Image-Based Topographic Mapping of the Moon

Response to "Request for Information (RFI): Developing a Strategy for Future Exploration of the Moon and Beyond"

12 May 2006

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Introduction

Our objective in this response to the NASA Request for Information is to point out the critical need for a topographic mapping program as one component of the future exploration of the Moon and beyond. Such a suggestion may seem unusual in comparison to the types of ideas that are likely to constitute the majority of responses to the RFI, namely, specific scientific objectives, mission architectures, and the like. Nevertheless, the past history of lunar and planetary exploration strongly supports the proposition that a robust and effective mapping effort is an absolutely critical support component for any successful program of exploration, whether lunar or trans-lunar, robotic or human. Topographic mapping is merely one component of this cartographic infrastructure that is required for exploration. Others include global geodesy and production of image mosaics (to develop the well-defined coordinate system to which all exploration and exploitation activities will be referenced, and populate it with accurately registered data from multiple missions); geologic mapping (to identify both the scientific questions and the in situ resources of greatest value, and to indicate the locations where these high-value objectives may best be pursued); and geographic information systems (to store the enormous amounts of map data produced by the other activities and provide tools for their analysis). These aspects of an overall cartographic program are the subjects of separate submissions from the Astrogeology Team, U.S. Geological Survey.

In this document, we first describe how topographic mapping—by which we mean the analysis of image data by photogrammetry (stereo) and photoclinometry (shape-from-shading) techniques to provide more detailed datasets than can be obtained by altimetry alone—relates to all elements of the lunar exploration strategic plan. Detailed topographic information is useful in every step of the exploration process, but is particularly critical to the objective of landing either robotic probes or humans safely. We next discuss the current state of the art in topomapping and indicate why the laser altimeters that will be carried on the next generation of lunar probes will not completely satisfy the need for high-resolution topographic data. As part of this discussion, we identify areas where investments in research, development, and infrastructure are likely to be necessary. The range of applications for lunar topographic data and the realities of producing topographic data from images lead to some general conclusions about the dependencies of such mapping work on missions that supply data, and dependencies of customer missions on the topographic mapping effort. The specifics of a timeline for lunar topographic mapping will depend in large measure on the timing of customer missions, as well as on the decision whether to support only mapping focused on specific needs (such as landing site certification) or to initiate a systematic program of lunar mapping, costing a few millions to tens of millions of dollars at most, that would exploit the full potential of the image sets that NASA and other space agencies are spending hundreds of millions of dollars to obtain. The characteristics of the datasets from past and planned missions, which are better known, are also an important determinant. This document therefore concludes with a description of the most important lunar image datasets and the kinds of topographic products that could be generated from them.

Relation to the Key Elements of the Lunar Exploration Strategy

Because topographic data are an important ingredient of all phases of exploration, from design and planning of missions to analysis of the results, the need for a systematic program of topomapping arises in every key element of the exploration strategy. In consequence of this breadth of applicability, the following examples are necessarily selective and illustrative only.

Lunar exploration activities that are an integral part of a broader exploration strategy that encompasses Mars and other destinations

The interaction between topomapping in support of lunar exploration and that in support of planetary (particularly Mars) exploration is bidirectional. The recent Mars program has generated a large experience base with planning and operating complex missions, and provides many of the examples listed below of how topomapping is essential to these activities. The Mars program also provides some examples of mistakes to avoid. (Similar conclusions and examples can be drawn from the period of lunar exploration in the 1960s-70s, though the specific technologies are less relevant today.) Looking in the other direction, a well-planned program of lunar topomapping will serve as an example for how to support the exploration of other bodies in the future. Specific investments in topomapping capabilities (e.g., research into more efficient methods of controlling and analyzing images, acquisition of specialized computer facilities for large-volume topomapping, or development of advanced sensors optimized for stereo imaging) that might be made by the lunar program would directly benefit subsequent exploration efforts elsewhere.

Lunar robotic activities that collect key strategic information and develop key capabilities to enable and enhance human exploration

This connection operates both directly and indirectly. As we argue throughout this section, topographic information is used at all steps of the exploration process: framing scientific (and, later, exploitation) objectives, locating safe landing sites, conducting surface operations, and interpreting scientific observations from a given mission. The eventual human missions to the Moon will make use of topographic data in all these ways. They will thus be reliant on the robotic missions that have already provided stereo imagery of the Moon (Lunar Orbiter, Clementine, SMART-1), those that are being prepared to do so in the near future (SELENE, Chandrayaan-1, Chang'E-1, Lunar Reconnaissance Orbiter), and follow-on missions, which might offer the opportunity to obtain images optimized for stereo mapping needs. Processing of the stereo images returned by these missions into digital topographic products can be seen as the final, critical step that the missions need to carry out in order to fulfill their obligations toward future human exploration efforts. We do not mean to suggest that such processing must be carried out within the budget of each given mission (this is clearly an impossibility for the past missions, and may be impractical even for future ones), but it *must* be carried out somehow, and the overall program of exploration must therefore find a way to provide the needed resources.

The indirect connection is analogous but even more time-critical. Eventual human exploration of the Moon will be partly reliant on scientific and engineering data provided by robotic expeditions to the lunar surface. These robotic landers will have many of the same needs for topographic data for landing site safety assessment and for surface operations as will the human missions, but they will need the data much sooner. The need for systematic, high resolution topomapping of candidate landing sites as part of the process of selecting and validating a safe site (Golombek et al., 2003; Arvidson et al., 2006; Kirk et al., 2003b; 2006b) is now fully recognized within the Mars exploration program and some funds have been set aside (in the Mars Critical Data Products Initiative, which the lunar exploration program might do well to emulate) for this mapping activity. This recognition was somewhat slow in coming, and, in the past, the purely engineering activity of topomapping landing sites has been outside the budget scope of the interested missions and a "hard sell" to science-oriented research and analysis programs. The lunar exploration program clearly stands to benefit by incorporating the lessons learned by the Mars program in this area into its strategic planning.

