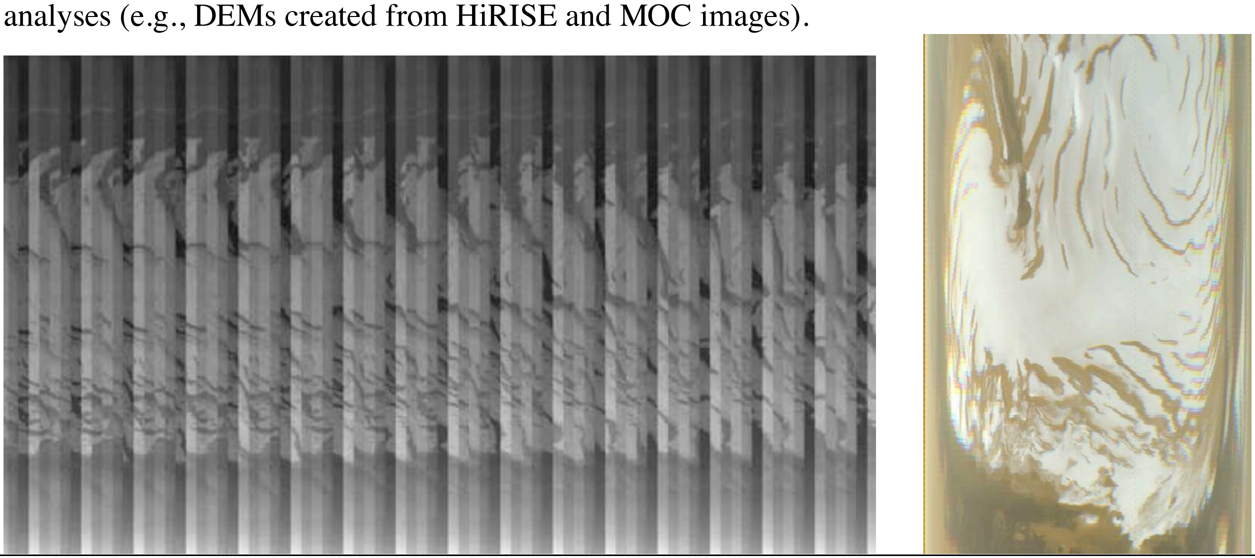

Figure 2. Example of (*left*) RAW MARCI image from the PDS, and an unprojected, false-color composite (*right*) constructed from left image.

Our recommendations are to plan for development of algorithms, software, and techniques to support processing of large datasets in advance of missions, as stated above, and to carefully balance the initial costs for instruments against the costs for future data processing needs to provide suitable products to complete the original science goals of the mission. Although innovative designs (as exemplified here by MARCI) may reduce the size of an instrument and the initial cost of building, flying, and operating it, they generally incur greatly increased processing costs if useful cartographic products are to be made from the complex raw data. A related point is that preflight radiometric and geometric calibration of instruments is an investment whose importance grows with the complexity of the data set. Skipping or simplifying such calibrations reduces the initial cost of building the instrument, but generally entails a massive research effort to reconstruct the missing calibration data from in-flight observations. In the worst case, it may compromise the ability to make the quantitative measurements needed to achieve science goals.

3. Mission Planning – Design and Operation

The examples provided above demonstrate how geodesy and cartography considerations need to be included in mission and instrument design well before the mission acquires its first data. Instrument teams often have little to no expertise in this area, and image processing software is often not in place until after the mission begins. Geodetically controlled products are rarely considered in either instrument design or data collections during mission operations, particularly with regard to international missions. Most often, image ingestion tools and radiometric/geometric camera models are written by mission team members, resulting in proprietary software that (at best) becomes available to the community only well after the mission is over. This results in duplication of processing software by others needing to make use of the data. The USGS Astrogeology team has often been asked to provide assistance to spacecraft teams after the mission has begun, and has been able to help to the extent that availability of its team members allows. Final generation of useful scientific data products is often reserved for later processing under Research & Analysis funds.

Current examples of the consequences of this lack of planning can be drawn from the LRO and Dawn missions. As described in the Introduction, the LRO mission did not include instruments to collect uniform global topography. Camera model development for the NAC and Wide Angle Camera (WAC) was delayed and later revealed that significant challenges are faced regarding how to geometrically control the WAC camera. As a result, it is likely that the main data sources required to generate a high resolution lunar DEM will be from the international missions. However, this will require advanced NASA/international mission cooperation that is only now being pursued. For the Dawn mission, the goals to “Determine volume, shape, spin state, composition, mass and environment” of Vesta and Ceres will require a high level of mapping and cartographic effort. Combining images from the Framing Cameras (provided by DLR, Institut für Planetenforschung and IDA, Institut für Datentechnik und Kommunikationsnetze) and the Visible/Near-infrared spectrometer (provided by the Italian Space Agency) will be difficult without formulating a detailed cartographic mapping effort prior to the first encounters.

Our recommendations are to require instrument teams to have expertise in geodesy and cartography, to have processing software in place before the start of missions, and to make available basic image ingestion and processing software (photometric and geometric camera models) to allow community use of images (e.g. using the public-domain ISIS or VICAR software packages). We also recommend that these teams assure that such processing software is released for use and supported. Additionally, mission teams should plan as part of mission development whether full processing (radiometric, geometric) of data will be done with mission funding or separate funding. Finally, we recommend that important international missions/instruments in development be identified early and that agreements be established to exchange data and work toward the generation of the products needed for future science and exploration.

