The Clementine Satellite

The Clementine satellite tested 23 advanced technologies during its mission for the Ballistic Missile Defense Organization. In fulfilling its scientific goals, Clementine provided a wealth of information relevant to the mineralogy of the lunar surface. Using six on-board cameras designed and built at the Laboratory, Clementine mapped the entire surface of the Moon at resolutions never before attained. Clementine also provided range data that will be used to construct a relief map of the lunar surface.

THE first U.S. satellite to the Moon in more than two decades was launched from Vandenberg Air Force Base (Santa Barbara County), California, on January 25, 1994. The satellite (Figure 1) was named Clementine because it carried only enough fuel to complete its mission before it was "lost and gone forever," as in the old ballad "My Darling Clementine."

The satellite orbited the Moon for more than two months beginning February 19, taking and transmitting high-resolution pictures and range data until it built up a detailed map of the entire lunar surface. Clementine completed its lunar orbit on May 3, 1994, sending back more than 1.5 million images of the Moon.

The Planned Mission

Clementine's primary mission was to demonstrate in the harsh environment of space advanced, lightweight technologies developed by the Department of Defense for detecting and tracking ballistic missiles. Its sensor suite consisted of six state-of-the-art cameras, and the basic system included many other new lightweight technologies, such as inertial measurement units, reaction wheels, a battery, a computer, and a solid-state recorder. Clementine used the Moon and the spacecraft's own solid-rocket motor (after it separated from the satellite) as targets to demonstrate how the lightweight components and sensors would perform during flight.

Clementine's secondary mission—and the main focus of this article—was to return valuable information of interest to the scientific community. Clementine represents a new class of small, low-cost spacecraft suitable for long-duration missions into deep space. In this respect, it can open the door to new scientific missions, such as planetary exploration, that are much more cost-effective and have a quicker return of data. Moreover, Clementine completely mapped the lunar surface in 14 discrete spectral bands ranging from the near ultraviolet (0.415 μm), through the visible spectrum, to the far infrared (9.5 μm). Although Clementine involved the participation of many organizations and had several different objectives (see the box on p. 2 for more details), the primary objective was to test the optical sensors developed by LLNL.

The last phase of the scheduled mission was to be a flyby of the near-Earth asteroid Geographos, which is about 5 km long and crosses Earth's orbit about every 18 months. Even though near-Earth asteroids tend to be much larger than missiles, Geographos would have provided a meaningful target as Clementine attempted a near-miss intercept using the new sensor technologies. This flyby was also expected to provide the first close-up view of an Apollo asteroid and spectral information relevant to its surface geology. The combined lunar and asteroid data would add to our knowledge of the solar system and its evolution.

After successfully mapping the Moon, Clementine left lunar orbit and began its journey to Geographos on May 5. On May 7, however, one of the on-board processors failed and turned on the attitude-control thrusters, which sent the spacecraft into a spin (81 revolutions/minute). That failure drained the attitude-control system of its fuel (although there was still fuel for the main thruster), effectively canceling the Geographos portion of the mission. At this angular velocity, Clementine could still have flown to Geographos, but it would not have sent back useful images, and contact with it probably would have been lost. As a result, Clementine spent its final days orbiting Earth, continuing to collect lifetime data on the new on-board technologies. Although the asteroid portion of the mission was not completed, the principal instruments and sensors functioned extremely well, and Clementine is viewed as a landmark project in terms of cost effectiveness and its demonstration of next-generation components and technologies.

Some Facts About Clementine

Clementine is a Department of Defense program to demonstrate a new generation of technology for both military and civilian space applications. Clementine is also known as the Deep Space Program Science Experiment. It is the first in a series of technology demonstrations sponsored by the Ballistic Missile Defense Organization—formerly called the Strategic Defense Initiative Organization.

Clementine is an example of one of the "smaller, cheaper, faster" satellites. Despite a degree of technical risk, this approach showed that data could be returned promptly from the lunar surface without the large monetary and time investment required of a more traditional approach.

The total cost of the project, including mission control and the launch vehicle, was $75 million. In this respect, Clementine is a landmark satellite because it demonstrates that small, highly capable satellites can be built and launched for under $100 million using advanced, miniaturized technology and a streamlined management approach.

The total time from initial concept to launch of the satellite was about 22 months. This time included hardware design, procurement and fabrication, assembly, integration, and test. This short development time was made possible because a dedicated team was responsible for all phases of the effort and followed the satellite's development from concept to launch and operation.

The Naval Research Laboratory designed, fabricated, integrated, and operated the spacecraft. NASA's Goddard Space Flight Center and the Jet Propulsion Laboratory provided design support. The NASA Deep Space Network helped the Naval Research Laboratory track and communicate with Clementine. Lawrence Livermore National Laboratory designed, developed, and calibrated the suite of on-board Clementine imaging and ranging sensors.

The launch vehicle was a Martin Marietta Titan IIG ballistic missile. It carried two experiments into space: the Clementine satellite for lunar mapping, and a solid-rocket motor containing several radiation detectors to take measurements in Earth's radiation belts. The rocket motor is expected to orbit Earth for more than a year, passing through the radiation belts twice per orbit. In addition to using celestial bodies as imaging targets, Clementine also tracked and imaged the rocket motor as a test of the missile-imaging capability of the sensor suite.

In launch configuration, Clementine had a total mass of 1690 kg, including the solid-rocket motor. The dry mass of the satellite was 228 kg, and it carried 200 kg of fuel.

Launch and the Orbit Path

The launch vehicle for Clementine was a refurbished Martin Marietta Titan IIG ballistic missile, which carried one other experiment in addition to the Clementine satellite. On December 29, 1993, Clementine was delivered to Vandenberg Air Force Base for integration to the Titan IIG launch vehicle and was launched on January 25, 1994.

Clementine followed a complicated path on its way to the Moon. To minimize the amount of required on-board fuel (and, therefore, the total mass of the spacecraft), Clementine completed two and one-half looping orbits about Earth's poles after leaving low-Earth orbit and before going into lunar orbit. Technically known as "phasing" loops, the path consisted of elliptic orbits with a large eccentricity. These phasing loops provided a more precise measurement of the satellite's position and minimized the number of velocity adjustments needed prior to lunar orbit. Figure 2 shows the path of the spacecraft prior to entering lunar orbit.

