Pergamon

Adv. Space Res. Vol. 19, No. 10, pp. 1523–1533, 1997

Printed in Great Britain
0273-1177/97 $17.00 + 0.00

PII: S0273-1177(97)00365-7

MAPPING OF THE MOON BY CLEMENTINE

A. S. McEwen*,** and M. S. Robinson*,***

* *U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff AZ 86001, U.S.A.*
** *Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, U.S.A.*
*** *Northwestern University, Chicago IL, U.S.A.*

ABSTRACT

The "faster, cheaper, better" Clementine spacecraft mission mapped the Moon from February 19 to May 3, 1994. Global coverage was acquired in 11 spectral bandpasses from 415 to 2792 nm and at resolutions of 80-330 m/pixel; a thermal-infrared camera sampled ~20% of the surface; a high-resolution camera sampled selected areas (especially the polar regions); and a lidar altimeter mapped the large-scale topography up to latitudes of ±75°. The spacecraft was in a polar, elliptical orbit, 400-450 km periselene altitude. Periselene latitude was -28.5° for the first month of mapping, then moved to +28.5°. NASA is supporting the archiving, systematic processing, and analysis of the ~1.8 million lunar images and other datasets. A new global positional network has been constructed from 43,000 images and ~0.5 million match points; new digital maps will facilitate future lunar exploration. In-flight calibrations now enable photometry to a high level of precision for the uv-visible CCD camera. Early science results include: (1) global models of topography, gravity, and crustal thicknesses; (2) new information on the topography and structure of multiring impact basins; (3) evidence suggestive of water ice in large permanent shadows near the south pole; (4) global mapping of iron abundances; and (5) new constraints on the Phanerozoic cratering rate of the Earth. Many additional results are expected following completion of calibration and systematic processing efforts.

INTRODUCTION

Clementine was a unique experiment in planetary exploration. The mission was designed primarily to flight-qualify advanced light-weight technologies developed by the Ballistic Missile Defense Organization (BMDO--formerly known as the Strategic Defense Initiative Organization, SDIO) (Rustan, 1994). Clementine also provided a bonanza for lunar science, including global multispectral imaging and topographic mapping, thus filling critical gaps in knowledge left from previous lunar missions (Nozette and Garrett, 1994). Lunar Orbiter returned global imaging but no compositional data, and the Apollo program revolutionized our knowledge of the Moon but returned detailed information from only very limited geographical areas. A global dataset acquired by modern detectors for compositional and topographic mapping was needed to extend the Apollo results to the global scale. Clementine was the first demonstration that significant planetary exploration could be accomplished with the "faster, cheaper, better" approach consisting of a fixed budget, fast schedule, and a lean but flexible management style. The mission was accomplished with cooperation among several different groups in addition to BMDO: the spacecraft was built and operated by the Naval Research Laboratory (NRL), detectors and other technologies were provided by the Lawrence Livermore National Laboratory (LLNL), NASA provided tracking support and a science team, and many components and technical support came from the aerospace industry and small businesses.

The main instrumentation on Clementine that was useful for lunar science consisted of six cameras and a laser-ranging system: two star tracker (ST) cameras, an ultraviolet-visible (UVVIS) camera, a near-infrared (NIR) camera, a long-wave infrared (LWIR) camera, a high-resolution (HIRES) camera, and the laser ranger (LIDAR) (Table 1). For more details on the spacecraft and payload, see Nozette *et al.* (1994) and Regeon *et al.* (1994). In this paper we present a brief history of the mission with emphasis on events affecting the lunar science results, describe the lunar mapping phase and the systematic processing of the datasets, and give a brief summary of important early science results.

Table 1. Clementine Instrument Parameters

	UVVIS	ST	NIR	LWIR	HIRES	LIDAR
Focal plane array	CCD	CCD	InSb	HgCdTe	CCD	Si APD
Pixel format	384 x 288	384 x 576	256 x 256	128 x 128	384 x 288	Single Cell
Field of View (°)	5.6 x 4.2	28 x 43	5.6 x 5.6	1.0 x 1.0	0.4 x 0.3	0.057
Spectral Bandpasses	415 ± 20	400-1100	1102 ± 30	8000-9500	415 ± 20	1064
(nm)	750 ± 5		1248 ± 30		560 ± 5	
	900 ± 10		1499 ± 30		650 ± 5	
	950 ± 15		1996 ± 31		750 ± 10	
	1000 ± 15		2620 ± 30		400-800	
	400-1000		2792 ± 146		Opaque	
Approx. Resolution at 425 km altitude (m)	115	1150	178	65	30	430

HISTORY OF THE CLEMENTINE MISSION

Since the mid-1980's the Department of Defense (DoD) has actively developed advanced sensor and spacecraft technologies for missile defense systems. The Clementine mission concept emerged from discussions held at the White House National Space Council in 1989. In April 1991 a joint NASA and DoD study concluded that a collaborative mission could test these technologies and provide a significant science return (Worden, 1992). In January 1992 the SDIO announced its intention to test the lightweight technologies while orbiting the Moon and flying by the near-Earth asteroid Geographos. Clementine's sponsors in the SDIO realized that it was less expensive to test these technologies in near-Earth space rather than in low-Earth orbit, and that using an asteroid as a target for testing the automated navigation avoided potential legal conflicts with missile treaties. Science advisor Eugene M. Shoemaker (U.S. Geological Survey) wanted to fly by a near-Earth asteroid first, then orbit and map the Moon, and hoped that the spacecraft might still have sufficient resources to fly by a second near-Earth asteroid or comet. However, the project manager (Colonel Pedro Rustan) thought that the less-risky lunar mission should be done before the asteroid flyby to better insure accomplishment of the primary objective of testing the in-flight performance of the new spacecraft and sensor technologies.