4. Cartographic Standards and Conventions

As described above, there is always a need for NASA and international cooperation regarding coordinate standards and cartographic product conventions. When differences in a coordinate system/frame are discovered, datasets must be reprocessed and geodetically controlled, often at great expense. Further, such differences cause problems when comparing or understanding the derived data products. The solution of this problem involves both education and management to improve awareness of existing standards and conventions. For example, discrepancies up to kilometers can result from possible lunar coordinate differences owing to confusion over standards involving different mapping systems and frames. Such differences can be completely eliminated by the consistent adoption of standards and conventions.

Our recommendations are to continue to follow high-level IAU Standards and to provide funding to continue the working groups tasked with determining standards. It would also be useful to determine whether subgroups are desired for various planetary bodies that have no such standards working group. Finally, it should be discussed how modes of tracking adherence to these standards for derived products should be established.

5. Advanced Capabilities

This section is similar in some respects to the "Data Complexity" section above, insofar as it advocates for advanced, long-term development of algorithms and software needed to process data from many new camera systems. This level of algorithm development is traditionally difficult and requires sufficient lead time to ensure successful acquisition of data. For example, little effort has gone into processing of radar images (such as that required for use of Mini-RF data from LRO), or techniques necessary to project data onto complex three-dimensional surfaces. Such processing is critical for surface operations (e.g., MSL, MER) and for the integration of orbital, descent, and surface images and other data. Automatic stereo matching software for use with planetary images is only now under development. Presently available algorithms and software used to geodetically control global image datasets are now near their limits, at least in regard to the data volumes and numbers of images that can be processed. Improved algorithms and software are needed to geometrically control, mosaic, and photometrically correct large numbers of images (e.g., > 1000).

Our recommendations are to prepare in advance the necessary techniques and software to handle various camera types and radar instruments, as well as the geometric controlling of large numbers of images and associated photometric processing required for mosaicking.

6. Strategic planning for large scale projects

A frequent occurrence in planetary science is that instruments and missions are often approved and funded without sufficient regard to the total costs of making useful final products from the data obtained. The lunar global DEM example highlights the problems caused by this lack of foresight. International mission teams currently lack necessary algorithms and software to generate DEMs (although some are under development). Adequate algorithms and software are not currently available to combine altimetry data from each mission. The combination of image and altimetry data sets can help increase the coverage of DEMs, but only if all data are placed in the same reference frame. However, there are no plans to bring multiple DEM sources into same reference frame. This type of coordination would also benefit generation of global DEMs for Mercury using the MESSENGER Laser Altimeter and images from the Mercury Dual Imaging System (MDIS) combined with Mariner 10 images.

For Mars, the global DEM would have greatest fidelity by combining Mars Orbiter Laser Altimeter (MOLA), Mars Express High Resolution Stereo Camera (HRSC), the Context Imager (CTX) and THEMIS imagers on Mars Odyssey, Viking orbiter, and HiRISE stereo data from the Mars Reconnaissance Orbiter (MRO). However, there are no current plans to make global mosaics with THEMIS VIS images. For Mars Express HRSC data, photometric algorithms and software are needed to create global color mosaics and the camera team is only now proposing to begin the development of such tools. Similarly for data from MARCI and Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on MRO, mosaic processing algorithms and software that do not require proprietary software licenses still remain to be developed for the benefit of researchers outside the instrument teams.

For Cassini images from Saturn, there were originally no plans to make geodetically controlled Imaging Science Subsystem (ISS) mosaics of Saturnian moons. Limited work now is underway through R&A programs. However, there are no plans to make controlled Visual and Infrared Mapping Spectrometer (VIMS) mosaics of Saturnian moons. In particular, there are no long-term plans to register all Titan data. An interesting speculation is that if suitable cartographic planning had been performed prior to the Titan encounters, it is possible that Titan's liquid ocean would have been discovered much earlier. Indeed it still may be possible that a liquid ocean could be discovered on Enceladus using techniques developed to cartographically control overlapping images of that surface.

Our recommendations are to use long range planning to identify what planetary cartographic products would most benefit science and exploration, followed by advocating which future instruments and missions are required to obtain data for such products. As missions and instruments are proposed, we also recommend that the key final products be identified, such as geodetically controlled mosaics and DEMs. Creation of these products will require adequate funding during the mission (e.g. while the instrument team is still assembled to do so). Alternatively, suitable resources (funding, teams) should be identified for creating such products after the mission is over.

7. Final Recommendation

Our key recommendation centers on the need to create a long range planetary mapping and cartography plan. This could be done by the PCGMWG, with advocacy voiced by this Decadal Survey process (or a similar NRC study). With such a plan, cartography can become an integral part of all spacecraft missions and instruments, beginning in the development stages and continuing through mission operations and the data analysis portions of the mission. Without such a plan, the status quo will remain and the potential utility of the vast amounts of detailed data provided by these missions will remain either delayed or underutilized for the benefit of scientific discovery.