An on-board solid-rocket motor boosted the spacecraft into its initial phasing loop—with a perigee of 277 km and an apogee of ~170,000 km. This initial phasing loop was also used to insert the solid-rocket motor into its planned orbit. Another firing of the

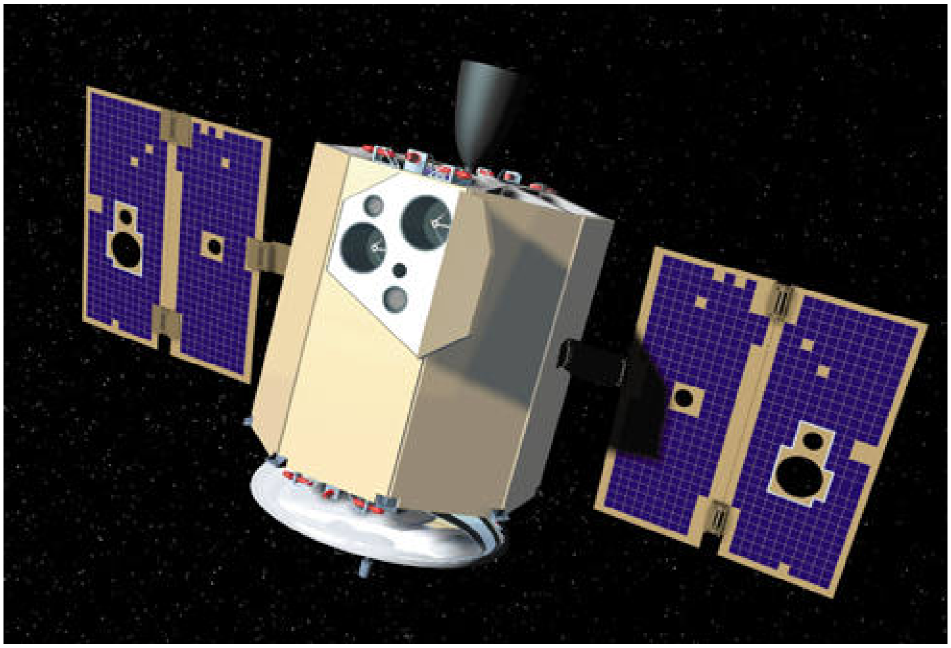


Figure 1. The Clementine satellite was designed to demonstrate performance of lightweight imaging sensors and component technologies developed for the Ballistic Missile Defense Organization. This spacecraft measured 1.88 m in diameter and was 1.14 m long.

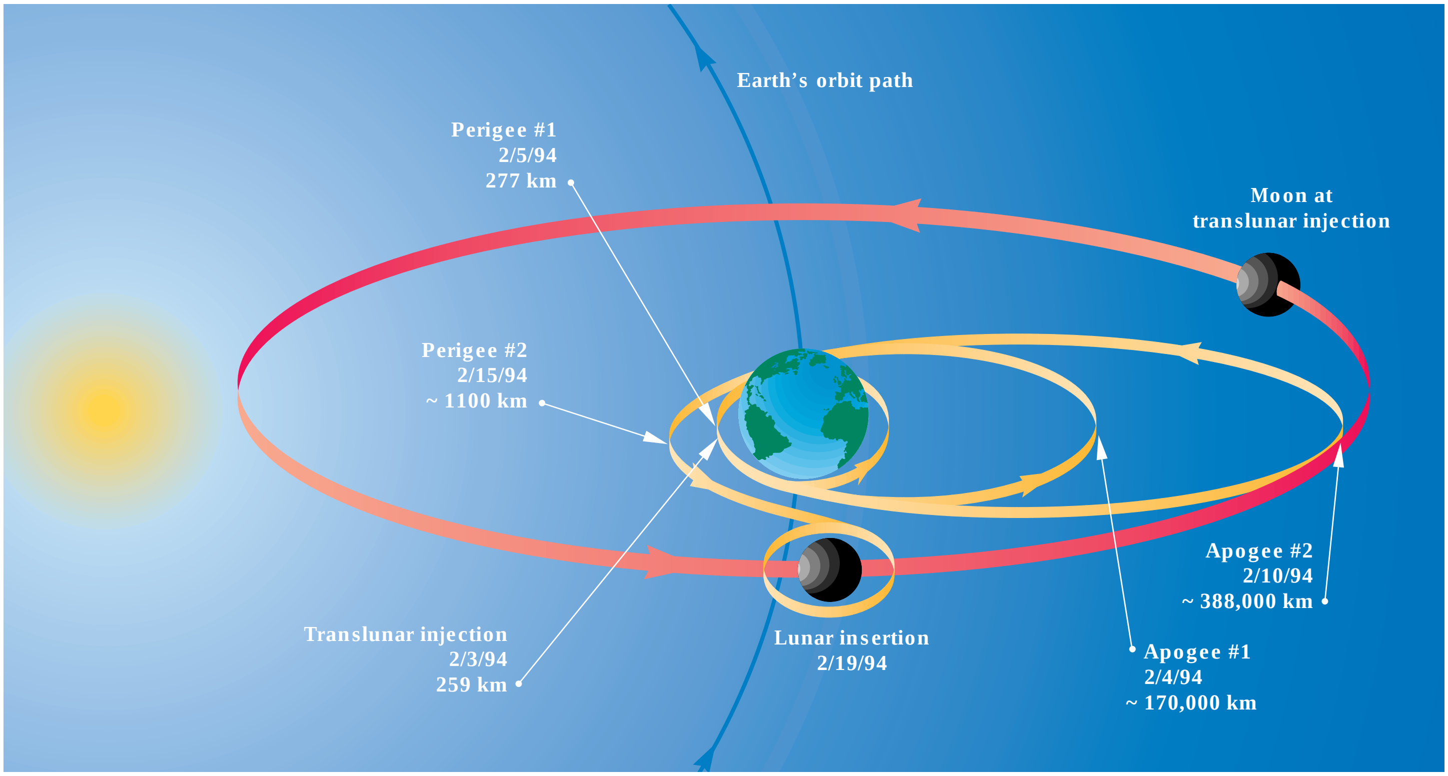


Figure 2. Path of Clementine on its way to the Moon. The spacecraft completed two and one-half phasing loops about Earth's poles before entering lunar orbit.

main thruster boosted the spacecraft into its final phasing loop with an apogee of ~388,000 km.

On February 19, Clementine began its orbit of the Moon. Initially, it was placed in a polar orbit with a period of 5 hours (Figure 3a). During its 70 days of orbit, Clementine's imaging sensors were, for the most part, pointed directly down to the lunar surface as it passed over the sunlit side. To maintain a near constant solar illumination of the surface during imaging, the orbit was adjusted half way through the mapping phase (Figure 3b). To obtain images of surface features under different lighting conditions, the cameras also took images at selected oblique angles. In addition, the cameras took images of the dark space background in order to verify that the camera's dark levels and performance had not changed during the mission.

The Cameras and Sensors

The Laboratory, with the support of its industrial contractors, was responsible for the design, development, and flight qualification of seven lightweight spacecraft sensor components for the Clementine mission. Table 1 lists the mass of each sensor, which altogether totaled only 0.32% of the dry mass of the satellite. Table 2 lists the field of view and the instantaneous field of view (i.e., angular measure of a pixel)

Table 1. Mass of LLNL-developed sensors for the Clementine mission.

