Lunar Coordinates and Cartography: Coordinate System Establishment, Improvement, and Control (Registration) of Lunar Datasets, from Past, Present and Future U. S. and Foreign Missions

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

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Table of Contents:

1. Introduction

The primary lunar exploration objective that we are addressing here is the need to define a global lunar reference coordinate system and then to realize that system by successively controlling (registering) mission data to it. Operations in the vicinity of and on the surface (and subsurface) of the Moon simply cannot take place unless this type of need is met. This issue is a critical one *now* because confusion about lunar coordinate systems already exists among missions currently being carried out and planned, and because we know of essentially no current or future planning to integrate the datasets from the multiple past, present, and future missions, or even the datasets obtained from any one such mission. Multiple missions are currently being prepared by the U.S. and other nations to collect unprecedented volumes of data from lunar orbit, and co-registered cartographic products generated from these data will be essential for planning and operating subsequent missions. Yet, despite the significant investment in data collection (typically hundreds of millions of dollars per mission), we are concerned that the smaller but still significant resources (totaling perhaps a few millions of dollars) needed to process the data into useful form will be available.

We prepared this response because we see no plans to provide the type of infrastructure for lunar exploration that we discuss here, either in available Exploration Systems Mission Directorate documents or in NASA or LRO mission related documents or announcements. We have informally provided some of this information through NASA channels and proposals, but have seen little response thus far. We hope that this submission will provide a mechanism for distributing this critical information within NASA.

The rest of this response to the RFI is organized as follows. In the rest of this Section we first define what we mean by a global lunar reference system and a lunar reference frame. We then address the specific Guidelines of the RFI. We will describe how the major objective we are describing supports all seven of the key elements of the exploration strategy, and provide specific near to long term examples of the critical needs for products based on this objective. We will address finally the issue of “dependencies” and “milestones” and “decision points”, primarily by noting what tasks need to be undertaken currently and as the various planned lunar exploration missions proceed.

Subsequent sections provide additional details about the specific geodetic-cartographic work that is essential to the lunar exploration program. First (Section 2), there is a brief overview of lunar coordinate systems, describing the current best frame and global topographic model, the Unified Lunar Control Network 2005 that has been recently created here at USGS. This is followed (Section 3) by information on how this network is currently being improved with existing data, how it could be improved further in the future, and what global mosaic products (Section 4) should be regenerated using these improved frames. We then list (Section 5) what critical algorithm/software developments are needed in order to prepare for processing data from current and future missions. We also describe the cooperative efforts (Section 6) that are critically needed *now* within NASA missions and between NASA and foreign missions so that the datasets from these missions will be useable and made compatible with each other. Finally we list (Section 7) the efforts that will be needed – which to our knowledge are currently not planned and are certainly unfunded – to control/register the data and to create useful digital mosaics and digital elevation models (DEMs) from the future planned missions through the Lunar Reconnaissance Orbiter (LRO) and beyond (Section 8). Finally we summarize the various recommendations made in this response (Section 9) and provide some examples of how administration of those recommendations could be carried out at NASA.

Global Lunar Reference System and Reference Frames: It is important to clarify one particular aspect of terminology. The terms *reference system* and *reference frame* often are used interchangeably but in precise usage have two different meanings. A *reference system* is indeed a "system" that includes some definition of a physical environment, specific terminology, and associated theories that form an idealized model for defining positions on a particular body (or in space generally). A *reference frame* is the materialization of a reference system in reality, e.g. (in most cases) a solution which defines from observational data the specific numerical location of given points in the reference system [Kovalevsky and Mueller, 1981].

For the Moon, there are two commonly used global reference systems. These are the *mean Earth/polar axis system* and the *principal axis system*. These will be described in more detail below in Section 2 – but it should be pointed out now that we recommend the use of the former system. Several different reference frames exist for the Moon, each based on lunar coordinates derived in one or the other system, from a specific dataset or combination of datasets. What we believe is strongly needed is a continued succession of improved reference frames, which will connect (and, indeed, reconcile) existing and future datasets at the highest possible level of accuracy. Such a succession can begin with our Unified Lunar Control Network 2005, the current densest global representation for horizontal and vertical positions. More details will be given on this and other frames in Section 3.

Support of All Key Elements of the Exploration Strategy: The objective we are describing here will serve to establish the basic coordinate reference system and frames to be used for registering all lunar data from the past, present, and future. Clearly, the existence of such a system in which all geographic data are consistently available will be essential to any conceivable activities related to, or on, near, or even under the surface of the Moon. The RFI lists 7 key elements of the exploration strategy, which are supported as follows.