Lunar activities that enable humans to live and work productively on the Moon, including developing and using lunar resources

The ultimate requirement for living and working on the Moon is landing safely on the Moon, and the ultimate example of the importance of topographic knowledge comes from the first human landing. Apollo 11 came within seconds of running out of descent engine propellants (with loss of the crew a likely outcome, and mission failure guaranteed) because of the need to avoid an unexpected topographic hazard at the targeted landing point. When NASA resumes human exploration of the lunar surface, this kind of unpleasant surprise will simply be unacceptable. It will be necessary to know in advance every topographic feature in the landing area is big enough to potentially interfere with a successful landing. Moreover, the positions of such features must be accurately established within a well-defined coordinate system that is also used in navigating the spacecraft. There is little point in having a good map of the wrong part of the Moon.

Less dramatically, topographic data will also enter into the planning and conduct of everyday activities of astronauts on the Moon in ways that are clear by analogy to current robotic rover missions and to Earth-bound engineering activities. For example, topographic maps will be essential for planning of surface traverses because they define many of the most important constraints such as trafficability, communication lines of sight, and availability of solar power. The topomaps of the MER landing sites that we (USGS) have derived from orbital images are already being used in all these ways in the operation of the Spirit and Opportunity rovers (Li et al., 2005). Good topographic information will also be a requisite for determining the sites, locating the materials, and planning the construction of lunar infrastructure from bases and landing pads to observatories and resource mining activities.

Activities that enable opportunities for international collaboration through merging of common interests in respective strategic plans for exploration

The needed program of topographic mapping in support of lunar exploration offers multiple opportunities for international collaboration. At present, four nations or groups of nations besides the US are conducting or planning lunar missions that will collect stereo images that could be used to map at least parts of the Moon at various scales: Europe (SMART-1), Japan (SELENE), India (Chandrayaan-1), and China (Chang'E-1). It is clearly in the interests of the United States and of NASA not only to negotiate access to these datasets for use in planning and operating our own missions, but also to collaborate as closely as feasible on the planning and execution of the missions. By addressing such issues as the optimal design of image sequences for mapping, and by negotiating clear international standards for formatting, cataloguing, and archiving the data, NASA can maximize the value of such datasets for planning of its own missions, for its own program of scientific research, for collaborative research with foreign agencies, and, ultimately, for foreign and international landed missions. Finally, it should not be forgotten that countries besides the US have significant experience in photogrammetric mapping techniques, including extraterrestrial mapping. The High Resolution Stereo Camera experiment on the current ESA Mars Express orbiter is a showcase for such expertise (Scholten et al., 2005; Albertz et al., 2005), which NASA could benefit from by pursuing two-way collaborations on lunar mapping. The Mars Express mission is also (along with Cassini/Huygens) an outstanding example of the way in which exploration missions can be undertaken collaboratively.

Characterization of opportunities for science investigations on the Moon
The value of topographic information for geoscientific investigations is well established, so a few examples of applications will suffice here. The most important is that geologic mapping—which addresses the history and location of events by which features were formed, and thus points the way to the locations of greatest value for both science and resource exploitation—is critically dependent on topographic data. Although it is possible to make photogeologic interpretations from "flat" two-dimensional image data in simple cases, geologists are trained to make use of stereo images and topographic maps because such products greatly clarify superposition relationships, which in turn are the keys to sequence and timing of geologic activity. In some cases, the three-dimensional view may even reveal subtle differences of elevation or texture that distinguish adjacent geologic units and would otherwise go unsuspected. *Quantitative* topographic information spans the gap between geology and geophysics by constraining the details of processes (e.g., formation and degradation of impact craters, or intrusive and extrusive volcanic activity) that formed the landscape. One perhaps less obvious scientific application of digital topographic data is its use in correcting multispectral image data for orientation-dependent photometric effects (Kirk et al., 2006a). Without such correction, variations in brightness and color that are actually due only to slopes could mask or even be mistaken for subtle spectral variations that indicate compositional variations of scientific or resource value.

Activities that can enable lunar commerce
In the interest of brevity, we merely point out that most such commercial activities that have been discussed involve civil engineering activities such as base construction or mining on the lunar surface. On the Moon, as on Earth, civil engineering cannot proceed without accurate topographic maps.

Activities that can engage the general public in lunar exploration

The value of topographic data in this area has been amply demonstrated by the robotic lunar and planetary exploration program to date. Digital topographic models are the key ingredient (along with co-registered image data) in the production of synthesized perspective views of planetary surfaces. Such perspective views, either as stills (including free-viewing 3D images; see Buchroithner et al., 2005) or as "flyover" video clips, have been the mainstay of recent missions in bringing their results before the public. Future advances in technology will only increase the range of possible products of this kind and their public appeal. For example, high resolution imagery from orbit and from landers/rovers would lead to visualization at the "walk-through" rather than flyover level, and advances in computer technology could make this experience of walking on the Moon interactive rather than strictly pre-programmed. Nested data of increasing resolution, as are likely to be available around landing sites, could also be used to relate the human-scale environment on the surface to the bigger global picture: it will be possible to "zoom" continuously from the view of the Moon as seen from Earth to the experience of standing on the lunar surface, *and to do this with real data for a specific site, rather than as a generic simulation*.