Sensor	Mass, kg
Star Tracker 1	0.280
Star Tracker 2	0.286
Ultraviolet/visible camera	0.426
High-resolution camera	1.120
Laser transmitter	0.635
Laser transmitter power supply	0.615
Near-infrared camera	1.880
Long-wave infrared camera	2.075
Total mass of sensors	**7.32**

Table 2. Performance of LLNL-developed sensors for the Clementine mission.

Sensor	Field of view, deg × deg	Instantaneous field of view, μrad	Image size, km × km*	Resolution, m*,†
Star Tracker	28.9 × 43.4	1.31 × 1.31	–	524
Ultraviolet/visible camera	4.2 × 5.6	255	29.30 × 39.10	108
High-resolution camera	0.3 × 0.4	18	2.09 × 2.97	8
Near-infrared camera	5.6 × 5.6	396	39.12 × 39.12	168
Long-wave infrared camera	1.0 × 1.0	143	6.98 × 6.98	61

*Image size and resolution are based on periselene (closest approach) of 400 km.
†Theoretical limit.

(a) Typical lunar mapping orbit—first month

(b) Typical lunar mapping orbit—second month

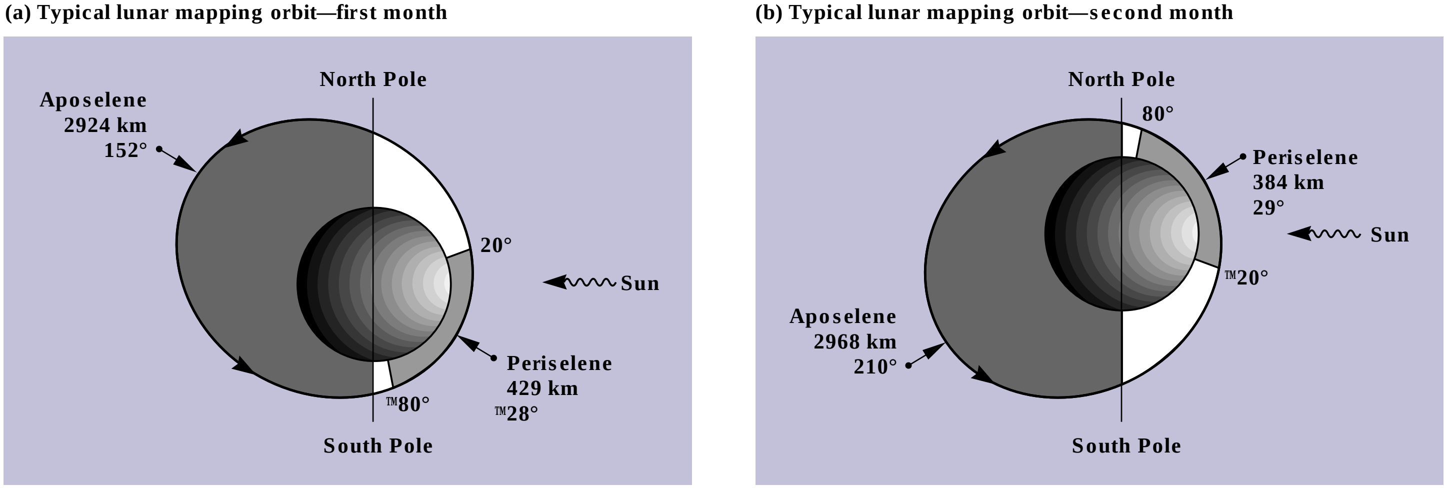


Figure 3. Typical lunar orbits during the first (a) and second (b) months of mapping. The orbit was adjusted to maintain a near constant solar illumination of the surface during imaging. The Clementine satellite orbited the Moon from the South Pole to the North Pole, obtaining optimal range measurements between –80 deg and +80 deg latitude (light shading) and images between –90 deg and +90 deg latitude (white). Also shown are the aposelene (farthest approach) and periselene (closest approach) of the satellite to the Moon.

of each camera on board the spacecraft. Also listed are the areal coverage and the theoretical resolution for each sensor at a close approach to the Moon.

Altogether, Clementine's sensor package imaged the Moon in 14 selectable, narrow-wavelength bands ranging from 0.415 µm to 9.5 µm. The cameras were equipped with a set of special color filters selected to provide the maximum amount of information about the surface mineralogy of the Moon and Geographos. The images and other data returned from lunar mapping cover 100% of the Moon's surface at spatial resolutions that cannot be obtained from observatories on Earth.

Common rock-forming minerals on the Moon and in meteorites can be identified by color in the visible and infrared portion of the spectrum. Major silicate minerals can be recognized by their absorption of particular colors in the near-infrared from reflected sunlight (see Figure 4). Thus, rocks composed of various amounts of these minerals can be distinguished and mapped by means of the multispectral images taken with Clementine's cameras.

In addition, Clementine's light detection and ranging (LIDAR) system was selected to make detailed measurements of the relative heights of features on the Moon. The information it provided will be used to develop a three-dimensional map of a selected portion of the lunar surface.

Wide-Field-of-View Star Trackers

Two units on Clementine, called Star Tracker Stellar Compasses, provided inertial reference for the Clementine spacecraft by comparing images of star fields with an on-board star map. The two Star Trackers were designed, tested, and built by the Laboratory and its contractors. The Star Tracker is a digital camera and