- "Lunar exploration activities that are an integral part of a broader exploration strategy that encompasses Mars and other destinations." These activities are addressed by the part of this objective that a) proposes that substantial cooperation and standardization is needed between the various national space agency missions to the Moon, and b) the development of procedures, algorithms, and software to successfully process data from the massive and complex new datasets as they arrive. These same types of activities are needed for Mars exploration and exploration of other planetary bodies. The establishment of international cooperation between missions to the Moon can and should of course be extended to missions to other bodies. The procedure, algorithm, and software development described in Section 5 can be directly applied – and in fact in several cases is also critically needed *now* for processing of Mars datasets (e.g. software for line scanner camera, partitioned solutions) and those from other bodies (e.g. radargrammetric processing (already needed for analyzing Cassini RADAR images of Titan).

- "Lunar robotic activities that collect key strategic information and develop key capabilities to enable and enhance human exploration." Standardized coordinate systems and frames are needed so the strategic information collected can be properly registered and related to other datasets.
- "Lunar activities that enable humans to live and work productively on the moon, including developing and using lunar resources." For human activity to take place on any planetary body, global and local coordinate systems and frames must be established so that such activities can be planned and undertaken. Part of this effort should involve the creation of a substantial Geographic Information System (GIS) or Systems, in which various datasets and operational plans can be registered. The need for such GIS systems will be discussed in a companion response to the RFI from the USGS Astrogeology Team.
- "Activities that enable opportunities for international collaboration through merging of common interests in respective strategic plans for exploration." This has already been addressed, in that clearly international collaboration is clearly needed now if the datasets that have been and will be collected by respective national space agencies are to be integrated into a common coordinate system and frame or frames. Without such cooperation the various (national) datasets will be nearly unusable for cross-comparison and joint analysis; at best, each will be usable only in isolation. With such cooperation their value is magnified many-fold due to the synergistic nature of being able to compare and process properly registered but diverse datasets.
- "Characterization of opportunities for science investigations on the moon." As noted in regard to robotic and human activities above, such activities (investigations) simply cannot take place unless the datasets used are placed into common coordinate systems and frames and the accuracy with which they are registered is known and documented. Not only would it be impossible to compare multiple, unregistered datasets together, even the scientific analysis of information (e.g. images) from a single dataset may be difficult or impossible until the images are registered. For example, it is possible to produce "uncontrolled" or "semi-controlled" mosaics of images, but unless full control of such images is done they may be little more than "pretty pictures". With full control of images and other datasets into a common frame, scientific analysis and even discoveries can take place that would be impossible without such efforts.
- "Activities that can enable lunar commerce." It may be repetitious, but the same arguments made above for robotic and human activities and scientific investigations apply. One must know, and at what level of accuracy – the coordinates (including velocity and acceleration) of landed or moving assets with specifiable accuracy, or else such commerce simply cannot occur. A global lunar

reference system and frame can be used to define and determine these coordinates, and in turn can serve to locate resources of interest as measured from any given global or local dataset.

- "Activities that can engage the general public in lunar exploration." Is there any better way to engage the public than via graphical, multi-colored, multi-dimensional displays of digital data? Such products could consist of fairly straightforward global, regional, or local maps. Or they could extend to more interactive products such as 3-D flyovers, or a spinning and zoomable 3-D lunar globe. Or they could extend to state of the art products/displays such as a fully interactive GIS system displaying all available lunar datasets, visible in multi-dimensions and 3-D, or even 4-D with e.g. sequences showing the change in illumination at the lunar poles. None of these products will be possible without the foundation of a global lunar reference system and frame for registering the datasets involved.

As further examples of how the major objective here supports such elements, we provide a simple list such possibilities (where detailed examples can be provided upon request).

- Operations, such as targeting, landing hazard avoidance, landing site operations, trafficability, and placement of resources.
- Regional and local mapping, e.g. landing site three dimensional mapping.
- Geologic and mineralogic mapping, for the identification of resources needed operationally and for future economic development.
- Global and local GIS, for the simultaneous examination of multiple datasets, including planning and infrastructure datasets for landed operations.

In the case of the last three points, the USGS Astrogeology Team will submit separate responses to the RFI.

Dependencies: The RFI requests documentation related to the issue of dependencies on "other objectives, architecture and operations assumptions." In addressing the primary objective of establishing a global lunar reference coordinate system and reference frame realizations of it, we obviously are covering so many possible areas of interest and objectives, etc. that may be affected that it would be difficult to impossible to adequately list such dependencies. However, we will note here – and add information late in this document where appropriate – that the main dependencies are driven by the following considerations:

A. Standardization and cooperation issues, whether among instruments on a mission or between international missions, must be addressed as early as possible in the design of each mission and instrument.
B. Algorithms, procedures, and software for processing datasets should be in place and well tested before such datasets become available.
C. Datasets will be processed as they become available.

