CARTOGRAPHY FOR LUNAR EXPLORATION: 2006 STATUS AND PLANNED MISSIONS

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Commission IV, WG IV/7

KEY WORDS: Photogrammetry, Cartography, Geodesy, Extra-terrestrial, Exploration, Space, Moon, History, Future

ABSTRACT:

The initial spacecraft exploration of the Moon in the 1960s–70s yielded extensive data, primarily in the form of film and television images, that were used to produce a large number of hardcopy maps by conventional techniques. A second era of exploration, beginning in the early 1990s, has produced digital data including global multispectral imagery and altimetry, from which a new generation of digital map products tied to a rapidly evolving global control network has been made. Efforts are also underway to scan the earlier hardcopy maps for online distribution and to digitize the film images themselves so that modern processing techniques can be used to make high-resolution digital terrain models (DTMs) and image mosaics consistent with the current global control. The pace of lunar exploration is about to accelerate dramatically, with as many of seven new missions planned for the current decade. These missions, of which the most important for cartography are SMART-1 (Europe), SELENE (Japan), Chang'E-1 (China), Chandrayaan-1 (India), and Lunar Reconnaissance Orbiter (USA), will return a volume of data exceeding that of all previous lunar and planetary missions combined. Framing and scanner camera images, including multispectral and stereo data, hyperspectral images, synthetic aperture radar (SAR) images, and laser altimetry will all be collected, including, in most cases, multiple datasets of each type. Substantial advances in international standardization and cooperation, development of new and more efficient data processing methods, and availability of resources for processing and archiving will all be needed if the next generation of missions are to fulfil their potential for high-precision mapping of the Moon in support of subsequent exploration and scientific investigation.

1. INTRODUCTION

Lunar cartography is in a time of transition. Numerous missions during the Apollo era (1960s–70s) and the 1990s (Clementine and Lunar Prospector) provided fundamental imaging and other data for the Moon at many scales. Many types of cartographic products have been and are being generated from these data, from the paper maps of the 1960s and 70s, to digital image mosaics and terrain models (DTMs) of the 90s and today.

However, now we face a dazzling array of current, about to be launched, and planned new missions to the Moon, many of which will produce torrents of new data, all of which will need to be registered into a common reference frame. Cartographic products such as global mosaics and DTMs will have to be generated from a large portion of these datasets. With their laser altimeters; stereo, high-resolution, and multispectral cameras; and radar instruments, a deluge of new, high-accuracy, and complex datasets will be generated. All will need to be properly calibrated, pre-processed, co-registered, and (for images) mosaicked and/or stereoanalyzed to make DTMs for local, regional, and global areas. We stand at a crossroads where the needs are many: the need for greatly increased international cooperation; the need for new algorithms and software to handle such increasing complex and large datasets; the need for new data processing techniques to store, process, and archive such datasets; the need to administer the greatly increased efforts required to process such datasets; and the need for adequate funding to address all these concerns. A further requirement is the realization among all involved that as the reference frames improve and our knowledge of the data increases, multiple repeat processing of past and current datasets is required in order keep the datasets registered in a common system and properly calibrated, so that the data can be used together.

2. PAST LUNAR MAPPING MISSIONS

The history of lunar cartography extends back hundreds if not thousands of years by virtue of the Moon being the only celestial body whose solid surface is resolved by the unaided eye (Batson et al., 1990; Whitaker, 1999). In this paper, however, we limit our scope to a discussion of lunar mapping carried out wholly or primarily with data acquired by spacecraft. In this context, the history of lunar mapping divides naturally into two periods. The initial phase of vigorous exploration started with the first robotic probes of the late 1950s and 1960s and culminated in the final Apollo missions of the early 1970s, which carried instruments dedicated to precision mapping. After a considerable hiatus, a renaissance in lunar exploration began with the Clementine and Lunar Prospector missions of the 1990s. This new golden age continues to gather momentum, with numerous missions planned for the near future as described in Section 4 below.

2.1 The First Era of Lunar Exploration

Soviet Missions: Despite a number of early and unpublicized failures, the Soviet Union captured many of the "firsts" of the early space age, including the first successful lunar probe (Luna 2, which impacted the Moon in September, 1959, but did not carry a camera), and the first craft to photograph the far side of the Moon (Luna 3, October, 1959). Film from the two cameras on Luna 3 was developed onboard, and then imaged with a facsimile camera that transmitted the results to Earth. A combination of less-than-ideal lighting conditions and radio interference with the facsimile signal resulted in images of low quality, but the mission nevertheless revealed approximately 70% of the hidden side of the Moon for the first time (Reeves, 1994, pp. 46–49). In 1965, the Zond 3 probe, on its way to Mars, took additional photos of the far side with a similar but improved imaging system under better lighting conditions. Together, the two missions imaged roughly 92% of the far side (ibid, pp. 96–98). The Zond 6-8 missions (1968–70) obtained even higher resolution images of the far side by returning the exposed film to Earth (another first), and additional images of the near and far sides were obtained by the Luna 12, 19, and 21 orbiters in 1966, 1971, and 1974 (Batson et al., 1990).

Additional Soviet "firsts" included the first soft landing (Luna 9, 1966), the first robotic sample return mission (Luna 16, 1970), and the first lunar rover (Luna 17/Lunakhod 1, 1970). All these missions returned extensive images from the surface, and all were followed by additional missions of similar type in the period through 1973. Bol'shakov et al. (1992) present maps of the coverage of both Soviet and U.S. images of the Moon. The subset of images that have been published have been scanned and are available online at http://www.mentallandscape.com/C_CatalogMoon.htm.

Lunar Orbiter: The U.S. Lunar Orbiter missions (Bowker and Hughes, 1971) were intended to provide the high resolution images (including stereo) needed to select safe yet scientifically interesting landing sites for the Apollo manned missions. This task was successfully completed by the first three missions in 1966–7, freeing Lunar Orbiters IV and V to obtain systematic, near-global coverage at lower resolution. These missions thus provided a considerable fraction of the most important cartographic data for the early era. Each Orbiter carried an 80-mm focal length Medium Resolution (MR) camera and a 610-mm focal length High Resolution (HR) camera that simultaneously exposed separate sections of a single 70-mm film strip. The film was then developed on board and scanned, in a process resembling that used by the Soviet Lunas but at considerably higher resolution, with over 16,000 scan lines across the width of the film. The original film was scanned in narrow strips (27 per MR, 86 per HR frame), which were recorded on film on the ground as separate "framelets". Prints of the framelets were then hand-mosaicked and rephotographed. Low resolution scans of the images are available online at http://www.lpi.usra.edu/resources/lunar_orbiter/. Geometric imperfections in the mosaics considerably limited their cartographic potential at the time. Fortunately, the images contain geometric information in the form of fiducial marks and a preprinted reseau that allows more accurate reconstruction by modern, digital techniques, and this is in fact being done, as described in Section 3.5. The effective resolution[1] of the HR images ranges from 0.5 m for the early missions to 30 m for LO IV. The resolution of the corresponding MR images is 7.6 times coarser.