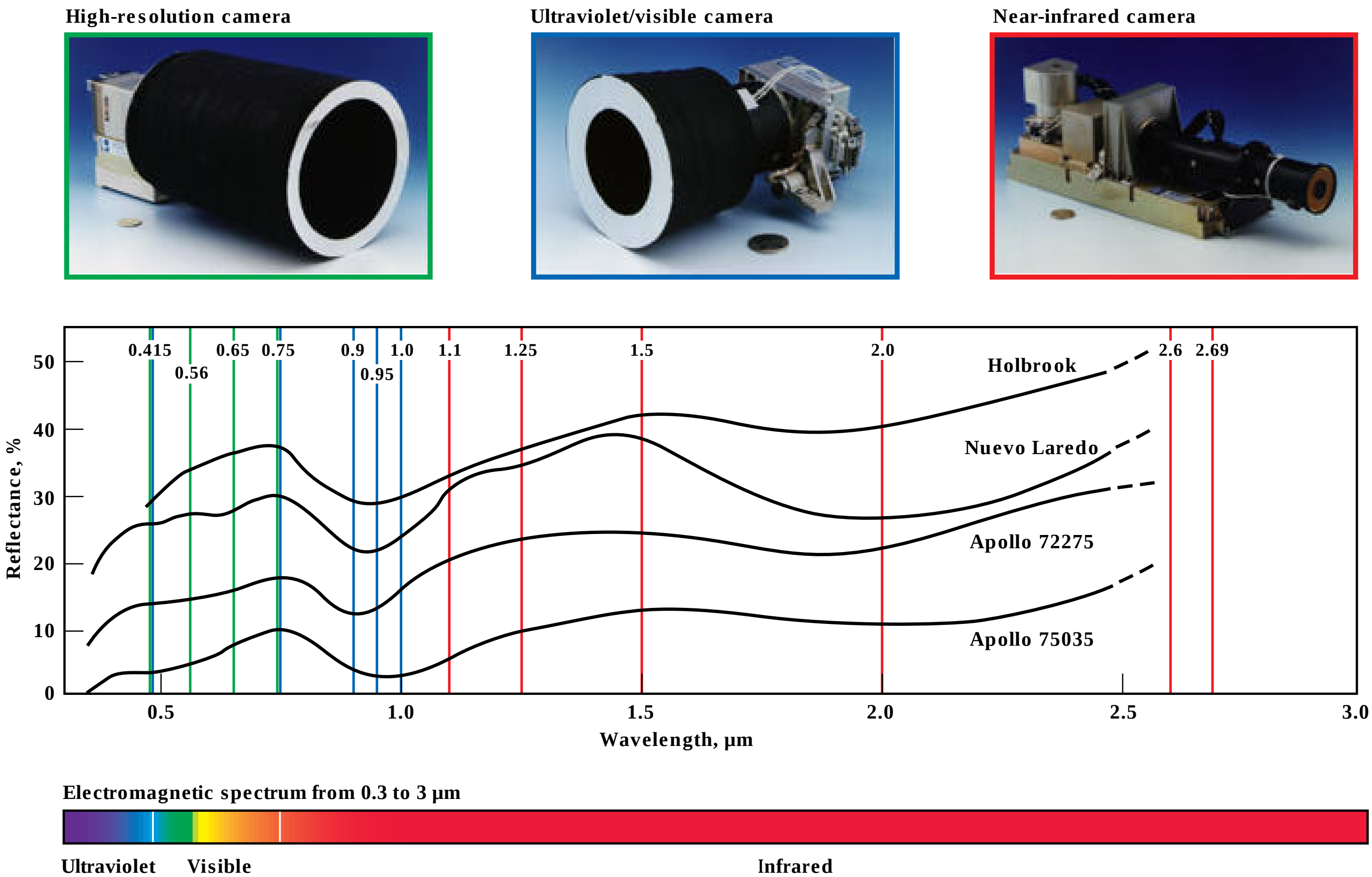


Figure 4. The graph shows the diffuse reflectance of samples of extraterrestrial materials as a function of wavelength. These samples, returned to Earth from various space missions, provided us with the wavelengths of interest in designing the cameras and sensors for Clementine. The vertical lines in the graph indicate the center wavelengths of the filters for the cameras, three of which are shown here. The filters used for each camera can be identified by matching the color of the filter line to that of the box surrounding the camera. Also shown is the relevant portion of the electromagnetic spectrum.

weighs only 0.29 kg (Figure 5a). The camera has a wide (29 deg by 43 deg) field of view and can detect stars down to a visual magnitude of 4.5. The camera, in combination with a highly sophisticated star-matching algorithm and an on-board star catalog, provides spacecraft attitude with respect to the celestial sphere.

To use stars for navigating, the star-matching algorithm scans each image obtained, such as the one shown in Figure 5b, and generates a series of triangles using the twelve brightest objects in the image. These triangles are compared to an on-board database of triangles from 500 star positions listed in a whole-sky star catalog. If a candidate star turns out to be some other object, such as a planet that is not in the correct position to be a star, the Star Tracker algorithm ignores the object.

The Star Tracker was also used to image both the Moon and Earth. Figure 6 shows the Star Tracker's view of the airglow of Earth and the light from urban areas. Figure 7 shows a composite of the Moon made from six separate Star Tracker images.

Ultraviolet/Visible Camera

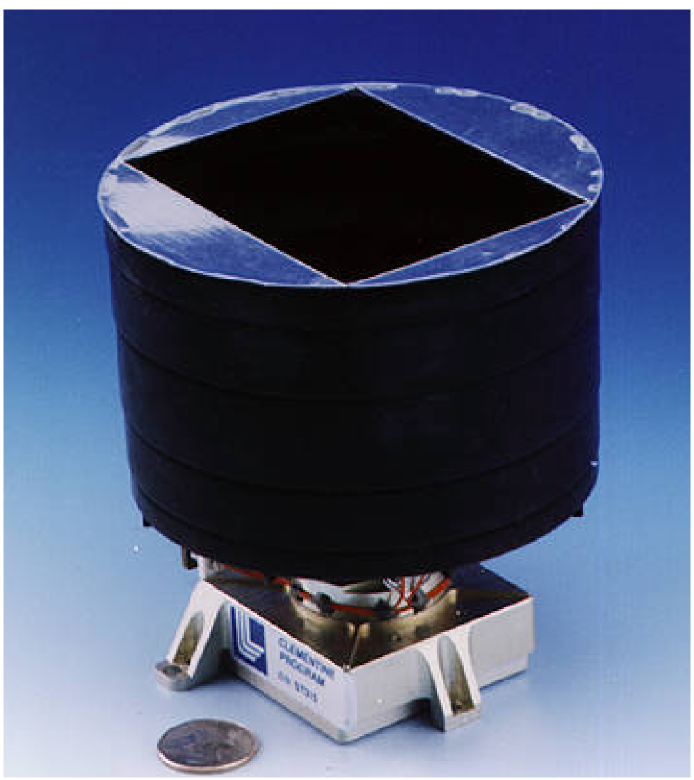
To provide reliable, solid-state, cost-effective imaging in the near-ultraviolet, visible, and near-infrared regions of the spectrum (from 0.3 to 1.0 μm), LLNL designed and built a medium-resolution, 0.426-kg camera that uses silicon charge-coupled device (CCD) technology. For Clementine, this camera was combined with a six-position spectral filter wheel for remote sensing applications and, specifically, for mineral typing studies of the Moon.

Figures 8a through 8e show the African continent imaged by the ultraviolet/visible camera at five different wavelengths on a clear day from a distance of 384,000 km. Figure 8f is a composite view. Figure 9 shows the crater Tycho on the Moon, which is about 80 km in diameter; Figure 10 is an image mosaic of the lunar South Pole showing a dark depression at the center.

Near-Infrared Camera

This 1.9-kg camera, produced by LLNL and Amber Engineering, uses a cryogenically cooled indium–antimonide array to provide solid-state imaging from the near-infrared (0.9-μm) region to the short-wave-infrared (3.1-μm) region at medium resolution. The Laboratory combined the camera with a modular, six-position spectral filter wheel to obtain data in discrete spectral bands.

