UNIFYING LUNAR TOPOGRAPHIC AND OTHER DATASETS. B. A. Archinal, R. L. Kirk, L. R. Gaddis, and M. R. Rosiek, Astrogeology Science Center, 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 national and international space agencies. To obtain maximal value for science and exploration, the data must be registered to a common coordinate reference frame. Only such an effort will ensure the greatest return on the tremendous investments made in the collection, calibration, registration, error analysis, and permitting full comparative and synergistic use of the datasets. This summary describes the steps needed to ensure the development of these high-value lunar data products.

Topographic, imaging, and spectral data from all missions need to be brought together into a common frame via geodetic control (e.g., photogrammetric, radargrammetric, and altimetric crossover) solutions. Done rigorously, this process will allow for the merging and registration necessary to generate the most accurate, highest resolution global lunar topographic model (digital elevation model or DEM). Such a model can then be used to support photometric calibration and orthorectification of the datasets. Once the imaging data are brought into a common frame and a common DEM is in use, the datasets can be finally converted 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 accuracy. Equally important for future decision making, the accuracy level of such products will be known and documented as a result of the merging process.

The general requirement of science and exploration users is that datasets can be used and compared at the pixel level with accuracy on the order of tenths of a pixel required for color and spectral data. Such accuracy is only possible with geodetically controlled products that are orthorectified onto DEMs with resolutions approaching those of the output image products.

We and others have argued before that more extensive cartographic efforts are needed to exploit past missions fully and prepare for future ones [1]. The NASA Advisory Council also has recognized the importance of such processing, recommending that all lunar data sets be geodetically controlled [2].

Progress has recently been made toward controlling data from specific missions and to make cartographic products, both by instrument teams [3] and under the NASA Lunar Mapping and Modeling Project [4]. The U.S. efforts have so far resulted in controlling only a tiny fraction of the Lunar Reconnaissance Orbiter (LRO) mission. However there have been few cases of multi-mission data registration and product generation from these new datasets [e.g., 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. If necessary, significant progress could be made even without requiring the release of raw data from all missions. Joint efforts at mapping would be a good first step that would greatly encourage and facilitate broader international cooperation in the exploration of the Moon.

In the remainder of this abstract we describe the *need* for *controlling the data* and for a *global DEM,* and *systems and frames*. "Base" *datasets* are listed that need to be connected initially and *principles* of processing are described to outline in what order and how datasets could be registered to each other in 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 site selection, landing and landed operations. Controlling any single dataset provides many benefits including (a) the best method of removal of mosaic seams for qualitative work; (b) proper orthometric projection of data (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, including those from Kaguya Laser Altimeter (LALT) altimetry [6], LRO Orbiter Laser Altimeter (LOLA) altimetry [3], and Global Lunar DTM 100 m [7]. Unreleased global models are also said to exist based on other datasets such as Kaguya Terrain Camera (TC) stereo and Chang'E-1 altimetry and stereo. As revolutionary and scientifically valuable as these models are, there is still a need for global topographic modeling at higher resolution and accuracy. For example, the laser altimetry models have substantial longitudinal data gaps in the mid-latitudes and particularly in the equatorial regions. The Global Lunar DTM 100 m [7] is based on ~100 m resolution images that although aligned with LOLA solution spacecraft position information are uncontrolled and may have errors up to a substantial fraction of that resolution. These existing global models are therefore insufficient for the orthoprojection of high resolution images such as LRO Narrow Angle Camera (NAC), Apollo Metric or Panoramic, Chandrayaan-1 Terrain Mapping Camera (TMC), or Kaguya TC 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 Multi-Band Imager (MI) or SP, LRO WAC or Diviner Lunar Radiometer Experiment, Chandrayaan-1 M^3) where topography is required at the pixel level of horizontal accuracy and tenth of a pixel level of vertical accuracy. 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, particularly (from highest to lowest 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 the accuracy of the underlying DEM.

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 [8], 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? 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" - http://naif.jpl.nasa.gov/naif/ - or similar data) 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 remote sensing data from the recent missions (SMART-1, Kaguya, Chang'E-1, Chandrayaan-1, LRO, and Chang'E-2) and from earlier missions as well (Lunar Orbiter, Apollo, Clementine, Lunar Prospector).

Processing Principles: Some flexibility exists in the order of how data should be processed or algorithms, software, and procedures need to be developed. However deriving and registering data to a common frame and DEM early on are important steps. For some datasets, key processing has recently been accomplished or is planned for the near future. For others planning has not begun and funding has not been identified. The following steps are recommended: 1) The global DEM should be created first, so that datasets can be controlled and calibrated relative to it and projected onto it. 2) "Co-located" data (i.e., simultaneously collected data, like LOLA and LROC) should be tied and adjusted together. These first two steps benefit one another and will likely have to be iterated. 3) Less accurately located datasets need to be registered to more accurately located datasets. 4) Control, calibration (photometric corrections based on topography) and orthomosaicking of lower resolution images and image-like (spectral, thematic, etc.) data should be done last. Because these steps are unlikely to be carried out in strict order, resources need to be set aside for some limited reprocessing of data 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 deceptively simple steps listed above will involve many challenges. Here are some of the technical challengs that we have identified: 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) 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) Making geometric camera models available in various software packages (or in a common package). 9) Improving algorithms and software for reliable automatic tie pointing, large photogrammetric solutions, automated stereo processing, outlier detection, altimetric solution, etc. There will also be political/financial challenges: 1) Finding sufficient funding for such work in an era of constrained budgets. 2) 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://bit.ly/x0HnnM. [3] Smith et al. (2010), Geophys. Res. Lett. 2010;37 6. [4] Noble et al. (2009), LEAG #2014. [5] Iz et al. (2011), J. Geod., June 24. [6] Araki et al. (2009), *Science*, **323** (5916): 897-900. [7] Scholten et al. (2011) LPSC 42, Abstract #2046 [9] 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.