Milestones and Decision Points: Regarding the RFI's request of documentation of "intermediate milestones and key decision points", essentially the same points apply. Again, the primary dependency is on availability of data, e.g. when data starts to become routinely available from a mission or when it is archived to the Planetary Data System (PDS) or its international equivalent. However, note in particular, that datasets will need to be mosaicked more than once and perhaps repeatedly, as any global reference frame is updated with improvements that include larger spatial changes than the resolution of the given dataset, and also as new and improved versions of datasets become available, e.g. due to more or final data, or better calibration.

2. Recommended Lunar Coordinates

Global Coordinate Systems: The global coordinate system that has been used historically for the Moon and as recommended by the IAU and IAG [Seidelmann, et al., 2002, 2005] as the preferred system for cartographic products is the *mean Earth/polar axis system*, based on the mean direction to the Earth as defining the prime meridian. The other coordinate system is the *principal axis system*, which is aligned with the Moon's axes of figure, e.g. with the prime meridian direction defined by the direction of the longest axis which points approximately but not exactly toward Earth. This latter system is used for internal dynamical calculations, e.g. for the Moon's gravity field. The difference between the two systems is about 1 km in longitude - not very large, but large enough to notice on current maps, and certainly large enough to cause serious problems relative to landing site locations. Further information on these systems is given by Davies and Colvin [2000] and Roncoli [2005].

We see two problems regarding the global coordinate system. The first is simply that there appears to be a lack of awareness that the mean Earth/polar axis system is the one that has been recommended for general use. The second is more complicated, but suffice it to say that the IAU/IAG recommendations for the orientation of the Moon (i.e. the orientation of this system) are not precise enough and need to be improved. We are already working to develop a consensus of how to do this through interactions with scientists at JPL, the LRO mission, and the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements.

One of these systems, preferably the mean Earth/polar axis system adopted by the IAU and IAG, should be the default system, and must be adopted by the various missions and providers of datasets, so that conversions between the two (or more) different systems can be avoided.

Global Coordinate Frames: The most accurate global coordinate frame is that based on the most recent solution with lunar laser ranging (LLR) data [Williams, et al., 2004]. Although accurate to the cm level or better, as an accessible network it suffers from the availability of having only 4 points available on the lunar surface. The densest global solution, based on a photogrammetric solution of 43,866 Clementine images and earlier data, for the 3-D position of 272,931 points, is our Unified Lunar Control Network

2005, recently completed and about to be released [Archinal, et al., 2005a-e, 2006; 2006 USGS Open File report and paper in preparation]. This is the largest planetary control network ever completed and was developed under funding from the NASA Planetary Geology and Geophysics Program. The software used for this effort was originally developed at the RAND Corporation by Davies, et al. [Colvin, 1990, 1992] and then transferred to the USGS Astrogeology team and further modified [Archinal, et al., 2000, 2001a-b, 2002, 2003, and 2004]. It has now been incorporated in the USGS ISIS planetary image processing software [Elias, 1997; Gaddis, et al., 1997, Torson, et al., 1997; also see http://isis.astrogeology.usgs.gov/]. This network is a combined solution, using data from the previous Unified Lunar Control Network [Davies, et al., 1994] and the Davies, et al. Clementine Lunar Control Network (CLCN) [Edwards, et al., 1996]. It corrects for known large horizontal errors in the CLCN that propagated to the corresponding Clementine image mosaics [Malin and Ravine, 1998; Cook, et al., 2000, 2002]. Via the original ULCN it provides ties to the Apollo landing sites and the LLR reference frame, as well as other image data (Mariner 10, Galileo). In the ULCN 2005, the three dimensional position of the points were solved for, thus providing a global topographic model for the Moon that is denser than any other control network.

The ULCN 2005 is the best current realization (in terms of accessibility and density) of a global lunar coordinate system – in this case the mean Earth/polar axis system in which it was derived. The main objective of this response to NASA is to continue to update this reference frame with data from existing and future datasets, so that *all lunar datasets can be used in the same system*.

3. Improving the ULCN 2005 with Existing Data

Work is currently underway, supported by the cartography element of the NASA Planetary Geology and Geophysics Program, to further improve the ULCN 2005. This is currently being done by expanding the solution by directly including measurements from Lunar Orbiter, Mariner 10, and Galileo images and will result in the creation of the ULCN 2007.

Note that the Lunar Orbiter measurements are being collected as part of the creation of a digital global Lunar Orbiter image mosaic of the Moon here at USGS [Becker, et al., 2005; Weller, et al., 2006; http://astrogeology.usgs.gov/Projects/LunarOrbiterDigitization/]. This mosaic will be initially tied to the ULCN 2005 frame. It will be the first orthomosaic of the Moon, using projection onto the ULCN 2005 topography to correct parallax distortions in the images. It should serve for the immediate future of the next few years as the primary lunar "map", i.e. for use in image targeting by the planned missions of the near future.

