CARTOGRAPHY FOR LUNAR EXPLORATION:
2008 STATUS AND MISSION PLANS

R.L. Kirk, B.A. Archinal, L.R. Gaddis, and M.R. Rosiek

U.S. Geological Survey, Flagstaff, AZ 86001, USA – rkirk@usgs.gov

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ABSTRACT:

The initial spacecraft exploration of the Moon in the 1960s–70s yielded extensive data, primarily in the form of film and television images, which 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 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 accelerating dramatically, with as many as eight new missions already launched or planned for the current decade. These missions, of which the most important for cartography are SMART-1 (Europe), Kaguya/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 data sets 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 fulfill 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 initial era of exploration (1960s–70s) and the 1990s 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.

We now 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 data sets. With their laser altimeters, stereo, high-resolution, and multispectral cameras, and radar instruments, a deluge of new, high-accuracy, and complex data sets 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 data sets; the need for new data processing techniques to store, process, and archive such data sets; the need to administer the greatly increased efforts required to process such data sets; 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 data sets is required to keep the data sets 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 because the Moon is 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 under way or 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. An increasing amount of detail about these missions has become available in the west in recent years (Reeves, 1994; Siddiqi, 2000; Ulivi and Harland, 2004; Harvey, 2007; Stooke, 2008). They included the first successful lunar probe (the Second Cosmic Rocket, or 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 (the Automated Interplanetary Station, or 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 more than 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 (Gillis et al., 1999) are available online with the text of Bowker and Hughes (1971) at http://www.lpi.usra.edu/resources/lunar_ orbiter/, and as a photo gallery including cosmetically destriped images at http://www.lpi.usra.edu/resources/lunarorbiter/. 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, as described in Section 3.5. The effective resolution[1] of the HR images, sampled at 50 µm, 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 72 pixel/inch (350 µm) 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 Mapping (or Metric) 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 ~8 m when scanned at 5 µm, and the Panoramic images cover a 339 (across-track) by 22 km "bowtie" with resolutions ranging from ~1 m in the center to ~2 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. A project to digitize all the Apollo Metric, Panoramic, and Hasselblad images on a high-quality photogrammetric scanner at 5 µm raster is currently underway at the NASA Johnson Space Center (Robinson et al., 2008). Scanning of the Metric images has been completed and scanning of the Panoramic images is expected to be complete by the end of 2008 September (M. Robinson, personal communication).

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 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.

[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).

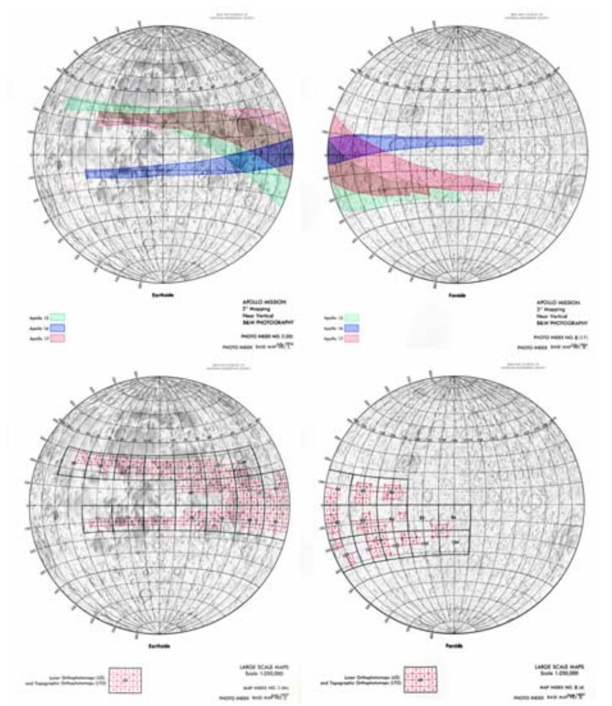

Figure 1. Top, coverage of Apollo 15, 16, and 17 vertically oriented Mapping camera images. Bottom, published maps in the LTO (Lunar Topographic Orthophotomap) series based on Metric camera data. Lunar near side and far side hemispheres appear at left and right, respectively. Taken from Schimerman (1975).

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 data set is presented as a separate overlay on transparent plastic, making the *Dossier* especially valuable for comparing multiple data sets; Figure 1 was generated by digitally combining the relevant overlays with the base maps also provided in the *Dossier*. The full set of overlays has been scanned and made available online as a PDF document by the Lunar and Planetary Institute (http://www.lpi.usra.edu/lunar_resources/lc_dossier.pdf). Conversion of the raster-scanned coverage outlines to a vector format that could be used in a geographical information system (GIS) and transformed to other projections would be even more valuable and has been proposed to NASA.

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 data set 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 data sets 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 airbrushed 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.