The name "Clementine" (after the old ballad about the miner's daughter) was used by LLNL, whereas NRL called this project the Deep Space Program Science Experiment (DSPSE). A third name, Sensor Integration Experiment (SIE), was also used by some individuals. DSPSE was awkward and "SIE" was easily confused with "SEI" (George Bush's Spacecraft Exploration Initiative), so "Clementine" won the popularity contest. "Clementine" seemed a rather inauspicious name on launch day, considering that the miner's daughter died by drowning.

Early spacecraft design concepts from LLNL were essentially for SDIO's Brilliant Pebbles spacecraft, but the manufacturing was contracted to NRL, who have been building spacecraft since the early 1960's, and the actual Clementine spacecraft was more conventional. The marriage of new SDIO technology from LLNL with an experienced spacecraft engineering team from NRL was orchestrated by Stewart Nozette, deputy project manager of Clementine. The launch vehicle was initially expected to be a Pegasus, later changed to the more capable Titan IIG.

A Clementine science advisory committee was assembled by NASA in early 1992 under the direction of Shoemaker. The first meeting between the scientists and the Clementine project personnel occurred during the 23rd Lunar and Planetary Science Conference (LPSC) in Houston, Texas. There was lots of enthusiasm that year at LPSC for the Space Exploration Initiative (SEI) and its scientific precursor, Lunar Scout. Few individuals in the planetary science community had heard of Clementine. At this meeting scientists and engineers from NRL and LLNL were talking quite confidently about building and launching a spacecraft with many new technologies never before flight tested, and doing so in 22 months and for a cost of $75 million ($80 million including mission operations). Compared to recent NASA missions, this was very startling!

The initial lunar mapping plan, which Shoemaker had prepared during a recent airplane trip, was for a polar elliptical orbit with periselene at an altitude of ~500 km near the Moon's equator. This orbit would enable global multispectral mapping of the Moon in just two months time at about 150-600 m/pixel resolution. The global mapping would be accomplished by the wide-angle UVVIS and NIR imaging systems (Table 1). Another instrument to be flown consisted of a laser range detector (LIDAR) and a high-resolution imaging system (HIRES) with a shared telescope. The HIRES would be useful for imaging the asteroid and selected lunar targets, but the LIDAR was not expected to provide valid ranging data over distances greater than about 500 km, so the initial plan was to simply leave the LIDAR turned off during lunar orbit. During a break in the Houston meeting Jordin Kare (LLNL) suggested to one of us (ASM) the idea of trying to use the LIDAR for lunar altimetry by lowering periselene and alternating periselene latitude between the southern and northern hemispheres in the first and second months in orbit. We realized that we could still achieve global multispectral coverage in two months via an orbit with periselene at ~425 km altitude at about -30° and +30° latitudes. Although the global mapping would be less uniform, the polar resolutions would be greatly improved. If the LIDAR provided valid returns at up to 500 km altitude, then this orbit would provide useful altimetry from about -50° to +50° latitude. This plan was soon accepted by the NRL team. Later we realized that the initial LIDAR ranging estimates did not consider two factors about the lunar surface: (1) it is brighter at the laser wavelength (1.064 microns) than at visible wavelengths; and (2) there is a pronounced brightness spike at 0° phase angle--which is the geometry of the LIDAR--even at wavelengths near 1 micron (Buratti *et al.*, in press). We actually acquired useful data right up to a data encoding limit of 640 km range, and mapped the Moon's topography from about -75° to +75° latitude. Some of the most significant early science results from Clementine resulted from this dataset (Zuber *et al.*, 1994; Spudis *et al.*, 1994).

The science advisors (and formal NASA science team selected in 1993) were very happy with their relationship with the Clementine project, in spite of being second in priority to the technology experiment. Initially some of us thought that few modifications to the instruments, mission, or observation plan would be considered, especially considering the schedule and budget. We proposed a variety of changes anyhow. The Clementine project agreed to a number of modifications, including selection of spectral filters, modification of the NIR optics to match the UVVIS field of view, modification of the LIDAR to improve its ranging sensitivity, addition of on-board compression to increase the data return, addition of certain pre-flight calibrations, addition of many special in-flight observations, and modification of the lunar orbit. The image compression system from Matra Marconi Space was provided by the Centre National D'Etudes Spatiales (CNES); the same compression system will fly to Saturn on the Cassini spacecraft. Henry Garrett (BMDO) expedited the CNES/Matra technology transfer. Without the data compression Clementine could have mapped only ~20% of the Moon rather than 100%, so this was an especially valuable mission enhancement. The project managers responded to science team requests in a fast and flexible manner. According to Shoemaker, this is how NASA and the Jet Propulsion Laboratory did things on the Ranger Project in the 1960's. Clementine demonstrated that late science requests can often be accommodated without contributing to cost overruns or schedule delays.

