The Clementine mission – A 10-year perspective

Trevor C Sorensen[1,*] and Paul D Spudis[2]

[1] *University of Kansas, Lawrence KS, USA.*
[2] *Applied Physics Laboratory, Laurel MD, USA.*
* *e-mail: sorenst@ku.edu*

Clementine was a technology demonstration mission jointly sponsored by the Department of Defense (DOD) and NASA that was launched on January 25th, 1994. Its principal objective was to use the Moon, a near-Earth asteroid, and the spacecraft's Interstage Adapter as targets to demonstrate lightweight sensor performance and several innovative spacecraft systems and technologies. The design, development, and operation of the Clementine spacecraft and ground system was performed by the Naval Research Laboratory. For over two months Clementine mapped the Moon, producing the first multispectral global digital map of the Moon, the first global topographic map, and contributing several other important scientific discoveries, including the possibility of ice at the lunar South Pole. New experiments or schedule modifications were made with minimal constraints, maximizing science return, thus creating a new paradigm for mission operations. Clementine was the first mission known to conduct an in-flight autonomous operations experiment. After leaving the Moon, Clementine suffered an onboard failure that caused cancellation of the asteroid rendezvous. Despite this setback, NASA and the DOD applied the lessons learned from the Clementine mission to later missions. Clementine set the standard against which new small spacecraft missions are commonly measured. More than any other mission, Clementine has the most influence (scientifically, technically, and operationally) on the lunar missions being planned for the next decade.

1. Introduction

The Ballistic Missile Defense Organization (BMDO) informed NASA in January 1992 of its intention to test lightweight miniature sensors and components by exposing them to a long duration space environment while obtaining imagery of the Moon and the near-Earth asteroid, Geographos (Worden 1992). NASA agreed to provide science support in return for access to data collected during the mission. The result was the Deep Space Program Science Experiment (DSPSE) Clementine mission. The BMDO selected the Naval Research Laboratory (NRL) as its executing agent with responsibility for mission design, spacecraft engineering, spacecraft manufacture and test, launch vehicle integration, terrestrial support, and flight operations. The Lawrence Livermore National Laboratory (LLNL) provided lightweight imaging cameras developed under the sponsorship of the BMDO, the Goddard Space Flight Center provided trajectory and mission planning support to the NRL for the lunar mission phase, and the Jet Propulsion Laboratory (JPL) provided asteroid encounter planning and the Deep Space Network (DSN) for deep space communications and orbit determination. Besides the parts suppliers, several contractors were used by NRL during the project.

Clementine was launched on a Titan IIG expendable launch vehicle from Vandenberg Air Force Base into low Earth orbit (LEO) on January 25th, 1994. Eight days after launch, it executed a Translunar Transfer Injection (TTI) burn that placed it

Keywords. Polar deposits; Clementine; bistatic radar; Moon; mineral mapping.

J. Earth Syst. Sci. **114**, No. 6, December 2005, pp. 645–668

into a lunar phasing loop orbit with two Earth flybys. The STAR 37FM Solid Rocket Motor (SRM) and ISA, collectively referred to as the Interstage Adapter Subsystem (ISAS), separated from the spacecraft during the first phasing orbit. The ISAS remained in a highly elliptical orbit for three months collecting and transmitting radiation data from the Van Allen belts (Regeon *et al* 1994).

On February 19th, 1994, a 460 m/s burn of the spacecraft's bi-propellant propulsion system put the spacecraft into a highly elliptical polar orbit with an 8-hour period. This was the first time an American spacecraft had been in lunar orbit since Apollo 17 in 1972. Two days later a burn put Clementine into a 5-hour period elliptical orbit for mapping. Clementine spent 73 days in lunar orbit, during which time it accomplished the goal of a complete global multispectral mapping of the Moon, a gravimetric map, and the first global topographic map, and making several other important scientific discoveries.

1.1 *New technologies*

The primary new technologies that BMDO wanted to test during the lunar mission were the lightweight sensors: Ultraviolet/Visible (UV-Vis) camera, High Resolution (HiRes) camera, Near Infrared (NIR) camera, Long Wave-length Infrared (LWIR) camera, and two star tracker cameras (STCs); spacecraft subsystem components, e.g., NiH Common Pressure Vessel (CPV) battery, lightweight solar arrays, lightweight reactions wheels and inertial measurement units (IMUs), and a R3000 RISC processor; and innovative software, e.g., Spacecraft Command Language (SCL), autonomous position estimation, autonomous attitude determination, and autonomous operations scheduling software (Rustan 1994).

1.2 *Science objectives*

The lunar mapping science objective was to obtain topographic imaging, altimetry data, and multispectral imaging of the lunar surface (Nozette *et al* 1994). The topographic imaging and altimetry data were to be obtained for as much of the Moon's surface as possible, but due to the limitations of the HiRes camera and the laser ranger, 100% coverage was not possible. Two camera (UV-Vis camera, NIR camera) multispectral imaging with wavelengths specifically selected for lunar mineral identification was planned for 100% of the Moon's surface.

Thermal mapping was desired for the sunlit areas. This was to be accomplished by the LWIR camera with its single filter. The objectives of the LWIR global mapping were to

- derive surface roughness and 'beaming' properties,
- understand LWIR calibration through observation of the Apollo landing sites, and
- assist interpretation of other data.

The tracking data from the Clementine spacecraft can be used to help determine and refine the lunar gravitational potential field model, especially when combined with the earlier lunar missions and the subsequent Lunar Prospector mission. The Apollo missions were very useful in defining the lunar potential field, but their orbits were restricted to the equatorial region. Two of the Lunar Orbiter spacecraft of the mid-1960s were placed in polar orbits, but the tracking resolution of the time was sufficient only to provide a fairly coarse potential field model.

Additional science objectives included a luminescence experiment, a lunar horizon glow (LHG) experiment, stereo mapping, a high resolution stereo camera (HRSC) experiment, a bi-static radar (BSR) experiment, and various tests to aid in the calibration of the images. These tests also included engineering and calibration sequences that included dark field imaging, flat field imaging, stray (scattered) light, point spread function, infrared camera temperature response (deep space stare), data compression, and radiometric calibration using stars and lunar calibration sites as targets.

2. Clementine spacecraft

The spacecraft consisted of hardware and software subsystems, a payload subsystem, and the ISAS. The spacecraft was designed, integrated, and tested by the NRL. Table 1 provides an overview of the spacecraft system characteristics and figure 1 shows the Clementine spacecraft in its launch configuration with the ISAS and also in its operational configuration. Figure 2 illustrates Clementine's configuration. A more detailed description of the spacecraft subsystems can be found in Regeon *et al* (1994).

2.1 *New spacecraft technologies*

One of the primary objectives of the Clementine mission was to demonstrate advanced lightweight BMDO components technology (Regeon *et al* 1994). Some of the technologies flown for the first time on Clementine were (Horan and Regeon 1995):

Table 1. *Clementine spacecraft characteristics.*

Subsystem	Characteristics
Attitude control subsystem (ACS)	• 3-axis stabilized for all modes except spin stabilized TTI burn • 0.05 degree control; 0.03 degree knowledge; 6 degrees maximum rotational acceleration • Two STCs, one interferometric fiber optic gyro (IFOG), and one ring laser gyro (RLG) IMUs for attitude determination • Reaction wheels (4) and thrusters (12) for attitude control
Electrical power subsystem (EPS)	• Gimbaled (single axis) GaAs/Ge solar array ($2.3\,m^2$; 360 W@ 30 Vdc) • $1.21\,m^2$ GaAs/Ge solar array coverage on ISA assembly • Maximum solar eclipse (2 hours)
Propulsion	• SRM auxiliary kick motor; STAR 37FM • Bi-propellant (N_2O_4/MMH) for delta-V; monopropellant (N_2O_4) for momentum dumping, orbit maintenance, nutation control and spin-up/down
Structures	• Conventional (Aluminum) longerons with honeycomb skins • Composite interstage adapter, solar array panels and high-gain antenna • Space vehicle (launch adapter, kick motor, interstage and spacecraft)
Command, telemetry, and data handling (CT & DH) subsystem	• Primary controller - MIL-STD-1750A radiation-hardened processor • Image processor and backup controller - R3081 processor • 2.0 Gb (200 Mb) dynamic random access memory (DRAM) solid state data recorder
Communications subsystem	• S-band transponder; 125 b/s and 128 kb/s forward error correction (FEC) downlink; 1 kb/s uplink • 1.1 m diameter directional high rate antenna • S-band omni-directional transmit and receive antennas
Payload and sensors	• Payload interface electronics incorporated into DSPSE spacecraft controller • NIR; LWIR; UV-Vis; STC • Laser transmitter coupled with HRC provides miniature LIDAR system • Dosimeters; RRELAX; CPT
Ground systems	• DSN compatible • Primary command, control and communications from NRL's pomonkey field site during lunar mapping mission; DSN Madrid/Canberra sites provide full lunar coverage • AFSCN provided alternate LEO/lunar command backup • DSN was to provide asteroid flyby command, control and communications

Figure 1. Clementine configuration.

- Advanced lightweight sensors developed by LLNL,
- Single container NiH_2 CPV battery developed by Johnson Controls Inc.,
- GaAs/Ge solar cells (at 0.14 mm, the thinnest ever flown up to that time) developed by Applied Solar Energy Corporation,
- Radiation-tolerant SSDR developed by SEAKR Engineering Inc.,
- Frangibolt™ actuators developed by TiNi Aerospace Inc.,
- Spacecraft Control Language developed by Interface Control Systems Inc. under contract to NRL,
- Two lightweight (< 1 kg) IMUs, one based on ring laser gyroscope (RLG) developed by Honeywell Inc. and the other on interferometric fiber optic gyroscope (IFOG) developed by Litton Guidance and Control Systems,
- Lightweight reaction wheels with electronics in wheel housing developed for BMDO by Ball Aerospace,

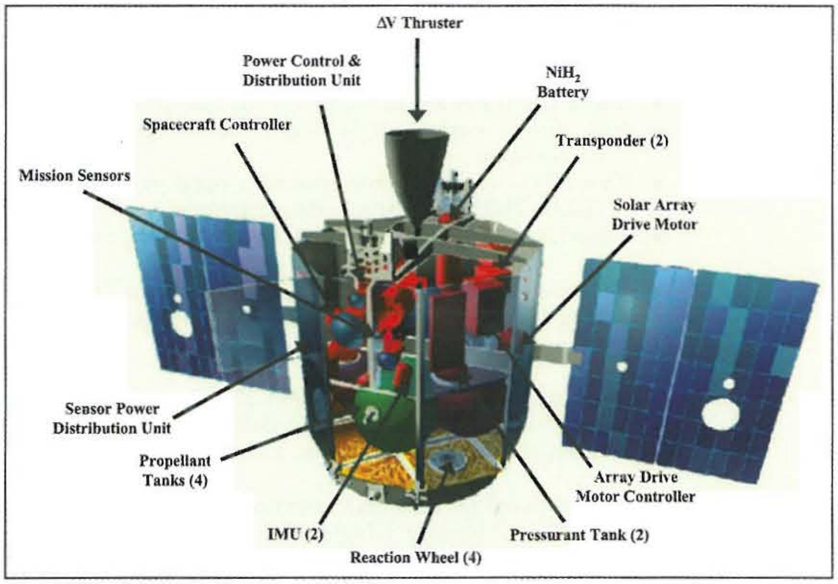

Figure 2. Clementine spacecraft internal layout.

- A high performance 32-bit Reduced Instruction Set Computer (RISC) microprocessor,
- J-PEG data compression chipset developed by Matra Marconi Space (France).

3. Sensor complement

In addition to the imaging sensors listed previously, Clementine also carried a Laser Imaging Detection and Ranging (LIDAR) and HiRes imaging and laser ranging system (Regeon and Chapman 1994). Characteristics of the imaging sensors are shown in table 2, and the comparative sizes of their fields of view are shown in figure 3. The spacecraft's payload also included four dosimeters, a Radiation and Reliability Assurance Experiment (RRELAX), and a Charged Particle Telescope (CPT) that measured plasma, total dose, and heavy ion radiation.

3.1 *Ultraviolet-Visible camera*

The lightweight UV-Vis camera (0.4 kg) was designed for inexpensive manufacture, test, and calibration. The optics, filter wheel, and camera assembly were modular. The Focal Plane Array (FPA) was a phosphor overcoated silicon Charged Coupled Device (CCD) with ultraviolet and visible response between 300 and 1110 nm. The CCD array was 384×288 with a pixel size of 23×23 microns. The optics consist of a catadioptrics SiO_2 glass with 46 mm aperture and a speed of f/1.96. The imaging field of view (FOV) was 4.2 degrees $\times$ 5.6 degrees. The UV-Vis camera electronics operated at a maximum frame rate of 30 Hz with an 8-bit Analog to Digital Converter (ADC). Wavelengths of 415, 750, 900, 950, and 1000 nm were selected to characterize absorption features of common lunar minerals. A sixth broadband filter covering 400–950 nm was included to enhance the ability to detect the Geographos asteroid for optical navigation (Regeon *et al* 1994).

