CAN (AND WILL) THE DATA BE PROCESSED? TECHNOLOGY DEVELOPMENT TO ADDRESS SCIENCE QUESTIONS. Brent A. Archinal, Randolph L. Kirk, Lazlo P. Keszthelyi, Lisa R. Gaddis, and Mark R. Rosiek, Astrogeology Science Center, U. S. Geological Survey (2255 N. Gemini Drive, Flagstaff, AZ 86001, barchinal@usgs.gov)

Introduction: If a spacecraft instrument is built and flown successfully, does that guarantee that the collected data can be or will be fully processed to the community desired level of geodetically controlled science products? Although many users seem to believe that data are "publication ready" from the moment they are collected, further data processing is almost always required in order to fully understand and use the data, particularly relative to other datasets. Here we focus on one of the meeting objectives by discussing how a key portion of the "technology needed to address" science questions consists of calibration and processing capabilities on the ground. We also address the meeting topic of "lessons learned and vision for what is needed [for the] next generation of instruments." We provide recommendations that support the goal that instrument data can and should be processed into useful products. We describe standards and design criteria that will not merely enable but significantly facilitate the processing of data into scientific products, which in turn can be used for further scientific investigations or operational support of science missions.

Many of the issues discussed below were noted earlier in [1], or in our other reviews [2, 3, and 4]. Unfortunately, most of these issues still need to be addressed and must be considered in the context of future instruments and missions.

Instrument Calibration and Sensor Model Development: The geometric and radiometric calibration of essentially every planetary instrument flown is performed by a different team, using different techniques, standards, calibration methods, and levels of completeness, etc. There is clearly a strong need for standardization in such techniques, in order to assure that sufficient calibration has been completed, and to assure that users understand and can properly use the calibration data [5].

As noted by [4], there are currently only two broadly available software packages that are primarily intended for cartographically correct image analysis of *planetary* data: JPL's VICAR and USGS's ISIS. A huge barrier in using these packages is that for every new dataset to be handled, a geometric and radiometric sensor model embodying the full behavior of the instrument must be developed. In the past these models have often been added ad hoc, as a result of involvement by an investigator with a particular instrument or mission. Others are added years later as funding from various sources permits. Models for many instruments (including some currently active and others that obtained historically important coverage) still do not exist in such public software. The calibration standardization just discussed would greatly ease the development of such models. Further, instruments and missions need to plan to develop such models in VICAR or ISIS at the outset of mission planning (whether to be used in that software or by external software, such as the NASA Ames Intelligent Robotics Group Stereo Pipeline; see http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/ngt/stereo/), so that the collected data can be quickly used by the planetary community. A secondary benefit of this approach is that the instrument teams will be available to verify the correctness of the models. Instrument teams often develop their own custom software for such models, but this thoroughly validated software often exists in a one-of-a-kind or proprietary processing environment and is easily lost when the mission ends and the team disbands.