Apollo: The Apollo astronauts used hand-held, 70-mm Hasselblad cameras to photograph the Moon from orbit, beginning with Apollo 8 (1968) and from the surface beginning with Apollo 11 (1969). These images have been digitized at very low resolution and placed online at http://www.lpi.usra.edu/resources/apollo/ but their cartographic potential (in particular, that of the high-resolution surface images) has not been exploited to date. More pertinently, the last three lunar missions, Apollo 15, 16, and 17 (1971–2) carried a dedicated orbital mapping system consisting of a Metric (or Mapping) camera, Panoramic camera, star tracker cameras, and laser altimeter (Livingston et al., 1980). The Metric camera was a Fairchild frame camera with 76 mm focal length and 114 mm square image size. The Panoramic camera, a modified version of the Itek KA-80A "optical bar" camera used by the Air Force, used a moving lens of 610 mm focal length to capture a 114x1140 mm image. The Metric images cover a 160-km square region at a useful resolution of ~15 m, and the Panoramic images cover a 339 (across-track) by 22 km "bowtie" with resolutions ranging from ~2 m in the center to ~4 m at the ends. Stereo convergence is provided by the along-track overlap of the Metric images, and by pitching the Panoramic camera alternately 12.5° fore and aft of nadir. Image coverage from these cameras was limited to the illuminated portion of the near-equatorial zone straddling the ground tracks of the three missions. Coverage was increased slightly by rolling the spacecraft to obtain oblique images on either side of the track, giving a total area between 20 and 25% of the Moon (Figure 1). Low resolution "browse" versions of the images are available online at the same URL given above for the Apollo handheld photographs.

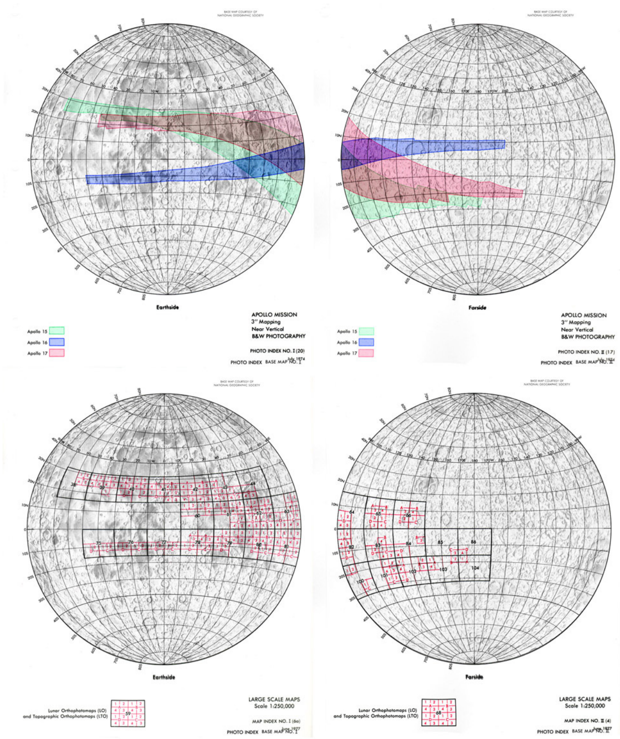

Figure 1. Top, coverage of Apollo 15, 16, and 17 vertically oriented Mapping camera images. Bottom, published maps in the LTO (Lunar Topographic Orthophotomap) series based on Mapping camera data. Lunar near side and far side hemispheres appear at left and right, respectively. Taken from Schimerman (1975).

Other US Missions: The Lunar Ranger series of spacecraft were hard landers that carried a set of vidicon cameras capable of transmitting 800x800 full-frame and 200x200 partial-frame pixel television images to Earth. The field of view of these cameras ranged from 2° to 24° across. Rangers 7. 8, and 9 (1964–5) were successful, and yielded nested coverage of limited regions centered on their respective impact points, with a best resolution on the order of 25 cm (Livingston et al., 1980). The Ranger 8 and 9 images are online at http://www.lpi.usra.edu/resources/ranger/. The Rangers were followed in 1966–8 by the Surveyor soft landers, which carried a 600x600 pixel vidicon camera with a variable focal length lens. This camera was articulated so that complete, panoramic views could be built up out of ~200 frames at 1 mRad/pixel resolution or 1600 frames at 0.25 mRad/pixel (Livingston et al., 1980). In

[1] In this paper, we adopt the widespread (but, technically, incorrect) contemporary usage of referring to the ground sample distance (GSD) between pixels as "resolution". LO film images do not reveal additional detail on the lunar surface if digitized at GSDs substantially smaller than those indicated. References from the early space age express resolution in terms of line pairs, yielding numbers that are about twice as large and more indicative of the most closely separated features that can be distinguished (resolved).

addition, stereo imaging was acquired by viewing the image of the surface in a small mirror, and by firing the landing rocket briefly to move the entire Surveyor 6 spacecraft. Of the seven missions, all but Surveyors 2 and 4 were successful.

The final U.S. mission to return cartographically useful images of the Moon in the 1970s was Mariner 10. Bound for encounters with Venus and Mercury, it flew over the northern hemisphere of the Moon shortly after its 1973 launch. The camera system consisted of two identical 700x832 pixel vidicons, each with two lenses. The 62-mm wide-angle lens provided an 11°x14° field of view, while the 1500-mm lens yielded a field of view of only 0.36°x0.48° and could be used in conjunction with any of 3 colors, polarizing, or clear filters (Dunne and Borges, 1978). The several hundred images acquired, with resolutions from ~1 to 20 km/pixel, provided the first opportunity to characterize the spectral properties of the northernmost part of the Moon (Robinson et al., 1992).

Schimerman et al. (1975) compiled a *Lunar Cartographic Dossier* that includes maps of the image coverage of the U.S. missions listed here, along with information about map series and control networks. The coverage of each individual dataset is presented as a separate overlay on transparent plastic, making the *Dossier* especially valuable for comparing multiple datasets; Figure 1 was generated by digitally combining the relevant overlays with the base maps also provided in the *Dossier*. The full set of overlays is being digitized and will be made available online by the Lunar and Planetary Institute (http://www.lpi.usra.edu/resources/) in the near future.