However, we believe that the direct incorporation of the new image measures into the ULCN 2005 to create the ULCN 2007 will result in a further improvement in horizontal accuracy, due to the increased image size relative to resolution, of the Lunar Orbiter and

Galileo images relative to Clementine images. The increased number of points will also further densify the global lunar topographic model.

Further improvements could be made to this network and further useful existing datasets could be registered at any time if funding were available. This could include the use of the Apollo ~15 m resolution metric camera photographs and the up to ~1 m resolution panoramic camera photographs, which cover a significant portion of the near side. It could also include the use of complete Earth based telescopic coverage of the near side, e.g. from the Meyer [1980] network. It could further include the use of Earth based radar measurements and images, such as from the work of Margot, et al. [1999]. The connection of Ranger and USSR photographic coverage would also be desirable. Network improvement would be unlikely, but as explained above simply would allow proper registration of this data with other datasets for the first time, for use in e.g. change detection, illumination, and phase angle studies.

4. Generation of Improved Image Mosaics with Existing Data

With the improvements provided by the ULCN 2005 and again with the planned improvements of the ULCN 2007 or later versions, the corresponding digital mosaics should be regenerated – or even properly generated for the first time. It is now known how to improve the radiometric calibration of the Clementine images. Therefore, with the large horizontal errors now corrected in the (mostly Clementine based) ULCN 2005, the *various Clementine global digital mosaics can now be updated geometrically and, at the same time, radiometrically*. This includes the Clementine 750 nm basemap, UVVIS, and infrared multiband mosaics [Isbell, et al., 1997; USGS, 1999; USGS, in preparation]. Such new mosaics, along with the new LO mosaic, would prove invaluable for the next few years for targeting and (using Clementine multispectral mineralogical maps) resource planning. All that is needed is proper funding…

Using the ULCN 2007, digital mosaics could also be made of the Mariner 10 and Galileo imagery; again providing useful now properly registered unique imagery for large areas (particularly the north polar region for Galileo) of the Moon. The LO mosaic could also be updated using the ULCN 2007, likely improving the horizontal positional accuracy of the LO mosaic.

If, as suggested above, further datasets were connected to the frame, then other types of regional mosaics could also be generated, e.g. imagery from Apollo (at down to 1 m resolution in some areas!) , high resolution LO, Ranger, near-side telescopic, Earth based radar (particularly of the polar areas), etc.

In short, much could be accomplished *now* from already existing datasets, in terms of further improving lunar control and creating global, regional, and local digital mosaics from multiple types of imagery and (in the case of Clementine) from multiple wavelengths. These products would facilitate greatly both near and long term operations in lunar orbit, and on the lunar surface.

5. Preparations for Processing of Future Datasets

Before continuing below with discussions on the processing of data from the future LRO and foreign missions, it is important to note that some significant technology development is needed in order to process the data from the increasingly complex instruments on these missions. In order of their likely priority (which we provide without substantial comment – further information is available on request) we take note here of a number of areas where development of appropriate procedures, algorithms, and software are needed.

- Procedures, improved algorithms, and software are desperately needed *now* in order to photogrammetrically control line scanner (and related pixel-scanner) cameras. Such procedures have been developed for terrestrial based cameras (aircraft and Earth orbiting). The USGS Astrogeology Team has also developed procedures for mapping and DEM generation from small image sets (pairs of images) from Mars Orbiting Camera (MOC) images. We are also working on developing algorithms and software for processing images from the 2001 Mars Odyssey THEMIS IR line scanner camera. However, robust, efficient methods for processing large numbers of such images from the various Mars missions that have such cameras (MGS MOC, MO THEMIS, Mars Express HRSC, and MRO HiRISE) do not yet exist. Line scanner cameras also have a substantial disadvantage over framing cameras in that the images are strongly affected geometrically by spacecraft "jitter", i.e. random to systematic motion while an image is being collected. It may be possible to resolve this problem to some extent with specially designed CCD arrays (e.g. as with the MRO HiRISE camera), but currently such methods are untested and the proper procedures and software have yet to be developed. Algorithms used for Earth based imaging are also often inadequate, as they assume that accurate ground point (surveyed) coordinates or GPS derived platform coordinates are available. Unfortunately, all the upcoming lunar missions are planned to have line scanner cameras including SMART-1 (AIME, in some modes), Chang'E-1, Chandrayaan-1, Selene, and LRO (LROC). In fact it is somewhat surprising that such systems were approved, particularly for mapping purposes, due to the problems of jitter and since software to photogrammetrically control the images does not exist. Presently there also appears to be no funded plans to develop such software. Therefore, some substantial effort will be needed to allow these images to be controlled in order to properly register them with the previous and concurrently collected datasets.