Need for Geometric Stability: The best possible geometric qualities and stability are usually desired in any instrument, so that the collected data can be properly processed into scientifically useful products. So far, only one high quality high resolution camera system of a fully photogrammetric design has been flown beyond Earth orbit: the Metric or Mapping Camera system flown on Apollo 15-17 [6]. The Apollo system not only included a large format framing (film) camera, but had properties that made it possible to accurately reconstruct the internal configuration of the camera ("interior orientation"). Reseau marks were used on the film platen (as they were also on vidicon tubes for missions with such sensors) in order to assist with such reconstruction. Such reseau information is no longer necessary in modern solid state (e.g., CCD and CMOS) sensors; what remains clear is that accurate reconstruction of the image geometry is still quite important, and that framing cameras provide many advantages in this regard. Current line scanner (or push broom) and push frame cameras are perceived to provide higher resolution data (for a given signal-to-noise ratio) and wider fields of view than framing cameras, at a lower cost. However, their primary disadvantage (even for cameras like the Mars Express High Resolution Stereo Camera (HRSC) where it otherwise could be – and has been – argued have the properties of a good photogrammetric system) is that the geometric accuracy of the collected data depends on accurate *and highly time-resolved* knowledge of spacecraft position and orientation. This has been shown to be problematic, since unmeasured and unmodeled spacecraft motions (particularly at high frequencies) known as "jitter" leave the actual geometric knowledge of image collection uncertain (at best) and often poor relative to the resolution of the camera. Jitter may in some cases be minimized by freezing moving parts such as antennas and solar panels during the collection of images, but the constraints of mission operations do not always permit this. In certain cases, distortions can be modeled and removed through photogrammetric processing of stereo image sets or data from multiple overlapping detectors (as on the HRSC and Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE) cameras, respectively). However, little can be done in the most common case of single image coverage and non-overlapping sensors. Even where the effects of unwanted spacecraft motion can be corrected, greatly increased processing difficulty and costs result. Therefore, for optical imaging, the first choice under geometrical considerations alone would be to use a framing camera. If a line scanner or push frame sensor is used, consideration should be given to simplifying spacecraft and payload designs to minimize the use of moving parts that contribute to jitter, and also as to what modeling and software development will be needed to process such images at the sub-pixel level of geometric precision and accuracy. To handle the data from a very high resolution camera correctly, the spacecraft and even the entire mission may need to be designed around the instrument, rather than the other way around. See [3] for more on this issue.

A related problem of geometric accuracy is that all images contain distortions due to topographic parallax unless a digital elevation model (DEM) of suitable coverage and resolution is used to orthoproject them. Global laser altimetry datasets exist for a few bodies (Mars, the Moon, Eros) at present and address this need in part (as well as providing the definitive reference for surface coordinates). Because of their resolution and especially inter-orbit gaps, however, these altimetric DEMs are inadequate for processing images from cameras such as Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) and HiRISE. If these very high resolution images are to be used to full advantage, a source of high resolution DEM data must be identified, either by stereo imaging with the camera in question or with another camera of sufficient resolution, or by future high density (scanning or flash lidar) altimetric instruments.

Need to Control Data: The need to register data to known levels of accuracy (i.e., control the data) is well known. This issue has already been discussed in [1, 2, 3, 8], but we repeat some important points here for emphasis.

The only way to connect/register/compare data with quantified precision and accuracy is to geodetically (usually photogrammetrically) process the data into controlled products. Otherwise the uncertainties in the relative and absolute positioning of data sets undermine their synergistic value. Users always want the best precision and accuracy possible and require that the precision and accuracy be quantified. Such knowledge is critical for mineralogic, geologic, and scientific investigations and exploration purposes such as site selection, landing and landed operations. Controlling any single dataset provides many benefits including a) the best method of removal of mosaic seams for qualitative work; b) proper orthometric projection of data (i.e., registration of images to topography in order to make or match existing mosaics and maps); c) registration of multispectral data; and d) proper photometric correction of data. The value of such control increases combinatorially when multiple datasets are considered, so it is essential that this work be planned for, and done with, all datasets of interest, whether past, present, or future. Geodetic control adds substantial value to the data, especially relative to the cost of data collection. Furthermore, if one considers the cost of the initial data collection or even the loss of a mission (e.g., landing at incorrect coordinates), such costs are absolutely necessary and relatively insignificant. Therefore, an important step in planning for the use of any instrument's data is to assure that it can and will be properly controlled, to the pixel and preferably (as users will request) to the subpixel level of the instrument's resolution. For example, LRO Wide Angle Camera (WAC) images have been successfully mosaicked into highly useful products [7], but whether their accuracy is better than the pixel level (e.g., a few hundred meters) is unknown. Mismatches at that level are visible in some comparisons we have made with LRO Lunar Orbiter Laser Altimeter topography models, but whereas a control solution would include documented accuracy statistics for the whole mosaic, at present such visual inspections must be made locally each time the use of the mosaic for critical applications is considered.