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 Apollo 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 Figure 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) and Rükl and Seronik (2007), which use a hand-drawn base, Bussey and Spudis (2004), based on mosaicked Clementine data, and Byrne (2005; 2007), with Lunar Orbiter images 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. Stooke (2008) provides an extraordinarily thorough collection of materials relating to lunar missions, including those that failed or were cancelled as well as the image coverage, landing sites (candidate as well as selected), and surface activities of successful missions. Products in this volume include both original maps and image mosaics, often annotated by Stooke, and new digital image mosaics and airbrush maps produced by him. 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 Gazetteer of Planetary Nomenclature, is currently available online at http://planetarynames.wr.usgs.gov/. A definitive digital atlas of lunar nomenclature is in preparation and a preliminary version is available at http://planetarynames.wr.usgs.gov/dAtlas.html.

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).

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, LAC, and LSR series airbrush shaded relief maps, 1:1,000,000 geologic maps, and 1:2,500,000 LEMC Lunar Orbiter controlled mosaics, as well as index maps of the Apollo photographic coverage at 1:7,500,000 and 1:5,500,000 scales. 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 data set 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, topographic, 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 (MAP) website (http://www.mapaplanet.org/). A similar 100 m multispectral mosaic of the 6 NIR bands has recently been completed (Gaddis et al., 2007); this processing proved considerably more challenging because of the more complicated radiometric calibration needed in the near infrared (Eliason et al., 2003). At present, the preliminary 100 m NIR mosaic (under review by the PDS) is available online at http://astrogeology.usgs.gov/Projects/ClementineNIR/ and at MAP. Like the UVVIS data, final NIR products will be available from the PDS Image Atlas (http://pds-imaging.jpl.nasa.gov/Missions/Clementine_mission.html) and MAP sites.

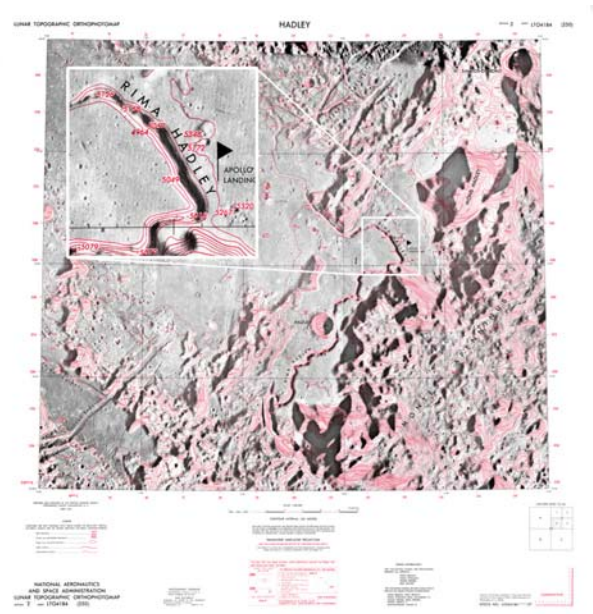

Figure 2. Lunar Topographic Orthophotomap (LTO) 1:250,000 quadrangle 41B4 containing Rima Hadley and Apollo 15 landing site, from digitized version available online at http://www.lpi.usra.edu/ resources/mapcatalog/. Inset shows detail around the landing site.

Mosaics of the Clementine HIRES images have been produced by Malin Space Science Systems and are available through the PDS Image Atlas. These mosaics were generated at 30 m/pixel 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 data set 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.

Other workers have used the lower convergence Clementine imagery to produce a 1 km/post DTM with about 69% coverage "planetwide" (Cook et al., 2000a) and a nearly complete global DTM at 5 km/post (Cook et al., 2002b). An effort is nearly complete at USGS to register a portion of this data set to the ULCN 2005, as discussed below. Finally, Gaskell and Mastrodemos (2008) have produced an unreleased DTM of the lunar south polar area by "stereophotoclinometry" (i.e., a modeling technique that makes use of both geometric and radiometric clues to topography) and have announced plans for a global DTM.

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 released (Archinal, et al., 2006; 2007a). This is the largest planetary control network ever completed and was developed under 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., 2000b, 2002a). 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 positions of the points were solved for. This provided a global topographic model for the Moon that was denser than any other control network, though it will soon be superseded by lidar altimetry, e.g., by Kaguya data already collected, once these are released. See Figure 3.