2.2 A New Beginning

Galileo: The second age of lunar exploration began much as the first had ended (if one temporarily overlooks the Luna 22 orbiter), with a flyby of a craft headed for a more distant destination. En route to Jupiter, the Galileo spacecraft flew through the Earth-Moon system in 1990 and 1992 taking numerous images during both encounters. Coverage from the first flyby was centered on Mare Orientale but covered a significant part of the lunar far side at resolutions of a few km per pixel (Belton et al., 1992). Images from the second encounter covered the Earth-facing side of the Moon, north polar region, and eastern limb at resolutions down to 1 km (Belton et al., 1994). The Galileo Solid State Imager (SSI) was the first planetary camera to use a charge-coupled device (CCD) as a detector, resulting in significant improvements in the stability of both geometric and radiometric calibration of the images. Thus, these images proved to be of tremendous value both for lunar geodesy and for multispectral studies, including definitive identification of the South Pole Aitkin basin on the southern far side (Belton et al., 1992). In all, about 75% of the Moon was imaged at wavelengths of 0.4–1.0 μm.

Clementine: Early in 1994, Clementine became the first new spacecraft in two decades to orbit and investigate the Moon. The mission was a joint project of the U.S. Department of Defense and NASA, intended primarily to test sensors and other technologies for strategic defense by rendezvousing with an asteroid after a period of checkout in polar orbit around the Moon. A hardware malfunction prevented the asteroid encounter from taking place, but the two months of lunar observations were extremely successful. Clementine carried a star tracker camera, a LIDAR altimeter, and four small-format CCD cameras for observing and mapping the Moon (Nozette et al., 1994). The UVVIS and NIR cameras obtained nearly global coverage, with 5 spectral bands in the range 0.4–1.0 μm and 6 bands between 1.1 and 2.8 μm, respectively. Maximum resolutions obtained with these cameras at periapsis were ~100 and ~150 m/pixel, with resolution degrading by about a factor of 2 at high latitudes. Extensive stereo coverage of the polar regions at resolutions of 200–300 m/pixel was also obtained by pitching the spacecraft on alternate orbits. Smaller amounts of high-convergence stereo coverage were obtained in a few low-latitude areas by rolling the spacecraft, with the primary objective in this case being to fill gaps in the systematic coverage obtained with nadir pointing. Overlap between the nadir-pointed images, which have fields of view on the order of 5°, also provides rather weak but near-global stereo coverage (Cook et al., 1996). The LWIR and HIRES cameras had substantially smaller fields of view and thus obtained image strips along each orbit with complete coverage only at the highest latitudes. The LWIR images obtained thermal infrared (8.0-9.5 micrometer) images with ~60 m maximum resolution. The HIRES camera had four narrowband filters and one broad bandpass in the range 0.4–0.8 μm, and achieved a maximum resolution of ~7 m. In all, nearly 1.7 million images of the Moon were acquired. The LIDAR achieved a ranging precision of 40 m, but the dataset was substantially undersampled, with a footprint on the order of 200 m but only about 72,000 valid range measurements distributed between ±75° latitude (Zuber et al., 1994). Altimetric observations at higher latitudes were precluded by Clementine's elliptical orbit. Nevertheless, the extensive set of elevation measurements, like the UVVIS and NIR multispectral imagery, was unprecedented at the time. Together, the altimetry and image datasets have revolutionized lunar science in the modern era.

Lunar Prospector: This low-cost NASA mission orbited the Moon pole-to-pole in 1998–1999. It carried gamma-ray, neutron, and alpha-particle spectrometers for mapping the elemental composition of the lunar surface, as well as a magnetometer/electron reflectometer to investigate the remnant magnetization of the Moon. The lunar gravity field was also mapped by analyzing the spacecraft tracking data (Binder, 1998). Thus, the significance of Prospector to cartography was as a source of scientifically valuable thematic data, rather than as a provider of imaging or altimetric data that provide a high-precision backdrop for such thematic data. The mission ended in July, 1999 when the spacecraft was deliberately crashed into a permanently shadowed crater near the south pole. This crater was later named in honor of Dr. Eugene M. Shoemaker, a founder of modern lunar and planetary geology. A small vial of Shoemaker's ashes was carried by the spacecraft.

3. CURRENT CARTOGRAPHIC PRODUCTS

3.1 Hardcopy Maps and Atlases

United States Maps: The following summary is taken from Inge and Batson (1992). The online version of this map index (http://astrogeology.usgs.gov/Projects/MapBook/) is periodically updated, but only a few new lunar maps have been printed since 1992. Beginning in 1960, the U.S. lunar mapping program, under the auspices of military mapping agencies, compiled many shaded relief maps, photo maps with and without contours, and controlled photomosaics, primarily in support of the Apollo missions.

A variety of small-scale shaded relief maps, geologic maps, and photomosaics were made that cover selected lunar regions and the entire lunar surface at scales ranging from 1:2,000,000 to 1:10,000,000. The last pre-Clementine compilation was a series of 1:5,000,000-scale maps showing shaded relief and shaded relief with surface markings published by the U.S. Geological Survey (USGS).

The 1:1,000,000-scale Lunar Astronautical Chart (LAC) series is based almost exclusively on Earth-based pictures and covers only the lunar near side. The 44 air brushed shaded relief and albedo maps in this series show contours (with some exceptions) and nomenclature. All but two of the near side maps were compiled by the USGS, as were geologic maps based on the LAC series. Nine quadrangles in the LAC series were revised using Lunar Orbiter and Apollo photographs and published in 1976 through 1978. Two new compilations of far side quadrangles are included in this series and all but two of the near side maps were compiled by the USGS.

The Apollo Intermediate Chart (AIC) 1:500,000-scale series, limited to the lunar near side equatorial region, was compiled from Earth-based pictures and additional image data provided by the Lunar Orbiter spacecraft. Twenty shaded relief and albedo maps, including feature elevations and nomenclature were prepared.

Lunar site maps, produced to support study of potential Apollo landing sites, are identified as ORB maps. They cover selected regions of the near side at scales of 1:100,000 and 1:25,000. Shaded relief maps containing contours and nomenclature and photomaps are available. Additional maps prepared from Lunar Orbiter data are referred to for convenience as ORB maps by Inge and Batson (1992), though they were not part of the original series. The sheets were prepared at scales of 1:250,000 and 1:25,000. Sources for the photomap, topographic photomap, and shaded relief compilations were Lunar Orbiter III and V medium and high resolution images; only the photomaps and shaded relief maps show contours and nomenclature.