(a)



(b)

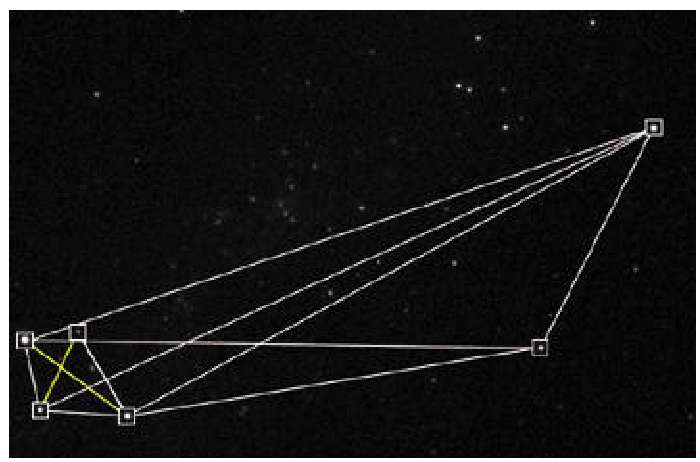


Figure 5. (a) Two Star Tracker Stellar Compasses were used to provide inertial reference for the Clementine satellite. Each Star Tracker weighed only 0.29 kg. (b) This image was taken by the Star Tracker on February 15, 1994, from the Clementine spacecraft during its second loop around Earth prior to lunar orbit. Triangles illustrate how a star match is achieved by comparing the position of detected objects with an on-board database of triangles prebuilt from star positions listed in a whole-sky star catalog. In this case, a match with the Southern Cross constellation, shown in yellow, was achieved.

During the Clementine mission, the spectral bands covered by the near-infrared camera allowed scientists to obtain mineral typing data for 100% mapping of the Moon. Figure 11 shows a view of several lunar craters captured by the near-infrared camera; Figure 12 shows a view of the 35-km-diameter Rydberg crater.

High-Resolution Camera

This 1.1-kg camera operates at visible wavelengths (0.415 to 0.75 μm) with silicon CCD technology combined with a compact, lightweight image intensifier. A six-position, spectral filter wheel provided imagery in discrete spectral bands.

As an example of the camera's capability, Figure 13 shows an image of Earth taken by the high-resolution camera from lunar orbit at 1250 km above the surface of the Moon and at a distance of 384,000 km from Earth. During the lunar-mapping portion of Clementine, the camera produced high-resolution images for mineral typing of the lunar surface.

LIDAR System

The optics of the high-resolution camera also served another purpose on the Clementine mission, namely ranging. (Range measurements in the context of orbiting the Moon are measurements of the distance from the spacecraft to the lunar surface.) The laser-ranging altimeter shared the optics of the high-resolution camera and was used to obtain altitude measurements during mapping orbits around the Moon. The LIDAR was used to determine the relative heights of features on the Moon's surface.

A compact, lightweight, diode-pumped, neodymium, infrared (1.06 μm) laser manufactured by McDonnell Douglas Corporation provided the high-energy pulses (180 MJ) needed for ranging at lunar distances. In essence, the laser transmitter pinged the Moon's surface from an altitude as far as 640 km.

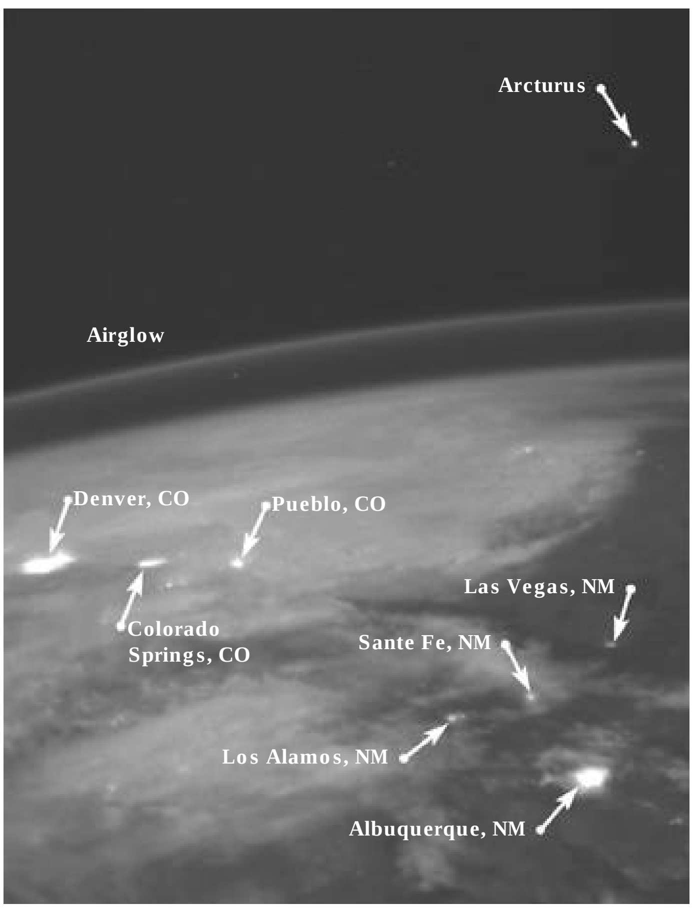


Figure 6. A Star Tracker view of Earth's limb (i.e., outer edge). The airglow caused by Earth's atmosphere and the light from major urban areas are visible.

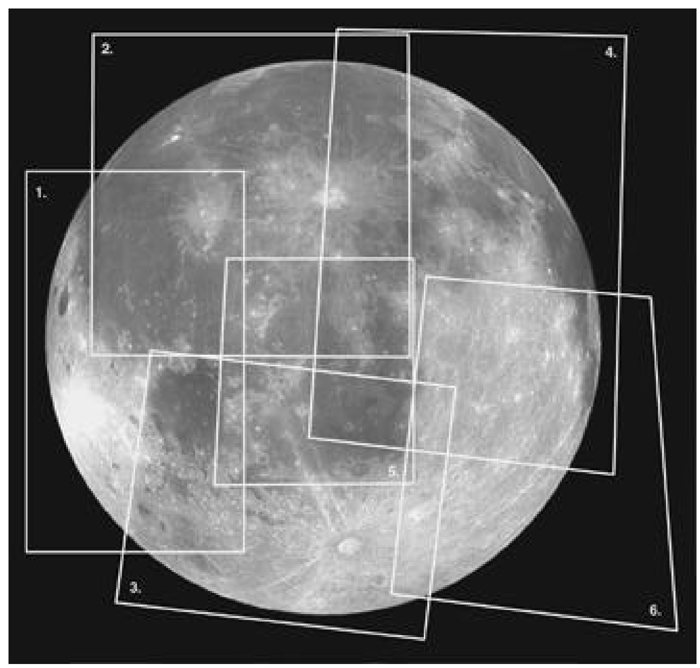


Figure 7. A composite of the Moon made from six separate Star Tracker images.