Digital Topographic Mapping: State of the Art and Needed Developments

Perhaps the most obvious questions about image-based topographic mapping are whether it is needed, when the next generation of lunar orbiters will all carry laser altimeters that will yield millions to billions of height measurements directly, and, if so, why. The recent period of robotic exploration of Mars provides an analogy that is directly relevant in answering the first question. The Mars Orbiter Laser Altimeter (MOLA) made over 600 million height measurements, yielding a topographic dataset of unprecedented accuracy and phenomenal value that literally revolutionized the fields of martian geology and geophysics (Smith et al., 2001). Nevertheless, the production of digital topographic models (DTMs) and topographic maps from image data remains an active part of the Mars cartography program, and such products are desired for geologic mapping studies and strictly required in support of landing site selections and surface operations (Kirk et al., 2003b; 2006a; 2006b; Scholten et al., 2005; Albertz et al., 2005; Rosiek et al., 2005). The current generation of Mars orbiting missions includes a camera that was designed from the ground up to obtain optimal stereo images for topographic mapping (Mars Express HRSC) and one that, though not designed exclusively for such mapping, features stereo pair collection and DTM production as a central part of its operations plan (MRO HiRISE). To understand why image-based topomapping is valuable even in an era of abundant altimetry data, it is useful to understand the essentials of producing DTMs from images. This will also lead to a set of recommendations as to where strategic investments by the lunar exploration program could improve the process of topographic map production.

The primary means of deriving topographic data from images is photogrammetry, defined as the art and science of making (geometric) measurements on images. The field, which dates from the nineteenth century, rests on the realization that knowing the position of some object or feature in an image does not tell us the position of the object in the real world, but it does indicate that the object lies somewhere along a particular line passing through the camera. Only the distance from camera to feature along this line is unknown. With two images showing the same object, the real-world location can be calculated as the place where the lines from the two cameras intersect. Thus, the main work of making a topographic model or map by photogrammetry is to identify the same feature in two or more images, and to do this for as many features as closely spaced as possible. As each such "match" between the images is determined, calculating the coordinates of the feature on the ground is a matter of straightforward geometry. The ground coordinates are derived in relation to the positions and pointing of the cameras, which may not be known accurately in advance, so a usual preliminary step is to *control* the images: pick a few features for which ground coordinates are already known (e.g., from altimetry) and adjust the positions and orientations of the cameras until the photogrammetric calculations give the right result for the ground positions of these features. If this is done, subsequent products derived from the image pair are said to be controlled, and will be consistent with the dataset they were adjusted to fit. If it is *not* done, the topographic map may contain accurate details, but they will not be correctly positioned and will lead to erroneous (and potentially fatal, in situations such as precision landing) conclusions.

In the Apollo era, the process of identifying matching features in stereo pairs of images was done entirely by the human brain: skilled operators would view the images through a complex (and expensive!) opto-mechanical device and steer a floating mark along the surface to measure out elevation contours. Since the late 1980s, it has been possible to use digital image processing techniques to identify large numbers of corresponding points in an image pair relatively rapidly (Agouris et al., 2005). Such automated stereomatching is not only faster and than manual contour tracing, but also results in a dense set of elevation measurements (a digital topographic model) rather than isolated contour lines. The resulting DTM is thus useful for applications such as slope distribution modeling, photometric correction of images, and 3D visualization, that would not be possible with contour data. Of course, contour maps can also be derived from the DTM if desired. The achievable horizontal resolution of a stereo-derived DTM is a few image pixels at best, because the image matching process is based on identifying corresponding patterns or "patches" of pixels. The vertical precision of measurements depends on the resolution of the images, the stereo geometry, and the precision with which matches can be made, which is usually about 0.2 pixel (e.g., Kirk et al., 2003b). Thus, stereomapping with MRO HiRISE images (at 0.3 m /pixel) would yield a DTM with a vertical precision of a fraction of a meter (comparable to MOLA altimetry). The horizontal resolution, however, would be on the order of 1 m, which vastly exceeds the MOLA resolution as limited by spot size (~100 m), along-track point spacing (300 m) and inter-track separation (gaps of 1 to several km are common).

Automated, "softcopy" stereomatching is directly applicable to modern images, which are obtained in digital form by electro-optical sensors such as CCD cameras. Softcopy mapping can also be applied to the photographic images, however, once these images are digitized and supporting data are made available. As discussed below, the lunar photographs obtained by the Lunar Orbiter and Apollo 15, 16, and 17 missions have tremendous potential value for mapping of significant portions of the Moon, including past landing sites and many sites of high interest for science and potential future landings (Rosiek et al., 2006). Systematically digitizing such images would also increase their availability for photogeologic interpretation, but whereas such interpretive use places only loose requirements on image quality, photogrammetric use requires that the images be scanned with a high-quality, geometrically accurate system intended to support such analysis.