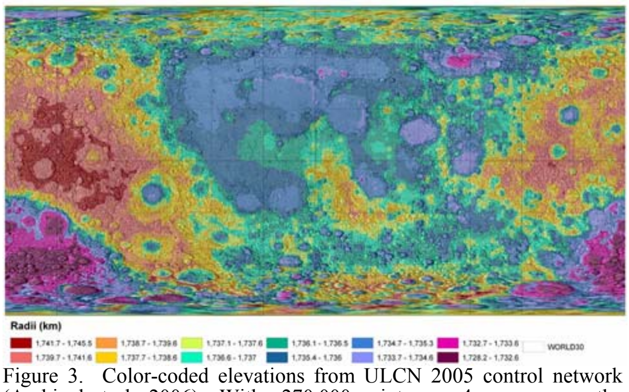

Figure 3. Color-coded elevations from ULCN 2005 control network (Archinal et al., 2006). With ~270,000 points, or ~4x as many as the Clementine lidar data set, this is the densest global topographic data set for the Moon. Base image is the USGS airbrush shaded relief map, updated based on Clementine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

3.5 USGS Lunar Orbiter Digitization and Mosaicking

Modern use of the enormous Lunar Orbiter data set (hundreds of images with the equivalent of hundreds of megabytes of information per image) was 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 discontinuous 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. With this software, the images can be controlled, map-projected, mosaicked, and combined with other data sets such as Clementine. A global set of LO III, IV, and V images has been digitized and reconstructed (Weller et al., 2007), and a global image mosaic at 512 pixels/degree (~60 m/pixel) based on a LO control network tied to the ULCN 2005 has been completed (Becker et al., 2008) and is available via MAP. 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) completed 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. Because of technical limitations of the scanner available for the task, the Apollo images were digitized at 10 µm raster. 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, 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.

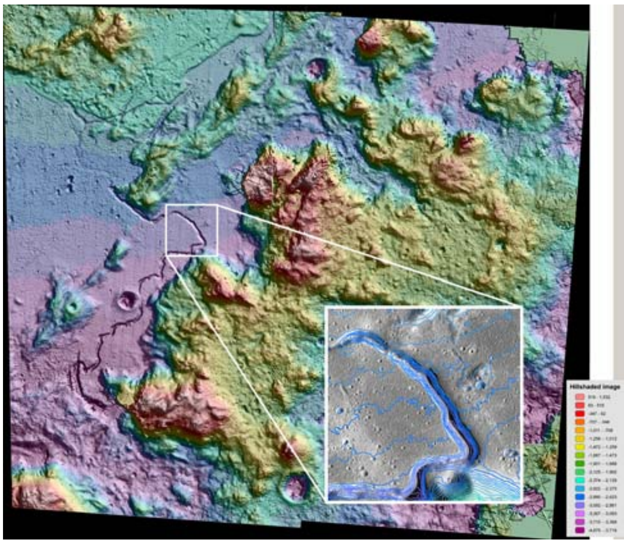

Figure 4. Color-coded shaded relief from a DTM of the Rima Hadley/Apollo 15 landing site area produced from Apollo Mapping camera images (Rosiek et al., 2006). Inset shows detail of a digital orthophotomosaic with contours from the same DTM. Compare Figure 2.

Figure 4 shows the Mapping camera DTM, which may be compared to the equivalent analog product seen in Figure 2. The Panoramic camera DTMs, in particular, were produced at 10 to 15 m grid spacing, comparable to products that have been used to select and validate safe landing sites on Mars (Kirk et al., 2003). Scanning the images at 5 µm, which, as discussed above, is now underway, could improve the DTM grid spacing to 5–8 m; the much greater dynamic range with which the original films are being scanned will also improve the reliability of stereo matching in shadows and highlights. 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 with imagery already in hand. The Metric and LO global images provide lower resolution stereo coverage over multiple latitude zones totaling a significant fraction of the Moon. Broxton and Edwards (2008) describe an automated stereo processing software system with which they have produced DTMs from Apollo Metric and Panoramic images.

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 are creating a successor network, tentatively called the ULCN 2008. The new network and topographic model will include measures from Mariner 10 and Galileo, and the measures that were 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 are also adding some features (those that 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.

As noted in the next session, and as funding permits, we hope to continue to update the ULCN series of networks with new data sets as they become available. Ultimately one of the altimetry data sets or a combination of them, once tied to the LLR network, will provide for a highly stable, dense, and accurate reference frame. However, the ULCN data sets and future imaging data sets will then have to be tied to that frame. The goal will become not so much further improvement in absolute accuracy of density of points, but rather assuring that all lunar data sets, past and present, are tied together in the same frame so that they can be used and intercompared. This will help to address the recommendations of the NASA Advisory Council, that all past and future lunar data sets be geodetically controlled.

We have also been working to place other products into the ULCN 2005 system, and to assure that such products can be updated along with the ULCN series of networks. Details regarding these products are given by Archinal et al. (2008) and Hare et al. (2008). This includes such items as: a) the Lunar Orbiter digital mosaic already described; b) versions of the USGS airbrush map and Clementine mosaics that have been "warped" from their current CLCN based geometry to the ULCN 2005 geometry (available via the USGS Pigwad site http://webgis.wr.usgs.gov/pigwad/down/moon_dl.htm); c) a full regeneration of the Clementine basemap mosaic in the ULCN 2005 system (to be available late in 2008), and d) reregistration of a subset of the Cook et al. (2000a; 2000b; 2002b) Clementine stereo DTMs to the ULCN 2005.