The LIDAR system took long strings of images with a resolution of about 10 m and range measurements with a precision of ±40 m at intervals of about 1 km. The LIDAR was also operated in burst mode to take up to eight range measurements per second. Near the lunar poles, the high-resolution LIDAR provided detailed pictures of the topography and geologic structure of the lunar surface. Early and late in the lunar mission, it was also used to take mosaics of high-resolution frames covering various Apollo and Surveyor landing sites. Craters up to 12 km deep were discovered during the Clementine mapping, far deeper than previously known.

Long-Wave Infrared Camera

To measure thermal emission from the Moon, LLNL, together with Amber Engineering, developed a small, 2.1-kg, long-wave infrared camera (Figure 14). This camera uses mercury–cadmium–telluride array technology to operate in the thermal infrared region of the spectrum (8 to 9.5 μm). Using a split-cycle cryocooler, the camera operates at 65 K (–208°C).

To appreciate the remarkable imaging capabilities of the cameras we contributed to the Clementine mission, Figure 15 compares a map of the lunar North Pole from the U.S. Geological Survey dating from 1985 with the state-of-the-art images made possible with our new components. An image from the long-wave infrared camera appears at the bottom right corner of this figure.

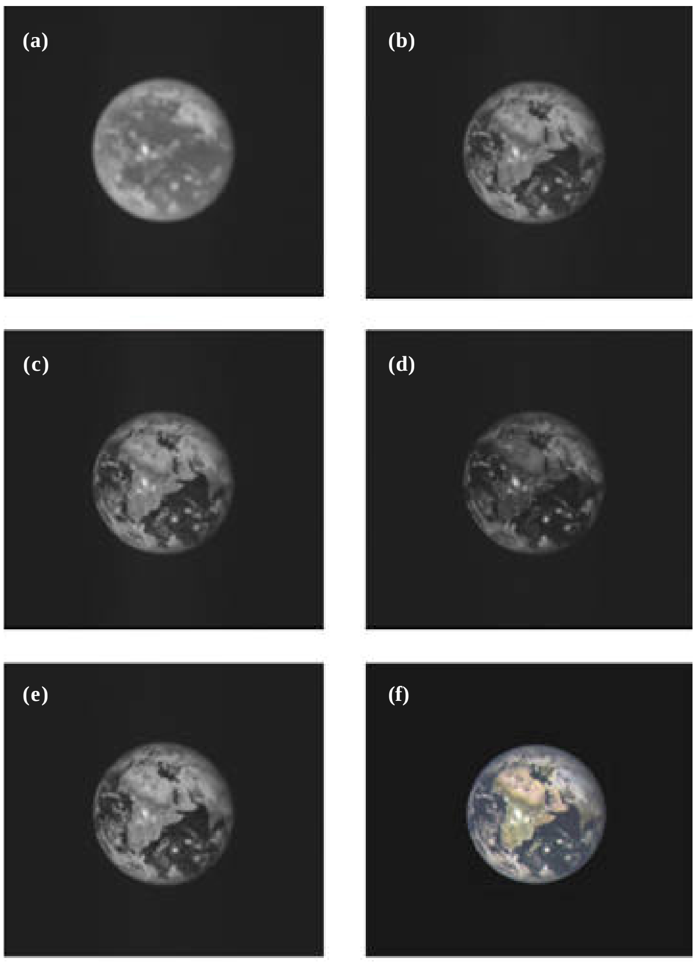


Figure 8. (a) to (e) The African continent on Earth imaged by the ultraviolet/visible camera at five different wavelengths on a clear day, March 13, 1994, from a distance of 384,000 km while Clementine orbited the Moon. (f) A broadband, composite view of the African continent.

Figure 9. The crater Tycho on the Moon, viewed by Clementine's ultraviolet/visible camera on February 28, 1994, from an altitude of 425 km. This image shows reflected sunlight at 1000 nm. The Tycho crater is about 80 km in diameter.

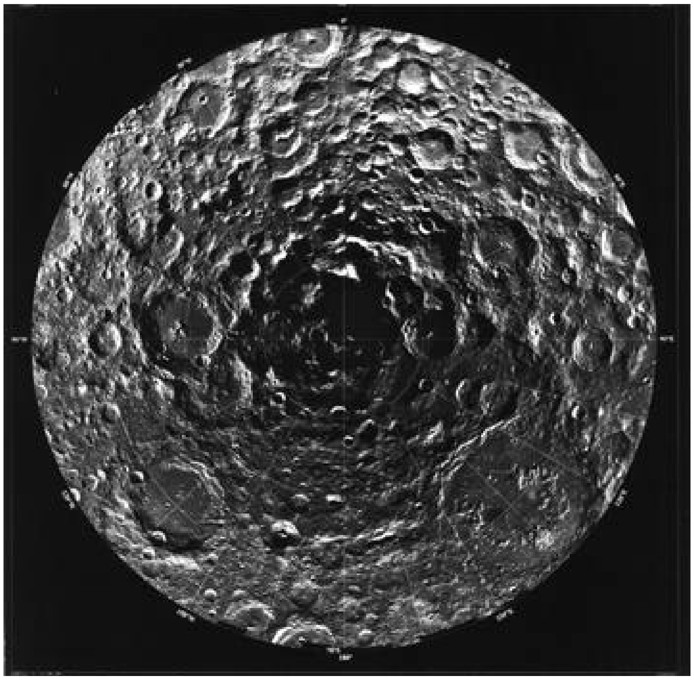


Figure 10. A mosaic of 1500 images taken by the ultraviolet/ visible camera of the lunar South Pole. The images reveal for the first time a 300-km-wide depression near the pole, probably an ancient impact basin, that may never receive sunlight. (Courtesy of NASA, Naval Research Laboratory.)

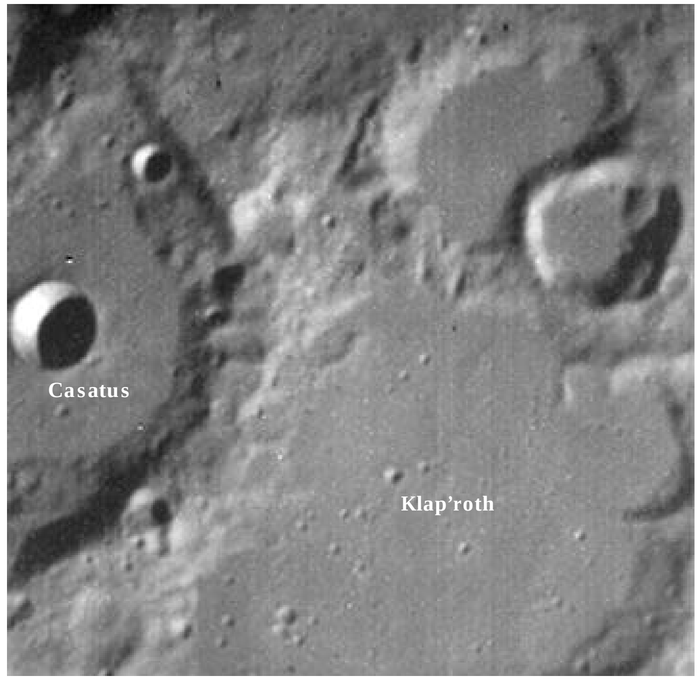


Figure 11. This partial view of the Moon's Casatus and Klap'roth craters was captured by the near-infrared camera on April 25, 1994. The image shows reflected light at 1.25 mm from an altitude of about 1300 km. The image is of an area 125 km ¥ 125 km.