3.2 *Near-Infrared camera*

The low mass NIR camera (1.9 kg) was a compact imager used to detect and track in the IR range. The FPA was a photovoltaic InSb array with a 256×256 pixel format. The optics were catadioptric with a 2 cm aperture and a speed of f/3.33. The camera's FOV was $5.6° \times 5.6°$ with a rotating filter wheel that selected wavelengths of 1100, 1250, 1500, 2000, 2600, and 2780 nm. One of the filters was selected by BMDO and the others by the Science Team for mineralogy. The camera electronics operated at a frame rate of 10 Hz. A split stirling cycle cryocooler was integrated with the camera to maintain the FPA at 70 K (Regeon *et al* 1994).

3.3 *Long Wave Infrared camera*

The lightweight LWIR camera (2.1 kg) allowed investigation of cold objects against a space background. The FPA was a photovoltaic HgCdTe array of 128×128 with a pixel size of 50×50 microns. It used a Cassegrain telescope with relay optics with an aperture of 131 mm and a speed of f/2.67. The array FOV was one degree by one degree and imaged from 8 to 9.5 microns without filter wheels. The electronics operated at a

Table 2. *Sensor specifications and performance.*

Parameter	UV/Vis	NIR	LWIR	HiRes	Star tracker
Pixels	288 × 384	256 × 256	128 × 128	288 × 384	576 × 384
Field of view (FOV)	4.2° × 5.6°	5.6° × 5.6°	1.0° × 1.0°	0.3° × 0.4°	28.4° × 43.2°
Instantaneous FOV (IFOV)	0.255 mr	0.385 mr	0.136 mr	0.018 mr	1.3 mr
Ground resolution (@425 k, 40 mr/40 ms @ 10% MTF)	80	115	43	13 m (short integ) to 30 m (long integ)	
Filters/wavelength, nm	415 ± 20	1100 ± 15	BB: 8000–9500	415 ± 20	400–1100
	750 ± 5	1250 ± 30		560 ± 25	
	900 ± 10	1500 ± 30		650 ± 25	
	950 ± 15	2000 ± 30		750 ± 25	
	1000 ± 15	2600 ± 30		B.Band: 400–950	
	BB: 400–950	2780 ± 150		Opaque	

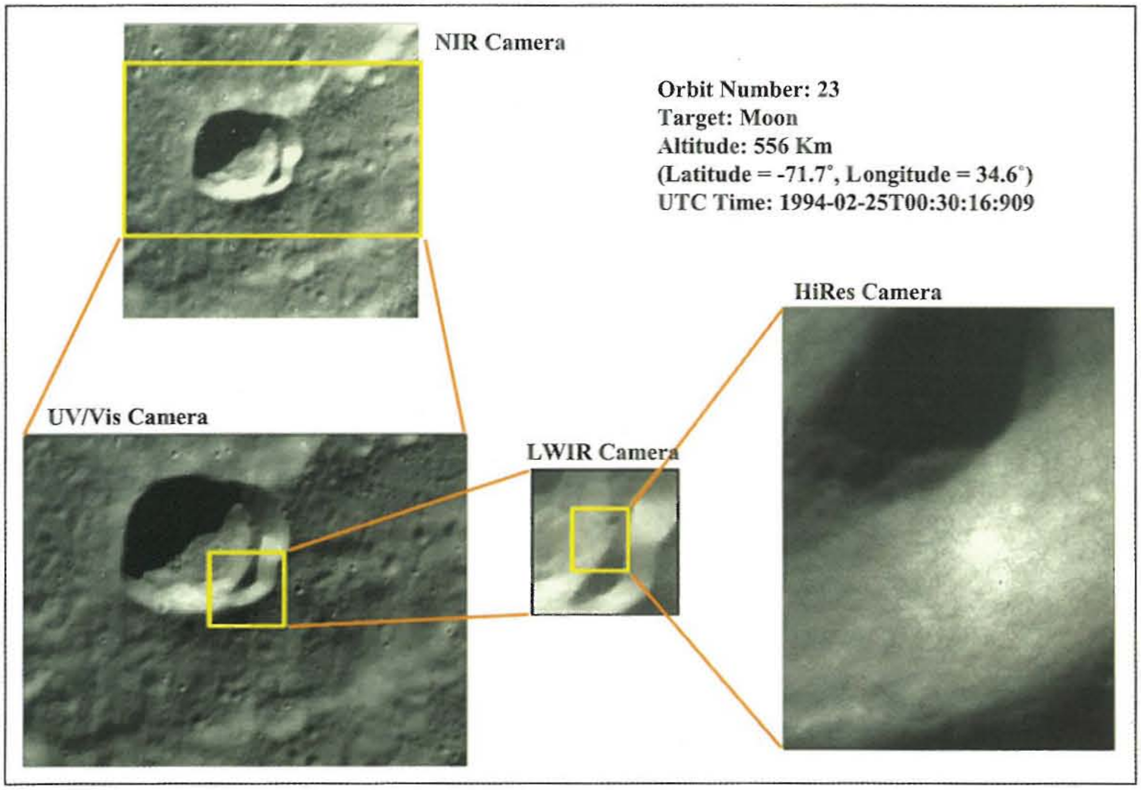

Figure 3. Sensors' comparative imagery.

repetition rate of 30 Hz. A split stirling cycle cryocooler was integrated with the camera to maintain the FPA at 65 K (Regeon *et al* 1994).

3.4 *Laser Imaging, Detection, and Ranging system*

The LIDAR system was an active imaging and ranging system that provided a passive imaging capability. The laser transmitter (1.1 kg) had a 532 nm active imaging wavelength and a 1064 nm ranging wavelength. It was a Nd:Y-AG diode pumped laser operated at 1064 nm/532 nm. The pulse energy was 180 millijoules (90% at 1064 nm; 10% at 532 nm) with a 10 ns pulse length. The laser transmitter could be operated continuously at 1 Hz or in bursts at a higher repetition rate. The spacecraft's thermal management system allowed operation at up to 400 pulses at 8 Hz (Regeon *et al* 1994).

3.5 *High Resolution camera*

The HiRes camera (1.12 kg) provided both imaging and range gate measurements. The imaging portion of the HiRes camera was based on a silicon CCD coupled to a microchannel plate image intensifier. The spectral range was 400 nm to 800 nm. The pixel format was 384 × 288 with a design instantaneous FOV of 18 microradians and a FOV of $0.4° \times 0.3°$. The optics consisted of a shared Cassegrain telescope with a beam splitter, a 13.1 cm aperture, and a speed of f/9.5. Selectable filters in the optics train were 415, 560 nm (10 nm), 650 nm (10 nm), and 750 nm (20 nm), and one opaque cover to protect the image intensifier. The return signal from the laser transmitter was directed to an avalanche photo diode using the shared beam splitter in the telescope. A time difference of laser fire and signal return provided the range information. By design the minimum range detection was 240 m, and maximum range detection was 640 km with a minimum resolution of 40 m (Regeon *et al* 1994).

3.6 *Star Tracker cameras*

The Star Tracker Camera (STC) was a miniaturized, 290 gram, wide FOV (WFOV), visible light sensor. The STC performed a three-axis attitude determination using only one starfield image that was processed by the spacecraft's onboard processor. The STC's WFOV ($29° \times 43°$) allowed for a reduction of the onboard star catalog. The STC's FPA was a silicon CCD operating between 400 and 1100 nm with a pixel format of 384×576 and a pixel size of 23×23 microns. The STC's aperture was 14.4 mm with a focal length of 17.7 mm, and it operated at a speed of f/1.28. The STC electronics operated at a maximum frame rate of 10 Hz with 8 bits resolution in the ADC (Regeon *et al* 1994).

3.7 *Dosimeters*

The Clementine dosimeter package consisted of four p-MOSPET dosimeters with a total radiation capability of $\approx$ 20 kRAD (Si). The dosimeters were located at different spacecraft locations to monitor radiation exposures at different levels of spacecraft structural shielding (Regeon *et al* 1994).

3.8 *Radiation and Reliability Assurance Experiment*

The RRELAX consisted of static random access memory (SRAM) and complimentary metal oxide semiconductor field effect transistor (FET) chipsets. The characterized SRAM provided a single event upset (SEU) monitor distinguishing among high energy protons, alpha particles, and heavy cosmic ray SEU between 0.9 MeV and 20 MeV. Total radiation dosages were measured using a p-MOSPET and measuring the threshold voltage shift in the p-FET (Regeon *et al* 1994).

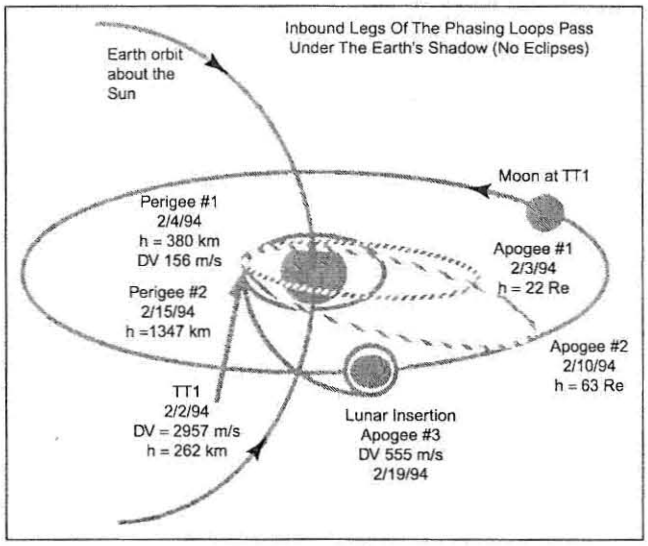

Figure 4. Trans lunar orbit.

3.9 *Charged particle telescope*

The CPT measured the fluxes and spectra of electrons and protons encountered by the spacecraft throughout its mission. The CPT had nine channels covering the electron energy range from 25 keV to 500 keV (6 channels) and protons from 3 MeV to 80 MeV (3 channels). The instrument measured the energy spectra of protons from solar flares occurring during the mission. The CPT's low-energy electron channels provided data on the interaction between the Moon and the Earth's magnetotail (Regeon *et al* 1994).

4. Mission description

4.1 *Orbits and trajectories*

The launch of Clementine on a Titan IIG booster on January 25th, 1994 put the spacecraft into LEO, where it spent the next eight days performing system checkouts. It then executed a 2957 m/s TTI burn to place it into a lunar phasing loop trajectory with two Earth flybys (also called a two-and-a-half phase trajectory) as shown in figure 4 (Kaufman *et al* 1995). At perigee of the first phasing loop, another delta-V burn was performed to raise the apogee of the orbit to intersect the Moon's orbit and on the second loop on February 19th, Clementine reached the Moon. A 460.3 m/sec Lunar Orbit Insertion (LOI) burn put the spacecraft into a highly elliptical orbit with an 8-hour period, which was reduced to the 5-hour period elliptical mapping orbit a couple of days later.

Based on the characteristics of the baseline sensor complement, the mapping of 100% of the

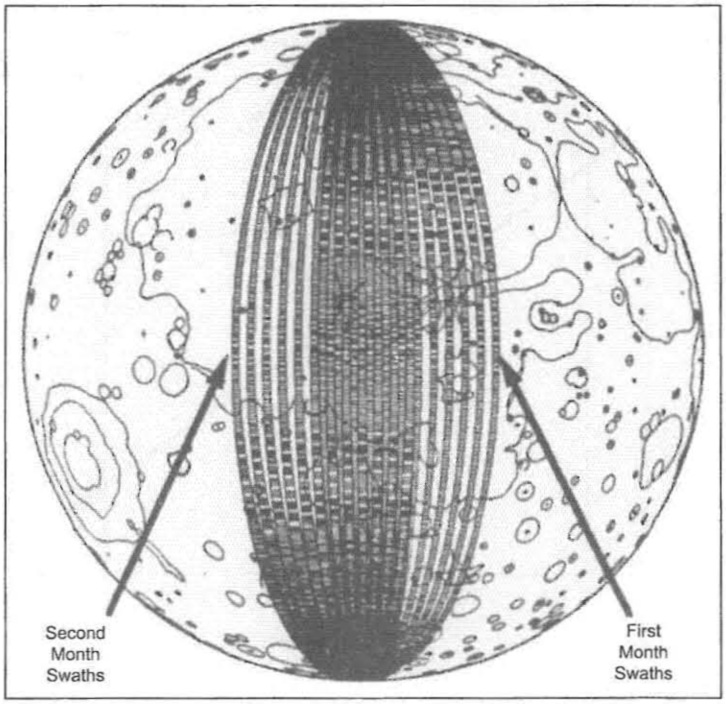

Figure 5. Mapping coverage – first and second month UV-Vis swaths.

lunar surface was done in approximately two lunar days (two Earth months). During the nominal two month mapping mission, the desired nominal image overlap for the UV-Vis and NIR cameras was 15% each side in the down track and 10% each side in the cross track directions. The absolute requirement for cross track overlap was a minimum of 10% total, with 2% on one side and 8% on the other (Regeon *et al* 1994). This strategy required that the periselene* of the lunar orbit had to be maintained at an altitude of 425 ± 25 km in a polar orbit. This requirement was satisfied by having the inclination of the orbit to be $90° \pm 1°$ with reference to the lunar equator. To provide the necessary separation for the alternating imaging swaths to cover the entire surface of the Moon during the two months, the orbital period had to be about five hours. During this orbital period the Moon rotated approximately 2.7° beneath the spacecraft. The second month's imaging swaths covered the gaps left between the first month's imaging swaths (figure 5). The orbit also had to have a sufficiently long period to allow the transmission to Earth of data collected during the imaging phase of each orbit.