The main limitation of automated digital stereomapping techniques is that they are not completely reliable. Although it is sometimes claimed otherwise in the planetary science community, it is extremely well established in the broader photogrammetry and mapping community that automated matching alone is not sufficient to produce reliable, error-free DTMs. Automatically generated DTMs must be quality controlled by a human operator (who uses a stereoscopic computer display to view the height points overlaid on the images and detect places where the computer-generated points do not lie on the surface), and anywhere from 5 to 30% of the points must be edited manually (Agouris et al., 2005, p. 961). This quality control and editing step is the most labor intensive part of photogrammetric mapping (followed somewhat distantly by controlling the images, all other steps being largely automated). It also requires specialized hardware (stereo display and 3D input device such as a mouse with thumb wheel) and software to make use of this hardware for DTM editing. Such capabilities (along with automatic matching, image control, and other processing tools) are available as part of several commercial systems for digital stereomapping. Prices for such systems typically range up to about $100K per workstation. A wider variety of automated matching algorithms have been developed by individual research teams (and thus may be available freely or at lower cost than commercial systems), but generally do not include quality control/editing capabilities and are therefore not useful for producing topographic models and maps.

The success rate for automated stereomatching techniques depends on a variety of factors, some of which are under human control and some of which are not. For example, image matching is made more difficult by any factors that decrease the resemblance between the images, such as large differences in resolution, differences in illumination, actual changes to the surface (and, for Mars, the atmosphere) between acquisition of the images, or very large convergence angles between the images. Matching success can be optimized, and manual editing minimized, by obtaining image pairs with similar resolution and illumination, separated by as short a time as possible, and with modest convergence angles in the range 15° to 45°, depending on the surface roughness. Other factors are not under control; for example, automated matching tends to fail both for very smooth surfaces (which lack features that can be identified and matched) and very rugged ones.

One additional factor that can greatly complicate the stereomapping process and is not under the control of the photogrammetrist is the type of camera used. Recent Mars orbiters, and the lunar missions currently being planned, have favored "pushbroom" scanning cameras, mainly because they can collect very large images compared to more traditional framing cameras. Each line of output from such a scanner is geometrically a separate image, however, which greatly complicates the photogrammetric analysis. Whereas the geometry of a frame image is characterized by a three-dimensional camera position and three pointing angles, a scanner image in principle requires this set of six parameters for every line. Software exists for working with scanner images, and is based on the assumption that the position and pointing of the camera vary rather smoothly from one line to the next. In fact, the effects accounted for are usually limited to an overall deviation of position and pointing from the previously assumed values (just as for a frame image) and perhaps linear drifts of these parameters during the time the image was taken. Such a limited set of parameters can be solved for (i.e., the scanner image can be controlled) with only a few more ground control points than for a frame image. Unfortunately, the real world is not so simple. Scanner images are subject to complex internal distortions because of relatively rapid, uncontrolled and largely unmeasured motions of the spacecraft platform, commonly described as "jitter". Such distortions are subtle enough that they are generally invisible in a single image (though close attention might show "wandering" of straight features such as faults) but show up dramatically when pairs of images are compared in stereo, especially if the image resolution is very high. If uncorrected, these distortions introduce washboard-like artifacts into the DTM, and in severe cases they can make automated stereomatching much more difficult or impossible (Kirk et al., 2003b). In principle, it should be possible to model (and correct for) spacecraft jitter as part of the process of controlling the images. In practice, this will take a significant development effort to incorporate a model of the jitter motions into the adjustment software used, and will necessitate the collection of a much larger volume of control point measurements for each stereopair, in order to constrain the complex motions.

Another image processing technique that can be used to generate useful topographic data is photoclinometry, known more descriptively in the terrestrial community as shape-from-shading. This class of techniques (which have been implemented in many different ways; see, e.g., Kirk, 1987; Kirk et al., 2003a) are based not on the geometry of the images, but on photometry: bright areas are inferred as sloping toward the sun and dark areas as sloping away, and from these slope estimates a DTM can be built up. As a result, photoclinometry lacks the geometric rigor of stereomapping, but it can be used to produce a DTM with details at the scale of individual image pixels, as compared to no better than 3 to 5 pixels for stereo. The two methods are thus complementary, and the best use of photoclinometry may be to refine the small details of a DTM derived from stereo, while retaining the absolute accuracy of placement for larger features. Photoclinometry has been used extensively in the process of assessing landing site safety for Mars missions, because it improves the resolution of topographic information that can be derived from a given type of images. The techniques currently in use have some shortcomings, however. They are computation-intensive and require a substantial amount of experience and human supervision to apply. In addition, most current techniques deal with a single image and cannot discriminate between slope-related brightness variations and actual differences in reflectivity (albedo). Where stereo data are available, these limitations can be mitigated by using the stereo DTM as a starting point for photoclinometry and as a guide to separating out albedo variations. More advanced photoclinometric methods that compare multiple images and use both stereo and brightness information to deduce topography and albedo simultaneously are currently on the cutting edge of development (Lohse et al., 2006).

We note in passing that both the Chandrayaan-1 and LRO missions will carry synthetic aperture radar (SAR) instruments, and that SAR images can be analyzed to yield topographic measurements by radar-stereogrammetric (Howington-Kraus et al., 2000; 2002) and radarclinometric (Kirk, 1987; Kirk et al., 2005) methods that are directly analogous to photogrammetry and photoclinometry. These methods offer the possibility of making topographic maps of permanently shadowed areas of the Moon based on radar imagery.

The discussion above leads to the identification of the following areas where NASA can improve the efficiency and probability of success of topographic mapping in support of lunar exploration by strategic investment in the following areas:

- Facilitate the participation of photogrammetric and cartographic experts on lunar imaging experiment teams (including international cooperation, where appropriate), in order to ensure that images are collected in ways that are optimal or at least adequate to support topographic mapping requirements.