An especially large number of maps are available at scales of 1:250,000, 1:50,000, and 1:10,000 as a series called Lunar Topographic Orthophotomaps (LTO) and Lunar Orthophotomaps (LO). Over 250 sheets were compiled in each version from images returned by Apollos 15, 16, and 17. The LTO sheets contain a graticule, contours, and names, while the LO maps display the photomosaic unencumbered by any linework except for border ticks. Several geologic maps have been prepared in the LTO format. A map of the LTO quadrangles published, taken from Schimerman (1975), is shown in Fig. 1.

Ranger Lunar Charts (RLC) with scales ranging from 1:1,000,000 to 1:1,000 and Surveyor landing-site maps with scales as large as 1:100 are the largest scale published lunar maps.

In addition to these published maps, a considerable number of other cartographic products was produced and either distributed in limited numbers (e.g., as planning maps) or used as illustrations in research papers. Examples of the latter are shown by Wu and Doyle (1990).

Soviet Maps: A relatively smaller number of lunar maps were printed in the Soviet Union; these are for the most part not well known or readily available in the west. Airbrush maps of shaded relief and albedo with nomenclature at scales of 1:25,000,000, 1:10,000,000, 1:5,000,000, and 1:1,000,000 were based on a combination of telescopic and spacecraft observations. Photomaps based on spacecraft imagery were also produced at scales of 1:20,000,000, 1:5,000,000, and 1:2,000,000. Bol'shakov et al. (1992) catalog these maps with thumbnail reproductions and maps indicating the regions covered. A variety of U.S. maps are also represented in this catalog.

Atlases: The series of Soviet atlases of the far side of the Moon (Barabashov et al., 1960; Lipskiy, 1967; Efremov, 1975) are historically noteworthy because of the new terrain that they revealed cartographically for the first time. The more recent atlas of the terrestrial planets and satellites (Bol'shakov et al., 1992) has already been mentioned. Used copies of several of the U.S. atlases from the early era can still be found on the internet and are useful for some purposes. Bowker and Hughes (1971) reproduce Lunar Orbiter images of the whole Moon, whereas Gutschewski et al. (1971) cover only the near side but provide nomenclature and a more user-friendly layout. More recent atlases include those by Rükl (1990), which uses a hand-drawn base, Bussey and Spudis (2004), based on mosaicked Clementine data, and Byrne (2005), with Lunar Orbiter images of the near side processed on a modern computer to improve their cosmetic appearance. The Lunar Orbiter based atlases are all presented image by image, whereas the others cover the Moon with a regular series of map quadrangles in standard projections. It should be noted that none of these atlases is ideal as a reference for lunar nomenclature. Lunar (and planetary) names are approved by the International Astronomical Union Working Group on Planetary System Nomenclature, and are maintained in a database by the USGS. This database, the lunar and planetary gazetteer, is currently available online at http://planetarynames.wr.usgs.gov/. A definitive atlas of lunar nomenclature is currently in preparation and will be accessible via the same website.

Control: We note briefly that the many products listed above were produced with reference to a large number of early lunar control networks, each of which covered only a portion of the Moon, and all of which are now obsolete. As listed by Davies (1990), several telescopic networks, a Lunar Orbiter network, several Apollo-derived networks, and several Zond networks were in use in the 1970s. A Unified Lunar Control Network (ULCN) was subsequently produced that incorporated data from several of these, plus Mariner 10 and Galileo observations (Davies et al., 1994).

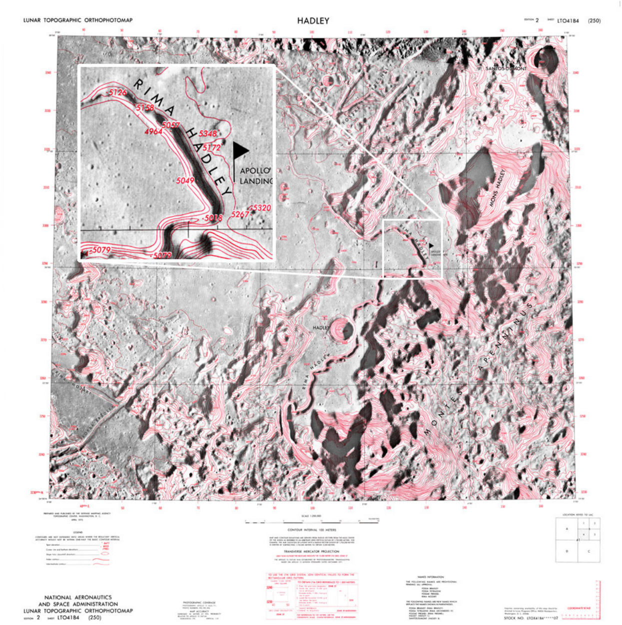

Figure 2. Lunar Topographic Orthophotomap (LTO) 1:250,000 quadrangle 41B4 containing Rima Hadley and Apollo 15 landing site, from digitized version available online at http://www.lpi.usra.edu/resources/mapcatalog/. Inset shows detail around the landing site.

3.2 Online Maps from the Early Space Age

Many of the most useful of the U.S. maps described above have been digitized and placed online by the Lunar and Planetary

Institute at http://www.lpi.usra.edu/resources/mapcatalog/. Holdings include 1:10,000,000 LPC, 1:5,000,000 LMP, and 1:1,000,000 LM and LAC series airbrush shaded relief maps, and 1:2,500,000 LEM Lunar Orbiter controlled mosaics. The most numerous and likely the most valuable products are the LTO series of orthophotomosaics with contours derived from Apollo imagery. A subset of the maps published at scales of 1:250,000 (Figure 2), 1:50,000, 1:25,000, and 1:10,000 are currently available. The Lunar Orbiter atlas of Bowker and Hughes (1971) and the Consolidated Lunar Atlas (based on telescopic photographs and hence not discussed above) are also online at http://www.lpi.usra.edu/resources/.

Another valuable online collection of data from the first era of lunar exploration is the Lunar Consortium dataset at http://astrogeology.usgs.gov/Projects/LunarConsortium/. This collection includes Earth-based albedo maps, global geology, a map of surface ages derived from Lunar Orbiter images, airbrush shaded relief maps, Galileo multispectral mosaics, and Apollo compositional, topography, and magnetic data, all in a consistent set of map projections. Unprojected Zond 8 images are also provided.