Regarding this last product, the original set of DTMs consisted of a set of some 700,000 stereo pairs of Clementine images at a resolution of 100-150 m/pixel. Using only stereo pairs for which both images have updated (ULCN 2005) camera angles (43,866 were available), and after filtering of suspect data, we are left with 28,698 stereo models. This data set provides for radii estimates at 1 km spacing for about 35% of the Moon, down from 69% for the original data set. Still, this provides for a tremendous improvement in density over that available from the Clementine lidar measurements and the ULCN 2005 itself. The revised DEM has potentially several uses: 1) for statistical studies on local surface roughness, 2) for determining regional limits for minimum altitudes for low orbiting spacecraft, 3) to assist in range binning for future lidar or radar instruments, 4) for crustal thickness measurements when used in conjunction with gravity data, 5) to identify previously unknown impact basins and to confirm/reject previously suspected impact basins, and 6) for use in determining limb slope and profiles for Earth-based occultation astronomers and for astronomers planning on using the limb to determine atmospheric point spread function for Earth-based diffraction limited imaging. The 1 km/pixel "planet-wide" DEMs can supply local topographic details and profiles to ±100 m relative height accuracy within a stereomodel tile in areas of the Moon that existing lidar or shadow height measurements have been unable to measure. With additional effort it should also be possible to match images from the unused stereo pairs to the ULCN 2005 or 2008 images and bring them into the same system. However, by the time such work would be completed it would likely be superseded with data from new missions. Indeed, press releases indicate that gridded Kaguya laser altimeter data (Figure 5) already provides height measurements with a similar density and higher accuracy, although the data will likely not be released publically for some time, nominally until 1 year after the end of the Kaguya mission. In the meantime we plan to make the revised "USGS NASM 1 km" data set available for download by ftp from the USGS Pigwad site within a matter of months. (Rosiek, et al., 2007).

4. CURRENT AND PLANNED MISSIONS

The first decade of the 21st century promises to be an era of greatly increased activity in lunar exploration. Six space agencies have launched a lunar spacecraft or announced plans to do so in this period. These missions are listed in Table 1. So are a study of low-cost lunar missions in the UK (Gao et al., 2008) and the Google Lunar X-Prize, a competition intended to stimulate privately funded lunar exploration. Several previously announced commercial lunar missions (Ulivi and Harland, 2003; Stooke, 2008) have been omitted from the table because their original launch dates have long passed with no further announcements of progress. The Japanese orbiter/penetrator mission Lunar-A, which was cancelled in 2007, is also omitted. We have attempted to list in the table the instruments most relevant to lunar cartography carried by each mission, 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 in greater detail the five missions of the current decade that have been described in detail and are likely to have the greatest impact on lunar cartography.

4.1 SMART-1

The ESA SMART-1 mission ended with the deliberate impact of the spacecraft into the lunar surface on 2006 September 3. The mission team is currently working to prepare the data, including the images and auxiliary data from the AIME CCD framing camera, for archiving to the ESA Planetary Data Archive in PDS format. Although often referred to as obtaining "pushbroom" imagery, this is in fact a "push frame" camera, i.e., a framing camera with color filters covering subareas of the detector, so that color images can be obtained by combining partly overlapping exposures (Josset et al., 2006; Cerroni et al., 2007). Approximately 32,000 images were obtained, providing global coverage at ≤250 m/pixel and coverage of the southern hemisphere at ≤100 m/pixel (Grieger et al., 2008). Many of the higher resolution images, 50 m/pixel and better, provide stereo or color coverage of areas of scientific interest (B. Foing, personal communication). If measurements from these images were added to the ULCN 2005 or to a successor network in the ULCN series, this would likely greatly strengthen the horizontal accuracy of the network, and, of course, tie this significant image set to the earlier and later imagery as the ULCN is updated. These images appear to be the last planned orbital framing camera images of the Moon for some time, and therefore should provide greater geometric strength to the ULCN than later line scanner camera images of similar resolution (e.g., the Chang'e-1 CCD camera and LRO LROC). 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 definite plans to make controlled mosaics of these images, although some processing of the images is being done and uncontrolled mosaics are being generated by European investigators (D. Despan, personal communication). Because 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 Kaguya

The Japanese Kaguya mission (originally named SELENE) was launched successfully in 2007 September and began operations in December (Kato et al., 2008). All of the instruments are operating and generating data, as reported in special sessions of the 2008 Lunar and Planetary Science Conference. The three main instruments collecting globally useful cartographic data sets are: a) the Terrain Camera (TC), which has fore and aft (15°) 10 m resolution line scanner cameras (Haruyama et al., 2008); b) the Multi-band Imager (MI), with 20 m resolution in 5 visible bands, and 60 m resolution in 4 near-IR bands (Ohtake et al., 2008); and c) the laser altimeter (LALT), collecting data with 1.6 km along track spacing and 5 m vertical resolution (Araki et al., 2008). The initial results of two weeks of LALT operation (Figure 5) already surpass the topographic detail of the ULCN 2005, except in the polar regions. In addition, radio tracking of the main spacecraft and the Okina (Rstar) and Ouna (Vstar) subsatellites is yielding an improved model of the lunar gravity field that will be crucial for operations and precision cartography with this and future missions (Matsumoto et al., 2008; Namiki et al., 2008). Data from the mission will be released one year after the end of the prime mission, but the gravity field information will be shared with other missions that require it operationally. The use of line scanner cameras by this mission and the others described here presents problems in processing (see Section 5.2), but 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. Although the plans of the other missions listed here are not clear in this regard, the Kaguya team apparently does plan to generate the global image-derived DTM products themselves (Haruyama et al., 2006; Haruyama, 2008, this conference).