Selection of spectral filters for the UVVIS, NIR, and HIRES imaging systems was difficult because each filter wheel contained only six slots. One science advisor felt that we should emphasize spectral bandpasses that fall outside the range expected from the multispectral mapper planned for Lunar Scout, whereas others argued that Clementine should be optimized as a standalone mission. In addition, NRL required a clear filter on the UVVIS (as well as the HIRES) as a backup system for optical navigation to Geographos, and BMDO required the inclusion of a NIR filter at 2792 nm wavelength for tracking satellites from space as they pass over clouds. Final bandpasses are listed in Table 1. Although more bandpasses would have been desirable, these filters enable mapping of the major mineralogy including pyroxenes, anorthite, and olivine (Pieters *et al.*, 1994; McEwen *et al.*, 1994), soil maturity variations (Fischer and Pieters, 1996; Malaret and Lucey, 1996), and Ti and Fe abundances (Johnson *et al.*, 1991; Lucey *et al.*, 1995). It may be possible to constrain the abundances of hydrated minerals from the 2792 nm/2600 nm ratio. Note that Nozette et al. (1994) listed a NIR filter at 2780 ± 60 nm, but the actual bandpass is 2792 ± 146 nm.

Clementine arrived at the Moon on February 19, 1994. The mission was operated from a converted warehouse in Alexandria, Virginia, called the Bendix Alexandria Technical Center for Aerospace Vehicle Experiments (BATCAVE). It took several days for the mission operations staff to fully understand how to operate the spacecraft and instruments. There had been very little time for rehearsals before lunar orbit insertion. The spacecraft used a reduced-instruction set (RISC) processor for image processing and autonomous operations, the same kind of computer chip used in modern desktop computers. Previous spacecraft missions have used special fault-tolerant computer chips with high reliability but much less speed and memory, and which required highly specialized programming. The Clementine software was largely new and untested, resulting in a variety of unplanned technology experiments. Nevertheless, all of the sensors and spacecraft components worked as well or better than expected, and the flight validation of new hardware technologies was an unqualified success.

The activity in the BATCAVE was frenetic during the first weeks in lunar orbit. Along with data from the initial orbits came the first accurate measurements of detector performances, compression ratios, and downlink capabilities, so we had to rapidly replan the observation sequences. Every five hours a new load of data was returned as the spacecraft passed over the Moon's night side, and it was exhilarating to watch the large central video projection of new images at a rate of about one per second. There were more than a dozen spacecraft computer upsets resulting in partial or complete loss of data for particular orbits, but the diligence and the flexibility of the project personnel enabled the accomplishment of nearly 100% multispectral coverage of the Moon (Sorensen, 1995). Four individuals received special achievement awards from NASA for their contributions during the lunar mission: D. Horan (NRL), I. Lewis (LLNL), C. McCarl (Software Technologies, Inc.), E. Malaret (Applied Coherent Technologies), R. Reisse (Science Inquiries, Inc.), and T. Sorensen (AlliedSignal).

Clementine departed the Moon on May 3, 1994, to begin its journey to Geographos. The spacecraft had sufficient resources for a second asteroid flyby as well. Then on May 7 a combination of software errors resulted in repeated firings of the attitude thrusters, spinning up the spacecraft and exhausting the attitude control fuel. Software tests on the ground did not detect the problem because of configuration differences between the spacecraft and the software verification tool. This effectively ended the mission, although the spacecraft was briefly recontacted a year later.

LUNAR MAPPING

Overview

Clementine's lunar orbit was designed to optimize global multispectral coverage and altimetry (Sorensen, 1995). The spacecraft was in a polar, elliptical orbit at 400-450 km periselene altitude (Figure 1). During the first five weeks in orbit periselene was at -28.5° latitude for the highest-resolution coverage and altimetry over the southern hemisphere; for the remaining ~5 weeks periselene was moved to +28.5° latitude to best cover the northern hemisphere. The region from latitude -50° to +50° requires interleaving of data from both months for complete coverage. Orbit insertion was executed to provide low-phase (0°-35°) coverage of the equatorial regions, thus optimizing the signal-to-noise ratio (SNR) for multispectral mapping. Phase and illumination angles increase to 90° at the poles. Systematic mapping alternated between type A and type B orbits (Figure 1), designed to minimize redundant polar coverage and to provide oblique polar coverage in type B orbits.

The lunar mission was divided into three phases: pre-mapping (31 orbits), systematic mapping (266 orbits), and post-mapping (54 orbits). During the pre-mapping phase spacecraft and instrument engineering tests were performed along with acquisition of special image sequences. The systematic mapping phase included two periods designated month 1 and month 2, distinguished by periselene latitude. During this period the data acquisition goals were:

1) map the entire lunar surface in eleven wavelengths with the UVVIS and NIR,
2) measure lunar radii with the LIDAR when the spacecraft altitude was less than 640 km,
3) acquire oblique polar images (in addition to the nadir-looking coverage),
4) image the polar regions at 30-60 m/pixel with the HIRES camera,

5) acquire pole-to-pole strips of LWIR images centered along each orbit track, and
6) acquire HIRES color observations of selected targets.

In addition to these mapping goals, several special data sequences were acquired during systematic mapping, including a bistatic radar experiment over the polar regions (Nozette *et al.*, 1996), Earth images, stellar calibration images, and dark frames. During the post-mapping phase, gores in the systematic mapping were filled, oblique images for stereo coverage were acquired over the Orientale basin and other features from longitudes 30° to 120° W, and other special sequences were acquired. The stereo mapping experiment has proven successful, although the small image sizes and large number of images complicates the data processing (Oberst *et al.*, in press).

