REGISTERING PLANETARY DATASETS FOR DATA FUSION: A “FORCE MULTIPLIER” FOR PLANETARY SCIENCE.

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Introduction: To optimize the usefulness of planetary data, they must be converted into knowledge by registration in a common coordinate system at known levels of accuracy. This step is essential for use of both individual data sets and of multiple data sets in combination. The latter is often called data fusion, and it is greatly enhanced by proper photometric processing and projection onto topography of any data sets, whether monochrome, color, multispectral, hyperspectral, radar, or lidar. This full suite of processing steps multiplies the value of registered data by orders of magnitude, promoting what could be the motto “more understanding and more science per dollar.” Our discussion here is one of a set of coordinated abstracts by the new NASA community-based Mapping And Planetary Spatial Infrastructure Team (MAPSIT, [1]) on the importance of cartographic processing for the successful use of planetary data.

Precision Cartography for Data Fusion: Registration of planetary data is part of an intertwined process of “precision cartography.” Geodetic control (i.e., improving consistency and accuracy of spacecraft trajectory and pointing information) is the biggest part of such cartographic processing [2], but it also includes calibration (i.e., knowledge of instrument geometry and its geometry relative to other spacecraft instruments) and topography (i.e., knowledge of the target geometry) to properly register data. Specification and use of an appropriate standard coordinate reference system and frame are also necessary [3]. All of these steps are in turn interwoven; calibration can be refined as part of the geodetic control process (“self-calibration” [4]), and the data used to generate topographic models and to register other data to topography must also be controlled.

Methods of Data Registration or Geodetic Control: Geodetic control essentially consists of performing least squares photogrammetric, radargrammetric, and/or altimetric solutions to register data into a common frame with known levels of accuracy. Control usually provides significant improvement over dead reckoning (i.e., positioning data based on *a priori* geometry data). Although the need for control solutions has been critical for early missions with lower accuracy *a priori* data, it is now even more essential for the massive, high-spatial resolution data sets now being obtained, where the resolution requires substantially better instrument and target geometry information for registration. And ***in all cases***, only control solutions support proper assessment of the relative and absolute uncertainty in the position of the data, a critically important (but sometimes overlooked) element of data fusion that helps to optimize its use for planetary exploration.

Tools to improve the development of control solutions for planetary data are critically needed [5]. Examples include the development of: a) better tie-pointing methods and statistical outlier detection algorithms; b) algorithms and software to efficiently process and store the massive data sets being returned by missions; c) development of methods to jointly tie together or process image, radar, and altimetry data; d) photoclinometric methods with error analysis capabilities; e) novel mapping methods for small and irregular bodies [6], which will be critical for properly processing existing and future datasets; and f) tools for near- or real-time data processing, for mission operations and fast science turnaround.

Data Fusion Examples: Precision cartography is required for effective and efficient planetary data processing. Examples of benefits include: a) ensuring that features appear only once via image correction such as mosaic seam removal; b) calculation of precision and accuracy of data placement in a mosaic; c) pixel averaging to improve signal to noise ratio (SNR) or for super resolution; d) analysis of illumination changes; e) change detection; f) development of consistent solutions for detailed topographic modeling; g) high-accuracy projection of images and other data onto topography; h) effective photometric corrections using topography; i) registration of *all* data from different instruments or missions into the same spatial frame; j) calculation of geophysical parameters such as body size, orientation, internal structure (including internal oceans); k) small body mapping using the required combination of imaging and lidar (for scale) to derive body shape models, and true albedo information; and l) accurate registration of color, multispectral, hyperspectral data for a given area acquired at different times. It is important to note that there is great value and economy of scale in having all data controlled in a single effort, both to provide the benefits listed here and to allow processing to be done most efficiently by experts using the most rigorous algorithms and software.

Several recent, high-value examples highlight the value of precision cartographic data processing in planetary science and exploration:

- Use of detailed surface topography of the lunar Apollo 17 landing site to properly project and photometrically correct Clementine Ultraviolet-Visible images of the Moon [7] and to substantially improve our understanding of the stratigraphy and context of samples collected from that site.

