

## **Post-Apollo Lunar Missions and Datasets**

### MUSES-A / Hiten

The Hiten spacecraft, built by the Institute of Space and Astronautical Science of Japan, was launched on January 24, 1990. It was Japan's first lunar probe, the first robotic lunar probe since the Soviet Union's Luna 24 in 1976, and the first lunar probe launched by a country other than Soviet Union or the United States. The only scientific instrument on Hiten was the Munich Dust Counter (MDC). On October 2, 1991 Hiten reached the Moon and went into a looping orbit which passed through the L4 and L5 Lagrange points to look for trapped dust particles. No obvious increase was found by the Munich Dust Counter (MDC). After two months in lunar orbit, the spacecraft's orbit was decaying, so the last of Hiten's fuel was used to crash it into the lunar surface on April 10, 1993.

### Galileo (1990, 1992)

The primary mission of the Galileo orbiter and probe was to explore Jupiter and its satellites. The Galileo spacecraft flew by the Earth and Moon on Dec. 8, 1990 and Dec. 8, 1992. The image at the top of the page is a false color image of the Moon created by combining 53 images taken from three different filters on Galileo during the 1992 flyby. Pink represents highlands, blue to orange denote volcanic flows.

These flybys gave Galileo an opportunity to image the Moon at various wavelengths with the Solid State Imaging (SSI) camera. The camera uses a high-resolution, 800 x 800 charge-coupled device (CCD) array with a field of view of 0.46 degrees. Multi-spectral coverage is provided by an eight-position filter wheel on the camera, consisting of three broad-band filters: violet (404 nm), green (559 nm), and red (671 nm); four near-infrared filters: 727 nm, 756 nm, 889 nm, and 986 nm; and one clear filter (611 nm) with a very broad (440 nm) passband.

### Clementine (1994)

The Clementine mission mapped most of the lunar surface at a number of resolutions and wavelengths from UV to IR. The DOD-developed spacecraft was launched on January 25, 1994 at 16:34 and the nominal lunar mission lasted until the spacecraft left lunar orbit on May 3. The image of the full Moon at the top of the page was taken on orbit 100, 15 March 1994 at 00:01:26 UT from 2200 Km by the Star Tracker camera. Clementine had five different imaging systems on-board. The UV/Visible camera had a filter wheel with six different filters, ranging from 415 nm to 1000 nm, and including a broad-band filter covering 400 to 950 nm. The Near Infrared camera also had a six-filter wheel, ranging from 1100 nm to 2690 nm. The Longwave Infrared camera had a wavelength range of 8000 to 9500 nm. The Hi-Res imager had a broad-band filter from 400 to 800 nm and four other filters ranging from 415 to 750 nm. The Star Tracker camera was also used for imaging.

### Lunar Prospector (1998-1999)

The Lunar Prospector mission was the third Discovery mission. It lasted for 19-months in a low polar orbit investigation of the Moon, including mapping of surface composition and possible polar ice deposits, measurements of magnetic and gravity fields, and study of lunar outgassing events. The mission ended July 31, 1999 when the orbiter was deliberately crashed into a crater near the lunar south pole in an unsuccessful attempt to detect the presence of water.

Data from the mission allowed the construction of a detailed map of the surface composition of the Moon, and helped to improve understanding of the origin, evolution, current state, and resources of the Moon. The spacecraft carried 6 instruments: a Gamma Ray Spectrometer, a Neutron Spectrometer, a Magnetometer, an Electron Reflectometer, an Alpha Particle Spectrometer, and a Doppler Gravity Experiment. The instruments were omnidirectional and required no sequencing.

- The Lunar Prospector Gamma Ray Spectrometer (GRS) provided global maps of elemental abundances on the lunar surface. The GRS recorded the spectrum of gamma rays emitted by

the radioactive decay of elements contained in the Moon's crust; and elements in the crust bombarded by cosmic rays and solar wind particles. The most important elements detectable by the GRS were uranium (U), thorium (Th), and potassium (K), radioactive elements which generate gamma rays spontaneously, and iron (Fe), titanium (Ti), oxygen (O), silicon (Si), aluminum (Al), magnesium (Mg), and calcium (Ca), elements which emit gamma rays when hit by cosmic rays or solar wind particles. The uranium, thorium, and potassium in particular were used to map the location of KREEP. The precision varies according to element measured. For U, Th, and K, the precision is 7% to 15%, for Fe 45%, for Ti 20%, and for the overall distribution of KREEP 15% to 30%. The GRS achieved global coverage with a surface resolution of 150 km.