The best data for the lunar mineral mapping mission are obtained when the solar phase angle is less than 30°. The solar phase angle is defined as the angle between the vector to the Sun and the vector to the spacecraft from a point on the Moon's surface. To maximize the time period in which the solar phase angle was within 30°, the plane of the lunar orbit contained the Moon–Sun line half way through the two-month lunar mapping period (figure 6). Therefore, insertion into the lunar orbit was selected so that as the Moon–Sun line changed with the Earth's motion about the Sun, the Moon–Sun line initially closed on the orbital plane, and then laid in the orbital plane half-way through the mapping mission. With a two-month mapping mission and several days checkout time in lunar orbit prior to systematic mapping, the angle between the Moon–Sun line and the orbital plane closed for approximately five weeks before becoming zero.

The DSPSE Science Advisory Committee decided that an elliptical orbit with periselene at the equator would put the spacecraft too high at the poles to obtain the desired level of resolution. The equatorial band had been imaged in high resolution by the Apollo spacecraft, but only poor resolution or no imaging of the polar regions existed. It was thus decided to divide the systematic mapping into halves, with the periselene located near 30°S during the first month, and near 30°N during

*Although the terms 'perilune' and 'apolune' are commonly used to designate lunar periapsis and apoapsis respectively, during the Clementine mission the more archaic terms 'periselene' and 'aposelene' were mostly used and are retained in this paper.

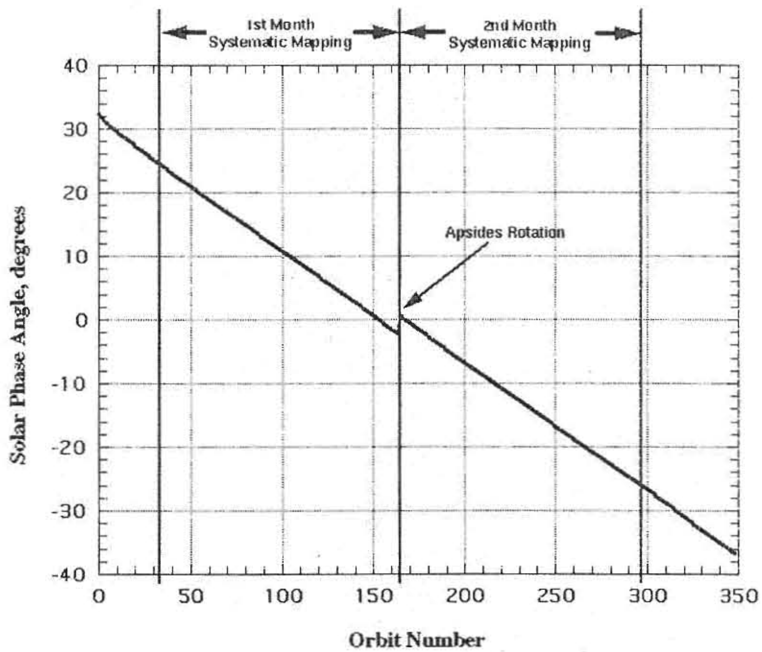

Figure 6. Solar angle during lunar orbit.

the second month. This permitted higher resolution imaging near the poles, and extended the effective coverage by the laser altimeter, which was constrained by its electronic counter to a maximum altitude of 640 km. This rotation of the line of apsides half way through systematic mapping required the use of two large maneuver burns.

Maintenance burns were required to keep the spacecraft inside the altitude envelope (425 ± 25 km) during systematic mapping. The number of burns was minimized to avoid unnecessary disruptions to the systematic mapping, and were designed to occur as far away from periselene, which occurred in the middle of imaging, as practical. The Clementine Trajectory Analysis and Maneuver Planning (TAMP) team, including the Flight Dynamics Facility at NASA Goddard Space Flight Center, were successful in meeting these requirements. Only two maintenance burns were needed (one each month), and no gaps in the mapping coverage resulted from their executions.

4.2 *Attitude measurement and control*

The spacecraft had an attitude measurement accuracy requirement to determine where the spacecraft was pointing of $\pm 0.03°, \pm 0.5$ milliradian. This accuracy had to be achievable in realtime, in darkness or sunlight throughout the lunar mapping phase. The spacecraft was three-axis stabilized and capable of autonomous, open loop inertial pointing, with an accuracy of at least $\pm 0.05°, \pm 0.87$ milliradian. Three reaction/momentum wheels provided attitude control during mapping. Momentum had to be dumped periodically using the monopropellant attitude thrusters. The spacecraft could execute controlled, relative pointing motion about a pointing vector for scanning across targets.

During lunar imaging, the spacecraft had to maintain a nadir pointing attitude. This required a greater than 180° rotation over the approximately 1.5–2.0 hour imaging period during each lunar orbit. This rotation was accomplished by an onboard mode of the attitude control system (ACS) software. This nadir mapping mode also allowed an angular bias to be specified, which allowed an imaging ground track at a constant offset from the nadir ground track. Another ACS mode automatically pointed the high-gain antenna (HGA) to the Earth center or a specified tracking station site for the dumping of data. For attitude determination, the spacecraft had two inertial measurement units (IMU) and two star trackers. Because of a solar exclusion angle constraint, one of the two star trackers was usually covered during lunar orbit. To meet the pointing requirements, during lunar orbit a star tracker image was processed and the spacecraft attitude knowledge updated via a Kalman filter at least once every 10 seconds.

4.3 *Lunar mission phases*

The lunar mission of Clementine was divided into four phases (see table 3), the pre-mapping phase,

Table 3. *Major lunar mapping phase.*

Dates	Orbit numbers	Event
9/19/94 to 2/26/94	0–31	Pre-mapping activities: Establish proper mapping orbit Optimize camera parameters (gain, integration, etc.) Optimize image data compression matrices Verify flight software and commanding ability Determine effect range and setting for laser altimeter Calibrate cameras (flat & dark fields, radiometric, etc.) Verify spacecraft ACS and GNC subsystems Verify spacecraft power and thermal models Perform special science experiments
2/26/94 to 3/26/94	32–163	First month systematic mapping (periselene in southern hemisphere)
3/26/94 to 4/22/94	165–297	Second month systematic mapping (periselene in northern hemisphere)
4/22/94 to 5/04/94	298–352	Post-mapping activities: Fill gaps in coverage to complete global map Calibrate cameras (flat fields, scattered light, etc.) Collect HiRes images of specified lunar targets Oblique viewing to east for stereo imaging Extended laser altimetry to north pole region Perform special observations (luminescence, etc.) Perform autonomous operations experiment Perform Bistatic Radar (BSR) experiments (north pole) Prepare for lunar departure

the first month systematic mapping, the second month systematic mapping, and the post-mapping phase. Polar views of the pre- and post-mapping zones are shown in figure 7.

4.3.1 *Pre-mapping phase*

The primary objectives of the pre-mapping phase of the mission were to insert the spacecraft into the precise orbit required for global mapping, calibrate the sensors, and verify the procedures and operations required to successfully conduct the lunar mapping phase. When possible, activities were included to meet both BMDO and science mission objectives. The end of pre-mapping and the start of systematic mapping was designed to occur after the spacecraft had passed over the Apollo 16 landing site (15.5°E, 9.0°S), since this was considered to be the primary calibration site by the Science Team. That site was imaged on orbit 30, and orbit 31 was used to dump the data. Systematic mapping started February 26th, on orbit 32.

4.3.2 *First month systematic mapping phase*

During the first month of systematic mapping the periselene was in the southern hemisphere at $28.5°S \pm 0.5°$. This provided laser altimetry from 80°S to 20°N and higher resolution imaging of the South Pole region (however, in practice useful results from the laser altimetry were not collected above about 70° latitude). The first month mapping encompassed orbits 32 through 163. The first line-of-apsides rotation burn was performed on orbit 163/164, the second on orbit 165 (both on March 26th).

4.3.3 *Second month systematic mapping phase*

During the second month of systematic mapping the periselene was in the northern hemisphere at $28.5°N \pm 1.5°$. This provided laser altimetry from 20°S to 80°N and higher resolution imaging of the North Pole region. During this phase BSR experiments were successfully executed to investigate the possibility of ice in the South Pole region.

4.3.4 *Post-mapping phase*

The primary objectives of the post-mapping phase of the mission were to recover gaps in the mapping coverage, improve on the quality of mapping images of the early mapping orbits, calibrate the sensors, provide oblique viewing to the east to enable stereo imaging of the Oceanus Procellarum and Mare Orientale regions, perform the autonomous operations scheduling experiment,

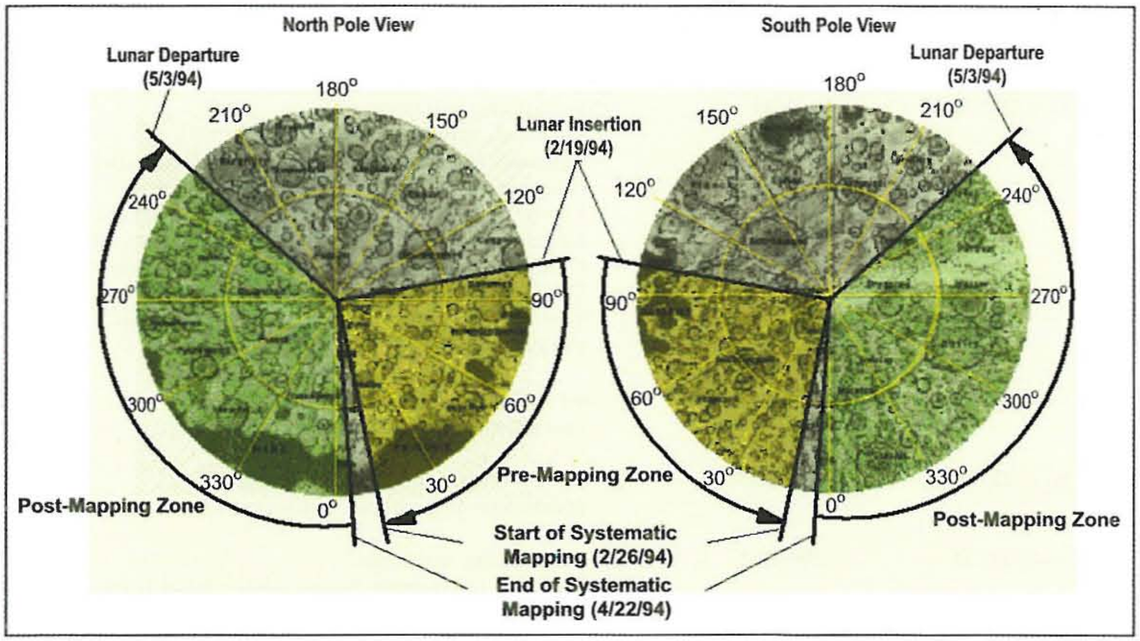

Figure 7. Polar view of mapping zones.

perform the BSR experiment to investigate the possibility of ice at the North Pole, perform special observations and experiments as requested by the Science Team, obtain additional laser altimetry and gravimetrics, and prepare for lunar departure.

The second maintenance burn (April 11th) boosted the periselene altitude only high enough to ensure that the spacecraft did not sink below the minimum altitude of 400 km before the end of systematic mapping on orbit 297 (April 22nd). During the post-mapping phase the spacecraft's altitude was allowed to sink, falling to 369 km on the last imaging orbit, orbit 348. The lower altitudes had the benefit of allowing the laser altimeter to be effective to a higher latitude, well into the north pole region (above 80°N), and also to allow the scale height of the gravimetrics to decrease, which provides additional information concerning crust thickness and mass concentrations.

4.4 *Systematic mapping methodology*

Each mapping orbit had a period of nearly five hours. The spacecraft spent approximately 90 minutes imaging as it traveled from the south pole to the north pole on the sunlit side, passing periselene on the way. The remaining three and a half hours of each orbit were used to downlink the data, collect calibration data for the sensors, and perform slews. The major activities for a typical first month mapping orbit are shown in figure 8. The time in brackets next to each activity in the figure is the orbit time, which was measured from aposelene, since this usually occurred in the middle of the data dump period when generally no scripts were being executed.

For the Clementine lunar mission, the protocol used for numbering orbits differed from the accepted standard, in which the orbit number is incremented when the spacecraft passes the ascending node. During the Clementine mission the ascending node was in the middle of the imaging period so the orbit number for an imaging pass was defined as the actual orbit number at the time the spacecraft crossed the south pole (Sorensen 1995).