- Concurrent with line scanner camera related developments, it is also necessary to further and substantially improve methods for automatic tie-pointing of overlapping image and other (i.e. altimetric) data. The USGS Astrogeology Team is now addressing this issue by developing techniques to accurately locate overlapping regions of images and then using "plug-in" algorithms for image matching. However, the success rate of these methods needs to be improved in order to automatically handle the hundreds of thousands to millions of images that will be generated by even one of the cameras from the many future lunar and Mars missions.

- Similarly, although the ULCN 2005 solution is the largest planetary control network ever completed, it required the use of quite sophisticated sparse matrix and conjugate gradient solution techniques in order to derive a solution. The image sets acquired by even one of the future missions will dwarf by at least an order of magnitude and possibly two the data processed in the ULCN 2005. In order to control the hundreds of thousands to the tens of millions of images that will become available in the next several years, the addition of quite complex multiple-partitioned matrix solution procedures will be required. Such software is needed *now* in order to properly create controlled THEMIS IR Mars mosaics, and will definitely be needed to process the image data received as part of Chang'E-1, Chandrayaan-1, Selene, and LRO.

- With the increased use of radar instruments, e.g. on Cassini, Chandrayaan-1, and LRO, it will be necessary to add algorithms and software for joint radargrammetric processing of data along with the photogrammetric processing of data. Without such methods, the radar data simply cannot be properly registered to the image data for many operational and scientific purposes. It is worth noting in this context that the radar images, in addition to being of interest in their own right, provide significant value for mapping and analysis with the optical images in the form of improved absolute accuracy. Unlike optical images, radar images are formed by a process that is insensitive to spacecraft pointing. Thus, small errors in pointing knowledge will degrade the accuracy of maps.

- Lastly, it goes without saying that the efficiency of existing procedures will have to be radically improved, or entirely new procedures developed, in order to handle the massive datasets that will be acquired by the upcoming lunar missions. There will be substantial costs involved in not only simply storing copies of the datasets, but in storing the intermediate products generated during image processing, which often require an order of magnitude more disk space than the original dataset. Any one of the upcoming lunar missions is likely to generate more data than all previous lunar and planetary missions combined. Instead of dealing with the few hundred Megabyte levels of data for the Clementine mission, it will be necessary to deal routinely with hundreds of Terabytes of data, if not several Petabytes of data for the total lunar data set. No institution, including particularly the PDS which must archive the data, is remotely prepared for such data processing problems. Substantial development is clearly required *now* in order to prepare for the future missions, or else much of the data acquired by these missions will simply not be processed and will eventually even be lost entirely.

6. Standardization in U.S. Missions and With Foreign Missions

Standardization procedures are required within U.S. missions and between NASA and foreign missions, to assure that datasets can be registered and processed.

In the past most U. S. missions and/or instruments had one or more geodesists, cartographers, photogrammetrists, or geologic mappers on their team who planned and coordinated data collection and mapping. This is often unfortunately no longer the case. In fact the Planetary Cartography and Geologic Mapping Working Group (PCGMWG) of the NASA Planetary Geology and Geophysics Program is currently developing a long-range plan for planetary mapping and is considering recommending that such personnel be a part of new missions and that reviews of missions and instruments cartographic planning be done as part of the normal review procedure. In the meantime, for U.S. lunar missions currently in development, such as LRO, it is important that the instrument teams become aware of the international and U. S. national standards for lunar mapping (as well as for data collection, data formats, archiving, supporting metadata etc.). This could be done either by the missions actively seeking out advice on such subjects, or adding a participating scientist program or similar, designed to add team members who can assist with such work.

An additional step that should be taken is to create some sort of working group that would be responsible for establishing standards for U. S. lunar missions. As an example, there already exists a NASA Mars Geodesy and Cartography Working Group, chaired by T. Duxbury (JPL), which coordinates Mars data acquirers, data processors, and customers. A similar Lunar Geodesy and Cartography Working Group could be established with proper funding. Alternatively, this function could be handled by the PCGMWG (as described in their 1992 charter), if it was clearly required of this group and properly tracked and funded.