3.3 Clementine Image Mosaics and Topography

Beginning in the late 1990s, the USGS undertook the task of assembling the Clementine UVVIS and NIR images into global mosaics with a total of 11 spectral bands. The first step was to create a Clementine Lunar Control Network (CLCN) with the aid of the late Merton Davies and colleagues at the RAND Corporation (Edwards et al., 1996). This network was based on pass points measured between nearly 44,000 Clementine images in the 750 nm spectral band, with only 22 near-side ties to the ULCN. Ground points were constrained to lie on a mass-centered sphere of radius 1736.7 km, and camera angles were unconstrained by their a priori values. The result was a control network with subpixel RMS residuals (but, it was later discovered, systematic long-wavelength positional errors of 15 km or more). The USGS ISIS software system for planetary cartography (Eliason, 1997; Gaddis, et al., 1997, Torson, et al., 1997; see also http://isis.astrogeology.usgs.gov/) was then used to produce a controlled basemap by projecting and mosaicking the 750 nm images at a grid spacing of 100 m (Isbell et al., 1997). The remaining UVVIS bands were automatically registered to the controlled 750 nm images, projected, and mosaicked with photometric normalization to produce a 5-band multispectral mosaic (Eliason et al., 1999a). These products are available through the NASA Planetary Data System (PDS; Eliason et al., 1999b) and online from the USGS Map-a-Planet website (http://astrogeology.usgs.gov/Projects/Map-a-Planet/). A similar 100 m multispectral mosaic of the 6 NIR bands is in preparation; this processing has proven considerably more challenging because of the more complicated radiometric calibration needed in the near infrared (Eliason et al., 2003). At present, a reduced-resolution version of the mosaic at 500 m grid spacing is available online at http://astrogeology.usgs.gov/Projects/ClementineNIR/.

Mosaics of the Clementine HIRES images have been produced by Malin Space Science Systems and are available through the PDS. These mosaics were generated at grid spacings of 30 m for the poles (where coverage is nearly complete) and 20 m for selected areas at lower latitudes. The mosaics are controlled to the USGS base map (Malin and Ravine, 1998).

Finally, the USGS also utilized 200–300 m/pixel Clementine stereo imagery to compile DTMs of the regions poleward of ~65° north and south latitude with 1 km grid spacing (Rosiek et al., 1998). These stereo DTMs were then merged with the much lower density Clementine dataset available for latitudes between ±75° (Rosiek et al., 2001). The combined DTM was used to prepare a set of maps of the Moon in 1:10,000,000 scale, with color-coded elevations overlaid on a shaded relief base (U.S. Geological Survey, 2002; described by Rosiek et al., 2002). The base used for these maps is also partly a Clementine product; the pre-Clementine airbrush base was digitized, "warped" to coregister to the Clementine mosaic, and details of a small area (~1.3% of the Moon) near the south pole that was not imaged by earlier spacecraft were added by digital airbrushing based on the Clementine data (Rosiek and Aeschliman, 2001). The finished maps are available online at http://geopubs.wr.usgs.gov/i-map/i2769/. The shaded relief and DTMs can also be downloaded from ftp://ftpflag.wr.usgs.gov/dist/pigpen/moon/, subdirectories shaded_relief and usgs/topo, respectively

3.4 The ULCN 2005 Control Network

The most accurate lunar global coordinate frame is that based on the most recent solution with lunar laser ranging (LLR) data (Williams, et al., 2006). Although accurate to the cm level or better, as a practical network it suffers from having only 4 points available on the lunar surface. The densest global network, 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., 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, 1992) and then transferred to the USGS Astrogeology team and further modified (Archinal, et al., 2003; 2004). It has now been incorporated in the USGS ISIS planetary image processing software. This network is a combined solution, using data from the previous ULCN (Davies, et al., 1994) based on Earth based photography, Apollo, Mariner 10, and Galileo images; and the CLCN (Edwards, et al., 1996). It corrects for the 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 the 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. See Figure 3.

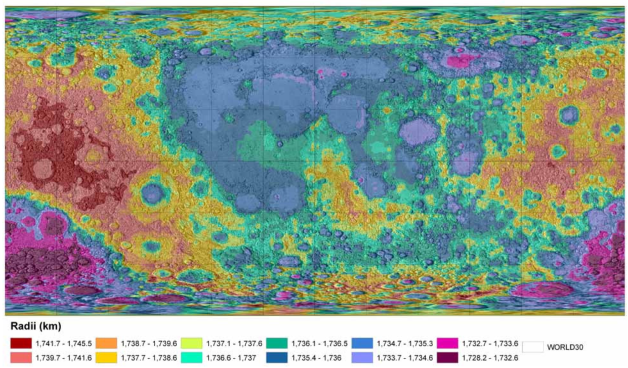

Figure 3. Color-coded elevations from ULCN 2005 control network (Archinal et al., 2006). With ~270,000 points, or ~4x as many as the Clementine lidar dataset, this is the densest global topographic dataset for the Moon. Base image is the USGS airbrush shaded relief map, updated based on Clementine imagery (Rosiek and Aeschliman, 2001).

3.5 USGS Lunar Orbiter Digitization and Mosaicking

Modern use of the enormous Lunar Orbiter dataset (hundreds of images with the equivalent of hundreds of megabytes of information per image) has been hampered by the availability of the images only in analog form. Furthermore, as noted above, the reconstruction of framelets into frames by hand-mosaicking photographic prints resulted in the smooth geometric distortions within the framelets being retained, and discontinous errors being introduced at the framelet boundaries. This largely negated the value of the many image pairs obtained for stereoanalysis. The USGS has therefore undertaken a multi-year project to "revive" Lunar Orbiter by scanning and digitally reconstructing the most important images and using them to make higher level cartographic products (Gaddis et al., 2003). The process begins with the use of a commercial flatbed scanner to digitize film strips containing individual framelets to a resolution of 50 μm. Reseau marks preprinted on the original film carried by the Orbiters are then automatically detected and used to remove geometric distortions within the framelets and position them relative to one another. Cosmetic processing is done at this stage to remove brightness variations within the framelets. The framelets are then mosaicked, and fiducial marks around the perimeter of the image are measured and used as reference points to relate the digital image to the interior geometry of the LO cameras. ISIS camera model software has been developed for the MR and HR cameras on the various Orbiters, based on the original camera calibration data. Wioth this software, the images can be controlled, map-projected, mosaicked, and combined with other datasets such as Clementine. To date (Weller et al., 2006) a global set of LO III, IV, and V images has been digitized and reconstructed, and the production of a global image mosaic at 512 pixels/degree (~60 m/pixel) is under way. This mosaic will be made available via the Map-a-Planet website. Reconstruction of a subset of very high resolution (VHR) frames of greatest scientific value, selected based on input from the U.S. lunar geologic community, is ongoing. The reconstructed but unprojected global and VHR frames are available at http://astrogeology. usgs.gov/Projects/LunarOrbiterDigitization/.