4.4.1 *Imaging scheme*

In order to minimize the number of images acquired, stored, and downloaded, and still maximize the science return, an interleaving periselene strategy was developed (figures 9 and 10). Because of the sizes of the camera fields of view (figure 3) and the orbit characteristics, complete global mapping was only planned for the UV-Vis and NIR cameras; however, all mapping cameras imaged at variable rates based on latitude to form a continuous South to North swath (except for the HiRes camera). The NIR and LWIR cameras imaged from pole to pole. The HiRes camera's nominal imaging range was from 90°S to 50°S, and from 50°N to 90°N. Due to the small field of view of this camera, it required many more images than the other cameras to form a continuous swath. Because of camera sequence timing limitations, it

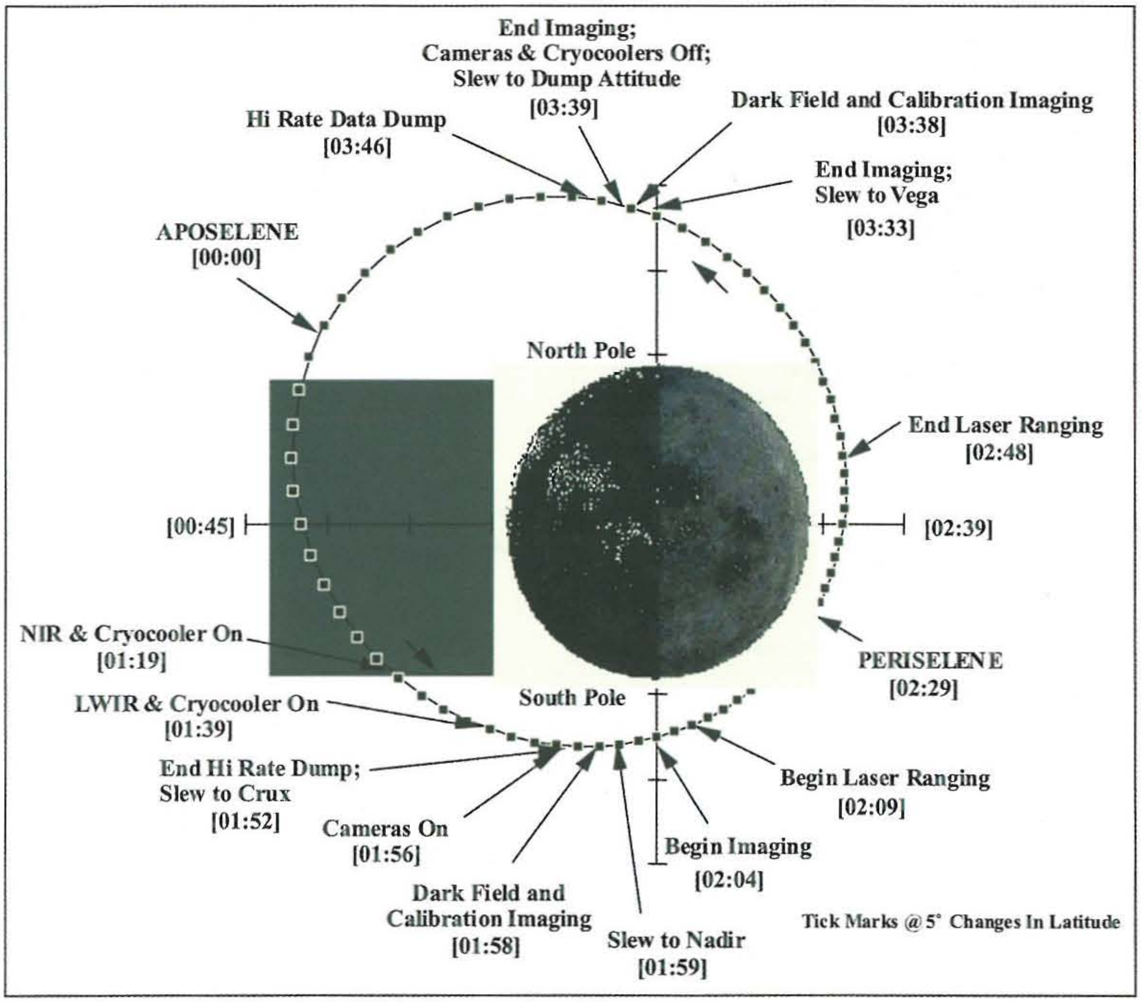

Figure 8. Major activities during each mapping orbit.

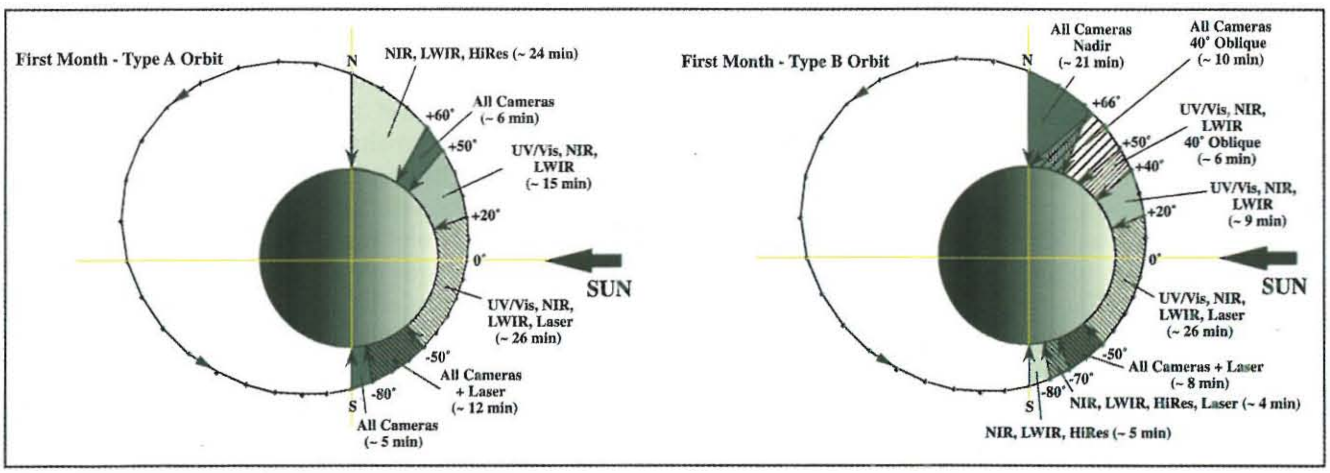

Figure 9. Systematic mapping plan for first month.

was not possible to perform multispectral (color) HiRes imaging near periselene without interrupting the continuous swaths of the other cameras. Color HiRes images were considered low priority given mission constraints (downlink, image intensifier lifetime), so for normal mapping the HiRes images were monochromatic. However, HiRes color bursts or strips were taken on some orbits over

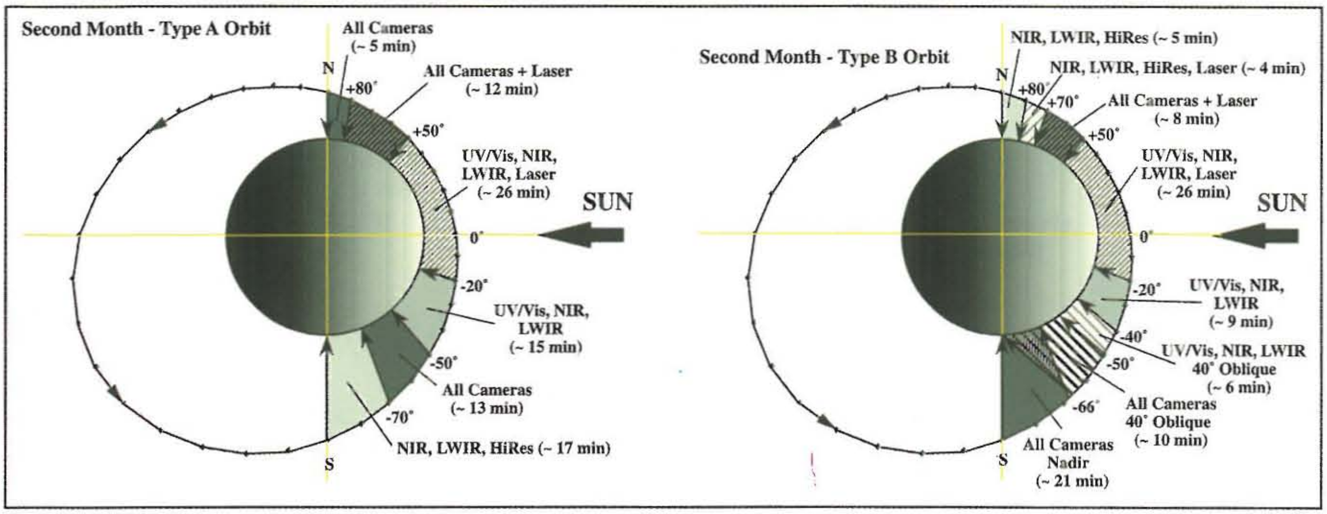

Figure 10. Systematic mapping plan for second month.

Table 4. *Ranges of continuous imaging.*

First month	
Type A: Orbit $\#n$	$-90°$ to $+70°$
Type B: Orbit $\#(n+1)$	$-70°$ to $+40°$ (nadir pointing)
[n is even]	$+40°$ to $\sim +65°$ (held at constant attitude until LOS @ $+90°$)
	$+65°$ to $+90°$ (nadir pointing)
Second month	
Type A: Orbit $\#n$	$-70°$ to $+90°$
Type B: Orbit $\#(n+1)$	$-90°$ to $-65°$ (nadir pointing)
	$-65°$ to $-40°$ (held at constant $-40°$ nadir attitude)
	$-40°$ to $+70°$(nadir pointing)

areas selected by the Science Team that were away from periselene. On some orbits, especially during the first month, continuous pole-to-pole HiRes swaths were acquired.

Redundant imaging between adjacent orbits occurred for the UV-Vis and NIR cameras at high latitudes, so a scheme was developed to alternate which polar region was imaged by these cameras on adjacent orbits. The type A orbit imaged the near pole (closer to periselene), while the type B orbit imaged the far pole. Shortly before the mission, the Science Team requested that the NIR be imaged from pole to pole regardless of the redundant coverage. The ranges of contiguous imaging shown in table 4 are thus for the UV-Vis camera only. The original cutoff point was 60° instead of 70°, but this was changed during the mission to improve the image resolution between 60° and 70°.

Members of the Science Team expressed a strong desire to obtain low phase angle (oblique) images of the far pole region. Redundant overlap of images occurred lower than 40° latitude in the far pole hemisphere, which allowed the spacecraft to obtain oblique imaging from 40° to the far pole on every second (type B) orbit. During the first month of mapping, normal nadir imaging was conducted on type B orbits to 40°, then the spacecraft attitude was held at constant inertial angle in the orbital plane instead of turning it to follow a nadir track. The line-of -sight track then remained parallel to the nadir line-of-sight (LoS) at 40° until the LoS reached the far pole, which occurred when the sub-spacecraft point was close to 65° latitude (66° when the periselene was 425 km). From this point, the spacecraft resumed nadir imaging. Oblique images obtained by this method when combined with the nadir images of the same lunar surface results in stereo observations reducible to quantitative topographic measurements.

During the second month of mapping the spacecraft performed nadir imaging on type B orbits until about 65°S, then slewed around to put the sensor line-of-sight on the South Pole using the pre-calculated inertial pointing quaternion for nadir viewing at 40°S. This quaternion was calculated at the DSPSE Mission Operations Center (DMOC) and uploaded to the spacecraft with the mapping

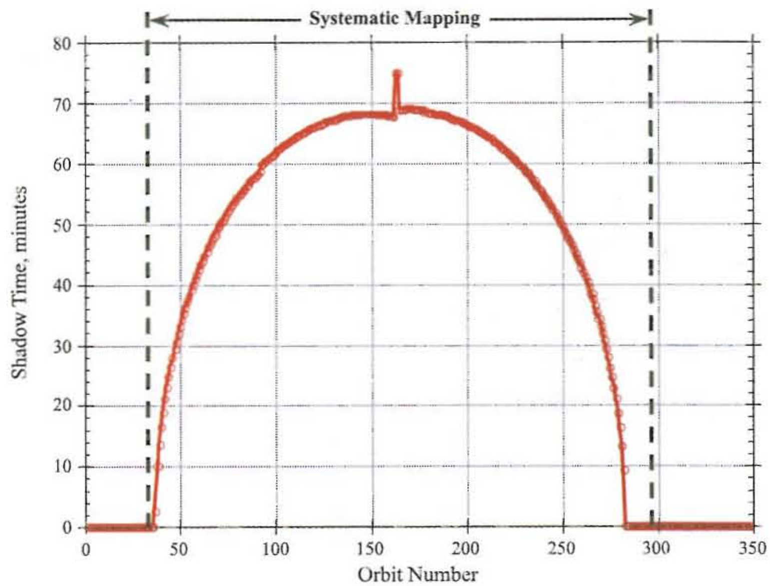

Figure 11. Umbra shadow time.

script for that orbit. The spacecraft then held that attitude until it reached 40°S, at which time the pointing angle of the sensors had converged with the nadir angle, and normal nadir mapping was resumed for the rest of the imaging period. Figure 5 shows how the first and second months imaging swaths combined to provide global mapping coverage of the Moon. The field of view boxes shown are for the UV-Vis camera, and follow some of the actual orbit tracks of the Clementine spacecraft. The first month swaths, when the periselene was in the south, are to the east, and the second month swaths are to the west, with a total overlap of about ten orbits. The boxes are plotted at a constant rate of one every 15 seconds from beginning to end, which was the approximate rate required near periselene to ensure along track overlap of images. However, at higher altitudes the spacecraft actually took images less frequently to reduce data, while maintaining the required along track image overlap.