- The LP Neutron Spectrometer (NS) was designed to detect minute amounts of water ice which were believed to exist on the Moon. It was capable of detecting water ice at a level of less than 0.01%. The Moon has a number of permanently shadowed craters near the poles with continuous temperatures of -190 °C. These craters may act as cold-traps of water from incoming comets and meteoroids. Any water from these bodies which found its way into these craters could become permanently frozen. The NS was also used to measure the abundance of hydrogen implanted by solar wind. The NS had a surface resolution of 150 km.
- The Doppler Gravity Experiment (DGE) was the first polar, low-altitude mapping of the lunar gravity field. The Clementine mission had previously produced a relatively low-resolution map, but the Prospector DGE obtained data approximately five times as detailed. The practical benefits of this are more stable long-term orbits and better fuel efficiency. Additionally, the DGE identified three new near-side mascons (mass concentrations). The experiment was designed to give the near-side gravity field with a surface resolution of 200 km and precision of 5 mGal (0.05 mm/s).
- The Magnetometer and Electron Reflectometer (collectively, MAG/ER) detected anomalous surface magnetic fields on the Moon. Field strengths as small as 0.01 nT could be measured with a spatial accuracy of about 3 km at the lunar surface. The MAG measured the magnetic field amplitude and direction at spacecraft altitude with a spatial resolution of about 100 km when ambient plasma disturbances were minimal.
- The Alpha Particle Spectrometer (APS) was designed to detect radon outgassing events on the surface of the Moon. These putative outgassing events, in which radon, nitrogen, and carbon dioxide are vented, are hypothesized to be the source of the tenuous lunar atmosphere, and may be the result of the low-level volcanic/tectonic activity on the Moon. Information on the existence, timing, and sources of these events may help in a determination of the style and rate of lunar tectonics. However, it was damaged during launch, and, due to sunspot activity peaking during the mission, the lunar data is obscured by solar interference. The APS has not yielded any useful results.

#### SMART-1 (2003 - 2006)

The SMART-1 (Small Missions for Advanced Research in Technology 1) is a lunar orbiter from the European Space Agency (ESA) designed to test spacecraft technologies for future missions. The primary technology tested was a solar-powered ion drive. It also carried an experimental deep-space telecommunications system and an instrument payload to monitor the ion drive and study the Moon. It entered initial lunar orbit on 13 November 2004. SMART-1 ended its mission by being deliberately crashed onto the Moon's surface at 34.24°S 46.12°W. Though no impact plume was seen, the impact may have kicked up a large quantity of fresh lunar "soil" detectable by other missions.

While testing these technologies, SMART-1 also mapped the lunar surface in X-ray and infrared, taking images from several different angles so that the Moon's surface can be mapped in three dimensions. It also determined the Moon's chemical composition using X-ray spectroscopy. A specific goal was to use infrared light to search for frozen water at the Moon's south pole, where some areas of the surface are never exposed to direct sunlight. SMART-1 also mapped the Moon's Peaks of Eternal Light (PELs), mountaintops which are permanently bathed in sunlight and surrounded by craters shaded in eternal darkness

- The Advanced Moon micro-Imager Experiment [AMIE] was a CCD camera with three filters of 750, 900 and 950 nm and an average pixel resolution of 80 m
- The Demonstration of a Compact X-ray Spectrometer [D-CIXS] detected the x-rays emitted by elements when interacting with the solar wind. D-CIXS mapped global abundances of magnesium, silicon and aluminium, and to a lesser degree, iron, calcium and titanium (depends on the solar activity). The X-ray solar monitor [XSM] studied the solar variability to complement D-CIXS measurements.
- The Smart-1 Infrared Spectrometer [SIR] was an infrared spectrometer for the identification of mineral spectra of olivine and pyroxene, at wavelengths from 0.93 to 2.4  $\mu\text{m}$  with 256 channels. Problems with the calibration continue to plague the SIR.

#### Chang'e 1 (2007 - 2009)

Chang'e 1 was launched at 10:05 GMT on October 24, 2007 from the Xichang Satellite Launch Center. It left lunar transfer orbit on October 31 and entered lunar orbit on November 5. The first picture of the Moon was relayed on November 26, 2007.[5] On November 12, 2008, a map of the whole lunar surface was released, produced from data collected by Chang'e 1 between November 2007 and July 2008.[6]

The mission was scheduled to continue for a year, but this was later extended and the spacecraft operated until March 1, 2009, when it was deorbited. It impacted the Moon at 08:13 UTC.[2]

The Chang'E mission had four primary goals.