Similar problems exist with foreign missions, where no one involved with the missions or particular (mapping) instruments has previous experience in the creation or cartographic processing of planetary datasets and where no standards group exists or is acknowledged. Here it would be of the greatest benefit to NASA and the foreign missions for NASA to establish Co-Investigator programs so that U. S. investigators can participate in and assist with the foreign missions, providing advice in particular on standards for coordinate systems, processing algorithms and techniques, data archiving (including auxiliary data in the JPL NAIF SPICE format), and final product creation. An excellent example of such cooperation already exists in the case of Mars Express, where NASA has supported a number of U. S. Co-Investigators to the mission, particularly for the HRSC camera. This cooperation has resulted in the adoption by the HRSC Camera Team of the appropriate international (and NASA) standards for Mars, for archiving of the data, and for the creation of final products (e.g. digital map quads). It is likely that the HRSC data would have been much more difficult to use, if not impossible to use routinely by U. S. investigators, if this cooperation had not occurred. It is encouraging that NASA has apparently made some contacts with representatives of the various foreign missions, and particularly encouraging that agreement has been reached to fly two NASA sponsored experiments on India's Chandrayaan-1. However, much more critically needs to be done. We therefore strongly recommend that programs similar to those done with Mars Express be started now with the currently planned foreign lunar missions, and as early as possible in the case of future foreign missions.

7. Plan for Control and Mosaicking of Planned Future Mission Datasets

Before discussing the individual current and planned future missions, some common points should be made that apply to all of them.

- Our recommendation (just stated) that U. S. participation in these missions be actively planned and promoted as soon as possible applies to all of them.
- The primary image datasets (some have more than one) of each of these missions should be tied to successive versions of the ULCN or some equivalent frame, for the many reasons already given.
- Each of these missions has other, either non-imaging, or lower resolution imaging datasets that should also be tied into ULCN. However, it is assumed that this can be done via the use of measured spacecraft geometry and simultaneity information relative to the primary image datasets or altimetry data.
- The altimetry datasets must be tied to the ULCN in some way. Ideally, the altimetry datasets should first be adjusted based on altimeter crossover information and orbit correction information if available, and merged with the other available datasets. Then the ULCN can be registered to the altimetric data via ties based on the relative geometry of simultaneously acquired spacecraft imagery, or via ties between images and illuminated DEMs generated from the altimetric data. The later technique has been pioneered already by tying Viking images to MOLA DEMs [Archinal, et al., 2002, 2003, 2004; Kirk, et al., 1999, 2000, 2001; http://astrogeology.usgs.gov/Projects/MDIM21/]. The absolute geometric strength of the altimeter data (based on spacecraft tracking in inertial space) will then serve as the absolute framework on which all of the other data tied to the ULCN can be based.

Given these commonalities, we now discuss, in the approximate order of their appearance, steps that should be undertaken in order to process the currently planned new lunar datasets.

SMART-1: The ESA SMART-1 mission will be completed when the spacecraft impacts the lunar surface in early October of 2006. Sometime soon after that, the mission data, including the images and auxiliary data from the AIME CCD framing camera are to be archived to the ESA Planetary Data Archive in PDS format. Preparations should begin *now* to process and control those images. Around 10,000 such images exist at generally 100 m/pixel resolution or better. In the first month of operation the Moon was completely imaged. Later data targets specific areas at high resolution and often in stereo, and provides for color imagery (often using the camera in line scanner mode) [personal communication, B. Foing]. If measurements from these images were added to the ULCN 2005 or 2007 it would likely greatly strengthen the horizontal accuracy of the network and further densify the lunar topographic model, particularly since altimetric data that could accomplish this purpose will not be available until at least a few more years. These images also appear to be the last planned orbital framing camera images of the Moon to be obtained for some time, and therefore should be able to provide geometric strength to the ULCN that later line scanner camera images of similar resolution (e.g. from Chang'E-1, LRO LROC) will not The images could also then be mosaicked, providing a second or third (after LO and redone Clementine mosaics) medium resolution mosaic for future lunar and planning and targeting, possibly in multiple colors. Since most of the images are framing camera images, the software and procedures to process them could be developed with relatively little effort, and the control and mapping program undertaken and completed (with reasonable few hundred $k funding) within a year or so.

<u>SELENE</u>: To be launched in 2007, the Japanese SELENE mission will have primarily three instruments collecting globally useful cartographic datasets. These are: a) the Terrain Camera (TC), which has fore and aft (15°) 10 m resolution line scanner cameras; b) the Multi-band imager, with 20 m resolution in 5 visible bands, and 60 m resolution in 4 near-IR bands, and c) a laser altimeter, collecting data with 1.6 km along track spacing and 5 m vertical resolution. Although the use of line scanner camera presents problems in processing this image data and that of the other missions listed below, if these can be properly addressed, it should be possible to control TC camera images and via stereo matching, collect global DEM information at the ~20 m level of vertical accuracy, and controlled by the laser altimeter data. Apparently, unlike any of the other missions listed here, the SELENE team does plan to generate the global image derived DEM products themselves [Haruyama, et al., 2006].