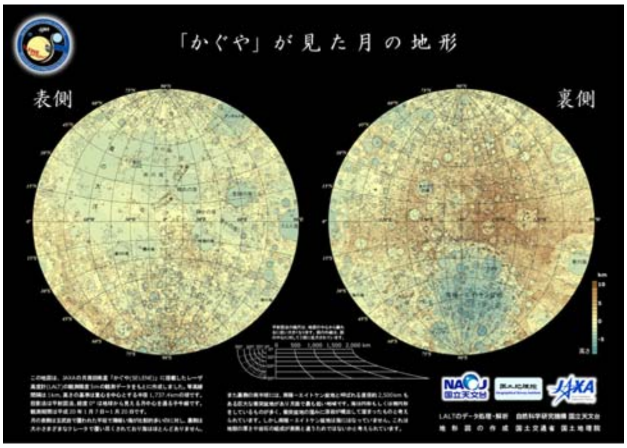

Figure 5. Global topographic contour map of the Moon, based on 1.1 million points from the first two weeks of operation of the Kaguya Laser Altimeter (http://www.jaxa.jp/press/2008/04/20080409_kaguya_j.html, accessed 2008 April 24).

4.3 Chang'e-1

The Chinese Chang'e-1 orbiter (Yue et al., 2007) was launched successfully in 2007 October and entered lunar orbit in November. It carries a CCD stereo line scanner camera consisting of 3 arrays, nadir-pointing and fore and aft looking 17° off-nadir, with a 60 km swath and 120 m resolution and a laser altimeter with a 200 m footprint and 5 m vertical resolution. A third mapping instrument is an imaging interferometer, with a 25.6 km swath and 200 m resolution at wavelengths of 0.48~0.96 µm. Reports on the results of the mission have yet to appear in the English-language scientific literature, but a series of press releases have indicated that the instruments are functioning normally and have included both image mosaics and DTM products from the CCD camera (collected in Planetary Society, 2008; see also Lakdawalla, 2007 for additional images and links). The Chinese National Space Administration has also stated its intention to make all data publically available, though no schedule has been announced. Expected data volumes are 2 terabytes (TB) from the CCD camera and 19 TB for the imaging interferometer. As with Kaguya, 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 (via connection to the altimetry data set(s) and/or by incorporation in an updated version of the ULCN) 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. Plans to fly a duplicate of the Chang’e-1 spacecraft in 2009 were announced at the end of 2007.

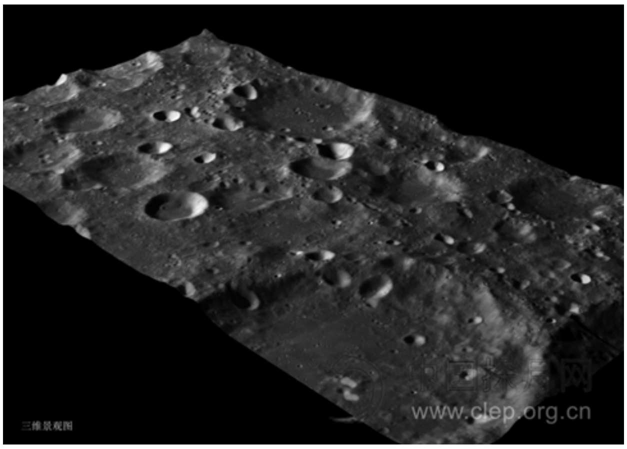

Figure 6. Perspective view of the lunar surface centered near 60°S, 70°E, based on a stereo DTM and mosaic produced from the first Chang’e-1 images. Vertical exaggeration is unknown. (http://www.planetarysociety.org/explore/topics/space_missions/chang_e_1/data.html, accessed 2008 April 24).

