High-Value, Unified Lunar Topographic and Other Datasets. B. A. Archinal, U. S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA, barchinal@usgs.gov)

Introduction: A flood of new, high geometric and spectral resolution lunar data has been and is being returned to Earth by missions from several countries and space agencies. To obtain maximal value for science and exploration, these data must be registered to a common coordinate reference frame and to each other. These steps will ensure the greatest return on the tremendous investments made in collecting these data, allowing for their proper calibration, registration, and error analysis and thereby providing the best comparative and synergistic use of these datasets. This summary describes the steps needed to ensure the development of these high-value lunar data products.

Recent lunar data first need to be brought together into a common frame via geodetic control (e.g., photogrammetric, radargrammetric, and altimetric crossover) solutions. This includes the merging and registration necessary to generate the most accurate, highest resolution global lunar topographic model (or digital elevation model or DEM). Such a model can then be used to support photometric calibration and orthorectification of the various datasets. Use of a common frame and a common DEM allows the data to be converted finally into *information*, primarily in the form of useful cartographic products. Such products are essential for addressing lunar science and exploration goals at the highest possible level of (known) accuracy.

The expectation of science and exploration users is that collected datasets have achieved sub-pixel levels of accuracy. Such accuracy is only possible with geodetically controlled products and projection onto DEMs of comparable resolution to the products (and preferably, particularly for color and multispectral data, at a resolution approaching a few tenths of the product resolution). Such accuracy would seem an obvious requirement given the labor and resources expended to collect data at a sufficient level of precision that such accuracy could be achieved. The costs to create such information products are quite small relative to these data collection costs.

I and others have proposed before that such efforts are needed [1]. The NASA Advisory Council also has recognized the importance of such processing, recommending that all lunar data sets be geodetically controlled [2]. The utility of past, current and future lunar datasets will be severely hampered if they cannot be correlated/compared with each other or if the positional uncertainties are not well characterized.

Progress has been made toward controlling recent data and making high-quality lunar cartographic products, either by instrument teams [3] or under the NASA Lunar Mapping and Modeling Project [4]. However, so far only a tiny fraction of data such as those from the Lunar Reconnaissance Orbiter (LRO) mission have been controlled, and there are only a few examples of multi-mission data registration and product generation from these new datasets [5]. Given the funding constraints on recent major international missions to the Moon, an international cooperative project would greatly facilitate accomplishment of the work described here. Not only would the registration of image data (even without the release of raw data) likely be achieved more efficiently and quickly, but the comparative analysis of such data for science and exploration will be simpler and less costly. Collaboration will also greatly encourage and facilitate international cooperation in the exploration of the Moon.

I describe here additional details regarding the *need* for *controlling the data* and for a *global DEM*, and *systems and frames*. "Base" *datasets* are described that need to be connected initially as part of this process. *Principles* of processing are given in order to give some indication of in what order and how datasets could be registered to each other and a common frame. Some of the many and difficult *challenges* in accomplishing such work are briefly considered.

Need for Geodetic Control: The only way to connect/register/compare data with quantified precision and accuracy is to geodetically (usually photogrammetrically) process the data into controlled products. Otherwise the uncertainties in the comparison of data sets undermine their synergistic value. Users always want the best precision and accuracy possible and require that they be quantified. Such knowledge is critical for mineralogic, geologic, and scientific investigations and exploration purposes such as landing and landed operations. Controlling any single dataset provides many benefits including (a) the best method of removal of mosaic seams for qualitative work; (b) proper orthometric projection of data (registration of images to topography in order to make or match existing mosaics and maps); (c) registration of multispectral data; and (d) proper photometric correction of data. ***The value of such control increases exponentially when multiple datasets are considered, so it is essential that this work be planned for and done with new lunar data.*** Geodetic control adds substantial value to the data, especially relative to the cost of data collection. Furthermore, if one considers the cost of the initial data collection or even the loss of a mission (e.g. landing at incorrect coordinates), such costs are absolutely necessary and relatively insignificant.

Need for Global Topography: Several new global DEMs have been produced in the last few years, either from Kaguya altimetry [6], LRO Orbiter Laser Altimeter (LOLA) altimetry [3], or LRO Wide Angle Camera (WAC) stereo [7]. Apparently unreleased global models also exist based on other datasets (Kaguya Terrain Camera (TC) stereo, Chang'E-1 altimetry and stereo, etc.). As amazing and high-quality as these models are, there is still a need for global topographic modeling at higher resolution and/or accuracy. For example, the altimetry models have substantial longitudinal data gaps in the mid latitudes and particularly the equatorial regions. The WAC stereo DEM is based on ~100 m resolution images that although aligned with LOLA solution geometry information are uncontrolled and may have errors up to a substantial fraction of that resolution. These existing global models are therefore not sufficient for the orthoprojection of high resolution single band (e.g. LRO Narrow Angle Camera (NAC), Apollo Metric or Panoramic, Chandrayaan-1 Terrain Mapping Camera (TMC), or Kaguya TC or Multi-Band Imager (MI)) at or even near the resolution of such data. They are also not sufficient for the orthoprojection and slope correction and calibration of even medium resolution color, multispectral, or infrared data (e.g. Kaguya MI or SP, LRO WAC or Diviner Lunar Radiometer Experiment, Chandrayaan-1 M^3) where topography is required at the few tenths of a pixel level. There is a need for the highest possible resolution global DEM to process the global datasets, and even higher resolution DEMs to process local to regional high-resolution data. Such a DEM can be generated from the combination of the altimeter data and stereo data, such as (in order of increasing resolution) NAC, Apollo, TMC, TC, MI, and LRO Mini-RF data.