<u>Chang'E-1</u>: To be launched late in 2007, the Chinese Chang'E-1 will carry a CCD stereo line scanner camera, consisting of 3 arrays, fore and aft looking by 17° and nadir, with a 60 km swath and 120 m resolution. The camera is expected to return 2 Tb data during the nominal mission. It will also have a laser altimeter with a 200 m footprint and 5 m vertical resolution. A third "mapping" instrument will be an imaging interferometer, with a 25.6 km swath and 200 m resolution at wavelengths of 0.48~0.96 μm. It is expected to return 19 Tb of data. In a similar case to SELENE, it should be possible to process the data returned from the camera system and altimeter in order to generate a global DEM. Unfortunately, the camera resolution is relatively low, so processing that image set for the topographic content might not be productive if the planned higher resolution data from the other missions becomes available. Still, the imagery should be connected to the other data sets (again, via an update of the ULCN) because due to the image width (60 km) it should provide useful horizontal geometric strength to the global network, and since it will serve as an additional source of visible imaging under different illumination from the other missions. The total dataset for the nominal mission (including the other types of data) is predicted to be 23.6 Tb.

<u>Chandrayaan-1</u>: To be launched in 2007 September or later, this Indian mission will contain at least 4 major global mapping instruments and operate for a nominal 2 year mission. The mapping instruments include: a) a Terrain Mapping Camera (TMC), which is a line scanner camera with 3 arrays, e.g. fore and aft looking by 17° and nadir, with a 40 km swath and 5 m resolution; b) the lunar Laser Ranging Instrument (LLRI), a 5 m vertical resolution laser altimeter; c) the U.S. supplied Moon Mineralogy Mapper (M3)

with 140 m/pixel (global) and 70 m/pixel (targeted) resolution and a 40 km swath; and d) the U. S. supplied Mini-SAR instrument, which will image the polar regions at ~150 m/pixel. Generally, the same comments can be made here as made for SELENE, since the primary camera and altimeter instruments have similar resolutions. However, the 5 m resolution of the Chandrayaan-1 camera will provide the likely highest resolution global coverage of all the missions being discussed here. It should be used to densify the accompanying altimeter global dataset or some type of combined altimeter dataset derived from the data from the multiple missions having such a system.

Lunar Reconnaissance Orbiter (LRO): The U. S. LRO mission will have primarily three instruments that will provide globally geodetic information. These are the LROC camera system, the LOLA laser altimeter, and the Mini-RF SAR radar system. Little information seems to be available on the SAR system so it will not be discussed further here. The LROC system will consist of three line scanner cameras, including: a) a wide field 7 color camera of 100 m resolution, capable of obtaining visible light images in 88 (color) or 110 (monochromatic) km swaths, and UV images in 88 km swathes; and b) two high, 0.5 m resolution cameras, which together will provide a 5 km swath. 62 Tb of raw data is expected from this camera system during the nominal one year mission. The LOLA laser altimeter is a multi-spot altimeter, which will collect spot data at 50 m spacing and vertical information with 10 cm resolution. A SAR instrument has also been added to LRO, of unknown resolution. Clearly, the LOLA altimeter should provide very high density altimetric data, which particularly when combined with altimetric data from the other missions will revolutionize knowledge of lunar topographic in an absolute sense. The ultimate accuracy of such topographic information will however depend on how accurately the spacecraft orbits are determined. In other words, the 50 cm vertical resolution of LOLA will certainly be useful for some applications, but for the purposes of determining global absolute topography it is the accuracy of spacecraft tracking and/or altimetry crossover solutions that are important. The high resolution camera data is expected to cover limited areas of the Moon, at resolutions similar to or slightly better than those obtained by Apollo panoramic camera photography. However, those images, particularly given their high resolution, must be properly tied to the global (e.g. ULCN) frame using photogrammetric procedures. The 100 m resolution images should be similar in resolution to the Lunar Orbiter, Clementine, and Chang'E-1 image sets, and might help to improve the horizontal strength of the global network, but by the time such data are processed the multi-mission altimetry data will be more valuable for that purpose. Still, the images should be tied together for a number of reasons, such as a) to serve as one more useful global image dataset; or b) because the information derived from the planned repeat coverage of the poles should be extremely useful; or c) it is needed for referencing the other LRO instrument datasets. Unfortunately, we note that in the currently available information about LROC there appear to be no current plans to control the images, a situation which must be rectified in order for the LRO mission to reach its desired potential. The correct position of uncontrolled LROC images will be limited to the 150 m expected horizontal accuracy of orbit determination (with pointing accuracy of 60 arc seconds in a 50 km orbit only contributing a negligible 14.5 m when RMSed to 150 m) [LRO Proposal Information Package, 2004, p. 7]. This will total ~1.5 pixels for the low resolution camera, but ~300 pixels for the high resolution cameras.