4.4 Chandrayaan-1

With a launch date postponed from 2008 April to June or later, this Indian mission (Goswami et al., 2006) 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, nadir and fore and aft looking 17° off-nadir, with a 40 km swath and 5 m resolution; b) the Lunar Laser Ranging Instrument (LLRI), a 5 m vertical resolution laser altimeter; c) the U.S. supplied Moon Mineralogy Mapper (M3) with 140 m/pixel (global) and 70 m/pixel (targeted) resolution and a 40 km swath; and d) the U.S. supplied Mini-RF "Forerunner" synthetic aperture radar (SAR) instrument, which will image the polar regions from 80° to the limit (likely 88°) imposed by the orbital inclination with ~150 m resolution and 75 m/pixel image raster. Generally, the same comments apply as for Kaguya, 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 likely provide the highest resolution global stereo coverage of all the missions discussed here. This imagery should be used to densify the accompanying altimeter global data set (or, ideally, a joint data set produced by reconciling and combining data from the altimeters flown on multiple missions). The radar imager will obtain overlapping stereo coverage near the poles, and the instrument team plans to produce DTMs with particular emphasis on areas not illuminated by sunlight (Kirk et al., 2008b, this conference). The accuracy of reconstructed spacecraft positions may be no better than 500 m, which will complicate the generation of cartographic products but may be overcome by controlling data to laser altimetry data from other missions.

4.5 Lunar Reconnaissance Orbiter

The U.S. LRO mission has a planned launch date at the end of 2008 October, but may be delayed to December or beyond. The spacecraft will carry three cartographically important instruments that will provide global geodetic information (Chin et al., 2007). 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 push frame 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 swaths; and b) two 0.5 m/pixel high resolution line scanner 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 (75 m/pixel raster) similar to that of Forerunner and a zoom mode with 30 m resolution in range and 15 m in azimuth (7.5 m/pixel raster). 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 LRO mission is cognizant of this issue and is paying close attention to improving the orbit determination accuracy as much as possible, even planning to obtain one-way laser ranging from Earth to the LRO spacecraft for use in this effort. However, the final absolute orbit accuracy remains to be seen (G. Neumann, personal communication). 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 data set 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 data sets. 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. Again, it is hoped the actual orbit determination accuracy of the LRO spacecraft will be better than this, but how much better—and how often during the mission orbits will be updated—is yet to be determined.

4.6 Future Missions

Table 1 also includes three mission concepts for which target dates in the current decade have been announced, but about which much less is known. Luna Glob (Mitrofanov, 2006; Shevchenko, 2008) is the first step in an ambitious Russian program of lunar exploration that has been under discussion since the 1990s. It would be an orbiter, perhaps launched as early as 2009, primarily meant to search for lunar resources such as polar ice with a suite of imaging instruments and neutron detectors. MoonLITE (Gao et al., 2008) is a British study for a low-cost lunar orbiter that would carry several penetrators and demonstrate communications technology for later missions; thus, its cartographic potential is limited. Google Inc. has announced a competition (Google, 2007) with a total of $30 million in prizes for the first private group to land a spacecraft on the Moon, travel at least 500 m, and return images. The basic prize of $20 million would be increased if past artifacts were imaged (requiring precision landing and/or long-distance mobility) but decreased if the landing does not take place by 2010 December 31. Ten teams based in four nations have so far registered for this competition. If successful, these private missions could provide useful data for high resolution mapping and studies of one or more regions.

The numerous missions that are being planned or considered for the longer term can be divided broadly into producers and consumers of cartographic information. In the former category are GRAIL, LEO, and SELENE-2. GRAIL (Zuber et al., 2008) is a NASA Discovery mission selected in 2007 that would use a pair of orbiters to improve knowledge of the lunar gravity field by three orders of magnitude compared to Kaguya. A 2011 launch is scheduled. LEO (Jaumann et al., 2007; Heward, 2007) is an orbiter being studied by the German aerospace research center DLR to map the Moon at high resolution in 2012. Instruments would include cameras for stereo and spectroscopic mapping at high resolution with global coverage, as well as a radar sounder and investigations of the magnetic and gravitational fields. SELENE-2 is a Japanese mission study for a lander with a long-duration rover and a communications relay satellite, to explore the lunar pole in 2012 or 2013 (Tanaka et al., 2007). In addition to surface imaging and compositional studies with a variety of instruments, the mission could contribute to lunar geodesy by VLBI tracking, laser ranging, and astrometric observations to constrain the lunar rotation. A variety of other surface missions being planned for the decade of the 2010s are likely to require precision cartographic products for landing site selection and operations, but will only contribute to mapping of limited areas. These include a U.S. LPRP-2 lander (2011), a joint Russian/Indian rover combining the second phase of Luna Glob with Chandrayaan-2 plans (2011), advanced Russian or Russian/Indian landers including sample return (2012–2015), Chinese Chang'e-2 lander (2013) and Chang'e-3 sample return (2017). Planned launch dates (in parentheses) are largely from early press releases on these missions and must be viewed skeptically. Other mission concepts, including a U.S. testbed for human crewed landers and the UK Moonraker lander have no clear target date. The U.S., Russia, China, and ESA are all discussing plans for human landings on the Moon in the late 2010s and beyond.

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. Some additional details and urgent recommendations are given by Archinal et al. (2007b).