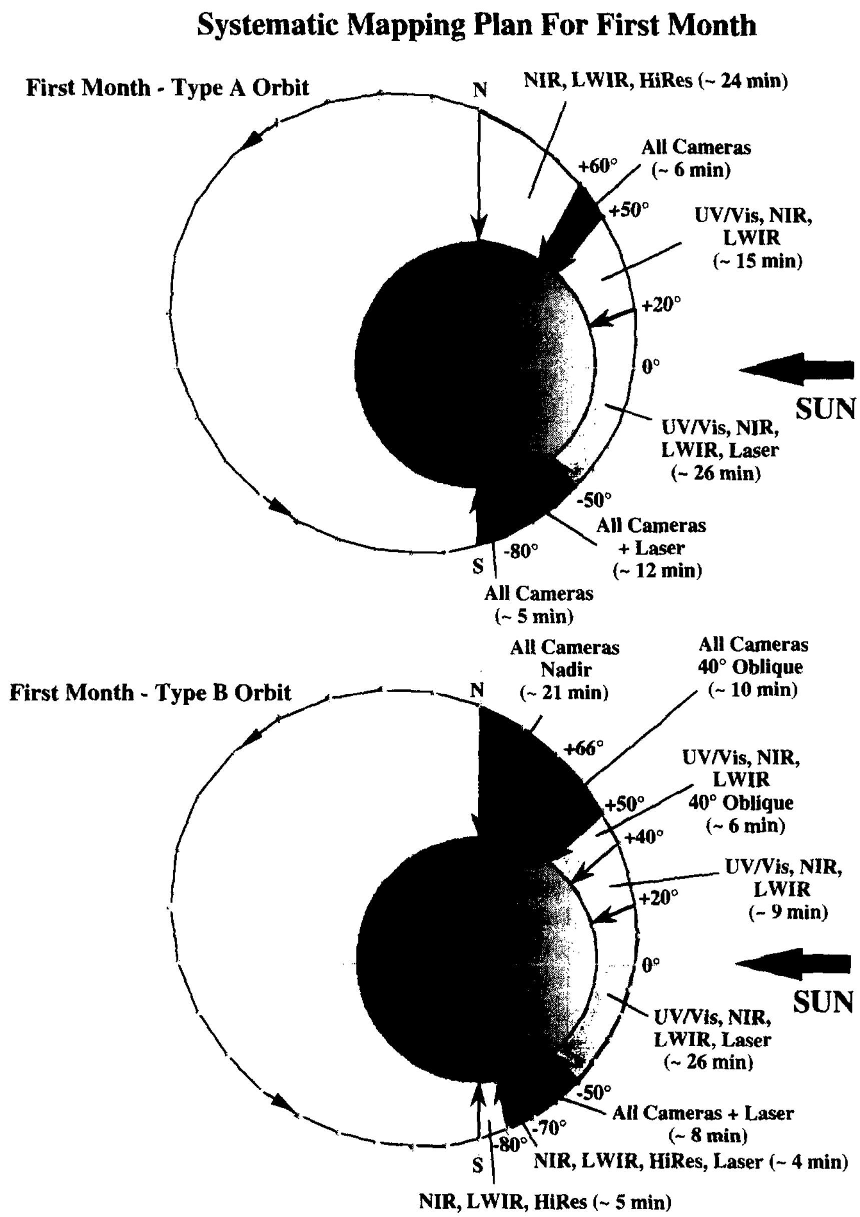

Fig. 1. Systematic mapping geometry for month 1, showing the spacecraft orbit with times and latitudes for science observations. Type A orbit shown at top, type B at bottom. The month 2 geometry, with periselene shifted to +28.5° latitude, was a mirror image of month 1.

Observation Strategy During Systematic Mapping

Observations were constrained by the quantity of data that could be downloaded during each orbit. About 100 megabytes (MB) could be returned from most 5-hour orbits, reduced to as little as 60 MB during orbits with partial communication blockage by the Moon. Observation and compression strategies were adjusted to achieve the science goals (Table 2). One observational goal was to acquire double imaging with the UVVIS, at long and short exposure times (or different gain/offset states) in order to acquire the best possible SNR without saturation. Typically the short-exposure image is unsaturated even for the brightest lunar features, but has a poor SNR over dark regions, whereas the long exposure image has much better SNR over dark regions but is saturated over bright craters or sunlit slopes. Because of concerns about the effects of lossy compression on the multispectral data, a 10° latitude strip of UVVIS and NIR images was acquired without compression in most orbits. Due to the polar elliptical orbit of Clementine, redundant polar coverage was possible for the UVVIS and NIR. For the UVVIS we chose to eliminate the redundant coverage, but we did attempt to cover each polar region twice: once nadir-looking at highest resolution, and once looking ahead of the orbit to cover the polar regions at lower phase angles and in stereo. We chose to image pole-to-pole with the NIR because of SNR concerns at high latitudes (double imaging was not an option due to the frame rate of the NIR). Due to lifetime concerns about the HIRES intensifier we chose to use low gain settings and limit the number of HIRES images acquired at the Moon. The HIRES was of primary importance to the planned Geographos observations and of secondary importance at the Moon. We chose to limit the HIRES to primarily monochromatic (750 nm) imaging of the polar regions, where illumination angles are good for imaging of surface morphology; color HIRES imaging over 10° latitude segments was a second priority. Both the HIRES color and the UVVIS/NIR uncompressed strips had to occur at least 40° away from the periselene latitude, when there was sufficient time in the sequence.