8. Plan for Control and Mosaicking of Post LRO Mission Datasets

Beyond the currently planned lunar missions (e.g. LRO), it will be necessary to continue to the kinds of processes described above. U. S. and foreign missions will continue to require cooperation and expertise to adopt existing standards and methods and jointly develop new ones as necessary. Imaging data, stereo imaging data, and altimetric data must be combined into a unified network, e.g. successive future versions of the ULCN reference frame and associated (or at least registered) topographic models. Other types of (lower spatial resolution) spacecraft data will also have to be registered in some way with these datasets so that all datasets are in the same system.

In addition, as the horizontal accuracy of the ULCN frames improve and as the topographic representation for the Moon improves, the existing datasets will continue to have to be re-mosaicked using the improved coordinate systems and topography (at least when the improvements in accuracy are greater than the pixel or ~half-pixel size of the datasets).

NASA and the international space agencies should also consider once and for all doing a rigorous lunar mapping mission, either as a stand-alone mission or as a package on another related scientific or operational mission. Such a mission could use a scanning lidar instrument to collect high resolution (e.g. several meters horizontal resolution) global topographic coverage of the Moon. Stereo mapping cameras (e.g. looking at nadir and either or both fore and aft) could then be used for simultaneous further densification of the topographic information and also provide necessary real imagery of the areas covered with the lidar data. Such cameras should be large-format high-resolution CCD framing cameras, so they could acquire data at the ~50 cm to few m level, without concerns of spacecraft "jitter" and processing and modeling problems currently associated with line scanner cameras. Some technology development may be required to qualify such large format CCD cameras for flight, but this will be necessary in any case for Earth observation and other planetary missions. For scientific and resource mapping purposes, such cameras could additionally be multicolor or spectral, and also collect polarization information. With such a mission, finally a definitive model of the Moon's surface could be generated at the 1 to a few m level of accuracy, providing a base for future lunar exploration that could last for decades, and with an accuracy and resolution that surpasses even that with which the Earth has been mapped.

9. Recommendations

The following summarizes the critical recommendations made in this response.

- The mean Earth/polar axis system should continue to be the fundamental coordinate system for the Moon.

- Although oriented on the basis of an LLR reference frame, the ULCN 2005 and its follow-on frames should be the fundamental reference frames for the Moon.
- The ULCN 2005 (and planned ULCN 2007) should be extended *now* so that all existing datasets have been registered to the same system.
- The Clementine mosaics should be re-created using improved radiometric calibration information and tied geometrically to the ULCN 2005 or later versions of it.
- Digital mosaics of the other existing datasets should be generated (Apollo, Mariner 10, and Galileo).
- All image mosaics should be recreated as necessary in the future, when warranted by the geometric improvements to the ULCN frames.
- Procedures, algorithms, and software require development must take place starting *now* in order to process many current and future datasets. Such development include efforts to control line scanner camera images, to improve automatic tie pointing of images, to conduct large partitioned matrix solutions, to do radargrammetric solutions, and to handle the extremely large datasets that will be arriving in the next few years.
- Much better standardization and cooperation is needed, both within U. S. missions and between the U. S. and foreign missions, to the benefit of all parties involved.
- Work must begin *now* to process the current and future lunar datasets, and their data must be registered together in uniform and successive steps to the ULCN frames.

We will add that perhaps the best way to be sure that this tasks are undertaken now and in the future is to establish a well-funded data analysis program to ensure the proper processing of data, particularly as needed by subsequent missions. This program should have the resources to fund advanced development of needed tools and techniques as well as the production (and necessary repeat production) of specific super large datasets and mosaics. A somewhat analogous example would be the NASA Mars Critical Data Products program, which although currently substantially underfunded, provides products that are needed operationally for current and future Mars missions. Other options might be to direct and fund such activities through the NASA Planetary Geodesy and Geophysics Cartography Program or a new lunar science data analysis program (e.g. LDAP). However, the funding required for the Tasks we describe would probably require an order of magnitude increase to the PG&G Cartography program. In addition, since both programs are under the NASA RSA program that is currently being cut, it seems unlikely that funding should be expected from or carried through those sources. We have also often found in the past that pure science programs (like a likely LDAP) will not support cartography efforts with the (perhaps proper) justification that these efforts need to be funded as part of the missions or other overall infrastructure planning. Therefore, a separate program for needed large-scale processing and products will be necessary.

These are substantial tasks, but they are tasks that need to be done if lunar datasets are to be intercompared and of any real use operationally or scientifically. The costs will be quite high compared to the resources currently devoted to similar tasks, e.g. by the NASA

PG&G Program. Nevertheless, the costs are comparatively small, probably on the order of 1% compared to the costs of collecting the data in the first place. Moreover, the cost will be very small compared to the high cost of doing little with these datasets – which given published information appears to be the current plan or at least the direction being taken. We hope the information presented here will go far toward changing that direction.

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