3.6 Digital Topography from Scanned Film

The digitization of the Lunar Orbiter images creates the possibility of their use for topographic mapping with modern, "softcopy" (i.e., digital) methods, and their precision reconstruction based on the preprinted reseau offers at least a hope that the resulting DTMs will not contain discontinuities at the framelet boundaries. The latter effect greatly limited the utility of LO stereopairs for topographic mapping in the 1960s-70s. Furthermore, DTMs produced today from these images, and also from the Apollo Metric and Panoramic camera images, which can be scanned and utilized without the complicated reconstruction process needed for LO, can be made consistent with the global coordinate system defined by the ULCN 2005. Rosiek et al. (2006, this conference) report on a pilot study designed to test these assertions and pave the way for possible systematic mapping with LO and Apollo images. The Apollo 15 landing site at Rima Hadley was mapped by using LO IV frames from the global set, VHR frames from LO V, and Apollo 15 Metric and Panoramic images. All these images were controlled to the ULCN 2005 in a simultaneous bundle adjustment, and DTMs were produced by using commercial stereomapping software. The LO DTMs were, indeed, found to be free of major discontinuities, although there were some residual distortions. The Apollo images were substantially easier to work with than the LO data, and yielded high resolution DTMs requiring minimal editing. Figure 4 shows the Metric camera DTM, which may be compared to the equivalent analog product seen in Fig. 2. The Panoramic camera DTMs, in particular, could be produced at 10 to 15 m grid spacing, comparable to the products currently being used to select and validate safe landing sites on Mars (Kirk et al., 2003). DTMs of this resolution could be generated for roughly 20% of the Moon within the equatorial zone from Panoramic images, and for additional sites at higher latitudes known (since the 1960s!) to be of high scientific interest from Lunar Orbiter VHR frames. Thus, at least some future landing sites could probably be assessed for safety without imagery already in hand. The Metric and LO global images provide lower resolution stereo coverage over multiple latitude zones totalling several tens of percent of the Moon.

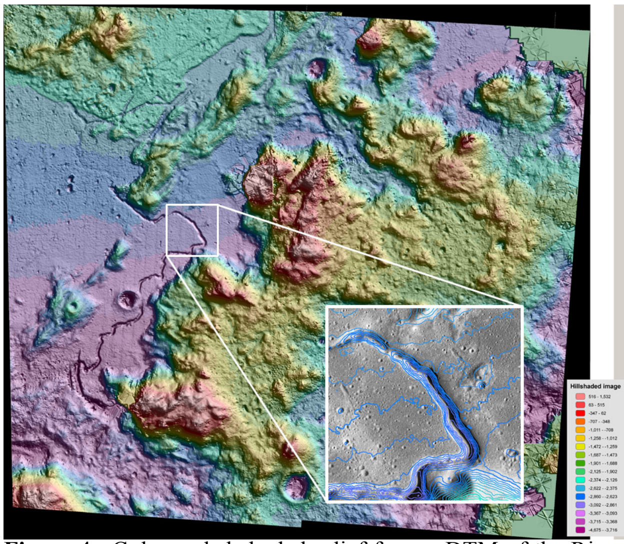

Figure 4. Color-coded shaded relief from a DTM of the Rima Hadley/Apollo 15 landing site area produced from Apollo Mapping camera images (Rosiek et al., 2006, this conference). Inset shows detail of a digital orthophotomosaic with contours from the same DTM. Compare Fig. 2.

3.7 Improving the ULCN 2005 Control Network

We are continuing to improve on the ULCN 2005 by the direct incorporation of further image measures, and plan to create a successor network, tentatively called the ULCN 2007. The new network and topographic model will include measures from Mariner 10 and Galileo, and the measures now being gathered for the LO mosaicking work. This should 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. We also plan to add some features (as they are visible) near Apollo landing sites listed by Davies and Colvin (2000), in order to tie the new network more directly to the Apollo landing site (i.e. LLR and ALSEP derived) coordinates. Finally, we are working with Cook et al. (2000), to tie their Clementine stereo DTMs to the ULCN 2005 and its successor versions. Although missing data in many areas, and with precision/accuracy probably only at the few hundred meter level, this should densify by a few orders of magnitude the ULCN 2005 topographic model.

4. CURRENT AND PLANNED MISSIONS

The first decade of the 21st century promises to be an era of greatly increased activity in lunar exploration. Five national or international space agencies and one private corporation either launched a lunar spacecraft or announced plans to do so in this period. The missions, seven in all, are listed in Table 1, along with the instruments relevant to lunar cartography that each carries and the most important parameters of those instruments. Also included in the table are URLs of websites that provide additional information, because, in many cases, the definitive papers describing these missions and instruments have yet to be written. In the following subsections, we describe the five missions that are likely to have the greatest impact on lunar cartography in greater detail.

4.1 SMART-1

The ESA SMART-1 mission will be completed when the spacecraft impacts the lunar surface in early September 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. Around 10,000 such images exist, most with 100 m/pixel resolution or better. In the first month of operation the Moon was completely imaged. Later images targeted specific areas at high resolution and often in stereo, and provide 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 because altimetric data that could accomplish this purpose will not be available for at least a few more years. These images also appear to be the last planned orbital framing camera images of the Moon 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 and LRO LROC) will not. Once controlled, the AIME images could also be mosaicked, providing a second or third (after LO and redone Clementine mosaics) medium resolution mosaic for future lunar planning and targeting, possibly in multiple colors. Currently we know of no funded plans to mosaic these images. Because most of the images were obtained in framing mode, the software and procedures to process them could be developed with relatively little effort, and the control (to the ULCN 2005 or an improved version of it) and mapping program could be completed fairly quickly, at least in comparison to the USGS creation of the Clementine mosaics and the mosaicking efforts needed for the other missions described below.

4.2 SELENE

To be launched in 2007, the Japanese SELENE mission will have three main 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 cameras by this missions and the others described below presents problems in processing (see Section 5.2), if these problems are properly addressed, it should be possible to control TC camera images and collect global stereo DTM information at the ~20 m level of vertical accuracy, controlled by the laser altimeter data. Unlike any of the other missions listed here, the SELENE team apparently does plan to generate the global image-derived DTM products themselves (Haruyama, et al., 2006).