Some of the observations requested by the Science Team, such as the Lunar Horizon Glow experiment, required the spacecraft to be in the Moon's umbra. However, due to the geometry of the trajectory in relationship to the position of the Sun, the only eclipse periods occurred during the systematic mapping phase (figure 11). To conduct the required experiments required interrupting the regular data downlinking period and performing attitude maneuvering with sensors operational, thus using power in a spacecraft power negative condition (since the solar arrays were shadowed). This required careful planning by the Clementine operations team, because the systematic mapping, which was highest priority, could not be jeopardized.

4.5 *Communication links*

The Clementine spacecraft's lunar mapping orbit was designed to always have periselene and the imaging activities occur over the sunlit side of the Moon. Due to the relative orientation of this orbital plane to the Earth, there were periods during the two months when the communications were restricted due to occultation (figure 12). Complete RF blockage occurred for 10 to 73 minutes per orbit while over the dark side of the Moon for about four days centered around full Moon (figure 13) due to occultation by the Moon. This reduced the time available to dump the stored data. For about eight days centered around new Moon, occultation and the resulting communication blockage occurred for 10–40 minutes per orbit near periselene. This prevented real-time monitoring and commanding of the spacecraft while it was imaging.

The pre-mission analysis of the data storage requirements during systematic mapping are shown in table 5 and summarized in table 6. The actual amount of data stored varied greatly from orbit to orbit, depending on how many valid HiRes images and bands of uncompressed UV-Vis and NIR images, if any, were taken. The Science Team requested one such band each orbit, if possible. The LWIR images were normally stored uncompressed, as opposed to the plan shown. During the periods of RF blockage during the data dump period, most or all of the HiRes images and the

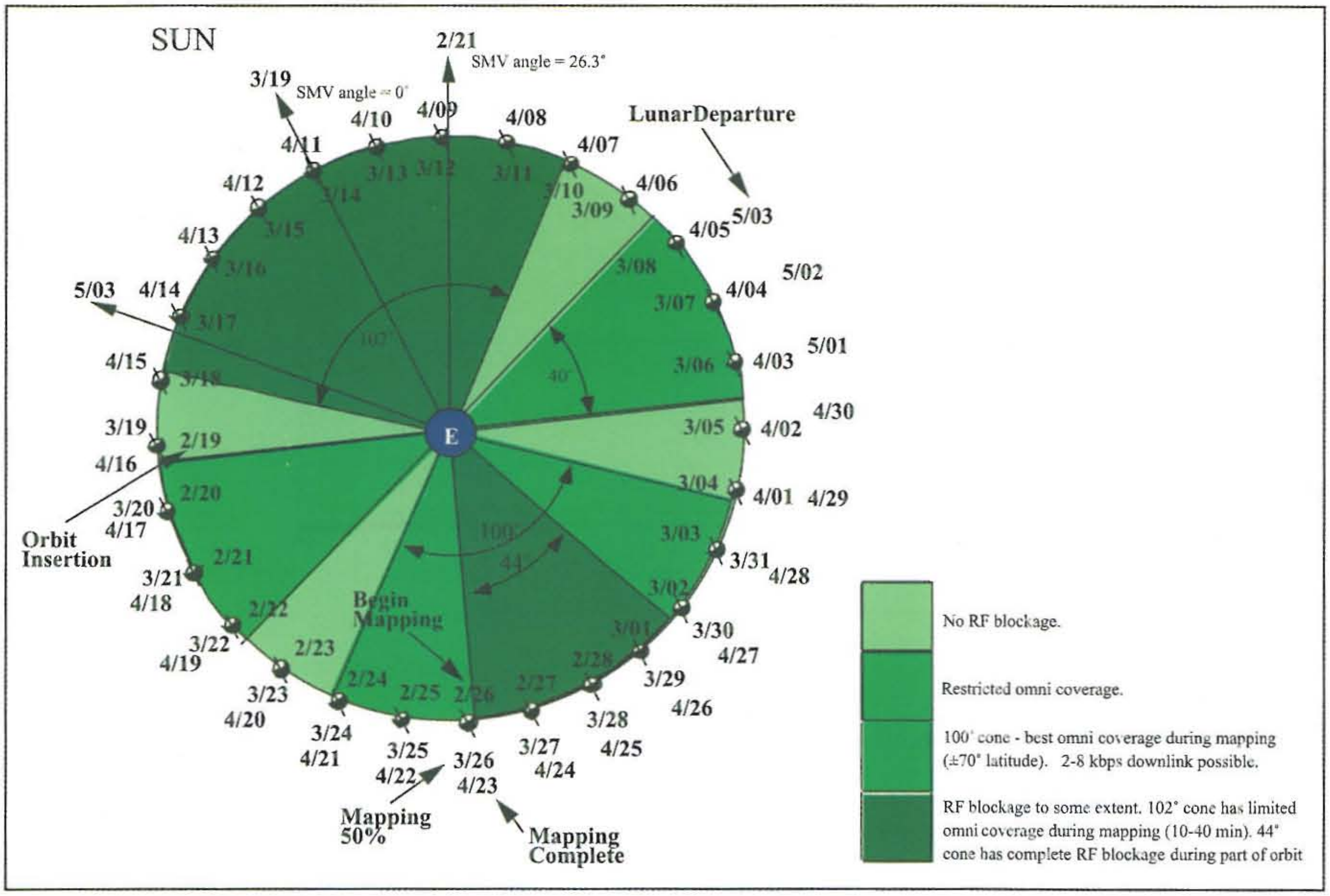

Figure 12. Lunar mapping relative geometries and RF blockage.

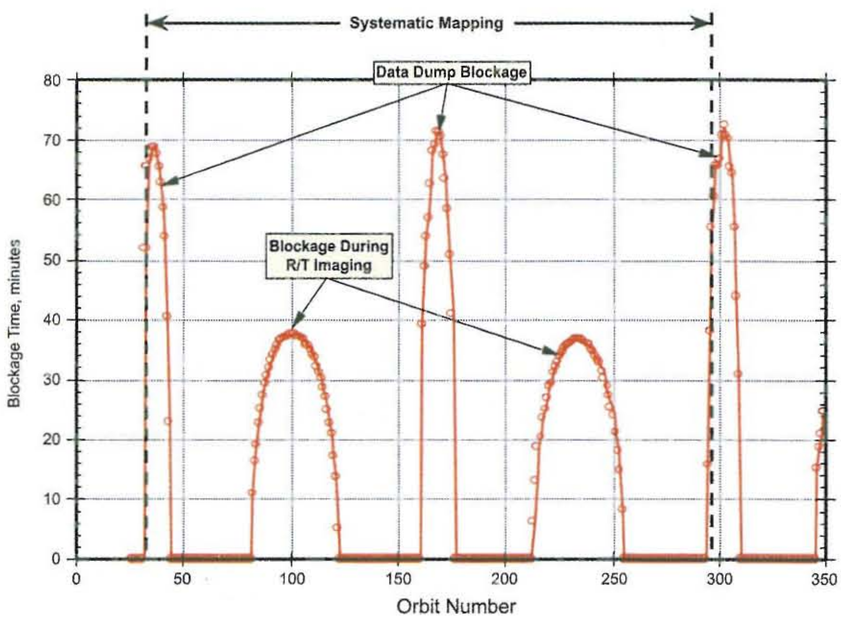

Figure 13. RF blockage periods.

uncompressed band of images were sacrificed in order to have enough time for downlinking the data. With the reduced data set, the images from two mapping orbits could be stored on the solid state data recorder (SSDR).

5. Science mission planning and operations

Although the science mission planned for Clementine was very complex, the program budget did not

Table 5. *Lunar mapping data storage requirements.*

Sensor	X Pixels	Y Pixels	Bits	Total frames per orbit	Compression ratio	Total bytes generated (Mbytes)
Orbit A (Nominal plan – does not include calibration or uncompressed images)						
LWIR	128	128	8	870	4:1	3.56
NIR	256	256	8	984	4:1	16.12
UV/Vis	288	384	8	1640	4:1	45.34
HiRes	288	384	8	3956	10:1	43.75
Orbit B						
LWIR	128	128	8	870	4:1	3.56
NIR	256	256	8	906	4:1	14.84
UV/Vis	288	384	8	1510	4:1	41.75
HiRes	288	384	8	4436	10:1	49.06

Table 6. *Data storage requirements summary.*

Parameter	Orbit A	Orbit B	Units
Total data/orbit	110.61	111.05	Mbytes
Maximum storage	200	200	Mbytes
Fraction of maximum	55.3	55.5	%
Minutes to downlink	115.22	115.368	@ 128000 bits/sec
With 10% overhead	126.74	127.24	minimum
Maximum time available	180	180	minimum
Margin	53	52	minimum
Minimum time available	108	108	minimum
Deficit (pre-mapping)	19	20	minimum

permit an extensive organization (figure 14) to support planning and operations.

A key feature of this organization was the role of the mission manager, who was responsible for the detailed planning and execution of a major segment of the mission. Due to the nature of the Clementine mission, there were two mission managers, one for lunar orbit activities, and the other for all non-lunar orbit activities, especially the planned asteroid encounter. One of the primary functions of the mission manager was to act as the principal liaison with the Science Team to ensure that the science objectives were being addressed in the mission planning. However, all the members of the Science Mission Operations and Planning (SMOP) and the Sensor Analysis groups were highly qualified (nearly all had PhDs) and worked closely with the Science Team. The primary mission planning was done by the mission managers and the two full-time and two part-time members of the SMOP group. After Clementine was launched, the SMOP group added two engineers to work on console.

Mission planning prior to launch was facilitated through the use of multi-disciplinary working groups and the development of several Activity Operations Plans (AOPs), which covered various aspects of the mission in increasingly greater detail. The AOPs became the mission planning handbooks, which detailed the mission objectives, requirements, constraints, operational plan, schedule, and sample command sequences required for the mission phase covered (Sorensen *et al* 1995a). These AOPs constituted the Mission Operations Plan developed prior to the mission, which was the guiding principle that was used to help develop the daily timelines and schedules.

5.1 *Interaction with the Science Team*

One of the basic principles of the Clementine science mission planning philosophy was to let the Science Team actively participate in the planning and implementation process, and to make that process as responsive to their inputs as possible. The Science Team provided the prioritization of the imaging, calibrations, and experiments to the mission planners, who incorporated these activities into the mission plan as best as they could. Instead of developing the command sequence for each orbit days or weeks in advance and requiring a major review cycle to approve changes, the Clementine command sequences were normally built just hours before execution and were able to incorporate changes requested by the Science Team (or others) based on analysis of the most recent data. Changes were normally approved only by the mission manager, or the SMOP console operator. All command sequences were tested on

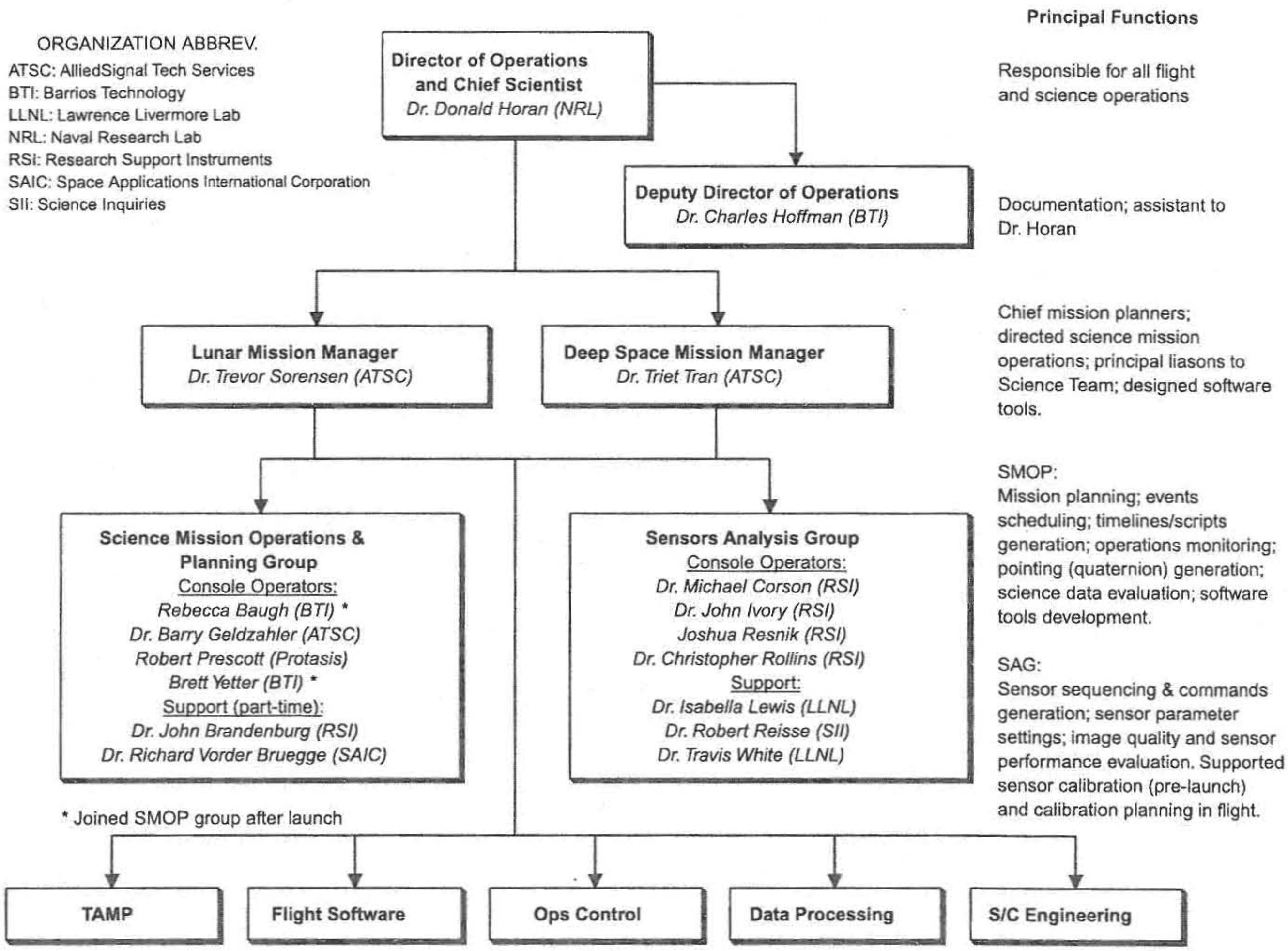

Figure 14. Clementine mission operations organization.

the DSPSE Operational Test Bed (DOTB) before uploading to the spacecraft.