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 data sets 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. Regrettably, this is often no longer the case. The Planetary Cartography and Geologic Mapping Working Group (PCGMWG) of the NASA Planetary Geology and Geophysics Program is, however, currently developing a long range plan for planetary mapping. It is considering recommending that such personnel be a part of new missions, and that cartographic planning should considered as a standard part of reviews of missions and instruments proposals. 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, the Lunar Robotics Precursor Program (LPRP), and the Constellation Program, two (Archinal and Gaddis) have been chosen as LRO Participating Scientists, as have several other

cartographers and photogrammetrists, and a third author (Kirk) has been invited to join the Chandrayaan-1 and LRO Mini-RF teams to provide cartographic expertise. However, this type of activity needs to be expanded so that it is standard practice for all missions, and formalized by explicitly soliciting cartographic and geodetic experts to apply for membership in instrument teams either at the initial selection or as Participating Scientists.
An encouraging step is the recent creation of a new working group responsible for establishing standards for U.S. lunar missions. The LPRP has formed a Lunar Geodesy and Cartography Working Group (LGCWG), modeled on the NASA Mars Geodesy and Cartography Working Group that has existed since the 1990s (LGCWG, 2008). The new group, chaired by Archinal, has a core membership representing the U.S. missions and instruments that produce and require cartographic data and the technical experts who process such data. Broad, international participation has also been invited in order to encourage communication and shared data standards between all the members of the "international lunar fleet." Note that the International Astronomical Union and the International Association of Geodesy have a joint Working Group, on Cartographic Coordinates and Rotational Elements—currently also chaired by Archinal—that is ultimately responsible for planetary coordinate systems, constants, and standards, including those for the Moon (Seidelmann et al., 2007). However, the IAU/IAG group generally addresses only high-level standards issues, and of course cannot address issues at the individual mission or even individual space agency/country level. The LGCWG is attempting to address lower-level issues such as the formatting of digital map products, to achieve consistent standards for all NASA lunar missions, and to provide both a forum for communication and an example of cartographic standardization to the other lunar exploration programs.

Given that prior experience with large digital mapping programs may be limited in the non-U.S. lunar programs and that, apparently, in most cases no acknowledged standards group currently exists, an additional step that would be of great potential benefit both to the non-U.S. missions and to NASA would be the establishment of 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 NAIF SPICE format; Acton 1999), 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 have had some success in implementing algorithms and software for processing images from the 2001 Mars Odyssey THEMIS IR line scanner camera, the Mars Global Surveyor Mars Orbiter Camera (MGS MOC), and the Mars Reconnaissance Orbiter High Resolution Experiment (MRO HiRISE) camera within the ISIS 3 software system currently under development. However, robust, efficient methods for processing large numbers of scanner images from the various Mars and lunar missions 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 Chang'e-1, Chandrayaan-1, Kaguya, 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 Kaguya) 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 data sets.

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, Kaguya, and LRO.

With the increased use of radar instruments, e.g., on Chandrayaan-1 and LRO, as well as on the Cassini mission to Titan, 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 for the information they may provide about subsurface ice and their ability to reveal permanently shadowed areas, 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 (Kirk et al., 2008b, this conference).

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 data sets that will be acquired by the upcoming lunar missions. There will be substantial costs involved not merely for storing the basic data sets, 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 data sets, multiple SAR data sets, 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 data sets 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 (Figure 4), but even such advanced methods are never perfectly successful (see Heipke et al., 2007), 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 coarser resolution than the best the images could support, while still improving on the density of DTMs interpolated from altimeter data. Highly automated mapping methods, such as the NASA Ames Stereo Pipeline (Broxton and Edwards, 2008) or the stereo pipeline developed by the DLR for processing Mars Express HRSC data (Gwinner et al., 2008) could provide even greater cost savings by eliminating the DTM editing step, but it must be noted that in pipeline processing, interactive editing of DTM artifacts is replaced by an automated filtering step. Such filtering requires a compromise between smoothing away real details in the DTM versus allowing artifacts to remain. A similar choice faces the human DTM editor, but for the foreseeable future the human brain is likely to perform better at making such choices than any available computer algorithm. As the missions described here are followed by first robotic and then human-crewed landers, 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; 2008a) and conduct surface operations (Li et al., 2005), and thus at least regional DTM production with human quality control and editing will continue to be needed.