The creation of controlled mapping products is strongly supported via a number of advisory groups in a variety of contexts, including: 1) the NASA Planetary Cartography and Geologic Mapping Working Group (PCGMWG) [9] which notes the need to plan for the creation of controlled cartographic products; 2) the NASA Advisory Council [10] has recommended to NASA that all cartographic products for the Moon (the only body considered in the specific context, but the implication is for all bodies) be geodetically controlled; 3) the Committee on the Planetary Science Decadal Survey [11] notes that "R&A programs like planetary cartography are also critical for mission planning by ensuring that (for instance) cartographic and geodetic reference systems are consistent across missions to enable proper analysis of returned data" (page 5-16), and that "separate support should be provided for development of high-level data products in cases where such support cannot be provided by mission funding" (page 10-6); and 4) the IAU Working Group on Cartographic Coordinates and Rotational Elements [12, Section 8] has noted in their first recommendation "the importance of geodetically controlled cartographic products." They also note that "Although a flood of new planetary datasets is currently arriving, it appears that the production of such products is often not planned for or funded. We strongly recommend that this trend be reversed and that such products be planned for and made as part of the normal mission operations and data analysis process."

A final example of where data has not been geodetically controlled is with the Cassini ISS, VIMS, and RADAR data. It is possible that if such data had been controlled early on in the Cassini mission, the apparent non-linear rotation of Titan, supposedly resulting from an internal ocean, might have been discovered sooner. Similarly, if such data for Enceladus were to be controlled, it is possible that a similar discovery could still result.

Processing Algorithms and Tools Lag Behind Instrument Development: As noted above, sometimes processing tools are not available at launch, at first use of instrument, or even much later, if at all. For instance, the Mars Global Surveyor (MGS) spacecraft was launched in 1996, but stereo processing of the MGS Narrow Angle (NA) camera line scanner images into DEMs was not accomplished until the early 2000s [13] and large scale controlled mosaics of such images have to our knowledge still not be made. As another example, we noted in 2007 [1] that neither photogrammetrically rigorous algorithms nor the software based on them for efficiently controlling push frame images from cameras such as MRO Mars Color Imager or LRO WAC existed. As far as we are aware, this gap has yet to be filled. Aside from the difficulties of tie pointing extremely large numbers of "framelet" images with little overlap, and of handling the statistics of their position and pointing parameters correctly in the control calculation, these wide field cameras may also require optical distortion modeling beyond that used for previous instruments. A more general concern for all missions is that, although image tie pointing technology is improving, tie pointing of a few thousand images is still a major task [14]; current needs are to tie point hundreds of thousands or millions of images. In order to control images to the proper reference frame and to properly orthoproject them, it is also necessary to tie the images to ground control provided by lidar tracks or DEM data. Such ground measurements are largely made manually at present, with techniques to automate the process still a research topic. In addition, the technology for the photogrammetric adjustment of planetary data has been improved and can now handle thousands of images, but still has a long way to go to process orders of magnitude higher number of images [8]. Tools to process such large volumes of data, including making and using very large high resolution DEMs and mosaics, are neither as automated nor as simple to use as is desirable. There are also still concerns that as novel processing methods and algorithms are developed they may be put into production before their accuracy is properly evaluated and compared to the existing state of the art. For example the "stereophotoclinometry" (SPC) method of Gaskell et al. [15] has, to our knowledge, never been carefully compared to stereo or even photoclinometry processing results, even though it is being used for several operational and science applications. An important comparison of various methods for stereo and SPC processing of LROC images is currently underway [e.g., 16] and may help to address this issue.

Standards Issues: There is an urgent need to both follow existing standards regarding coordinate systems and frames and to further improve on them. As noted in [4], a number of crises in the early operations of instruments can be avoided if a consistent set of cartographic standards is agreed upon early in the development process, and substantial confusion can be avoided later if such standards are followed. We note that the primary body for coordinating such activities at a high level is the International Astronomical Union (IAU), via their Working Group on Cartographic Coordinates (WGCCRE) [12]. There are also specific NASA Working Groups for Mars and the Moon [17, 18]. Following recommendations from these groups is also required by the Planetary Data System [19]. These recommendations also need to be considered as part of the proposal preparation and selection process. The simple step of either having sufficient expertise as part of the proposed missions/instruments or educating the developers about any ground data system in these standards, with compliance assessed as part of the formal reviews of mission progress, could avoid the recurrence of the standards problems that have affected past missions, and ensure that gaps in the existing standards are addressed well before an instrument begins to return data.