- Global three-dimensional images of the landforms and geological structures of the lunar surface, so as to provide a reference for planned future soft landings.
- Analysing and mapping the abundance and distribution of various chemical elements on the lunar surface as part of an evaluation of potentially useful resources on the Moon. China hopes to extend the number of elements studied to 14 (K, Th, U, O, Si, Mg, Al, Ca, Te, Ti, Na, Mn, Cr, La), compared with the 10 elements (K, U, Th, Fe, Ti, O, Si, Al, Mg, and Ca) previously obtained by Lunar Prospector.
- Probing the features of the lunar soil and assessing its depth, as well as the amount of helium-3 ( $^3\text{He}$ ) present
- Probing the space environment between 40,000 km and 400,000 km from the Earth, recording data on the solar wind and studying the impact of solar activity on the Earth and the Moon.

The Chang'E instruments include:

- Stereo camera with an optical resolution of 120 m and spectrometer imager operating at wavelengths of 0.48  $\mu\text{m}$  to 0.96  $\mu\text{m}$ .
- Laser altimeter with 1064 nm, 150 mJ laser, a range resolution of 1 m and a spotsize of 300 m.
- Imaging spectrometer
- Gamma and X-ray spectrometer working in an energy range of 0.5 to 50 keV for X-rays and 300 keV to 9 MeV for gamma rays.
- Microwave radiometer detecting 3, 7.8, 19.35 and 37 GHz with a maximal penetration depth of 30, 20, 10, 1 m and a thermal resolution of 0.5 K.
- High energy particle detector and two solar wind detectors capable of the detection of electrons and heavy ions up to 730 Me

#### Kaguya/SELENE (2007-present)

The SELENE (Selenological and Engineering Explorer) mission was originally scheduled to launch in 2003, but rocket failures on another mission and technical difficulties delayed the launch until 2007. Launch was planned for August 16, 2007, but was postponed due to the discovery that some electronic components were installed incorrectly. SELENE was nicknamed Kaguya and launched on September 14, 2007 on an H-IIA (Model H2A2022) carrier rocket from Tanegashima Space Center

There are three separate units comprising the spacecraft: the main orbiter with the scientific instruments, Okina, a small relay satellite (formerly called Rstar) and Ouna, a VLBI satellite

(formerly called Vstar). Kaguya carries 13 scientific instruments, including imagers, a radar sounder, a laser altimeter, an X-ray fluorescence spectrometer and a gamma ray spectrometer. Their objectives are "to obtain scientific data of the lunar origin and evolution and to develop the technology for the future lunar exploration", according to the official website.

- Terrain camera (TC) (resolution 10 meters per pixel)[17]
- X-Ray fluorescence spectrometer (XRS)
- Lunar magnetometer (LMAG)
- Spectral profiler (SP) (resolution per pixel is 562 by 400 m)
- Multi-band imager (MI) (resolution of visible light 20 meters per pixel, near-infrared 62 meters per pixel)
- Laser altimeter (LALT)
- Lunar radar sounder (LRS)
- Gamma ray spectrometer (GRS)
- Charged particle spectrometer (CPS)
- Plasma analyzer (PACE)
- Upper atmosphere and plasma imager (UPI)
- Radio wave repeater (RSAT) aboard Okina
- Radio wave source for VLBI (VRAD) aboard Okina and Ouna
- Two HDTV cameras with 3\*CCD 2.2 megapixels, one wide-angle camera and one telephoto camera, primarily for public relations purposes.

The main scientific objectives of the mission are to study the origins of the Moon and its geologic evolution, obtain information about the lunar surface environment, and perform radio science on lunar orbit. Kaguya's major results so far include:

- Greatly improved lunar global topography map (from LALT)
- Detailed gravity map of the far side of the Moon showing gravity lows
- First optical observation of the interior of Shackleton crater

#### Chandrayaan-1 (2008-present)

Chandrayaan-1 is India's first mission to the Moon launched by India's national space agency, the Indian Space Research Organization (ISRO). The unmanned lunar exploration mission includes a lunar orbiter and an impactor. The spacecraft was successfully inserted into lunar orbit on 8 November 2008. On November 14, 2008, the Moon Impact Probe separated from the Moon-orbiting Chandrayaan at 20:06 and impacted the lunar south pole in a controlled manner, making India the fourth country to place its flag on the Moon.

The stated scientific objectives of the mission are:

- To design, develop, launch and orbit a spacecraft around the Moon using an Indian-made launch vehicle.
- Conduct scientific experiments using instruments on-board the spacecraft which will yield the following results:
- Preparation of a three-dimensional atlas (with high spatial and altitude resolution of 5-10 m) of both the near and far side of the Moon.
- Chemical and mineralogical mapping of the entire lunar surface at high spatial resolution, mapping particularly the chemical elements Magnesium, Aluminium, Silicon, Calcium, Iron, Titanium, Radon, Uranium, & Thorium.
- The impact of a sub-satellite (Moon Impact Probe — MIP) on the surface on the Moon as a fore-runner to future soft-landing mission

The scientific payload contains six Indian instruments and five foreign instruments.