The CNES/Matra system achieves high compression ratios via the lossy Discrete Cosine Transfer (DCT) algorithm (Blamont and Lambert-Nebout, 1995). We planned to restrict the compression to the most conservative setting allowed by the hardware to minimize compression noise. This strategy produced compression ratios of about 5:1 for the UVVIS long exposures, 12:1 for the UVVIS short exposures, 2.2:1 for the NIR, 1.6:1 for the LWIR, and 3:1 for the HIRES. These compression ratios vary primarily as a function of high-frequency noise and scene contrast. The UVVIS images are almost entirely free of high-frequency noise, so high compression ratios were achieved, especially for the short exposures. The NIR has about 1% "hot" (bad) pixels and other high-frequency noise, resulting in much lower compression ratios. The LWIR has about 5% hot pixels and 10% noisy (but useful) pixels. Because of the poor LWIR compression ratio and because the array is small (128 x 128), we decided to return most of the LWIR data in uncompressed format. The HIRES has a broad point-spread function due to its fiber-optics intensifier, such that a resolution element is equivalent to about a 3x3 pixel area. Because of this blurring we expected to achieve high DCT compression ratios (>10:1), but this expectation proved false with the conservative compression setting due to the hexagonal responsivity pattern introduced by the intensifier. Hence, we chose to use less conservative settings to achieve ~ 10:1 compression. To reach our goals with these compression constraints we proposed the nominal mapping plan for each systematic mapping orbit shown in Table 2. The nominal 95 MB/orbit was easily returned (in the absence of downlink anomalies), except during orbits with partial radio blockage. During blockage the data volume was reduced by dropping the HIRES color and compressing all images. The actual data returned from each orbit often differed substantially from the nominal plan due to a variety of mishaps.

The highest science priority throughout the lunar mission was acquisition of global multispectral mapping. There were eight major spacecraft computer upsets or downlink problems during systematic mapping, resulting in loss of all or part of the data for these orbits. Gaps from month 1 were filled in month 2 (at lower resolution in the southern hemisphere), and gaps from the early part of month 2 (longitude 0°-100° W) were recovered during the post-mapping period. For the latter parts of month 2 (longitude 0°-230° E), a strategy was implemented to fill gaps in orbits immediately following an upset by pointing the spacecraft to the east, taking several orbits to fully recover (Sorensen, 1995). Most of the HIRES and LWIR observations were sacrificed during these late recovery efforts. Only a few small gaps, totalling less than 1% of the lunar surface, were left uncovered in the UVVIS/NIR mapping. There are larger gaps or bad data in certain bandpasses. For example bad gain/offset settings resulted in useless 1250-nm images over the Orientale Basin region during month 1, and a filter positioning problem late in the mission resulted in loss of several partial orbits of 750-nm mapping. Several frames per orbit were typically lost due to sequence timing errors.

Table 2. Nominal Systematic Mapping Plan for each Orbit

Observation	Compression Ratio	Number of Frames	Downlink (MB)
UVVIS 5-color long exp	5:1	820	18
UVVIS 5-color short exp	12:1	820	8
NIR 6-color pole-to-pole	2.2:1	1044	32
10-deg. lat uncompressed UVVIS/NIR	1:1	(included above)	7
LWIR pole-to-pole	1:1	870	14
HIRES 750-nm lat +/- 50-90	8:1	600	8
HIRES 4-filter, 10 deg. latitude	12:1	400	4
Calibration frames	1:1	68	4
LIDAR altimetry	1:1	N/A	<<1
TOTALS:		4622	95

Topographic and Gravity Modeling

The LIDAR measured the range from the spacecraft to the lunar surface, and the S-band microwave transponder provided gravitational information. A global 2° by 2° gridded topographic dataset has been produced at the Goddard Space Flight Center by first subtracting a precise orbit from the range profiles (Zuber et al., 1994). The topographic model reveals a dynamic range of topography of about 16 km, similar to that derived previously from Soviet Zond-8 stereo and limb data over a small portion of the farside that happened to include some of the lowest and highest lunar elevations (Lipskii, 1975). The gravitational information was determined from velocity perturbations of the Clementine spacecraft; the Goddard group combined the Clementine data with historical tracking observations to develop a new gravity model. These are the first near-global topography and gravity models of the Moon.

Systematic Processing for Global Multispectral Mapping

Introduction. A systematic processing effort is underway at the U.S. Geological Survey (USGS) and collaborating institutions to produce a global 11-bandpass image cube from the UVVIS and NIR images. Special attention has been given to the derivation and application of the best possible geometric, radiometric, and photometric calibrations and corrections, which is critical to the scientific value of the final product.