An additional cost driver that may be less obvious is the need to repeat the processing of various data sets 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 Kaguya) and far exceeds the scope of NASA's typical post-mission data analysis programs. The NASA Lunar Mapping and Modeling Project (Cohen et al., 2008) shows promise in funding some significant cartographic products required by the Constellation program, but is unlikely to be able to address more than a small fraction of the type of efforts we describe here needed to register the existing and coming lunar data sets. 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 should be implemented 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. This should be actively planned and promoted as soon as possible.
- Specifically, the respective national space agencies should establish working groups to ensure uniformity of lunar coordinate systems, standards, and constants across missions and organizations, and to further coordinate and cooperate with the corresponding working groups in other agencies (such as the recently formed NASA LGCWG) and the IAU/IAG WG on Cartographic Coordinates and Rotational Elements.
- The primary image data sets of every past and future mission (some have more than one) should be tied to successive versions of the ULCN or some equivalent frame, for the many reasons given above. As data are released from upcoming missions, cartographers should begin tying the data sets together and performing initial geodetic control and mosaicking.
- Each of the planned lunar missions has other, either non-imaging, or lower resolution imaging data sets that should also be tied into ULCN. 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 data sets or altimetry data and relative timing information (a process known historically as "C-smithing").
- The ULCN must be tied to the altimetry data sets, and these, in turn, must be tied to the LLR reference frame. Ideally, the altimetry data sets should first be adjusted based on altimeter crossover information and orbit correction information if available, and merged with the other available data sets, and then globally rotated into the LLR reference frame, via topographic matching of the areas of the Apollo landing sites (e.g. with our existing Apollo 15 site DTM and/or future high resolution DTMs). 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.
- Mapping of possible landing sites and scientific sites of high interest should proceed immediately, using high resolution Apollo, LO, and future mission data sets.
- The stereo data sets from Chandrayaan-1 and/or Kaguya should eventually be processed to densify the altimeter data and complete a global 5-10 m resolution lunar topographic model.

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 data sets 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 (Actual or Planned)	Cameras of Cartographic Interest	Camera Type	Camera Coverage & Res	Radar	LIDAR Altimeter	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 ("push frame")	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
Kaguya (SELENE)	Japan	JAXA	2007 Sep 14	?	Terrain Camera (TC)	2 line scanner	Global pan, stereo, 10 m	Lunar Radar Sounder	Laser Altimeter (LALT) 5 m resolution, 1.6 km spacing	?	?	?	Yes	http://www.jaxa.jp/projects/sat/selene/index_e.html
Chang'e-1	China	CNSA	2007 Oct 24 Duplicate spacecraft 2009	?	CCD Stereo Camera Imaging Interferometer	3 line scanner, 60 km swath 25.6 km swath	Global pan, stereo, 120 m 0.48–0.96 mm, 200 m	No	Laser Altimeter (LAM) 5 m res	?	?	?	?	http://www.cnsa.gov.cn (Agency homepage only) http://210.82.31.82/index.asp?modelname=eng\en-news http://www.planetarysociety.org/explore/topics/space_missions/chang_e_1/data.html
Chandrayaan-1	India	ISRO	2008 July?	?	Terrain Mapping Camera (TMC) Hyper Spectral Imager (HySI) Moon Mineralogical Mapper	3 line scanner, 40 km swath 40 km swath 40 km swath	Global pan, stereo, 5 m 32 bands 400–900 mm, 80 m Global 140 m Targeted 70 m	Mini-RF Forerunner S band SAR ±80° to 88° 150 m	Lunar Laser Ranging Instrument 5 m res	500 m?	?	?	?	http://www.isro.org/chandrayaan-1/announcement.htm http://www.isro.org/Chandrayaan/htmls/home.htm
Lunar Reconnaissance Orbiter (LRO)	USA	NASA	2008 Oct 31?	2009 Oct 31 (5 year extension possible)	LRO Camera (LROC)	Line scanner Pan 110 km swath, color 80 km swath Adjacent line scanners, 5 km total swath	Global repeat stereo? 100 m Targeted, some repeat stereo 50 cm	Mini-RF S/X band SAR Operates few minutes/month only	LOLA 5-beam 50 cm res 50 m spacing	50 m	60 arcsec	No	No	http://lunar.gsfc.nasa.gov/
Luna Glob	Russia	Roscosmos	2009 or 2010?	?	Visible and IR	?	?	?	?	?	?	?	?	http://lunar.gsfc.nasa.gov/library/3-03RSA_Future-Mitrofanov.pdf and Shevchenko (2008)
MoonLITE	UK	PPARC	2010	?	No?	N/A	N/A	No	No	?	?	No	No	http://www.mssl.ucl.ac.uk/planetary/missions/DGLR07_PPARC_lunar_study.pdf (Gao et al., 2008)
Google Lunar X-Prize	10 teams, 4 countries	Private funding	By 2010 Dec		Surface imaging	?	?	No	No	?	?	?	?	http://www.googlelunarxprize.org/

Table 1. Lunar Missions conducted or planned in the decade 2001–2010 and their cartographically relevant instruments. This table is originally based on http://www.spaceagepub.com/ilo/ilofleet.pdf (last updated in 2005), but has been updated based on http://www.planetarysociety.org/explore/topics/groups/space_missions/, http://en.wikipedia.org/wiki/List_of_future_lunar_missions and links therein, the mission pages referenced above, and reports to the Lunar Reconnaissance Orbiter Project Science Working Group at http://lunar.gsfc.nasa.gov/library-pswg.html as well as references cited in the text. All URLs accessed 2008 April 24