Some major experiments or observations requested by the Science Team during the lunar mission were designed and implemented with no more than a few days notice. One example of the effectiveness of this method was the incorporation of the bistatic radar (BSR) experiment into the mission. This experiment was not even suggested until after Clementine had started systematic lunar mapping. This experiment involved a complex sequence of events: swinging the high gain antenna (HGA) to point to the lunar polar region, shutting down normal telemetry, and using several quaternion tables to slew the spacecraft to point the emitted HGA radio/radar beam to the pole for reflection to a NASA DSN antenna. Another example was the development and execution of a highly complex slewing and imaging sequence to test the methodology to be used by the German High Resolution Stereo Camera (HRSC) on future planetary missions. It only took about four days from the time this experiment was first requested by the Science Team to its successful execution by the spacecraft. Such requests did not have to be submitted in writing or go through a review board. Usually it only took a Science Team member to speak to the mission manager to get it into the planning process. If there was a conflict between different experiment requests, then they would be referred back to the Science Team for resolution.

5.2 *The mission planning process*

Although the major activities of the 350 lunar orbits were defined before launch, detailed timelines were only developed for the first nine lunar orbits. The mission planning process for supporting operations was designed to maximize responsiveness to Science Team requests by developing detailed timelines no more than two days in advance of execution, and uploading the command sequence for each orbit only once the previous orbit's activities were complete and the spacecraft was downloading data. The ability to make last minute changes to the command scripts before

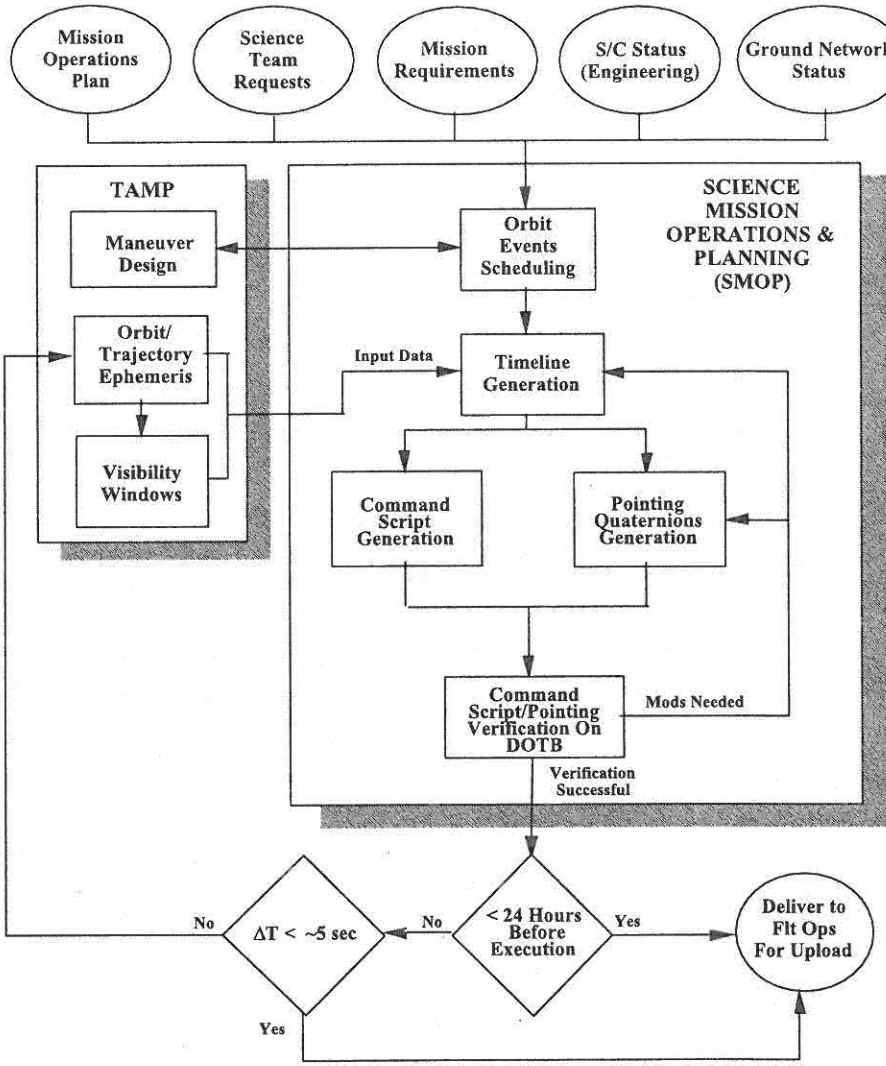

Figure 15. Mission operations planning process.

testing and uploading was a fundamental feature of this process. The following process was designed to plan lunar mapping timelines and generate spacecraft command language (SCL) command scripts for upload (figure 15):

- Mission operations plan – consult the detailed mission plan (AOPs) developed prior to launch.
- Mission (operational) requirements – these were the approved changes to the mission plan as requested by internal DMOC groups or external groups and agencies. These requests were defined, evaluated, and implemented using one of the following two methods:

(1) Nominal operations mode
This was for standard day-to-day operations in the DMOC. Mission operational requests (e.g., addition of or change to observations) that were internal to the DMOC including external groups (e.g., LLNL, Science Team) with personnel in the DMOC. The mission manager was responsible for the disposition of most operational requests. Requests with significant mission risk or programmatic issues were referred to the Director of Operations to be handled as special requests. Changes in sensor settings or tests, etc. were done by the Sensor Analysis Group without approval of the mission manager.

(2) Special operations mode
This was for all mission operational requirement requests from sources external to the DMOC (e.g., BMDO) or for special events or requests with significant mission risk or programmatic issues. All requests were submitted to the Director of Operations for consideration. The aim was for no effect on daily DMOC operations unless the Director of Operations determined the

request should be pursued. Examples of special mode requirements: lowering the lunar orbit for special observations; fundamental changes in operational philosophy.

- Spacecraft health and welfare status, resources schedule, and ground network status – the current operational factors external to the science mission that may affect the mission plan.
- Orbit events scheduling activities – a daily meeting of the SMOP, Trajectory and Maneuver Planning (TAMP) and Flight Ops groups planned the general spacecraft timeline and schedule for a couple of days in advance using the mission plan with the above inputs. Analyses were performed by groups as required to optimize or define activities needed for a detailed timeline. Orbit maneuver requirements (if any) were sent to the TAMP trajectory group for design.
- Timeline generation – a detailed timeline of spacecraft events was generated using a computer program. Input data for the timeline generator included applicable orbit/trajectory ephemeris or propagated data and visibility/shadow windows. Orbit data were provided by TAMP. Output data included:

    1. A hard copy of the spacecraft commands and associated events/activities.
    2. A data file of the timeline to be used as an input to the lunar operations program (LUNOPS) that is used for operations support in the mission control room.
    3. A timeline suitable for generating a spacecraft command script.
    4. Spacecraft-to-target pointing requirements for generation of pointing functions.

- Command script and pointing functions generation – converted the timeline into SCL script suitable for compilation and upload to the DOTB or to the spacecraft. Output consisted of spacecraft and sensor commands, and spacecraft pointing quaternions (single or in table).
- Command scripts integration – the scheduler combined the command scripts from the SMOP, TAMP and Flight Ops groups into a single integrated command script. The integration process identified major conflicts between the contributing scripts. Conflicting scripts were revised by or in consultation with the contributing groups.
- Integrated command script/pointing verification on DOTB – a complete set of commands and pointing functions planned for upload was tested and verified end-to-end on the DOTB before being released for upload. Testing and verification for the lunar mapping phase were done in compressed time mode to allow sufficient time for all uploads to be tested in a 24-hour operation.
- Any problems encountered with the command script or pointing functions were corrected, and the modified upload set was tested again on the DOTB. If the execution of the verified uploaded set was due to start more than $\sim$ 24 hours prior to its execution, the timeline and upload set were regenerated using the latest orbit/trajectory ephemeris approximately 24 hours before the execution. This upload set was retested and verified, after which it was sent to the DMOC for upload to the spacecraft, which occured at least an hour before execution.

5.3 *Autonomous operations scheduler*

A spacecraft autonomous operations experiment was successfully performed during the lunar mission (Sorensen *et al* 1995b). On lunar orbit 303, the spacecraft computer propagated a ground-supplied state vector to determine the time of significant orbital events (such as latitude, altitude and terminator crossings) upon which the mapping command sequences were based. These event times, usually calculated on the ground and inserted into the command sequence before upload, were used to trigger the rules in the script, which in turn issued all the commands required to successfully complete the mapping orbit.

The autonomous operations scheduler consisted of two basic functional elements: the SCL command rules script, and the guidance, navigation, and control (GNC) support software. The SCL script contained a set of rules, which if obeyed, would result in accomplishment of all spacecraft activities required during a mapping orbit. The GNC software provided a propagated orbit (i.e., ephemeris) from an initial state vector, provided the time values for an orbit events table, which was referenced by the SCL code during execution, and provided real-time parameters (such as current position and altitude) during the execution of the SCL script (this last feature was not used during the experiment).

5.4 *The effectiveness of the Clementine science mission operations*

The Clementine mission demonstrated how effective a small, but highly qualified group of mission planners and operations personnel can be in achieving complex science objectives. The Clementine spacecraft obtained nearly two million digital images of the Moon at visible and IR wavelengths covering > 99% of the lunar surface. These data are enabling the global mapping of the rock types of the lunar crust and the first detailed investigation of the geology of the lunar polar regions and global topographic figure of the Moon (see section 6). The BSR experiment that was added to the schedule after lunar insertion, yielded data consistent with the presence of ice in deep craters at the lunar south pole.

Although the Clementine lunar mission with its six imaging sensors, laser altimeter and complicated slewing scheme was as complex as comparable NASA mapping missions of that period, the Clementine team that provided science mission planning and operations did so with far fewer personnel and resources than in the NASA teams to perform the same functions (Sorensen *et al* 1995a). The work load on the Clementine operations team during the lunar mission was excessively high** mostly due to the incomplete software tools, such as the Command Script Generator, which were designed as an integral feature of the mission planning and operations process. However, the responsiveness of the process to requests for changes and additions to the scheduled events enhanced the science return by providing a fast feedback loop to optimize sensor settings and procedures, and the mechanism for obtaining additional data.

6. Science results

The Clementine spacecraft took over 2.8 million images of the Moon, at a variety of wavelengths in the visible and near-infrared. From laser ranging, it acquired a complete global topographic map between 70 degrees N and S latitudes. From radio tracking, it refined our knowledge of the Moon's gravity field. This basic data return is not the fundamental scientific output of the Clementine mission. The scientific return from Clementine continues to this day, as this mountain of data is analyzed and digested, gradually leading to new understanding and appreciation of our nearest planetary neighbor.

The global multi-spectral images of Clementine have enabled us to map the regional distribution of rock types on the Moon for the first time. We find that the Moon's crust is diverse and complicated, with evidence for intensive early bombardment, volcanic flooding, large basin formation, and a protracted period of mare basalt flooding, by lavas of varied and complex composition (e.g., Jolliff *et al* 2000; Robinson 2005). A new technique developed by some members of the Clementine Science Team allow us to use the Clementine images to map the distribution of iron and titanium (Lucey *et al* 1995; 2000). This one advancement has revolutionized the study of lunar geology, allowing us to map regional compositional units relevant to early lunar history (e.g., Lucey *et al* 1994), the stratigraphy and thickness of mare lava flows (e.g., Rajmon and Spudis 2004), the geology of Apollo landing sites and their regional contexts (Robinson and Jolliff 2002), and the history of the lunar far side (e.g., Gillis and Spudis 2000).