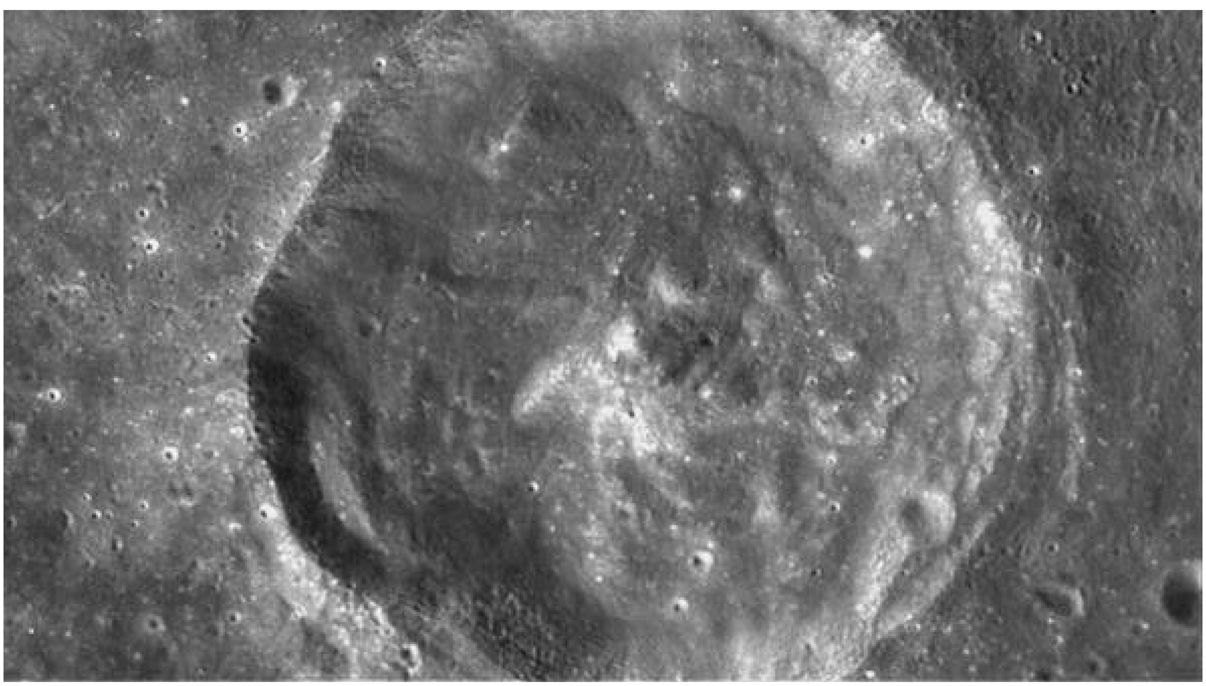


Figure 12. A view of the 35-km-diameter Rydberg crater taken by the near-infrared camera on March 6, 1994, from an altitude of 460 km.

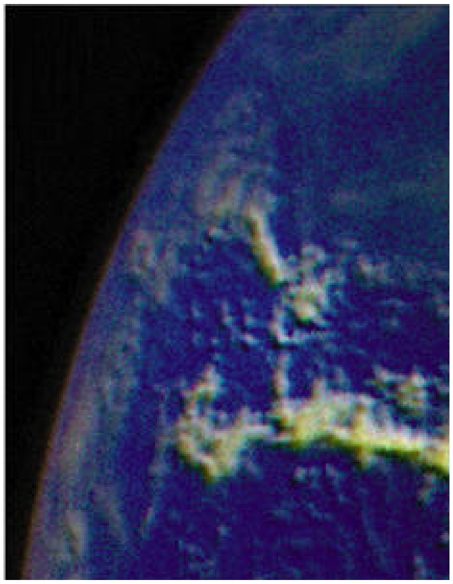


Figure 13. An image of Earth taken by the high-resolution camera on March 13, 1994, from lunar orbit at 1250 km above the surface of the Moon and 384,000 km from Earth.

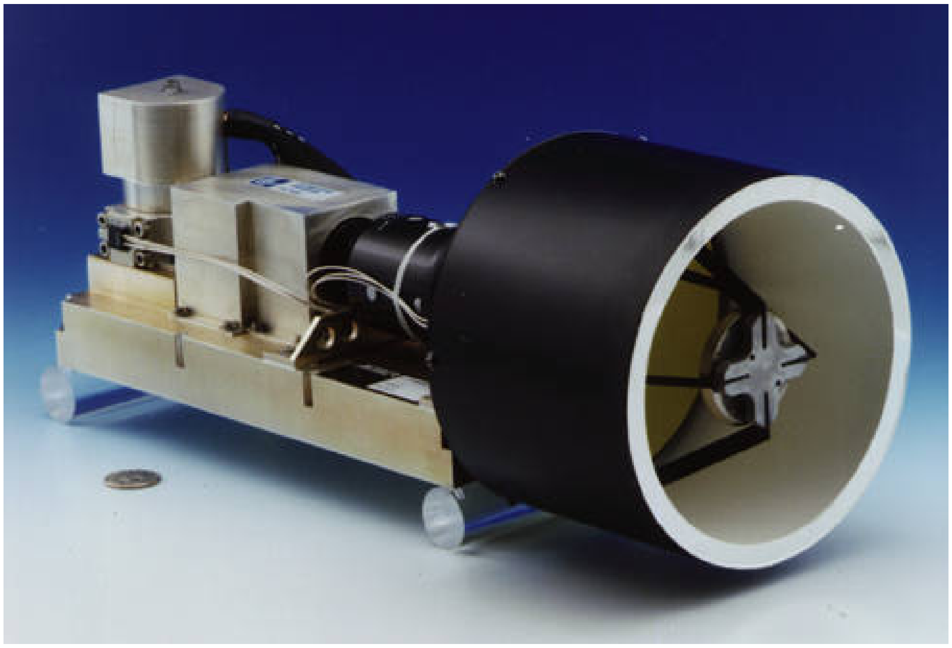


Figure 14. Operating in the thermal infrared region of the spectrum (8 to 9.5 µm), the long-wave infrared camera was used to measure thermal emission from the Moon's surface.