- Establish an enlarged photogrammetric mapping capability, adequate to produce topographic maps at the resolution, size, and rate that is determined to be necessary to support the exploration program (this is discussed further below). This activity includes the *timely* acquisition of multiple commercial stereogrammetric hardware/software systems, as well as hiring and training of personnel needed to operate them.
- Undertake a systematic effort to digitize the complete sets of Apollo Panoramic and Metric camera images, using a high-quality scanning system intended for photogrammetry (the majority of Lunar Orbiter frames, which are also useful, are already being scanned and reconstructed by the USGS). If possible, the original film rather than higher generation copies should be scanned. Support data (spacecraft position and orientation) should be made available in digital form along with the images.
- Support research and development of advanced automatic stereomatching algorithms that would improve matching reliability and hence reduce the reliance on interactive editing of DTMs.
- Support research and development on control software for pushbroom scanner images that incorporates models of spacecraft "jitter". Software to collect larger numbers of control points much more efficiently than is currently possible (i.e., by automatic identification and matching of such points rather than manual means) is also needed, as is software to remove distortions from the images based on the estimated jitter. Such techniques are also needed in order to control scanner images for production of image mosaics, particularly if large (global or regional, high resolution) mosaics are desired.
- Develop hardware systems for advanced missions that would eliminate the need to reconstruct jitter by photogrammetric analysis. Ideally, this means the development of CCD framing cameras with much larger image format than those flown in the past. The use of high-speed, high-precision attitude measurement systems to directly determine jitter affecting scanning imagery is another option.
- Support research and development of improved techniques for photoclinometry, with goals including better integration of existing photoclinometry processing into stereo DTM production workflow as a final "sharpening" step, reduced need for operator supervision, and development of multi-image methods (including combined photoclinometry-stereo techniques) that are not fooled by surface albedo variations.
- Support research and development of the sensor model software needed for radargrammetry and software for radarclinometry, in order to permit lunar topomapping with SAR data.

Dependencies and Milestones

In this section, we describe the backward (input) and forward (output) dependencies of a topographic mapping program in general terms. Specific details about the missions that provide useful images for topomapping and how their schedules will affect the mapping program are described below; much less is known at this time about the schedule for future landed missions that will be the most important customers for topographic data.

The primary input dependency is, obviously, the availability of data needed to support topographic mapping. These data include both images themselves and the supporting metadata that describe the camera position and pointing during image acquisition. In the case of legacy data from the 1960s-70s, images that exist in photographic (hardcopy) form must be scanned in order to be useful for mapping, and printed support data must also be digitized. Many (but not all) of the Lunar Orbiter images relevant for topomapping have already been digitized. Small numbers of Apollo images could be scanned in short order to allow a small-scale mapping program to begin almost immediately, but a longer term program of systematic, high-quality digitization of the Apollo images would be valuable for a variety of reasons. As for future missions, images and metadata need to be made available for cartographic use in well-understood and fully documented archival formats. Such archiving (through the Planetary Data System) has been an accepted part of NASA planetary missions in the past, though it is not clear that adequate resources will be available to permit the archiving (timely or otherwise) of the volume of lunar data that is expected. As for foreign lunar missions, international negotiation will be required to ensure that the sponsoring agencies archive the data and make them available for US mapping efforts. If at all possible, archival formats should be compatible with those used by the PDS; at a minimum, they must be fully documented and contain all the information needed in order to work with the images.

A second important input dependency is the availability of hardware and software tools needed to conduct a mapping program of the required scope and, in particular, to produce mission-critical results as they are needed. The areas where hardware procurement and software development are required were listed in the previous section.

A third, perhaps less obvious input dependency is the evolving state of the global coordinate system and frame (control network) for the Moon (Archinal et al., 2006). The need for ongoing geodetic analysis to refine the lunar coordinate frame and incorporate successive new datasets into it is described in detail in a companion submission to this RFI. It is essential that topographic datasets be controlled so that they register consistently to the best available lunar coordinate system, which will serve as the basis for carrying out mission operations such as targeting future observations and landing at desired points on the surface. At the same time, topographic data will be needed in the near term; topomapping cannot wait until the lunar coordinate system is perfected. It will therefore be necessary to devote some resources to revisiting the topographic products generated early on and updating them (probably by a simple coordinate transformation, but in worst case by regenerating them based on new control of the input images) to conform to the improved coordinate system.

The output dependencies are driven by the schedules of potential customers. A program of lunar geologic mapping has already been initiated, for example, and could benefit almost immediately from the availability of topographic products covering the quadrangles being mapped. This application is relatively low volume (as discussed in the next section) and perhaps noncritical. Landed missions will have a far more critical need for topographic data, but their schedule is less well known. We can therefore describe the timing of topomapping in support of such missions mainly in relative terms. Our experience with recent Mars landed missions, from Mars Pathfinder through Phoenix, indicates that the site selection process typically requires a period of at least 2 to 3 years, culminating in the selection of a safe (and interesting) site before launch (Golombek et al., 2003; Arvidson et al., 2006). Topographic mapping is needed throughout this process, first as an input to the geologic studies that generate suggestions for interesting candidate sites, then to provide at least some samples of terrain at every candidate site in order to assess landing hazards, and finally to map as much of the one or two leading candidate sites as possible. This last step serves both to provide a full validation of the topographic risks of landing at that site and is the first step toward a complete topographic map that can be used during surface operations. Given that the first new robotic mission to the lunar surface is currently scheduled for 2009, topographic mapping in support of geologic site studies could appropriately begin in the immediate future and the schedule for incorporating data from the 2007–2008 orbital missions into the site validation process is likely to be extremely tight. Human missions to the lunar surface will occur later, but are likely to require even greater efforts to certify site safety and will certainly have larger and higher resolution image datasets available for use. Thus, mapping candidate sites for these missions can also be expected to be a challenging, high-pressure task.