Geometric Calibration and Control Network. A first major step in the systematic processing of the imaging data is the production of an accurate base map, to which all bandpasses will be geometrically registered (Edwards *et al.*, 1996). The pre-Clementine control network is accurate to 500 m in the area covered by the Apollo mapping frames (15% of the Moon's surface), and is accurate to about 1-2 km for regions covered by telescopic, Galileo, and Mariner 10 observations (Davies *et al.*, 1994). However, most of the farside is not included in the network, and the only other positional dataset for these regions (Defense Mapping Agency, 1974) contains errors as large as tens of kilometers. Approximately 500,000 match points have been collected at USGS from ~43,000 UVVIS images providing global coverage. About 85% of these match points were collected via newly-developed autonomous procedures, whereas the other 15% required the more time consuming but highly accurate pattern-recognition capability of the human eye and brain. The automated procedures saved several person-years of effort; this capability will be useful for processing other planetary datasets. The automated success rate exceeded 90% along each spacecraft orbit track, where the overlap regions of successive images are highly correlated, but failed when the overlap region is narrow and/or nearly featureless. Across-track matching was more difficult due to changes in scale and illumination angle, but a high success rate (~75%) was nevertheless achieved via the use of "window-shaping" (local geometric reprojections). The oblique gap-fill images were the most difficult to match. All match points were found to 0.2 pixel precision, whether automated or supervised. The USGS match points were sent to RAND for analytic triangulations and determination of improved camera orientation angles (Davies *et al.*, 1996). The analytical triangulation is a least-squares formulation designed to adjust the camera orientation angles to best fit the coordinates of the match points, but forced to match the known coordinates of the Apollo 15, 16, and 17 landing sites. A constant radius of 1737.4 km was assumed.

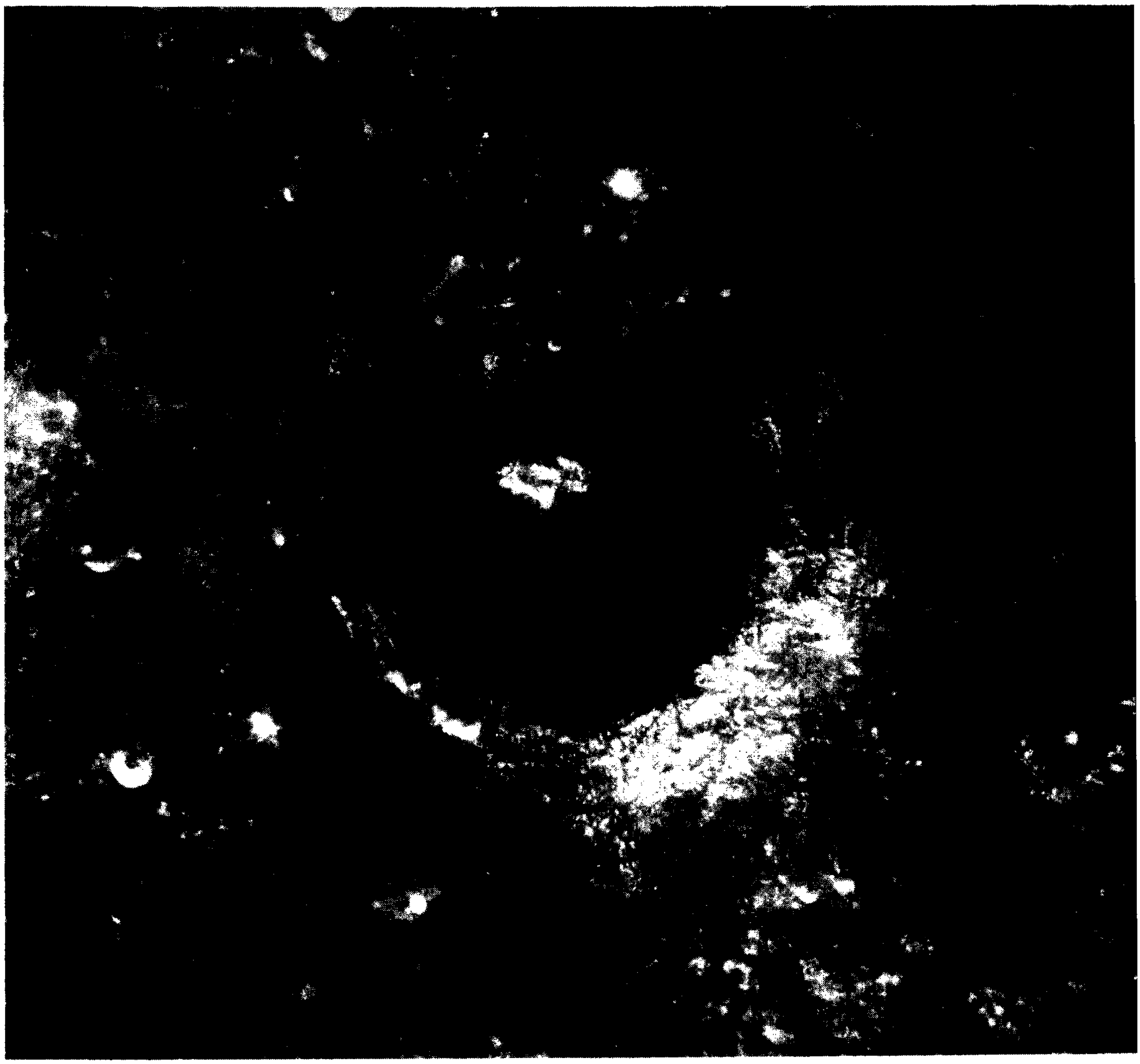

Fig. 2. Mosaic of Clementine 750-nm UVVIS images over Tsiolkovskiy Crater (180 km diameter), an example of the digital base map for ~1% of the lunar surface.

We estimate that we have achieved better than 0.5 km absolute positional accuracy everywhere on the Moon except for the highly oblique gap fills (~1% of the surface). In addition, the adjusted the camera angles result in excellent mosaics, as features on neighboring frames match each other to a mean accuracy of less than 1 pixel. The final base map is a global 750-nm albedo map; an example is shown in Figure 2. Gaps in 750-nm coverage due to the filter-positioning problem are being filled by 900-nm images, empirically normalized to match the 750-nm data. The mosaics primarily map albedos in the equatorial regions of the Moon and topographic shading at high latitudes. The data have been normalized to the brightness expected at illumination and phase angles of 30° and an emission angle of 0°. The digital mosaics (and the entire original Clementine dataset) are available via NASA's Planetary Data System (PDS). For network access to PDS data and information on Clementine, connect to the web address http://www.pdsimage.jpl.nasa.gov/PDS/.