Such a DEM is needed globally at "landing site scales" to allow for landings and surface planning and operations on the Moon, both for robotic and human missions. The morphological information is needed for scientific and geologic studies. The models are needed for the projection of data both for these purposes and also for change detection. They are also needed to make photometric and other calibration corrections that are based on illumination, both for single band photometric calibration, color and multispectral band calibration based on illumination levels and slope, and thermal band calibration based on slope and solar illumination and re-radiation. The location of mineralogical resources at high resolution will be heavily dependent on how accurate the underlying DEM is.

What system and frame? The recommended [8] coordinate system for the Moon is the mean Earth / polar axis (ME) system, and the recommended way to access it is via the JPL DE 421 ephemerides, with an appropriate rotation to the ME system. The recommended mean radius for the Moon is 1737.4 km [7], and fortunately most instrument teams and missions have adopted these recommendations. The real issue then becomes using or creating a reference frame within that coordinate system to which datasets can be referred. Currently the best lunar reference frames are those derived from Lunar Laser Ranging (LLR). These frames have coordinate system accuracies approaching the decimeter to centimeter level, but only for the 5 existing LLR targets. It will be necessary to tie the other datasets into an LLR frame or one based on it.

What datasets? Already noted above are some of the highest density or resolution altimetric and stereo datasets that can be used to build a fundamental lunar reference frame and uniform global DEM. Other required data includes spacecraft geometric ("SPICE" or similar) data and a current best lunar gravity model (eventually likely to be supplanted by or at least improved on by the results from the Grail mission). Once such a frame and model are established all lunar data can be tied to them. This includes data already mentioned and all of the data from the recent reconnaissance missions (SMART-1, Kaguya, Chang'E-1, Chandrayaan-1, LRO, Chang'E-2) and from earlier missions as well (Lunar Orbiter, Apollo, Clementine, Lunar Prospector).

Processing Principles: Some flexibility in the order of how data should be processed or algorithms, software, and procedures need to be developed exists, but deriving and registering data to a common frame and DEM early on are important steps. A few of these steps for some data have already been accomplished. In several cases these steps are being taken or will be in the near future. For others planning has not begun and funding has not been identified. The following steps are recommended: 1) Less accurately located (controlled datasets) need to be registered to more accurately located datasets. 2) "Co-located" data (i.e. simultaneously collected data, like LOLA and LROC) should be tied together. 3) The global DEM should be created (or more likely improved iteratively) first, so that datasets can be controlled and calibrated relative to it and projected onto it. 4) Control, calibration (photometric corrections based on topography) and orthomosaicking of lower resolution (e.g. other "imaging") data should be done nearly last. In addition plans for at least occasional reprocessing of data need to be in place, as frames, crossover solutions, tie pointing and photogrammetric solutions improve, at least until the subpixel resolution limit of the given dataset is reached.

Challenges: Completing the simple steps noted above will involve many challenges: 1) Tying any one of the dataset frames (e.g., LOLA) to an LLR frame. 2) Tying together "co-located" data (e.g., LOLA to LROC NAC and WAC, perhaps LALT to TC and MI). 3) Possibly doing (massive) combination altimetric and photogrammetric solutions to increase the positional accuracy of both altimetric and image data. 4) Tying together multi-mission altimetric data (possibly by merging or simultaneous cross-over solutions) into one frame and DEM. 5) Tying and merging stereo images or DEMs, with altimetric data. 6) Merging multiple DEMs together or high resolution DEMs into low resolution DEMs. 7) Controlling push frame images (e.g., from LROC WAC). 8) Providing adequate disk space and data processing speed to support the many colossal datasets involved. 9) Making geometric camera models available in various software packages (or in a common package). 10) Improving algorithms and software for reliable automatic tie pointing, large photogrammetric solutions, automated stereo processing, outlier detection (for all three), altimetric solution, etc. 11) Finding sufficient funding for such work in an era of constrained budgets. And 12) Arranging international collaborations and (at least limited) release of raw or partially processed data.

Summary: To make the best use of the new high-value lunar data, they must be registered using a common reference frame and DEM. This process could be accomplished most efficiently via international cooperation, and at minimal cost relative to the collection of the data.

References: [1] Archinal et al. (2007) Sci. Associated with the Lunar Exp. Arch., Tempe, AZ; Kirk et al. (2007) XXIII International Cartographic Congress 6410. [2] NAC (2007), S-07-C-13, http://www.hq.nasa.gov/office/oer/nac/reccommendations/Recommend-5-07.pdf. [3] E.g. Smith et al. (2010), Geophys. Res. Lett. 2010;37 6. [4] Noble et al. (2009), LEAG #2014. [5] E.g. Iz et al. (2011), J. Geod., June 24. [6] Araki et al. (2009), *Science*, **323** (5916): 897-900. [7] http://lroc.sese.asu.edu/news/?archives/484-Lunar-Topography--As-Never-Seen-Before!.html. [8] Archinal et al. (2011), *Cel. Mech. & Dyn. Ast.*, doi 10.1007/s10569-010-9320-4; LRO&LGCWG (2008), http://lunar.gsfc.nasa.gov/library/LunCoordWhitePaper-10-08.pdf.