Programmatic Assumptions

The main programmatic question that will determine the entire character of topographic mapping efforts in support of lunar exploration is whether NASA is content to "make do" with the minimum amount of mapping focused on selecting and validating a few landing sites, or whether it will choose to extract the full scientific value from images being collected by its own and foreign missions by undertaking a full-scale global program of topographic mapping.

In the former case, the scope of the required mapping program is very modest and recent activities for Mars and other planets provide a reasonable guide. The geologic mapping program typically supports the production of a handful of geologic maps per year (for Mars, these are typically 5° or ~300 km on a side, mapped at 1:500,000 scale; see Rosiek et al., 2005). Production of topographic map quadrangles occurs on a similar scale of 5-10 maps per year, with an annual budget of less than $100K. Every effort is made to ensure that topographic mapping directly supports geologic mapping. As a result, topographic mapping of a given quadrangle can only begin after the quad is assigned to a scientist for geologic mapping, but must finish as early as possible during the geologic mapping process in order to be of use. It would obviously be preferable, from the point of view of the geologists, to have the needed topographic data available "off the shelf" at the start of their investigation (or even while deciding what areas to propose to map) as the result of a systematic topomapping program. Topographic mapping in support of site selection for recent Mars missions (MER and Phoenix) has been on a similarly modest scale, producing DTMs from a few tens of MOC stereopairs in order to provide limited samples of the terrain types in no more than 5-10 promising sites for each mission (Kirk et al., 2003b; 2006b). This level of activity has been accomplished for on the order of $50K per year for three years per mission, but there are already indications that the increasing availability of data will drive up the volume and cost of topographic mapping. The Phoenix mission now requires first validation of its selected site with HiRISE stereo data, followed by mapping of as much of the landing ellipse as possible at ultra-high resolution (0.3 m per image pixel, ~1 m per DTM point). The cost of this activity is between $100K and $200K. The Mars Science Laboratory will have access to HiRISE images (as well as other datasets) from the beginning of its site selection process, and will no doubt want the highest resolution DTMs that can be made from them. Its advanced landing system also allows a much greater number of candidate landing sites to be considered. Thus, even if only a fraction of the most promising sites must be mapped topographically, the effort is likely to greatly exceed those for MER and Phoenix. The situation for future lunar landing missions is likely to be similar to that for MSL, as high-resolution stereo images become available in the next few years and many sites are considered.

Initiation of a systematic program of topographic mapping with the intent of achieving global coverage of the Moon at one or more resolutions supported by the images from the planned orbital missions would ultimately have substantial advantages in reducing the lead time for making maps available to the customers. Such a program would also extract much more of the scientific value from the images returned by those missions. The cost of a systematic mapping program would, naturally, exceed that for highly focused mapping in support of a few missions and geologic maps. Our experience to date with digitized Apollo imagery (Rosiek et al., 2006) indicates that high-resolution images are relatively easy to stereomatch and require much less editing than, for example, Viking Orbiter images of Mars. From these tests, we can make a rough estimate of the editing effort (which, as we have said, is the main cost-driving step) needed to map the entire Moon at some desired scale. We calculate that making a global DTM with 50 m point spacing would require approximately 30 work-years of interactive editing. The labor cost for this editing would be in the vicinity of $5M; the total cost of DTM production would be somewhat higher but of similar magnitude. In addition, to complete the task in a reasonable total time, it would be necessary to perform the editing in parallel on several photogrammetric workstations. Acquisition of 5 to 10 such systems at a cost approaching $100K each would add an additional $0.5M to $1M to the total cost of the mapping program. These estimates are large in comparison to the level at which planetary topographic mapping is currently funded, but even a few tens of millions of dollars is a small expenditure in comparison to the costs of hundreds of millions of dollars per mission that will be spent on acquiring images of the Moon, and that will be risked every time robotic landing is attempted. The costs and stakes for eventual human missions are, of course, even higher.

Past and Planned Datasets for Lunar Topographic Mapping

Data from existing, planned, and yet to be developed sensors can support landing site mapping from the site selection to the operational use phase. As an example, we can look at the Mars Exploration Rovers (MER) to see how using satellite and terrestrial data together can support exploration. Landing site selection for the MER rovers, Opportunity and Spirit, used MOC narrow angle images to reduce ptential landing sites to the 2 final selections, Meridiani Planum and Gusev Crater. MOC images were also helpful in providing a road map for Spirit to follow as she journeyed from her landing site and were helpful in the ascent and descent of Husband Hill. The road map supported slope analysis to select a long-range route and the rover was able to use her sensors to confirm trafficability as she traveled along the route. Using stereo cameras, the rover was able to provide higher detailed topographic information than was available from satellite data. The MOC images and DTMs were controlled to the global coordinate system for which MOLA provides the ultimate definition. Rover images and the DTMs derived from them are, at least initially, referenced to the instantaneous position of the rover itself. Relating the two coordinate systems is a challenging and ongoing task that begins with reconstructing the rover path from the image measurements and will hopefully result eventually in high-resolution maps of the entire traverse based on the rover images, controlled as part of the global coordinate frame. A similar process will ultimately be needed in order to integrate lunar surface observations into the global coordinate frame. This processing necessarily involves a fully three-dimensional photogrammetric solution, because the lunar or planetary surface is far from flat at the scale of a lander, rover, or astronaut.