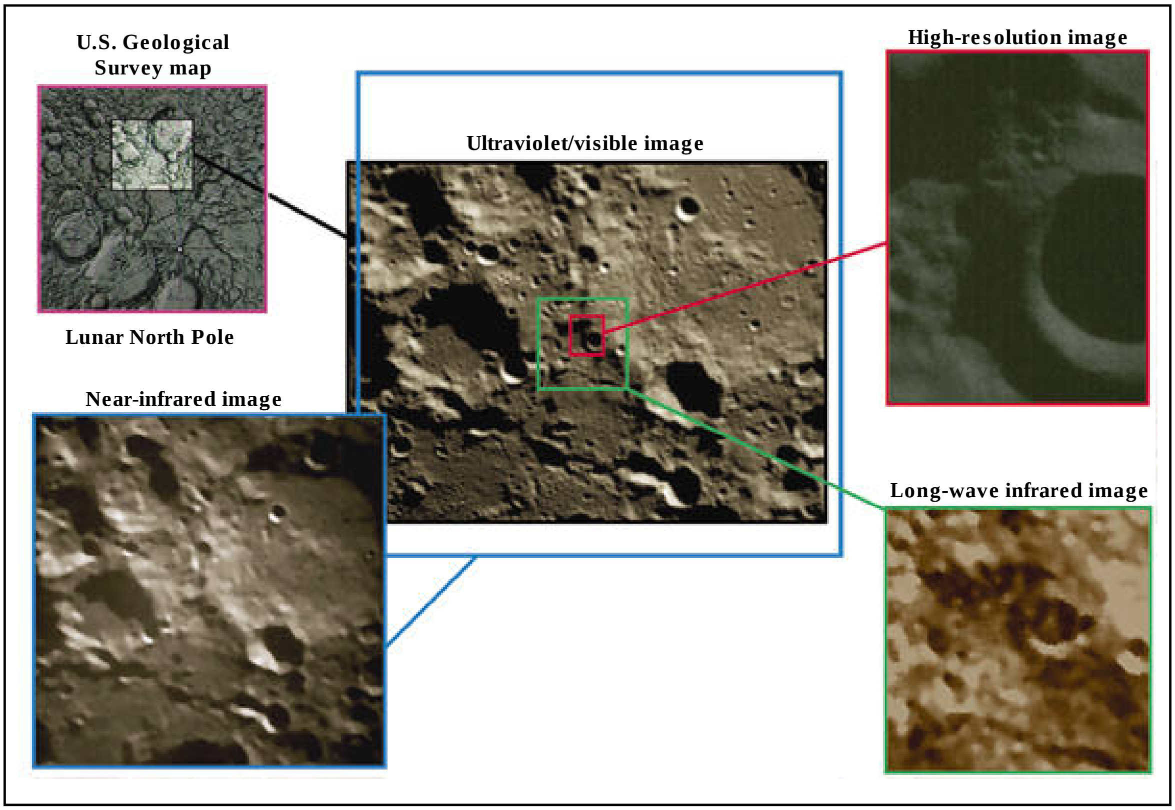


Figure 15. Detailed images of the Moon made possible by four of the LLNL-developed cameras that Clementine carried. A map of the lunar North Pole (latitude = 82° N; longitude = 104.6° E) provided by the U.S. Geological Survey can be used for comparison. This map (upper left), dating from 1985, was the state-of-the-art before the Clementine mission. Far greater detail is seen in images from the ultraviolet/visible, high-resolution, near-infrared, and long-wave infrared cameras. The latter four images were taken during Clementine's first lunar-mapping orbit on February 19, 1994.

Data Availability and Future Directions

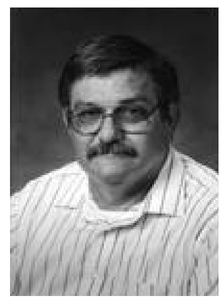
Clementine was launched successfully and on schedule. The amount of information it returned from lunar orbit alone will fill a small library of compact discs that will be distributed to NASA's Planetary Data System, a nationwide repository system for data returned from lunar and planetary flight projects and widely available to lunar and planetary scientists. Analyzing the data, including the results of a search for the existence of water on the lunar surface, will continue to occupy scientists for many years.

Students and teachers at all grade levels, and others across the country, can use Internet to access the pictures of the Moon and Earth taken by Clementine (see the box below). Information about the technology used to collect the data and explanations of how scientists are using these data are also available. This program is sponsored by LLNL's Science Education Program and the Department of Energy.

The miniaturized cameras, Star Trackers, powerful battery, and navigation instruments Clementine carried may aid in developing NASA's own line of small planetary missions (called Discovery) and its Martian environment survey (MESUR) program. Clementine may also provide a model for NASA's Lunar Scout—a pair of polar-orbiting spacecraft that will provide, among other things, a survey of the elements that make up the lunar crust and high-resolution images of the Moon's surface features.

Work funded by the Department of Defense's Ballistic Missile Defense Organization.

Key Words: asteroid—Geographos; imaging—Earth, Moon; missile—Titan IIG; satellite—Clementine; sensors—laser imaging, detection, and ranging (LIDAR) system, long-wave infrared (LWIR) camera, near-infrared (NIR) camera, Star Tracker Stellar Compass, ultraviolet/visible charge-coupled device (CCD) camera; spacecraft—Lunar Scout, Surveyor; space programs—Discovery, MESUR.



For further information contact Michael J. Shannon (510) 423-7580.

Exploring the Moon via Internet

Several million images have been taken of the Moon, Earth, and various star fields using the six LLNL-developed cameras on board the Clementine spacecraft. An extensive database containing thousands of Clementine images and information regarding the Clementine mission is currently available on a network server on Internet. This server, clementine.s1.gov, resides at LLNL from which network customers around the world can download images and access other information.

To access the images over the network, you must have networking software (TCP) on your local computer and a file transfer program, such as ftp. Mosaic can also be used to access the images. Mosaic is a graphical tool allowing users to browse through the data in a point and click fashion, pointing and clicking on highlighted areas to display additional information relevant to the highlighted topic. To access the images via Mosaic, open the URL named http://clementine.s1.gov.

To access the server via ftp, the process and software are somewhat different for each type of computer. Here is a list of some of the most commonly used local processors and a brief description of how to access the server.

- Macintosh users must be running MacTCP and get the "Fetch" program from one of a number of sources (e.g., ftp.dartmouth.edu). Start Fetch to go to host, clementine.s1.gov, with user name ftp. Any password will do.
- PC DOS users must be running TCP and get ftp client software on their local computers. To get started, run this ftp program to go to clementine.s1.gov.
- PC Windows users must be running Windows with Sockets and get ftp client software for their local computer (e.g., get ws_ftp.zip in /pub/pc/win3/winsock on ftp.cica.indiana.edu). You will need to unzip ws_ftp.zip and run this ftp progam to go to clementine.s1.gov.
- Unix users must be running TCP and have ftp installed on their local computers (these are bundled with most Unix systems). To get started, type ftp clementine.s1.gov.
- VAX/VMS users must be running Multi-Net or UCX and have ftp on the VAX. To get started, type ftp clementine.s1.gov.