One of the most astounding discoveries from the Clementine data is the significance and importance of the enormous South Pole-Aitken (SPA) basin, the largest basin on the Moon, centered on the southern far side (e.g., Spudis *et al* 1994; Lucey *et al* 1998; Pieters *et al* 2001). This impact crater is over 2500 km in diameter and was partly known from early studies (e.g., Wilhelms 1987). What was not appreciated until Clementine was the amazing preservation state of SPA basin; at nearly 13 km deep, it appears to preserve much of its original relief (Spudis 1993). This observation suggests that the rigid outer shell of the Moon (lithosphere) must have been strong enough to preserve this feature for more than 4 billion years of subsequent history.

The SPA basin was surprising for another reason – as the Moon's biggest impact crater, one might expect such a large impact to dig very deeply into the Moon, possibly completely through its outer, aluminum- and calcium-rich crust, down into its magnesium- and iron-rich mantle. Clementine compositional data show that the floor of the SPA basin is indeed the far side's major compositional anomaly, possessing significantly elevated iron and titanium contents than the rest of the far side (Lucey *et al* 1998). Although it is unclear whether SPA has indeed excavated down to the lunar mantle, clearly it has dug into lower crust, material significantly different from the average highlands surface exposed around the rest of the Moon. Our best chemical characterization of the SPA basin floor material indicates that it is unlike *almost* all the lunar samples in our collection from Apollo and Luna. For this reason, sampling the SPA basin floor has been given high priority in the NRC Decadal Study (2003) and NASA is currently contemplating sending a robotic sample return mission there. The impetus to send such a sampling mission would probably not have occurred without the data from Clementine.

The topography and gravity data from Clementine have rewritten the lunar history books. Our first look at global topography shows the Moon to be a cold, rigid planetary object, with a dynamic

**Due to the excessive work load, the Clementine operations team could not have successfully sustained the same level of operations for much longer than the two-and-a-half months that Clementine was in lunar orbit without additional personnel or automation.

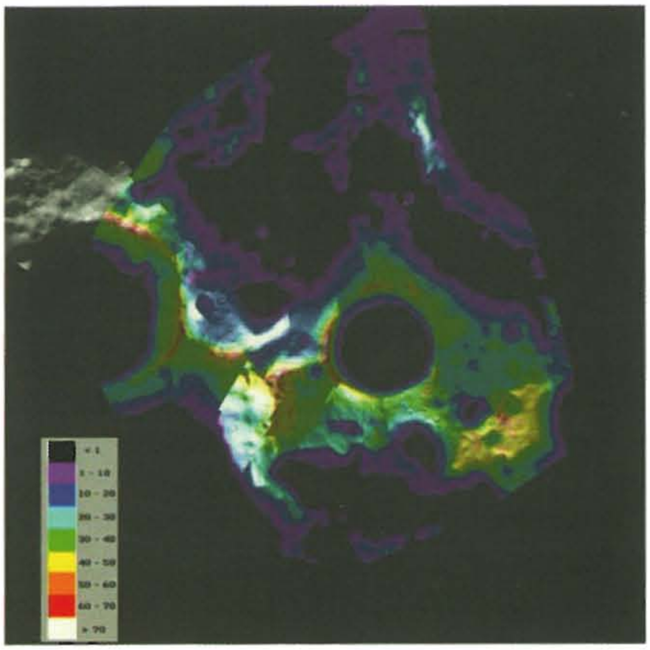

Figure 16. Data obtained during southern winter (maximum darkness).

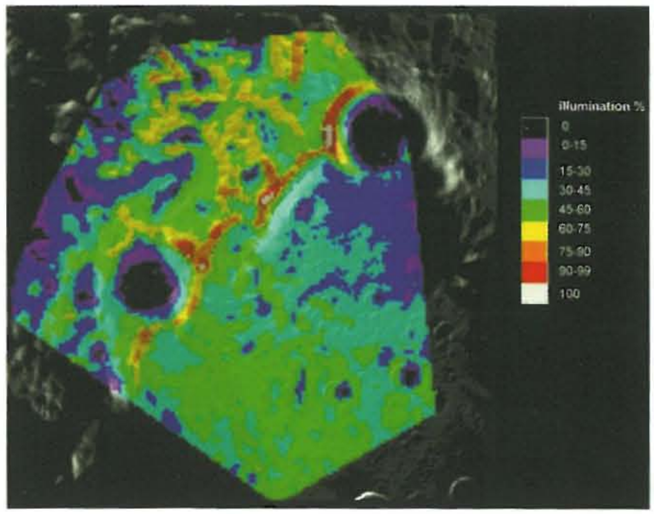

Figure 17. Data obtained during northern summer (maximum sunlight).

range of topography (16 km) equal to that of the Earth, it's dynamic opposite. On the Moon, this topographic range is caused entirely by the preservation of the very largest impact craters (basins) from the earliest stages of lunar history. The Clementine topography has verified the existence of many suspected, degraded impact basins and allowed us to discover many more. We now believe that 51 basins (impact features greater than 300 km in diameter) exist on the Moon, up from about 40 mapped from the previous, incomplete image data. Some basins postulated to exist from earlier mapping (e.g., the gigantic Procellarum basin on the western near side) are not evident in Clementine topography and either have a more complex form than previously thought or do not exist.

Clementine gave us our first clear, systematic look at the poles of the Moon and showed us that these regions are extremely interesting from a variety of perspectives. We saw that the extent of permanently dark areas around the poles may be significantly greater than previously estimated; at the south pole, Clementine mapping suggests over 30,000 km^2 of permanent shadow (Nozette *et al* 2001). In addition to finding permanent shadow, the Clementine images have also shown us that some regions near both poles (figures 16, 17) may be in near-permanent sunlight (Bussey *et al* 1999, 2004). Such areas are significant targets for future surface exploration not only because one may use solar power almost continuously, but such regions are thermally benign, never seeing either the searing heat of lunar noon (100°C) nor the numbing cold of lunar midnight (−150°C) on the equator (Spudis *et al* 1995).

6.1 *Bistatic radar experiment*

Although Clementine did not carry any instruments specifically designed to look into these shadowed regions, a simple radio mapping experiment was improvised in real time during the mission to test the hypothesis that water ice deposits might exist in these areas (Nozette *et al* 1996). As Clementine shifted its periselene from 30°S to 30°N for the second month of mapping, the spacecraft antenna was pointed directly at the pole of the Moon, beaming continuous wave RF into the polar areas (figure 18). During this time, the DSN 70 m dish received the echoes, in two polarization channels. Ice and dirt have distinct RF scattering properties, specifically, ice is partly transparent to RF, resulting in absorption and multiple scattering. The net effect of the presence of ice is to reflect some RF back in the same sense of polarization as was transmitted. During orbit 234 the RF groundtrack went directly through the polar dark areas (figure 19), returning a low SNR enhancement of same sense signature (figure 20). This observation is consistent with the presence of ice (Nozette *et al* 1996, 2001). Although this interpretation was questioned (e.g., Stacy *et al* 1997; Simpson and Tyler 1999), the subsequent Lunar Prospector mission found a strong neutron deficiency at the south pole, which was interpreted to indicate the presence of hydrogen. Such hydrogen deposits are consistent with the presence of ice in these

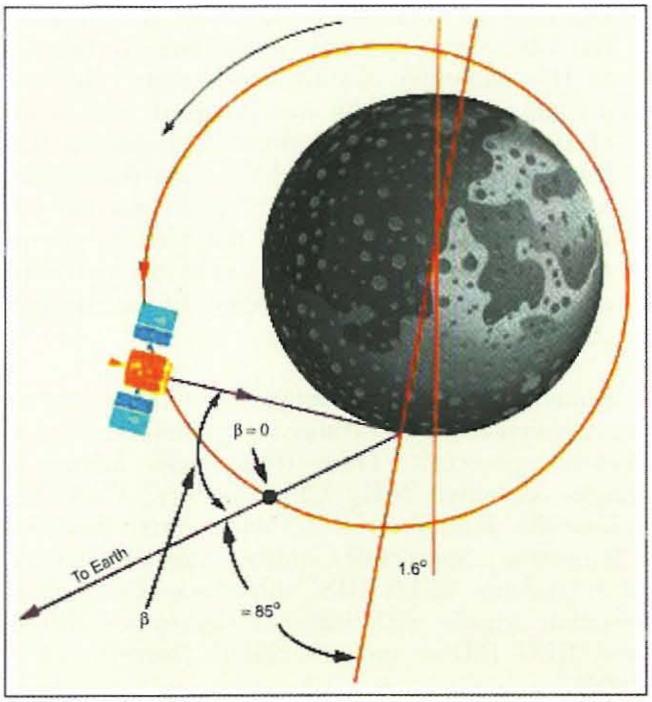

Figure 18. Bistatic radar experiment geometry.

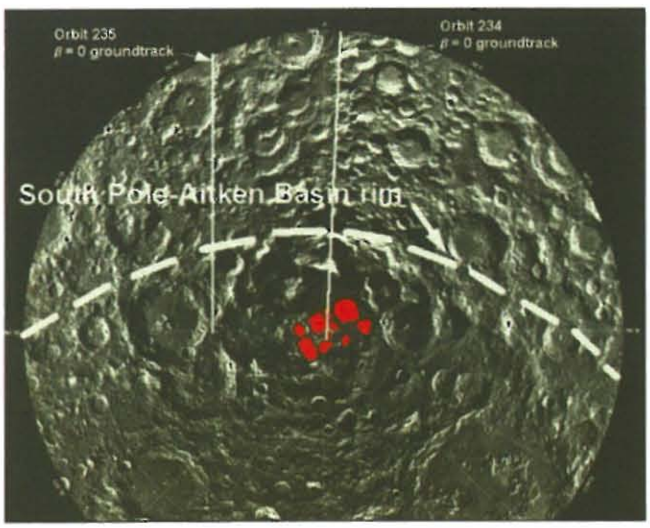

Figure 19. Orbit 234 track over permanently shadowed craters (red) at lunar south pole.

regions (Feldman *et al* 2001). Though tantalizing, the existing data cannot definitively determine the cause of the polarization or neutron anomalies. A prime objective of the Chandrayaan mission (2007) is to map polar anomalies at scales of 100 meters with the mini-SAR experiment (Spudis *et al* 2005). Such data will be the first step in determining the nature of these enigmatic deposits, and will be critical for future landed missions that could finally characterize the polar anomalies.

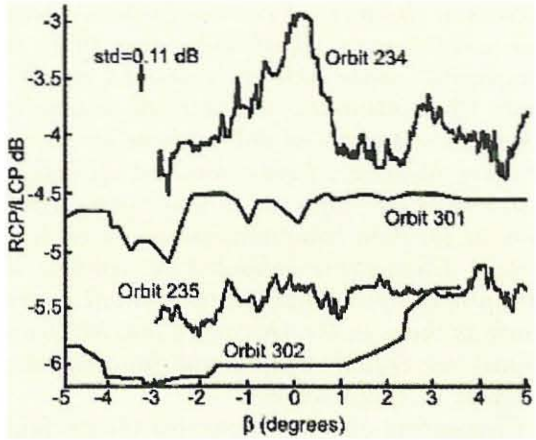

Figure 20. Polarization signature indicating presence of ice on orbit 234.

7. The Clementine legacy

The Clementine mission was highly successful due to its innovative approach to planetary exploration. It demonstrated that a successful collaboration between DoD and NASA is possible and mutually beneficial. It proved strategic technology demonstrations can obtain meaningful science data, including the first global multispectral map of the Moon, near global altimetry, and the characterization of polar deposits. The Clementine team demonstrated a streamlined method of space project management and science mission operations, including the first onboard autonomous operations demonstration. And it demonstrated the effectiveness of several new lightweight technologies, many of which are now in common use.

The reasons for Clementine's success (and ultimate failure) and the significance of the Clementine mission to future missions was stated by a report on the lessons learned from the Clementine mission by the Space Studies Board of the National Research Council (COMPLEX, 1997):

"The mission's success rested to a considerable degree on the operational team's substantial freedom to make decisions and on the easy access to technology already developed. The tight time schedule forced swift decisions and lowered costs, but also took a human toll. The stringent budget and the firm limitations on reserves guaranteed that the mission would be relatively inexpensive, but surely reduced the mission's capability, may have made it less cost-effective, and perhaps ultimately led to the loss of the spacecraft before the completion of the asteroid flyby component of the mission.

For the most part, within its constrained lunar science objectives, Clementine was *successful. Because of various factors. Clementine's costs were significantly less than most comparable space science missions might be. Since Clementine was not planned originally as a science mission and did not have science as a primary objective, funds were not allocated for instrument development and scientific calibration. or for data reduction and analysis. Nevertheless, Clementine validated the concept that, with proper operational profiles, small missions (such as those in the Discovery and MidEx programs) are capable of accomplishing significant research in space science.*

Clementine also demonstrated the usefulness to space science of missions emphasizing the testing of innovative technologies, fresh management styles, and new approaches to spacecraft operations. Future missions of this type should be initiated provided that they are capable of achieving first-class science and that the scientific community is actively involved in them as early as possible.

The extent to which traditional NASA programs could or should follow this model is unclear at present. What is clear is that Clementine provides an existence proof that a small team of non-NASA researchers can successfully assume the overall responsibility for a deep-space mission."