Imagery from past Moon missions is still useful for topographic mapping. Lunar Orbiter imagery supported Apollo mission planning and the Apollo command/service modules collected panoramic and metric frame photography. Topographic maps with contours were produced from this imagery. DTMs produced from contour maps are not as useful as DTMs produced from the original imagery. Also, our knowledge of the Moon's geodetic reference frame has increased since the 1960's and will increase further because of future lunar missions. Having DTMs tied to the current geodetic reference frame and being able to transform them into future geodetic reference frames will be very useful for human exploration and commerce on the Moon.

Apollo panoramic and metric frame imagery of about 15% of the Moon along the Apollo 15, 16, and 17 ground tracks exists as photographic film and can be digitized to produce digital images that can be used on modern photogrammetric workstations (Rosiek et al., 2006). These datasets would be useful for landing site analysis within the "Apollo zone", beginning immediately. Having all the film digitized at once in a consistent manner would be useful or we could digitize the film that is needed for mapping a particular site. Apollo panoramic imagery provides very high resolution data (1 m ground sampling distance (GSD) when digitized at 5 µm or 2 m GSD when digitized at 10 µm.) We have demonstrated the use of images scanned at 10 µm to produce DTMs with 10 m post spacing. Apollo metric frame imagery digitized at 10 µm produces digital images with 15 m GSD that would support the production of DTMs with 50 m post spacing. These data would be useful in support of resource exploration and scientific studies as well as landing site assessment.

There were 5 different Lunar Orbiter missions to collect imagery. The orbital elevations differed from each mission so the GSD of the imagery varies from 32 to 12 m (higher resolution data does exist but we have not used it for topographic mapping). A portion of this dataset has been recently digitized and is available for mapping (Becker et al., 2005). This provides gappy coverage of the Lunar nearside with nearly complete coverage above 50º to the poles.

Future missions SELENE, Chang'E-1, Chandrayaan-1, and Lunar Reconnaissance Orbiter will have line scanner sensor and framing cameras. The first 3 will have triplets of line scanners (aft, nadir, and forward looking) similar in design to the High Resolution Stereo Camera (HRSC) on Mars Express. As members of the HRSC Co-Investigator team, we have demonstrated our capability to use HRSC images for topographic mapping (Albertz et al., 2005; Kirk et al., 2006a). It would be extremely useful to have similar cooperative arrangements with SELENE, Chang'E-1, and Chandrayaan-1 in order to evaluate the accuracy and utility of their line scanner data for topographic mapping. The resolutions of these stereo cameras are 10, 120, and 5 m/pixel, respectively, so that the Chandrayaan imagery will likely be of the greatest value for detailed site mapping, while the Chang'E images would be useful only for regional to global mapping at comparatively low resolution (though still better than anything currently available). The Lunar Reconnaissance Orbiter will include a wide angle color camera with a resolution of 100 m/pixel (probably not relevant for topomapping), and a pair of narrow-angle pushbroom cameras that will map a 5-km wide swath at 0.5 m/pixel resolution. The latter system may be used, much like the MRO HiRISE camera is being used at Mars, to obtain stereo coverage of selected targets by pointing the spacecraft off nadir. Such stereopairs will be especially valuable for highest resolution mapping of landing site to assess small topographic hazards.

References

Agouris, P., Doucette, P., and Stefanidis, A, 2004, Automation and Digital Photogrammetric Workstations, in *Manual of Photogrammetry*, 5th Edition (J.C. McGlone, E. M. Mikhail,, J. Bethel, and R. Mullen, editors), American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 949–981.

Albertz, J., Attwenger, M., Barrett, J. M., Casley, S., Dorninger, P., Dorrer, E., Ebner, H., Gehrke, S., Giese, B., Gwinner, K., Heipke, C., Howington-Kraus, E., Kirk, R. L., Lehmann, H., Mayer, H., Muller, J.-P., Oberst, J., Ostrovskiy, A., Renter, J., Reznik, S., Schmidt, R., Scholten, F., Spiegel, M., Stilla, U., Wählisch, M., Neukum, G., and HRSC Team, 2005, HRSC on Mars Express—Photogrammetric and Cartographic Research, *Photogrammetric Engineering & Remote Sensing*, *71*(10), 1153–1166.

Archinal, B. A., Rosiek, M. R., Kirk, R. L., and Redding, B. L., 2006, Completion of the Unified Lunar Control Network 2005 and Topographic Model, *Lunar Planet. Sci., XXXVII*, Abstract #2310, Lunar and Planetary Institute, Houston (CD-ROM).

Arvidson, R. E., Barge, L., Barnes, J., Boynton, W., Friedson, J., Golombek, M. P., Guinn, J., Kass, D. M., Kirk, R., Malin, M., Mellon, M., Michaels, T., Paige, D., Parker, T. J., Rafkin, S., Seelos, K., Smith, M. D., Smith, P. H., Tamppari, L, and Tyler D., 2006, Overview of Mars Exploration Program 2007 Phoenix Mission Landing Site Selection *Lunar Planet. Sci., XXXVII*, Abstract #1328, Lunar and Planetary Institute, Houston (CD-ROM).

Becker, T., L. Weller, L. Gaddis, D. Soltesz, D. Cook, B. Archinal, A. Bennett, T. McDaniel, B. Redding, and J. Richie (2005). "Lunar Orbiter Revived: Update on Final Stages of Scanning, Archiving, and Cartographic Processing at USGS," *Lunar Planet. Sci., XXXVI*, Abstract #1836, Lunar and Planetary Institute, Houston (CD-ROM).