There is also a need to investigate, develop, discuss, and coordinate standards for products to allow for their easier use, registration, and understanding. This is particularly true for bodies other than Mars and the Moon, which already have their own NASA Working Groups to assist with that process. Similar groups may be needed for other bodies where multiple missions are being undertaken or for small bodies generally if they indeed are to become targets for more missions and human missions

Current Processing Needs: For data already in hand, we recommend the following: a) further development of tie pointing methods, particularly for images to DEMs; b) improvement of photogrammetric control algorithms and software, and development of better methods to handle large data volumes and products; c) development of techniques and software to control push frame cameras (a lack first noted in [1] in 2007!); d) enforcement of current coordinate system, mapping, and product format standards and addition of requirements for sufficient expertise in the use of such standards; e) improvement of existing standards and the development of new ones as required by advances in detector technology and mission design; and f) testing and comparison of instrument processing methods, particularly those for DEM generation. Although this review is not generally intended to list datasets that currently require further processing or products that need to be made, an especially urgent need – as was discussed in 2007 – is to create the highest resolution and quality global DEMs of the Moon and Mars. Such products are needed as the base for processing of other current (and future) datasets for the given body. The creation of such DEMs will require the control and merging of the various existing high to moderate resolution datasets, so that they and other (non topographic) datasets can be properly registered for science and exploration uses. Archinal et al. [2] address this specific issue in more detail. Along those same lines, of course substantial efforts are actually needed to perform the processing of available data, but these fall outside the scope of our abstract.

Future Processing Needs: There are a variety of new issues that may arise for possible future missions. As an example, we examine the technology development needed to conduct small body mapping in support of operations and scientific analysis for future robotic or human missions to an asteroid: a) rapid incremental mapping, in which new observations can be added to control solutions and cartographic databases as they are acquired; b) true 3D mapping of highly irregular bodies, which may have occlusion of features by other features and possibly even multiple surface intersections for a given radius vector; c) development of methods for rigorous joint (simultaneous) processing of images and lidar data; and d) properly combining (with appropriate testing) stereo and photoclinometric mapping, using the geometric strength of stereo processing and the higher (single pixel) resolution of photoclinometric processing. Aside from the SPC method mentioned earlier, other researchers have developed such methods [20, 21] that could be adapted, improved, tested, and integrated into existing planetary mapping software (e.g., VICAR or ISIS). Onboard processing will eventually need to be developed in order to allow for autonomous operations, and would also be useful in low data down and uplink situations. Some studies of future human missions [e.g., 22] have also assumed on-board overnight global mapping ("detailed remote sensing and NEA characterization") capabilities. The development of such highly advanced capabilities needs to begin now in order to be ready for missions in the 2020s.

Conclusions: We summarize by noting the following key points from the above discussion.

1) The need for adequate capabilities to *process* the data into useful, controlled scientific products cannot be forgotten during instrument and mission development.

2) Multiple areas have been identified in which present-day cartographic processing capabilities must be improved in order to make full processing of future (and even some existing) remote sensing data sets possible.

3) Tradeoffs of sensor types (e.g., line scanner camera vs. framing camera) need to be considered in terms of data acquisition (spacecraft stability) and the complexity of data processing, and not merely in terms of performance (resolution, SNR, etc.) and the up-front cost of building the instrument.

4) There is always a need for a topography (shape) model for the registration and orthoprojection of any instrument data. Fully integrated global models need to be developed for the Moon and Mars, and the need for such models on any body should be part of the planning of any new instrument or mission.

5) Standards need to be enforced and further developed, to ease the understanding and use of data and to reduce confusion.