There are some anecdotal events that have occurred since the end of the Clementine mission that have demonstrated its importance and legacy:

- In 1994, a JPL mission operations manager visited the DMOC in Alexandria, Virginia and was so impressed with what he saw that he sent a senior operations software engineer there a few weeks later to obtain ideas on improving their operations software (Wilson 1994).
- At the Small Satellites Conference at Utah State University in 1995, a team from JPL reported how the lessons learned from Clementine could benefit planned missions to Pluto (Carraway *et al* 1994).
- NASA JPL Director, Edward Stone, stated that he considered Clementine to be the first 'faster, better, cheaper' mission espoused by then NASA Administrator, D Goldin, and that JPL used Clementine as the standard to which they compared new missions (Stone 2000).
- The innovative mission operations used in Clementine affected current NASA missions, as stated by the Stardust Project Manager: 'JPL and NASA inherited some of (Clementine's) processes and procedures for low cost mission operations under the Discovery Program' (Duxbury 1997).
- Dr. Eugene Shoemaker, who was the head of the Clementine Science Team, was a stalwart in the planetary science community. He was a lunar geologist who was involved with most of the NASA lunar missions, including Lunar Ranger and Apollo (he helped train the Apollo astronauts in lunar geology). At a conference in 1995, he stated that he had not seen an operation team be so responsive to the science team as the Clementine team since Lunar Ranger (Shoemaker 1995).

Many of the new lightweight technologies tested on Clementine have come into common use in today's spacecraft. These technologies include a single container NiH_2 CPV battery, GaAs/Ge solar cells, Frangibolt^{TM} actuators (first flown on Clementine), Spacecraft Control Language, WFOV star trackers, 32-bit RISC processor, lightweight reaction wheels with internal electronics, IFOG and RLG IMUs, and the SSDR (Nozette *et al* 1994).

7.1 *The science legacy*

Scientific results from the Clementine mission dramatically shifted current thinking on the origin and evolution of the lunar crust. We now perceive the Moon as a complex little planet, with a unique and complex early evolution. Its crust is composed of myriad rock units, emplaced over a prolonged period of time. Its long history of basin formation and evolution hides subtle complexities of which we were previously unaware. The amazing polar regions not only contain a unique environment in near-Earth space (i.e., permanently illuminated areas), with unusual thermal properties, but the dark areas may contain the materials needed for humanity to gain a foothold off the Earth – billions of tones of water ice, available for use as human life support and to make rocket propellant to make traveling to and from the Moon much easier and more routine.

8. Conclusions

8.1 *Spacecraft*

The Clementine spacecraft was designed, built, tested, and launched within 22 months – a remarkable short period of time for such a sophisticated spacecraft incorporating many new technologies being flown for the first time. Although the short development cycle resulted in low program cost, it did extract a cost in the preparedness of the software and mission operations, and especially the personnel involved. This lack of time for thorough development and testing of the software was a major contributor to the failure that resulted in the loss of the asteroid flyby. Despite this ultimate failure, the mission is widely regarded as a success because of the rich harvest of science obtained, mostly in lunar orbit, and for the performance of the new technologies in a stressful environment. Despite some minor anomalies that occurred during various phases of the mission, the post-mission workshop held at Lake Tahoe in July 1994 revealed that on the whole the spacecraft performed very well and most of the new technologies met or exceeded expectations, thus helping to flight qualify them for use on future missions (Regeon *et al* 1994).

8.2 *Mission operations*

Based on the science data obtained and the opinions expressed by several Science Team members who had participated in several other planetary missions, the Clementine method of science mission planning and operations was highly effective despite the small number of personnel and resources involved. Features of the Clementine operations methodology that greatly improved the effectiveness of the science mission operations were: the direct participation of the Science Team; the highly qualified personnel that were responsible for science and sensor operations and had contact with the Science Team; the empowerment of the operations personnel to make and change timelines and command sequences without review by upper management; and the rapid response time brought about by the ability to make changes in command sequences only hours or minutes before their execution. Many lessons were learned from Clementine that may benefit future small, focused operations. The greatest aid to efficient mission operations will be the incorporation of autonomous operations scheduling, which was demonstrated so successfully by Clementine. If this system had been operational for the entire mapping mission, then the work load on the SMOP and supporting flight software team would have been greatly reduced, resulting in fewer errors and more time to plan special observations and experiments. All repetitive mapping sequences could be done automatically by the spacecraft, requiring only monitoring of the operation and periodic state vector updates to the spacecraft. The Command Script Generator program, when fully implemented, would also increase the productivity and accuracy of building timelines and command scripts for non-standard observations or experiments. Clementine showed that automation is critical for extended operations. The small, but talented, Clementine operations team would have expired if the lunar mission had lasted much longer without the introduction of extensive automation. This also points out a shortcoming of the Clementine project that will hopefully be a 'lesson learned' for future missions. If the Clementine mission had more time or money to complete the planning and analysis tools beforehand, the mission would have run smoother, there would have been fewer errors, and the pace could have been maintained for a longer mission. However, probably the most important lesson to be learned from the Clementine mission was that a small focused team *can successfully* run a complex mission, but adequate resources must be provided if any longevity is required.

8.3 *Science*

The Clementine mission demonstrated that significant scientific exploration can be achieved on a mission primarily designed as a technology demonstration testbed. The science data returned by Clementine (approximately 330 Gbits total) has revolutionized our knowledge and appreciation of lunar history and evolution. Clementine gathered a data set still actively studied by the science community and yielding new insights into lunar processes and history. The discovery of the unique environments of the lunar poles, and the probable discovery of water ice in the dark regions there are findings of enormous significance to humanity's future on the Moon and in space in general. Clementine demonstrated that fast-track, new technology missions can be scientifically productive. The Science Team and Mission Operations team worked in tandem in a high pressure environment, pulling off complex observations and changing experimental conditions in real time. The Clementine mission showed the enormous scientific potential of small, highly focused missions – an example that NASA later adopted as the 'faster, better, cheaper' approach to space exploration.

References

Bussey D B J, Spudis P D and Robinson M S 1999 Illumination Conditions at the Lunar South Pole; *Geophys. Res. Lett.* **26(9)** 1187.

Bussey D B J, Robinson M R, Fristad K and Spudis P D 2004 Permanent Sunlight at the Lunar North Pole; *Lunar Planet. Sci.* XXXV CD-ROM 1387.

Carraway J, Henry P, Herman M, Kissel G, Price H, Staehle R and Underwood M 1994 Lessons Learned from Clementine on the Way to Pluto; Proceedings of the AIAA/USU Conference on Small Satellites AIAA Washington DC.

COMPLEX (Committee on Planetary and Lunar Exploration; Space Studies Board; Commission on Physical Sciences Mathematics and Applications; National Research Council) 1997 Lessons Learned From The Clementine Mission; *National Academy of Science*, Washington DC.

Duxbury T 1997 Personal Communication (July).

Feldman W C, Maurice S, Lawrence D J, Little R C, Lawson S L, Gasnault O, Wiens R C, Barraclough B L, Elphic R C, Prettyman T H, Steinberg J T and Binder A B 2001 Evidence for Water Ice Near the Lunar Poles; *J. Geophys. Res.* **106 E10** 23,231–23,251.

Gillis J J and Spudis P D 2000 Geology of the Smythii and Marginis Region of the Moon Using Integrated Remotely Sensed Data; *J. Geophys. Res.* **105 E2** 4217–4233.

Horan D M and Regeon P A 1995 Clementine – A Mission to the Moon and Beyond; *1995 NRL Review*, Naval Research Laboratory, Washington DC, pp. 45–57.

Jolliff B L, Gillis J, Haskin L, Korotev R and Wieczorek M 2000 Major Lunar Crustal Terranes: Surface Expressions and Crust-Mantle Origins; *J. Geophys. Res.* **105 E2** 4197–4216.

Kaufman B, Middour J and Richon K 1995 Mission Design of the Clementine Space Experiment; AAS Paper 95–124 *Spaceflight Mechanics 1995 Advances in the Astronautical Sciences* **89(1)** 407–422.

Lucey P G, Spudis P D, Zuber M, Smith D and Malaret E 1994 Topographic-Compositional Units on the Moon and the Early Evolution of the Lunar Crust; *Science* **266** 1855–1858.

Lucey P G, Taylor G J and Malaret E 1995 Abundance and Distribution of Iron on the Moon; *Science* **268** 1150–1153.

Lucey P G, Taylor G J, Hawke B R and Spudis P D 1998 FeO and TiO_2 Concentrations in the South Pole–Aitken Basin: Implications for Mantle Composition and Basin Formation; *J. Geophys. Res.* **103 E2** 3701–3708.

Lucey P G, Blewett D and Jolliff B 2000 Lunar Iron and Titanium Abundance Algorithms Based on Final Processing of Clementine UV-Vis Images; *J. Geophys. Res.* **105 E8** 20,297–20,305.

Nozette S *et al* 1994 The Clementine Mission to the Moon: Scientific Overview; *Science* **266** 1835–1839.

Nozette S, Lichtenburg C, Spudis P D, Bonner R, Ort W, Malaret E, Robinson M and Shoemaker E M 1996 The Clementine Bistatic Radar Experiment; *Science* **274** 1495–1498.

Nozette S, Spudis P D, Robinson M, Bussey D B J, Lichtenberg C and Bonner R 2001 Integration of Lunar Polar Remote-Sensing Data Sets: Evidence for Ice at the Lunar South Pole; *J. Geophys. Res.* **106 E19** , 23,253–23,266.

NRC Space Studies Board 2003 New Frontiers in the Solar System: An Integrated Exploration Strategy; National Research Council, Washington DC, pp. 54–60.

Pieters C M, Head J W, Gaddis L, Jolliff B and Duke M 2001 Rock Types of the South Pole–Aitken Basin and the Extent of Volcanism; *J. Geophys. Res.* **106 E11** 28,001–28,022.

Rajmon D and Spudis P 2004 Distribution and Stratigraphy of Basaltic Units in Maria Tranquillitatis and Fecunditatis: A Clementine Perspective; *Meteor. Planet. Sci.* **39(10)** 1699–1720.

Regeon P A and Chapman R J 1994 CLEMENTINE: New Directions and Perspectives for One-of-a-Kind Spacecraft Missions; Proceedings of the AIAA/USU Conference on Small Satellites AIAA Washington DC.

Regeon P A, Chapman R J and Baugh R 1994 CLEMENTINE – The Deep Space Program Science Experiment, International Academy of Astronautics, Paper IAA-L-0501 Low Cost Planetary Missions Conference, Laurel MD.

Robinson M S 2005 Clementine: A Scientific Summary; *International Lunar Conference 6*, Udaipur, India.

Robinson M S and Jolliff B 2002 Apollo 17 Landing Site: Topography Photometric Corrections and Heterogeneity of the Surrounding Highland Massifs; *J. Geophys. Res.* **107 E11** doi:101029/2001JE001614.

Rustan Lt Col P L 1994 CLEMENTINE: An Experiment to Flight Qualify Lightweight Space Technologies; *EOS Transactions American Geophysical Union* **75(15)** 161–165.

Shoemaker E 1995 Personal Communication (February).

Simpson R A and Tyler G L 1999 Reanalysis of Clementine Bistatic Radar Data from the Lunar South Pole; *J. Geophys. Res.* **104 E2** 3845–3862.

Sorensen T C 1995 Global Mapping by the Clementine Spacecraft; AAS Paper 95-127 *Spaceflight Mechanics 1995, Advances in the Astronautical Sciences* **89(1)** 457–476.

Sorensen T C *et al* 1995a Effective Science Mission Planning and Operations – The *Clementine* Approach Paper RALGS31 1st Annual Reducing the Cost of Space Ground Systems and Operations Symposium; Rutherford-Appleton Laboratories.

Sorensen T C, Oswald D C, Shook R M and Van Gaasbeck J 1995b Spacecraft Autonomous Operations Experiment Performed During the Clementine Lunar Mission; *J. Spacecraft and Rockets* **32(6)** 1049–1053.

Spudis P D 1993 *The Geology of Multi-ring Basins: The Moon and Other Planets* (New York and Cambridge: Cambridge University Press) 263 pp.

Spudis P D, Reisse R A and Gillis J J 1994 Ancient Multi-Ring Basins on the Moon Revealed by Clementine Laser Altimetry; *Science* **266** 1848–1851.

Spudis P D, Stockstill K R, Ockels W J and Kruiff M 1995 Physical Environment of the Lunar South Pole from Clementine Data: Implications for Future Exploration of the Moon; *Lunar Planet. Sci.* **XXVI** 1339–1340.

Spudis P D, Bussey D B J, Lichtenberg C, Marinelli B and Nozette S 2005 Mini-SAR: An Imaging Radar for the Chandrayaan 1 Mission to the Moon; *Lunar Planet. Sci.* XXXVI CD ROM 1153.

Stacy N J S, Campbell D B and Ford P G 1997 Arecibo Radar Mapping of the Lunar Poles: A Search for Ice Deposits; *Science* **276** 1527–1530.

Stone E 2000 Personal Communication (November).

Wilhelms D E 1987 The Geologic History of the Moon; US Geol. Survey Prof. Paper 1347, 300 pp.

Wilson R 1994 Personal Communication (June).

Worden Col S P 1992 The Strategic Defense Initiative Organization CLEMENTINE Mission; Proceedings of the Near-Earth-Object Interception Workshop Jan 14–16 1992.