Buchroithner, M. F., Gruendemann, T., Kirk, R. L., and Habermann, K., 2005, Three in one: Multiscale Hardcopy Depection of the Mars Surface in True 3-D (Highlights article), *Photogrammetric Engineering & Remote Sensing*, *71*(10), 1105.

Golombek, M. P., Grant, J. A., Parker, T. J., Kass, D. M., Crisp, J. A., Squyres, S. W., Haldemann, A. F. Cs, Adler, M., Lee, W. J., Bridges, N. T., Arvidson, R. E., Carr, M. H., Kirk, R. L., Knocke, P. C., Roncoli, R. B., Weitz, C. M., Schofield, J. T., Zurek, R. W., Christensen, P. R., Fergason, R. L., Anderson, F. S., and Rice, J. W., Jr., 2003, Selection of the Mars Exploration Rover Landing Sites, *J. Geophys. Res., Planets*, *108*(E12), 8072, doi:10.1029/2003JE002074.

Howington-Kraus, E., Kirk, R., Galuszka, D., Hare, T., and Redding, B., 2000, Rigorous sensor model for topographic mapping of Venus using Magellan radar stereoimagery, *Lunar Planet. Sci., XXXI*, Abstract #2061, Lunar and Planetary Institute, Houston (CD-ROM).

Howington-Kraus, E., Kirk, R., Galuszka, D., Hare, T., and Redding, B., 2002, Validation of the USGS Magellan sensor model for topographic mapping of Venus, *Lunar Planet. Sci., XXXIII*, Abstract #1986, Lunar and Planetary Institute, Houston (CD-ROM).

Kirk, R. L., 1987, A Fast Finite Element Algorithm for Two-Dimensional Photoclinometry, Ph.D. Thesis, Caltech, pp. 165–258.

Kirk, R. L., Barrett, J. M., and Soderblom, L. A., 2003a, Photoclinometry made simple…?, ISPRS Working Group IV/9 Workshop "Advances in Planetary Mapping 2003", Houston,

March 2003, online at http://astrogeology.usgs.gov/Projects/ISPRS/Meetings/Houston2003/abstracts/Kirk_isprs_mar03.pdf.
Kirk, R. L., Callahan, P., Seu, R., Lorenz, R. D., Paganelli, F., Lopes, R., Elachi, C., and the Cassini RADAR Team, 2005, RADAR Reveals Titan Topography, *Lunar Planet. Sci., XXXVI*, Abstract #2227, Lunar and Planetary Institute, Houston (CD-ROM).
Kirk, R. L., Howington-Kraus, E., Galuszka, D., Redding, B., Hare, T. M., Heipke, C., Oberst, J., Neukum, G., and the HRSC Co-Investigator Team, 2006a, Mapping Mars with HRSC, ISIS, and SOCET SET, *Lunar Planet. Sci., XXXVII*, Abstract #2050, Lunar and Planetary Institute, Houston (CD-ROM).
Kirk, R. L., Howington-Kraus, E., Redding, B., Galuszka, D., Hare, T. M., Archinal, B. A., Soderblom, L. A., and Barrett, J. M., 2003b, High-resolution topomapping of candidate MER landing sites with Mars Orbiter Camera Narrow-Angle images, *J. Geophys. Res., 108*(E12), 8088, doi:10.1029/2003JE002131.
Kirk, R. L., Rosiek, M. R., Galuszka, D., Redding, B., Hare, T. M., Archinal, B. A., and Parker, T. J., 2006b, Topography of Candidate Phoenix Landing Sites from MOC Images, *Lunar Planet. Sci., XXXVII*, Abstract #2033, Lunar and Planetary Institute, Houston (CD-ROM).
Li, R., Squyres, S. W., Arvidson, R. E., Bell, J., Cheng, Y., Crumpler, L., Des Marais, D. J., Di, K., Ely, T. A., Golombek, M., Graat, E., Grant, J., Guinn, J., Johnson, A., Greeley, R., Kirk, R. L., Maimone, M., Matthies, L. H., Malin, M., Parker, T., Sims, M., Soderblom, L. A., Thompson, S., Wang, J., Whelley, P., and Xu, F., 2005, Initial Results of Rover Localization and Topographic Mapping for the 2003 Mars Exploration Rover Mission, *Photogrammetric Engineering & Remote Sensing*, *71*(10), 1129–1142.
Rosiek, M. R., Archinal, B. A., Kirk, R. L., Becker, T. L., Weller, L., Redding, B., Howington-Kraus, E., and Galuszka, D., 2005a, Utilization of Digitized Apollo and Lunar Orbiter Imagery for Mapping the Moon, *Lunar Planet. Sci., XXXVII*, Abstract #2171, Lunar and Planetary Institute, Houston (CD-ROM).
Rosiek, M. R., Kirk, R. L., Archinal, B. A., Howington-Kraus, E., Hare, T., Galuszka, D., and Redding, B., 2005b, Utility of Viking Orbiter Images and Products for Mars Mapping, *Photogrammetric Engineering & Remote Sensing*, *71*(10), 1187–1196.
Scholten, F., K. Gwinner, T. Roatsch, K.-D. Matz, M. Wählisch, B. Giese, J. Oberst, R. Jaumann, and G. Neukum, 2005. Mars Express HRSC data processing – Methods and operational aspects, *Photogrammetric Engineering & Remote Sensing, 71*(10), 1143–1152.
Smith, D. E., et al., Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars, *J. Geophys. Res., 106*(E10), 23,689–23,722, 2001.