Finally, we note that we have *not* addressed here the need for planning and funding to actually do the primary instrument data processing once a mission is underway or even over, or for that matter *what* products still need to be made. Such data processing efforts are usually no longer included in mission and instrument proposals because they are not formally required and it is widely assumed that high level data processing can be completed with research and analysis funding. Unfortunately, most R&A programs—with grant allocations targeted in the $50-150K/year range—are highly unlikely to be able to cover the costs of processing all the data from a particular instrument. In our experience, reviewers often argue that such processing is not scientifically important enough—even though it is a fundamental requirement for making the data from that instrument scientifically accessible. We can only echo and highlight the Decadal Survey [11, page 10-6] that "*separate support should be provided for development of high-level data products in cases where such support cannot be provided by mission funding.*"

References: [1] B. Archinal, et al. (2007), "Urgent Processing and Geodetic Control of Lunar Data," Wkshp. Sci. Associated with Lunar Exploration Arch., http://www.lpi.usra.edu/meetings/LEA/whitepapers/ArchinalLEA07_Archinal_datacontrol.pdf; [2] B. Archinal, et al. (2012), "Unifying Lunar Topographic and Other Datasets," *LPSC XLIII*, #2394; [3] R. L. Kirk, et al. (2012), "Landers and Rovers Need High Resolution Topographic Maps: Lessons from the NASA Mars Exploration Program," *Concepts and Approaches for Mars Exploration*, #4361; [4] M. Milazzo, et al. (2012), "Improved Data Processing Approaches for Future Mars Exploration Missions," Concepts and Approaches for Mars Exploration, #4351; [5] Salah and Kirk (2012), *this conference*; [6] R. Livingston, et al. (1980), "Aerial Cameras," *Manual of Photogrammetry, 4th Edition*, Slama & Theurer (eds.) American Society of Photogrammetry, Falls Church, VA, 187–278; [7] E. Bowman-Cisneros, et al. (2012), "The Lunar Reconnaissance Orbiter Camera PDS Data Node," Lunar Science Forum 2012; [8] K. Edmundson, et al. (2012), "Jigsaw: The ISIS3 Bundle Adjustment for Extraterrestrial Photogrammetry," *Int. Arch. Photogr. & Rem. Sen.*, in press; [9] J. R. Johnson, et al. (2010), "The Importance of A Planetary Cartography Program: Status and Recommendations for NASA 2013-2023," Planetary Science Decadal Survey White Paper. See http://www8.nationalacademies.org/ssbsurvey/publicview.aspx; [10] NASA Advisory Council (2007), "Recommendation S-07-C-13 of the NASA Advisory Council to NASA Administrator Griffin, p. 14, see http://bit.ly/x0HnnM; [11] Committee on the Planetary Science Decadal Survey (2011), "Vision and Voyages for Planetary Science in the Decade 2013-2022," National Research Council, Washington, D.C.; [12] B. Archinal, et al. (2011), "Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009," *Cel. Mech. & Dyn. Ast.*, 109, no. 2, 101-135; [13] R. L. Kirk (2003), "High-resolution topomapping of candidate MER landing sites with Mars Orbiter Camera narrow-angle images," *JGR*, 108, no. E12, 8088; [14] E. Lee, et al. (2012), "Controlled Polar Mosaics of the Moon for LMMP by USGS," *LPSC LXIII*, #2507; [15] R. W. Gaskell and N. Mastrodemos (2008), "Lunar topography from stereophotoclinometry," *LPSC XXXIX*, #1152; [16] R. Beyer, et al. (2011), "LROC DTM Comparison Effort," *LPSC XLII*, #2715; [17] T. Duxbury, et al. (2002), *ISPRS*, 34, pt. 4; [18] B. Archinal and the LGCWG (2009), *LPSC XL*, #2095; [19] PDS (2009), Ch. 2 of PDS Standards Reference; [20] S. Gehrke and I. Haase (2007), "HRSC Data Processing by Matching in Object Space: Joint Derivation of DTM and Orthoimage for an Impact Crater on Mars," *LPSC XXXVIII*, #1496; [21] V. Lohse, et al. (2006), "Derivation of Planetary Topography Using Multi-Image Shape-From-Shading," *PSS*, 54(7), pp. 661–674; [22] V. Friedensen, et al. (2011), "Meeting Objectives for Human Exploration of Near-Earth Asteroids: First Steps in Understanding How to Explore," *IAA Planet. Def. Conf.* Abstract at http://www.congrex.nl/11C03/docs/11C03_Planetary_Defense/session6.htm.