Multispectral Data Processing. Highly accurate radiometric calibrations and photometric normalization are needed for accurate compositional mapping. Calibration has been achieved by utilizing the many thousands of in-flight images for each camera/filter combination. Stellar images (primarily of Vega) have been analyzed by Applied Coherent Technologies to derive global calibration coefficients for the UVVIS (see http://www.actgate.com). Bias correction files have been derived at USGS from images of space. In addition, we have recently derived a correction for nonlinearity introduced by the camera electronics that eliminates residual calibration errors of up to about 3%. Another major task has been to derive pixel-dependent responsivity corrections ("flat field" files). We developed procedures to average selected areas from many thousands of images per filter following photometric normalization. Galileo lunar images have been used to derive a photometric function from 20°-100° phase (McEwen, 1996), and we used the Clementine data at lower phase angles. Because the flat field and photometric modeling procedures depend upon each other, the derivations have been iterative. These efforts have progressed to the point where UVVIS multispectral mosaics with photometry to the 1% level of precision can be systematically produced; a paper describing these results is in preparation. The NIR calibration requires additional work before systematic processing can proceed, but results to date are very encouraging (P. Lucey, personal communication, 12/96). We expect the NIR data to be of significant scientific value: local calibration of NIR images over Aristarchus crater resulted in the discovery of anorthosite in the central peaks and olivine-rich units in the crater walls (McEwen *et al.*, 1994).

SCIENCE RESULTS

Studies in five areas are summarized below to provide examples of major science results from Clementine. Some of these results and interpretations are controversial, as is usually the case for new ideas of significance.

Shape and Internal Structure of the Moon. Global topographic and gravitational models derived from Clementine data reveal an improved picture of the shape and internal structure of the Moon (Zuber *et al.*, 1994; Neumann *et al.*, 1996). The highlands are in a state of near-isostatic compensation, whereas impact basins exhibit a wide range of compensation states. A global crustal thickness map was derived, revealing crustal thinning under lunar basins.

Ancient Multiring Impact Basins. The Clementine laser altimetry has confirmed the existence of several highly degraded impact basins (Spudis *et al.*, 1994). The degraded Mendel-Rydberg basin is about 6 km deep, only slightly less deep than the much better preserved Orientale basin (8 km) of comparable diameter. The South Pole Aitken basin is revealed as a basin 2500 km in diameter and more than 13 km deep, the largest positively identified impact crater in the solar system. Clementine altimetry suggests that the nearside Procellarum basin exists as a circular region of apparently hydrostatic mare fill (McEwen and Shoemaker, 1995), but its origin via a giant impact event remains controversial (Lucey *et al.*, 1994).

Large Permanent Shadows and Potential Water Ice Near South Pole. Clementine has provided the first complete set of high-resolution images of the south polar region of the Moon, revealing especially rugged topography (Shoemaker *et al.*, 1994). An area of up to 15,500 km^2 remained in shadow during a full lunar rotation and is a promising area for location of permanent ice deposits. The Clementine bistatic radar experiment revealed a backscatter enhancement over the south polar shadowed terrain, suggestive of the presence of water ice (Nozette *et al.*, 1996).

Abundance and Distribution of Iron on the Moon. Lucey *et al.* (1995) have developed techniques to quantitatively map the abundances of iron from Clementine UVVIS multispectral data. The average iron content of the highland crust (~3% by weight) is significantly lower than Apollo-based estimates and supports the hypothesis that much of the crust was derived from a magma ocean. The data suggest that the bulk composition of the Moon differs from that of Earth's mantle, which favors the giant impact model for the Moon's origin (Hartmann *et al.*, 1986).

Phanerozoic Cratering Rate of the Earth. Impacts from comets and asteroids during the Phanerozoic (0.545 Ga) have had dramatic effects on Earth's biosphere. Although the terrestrial crater record is highly degraded, the relatively recent cratering rate may be accurately recorded by craters with bright rays on the Moon's farside, where the crustal composition is most uniform (McEwen *et al.*, in press). Many previously unknown farside rayed craters can be clearly seen in the low-phase-angle Clementine images. The abundance of farside rayed craters may support other evidence for an increase in the cratering rate in late geologic time.

CONCLUSIONS

Clementine has provided a wealth of scientific data at very low cost to the science community. The data has led to reevaluation of several of the 25 year old paradigms derived from Apollo, and has renewed scientific interest in the Moon. We hope that scientific observations will be supported in future technology missions.

Acknowledgments. We thank W. Travis White and Hye-Sook Park (LLNL), Carle M. Pieters (Brown University), Stewart Nozette (Phillips Lab), Trevor Sorensen (AlliedSignal), Eric Eliason, Gene Shoemaker, and Lisa Gaddis (USGS), and an anonymous reviewer for helpful comments.

REFERENCES

Blamont, J., and C. Lambert-Nebout, Clementine: On-board image compression, *Lunar and Planetary Science,* XXVI, 127-128 (1995).