- TMC or the Terrain Mapping Camera is a visible CCD camera with 5 m resolution and a 40 km swath in the panchromatic band and will be used to produce a high-resolution map of the Moon. The aim of this instrument is to completely map the topography of the Moon.

- HySI or Hyper Spectral Imager will perform mineralogical mapping in the 400-900 nm band with a spectral resolution of 15 nm and a spatial resolution of 80 m.
- LLRI or Lunar Laser Ranging Instrument determines the height of the surface topography
- C1XS or X-ray fluorescence spectrometer covering 1- 10 keV, will map the abundance of Mg, Al, Si, Ca, Ti, and Fe at the surface with a ground resolution of 25 km, and will detect solar flux
- HEX is a High Energy X-ray/gamma ray spectrometer for 30 – 200 keV measurements with ground resolution of 40 km, the HEX will measure U, Th, <sup>210</sup>Pb, <sup>222</sup>Rn degassing, and other radioactive elements
- MIP or the Moon Impact Probe developed by the ISRO, is an impact probe which consisted of a C-band Radar altimeter for measurement of altitude of the probe, a video imaging system for acquiring images of the lunar surface and a mass spectrometer for measuring the constituents of the lunar atmosphere
- SARA, The Sub-keV Atom Reflecting Analyser from the ESA will map composition using low energy neutral atoms sputtered from the surface
- M3, the Moon Mineralogy Mapper is an imaging spectrometer designed to map the surface mineral composition.
- SIR-2, A near infrared spectrometer will also map the mineral composition using an infrared grating spectrometer. The instrument will be similar to that of the Smart-1 SIR
- miniSAR is the active Synthetic Aperture Radar system to search for lunar polar ice. The instrument will transmit right polarised radiation with a frequency of 2.5 GHz and will monitor the scattered left and right polarised radiation.
- RADOM-7, Radiation Dose Monitor Experiment maps the radiation environment around the Moon

#### Lunar Reconnaissance Orbiter (2009) and Lunar CRater Observation and Sensing Satellite (LCROSS)

The Lunar Reconnaissance Orbiter (LRO) is a robotic spacecraft which the United States plans to place in orbit around the Moon. The launch date, originally planned to be October 2008, is currently scheduled for no earlier than May 20, 2009. LRO will be the first mission with a primary objective to implement the United States Vision for Space Exploration. To successfully attain the goals of "The Vision", that include human exploration of the Moon, LRO will survey lunar resources and identify possible landing sites. The LRO Atlas V launch vehicle will also carry the Lunar CRater Observation and Sensing Satellite (LCROSS), which is designed to detect water liberated as the launch vehicle's spent upper stage strikes a lunar crater.

Areas of investigation will include:

- Global topography.
- Characterization of deep space radiation in Lunar orbit.
- The lunar polar regions, including possible water ice deposits and the lighting environment.
- High-resolution mapping (max 0.5 m) to assist in the selection and characterization of future landing sites.

The orbiter will carry a complement of six instruments and one technology demonstration. LRO's high-resolution mapping will show some of the larger pieces of equipment previously left on the Moon, and will return approximately 70–100 TB of image data.

- CRaTER — The primary goal of CRaTER is to characterize the global lunar radiation environment and its biological impacts
- DLRE — The Diviner Lunar Radiometer Experiment will measure lunar surface thermal emission to provide essential information for future surface operations and exploration
- LAMP — The Lyman-Alpha Mapping Project will peer into permanently shadowed craters in search of water ice, seeing by the ultraviolet light from stars and the interplanetary medium
- LEND — The Lunar Exploration Neutron Detector will provide measurements, create maps, and detect possible near-surface water ice deposits

- LOLA — The Lunar Orbiter Laser Altimeter (LOLA) investigation will provide a precise global lunar topographic model and geodetic grid
- LROC — The Lunar Reconnaissance Orbiter Camera (LROC) has been designed to address the measurement requirements of landing site certification and polar illumination. LROC comprises a pair of narrow-angle cameras (NAC) and a single wide-angle camera (WAC).
- Mini-RF — This will demonstrate new lightweight SAR and communications technologies and locate potential water-ice.

Piggy-backing on the launch of LRO will be the Lunar CRater Observation and Sensing Satellite (LCROSS), which is designed to watch as the launch vehicle's Centaur upper stage strikes a permanently shadowed region near the south pole of the Moon. Spectral analysis of the resulting impact plume will help to confirm preliminary findings by the Clementine and Lunar Prospector missions which hinted that there may be water ice in the permanently shadowed regions. LCROSS will fly through the debris plume, then approximately 4 minutes after the Centaur impact will itself crash into a different part of the crater.