- Use of radargrammetry solutions and topography to control LRO Mini-RF images (Figure 1, [8]) of the lunar poles to support accurate identification and mapping of volatiles such as water.
- Remote and *in-situ* exploration of lunar polar volatiles [e.g., 9], including use of multiple registered data sets to identify and map volatiles and other resources to support long-duration human exploration and eventually real-time science operations.
- Advances in martian geology through detailed association of CRISM spectra with geologic features (defined by structure, layering, texture, etc.) and/or colors in HiRISE images. As a recent example, spectra of recurrent slope lineae indicate the presence of salts [10], supporting the idea that these are formed by brine flows.
- Assessment of the climate record of Mars through analysis of layers in the martian polar caps, including fine-scale characterization of layer thickness and orientation with HiRISE data [11].
- Use of topography to model "clutter" in sounding radar data (MARSIS [12] and SHARAD [13] at Mars, RIME [14] and REASON [15] under development for the Jovian system, and small body radar tomography by future missions [6]).
- Detection and mapping of volatiles and salts on icy satellites such as Europa [16] using high-spectral resolution telescopic data tied to color data from earlier missions such as Galileo. These studies support the existence of liquid oceans at the surfaces or interiors of outer Solar System bodies, expanding the search for habitable environments to our own neighborhood in space.
- Use of global control across multiple data sets over time to characterize the precise rotation state of the Saturnian moon Enceladus and to infer the presence of a global ocean on that body [17].
- Comparison of limited but high-resolution radar images of Titan with infrared images and spectra of lower resolution and broader coverage to understand and map geology (e.g., [18]) and to relate specular reflections to the geography of seas and lakes seen by radar [19]. Change detection and mosaic SNR improvement is also possible on Titan with visible [20] (see Figure 2), IR, or radar [21] images.

Summary: Planetary data must be registered in a common coordinate system to support the high level of accuracy and effectiveness enabled by the multiple high-quality data sets now in hand or planned for future planetary science and exploration. The precision cartography process outlined here must be a key element of any mission planning and execution. If sufficient resources are available to carry out such processing, the results hold the promise of substantially multiplying the value of planetary data and missions.

References: [1] Lawrence et al., this conference. [2] Edmundson et al. (2012) *Ann. Photog. I0-4*, 203. [3] Archinal et al. (2011) *CMDA*, 109, 101. [4] Brown (1976) *Int. Symp. On Geodetic Science*, Ohio State Univ. [5] Archinal et al. (2014) LPS XLV #2466; also see http://tinyurl.com/cartoplanning. [6] A'Hearn et al., this conference; Archinal et al. (2013), *IAA Planetary Defense*, PDC13-03-01P; Nefian et al. (2013) *NASA/TM–2013–216538*. [7] Robinson and Jolliff (2002) *JGR 107, E11*, 5110. [8] Kirk et al. (2013) *LPS XLIV*, #2920; Kirk et al. (2014) *LPS XLV*, #2548. [9] Heldmann et al. (2015) *Advances in Space Res. 55*, 2427. [10] Ojha et al. (2015) *Nature Geoscience, 8*, 829. [11] Hvidberg et al. (2012) *Icarus 221*, 405. [12] Orosei, et al. (2015) *Planet. Space Sci. 112*, 98. [13] Seu et al. (2007) *JGR 112*, E05S05. [14] Bruzzone L. et al. (2013) *IGARSS*, IEEE, 3907. [15] Paterson et al. (2015) *Amer. Astron. Soc. DPS Meeting 47*, 312.09. [16] Brown and Hand (2013) *Astron. J.*, *145*, 110. [17] Thomas, et al. (2016) *Icarus, 264*, 37. [18] Soderblom et al. (2007) *PSS 55*, 2025; Lopes et al. (2013) *JGR* 118, 416; Lopes et al. (2015) *IAU Gen. Assembly 29*, 2244602. [19] Barnes et al. (2014) *LPS XLV*, #1947. [20] Archinal, et al. (2013) *LPS XLIV*, #2957. [21] Hofgartner et al. (2015) *LPS XLIV*, #1538.

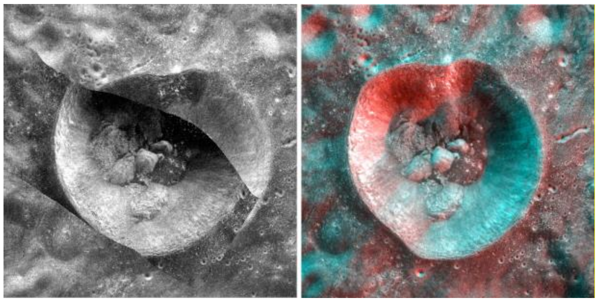

Figure 1: Comparison from [8] of uncontrolled (left) and controlled (right, with east-looking mosaic shown in cyan, west-looking in red) Mini-RF mosaics for Hermite A, a 20-km crater. Mismatches within and between mosaics are ~1-3 km uncontrolled, <30 m after control adjustment.

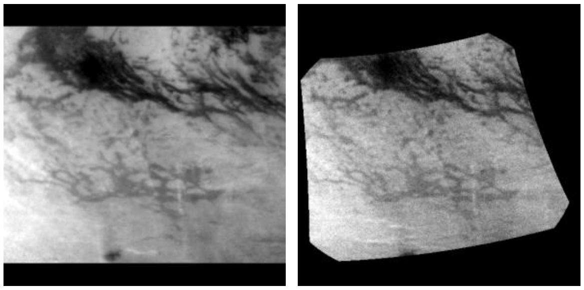

Figure 2: Controlled averaged Cassini ISS image mosaic [20] of a portion of Titan (left) vs. "best" image (right, N1624422569), showing SNR improvement.