Buratti, B.J., J. Hillier, and M. Wang, The lunar opposition surge: Observations by Clementine, *Icarus* (in press).

Davies, M.E., T.R. Colvin, and D.L. Meyer, 1994, The unified lunar control network -- 1994 version, *J. Geophys. Res.*, 99, 23,211-23,214 (1994).

Davies, M., T. Colvin, K. Edwards, D. Cook, E. Lee, T. Becker, and A. McEwen, Modern lunar geodetic control, in *International Moon Workshop*, Berlin (1996).

Defense Mapping Agency, *Catalog of Lunar Positions based in the Lunar Positional Reference System*, Defense Mapping Agency, Aerospace Center, St. Louis, MO (1974).

Edwards, K.E., T.R. Colvin, T.L. Becker, D. Cook, M.E. Davies, *et al.*, Global digital mapping of the Moon, *Lunar and Planetary Science*, XXVII, 335-336 (1996).

Fischer, E.M., and C.M. Pieters, Composition and exposure age of the Apollo 16 Cayley and Descartes regions from Clementine data: Normalizing the optical effects of space weathering, *J. Geophys. Res.*, 101, 2225-2234 (1996).

Hartmann, W.K., R.J. Phillips, and G.J. Taylor, (eds.), *Origin of the Moon*, Lunar and Planetary Institute, Houston (1986).

Johnson, J.R., S.M. Larson, and R.B. Singer, A reevaluation of spectral ratios for lunar mare TiO_2 mapping, *Geophys. Res. Lett.*, 18, 2153-2156 (1991).

Lipskii, Y.N. (ed.), *Atlas of the Farside of the Moon, Part 3*, 239 pp., Moscow (1975).

Lucey, P.G., P.D. Spudis, M. Zuber, S. Smith, and E. Malaret, Topographic-compositional units on the Moon and the early evolution of the lunar crust, *Science*, 266, 1855-1858 (1994).

Lucey, P.G., G.J. Taylor, and E. Malaret, Abundance and distribution of iron on the Moon, *Science,* 268, 1150-1153 (1995).

Malaret, E., and P.G. Lucey, Medium resolution global lunar mosaics of FeO, TiO_2, and I_s/FeO, *Lunar and Planetary Science,* XXVII, 797-798 (1996).

McEwen, A.S., A precise lunar photometric function, *Lunar and Planetary Science*, XXVII, 841-842 (1996).

McEwen, A.S., J.M. Moore, and E.M. Shoemaker, The Phanerozoic impact cratering rate: Evidence from the farside of the Moon, *J. Geophys. Res.* (in press).

McEwen, A.S., M.S. Robinson, E.M. Eliason, P.G. Lucey, T.C. Duxbury, and P.D. Spudis, Clementine observations of the Aristarchus region of the Moon, *Science*, 266, 1858-1862 (1994).

McEwen, A.S., and E.M. Shoemaker, Two classes of impact basins on the Moon, *Lunar and Planetary Science*, XXVI, 935-936 (1995).

Neumann, G.A., M.T. Zuber, D.E. Smith, and F.G. Lemoine, The lunar crust: Global structure and signature of major basins, *J. Geophys. Res.*, 101, 16,841-16,863 (1996).

Nozette, S., and H.B. Garrett, Mission offers a new look at the Moon and a near-earth asteroid, EOS, *Transactions of American Geophysical Union*, 75, 161 (1994).

Nozette, S., C.L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. Robinson, and E. Shoemaker, The Clementine bi-static radar experiment, *Science*, 274, 1496-1498 (1996).

Nozette, S., P. Rustan, L.P. Pleasance, D.M. Horan, P. Regeon, *et al.*, The Clementine mission to the Moon: Scientific overview, *Science*, 266, 1835-1839 (1994).

Oberst, J., T. Roatsch, W. Zhang, A.C. Cook, R. Jaumann, *et al.*, Photogrammetric analysis of Clementine multi-look-angle images acquired near Mare Orientale, *Planet. Space Sci.* (in press).

Pieters, C.M., M.I. Staid, E.M. Fischer, S. Tompkins, and G. He, A sharper view of impact craters from Clementine data, *Science*, 266, 1844-1848 (1994).

Regeon, P.A., R.J. Chapman, and R. Baugh, Clementine "The Deep Space Program Science Experiment", in *Low-Cost Planetary Missions Conference*, International Academy of Astronautics, IAA-L-0501, 13 pp. (1994).

Rustan, P.L., Flight-qualifying space technologies with the Clementine mission, EOS, *Transactions of American Geophysical Union*, 75, 161 (1994).

Shoemaker, E.M., M.S. Robinson, and E.M. Eliason, The south polar region of the Moon as seen by Clementine, *Science*, 266, 1851-1854 (1994).

Sorensen, T.C., Global lunar mapping by the Clementine spacecraft, Paper AAS 95-127, *Advances in the Astonautical Sciences*, 89, 457-476 (1995).

Spudis, P.D., R.A. Reisse, and J.J. Gillis, Ancient multiring basins on the Moon revealed by Clementine laser altimetry, *Science*, 266, 1848-1851 (1994).

Worden, Col. S.P., The Strategic Defense Initiative Organization CLEMENTINE mission, in *Proceedings of the Near-Earth-Object Interception Workshop*, Jan 14-16 (1992).

Zuber, M.T., D.E. Smith, F.G. Lemoine, and G.A. Neumann, The shape and internal structure of the Moon from the Clementine mission, *Science*, 266, 1839-1843 (1994).