4.3 Chang'E-1

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 pointing, with a 60 km swath and 120 m resolution. The camera is expected to return 2 terabytes (TB) of data during the nominal mission. The mission 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. As for SELENE, it should be possible to process the data returned from the camera system and altimeter in order to generate a global DTM. Unfortunately, the camera resolution is relatively low, so stereoanalysis of this image set might not be productive if the planned higher resolution data from the other missions becomes available. The imagery should, nevertheless, be connected to the other data sets (again, for example via an update of the ULCN 2005) because due to the image width (60 km) it should provide useful horizontal geometric strength to the global network, and because it will serve as an additional source of visible imaging under different illumination from the other missions. The total data volume for the nominal mission (including all types of data) is predicted to be 23.6 TB.

4.4 Chandrayaan-1

To be launched in 2007 September or later, this Indian mission will carry at least 4 major global mapping instruments and operate for a nominal 2 year mission. The mapping instruments are a) a Terrain Mapping Camera (TMC), which is a line scanner camera with 3 arrays, 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 "Forerunner" synthetic aperture radar (SAR) instrument, which will image the polar regions from 80° to the limit (likely 88°) imposed by the orbital inclination at ~150 m/pixel. Generally, the same comments apply as for SELENE, because the primary camera and altimeter instruments on the two spacecraft have similar resolutions. However, the 5 m resolution of the Chandrayaan-1 camera will provide the likely highest resolution global stereo coverage of all the missions discussed here. This imagery should be used to densify the accompanying altimeter global dataset (or, ideally, a joint dataset produced by reconciling and combining data from the altimeters flown on multiple missions).

4.5 Lunar Reconnaissance Orbiter

The U.S. LRO mission, to be launched in 2008, will have three cartographically important instruments that will provide global geodetic information. These are the LROC camera system, the LOLA laser altimeter, and the Mini-RF SAR radar system. 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 km (color) or 110 km (monochromatic) swaths, and UV images in 88 km swathes; and b) two 0.5 m/pixel high resolution cameras, which together will provide a 5 km swath. 62 TB of raw data are expected from this camera system during the nominal one-year mission. LOLA is a multi-spot altimeter, which will collect spot data at 50 m spacing and vertical information with 10 cm resolution. The

Mini-RF SAR instrument has been added to LRO as a technology demonstration. It operates in both S and X bands, with a 150 m baseline resolution similar to that of Forerunner and a zoom mode with 30 m resolution in range and 15 m in azimuth. Unfortunately, data collection opportunities for this demonstration are limited to one 4-minute pass per month plus a set of four consecutive 2-minute passes once per year. Clearly, LOLA should provide very high density altimetric data, which, particularly when combined with altimetry from the other missions, will revolutionize knowledge of lunar topography 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 images are 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 color camera images will 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. The images should, nevertheless, be tied together for several reasons, including a) to provide one more useful global image dataset with illumination and color information complementary to the others; b) because the information derived from the planned repeat coverage of the poles should be extremely useful in the search for permanently shadowed or illuminated areas; and c) as a necessary step for spatially referencing the other LRO datasets. Unfortunately, we note that in the currently available information about LROC there appear to be no 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 RSSed 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.

5. REQUIREMENTS FOR LUNAR CARTOGRAPHY

The international character of the impending era of lunar reconnaissance, the technical characteristics of the data to be returned by the instruments we have just described, and, most of all, the sheer volume of anticipated data, give rise to a series of programmatic, technical, and resource needs that we describe in the following subsections.

5.1 National and International Standards and Cooperation

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. It is considering recommending that such personnel be a part of new missions and that in reviews of missions and instruments cartographic planning should 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.). One of us (Archinal) has recently provided assistance of this nature to the LRO Data Working Group. However, this type of activity needs to be formally recognized by the missions, for example, by actively seeking out advice on such subjects, or by using a Participating Scientist program or other mechanism to add team members with the relevant expertise.

An additional step that should be taken is to create a new 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 and would be highly beneficial if properly funded. 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 it appears that no one involved with most missions or individual (mapping) instruments has previous experience in the creation or cartographic processing of planetary datasets, and where no acknowledged standards group exists. 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 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 of international participation similar to those established for Mars Express be started now by the cooperative efforts of the various space agencies involved.

5.2 Algorithms and Techniques

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 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 already 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) and to a limited extent for processing Mars Express HRSC images of Mars. The USGS Astrogeology Team has developed procedures for mapping and DTM 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 scanner images from the various Mars missions (MGS MOC, MO THEMIS, 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., the multi-segment array of the MRO HiRISE camera), but the necessary procedures and software to perform jitter correction for such cameras have yet to be developed and tested. In any case, such CCD arrays are currently not planned for use on any of the upcoming lunar missions. 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. In fact we find it surprising that such systems were approved, particularly for mapping purposes, given the problem of jitter and the lack of adequate software to photogrammetrically control the images on a production scale. Presently there also appear to be (except perhaps in the case of SELENE) no funded plans to develop such software. Some substantial effort will therefore be needed to allow these images to be controlled in order to properly register them with the previous and concurrently collected datasets.

In addition to making 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 the data processed in the ULCN 2005 by at least one and possibly two orders of magnitude. In order to control the large numbers of images that will become available in the next several years, the addition of complex multiple-partitioned matrix solution procedures will be required. Such software is needed already in order to create controlled THEMIS IR Mars mosaics, and will definitely be needed to process the image data received from 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. 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 not degrade the accuracy of maps.

Finally, 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 not merely for storing the basic datasets, but *a fortiori* for storing the intermediate products generated during image processing, which often require an order of magnitude more disk space than the original data. 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, if not several petabytes, of data for the total lunar data set. No institution, including particularly the PDS which must archive the U.S. 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 may eventually even be lost entirely.

5.3 Resources for Cartography

The preceding sections should begin to make clear the scope of the problem facing lunar cartographers in the coming decade. Production of the first global planetary image mosaics, the 100 m/pixel Clementine multiband mosaic (Isbell et al., 1997; Eliason et al., 1999; 2003) and the first Mars MDIM (Batson and Eliason, 1995), which has a comparable number of lines and samples, each constituted a multi-million-dollar effort. Faster computers and technological advances leading to greater degrees of automation, as discussed in the previous subsection, will of course reduce the work needed to create products of given resolution. This was already seen with the revised Mars mosaics, MDIM 2.0 and 2.1 (http://astrogeology.usgs.gov/Projects/MDIM21/), which were created for a fraction of the MDIM 1.0 budget. Nevertheless, the new missions will provide multiple altimetry datasets, multiple SAR datasets, and multiple image sets, including stereo and color coverage at resolutions either comparable to or greatly exceeding those of the best previous global imagery. Merely to control all these datasets so that they occupy the same cartographic coordinates and can be used conjointly will require a substantial effort. The extraction of high-resolution, quantitative topographic information from the stereo imagery will be an unprecedented and even greater task. Modern "softcopy" photogrammetric methods rely on automated image matching to produce high-density DTMs (Fig. 4), but even the most advanced such methods are never perfectly successful (see Heipke et al., 2006, this conference), so that interactive quality control and some editing of the DTMs will be required. Our experience indicates that this is likely to be the cost-driving factor for DTM production. The overall cost can be reduced somewhat by producing and editing global DTMs at a resolution than the best the images could support, while still improving on the density of DTMs interpolated from altimeter data. As the missions described here are followed by first robotic and then human-crewed landers, however, there will be an urgent need for topographic mapping of significant areas at the highest possible resolution in order to select and validate landing sites (Kirk et al., 2003) and conduct surface operations (Li et al., 2005).

An additional cost driver that may be less obvious is the need to repeat the processing of various datasets more than once, as the best available data on which to base global geodetic control continue to evolve. This pressure is already being felt with the evolution of the original ULCN and Clementine control network into the ULCN 2005 and beyond; a new generation of Clementine mosaics is needed to bring the multispectral data into registration with Lunar Orbiter data. Acquisition of dense, global altimetry by the next missions will increase the accuracy of the control network even further, as it did for Mars (Archinal et al., 2003; 2004) and necessitate the production of new versions of the most useful products. This process of iteration is likely to continue for the foreseeable future, driven by the need for precision maps by future landed missions. A combined effort of many tens of work-years will be required to meet these needs. Support for such an effort is not built into the next generation of missions (with the possible exception of SELENE) and exceeds the scope of NASA's typical post-mission data analysis programs. The best news is that the needed resources, though significant, are still only a small percentage of the total being spent to carry out the lunar missions. It is therefore to be hoped that the spacefaring nations will identify the incremental resources needed to ensure the greatest return from their efforts.

5.4 Recommendations

Based on the considerations discussed in the preceding sections, we offer the following specific recommendations for all upcoming missions:

- "Crosslinking" of the missions conducted by various space agencies by establishing formal and informal channels of communication with the other agencies and missions, and, in particular, by inviting guest investigators from other nations to participate on the mission teams, should be actively planned and promoted as soon as possible.
- The primary image datasets of each of these missions (some have more than one) should be tied to successive versions of the ULCN or some equivalent frame, for the many reasons given above.
- Each of the planned lunar missions has other, either non-imaging, or lower resolution imaging datasets that should also be tied into ULCN. However, it is likely that this can be done at the needed level of precision via the use of spacecraft geometry information derived from the primary image datasets or altimetry data and relative timing information (a process known historically as "C-smithing").
- 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 DTMs generated from the altimetric data. The latter technique has been pioneered already by our work tying Viking images to MOLA DTMs to produce MDIM 2.1 (Archinal, et al., 2003; 2004). 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.

6. CONCLUSIONS

This is an exciting time of great promise for the exploration of the Moon, as this new "age of lunar reconnaissance" leads to further scientific exploration of the Moon and even new human missions, possibly by several nations. However, the cartographic community faces perhaps its greatest challenge ever in handling the new datasets that are and soon will be arriving, with an order of magnitude more complexity and several orders of magnitude more volume than for all previous extraterrestrial missions. Mapping an entire world at the resolution of 50 cm or better will not be an easy task!

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Mission	Country	Space Agency	Launch Date (Actual or Planned)	End Date (Planned)	Cameras of Cartographic Interest	Camera Type	Camera Coverage & Res	Radar	LIDAR Altimeter	Orbit Positional Accuracy	Pointing Accuracy	Controlled Mosaics Planned?	Stereo DTMs Planned?	Websites
SMART-1	Europe	ESA	2003 Sep 27	2006 Sep 3	Advanced Moon micro-Imager Experiment (AMIE)	Framing + Line scanner	Global pan, some repeat stereo, some color, ~100 m	No	No	?	?	No	No	http://sci.esa.int/science-e/www/area/index.cfm?fareaid=10
TrailBlazer	USA	Private	?	?	Medium res.	?	Low Sun global pan, some repeat	No	No	?	?	?	?	http://www.transorbital.net/TB_mission.html
					High res.	?	Targeted							
Lunar-A	Japan	JAXA	?	?	Mapping Camera	?	Terminator imaging for topography, 30 m	No	No	?	?	?	?	http://www.jaxa.jp/missons/projects/sat/exploration/lunar_a/index_e.html
SELENE	Japan	JAXA	2007	?	Terrain Camera (TC)	2 line scanner	Global pan, stereo, 10 m	Lunar Radar Sounder	5 m resolution, 1.6 km spacing	?	?	?	Yes	http://www.jaxa.jp/missions/projects/sat/exploration/selene/index_e.html
Chang'E-1	China	CNSA	2007, late	?	CCD Stereo Camera	3 line scanner, 60 km swath	Global pan, stereo, 120 m	No	Laser Altimeter (LAM) 5 m res	?	?	?	?	http://www.cnsa.gov.cn (Agency homepage only)
					Imaging Interferometer	25.6 km swath	0.48–0.96 μm, 200 m							
Chandrayaan-1	India	ISRO	2007 Sep	?	Terrain Mapping Camera (TMC)	3 line scanner, 40 km swath	Global pan, stereo, 5 m	Forerunner S band SAR ±80° to 88° 150 m	Lunar Laser Ranging Instrument 5 m res	?	?	?	?	http://www.isro.org/chandrayaan-1/announcement.htm http://www.isro.org/chandrayaan-1
					Hyper Spectral Imager (HySI)	40 km swath	32 bands 400–900 μm, 80 m							
					Moon Mineralogical Mapper	40 km swath	Global 140 m Targeted 70 m							
Lunar Reconnaissance Orbiter (LRO)	USA	NASA	2008 Oct 15	2009 Oct 15 (5 year extension possible)	LRO Camera (LROC)	Line scanner Pan 110 km swath, color 80 km swath	Global repeat stereo? 100 m	Mini-RF S/X band SAR Operates few minutes/month only	LOLA 5-beam 50 cm res 50 m spacing	10–20 m	60 arcsec	No	No	http://lunar.gsfc.nasa.gov/missions/
						Adjacent line scanners, 5 km total swath	Targeted, some repeat stereo 50 cm							

Table 1. Lunar Missions conducted or planned in the decade 2001–2010 and their cartographically relevant instruments. Source of information: http://www.spaceagepub.com/ilo/ilofleet.pdf, accessed 2006 July 12.